Late Holocene relative sea-level changes and earthquakes around the upper Cook Inlet, Alaska, USA

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Volume One

Main Text, Tables and References

by

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Declaration

This thesis is the result of my own work. Data from other authors that are referred to in the thesis are acknowledged at the appropriate point in the text.

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Late Holocene relative sea-level changes and earthquakes around the upper Cook Inlet, Alaska, USA

PhD Thesis Abstract, 2003

The earthquake deformation cycle (EDC) produces a sequence of specific relative land- and sea-level movements associated with large (magnitude>8) plate boundary earthquakes forming pre-seismic, co-seismic, post-seismic and inter-seismic periods. Measurements available for the 1964 Alaskan earthquake allow a comparison between late Holocene earthquakes and an event of known magnitude.

This thesis analyses multiple late Holocene co-seismic events at three sites around the upper Cook Inlet, Alaska, including at least one complete EDC at each site, quantified using transfer function techniques. Results describe five definite co-seismic events at Girdwood and one each at Kenai and Kasilof, with further possible events at all three sites. These fall within six periods of co-seismic submergence, including 1964, spaced at irregular intervals over the last 4000 years.

Quantitative reconstructions suggest that submergence resulting from most co-seismic events studied are of similar magnitude to the 1964 earthquake but it is not possible to identify whether pre-1964 events affected the same area. A key finding is the identification and quantification of pre-seismic relative sea-level (RSL) rise before all those events attributed to co-seismic submergence. The maximum magnitude of pre-seismic RSL rise is +0.21 ± 0.10 m and for the 1964 event starts approximately 10 years before the earthquake. This is strong evidence to suggest it represents a precursor to a large event and independent work elsewhere describes possible mechanisms for this phenomenon.

Long-term patterns of RSL change show significant differences between sites around Turnagain Arm compared to Kenai and Kasilof. The latter show negligible permanent deformation over multiple EDC's but this is not the case at sites around Turnagain Arm. Before attributing this to only partial recovery between two earthquakes, other factors deserve further attention, especially sediment consolidation, tidal range change through time and improvements in GIA modelling taking into account local ice sheet reconstructions.

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Chapter 1
Context

1.1 Introduction

Over the past 25 years, the primary aims of sea-level research have changed with the development of scientific methodology, field, laboratory and numerical techniques. The past decade has seen litho- and bio-stratigraphic techniques used to interpret Late Devensian and Holocene coastal stratigraphies in passive environments (e.g. Shennan, 1986; Shennan *et al.*, 1995) applied to coasts in seismically active areas. They have experienced some of the most rapid changes in relative sea level accompanying large plate boundary earthquakes during the Holocene. Palaeo-environmental research in this area is important as an understanding of the past can help us to understand the future response of the coast. This is necessary in areas such as the Pacific Northwest of the USA (Northern California, Oregon, Washington) and British Columbia, Canada, where there are no historical records of a major earthquake occurring since the Caucasians first settled in the area 200 years ago.

Land movements associated with the 1964 Alaskan earthquake affected a large amount of coastline in southern Alaska. These movements have been measured and well documented in scientific literature (e.g. Brown *et al.*, 1977; Plafker, 1965, 1969; Savage & Plafker, 1991), and alongside the litho- and bio-stratigraphic information now being collected, represent the most complete data set available to help interpret stratigraphies found elsewhere. This allows a comparison between Holocene co-seismic land movements against an event of known magnitude.

This thesis aims to identify major seismic and non-seismic controls on relative sea level in the upper Cook Inlet, Alaska. Sections 1.2 to 1.6 outline the major controls on relative sea level along seismically active coasts, focusing in particular on the seismic controls associated with the earthquake deformation cycle (section 1.3) in south central Alaska. Sections 1.7 to 1.10 review the main techniques and literature relevant to this thesis and finally 1.11 defines the aims and objectives.

1.2 Controls on relative sea level

Plafker *et al.* (1992) suggest the interaction of four factors control relative sea level on seismically active coasts and determine whether a shoreline is stable, undergoes long-term net uplift or subsidence:

1. Tectonic uplift or subsidence of the land relating to relative land- and sea-level movements associated with the earthquake deformation cycle model
2. Eustatic sea-level change resulting from variations in ocean volume due to the growth and decay of ice sheets
3. Isostatic changes from the loading or unloading of continental shelves mainly due to glacio-isostatic and hydro-isostatic contributions
4. Sediment compaction resulting from sediment accumulation or ground shaking associated with an earthquake

1.3 Seismic controls on relative sea level

Seismic controls on relative sea-level change relate to the earthquake deformation cycle (EDC) (e.g. Savage, 1983; Thatcher, 1984a). This includes a sequence of relative land- and sea-level movements associated with large (magnitude 8 or 9) plate boundary earthquakes. In its simplest form (figure 1.1), the proposed model has two stages (Long & Shennan, 1994):

A) The inter-seismic period

During the inter-seismic period, slow strain accumulation along a seismogenically locked portion of the plate boundary causes the upper continental plate to shorten. It results in relative land subsidence close to the trench and uplift further landward.

B) The co-seismic period

An earthquake releases strain through slip along the locked portion of the plate boundary allowing the upper continental crust to extend. It results in sudden relative land uplift close to the plate boundary and sudden co-seismic submergence further landward. Near the plate boundary, deformation tends to be large but decays rapidly with time whereas at greater distances, deformation is smaller but it decays more slowly (Nelson *et al.*, 1996).

Following the co-seismic period, the inter-seismic period begins once more. This sequence of complex movements is dependent on distance from the plate boundary (e.g. Long & Shennan, 1994; Mitchell *et al.*, 1994; West & McCrumb, 1988).

Co-seismic submergence

In estuarine environments where co-seismic subsidence takes place, rapid submergence of the tidal and freshwater marshes occurs. The stratigraphy produced is a series of peat-silt couplets, the litho- and bio-stratigraphy of which record these relative sea-level changes (figure 1.2). The peat layers typically have a diffuse lower contact and show a gradual upward increase in organic content. They have a sharp upper contact overlain by silt and clay (figure 1.2a), similar to modern tidal sediment (e.g. Combellick & Reger, 1994; Shennan *et al.*, 1999). The deposition of a coarse sand layer at the peat-silt boundary possibly indicates a tsunami (figure 1.2b; Atwater, 1987). In addition, liquefaction features such as vented sand volcanoes may erupt onto the peat surface because of seismic shaking (figure 1.2c, Atwater & Hemphill-Haley, 1997).

However, peat-silt couplets with sharp upper contacts also form on passive coastal margins. Their formation is a result of non-seismic processes, for example, storm surges, local flooding, changes in tidal range, sediment supply and to the geomorphology of the tidal inlet, rather than gradual relative sea-level change. Nelson *et al.* (1996) suggest the investigation of five criteria before attributing the formation of a peat-silt couplet found on a subduction zone coast to seismic rather than non-seismic origin. They are:

1. Suddenness of submergence

   The presence of laterally extensive couplets of mud over peat with a sharp upper contact suggests rapid relative sea-level rise. Other evidence includes submerged trees that were healthy until death (e.g. Atwater & Yamaguchi, 1991; Yamaguchi *et al.*, 1989) and the presence of growth position stems of herbaceous plants rooted in the peat. This indicates the sharp upper boundary was not a result of erosion.

2. Amount of submergence

   Litho- and bio-stratigraphical evidence suggesting sudden submergence over 1.0 m is likely to be co-seismic in origin. For example, the presence of ghost forests rooted in the buried peat represents sudden submergence from freshwater to tidal flat environments. In addition, Atwater (1992) suggests that a sudden transition from peat to *Triglochin maritima* marsh (a pioneer community) represents a minimum submergence of 0.5 m.

3. Lateral extent of peat-silt couplets with sharp upper contacts
   Such couplets found across estuaries and in-between estuaries rule out their formation by local processes.

4. Tsunami deposits
   Sand sheets abruptly overlying peat that decrease in thickness, become finer grained and rise in a landward direction suggest a tsunami deposit associated with sudden co-seismic movements.

5. Synchroneity of submergence
   Radiocarbon dating that suggests exactly the same ages of peat-silt couplets at multiple sites indicates sudden co-seismic submergence and allows the estimation of recurrence intervals. However, there are many complicating factors, for example, earthquakes that occur in quick succession may not produce peat-silt couplets and there is the possibility of peat decomposition after burial (Atwater & Hemphill-Haley, 1997).

More recently, litho- and bio-stratigraphic evidence allow a detailed reconstruction of relative land- and sea-level movements. Microfossils help distinguish between seismic and non-seismic origins of peat-silt couplets (e.g. Long & Shennan, 1994; Nelson *et al.*, 1996) and the tendency approach (e.g. Shennan, 1986; Shennan *et al.*, 1983, 1995) helps in the recognition of periods within the EDC model (e.g. Long & Shennan, 1994). A positive sea-level tendency represents an increase in marine influence and a negative sea-level tendency represents a decrease in marine influence.

Co-seismic uplift

During a large magnitude earthquake, areas between the subduction zone and the region of submergence experience co-seismic uplift (figure 1.1). The elevation of uplifted marine terraces and intertidal fossiliferous sediment give an estimate of earthquake magnitudes and if dated, gives an estimate of recurrence intervals. Holocene marine terraces exist in Alaska (e.g. Plafker & Rubin, 1978), Chile (e.g. Kaizuka *et al.*, 1973) and Japan (e.g. Matsuda *et al.*, 1978).

1.4 Pacific Northwest of the USA and Canada

At the Cascadia subduction zone (figure 1.3), subduction of the Juan de Fuca plate beneath the North American plate occurs at a rate of approximately 30 to 40 $mmyr^{-1}$

(Heaton & Kanamori, 1984). There are no historical records of a major earthquake occurring along this coastline since settlement 200 years ago, but palaeo-seismic evidence suggests that great prehistoric earthquakes have occurred, with an average recurrence interval of 300 to 500 years (Mitchell *et al.*, 1994).

The stratigraphy of coastal marshes show multiple peat-silt couplets and buried forests, indicative of co-seismic relative land- and sea-level movements (e.g. Atwater, 1987, 1992, 1996; Atwater *et al.*, 1995; Atwater & Hemphill-Haley, 1997; Darienzo & Peterson, 1990; Darienzo *et al.*, 1994; Guilbault *et al.*, 1995, 1996; Hemphill-Haley, 1995a; Hughes *et al.*, 2002; Kelsey *et al.*, 2002; Long & Shennan, 1994; Mathewes & Clague, 1994; Nelson *et al.*, 1995, 1996, 1998; Peterson & Darienzo, 1996; Reinhardt *et al.*, 1996; Shennan *et al.*, 1996, 1998; Sherrod *et al.*, 2000). Shennan *et al.* (1996, 1998) identify eight episodes of rapid tidal marsh submergence over the last 5000 years at John's River, Washington, and four co-seismic submergence events over the past 3500 years at Netarts Bay, Oregon. Other evidence includes coastal deposits of tsunami generated sand layers (e.g. Atwater, 1992; Benson *et al.*, 1997; Clague *et al.*, 2000; Hemphill-Haley, 1996; Williams & Hutchinson, 2000) and deep-sea turbidites in the tributaries of the Cascadia channel (e.g. Adams, 1990). Geological data helps to constrain models of glacio-isostatic rebound, elastic *versus* permanent deformation, and provides a long-term constraint on geophysical models of the Cascadia subduction zone (Long & Shennan, 1998). They are important because tide gauge measurements, levelling surveys and GPS data are limited to the past few decades.

Numerous authors describe comparable work along the coastline of Japan (e.g. Hayashi, 1966; Maeda *et al.*, 1992; Mazzotti *et al.*, 2000; Sagiya & Thatcher, 1999; Savage & Thatcher, 1992; Sawai, 2001a; Thatcher, 1984b; Thatcher & Matsuda, 1981; Tsubokawa *et al.*, 1965). For example, the 1944 and 1946 earthquakes had an estimated magnitude of M_w=8 (Heaton & Hartzell, 1986) and an associated maximum tectonic submergence of 0.5 m (Ando, 1975) in southwest Japan.

It is now possible to compare these changes, both in the Pacific Northwest of the USA and Canada and Japan, against known movements associated with the 1964 Alaskan earthquake. Section 1.5 concentrates on this event and geologic evidence for Holocene events in south central Alaska.

1.5 South central Alaska

1.5.1 The 1964 Alaskan Earthquake

Southern Alaska is seismically very active, being located above a convergent plate margin, the north dipping Aleutian Megathrust (Bartsch-Winkler & Schmoll, 1992) where the Pacific and North American plates converge at approximately 6.3 $cmyr^{-1}$ in a N18°W direction (e.g. DeMets *et al.*, 1990; Minster & Jordan, 1978). On March 27, 1964, the world's second largest recorded earthquake occurred with a magnitude of 9.2 (e.g. Kanamori, 1977; Nishenko & Jacob, 1990), four years after the largest ever recorded earthquake of magnitude 9.5 in Chile (e.g. Atwater *et al.*, 1992; Bourgeois & Reinhart, 1989; Plafker, 1972). The 1964 epicentre was in northern Prince William Sound (figure 1.4) approximately 130 km east of Anchorage and 70 km west of Valdez (Christensen & Beck, 1994), although another asperity of smaller moment release was off Kodiak Island (Doser *et al.*, 1999). It was accompanied by vertical and horizontal tectonic deformation and tilting of the land over an area of 170,000 to 200,000 km^2 (Plafker, 1969). Co-seismic subsidence occurred over an elongate region (figure 1.4) including Kodiak Island, Kenai Peninsula, most of Cook Inlet and Copper River basin. Co-seismic uplift (as much as 11.3 m) occurred seaward of the subsidence zone, in an elongate region including Middleton Island, Montague Island, most of Prince William Sound and Copper River Delta (Combellick, 1994). The simplified contours of co-seismic uplift and subsidence in figure 1.4, derived from Plafker (1969), hide many local scale variations. In addition, for some areas they are based on interpolations over long distances. Following chapters give the best estimates for each of the field sites.

Resulting tsunami waves (Plafker, 1965) affected the Gulf of Alaska including the Pacific coast of the Kodiak Islands group and Kenai Peninsula, Prince William Sound and regions further away. For example, they moved southward across the Pacific Ocean at a velocity of 830 $kmhr^{-1}$, causing approximately $40 million damage on Vancouver Island alone (e.g. Clague & Bobrowsky, 1994; Clague *et al.*, 2000). The earthquake also produced numerous submarine and subaerial landslide-generated tsunami, each affecting relatively small areas but often causing considerable damage. Communities damaged by such tsunamis include Seward, Valdez and Homer (figure 1.4) but there were many other slides in sparsely inhabited areas, especially around Prince William Sound, adjacent to the epicentre (Plafker et al., 1969). In contrast to the Pacific coast, the sheltered waters extending from the northwest coast of Kodiak Island into the Cook Inlet as far as Seldovia and Homer (figure 1.4) experienced a diminished effect (Plafker *et al.*, 1969). Further north up the Cook Inlet, no tsunami occurred at

Kenai or any location along the Turnagain and Knik Arms (Plafker et al., 1969; Combellick, 2003 email communication).

1.5.2 Seismic displacements within the Cook Inlet

Co-seismic subsidence during the 1964 event was largest (>2 m) along a NE-SW axis near Portage and decreased westward to <0.6 m along the west coast of the Kenai Peninsula (Combellick, 1997). This resulted in the flooding of forests and tidal marshes at numerous locations around the Cook Inlet (figure 1.4). The rapid relative sea-level rise killed and preserved the vegetation (e.g. Bartsch-Winkler & Schmoll, 1992; Combellick & Reger, 1994; Ovenshine *et al.*, 1976) resulting in a buried peat layer that contains a large amount of plant material and remains of a forest (e.g. Bartsch-Winkler & Schmoll, 1992; Combellick, 1994, 1997; Combellick & Reger, 1994; Shennan *et al.*, 1999). This peat is sharply overlain by minerogenic material consisting predominantly of marine deposited silt and clay that rapidly accumulated following the earthquake (e.g. Atwater *et al.*, 2001; Bartsch-Winkler *et al.*, 1983; Bartsch-Winkler & Schmoll, 1992; Combellick, 1991; Ovenshine *et al.*, 1976). No tsunami propagated up the Turnagain Arm (section 1.5.1) but numerous clastic dykes associated with liquefaction are visible in the Portage area (Combellick, 1997; Walsh *et al.*, 1995).

1.5.3 Current rates of deformation

Several authors have studied the rapid post-seismic uplift experienced since the 1964 earthquake (figure 1.4) through levelling, GPS and tide gauge measurements (e.g. Brown *et al.*, 1977; Cohen, 1996, 1998; Cohen & Freymueller, 1997, 2001; Cohen *et al.*, 1995; Freymueller *et al.*, 2000; Plafker *et al.*, 1992; Savage & Plafker, 1991; Savage *et al.*, 1998; Zweck *et al.*, 2002). Levelling data indicates 15 cm of uplift around the Turnagain Arm occurred in the first year after the 1964 event. This decreased with time to give a maximum cumulative uplift of 50 cm over a decade (Brown *et al.*, 1977; Cohen, 1998). In the middle of the Kenai Peninsula, GPS measurements record up to 1.0 m post-seismic uplift over the past 30 years (Cohen, 1996; Cohen & Freymueller, 1997; Cohen *et al.*, 1995; Zweck *et al.*, 2002). GPS observations also record spatial variability in the contemporary horizontal motion of the Kenai Peninsula with NNW movement in the east, and SE movement in the west (Cohen & Freymueller, 2001). In all areas, post-seismic uplift together with sediment accumulation has allowed the development of new marsh and forest areas above tidal flat sediments (e.g. Atwater *et al.*, 2001; Bartsch-Winkler, 1988; Bartsch-Winkler & Schmoll, 1992; Combellick, 1997).

In contrast, tide gauge data do not register these rapid movements and record only small uplift rates. For example, Savage and Plafker (1991) and Cohen and Freymueller (2001) estimate rates of sea-level change at various locations around the Cook Inlet (table 1.1).

Table 1.1 Rates of sea-level change around the Cook Inlet. Site locations are in figure 1.4 and dates in brackets show the time intervals included in the calculation

Location	**Rates of sea-level change (mmyr^{-1})**	
	Cohen & Freymueller (2001)	**Savage & Plafker (1991)**
Seldovia	-9.3 ± 0.8 (1966-1998)	-7.2 ± 1.4 (1964-1988)
Nikiski	-9.9 ± 0.8 (1972-1998, no data from 1981-1996)	-18.7 ± 1.7 (1971-1979)
Anchorage	+0.8 ± 1.3 (1984-1998)	+1.9 ± 1.9 (1964-1988)

Cohen and Freymueller (2001) predicted uplift rates by taking the negative of the apparent rate of sea-level change and adding 2 mmyr^{-1} to account for eustatic sea-level change and postglacial rebound. From these data, they infer a crustal uplift rate of approximately 10 mmyr^{-1} at Seldovia and Nikiski along the west coast of the Kenai Peninsula and very little, if any, vertical crustal movement at Anchorage. This suggests a complex relationship between the amount of co-seismic submergence and the spatial and temporal patterns of post-seismic uplift.

Numerous authors suggest that the rapid uplift along the Turnagain Arm and the large cumulative uplift observed on the Kenai Peninsula indicates post-seismic slip along the plate interface at depths greater than that slipped during the earthquake (e.g. Brown *et al.*, 1977; Cohen 1996; Cohen *et al.*, 1995). Cohen and Freymueller (2001) suggest that an elastic dislocation model, attributing the deformation to strain accumulation at the locked plate boundary, may be responsible for movement in the eastern Kenai Peninsula. In contrast, for the western Kenai Peninsula, Cohen and Freymueller

(2001) suggest ongoing slip at depth, inferring that Seldovia and Nikiski lie in a tectonically different environment than the sites on the eastern side of the Kenai Peninsula.

The rapid rates of land uplift measured since 1964 cannot continue for the entire inter-seismic period and have slowed down substantially since the initial study by Brown *et al.* (1977). This rapid uplift introduces a third period into the EDC model (section 1.3) comprising co-seismic submergence, rapid post-seismic uplift and slower inter-seismic uplift.

1.5.4 Previous earthquakes in the area

Because of the short historic record of south central Alaska, data on earthquake recurrence intervals is poor, with translated Russian documents providing information before 1897 (Bartsch-Winkler & Schmoll, 1992). Seismic monitoring has complemented measurements taken before and after the 1964 event, but geologic evidence provides the only reliable method of deducing earthquake recurrence intervals (e.g. Bartsch-Winkler & Schmoll, 1992; Combellick, 1991, 1997; Plafker *et al.*, 1992).

In a number of localities around the Cook Inlet, the coastal stratigraphy comprises multiple peat-silt couplets at varying depths. Before the 1964 earthquake, Karlstrom (1964) attributed the burial of a forest layer at Girdwood to eustatic sea-level change. However, recent investigations suggest that these deposits record a history of relative sea-level movements associated with late Holocene earthquakes (e.g. Combellick, 1994). Radiocarbon dating of the buried peat layers around the Cook Inlet indicates a maximum of nine co-seismic events over the past 5000 cal yr BP, suggesting an average recurrence interval of 600 to 800 years (e.g. Combellick, 1991, 1994, 1997; Combellick & Reger, 1994; Plafker *et al.*, 1992). Many authors suggest the penultimate great earthquake to affect the Cook Inlet area occurred 600 to 900 cal yr BP (e.g. Combellick, 1991, 1993, 1994, 1997; Mann & Crowell, 1996; Plafker *et al.*, 1992). However, these estimates assume that all of the peat-silt couplets are seismic in origin, and do not record non-seismic relative sea-level change.

Other evidence indicating large plate boundary earthquakes include geomorphological features, for example, co-seismically uplifted terraces on Middleton Island, found closer to the subduction zone (figure 1.4). Radiocarbon dating from material within these terraces suggest uplift by 40 m in at least five distinct pulses during the past ~5100 cal yr BP, with a mean inter-seismic period of approximately 1000 years (Plafker *et al.*, 1992). The most recent uplift preserved by Middleton Island terraces was about 1300 cal yr BP and a terrace is now forming due to 3.3 m of uplift during the 1964 event (e.g. Nishenko & Jacob, 1990; Plafker *et al.*, 1992; Plafker & Rubin, 1967, 1978).

1.5.5 Long term tectonic deformation

The buried peat-silt couplets found around the Cook Inlet area suggest there has been long-term net land subsidence or relative sea-level rise. Plafker (1969) indicates this represents a significant downward directed component of regional strain preceding the earthquake with its duration being the approximate time interval since the last major tectonic earthquake in the same region. Other evidence includes cirque floors along the south coast of the Kenai Peninsula ranging in altitude from approximately 91 m below sea level to 245 m above sea level (Plafker, 1969; Plafker and Rubin, 1967). Schmoll *et al.* (1997) also report that the subsurface beneath the Anchorage lowland preserves evidence of a number of past glaciations that probably formed above sea level but are now 20 to 300 m below. Plafker and Rubin (1967) suggest that regional diastrophic deformation can only explain the submergence of the Kenai and Kodiak mountains but the balance between long-term tectonic deformation in the area and non-seismic controls is unclear.

1.6 Non-seismic controls on relative sea level

In addition to the seismic controls on relative sea level reviewed in section 1.5, non-seismic controls such as eustasy, isostasy and compaction affect the coastline of south central Alaska.

Eustatic and isostatic changes

Numerous authors (e.g. Mann & Peteet, 1994; Reger & Pinney, 1996, 1997) estimate that glacial ice inundated the Cook Inlet trough during the Last Glacial Maximum (LGM) approximately 22 ka cal yr BP. During this period the estimated ice thickness between Kenai and Kasilof was at least 315 to 335 m (Reger & Pinney, 1996), eustatic sea level was 125 ± 5 m lower than the present day (Fleming *et al.*, 1998) and the floor of the Cook Inlet trough was isostatically depressed a minimum of 105 to 112 m (Reger & Pinney, 1996).

Subsequently, these ice masses receded into their upland source areas depositing the glacioestuarine Bootlegger Cove Formation (e.g. Rymer and Sims, 1982; Schmoll & Yehle, 1986; Schmoll *et al.*, 1996) and eustatic sea-level rise and glacio- and hydro-isostatic rebound has occurred. Isostatic effects should be rapid in this tectonically active area due to the mantle having a low viscosity and strength (e.g. Thorson, 1989). Numerous authors (e.g. Clague *et al.*, 1982; Clague & James, 2002; James *et al.*, 2000; Matthews *et al.*, 1970; Williams & Roberts, 1989) investigate postglacial rebound at the northern Cascadia subduction zone and indicate that postglacial rebound was almost complete by the early to middle Holocene, following disappearance of the Cordilleran ice sheet at the end of the Pleistocene. Given a comparable tectonic setting, Combellick (1994) suggests that around the Cook Inlet glacio-isostatic rebound from the LGM was complete by 7000 cal yr BP.

Stratigraphical evidence shows that marine waters invaded middle Cook Inlet as early as ~19.7 ka cal yr BP and reached the upper Cook Inlet about 17.9 ka cal yr BP (Schmoll, 1977; Schmoll *et al.*, 1972; Reger & Pinney, 1996). More recently, models of eustasy predict a relative sea-level rise of 1.03 $mmyr^{-1}$ to 1.23 $mmyr^{-1}$ with no significant oscillations between 7000 and 4000 cal yr BP, with this rate slowing down to between 0.35 $mmyr^{-1}$ and zero from 4000 cal yr BP to the present day (Fleming *et al.*, 1998; Peltier, 1998).

Geophysical modelling can also estimate the isostatic component, for example, the ICE-4G and ICE-5GP models proposed by Peltier (2002) predict a current relative sea-level rise of approximately 0.5 ± 0.5 $mmyr^{-1}$ in south central Alaska due to glacio-isostatic adjustments. This contrasts with Cohen and Freymueller's (2001) assumption that over the past 35 years, eustatic sea level and postglacial rebound represents a rise of 2 $mmyr^{-1}$ around the Cook Inlet and Kenai Peninsula. However, these estimates are poorly constrained due to the limited availability of actual measurements and observations. These eustatic and isostatic components are further complicated by a number of smaller glacial advances and retreats, the last being the Little Ice Age, approximately 650 to 100 cal yr BP (e.g. Wiles & Calkin, 1994).

Other non-seismic controls

Other non-seismic effects on relative sea level include consolidation due to the weight of overlying sediment and during strong ground shaking. Plafker *et al.* (1992) suggest this is likely to be negligible in thin sediment sequences on or near bedrock, but could be locally significant in areas of thick, saturated sediments such as in the upper Cook

Inlet and the Copper River Delta. During the 1964 event, Plafker *et al.* (1969) estimated approximately 1.5 m of regional subsidence at Girdwood, but then added to this was 0.9 m of local subsidence due to compaction of the underlying sediment. Combellick (1994) also suggests that the depth of mud overlying the 1964 peat layer at Chickaloon Bay is greater than at Girdwood due to compaction-related subsidence of thicker unconsolidated material. Further processes, discussed later, include changes in tidal range, storm frequency and the El Nino Southern Oscillation (ENSO).

1.7 Investigation of relative sea-level change using microfossils

It is possible to distinguish seismic from non-seismic relative sea-level changes by investigating microfossils contained within the sediment. Numerous sea-level studies use diatoms (e.g. Hemphill-Haley, 1995b; Zong & Horton, 1999), pollen (e.g. Shennan, 1982; Hughes *et al.*, 2002), foraminifera (e.g. Scott & Medioli, 1978; Edwards & Horton, 2000) and testate amoebae (e.g. Charman *et al.*, 1998, 2002; Roe *et al.*, 2002). In a comparative study, Gehrels *et al.* (2001) found that diatoms and testate amoebae are the most accurate and precise sea-level indicators in UK salt marshes. In this PhD, diatoms are the main microfossil group studied as they live in all parts of the contemporary marsh, from the mudflat through to diverse raised bog communities. Foraminifera are rare (Hamilton, 1998) and pollen have an associated lag time from the change in environment to the development of different plants on new marsh areas.

Diatoms are microscopic, unicellular members of the Bacillariophyta of the algal kingdom that secrete a frustule or siliceous shell structure (Lowe & Walker, 1997). They range in size from 5 μm to 2 mm depending on species and live in the photic zone of most aqueous environments, existing in benthic, epiphytic, epilithic and planktonic forms (Lowe & Walker, 1997).

They are good sea-level indicators as their zonation across the marsh surface relates to tidal inundation, and hence, altitude of the marsh (e.g. Zong and Horton, 1999). Other influencing environmental conditions include: nutrients; pH; substrate preference; vegetation; water salinity; temperature and illumination (e.g. Denys, 1991; Juggins, 1992; Vos & de Wolf, 1993). Winter freezing of marsh surfaces and tidal channels is an additional factor needing consideration. The halobian system classifies diatoms by their salinity preference and divides them into polyhalobous, mesohalobous, oligohalobous-halophilous, oligohalobous-indifferent, and halophobous groups. However, other classifications also exist, which subdivide species by life form, pH, trophic conditions, oxygen requirement and tolerance to intertidal exposure (e.g. Denys, 1991).

All palaeo-environmental studies assume that past environments are similar to those found at the present day. However, a number of factors influence the composition of fossil diatom assemblages. These include the differential preservation of species due to their dissolution susceptibility, fragmentation and predation (e.g. Ryves *et al.*, 2001; Vos & de Wolf, 1993). There is also the debate between autochthonous *versus* allochthonous species. Autochthonous diatoms live in the place of deposition where as those that have undergone transportation, both vertically and horizontally are allochthonous. In low energy environments, such as lakes, allochthonous species are low, but in high-energy environments such as coastal areas, their numbers increase (Beyens & Denys, 1982; Vos & de Wolf, 1988, 1993). Sawai (2001b) suggests the transportation of dead frustules/valves in the early stages of fossilisation alter all diatom assemblages resulting in:

1. An upland assemblage that is autochthonous
2. A high marsh assemblage that is autochthonous due to limited tidal influence
3. A low marsh assemblage that is both autochthonous and allochthonous due to increased tidal influence
4. The removal of dead diatoms by tidal currents in the mudflat area results in a residual tidal flat assemblage

In addition, transport of diatoms by floating blocks of ice in the winter months may be important.

Qualitative interpretations classify diatom taxa into freshwater, brackish or marine forms. More recently, statistical modelling of the relationship between contemporary biological and environmental data, for example, diatoms and their relationship to a reference tide level, allows a transfer function (Imbrie & Kipp, 1971) to transform fossil biological data into quantitative estimates of relative sea-level change (Birks, 1995). Such studies include Edwards (2001), Edwards and Horton (2000), Gehrels (2000), Gehrels *et al.* (2001), Horton *et al.* (1999, 2000), Hughes *et al.* (2002) and McQuiod (2001). However, Gehrels (2000) suggests that the accuracy of the reconstruction depends on the training set, selecting the best regression model and standardising data sets from sites with different tidal regimes.

1.8 Dating techniques

This study uses radiocarbon and radionuclide dating to date sediment of different ages. It also considers tephrochronology where relevant and following sections review these approaches. Dendrochronolgy was not used because suitable tree remains were limited to the 1964 event.

1.8.1 Radiocarbon dating

Using peat-silt couplets of both co-seismic and non-seismic origin, radiocarbon (^{14}C) dating has focused mainly on transgressive and regressive contacts that have a known altitudinal relationship with sea level. All living organisms continually absorb ^{14}C through the carbon dioxide cycle but upon death, no replenishment takes place and so the amount present begins to decrease. Using its half-life (5570 ± 30 ^{14}C years), measurement of the remaining ^{14}C provides an age of death for sediment approximately 10^5 yr BP through to ~250 yr BP (Lowe & Walker, 1997). Two approaches measure the amount of ^{14}C in a sample, conventional radiocarbon dating and Accelerator Mass Spectrometry (AMS). This study uses AMS dating.

1.8.2 Radionuclide dating

Caesium-137 and lead-210 allow the dating of salt marsh sediment deposited over the last 100 to 150 years.

Caesium-137

Caesium-137 (^{137}Cs) is an artificially generated radionuclide (half-life of 30 years) deposited in sediment because of the atmospheric testing of nuclear weapons (e.g. Milan *et al.*, 1995; Pennington *et al.*, 1973, 1976; Wise, 1980). Using the shape of the ^{137}Cs profile (concentration *versus* depth), it is possible to identify two marker horizons in a well-preserved record:

1. 1954, the base of detectable ^{137}Cs activity
2. 1964, the peak of ^{137}Cs deposition due to the Nuclear Test Ban Treaty (e.g. Milan *et al.*, 1995; Patrick & DeLaune, 1990; Williams & Hamilton, 1995)

Since 1964, ^{137}Cs concentration has generally decreased, although the Chernobyl accident of 1986 provides another datable horizon in some localities (e.g. Ehlers *et al.*, 1993; Higgitt, 1995). ^{137}Cs has dispersed globally with greater levels in the northern hemisphere and a peak in mid latitudes (e.g. Davis, 1963). There is also regional variation in the year of peak ^{137}Cs deposition, probably reflecting time lags introduced by atmospheric circulation and local fluvial reworking of fallout from watershed surfaces (e.g. Craft *et al.*, 1993).

Lead-210

In comparison to ^{137}Cs, lead-210 (^{210}Pb) is a natural isotope and forms part of the ^{238}Uranium decay series. It provides a reliable method of dating sediments deposited over the last 100 to 150 years (e.g. Krishnaswamy *et al.*, 1971; Olsen *et al.*, 1985; Wise, 1980). The total ^{210}Pb concentration contained within the sediment is from two sources. The first is the supported ^{210}Pb, produced from the *in situ* decay of the parent isotope ^{226}Ra within individual soil or rock particles. The second is the unsupported or excess ^{210}Pb, deposited from the atmosphere by rain, snow, or dry fallout. If it falls onto a land surface, surface soils trap it (Benninger *et al.*, 1975) and if it falls into water bodies, subsequent accumulation buries it (Appleby & Oldfield, 1983, 1992).

If the rate of deposition of the unsupported ^{210}Pb to the sediment surface and the sediment accumulation rate are roughly constant through time, it is possible to date sediment from the decline of ^{210}Pb activity with depth in the sediment profile (Oldfield *et al.*, 1979).

Factors affecting radionuclide concentration

Local factors may affect the vertical distribution of ^{137}Cs and ^{210}Pb within a sediment profile. These include the marsh's accumulation rate, compaction, sediment reworking, ice, permafrost, bioturbation, the presence of vegetation and the location of the groundwater table (e.g. Hermanson, 1990; Milan *et al.*, 1995; Olsen *et al.*, 1985; Sharma *et al.*, 1987). In addition, ^{137}Cs and ^{210}Pb preferentially attaches to both organic matter and clay (e.g. Cundy & Croudace, 1995a; DeLaune *et al.*, 1978; Milan *et al.*, 1995; Ravichandran *et al.*, 1995). This may cause migration of the radionuclides down the sediment profile. Additionally, the diffusion of ^{222}Rn generated by the decay of ^{226}Ra sometimes affects ^{210}Pb profiles (Sharma *et al.*, 1987).

Usage

Both ^{137}Cs and unsupported ^{210}Pb are useful chronological tools in a variety of sedimentary environments including floodplains, lakes, salt marshes, reservoirs and ice caps. ^{137}Cs is particularly useful in identifying the 1964 Alaskan earthquake within a sediment profile, as its peak concentration corresponds to the timing of the event (e.g.

Hamilton, 1998; Noble, 2000; Shennan *et al.*, 1999; Zong *et al.*, 2003). Numerous other studies have used the technique to estimate soil erosion and sediment accretion rates (e.g. Andersen *et al.*, 2000; Cundy *et al.*, 1997, 2000; Cundy & Croudace, 1995b; Ehlers *et al.*, 1993; French *et al.*, 1994; Ravichandran, 1995; Stevenson *et al.*, 1985).

1.8.3 Tephrochronology

Tephrochronology is another useful dating tool. Eight volcanoes along the west margin of Cook Inlet (figure 1.4) mark the east end of the 2600 km long Aleutian volcanic arc formed by underthrusting of the Pacific plate beneath the North American plate (Miller & Chouet, 1994). From north to south, these are Hayes, Mt Spurr (including Crater peak), Double Glacier, Redoubt, Iliamna, Augustine, Douglas and Katmai (Novarupta).

Riehle (1985) identifies about 90 different layers of volcanic ash in the upper Cook Inlet region, deposited over the past 10,000 years, with the most widespread being from Hayes Volcano dated to 3591-4411 cal yr BP (e.g. Beget *et al.*, 1991; Combellick & Pinney, 1995; Riehle, 1985; Riehle *et al.*, 1990). Every source volcano produces tephra with distinctive petrologic and geochemical characteristics, for example, correlation of the Hayes tephra is based on approximate age (3,650 ± 150 ^{14}C yr BP), amphibole/pyroxene ratios greater than five and trace amounts of biotite (e.g. Riehle, 1985). Extraction of tephra from sediment and its identification means it is an important chronological tool.

1.9 Previous work in the area

Detailed microfossil work at Girdwood, Kenai and Ocean View, Anchorage (figure 1.4) develop quantitative estimates of relative sea-level change associated with the 1964 event using different methods including transfer function techniques (Hamilton, 1998; Noble, 2000; Shennan *et al.*, 1999; Zong *et al.*, 2003). However, these estimates are only for the top of the 1964 peat and overlying clastic unit. Some contemporary diatom data collected as part of this thesis is included in Zong *et al.* (2003).

Co-seismic relative sea-level movements

Zong *et al.* (2003) estimate co-seismic subsidence based upon diatom data to be 1.78 ± 0.23 m at Girdwood and 0.17 ± 0.12 m at Kenai and Noble (2000) predicts a value between 0.2 and 0.5 m at Ocean View (Anchorage). The value from Girdwood is very close to the value estimated by Plafker (1965), but the values from Kenai and Ocean View are much less.

Pre-seismic relative sea-level rise

Thatcher (1984b) suggests inter-seismic strain accumulation is not constant throughout the earthquake deformation cycle, and is especially variable around seismic periods. Microfossil work at Netarts Bay, Oregon (Long & Shennan, 1998; Shennan *et al.*, 1998) Girdwood (Shennan *et al.*, 1999; Zong *et al.*, 2003) and Kenai (Zong *et al.*, 2003) suggest a pre-seismic relative sea-level rise (positive sea-level tendency) within the peat, immediately before the seismic event. Diatom data from Girdwood and Kenai indicates a clear change in sedimentary conditions across the 1954 horizon (dated using ^{137}Cs) with a relative sea-level rise of 0.16 ± 0.13 m at Girdwood and 0.16 ± 0.09 m at Kenai (Zong *et al.*, 2003). The pre-seismic signal is less easily quantifiable at Ocean View, but there is a change in diatom assemblage directly below the peat-silt contact. This may indicate a period of environmental instability, inferred from ^{137}Cs to last approximately twenty years (Noble, 2000).

Shennan *et al.* (1999) suggest that the pre-seismic period may be an element of the EDC model, registering a fall in uplift caused by inter-seismic strain accumulation. They propose that the simple two stage EDC model described in figure 1.1, should now include four phases. In areas of co-seismic submergence, this results in:

1. Inter-seismic strain accumulation resulting in century-scale relative sea-level fall
2. Pre-seismic relative sea-level rise immediately below the peat-silt boundary
3. Co-seismic submergence resulting in a sudden relative sea-level rise
4. Rapid post-seismic recovery resulting in relative sea-level fall

This pre-seismic relative sea-level rise could provide an early warning of a large plate boundary earthquake. However, it could also result from non-seismic processes, for example sediment mixing or from the effects of the El Nino Southern Oscillation (ENSO), fluctuations in isostatic rebound or changes in eustasy. Long & Shennan (1998) and Shennan *et al.* (1999) consider these unlikely as rates of isostatic rebound vary little over a single earthquake cycle, and no mechanism exists to link eustasy to the EDC model. Other possible explanations include aseismic slip and precursory seismic quiescence. The theoretical development of these geophysical models uses direct observations, typically a few years to a decade, but geologic evidence provides an independent test using a much longer timescale, over decades to centuries.

1.10 Geophysical models and pre-seismic relative sea-level rise

Over the past few decades, numerous authors identify long-term, intermediate-term and short-term seismic precursors within the seismic cycle (e.g. Scholz, 1990). Possible mechanisms of pre-seismic relative sea-level rise include aseismic slip (e.g. Dragert *et al.*, 2001; Katsumata *et al.*, 2002; Linde *et al.*, 1988; Miller *et al.*, 2002) and elements of seismic quiescence (e.g. Kato *et al.*, 1997), both of which result in the reduction of uplift caused by inter-seismic strain accumulation (e.g. Long & Shennan, 1998). Following sections summarise these possible mechanisms.

Aseismic slip

Strain meters (e.g. Linde *et al.*, 1988), GPS (e.g. Dragert *et al.*, 2001; Ozawa *et al.*, 2002) and tide gauge data (e.g. Katsumata *et al.*, 2002) have detected aseismic slip before large earthquakes. GPS measurements suggest aseismic slip occurs over a large area of the deeper Cascadia subduction interface (Dragert *et al.*, 2001; Miller *et al.*, 2002). Dragert *et al.* (2001) indicates that there can be longer periods (possibly years) of slower sliding, together with brief periods (possibly days) of more rapid slip brought on by sudden changes in rheology or friction rather than seismic triggers. They suggest that these slip events may become a trigger mechanism for a great subduction thrust earthquake, and it is thought that such a mechanism was responsible for the 1960 Chilean earthquake and the 1944 and 1946 Nankai trough earthquakes. Aseismic slip could therefore explain the pre-seismic relative sea-level rise observed before large plate boundary earthquakes.

Seismic quiescence

Other possible explanations are different types of intermediate term seismic quiescence (e.g. Cao & Aki, 1985; Habermann, 1988; Kanamori, 1981; Mogi, 1969; Scholz, 1988; Wyss & Habermann, 1988). This is a large and abrupt decrease of mean seismicity rate by between 40 to 90% compared to the preceding background rate and occurs over a region equal to or several times larger than the rupture zone (Wyss & Habermann, 1988). There is uncertainty on how long seismic quiescence occurs before the earthquake (table 1.2), but numerous authors suggest the length of time relates to the magnitude of the main shock (e.g. Kanamori, 1981; Mogi, 1985).

Mechanisms of precursory phenomena

Mechanisms of precursory quiescence are unclear but evidence suggests a connection to the loading cycle as they have a clear spatial and temporal relationship with the principal rupture (Scholz, 1998). Scholz (1990) suggests the physical models fall into two main categories:

1. Those based on fault constitutive relations, that predict fault slip behaviour but no change in properties in the material surrounding the fault, for example, nucleation and lithospheric loading models
2. Those based on bulk rock constitutive relations that predict physical property changes in a volume surrounding the fault, for example, dilatency models

Table 1.2 Duration of seismic quiescence

Author	Period of Quiescence
Dieterich & Okubu (1996)	Several years
Kato *et al.* (1997)	Few years to a few decades
Main & Meredith (1991)	15 to 17 months
Scholz (1988, 1990)	Few weeks to several years
Wyss *et al.* (1981)	Several years
Wyss & Habermann (1988)	15 to 75 months

All of the models indicate that near surface strain accumulation should become non-linear near the end of the loading cycle as stress concentrates on the locked patch of the fault. The two main models that explain intermediate term seismic quiescence are stress relaxation because of slip weakening (e.g. Kato *et al.*, 1997) or dilatency hardening predicted by the dilatency-diffusion model (e.g. Nur, 1972) with some models including aseismic slip reviewed earlier.

Some authors claim it may have helped in many successful earthquake predictions, both on subduction zones and on other types of fault lines (e.g. Kisslinger, 1988; Ohtake *et al.*, 1977, 1981; Wyss & Burford, 1985; Wyss & Wiemer, 1999), although its success is open to debate. It may represent a physical mechanism for the pre-seismic relative sea-level rise observed, but problems exist relating geological data to geophysical models.

1.11 Aims and objectives

General aims

This thesis aims to identify major seismic and non-seismic controls on relative sea level in the upper Cook Inlet, Alaska during the late Holocene and the main objectives are:

1. To understand the spatial and temporal variation of late Holocene relative land- and sea-level movements associated with great earthquakes (magnitude>8.0)
2. To understand non-seismic controls on relative sea level through the late Holocene

These objectives are achieved by testing the following hypotheses:

1. Marsh stratigraphy records multiple co-seismic events around the upper Cook Inlet
2. The four-phase EDC model proposed by Shennan *et al.* (1999) is applicable to all late Holocene events
3. Pre-seismic relative sea-level rise is a precursor to a major earthquake
4. Events at different sites are synchronous
5. The 1964 event is a good model for other late Holocene events
6. It is possible to separate and quantify seismic from non-seismic controls on RSL

The final objective is to put the seismic and non-seismic components into context, investigate broader implications and identify areas for future research. The novelty of this research is primarily in the analysis of multiple earthquake deformation cycles, coupled with the emphasis on the pre-seismic component.

1.12 Summary

This chapter summarises background information relevant to this PhD. It outlines the factors controlling relative sea-level change along subduction zone coasts and the development of palaeo-environmental research in this area. Work carried out in the Pacific Northwest of the USA indicates it has experienced large earthquakes in the past and the 1964 Alaskan earthquake provides a modern analogue that allows the comparison of late Holocene co-seismic land movements against an event of known magnitude. This study aims to increase understanding in this particular area of research.

Chapter 2
Field Sites

2.1 Introduction

The aim of this chapter is to introduce the field sites and to describe their main characteristics. Kenai and Kasilof are located on the west coast of the Kenai Peninsula and Girdwood is located towards the head of Turnagain Arm (figure 2.1). Previous work at these sites show the marshes contain a sequence of buried peat-silt couplets and a broad range of contemporary surface environments (e.g. Combellick, 1991, 1993, 1994, 1997; Hamilton, 1998; Noble, 2000; Shennan *et al.*, 1999; Zong *et al.*, 2003). They will enable the testing of the hypotheses outlined in chapter 1 with the reconstruction of spatial variations in relative sea level for different periods of the 1964 earthquake and other late Holocene events. They underwent different amounts of co-seismic submergence during the 1964 event, ranging from 1.7 m at Girdwood to 0.5 m at Kenai and Kasilof calculated from the contours and point data from Plafker (1969).

2.2 The Cook Inlet

The Cook Inlet basin (figure 2.1) is approximately 325 km long, 95 km wide, occupies an area of 31,000 km^2, with 70% inundated by water (Schmoll & Yehle, 1986). At its inland extremity, it divides into the Knik and Turnagain Arms, with Anchorage located at the junction between the two. Both the Knik and Turnagain Arms are macrotidal with a mean tidal range of 11.0 m (Bartsch-Winkler & Ovenshine, 1984; Bartsch-Winkler & Schmoll, 1992). Strong currents typically range from 2 to 4 ms^{-1} (Bartsch-Winkler & Ovenshine, 1984) and tide gauge data are available from Seward, Anchorage, Seldovia, Nikiski and Kodiak. During winter months, the tide deposits ice blocks on the frozen intertidal flats (Bartsch-Winkler & Ovenshine, 1984) with section 2.7 describing this process further.

2.3 Turnagain Arm

The Turnagain Arm (figure 2.1) is a southeast trending estuary, 75 km long and 3 to 23 km wide (Bartsch-Winkler & Ovenshine, 1984). A tidal bore marks the flood tide that ranges up to 1.5 m in height and travels at approximately 4.5 ms^{-1} (Bartsch-Winkler *et al.*, 1983). Many glacier fed rivers drain into the Turnagain Arm, for example, the Placer River, Twentymile River, Portage Creek and Glacier Creek. They create seasonal variations in discharge and a salinity of only 7 to 15‰ at Anchorage in summer and 17 to 22‰ in winter (Batten *et al.*, 1978). The rivers have an annual sediment discharge rate of 2.5 million tons but the main source of sediment is from areas seaward of the estuary (Bartsch-Winkler & Ovenshine, 1984). Grain size analysis of suspended sediment at Girdwood and Hope indicates that tidewater transports as much as 40% very fine sand and 8% clay (Bartsch-Winkler & Ovenshine, 1984). It is an area of contemporary tidal flat and marsh accumulation with approximately 90% of the upper Turnagain Arm exposed at low tide.

2.4 Kenai

The Kenai River originates in the southern Kenai Mountains and its watershed drains an area of approximately 5,700 km^2, with glaciers covering approximately 10% (Dorava & Scott, 1998). It runs west across the Kenai Peninsula and enters into the Cook Inlet. A large marsh area has developed behind a coastal sand spit with Kenai City Pier being located 2 km and Kenai River Flats being located 7 km upstream from the river entrance (figure 2.2).

The diurnal tidal range (the difference between mean lower low water (MLLW) and mean higher high water (MHHW)) at Kenai City Pier is 6.09 m (data from the NOAA, Centre for Operational Oceanographic Products and Services web page, http://co-ops.nos.noaa.gov). The definition of MLLW is the average of the lower low water height averaged over the United States National Tidal Datum Epoch (Pugh, 1996) and it is usually chart datum for the western coast of the USA. MHHW is the average of the higher high water height of each tidal day, averaged over the United States National Tidal Datum Epoch (Pugh, 1996). The diurnal tidal range at Kenai City Pier may differ from the observed tidal range at Kenai River Flats due to the effects of shoaling of water at the Kenai River entrance and base flow of the river dampening the low tide estimate. Section 4.2 investigates this relationship further.

A transect was chosen across the marsh surface at Kenai River Flats to incorporate all of the contemporary environments, ranging from mudflat to salt marsh to raised bog communities (figures 2.2 and 2.3). It consists of seven vegetation zones (figures 2.4, 2.5 and table 2.1). Appendix 7 contains the altitude and vegetation description for each contemporary sample.

Table 2.1 Description of Kenai contemporary vegetation at sampling locations

Zone	Description	Vegetation	Altitude (m) relative to MHHW
1	Mudflat	Mudflat made up of 100% clay, silt and gravel with no vegetation	-5.28 to -0.28
2	Upper tidal flat/marsh pioneer zone	Mudflat with scattered *Puccinellia* sp.	-0.15 to +0.09
3	Low marsh	20 to 80% coverage by scattered *Puccinellia* sp., Poaceae, *Triglochin maritima*, *Potentilla egedii* and *Juncus* sp.	+0.17 to +0.82
4	Mid marsh	100% coverage of Poaceae, *Juncus* sp., *Triglochin maritima* with rare *Potentilla egedii*, *Puccinellia* sp. and *Plantago maritima* and the introduction of *Carex lyngbyei*	+1.01 to +1.12
5	High marsh	Dominated by *Carex lyngbyei* with smaller amounts of Poaceae, *Juncus* sp. and *Potentilla egedii*	+1.12 to +1.26
6	Transition zone	Transition zone into raised bog with the introduction of *Salix* sp. and *Sphagnum* sp.	+1.27 to +1.31
7	Raised bog	Diverse raised bog communities comprising of Poaceae, *Carex lyngbyei*, *Sphagnum* sp. and other unidentified mosses, *Vaccinium* sp., *Empetrum nigrum*, *Salix* sp., *Alnus* sp., *Picea* sp., and *Betula* sp. The ground at the most landward site is completely water logged with a floating mat of vegetation	+1.35 to +1.57, with one sample at +1.70 m MHHW

A levee (~0.5 m) separates the mudflat from the contemporary marsh surface, which is generally flat with occasional pools and low hummocks, ranging in height between +1.0 m and +1.7 m above MHHW. A tidal creek dissects the marsh at approximately 380 m along the transect. Occasional snags (dead tree stumps) are visible on the surface, which are rooted in the underlying peat layer, found 0.05 to 0.19 m below ground level.

As the extent of the mudflat is limited at Kenai River Flats, a second contemporary transect was established at Kenai City Pier where the mudflat is more extensive and the transition to low marsh more gradual (figures 2.2, 2.4, 2.6, 2.7 and appendix 7). The full transect ranges in altitude from -4.50 m to +1.47 m MHHW. However, only samples from the mudflat and transition to salt marsh are included in the contemporary training set to avoid repetition with the environments found at Kenai River Flats (figure 2.4).

The lower part of the transect at Kenai City Pier consists of three vegetation zones. Zone A is mudflat consisting of 100% silt, clay and gravel and ranging in altitude from -4.52 m to -0.28 m MHHW. Zone B, from -0.15 m to +0.09 m MHHW has scattered *Puccinellia* sp. colonising the marsh front. Zone C, from +0.17 m to +0.82 m MHHW consists of 100% low marsh vegetation, Poaceae, *Triglochin maritima* and *Potentilla egedii*. This is comparable to Zone 3 at Kenai River Flats. Following chapters refer to the vegetation descriptions listed in table 2.1.

A deep borehole taken at this site by Combellick and Reger (1994, figure 2.2) show the estuarine deposits are interbedded with peat and are about 8 m thick, underlain by sandy, gravely alluvium.

2.5 Kasilof

Kasilof River originates in the southern Kenai Mountains and flows west to enter the Cook Inlet, approximately 17 km south of the Kenai River entrance. Marsh areas are located 3.5 km upstream from the mouth of the river and cover an area of 6 km^2 (figure 2.8). The diurnal tidal range is 6.15 m (data from NOAA, http://co-ops.nos.noaa.gov). Location within the meandering river system determines whether a small cliff separates the mudflats exposed at low tide from the marsh surface or whether they gently grade into the low marsh environment. The marsh surface is generally flat and consists of a variety of vegetation zones. At the marsh front *Triglochin maritima*, Poaceae and *Potentilla egedii* dominate with the introduction of *Carex lyngbyei* further inland. Raised bog communities of *Sphagnum* sp., *Empetrum nigrum* and *Picea* sp. develop towards the landward limit of the marsh.

Radiocarbon dating of basal peat overlying sand and gravel indicates the estuarine deposits began accumulating about 12000 cal yr BP (Combellick & Reger, 1994). The riverbank exposes three extensive buried peat layers all with distinct upper boundaries (figure 2.9). The lowest of the three peat layers (~1 m thick) contains distinct layers of wood and two thick tephras. Combellick and Pinney (1995) suggest the uppermost tephra is the Hayes tephra dated 3591-4411 cal yr BP and that the lower tephra of unknown source has an age of approximately 5000-6000 cal yr BP. Combellick and Reger (1994) dated the base of this lowest peat layer to 5907-6266 cal yr BP and its top to 1334-1542 cal yr BP. The top of the middle peat has an age of 1009-1304 cal yr BP and the top of the uppermost peat has a modern radiocarbon age of 0-280 cal yr BP (Combellick & Reger, 1994). Appendix 3 contains all radiocarbon dates.

2.6 Girdwood

Girdwood is located towards the head of Turnagain Arm (figures 2.1 and 2.10) and it has a tidal range of approximately 10.18 m, estimated from the data available from Sunrise, 12 km west (data from NOAA, http://co-ops.nos.noaa.gov). Low tide exposes extensive tidal flats that constantly change with migrating channels. In most places, a small cliff (~1 m) separates them from the marsh surface, which is at the approximate height of MHHW. It is gently undulating and dominated by *Carex lyngbyei*, *Potentilla egedii*, *Juncus* sp., *Triglochin maritima* and pools of water. A number of tidal creeks divide the marsh surface and the Seward Highway and Alaska Railroad form its landward limit.

The small cliff face separating the tidal mudflat from the marsh surface provides continuous exposures of the buried 1964 peat layer (figure 2.11). It contains a large amount of *in situ* plant material, including the rooted trees that form the ghost forest visible on the surface today. A second peat layer buried approximately 1.0 m below the 1964 horizon has a second forest layer rooted within it, dated to 730-900 cal yr BP (Combellick, 1994). Combellick (1993, 1994) suggests that their burial was due to sudden co-seismic submergence, with evidence including a sharp upper contact between the peat and overlying silt, tree stumps being healthy until death and the mud above and below the peat layer containing the halophytic plant *Triglochin maritima*. This species dominates vegetation only in low marsh conditions (Atwater, 1987). Below the second buried peat layer, Combellick (1994, 1997) identifies four other buried peat layers with ages of 1170-1360, 1930-2120, 2730-2850 and 3370-4090 cal yr BP.

Over the two field visits, in May 2000 and 2001, migrating channels exposed some or all of these buried peat layers. Sampling of these deeper peat layers took place during 2001 and their descriptions alongside samples taken from Kenai and Kasilof are in the following chapters.

2.7 Winter conditions

A separate field season occurred in April 2002, funded by the USGS NEHRP project and additional to this NERC funded PhD. The marshes at Girdwood and Kenai were still experiencing winter conditions. At Girdwood, the small cliff (~1 m) that separates the salt marsh from the mudflat was not visible because of the amount of ice covering the mudflat area (figure 2.12). Melting blocks of ice on the frozen salt marsh surface deposit a significant amount of sediment that becomes part of the annual sediment accumulation. At Kenai River Flats, the small levee separating the mudflat from the marsh surface was not visible because of the amount of ice within the frozen river channel (figure 2.13). The tidal channel that dissects the contemporary transect was not visible due to the infilling of ice and coverage by snow. There was less ice on the mudflat at Kenai City Pier, but the mudflat was frozen down to a depth of approximately 0.5 m. Large ice blocks were on the mudflat surface and a few were on the salt marsh where they deposited their sediment load once melted.

Staats *et al.* (2001) suggest that frozen surfaces increase consolidation and reduce the erosion of surfaces during the winter months. However, the observations at Kenai and Girdwood show that ice does transport sediment within the intertidal zone. Ground conditions in April 2002 prevented, on safety terms, any systematic sampling to study this process in detail. This remains an area for future research. Subsequent chapters include such processes within the array of intertidal processes that contribute to diatom distribution in the contemporary and fossil record.

2.8 Summary

The three field sites described above allow the testing of the hypotheses outlined in chapter 1. The different amounts of co-seismic submergence encountered during the 1964 event alongside the number of buried peat layers gives us some insight into relative sea-level changes associated with entire earthquake deformation cycles. Chapter 3 describes the methodology used.

Chapter 3
Research Design

3.1 Introduction

This chapter introduces the sampling and research design used to address the hypotheses set out in chapter 1. It outlines the fieldwork undertaken at Kenai River Flats, Kenai City Pier, Kasilof and Girdwood during two field seasons, in May 2000 and May 2001 (refer to chapter 2 for description of field sites). Secondly, it outlines the methods used for microfossil analysis, the numerical techniques applied to interpret the results and dating methods.

3.2 Collection of contemporary surface samples

Kenai River Flats and Kenai City Pier provide contemporary diatom samples and related environmental variables for the full range of modern day environments from tidal flat through salt marsh to raised bog communities (section 2.4). Together with the Kenai contemporary diatom data from Zong *et al.* (2003) they form the modern training set, allowing the quantification of the spatial variation of relative sea-level movements associated with post-seismic, inter-seismic, pre-seismic and co-seismic periods for multiple events. They also allow understanding of other controls on relative sea level in the area including non-seismic processes, for example, eustatic and glacio- and hydro-isostatic changes.

Girdwood is less suitable for the collection of contemporary surface samples because the small cliff face (~1m) separating the salt marsh surface from the mudflat allows for no transitional zone between the two. In addition, the Seward Highway and Alaska Railroad alter the development of the raised bog community. Shennan *et al.* (1999) and Zong *et al.* (2003) took surface samples from Portage, approximately 10 km away, where the freshwater environments are more extensive but there is a significant increase in the effects of river discharge in this area. At Kasilof, the marsh area is less extensive than at Kenai.

A two-year sampling scheme limited the chances of a no-analogue situation when relating contemporary diatom assemblages to fossil diatom assemblages. In May 2000, sampling took place along a transect at Kenai River Flats (figures 2.2 to 2.5), then following subsequent analyses it was realised that a greater variety of samples were required from the tidal flat and from the raised bog areas of the marsh. Extending the existing transect landward at Kenai River Flats and establishing a new transect at Kenai City Pier accommodated this in 2001. At Kenai City Pier, the tidal flats are more extensive and there is a gradual transition onto the salt marsh (figures 2.2, 2.6 and 2.7). The scraping away of the surface and the collection of the top 1 cm of sediment allowed for seasonal variations in diatom blooms and the effects of winter freezing. Samples were sealed in bags and the sampling site levelled to a temporary benchmark (TBM) using a standard level and staff.

Associated environmental variables of interest for the contemporary diatom samples are their altitude (m) relative to mean higher high water (MHHW) and hours inundated per year. Pugh (1996) defines MHHW as the average of the higher high water height of each tidal day, averaged over the United States National Tidal Datum Epoch. The alternative is to define altitude relative to mean lower low water (MLLW), which is chart datum. Altitude (m) relative to MLLW is not suitable as the reference tide level because at Kenai, the base flow of the river dampens out the effect of low tide (chapter 4), and at Girdwood, it is impossible to measure as 90% of the upper Turnagain Arm becomes extensive tidal flats during low tide.

Hours inundated per year was chosen as a second environmental variable as Gehrels (2000) uses flooding duration, not height, as the predictor variable when using foraminiferal transfer functions to produce high resolution sea-level records from salt marsh deposits, Maine, USA. The repeated levelling (chapter 4) of high and low tide to the TBM's at Kenai River Flats and Kenai City Pier enabled the calculation of these two variables for each contemporary diatom sample.

3.3 Collection of fossil samples

Coring (using a 25 mm diameter gouge) along the established contemporary transect at Kenai River Flats allowed the investigation of the litho-stratigraphy of the marsh using the Troels Smith (1955) scheme of description. This characterises the large range of organic and inorganic sediment typical in most coastal lowlands. The transect started at the river and moved inland to the freshwater bog with levelling data available for contemporary surface samples relating to the surface heights of cores. The plotting of marsh stratigraphy allowed the selection and sampling of suitable peat-silt sequences.

A 25 cm monolith tin sampled the first peat-silt boundary, found approximately 5 cm below the surface. This method avoids contamination and enables the collection of a large volume of sediment. A gouge corer then sampled the sediment below. The removal of the upper peat layer using the monolith tin and the cleaning of cores using a knife helped reduce the risk of contamination and the collection of multiple cores from the same area checked consistency. As radiocarbon dating requires a greater volume of sediment, a Russian corer (50 mm diameter) sampled the deeper peat layers.

At Girdwood, good exposures of two buried peat layers containing ghost forests are laterally extensive along the marsh front. In 2000, cleaning of a section allowed the description of stratigraphy and sampling of sediment using a variety of monolith tins and tubing. A transect of cores could not be taken across the marsh surface as the ground was too compact. However, in 2001, a transect of cores was taken across the tidal flat area where a number of buried peat layers are found at greater depths (e.g. Combellick, 1994). The levelling of every fossil core to the established TBM allowed the plotting of stratigraphy that enabled the selection and sampling of sequences using a mixture of monolith tins, gouge and Russian corers. The sealing of samples in plastic allowed the transportation of sediment back to Durham for subsequent analyses.

At Kasilof, three buried peat layers are visible and laterally extensive along the riverbank. The cleaning of a section close to that described by Combellick and Pinney (1995) allowed the description of stratigraphy and sampling of sediment using a variety of monolith tins and tubing.

3.4 Organic content

The amount of organic material contained within surface sediments vary in intertidal and marsh environments. Typically, values are low on the mudflat and increase with altitude due to a decline in tidal inundation and greater vegetation coverage. Organic content values from the core samples should therefore differ depending on the period within the EDC model and figure 3.1 shows a schematic diagram of this relationship for areas that experience co-seismic submergence (Hamilton, 1998). There is an increase in organic material throughout the lower silt and into the above peat layer as inter-seismic strain accumulation results in relative land uplift and hence relative sea-level fall. Immediately below the peat-silt boundary, the amount of organic material within the peat decreases due to a pre-seismic relative sea-level rise. During co-seismic subsidence, the amount of organic material decreases rapidly due to the invasion and deposition of marine silt and clay and then it should start to increase once more as post-seismic uplift and inter-seismic strain accumulation causes relative sea level to fall, allowing the colonisation of the marsh surface by vegetation. Changes in organic content may be particularly useful in identifying any pre-seismic signal.

The weighing and burning of dry sediment in a furnace at 550°C for four hours allowed the calculation of percentage Loss on Ignition (LOI) using the following equation:

$$\% \text{ L O I} = 100 \times \frac{(\text{weight of dry sediment} - \text{weight of burnt sediment})}{\text{weight of dry sediment}}$$

3.5 Microfossil analysis

Sampling intervals for diatom analysis relate to the hypotheses outlined in chapter 1. Analysis of the full range of contemporary surface samples from Kenai River Flats together with additional tidal flat samples from Kenai City Pier and Zong *et al.* (2003) allows the development of a comprehensive contemporary data set, ranging from tidal flat through to raised bog environments. Sampling intervals of cores varied from 1 cm to 8 cm with smaller intervals taken around possible pre-seismic, co-seismic and post-seismic periods where greater resolution is required.

Preparation of diatom samples followed standard laboratory methods (Palmer & Abbott, 1986). The addition of 30% hydrogen peroxide to approximately 1 cm^3 of sediment, followed by gentle heating, digested the organic matter contained within the sample. After centrifuging, decanting and addition of distilled water, the desired amount was dried on a cover slip. The mounting of this cover slip onto a slide using Naphrax allowed the examination of diatoms using a light microscope at magnification x 1000.

A minimum count of 250 diatom valves was possible for most samples. In some instances, organic samples contained very few diatoms and in samples containing a large amount of minerogenic material, preservation varied greatly. No attempt was made to separate out the allochthonous and autochthonous diatoms because we assume that processes acting today are the same as those acting in the past. According to Sawai (2001b), the removal of dead diatoms by tidal currents may result in a residual assemblage for the surface tidal flat samples. However, this would also have occurred in the fossil tidal flat samples recorded by the silt units.

Diatom identification used Van der Werff and Huls (1958-1974) together with supplementary texts of Denys (1991), Hartley *et al.* (1996), Hemphill-Haley (1993) and Patrick and Reimer (1966, 1975). TILIA (version 2.0 b5; Grimm, 1993) allows the plotting of results and the halobian classification system divides the diatom species into five categories of salt tolerance (table 3.1).

Table 3.1 The halobian classification scheme (Hemphill-Haley, 1993)

Classification	Salinity range (‰)	Description
Polyhalobous	> 30	Marine
Mesohalobous	0.2 to 30	Brackish
Oligohalobous - halophile	< 0.2	Freshwater – stimulated at low salinity
Oligohalobous - indifferent	< 0.2	Freshwater – tolerates low salinity
Halophobous	0	Salt-intolerant

In broad terms, the order of salinity classes should reflect the change from tidal flat through salt marsh, to freshwater marsh and bog. The marine (polyhalobian class) and brackish (mesohalobian class) groups usually dominate tidal flat environments and freshwater groups tolerant of different degrees of saline inundation (oligohalobian-halophile and oligohalobian-indifferent classes) become dominant through the transition from salt marsh to freshwater marsh (e.g. Zong *et al.*, 2003). Salt-intolerant species (halophobe class) characterise the most landward communities, including acidic bog above the level of the highest tides. The testing of these pre-determined classifications occurs in the analysis of the contemporary data in chapter 4. They aid in the description of the contemporary and fossil diatom data but do not form the basis of any quantitative interpretations.

3.6 Numerical techniques

Numerical techniques establish the relationship between contemporary diatom data and their associated environmental variables, and they allow comparisons between the contemporary data set and every fossil sample analysed. Quantitative estimates enable the reconstruction of relative sea-level change throughout the entire profile, rather than just at stratigraphic boundaries.

The application of cluster analysis to the contemporary and fossil diatom data (e.g. Noble, 2000) aids in the description of the sediment and identifies any distinct classes within the diatom data set rather then giving any quantitative estimates. It also allows the comparison between the Kenai City Pier and Kenai River Flats contemporary samples. Transfer functions (e.g. Horton *et al.*, 1999, 2000) allow the quantification of relative sea-level change by comparing the contemporary data to the fossil data whilst the modern analogue technique (e.g. Edwards & Horton, 2000) identifies fossil samples with 'poor', 'close' and 'good' modern analogues within the contemporary data set. Following sections review these different techniques separately.

3.6.1 Cluster analysis

Noble (2000) uses cluster analysis to infer relative sea-level changes at Ocean View, Anchorage, Alaska. Unconstrained cluster analysis on the combined contemporary data set using CONISS within the TILIA program (version 2.0 b5; Grimm, 1993) produces a dendrogram. This groups the most similar samples together without taking into account their original order, which is important along a surface transect, as the change in environment may not be linear with distance. To compare the reliability of the results CONISS uses Euclidian distance (no transformation of the data) that classifies clusters based on the major taxa, and Chord distance (square root transformation) that reduces the importance of high counts. Cluster analysis helps in the description of the contemporary diatom assemblages by relating diatom classes to altitude (m) relative to MHHW.

Stratigraphically constrained cluster analysis using Chord distance (square root transformation) aids in the description of the fossil data. It can only group samples together if they are next to one another in the stratigraphic column. The dendrogram produced aids in the description of the main diatom changes through the core but it does not give any quantitative estimates.

3.6.2 Transfer function

The contemporary distribution of diatoms from tidal flat to freshwater environments allows the development of a transfer function that is able to reconstruct the magnitude of relative land and sea-level changes. Zong *et al.* (2003) use transfer functions to estimate values of co-seismic submergence associated with the 1964 earthquake in Alaska and a comparative study by Gehrels (2000) uses them to produce high resolution records from salt marsh deposits in Maine, USA. Other studies that use transfer functions to estimate relative sea-level changes include Zong and Horton (1999), Edwards and Horton (2000) and Horton *et al.* (1999). Following paragraphs review their development using relevant techniques.

Birks (1995) reviews the basic principles of quantitative environmental reconstruction. In this study, the primary aim of a transfer function (Imbrie & Kipp, 1971) is to predict environmental variables (altitude (m) relative to MHHW and hours inundated per year) for a fossil sample using a modern training set (figure 3.2). This involves regression that models the relationship between contemporary diatom assemblages and their associated environmental variables of interest. Calibration then uses this relationship to transform the fossil data into quantitative estimates of past environmental variables.

Most methods assume a linear or unimodal taxon-environment response model. In nature, most species-environment relationships are unimodal, as most taxa survive best in optimum environmental conditions (Birks, 1995). However, if the data spans only a narrow range of environmental variation then it may appear linear (Birks, 1995). For reconstruction purposes, it is essential to estimate the gradient length for the environmental variables of interest, i.e., altitude (m) relative to MHHW and hours inundated per year. CONOCO (version 3.12; ter Braak, 1991) uses Detrended Canonical Correspondence Analysis (DCCA) to estimate the gradient length in standard deviation (SD) units by detrending segments with non-linear rescaling. Gradient length is important as it governs what transfer function models are suitable for the data set.

If the gradient length is short (2 SD units or less), linear regression and calibration methods are appropriate, for example, Partial Least Squares (PLS) (e.g. Stone & Brooks, 1990). If the gradient length is longer (2 SD units or more), several taxa have their optima located within the gradient and unimodal based methods of regression and calibration are best (Birks, 1995). Such models include Weighted Averaging (WA), Weighted Averaging with Tolerance Downweighting (WA-TOL) and Weighted Averaging-Partial Least Squares (WA-PLS). Birks (1995) reviews the different statistical techniques in detail.

Statistical parameters produced during regression and calibration include the coefficient of determination (r^2) that measures the strength of a relationship between observed and inferred values (Birks, 1995). The Root Mean Square Error (RMSE) measures the predictive abilities of the training set in which the sample for which the prediction is made is included in the model (Birks, 1995). The Root Mean Square Error of Prediction (RMSEP), calculated by deleting a sample from the training set predicts its environmental variable using the other samples, a procedure known as jack-knifing (ter Braak & Juggins, 1993). This cross validation technique makes RMSEP more robust than RMSE (Birks, 1995).

The theoretical basis of Weighted Averaging (WA) and Weighted Averaging with Tolerance Downweighting (WA-TOL) is that species live in certain parts of environmental space. Species with their optima for the environmental variable (x) will be the most abundant present (Birks, 1995). It consists of three parts: WA regression, WA calibration and a deshrinking process, either inverse or classical. Bootstrapping estimates RMSEP (Birks, 1995). Weighted Averaging-Partial Least Squares (WA-PLS) improves on the WA method as it considers residual correlations in the biological data in an attempt to improve estimation of the optima for the taxa (Birks, 1995). The improvement is based on PLS and in each case, jack-knifing estimates RMSEP. The first component maximises the covariance between the vector of weighted averages and the environmental variable of interest (Birks, 1995). Subsequent components maximise the same criterion but are uncorrelated to earlier components (ter Braak *et al.*, 1993).

TILIA files contain the biological data as percentages with all zero counts removed and species names in the dictionary as two letter codes. TRAN1 (version 1.8; Juggins, 1999) transforms the TILIA files into readable Cornell condensed data. The program CALIBRATE (version 0.70; Juggins & ter Braak, 1997) runs PLS, WA and WA-TOL, whereas the program WA-PLS (version 1.5; Juggins & ter Braak, 2001) runs WA-PLS and produces sample specific error terms. A square root transformation of the biological data investigates whether the distribution of samples becomes more even along the environmental gradient and hence improves the model.

When calculating a relative sea-level change between two fossil samples, the change in altitude is simply the difference between the two reconstructed values and calculation of the associated error term uses the formula (Preuss, 1979):

$$\sqrt{(\text{error term } 1^2 + \text{error term } 2^2)}$$

3.6.3 Diatom optima and tolerance

Using the unimodal method of Weighted Averaging within the computer program CALIBRATE (version 0.70; Juggins & ter Braak, 1997) it is possible to calculate the optimum (the maximum of the response curve) and tolerance (breadth of the response curve) with reference to height (altitude (m) relative to MHHW) for each contemporary diatom taxon ($u \pm t$, section 4.4.2). The selection of Hill's N2 allows an unbiased statistical comparison of tolerances as it considers the effective number of occurrences of the taxon (Birks, 1995).

3.6.4 Modern analogue technique

The modern analogue technique (MAT) quantifies the similarity between fossil assemblages and the modern training set (Birks *et al.*, 1990) and is particularly useful in identifying whether fossil samples possess good modern analogues (e.g. Edwards & Horton, 2000; Zong *et al.*, 2003).

The computer program MODERN ANALOGUE TECHNIQUE (release 1.1; Juggins, 1997) models the full contemporary diatom data set against altitude (m) relative to MHHW. It estimates its results on the closest match and the weighted mean of the 2, 5 or 10 most similar modern samples (see section 4.6) using the Squared Chord Distance dissimilarity coefficient (e.g. Prentice, 1980; Overpeck *et al.*, 1985). The weights are the inverse of the dissimilarity values so that the modern samples with the lowest dissimilarity (most similar sample) have the greatest weight (Birks, 1995). MAT also determines whether the fossil data have reliable modern analogues.

3.7 Dating methods

A number of dating methods permit the correlation of co-seismic events between different sites and allows the dating of the pre-seismic signal.

3.7.1 Radionuclide dating

The Well Detector in the Geography Department, University of Durham allows the dating of sediment deposited over the past 100 to 150 years using Caesium-137 (^{137}Cs) and Lead-210 (^{210}Pb) (refer to section 1.8.2).

At Kenai and Kasilof, ^{137}Cs determines whether the burial of the uppermost peat layer together with any associated pre-seismic signal results from co-seismic submergence associated with the 1964 event. At Kasilof, this is important as previous radiocarbon results give an age of 0-280 cal yr BP (e.g. Combellick & Pinney, 1995; Combellick, 1994), illustrating the difficulty of using radiocarbon dating for sediments deposited during the past 300 years. At both sites sampling intervals range from 1 to 8 cm, from the surface down to the uppermost peat layer. Samples were first dried overnight in a furnace at 105°C and then heated to 550°C for four hours. Approximately 1.5 to 2.0 g of the remaining ash was weighed, placed in a tube, reweighed, and then run through the well detector for 48 hours. The detector is connected to a multiple channel analyser (MCA) and the output observed using a MAESTRO for Windows MCA Emulator (Lu, 1998).

The principle of ^{137}Cs determination is to establish the number of gamma emissions at 661.6 KeV over time. The same principle applies to ^{210}Pb that emits gamma radiation at 46.5 KeV (Lu, 1998). The determination of the concentration of ^{226}Ra allows the calculation of unsupported ^{210}Pb concentration by subtracting the ^{226}Ra concentration from the total ^{210}Pb amount. The results are in Becquerels (Bq), defined as one nuclear disintegration per second (Lu, 1998). The conversion to Bq per kilogram allows the calculation of concentration and permits comparisons between samples. The amount of error associated with the readings depends on the amount of time the detector has to measure the emissions from the sediment. Readings below 5 $Bqkg^{-1}$ for ^{137}Cs and 20 $Bqkg^{-1}$ for ^{210}Pb are insignificant.

Shennan *et al.* (1999) and Zong *et al.* (2003) undertook detailed ^{137}Cs analysis at Girdwood and so this PhD does not repeat these analyses.

3.7.2 Radiocarbon dating

The approval of 32 AMS dates by the Natural Environmental Research Council (NERC), allocation number 935 0901, allowed the dating of the top, start of any pre-seismic signal and base of each of peat layer (apart from the top of the 1964 peat, dated using ^{137}Cs and ^{210}Pb). Due to the absence of *in situ* macrofossils or the small volume of material collected, most AMS samples were bulk peat (approximately 0.5 cm thick) apart from the top of G/01/1A where there were abundant seeds of *Menyanthes trifoliata*. The NERC Radiocarbon Laboratory (NERC RCL) at East Kilbride prepared the samples to graphite before sending them to the University of Arizona NSF-AMS facility for ^{14}C analysis.

Pre-treatment of the raw samples followed set methods from NERC RCL. Samples were digested in 2M hydrochloric acid (80°C, 8 hours), washed free from mineral acid with distilled water then digested in 2M potassium hydroxide (80°C, 8 hours). The digestion was repeated using distilled water until no further humics were extracted. The residue was rinsed free of alkali, digested in 2M hydrochloric acid (80°C, 5 hours) then rinsed free of acid, dried and homogenised. The total carbon in a known weight of the pre-treated sample was recovered as carbon dioxide by heating with copper oxide in a sealed quartz tube. Iron/zinc reduction converted the gas to graphite (NERC RCL report).

The NERC RCL reports the ages as conventional radiocarbon years BP (relative to AD 1950) and percentage modern ^{14}C, both expressed at the $\pm 1\sigma$ level for overall analytical confidence. CALIB 4.3 (Stuiver & Reimer, 1993) calibrates the radiocarbon results to calendar years before present using the atmospheric decadal data set (file INTCAL98.14C, Stuiver *at al.*, 1998) and the 95% probability distribution method. Results in following chapters report calibrated ages as the range between the calculated minimum and maximum value, with the median age marked on figures.

3.7.3 Tephrochronology

Section 1.8.3 outlines the background to tephrochronology in south central Alaska. Jim Beget, at the University of Alaska, Fairbanks uses tephro-chronologic dating and other geochronologic techniques to provide quantitative geochronologic constraints on stratigraphic studies of terrestrial, lacustrine, and marine Quaternary sediments in Alaska. He identifies tephras using grain-mount thin sections and microprobe analysis and correlates them to Holocene tephras in his database (e.g. Beget, 1996; Beget *et al.*, 1991, 1994). Results of his analyses of samples taken from the sections at Girdwood and Kasilof are not available at the time of writing.

3.8 Summary

This chapter outlines the main techniques used throughout this PhD. Following chapters describe some of these techniques in more detail and present the results from the contemporary and fossil data.

Chapter 4
Contemporary training set from Kenai

4.1 Introduction

The combination of contemporary diatom data taken from Kenai River Flats and Kenai City Pier in 2000 and 2001, together with the contemporary diatom data set from Zong *et al.* (2003) form the basis of this chapter. Each of the 70 samples (containing 104 diatom species) has an associated altitude (m) relative to Mean Higher High Water (MHHW) and hours inundated per year to produce the contemporary training set. This chapter aims to describe the contemporary diatom assemblages from tidal flat through to freshwater environments and to produce a quantitative function whose application to the fossil data in later chapters, will allow quantitative estimates of relative sea-level change through time.

4.2 Environmental variables of interest

The two-predictor variables in the contemporary training set are altitude (m) relative to MHHW and hours inundated per year. Each of the contemporary diatom samples has a levelled altitude (m) relative to a temporary benchmark (TBM) and conversion of this value to altitude (m) relative to MHHW allows the calculation of relative sea-level change. Calculation of hours inundated for each individual sample uses its altitude (m) relative to MHHW.

4.2.1 Altitude (m) relative to MHHW

All tidal information and predictions are from the locally published tide tables and from NOAA, Centre for Operational Oceanographic products and Services (web page, http://co-ops.nos.noaa.gov).

Kenai River Flats and Kenai City Pier

Corrections applied to the tidal station at Seldovia where MHHW is 5.48 m above Mean Lower Low Water (MLLW) provide tidal predictions for the Kenai River. Daily predictions are available for Kenai City Pier where MHHW is 6.09 m above MLLW. However, the altitude (m) of MHHW differs at Kenai River Flats due to shoaling of water at the Kenai River entrance and base flow of the river dampening out low tide. Levelling of low and high tide to the TBM (value = 100) over two field seasons in May

2000 and 2001 allowed the determination of MLLW and MHHW at Kenai River Flats. Figure 4.1 (a) shows the observed low tide at Kenai River Flats against the predicted low tide at Kenai City Pier. It highlights that there is no relationship between the two and that MLLW at Kenai River Flats is difficult to predict. Figure 4.1 (b) shows the levelled height of high tide at Kenai River Flats against the predicted high tide at Kenai City Pier. As MHHW is 6.09 m above MLLW at Kenai City Pier the function $y = 1.0945x + 90.397$, with an r^2 value of 0.94, gives a MHHW value equivalent to a reading of 97.06 relative to the TBM at Kenai River Flats. This allows the contemporary surface samples taken from Kenai River Flats to have an associated altitude (m) relative to MHHW.

On 20th May 2001, the predicted high tide at Kenai City Pier was 5.46 m above MLLW and had a levelled ground height of 96.055 relative to TBM2 at the Pier. The reading taken from Kenai River Flats at the same time was extremely close to the best-fit line (figure 4.1b) and so represents an accurate estimate of the tide level without influence from other factors such as strong winds or increased river discharge. As we know MHHW at Kenai City Pier is 6.09 m, it is equivalent to a ground height of 96.685 m relative to TBM2. From this, all of the contemporary surface samples taken from Kenai City Pier can have an associated altitude (m) relative to MHHW and are directly comparable to those taken from Kenai River Flats.

The tidal range at Kasilof is 6.15 m (http://co-ops.nos.noaa.gov) similar to that at Kenai. However, MHHW was measured at Girdwood due to the increased tidal range and greater distance from Kenai.

Girdwood

The measurement of MHHW at Girdwood independently tests the accuracy of the fossil calibrations using the contemporary data from Kenai. The closest tidal station to Girdwood is Anchorage where MHHW is 8.84 m above MLLW. A correction exists to Sunrise, approximately 12 km west of Girdwood where MHHW is 10.18 m above MLLW. The repeated levelling of high tide to a TBM both at the front of the marsh and at the back of the marsh allows for any wind and wave action disturbing the measurement. Figure 4.2 shows the levelled height of high tide at Girdwood (m TBM) against that predicted at Sunrise (m MLLW). Application of linear and polynomial functions to both the back marsh measurements and combined (marsh front and back) measurements show MHHW is approximately 98.84 m relative to the TBM (table 4.1).

Table 4.1 Estimates of MHHW at Girdwood (mean = 98.84 m)

Data Set	Function	Altitude (m) of MHHW relative to TBM
Marsh front & Back	Linear	98.87
Marsh front & Back	Polynomial	98.83
Back marsh only	Linear	98.84
Back marsh only	Polynomial	98.80

4.2.2 Hours inundated

The NOAA web site (http://co-ops.nos.noaa.gov) provides hourly water level data for Seldovia from 1/7/2000 to 1/7/2001. Up-scaling of these measurements allows for the increase in tidal range with respect to Kenai City Pier and Kenai River Flats. The uneven distribution of data required separate calculations above and below MHHW. Best-fit trend lines for the observations provide individual values for each of the 70 contemporary samples (figure 4.3).

Figure 4.3 shows that the distribution of samples is non-linear with only 15 of the contemporary diatom samples inundated by the tide for more than 1000 hours per year. 45 samples have less than 50 hours tidal inundation per year and 26 samples have less than 20 hours tidal inundation per year, suggesting that the relationship between altitude (m) relative to MHHW and hours inundated per year is linear on the tidal flat but non-linear once on the salt marsh. Therefore, towards the upper end of the contemporary transect at Kenai River Flats a large altitudinal change may have little effect on hours inundated per year and so other factors, such as pH may have a greater influence on diatom distribution.

4.3 Multivariate analysis of contemporary diatoms - Cluster analysis

Unconstrained cluster analysis using Euclidian distance (no transformation of the data) and Chord distance (square root transformation of the data) aids in the description of contemporary diatom assemblages (diatom count information is in appendix 5 and sample altitudes (m relative to MHHW) and vegetation descriptions are in appendix 7. Samples prefaced YZ are from Zong *et al.* (2003)). Classes produced by the dendrograms are in a random order and do not relate to any environmental variable.

4.3.1 Euclidian distance

The dendrogram produced using Euclidian distance identifies six major classes within the contemporary diatom data. Figure 4.4 illustrates these classes with only the major taxa present (species above 5% of the total diatoms counted), figure 4.5 shows their altitudinal range and table 4.2 describes their main characteristics.

Table 4.2 Characteristics of diatom classes using Euclidian distance

Class	Dominant diatom species	Altitude (m) relative to MHHW
1	Polyhalobous species, for example, *Cocconeis peltoides*, *Odentella aurita*, *Paralia sulcata* and *Thalassiosira eccentrica* dominate class 1. It also has high counts of *Navicula cari* var. *cincta* and *Cymbella ventricosa*. Figure 4.5 shows that it is a mixture of the Kenai River Flats and Kenai City Pier samples	-5.28 to +0.18
2	*Navicula cari* var. *cincta* dominates class 2 together with lower counts of other polyhalobous and mesohalobous species. Again, it is a mixture of Kenai River Flats and Kenai City Pier samples	-0.15 to +1.16
3	*Navicula clementis* dominates class 3 alongside smaller amounts of *Navicula phyllepta*, *Navicula protracta* and *Nitzschia fruticosa*	+1.04 to +1.17
4	Oligohalobous-indifferent species dominate class 4, for example, *Navicula brockmanii*, *Nitzschia fruticosa*, *Nitzschia pusilla* and *Pinnularia lagerstedtii*	+1.15 to +1.47
5	*Eunotia exigua* dominates class 5 with smaller amounts of *Achnanthes minutissima*	+1.39 to +1.57
6	A mixture of oligohalobous-indifferent and halophobous species dominate class 6, for example, *Achnanthes minutissima*, *Diploneis ovalis*, *Eunotia exigua* and *Tabellaria fenestrata*. Class 6 also contains KE/01/S38, dominated by the planktonic taxa *Aulacoseira granulata*	+1.39 to +1.70

Using Euclidian distance, the Kenai City Pier samples compare well to those collected from Kenai River Flats because samples from each site are located within the same class. Figure 4.5 shows that class 1 occupies the largest altitudinal range of 5.46 m with class 2 occupying a range of 1.31 m. At higher elevations above MHHW, the classes are more constrained altitudinally, with ranges between 0.13 and 0.32 m.

4.3.2 Chord distance

The dendrogram produced using Chord distance separates the contemporary diatom data into eight distinct classes (figure 4.6). Figure 4.7 shows their altitudinal ranges and table 4.3 describes their main characteristics. Classes produced using Chord distance separates the samples taken from Kenai City Pier from those taken from the mudflat at Kenai River Flats but they do overlap altitudinally. These two classes (7 and 8) occupy the largest altitudinal ranges of 5.98 m and 5.54 m respectively. With increasing altitude above MHHW, the altitude range of classes decrease, varying from 0.03 m to 0.34 m.

By comparing the dendrograms produced by Euclidian and Chord distance similar samples are clustered together using both transformations, apart from the separation of tidal flat species into two classes using Chord distance. Major classes do not appear in samples found below MHHW indicating that diatom assemblages are the same over a large altitudinal range, approximately 5.0 m. Possible explanations may include the effect of river discharge, intense mixing of tidal flat sediment during the winter months by ice (section 2.7) or it being a residual assemblage where dead diatoms are washed away by tidal currents as described by Sawai (2001b). Hemphill-Haley (1995a) also found that tidal flat diatoms cover a wide altitude range in the Pacific Northwest of the USA. All these factors may have implications for the development of an accurate quantitative transfer function. However, at higher elevations above MHHW, diatoms are more sensitive to elevation and distinct classes are present over a smaller altitudinal range. This suggests that a transfer function may perform more accurately and precisely in salt marsh and raised bog environments.

4.4 Developing quantitative regression models

This section develops a regression model of the contemporary diatom data against the two environmental variables of altitude (m) relative to MHHW and hours inundated per year as described in section 3.6.2.

Table 4.3 Characteristics of diatom classes using Chord distance

Class	Dominant diatom species	Altitude (m) relative to MHHW
7	Polyhalobous species, *Navicula cari* var. *cincta* and *Navicula cryptocephala* dominate class 7. Figure 4.7 shows that it consists of samples only from Kenai River Flats	-5.28 to +0.70
8	Polyhalobous species, for example, *Cocconeis peltoides* and *Thalassionema nitzschioides* dominate class 8 together with *Navicula cari* var. *cincta* and *Navicula cryptocephala*. Small differences do exist between classes 7 and 8, for example, class 7 contains fewer *Cocconeis peltoides* and more *Navicula halophila*, *Navicula peregrina* and *Synedra fasciculata*. Figure 4.7 shows that it consists of samples only from Kenai City Pier	-4.53 to +1.01
9	*Navicula cari* var. *cincta* dominates class 9 together with other polyhalobous, mesohalobous and oligohalobous species	+0.82 to +1.16
10	*Navicula clementis* dominates class 10 together with smaller amounts of *Navicula Phyllepta*, *Navicula protracta* and *Navicula cari* var. *cincta*	+1.09 to +1.12
11	Class 11 contains a broad mixture of diatoms with dominant species being *Navicula phyllepta*, *Navicula protracta*, *Navicula clementis* and *Nitzschia fruticosa*	+1.17 to +1.27
12	Oligohalobous-indifferent diatoms dominate class 12, in particular, *Nitzschia fruticosa* together with *Navicula brockmanii*, *Nitzschia pusilla* and *Pinnularia lagerstedtii*	+1.26 to +1.47
13	Oligohalobous-indifferent and halophobous diatoms dominate class 13, for example, *Achnanthes minutissima*, *Diploneis ovalis* and *Tabellaria fenestrata*	+1.40 to +1.57
14	*Eunotia exigua* dominates class 14 with smaller amounts of *Achnanthes minutissima* and other halophobes. This class also contains sample KE/01/S38, dominated by the planktonic taxa *Aulacoseira granulata*	+1.39 to +1.70

Detrended Canonical Correspondence Analysis (DCCA) determines whether linear or unimodal methods are appropriate for the contemporary training set. Regression of the contemporary data can then produce a relationship between the contemporary diatom data and associated environmental variables. Statistical parameters, for example, the coefficient of determination (r^2), which is a measure of the strength of the relationship between observed and inferred values and the Root Mean Square Error of Prediction (RMSEP), which is a measure of the predictive abilities of the training set, determine the best models. Following chapters apply these regression models to the fossil data from Kenai, Kasilof and Girdwood allowing quantitative reconstructions of relative sea-level change through time.

4.4.1 Detrended Canonical Correspondence Analysis

Detrended Canonical Correspondence Analysis (DCCA) estimates the gradient length for the environmental variables of interest, altitude (m) relative to MHHW and hours inundated per year for the full data set of 70 samples (table 4.4). It is a pre-requisite to determine the appropriate numerical model.

Table 4.4 DCCA results for full contemporary data set

Environmental Variable	DCCA axis 1 length (SD units)
Altitude (m) relative to MHHW	3.459
Hours inundated per year	2.861

As DCCA results are greater than two standard deviation (SD) units, unimodal methods of regression and calibration are appropriate for the full contemporary data set for both altitude (m) relative to MHHW and hours inundated per year (refer to section 3.6.2).

4.4.2 Optimum conditions for diatom species

The unimodal method of Weighted Averaging (WA) (CALIBRATE version 0.7; Juggins & ter Braak, 1997) calculates the optimum (the maximum of the response curve) and tolerance (breadth of the response curve) with reference to height (m MHHW) for each individual diatom species ($u \pm t$). Figure 4.8 shows the most abundant taxa (those that reach more than 5% in at least one sample) and solid circles indicate those taxa that occur in five or fewer samples. The inset illustrates the entire data set (appendix 1).

The transition from tidal flat to vegetated marsh occurs around zero to 1.0 m relative to MHHW. Species with optima below MHHW have very large tolerances of approximately 3 m or more and those with optima above MHHW generally occur within a smaller altitudinal range. Large tolerances can be produced either by the taxa being present in a large number of samples over a wide altitudinal zone such as those species with an optima below MHHW. Alternatively, taxa found in a small number of samples (represented by solid circles), for example, the planktonic diatom *Aulacoseira granulata* dominates only one sample, and so the breadth of its response curve is also high. However, Hill's N2 should reduce these variations. Towards the upper end of the range, *Pinnularia mesolepta* and *Hantzschia virgata* have predicted optimums above 2.0 m. This suggests that species found in only a few samples may be subject to error because the highest contemporary sample taken from Kenai River Flats has an altitude of +1.70 m above MHHW.

The optima and tolerances of contemporary tidal flat diatoms again suggest that there may be potential problems with developing an accurate transfer function for the mudflat samples as species occur over a large altitudinal range. It indicates that a transfer function should perform well once on the salt marsh surface and agrees with the result from cluster analysis (section 4.3).

4.4.3 Transfer function – Regression of the full contemporary data

DCCA results for the full data set (table 4.4) suggest unimodal regression is appropriate for altitude (m) relative to MHHW and hours inundated per year. Suitable methods include Weighted Averaging-Partial Least Squares (WA-PLS), Weighted Averaging (WA) and Weighted Averaging-Tolerance Downweighted (WA-TOL). Regression models include all samples as they represent natural variation within the modern day environment. A high r^2 value and a low RMSEP suggest a good model (section 3.6.2).

Table 4.5 shows the statistical results from WA-PLS using components 1 to 3, WA and WA-TOL with both classical and inverse deshrinking on the 70 contemporary diatom samples against altitude (m) relative to MHHW. It also includes a square root transformation of the biological data. Table 4.6 shows the results for hours inundated per year.

Table 4.5 Statistical parameters for the regression of the full contemporary data set against altitude (m) relative to MHHW

Model	Transformation	RMSEP	r^2
WA-PLS component 1		0.97	0.61
WA-PLS component 2		0.93	0.65
WA-PLS component 3		0.94	0.64
WA-PLS component 1	Square root	1.01	0.59
WA-PLS component 2	Square root	0.93	0.65
WA-PLS component 3	Square root	0.92	0.66
WA inverse		0.97	0.62
WA-TOL inverse		0.95	0.65
WA inverse	Square root	1.01	0.59
WA-TOL inverse	Square root	1.08	0.55
WA classical		1.16	0.62
WA-TOL classical		0.99	0.65
WA classical	Square root	1.23	0.59
WA-TOL classical	Square root	1.13	0.56

Table 4.6 Statistical parameters for the regression of the full contemporary data set against hours inundated per year

Model	Transformation	RMSEP	r^2
WA-PLS component 1		1169.33	0.45
WA-PLS component 2		1137.97	0.49
WA-PLS component 3		1171.75	0.47
WA-PLS component 1	Square root	1198.56	0.43
WA-PLS component 2	Square root	1128.74	0.50
WA-PLS component 3	Square root	1112.10	0.52
WA inverse		1167.97	0.46
WA-TOL inverse		1260.93	0.41
WA inverse	Square root	1196.61	0.43
WA-TOL inverse	Square root	1323.32	0.34
WA classical		1551.04	0.47
WA-TOL classical		1348.33	0.42
WA classical	Square root	1618.06	0.44
WA-TOL classical	Square root	1398.21	0.36

All regression models for the full training set result in a high RMSEP of approximately 1 m for altitude (m) relative to MHHW and 1150 hours for hours inundated per year suggesting that the predictive abilities of these models are poor. The r^2 values are low with altitude (m) relative to MHHW performing better than hours inundated per year with the highest r^2 value being 0.66 using WA-PLS component 3 with a square root transformation. This indicates that the relationships between observed and inferred values are poor and any reconstruction based on these models will have a high associated error. A square root transformation of the biological data does not significantly alter the outcome of the regression.

Investigating these relationships further, scatter plots show a non-linear relationship for the observed against predicted altitude (m) relative to MHHW and hours inundated per year. Figure 4.9 shows the regression results for altitude (m) relative to MHHW using WA-PLS components 1, 2 and 3. Models appear to perform best above +1.0 m MHHW where the predicted values are close to the observed but predictions become less accurate below this value. Between +1.0 m and -1.5 m MHHW, regression models tend to predict samples to be at a lower altitude than observed. Below -1.5 m MHHW, they predict samples to be at a higher altitude than observed with both components 1 and 2 unable to predict any sample to occur below -3.0 m MHHW. The lowest contemporary tidal flat sample taken from Kenai River Flats had an altitude of -5.28 m relative to MHHW and so the regression models are unable to predict samples to occur in the lowest 2.0 m of the observed range. This problem relates back to cluster analyses being unable to define any subsets within the tidal flat samples (section 4.3) and the large tolerances of diatoms found below MHHW (section 4.4.2). The regression models are unable to discriminate between the tidal flat species and it appears that they are unable to predict any sample below +1.0 m MHHW with any accuracy.

Figure 4.10 shows the non-linear relationship for hours inundated per year using WA-PLS components 1, 2 and 3. Components 1 and 2 are unable to predict any sample having over 4000 hours inundation per year where as calculated values for the contemporary samples have a maximum of 7000 hours per year. Below 3000 hours per year, the models over-predict until zero.

The non-linearity of the results using both altitude (m) relative to MHHW and hours inundated per year, cluster analyses suggesting that there are no distinct classes below MHHW and the large tolerances of tidal flat diatoms indicate samples below MHHW are problematic. A separate investigation of this subset follows.

4.4.4 Regression of contemporary samples found below MHHW

The creation of a smaller subset consisting of 17 contemporary samples containing 65 diatom species and ranging in altitude from -5.28 to -0.15 m MHHW allows an investigation into the relationship between observed and inferred values for samples found below MHHW. DCCA re-established the gradient length for both altitude (m) relative to MHHW and hours inundated per year (table 4.7). This was necessary, as the environmental gradient may have become more linear with the smaller sample size.

Table 4.7 DCCA results for contemporary samples below MHHW

Data set	DCCA Axis 1 length (SD units)
Altitude (m) relative to MHHW	0.793
Hours inundated per year	0.740

As the lengths of the environmental gradients are less than two SD units, linear regression models are appropriate, for example, Partial Least Squares (PLS). Table 4.8 shows the statistical parameters for PLS regression of samples found below MHHW against predicted altitude (m) relative to MHHW and table 4.9 shows the same for hours inundated per year, using components 1 to 3 together with a square root transformation of the biological data.

Table 4.8 Statistical parameters for the PLS regression of contemporary samples found below MHHW against altitude (m) relative to MHHW

Model	Transformation	RMSEP	r^2
PLS component 1		1.70	0.05
PLS component 2		1.66	0.07
PLS component 3		1.59	0.11
PLS component 1	Square root	1.60	0.09
PLS component 2	Square root	1.56	0.12
PLS component 3	Square root	1.50	0.16

Table 4.9 Statistical parameters for the PLS regression of contemporary samples found below MHHW against hours inundated per year

Model	Transformation	RMSEP	r^2
PLS component 1		2165.31	0.06
PLS component 2		2102.28	0.08
PLS component 3		2022.87	0.12
PLS component 1	Square root	2026.52	0.09
PLS component 2	Square root	1965.82	0.13
PLS component 3	Square root	1887.90	0.17

For both altitude (m) relative to MHHW and hours inundated per year regression models have a large RMSEP and extremely low r^2 with the highest value being 0.17. This suggests that the strength of the relationship between observed and predicted values are very poor. Scatter plots of observed against predicted values for each of the regression models investigate the relationships further. Figure 4.11 shows the best regression results for contemporary samples below MHHW against altitude (m) relative to MHHW and hours inundated per year (PLS component 3 with a square root transformation).

With a smaller data set, the relationship between the observed and predicted values should become more linear. However, both graphs illustrate large amounts of scatter produced using both environmental variables and highlight the problems associated with using regression models for the tidal flat samples. This poor relationship implies that any regression model applied to the tidal flat samples and therefore any transfer function applied to the silt units within cores are likely to give inaccurate and imprecise estimates of predicted altitude (m) relative to MHHW and hours inundated per year. Other evidence includes the results using cluster analysis where there are no distinct classes below MHHW (section 4.3) and by the tolerances of contemporary diatoms below MHHW occupying large ranges (section 4.4.2).

Possible explanations, as mentioned earlier, include the effect of river discharge and intense mixing of tidal flat sediment by ice during the winter months (section 2.7). Both could severely disturb diatom distributions along the contemporary tidal flat. Other possible causes include tidal flat samples having residual diatom assemblages after the washing away of dead diatoms by tidal currents (e.g. Sawai, 2001b). This has implications for the reconstruction of relative sea-level change at Kenai, Kasilof and Girdwood.

During a large earthquake (magnitude>8) maximum co-seismic subsidence similar to that measured in 1964 could occur (approximately 2.0 m). In the contemporary Kenai environment, freshwater peat forms at an approximate altitude of +1.35 m MHHW and so co-seismic submergence of -1.8 m would lower the land to approximately -0.5 m MHHW. Therefore, the extensive lower part of the tidal flat may not be required for reconstructing relative sea-level movements during the EDC model assuming that raised bog communities fully develop during inter-seismic periods. It suggests that there are major problems for recording co-seismic events within clastic units, for example, if two earthquakes occur in quick succession, raised bog communities are unlikely to have developed in the intervening period. The litho- and bio- stratigraphy are unlikely to record these events, as there is no discrimination between samples found towards the upper part of the tidal flat and those found lower down, an altitude range of approximately 5.0 m. This ultimately influences estimates of earthquake recurrence intervals. At the extreme ends of the transect, i.e. the tidal flat and raised bog, the litho- and bio-stratigraphy may not clearly record evidence of large earthquakes. The best form of evidence occurs where both clastic and organic sequences are present and the litho- and bio-stratigraphy clearly record the EDC model as peat-silt couplets.

To try to increase the accuracy of the regression models section 4.4.5 describes the formation of training sets from restricted altitudinal ranges.

4.4.5 Regression of training sets from restricted altitudinal ranges

To increase the predictive power of the regression models, a smaller number of samples are included in the contemporary training set. This section aims to decrease the scatter and increase the linear relationship between the observed and predicted environmental variables. Problems arise in samples found below the altitude of the contemporary salt marsh surface, approximately +1.0 m above MHHW. The cut off points for the new smaller data sets are samples above -1.6, -1.0, -0.5, 0, +0.5 and +1.0 m relative to MHHW (table 4.10).

Table 4.10 Summary of smaller contemporary data sets

Data set (relative to m MHHW)	Number of samples	Number of species
Full	70	104
Samples above -1.6	63	103
Samples above -1.0	61	102
Samples above -0.5	57	100
Samples above 0	53	98
Samples above +0.5	50	94
Samples above +1.0	48	94

Table 4.11 shows the DCCA results for the six smaller training sets for both altitude (m) relative to MHHW and hours inundated per year. This was necessary, as the environmental gradient may have become more linear with smaller sample size.

Table 4.11 DCCA results for the smaller contemporary training sets

Data set	Range of data	DCCA Axis 1 length
Altitude (m) relative to MHHW	Samples above -1.6	4.055
	Samples above -1.0	3.945
	Samples above -0.5	4.124
	Samples above 0	4.572
	Samples above +0.5	5.978
	Samples above +1.0	5.029
Hours inundated per year	Samples above -1.6	3.426
	Samples above -1.0	3.194
	Samples above -0.5	3.075
	Samples above 0	2.684
	Samples above +0.5	3.798
	Samples above +1.0	5.201

The higher values of DCCA axis 1 length show that environmental gradients have generally become longer when compared to the results obtained for the full data set (table 4.4) and that unimodal methods of regression and calibration are appropriate. WA-PLS, WA and WA-TOL with both classical and inverse deshrinking are best, both with and without a square root transformation of the biological data. Tables 4.12 to 4.23 show statistical results for each model for both altitude (m) relative to MHHW (tables 4.12 to 4.17) and hours inundated per year (tables 4.18 to 4.23).

Tables 4.12 to 4.17

Statistical parameters for contemporary data sets using altitude (m) relative to MHHW

Table 4.12 Samples above -1.6 m MHHW using altitude (m) relative to MHHW

Model	Transformation	RMSEP	r^2
WA-PLS component 1		0.35	0.80
WA-PLS component 2		0.31	0.84
WA-PLS component 3		0.30	0.85
WA-PLS component 1	Square root	0.39	0.75
WA-PLS component 2	Square root	0.32	0.83
WA-PLS component 3	Square root	0.31	0.84
WA inverse		0.35	0.80
WA-TOL inverse		0.39	0.80
WA inverse	Square root	0.39	0.75
WA-TOL inverse	Square root	0.48	0.69
WA classical		0.37	0.80
WA-TOL classical		0.38	0.80
WA classical	Square root	0.42	0.76
WA-TOL classical	Square root	0.47	0.69

Table 4.13 Samples above -1.0 m MHHW using altitude (m) relative to MHHW

Model	Transformation	RMSEP	r^2
WA-PLS component 1		0.30	0.81
WA-PLS component 2		0.25	0.86
WA-PLS component 3		0.24	0.87
WA-PLS component 1	Square root	0.32	0.77
WA-PLS component 2	Square root	0.26	0.85
WA-PLS component 3	Square root	0.25	0.86
WA inverse		0.29	0.81
WA-TOL inverse		0.35	0.79
WA inverse	Square root	0.32	0.77
WA-TOL inverse	Square root	0.45	0.67
WA classical		0.31	0.82
WA-TOL classical		0.34	0.79
WA classical	Square root	0.35	0.78
WA-TOL classical	Square root	0.44	0.68

Table 4.14 Samples above -0.5 m MHHW using altitude (m) relative to MHHW

Model	Transformation	RMSEP	r^2
WA-PLS component 1		0.24	0.78
WA-PLS component 2		0.20	0.84
WA-PLS component 3		0.21	0.84
WA-PLS component 1	Square root	0.25	0.76
WA-PLS component 2	Square root	0.20	0.84
WA-PLS component 3	Square root	0.22	0.82
WA inverse		0.24	0.78
WA-TOL inverse		0.25	0.78
WA inverse	Square root	0.25	0.76
WA-TOL inverse	Square root	0.32	0.65
WA classical		0.25	0.79
WA-TOL classical		0.25	0.78
WA classical	Square root	0.27	0.76
WA-TOL classical	Square root	0.32	0.65

Table 4.15 Samples above 0 MHHW using altitude (m) relative to MHHW

Model	Transformation	RMSEP	r^2
WA-PLS component 1		0.18	0.71
WA-PLS component 2		0.15	0.78
WA-PLS component 3		0.15	0.79
WA-PLS component 1	Square root	0.18	0.69
WA-PLS component 2	Square root	0.14	0.81
WA-PLS component 3	Square root	0.15	0.79
WA inverse		0.18	0.71
WA-TOL inverse		0.19	0.71
WA inverse	Square root	0.18	0.69
WA-TOL inverse	Square root	0.22	0.60
WA classical		0.19	0.72
WA-TOL classical		0.18	0.73
WA classical	Square root	0.20	0.70
WA-TOL classical	Square root	0.22	0.62

Table 4.16 Samples above +0.5 m MHHW using altitude (m) relative to MHHW

Model	Transformation	RMSEP	r^2
WA-PLS component 1		0.09	0.81
WA-PLS component 2		0.09	0.81
WA-PLS component 3		0.09	0.83
WA-PLS component 1	Square root	0.09	0.81
WA-PLS component 2	Square root	0.08	0.83
WA-PLS component 3	Square root	0.08	0.83
WA inverse		0.09	0.81
WA-TOL inverse		0.10	0.77
WA inverse	Square root	0.09	0.81
WA-TOL inverse	Square root	0.10	0.75
WA classical		0.09	0.81
WA-TOL classical		0.10	0.77
WA classical	Square root	0.09	0.81
WA-TOL classical	Square root	0.10	0.75

Table 4.17 Samples above +1.0 m MHHW using altitude (m) relative to MHHW

Model	Transformation	RMSEP	r^2
WA-PLS component 1		0.07	0.85
WA-PLS component 2		0.07	0.85
WA-PLS component 3		0.06	0.87
WA-PLS component 1	Square root	0.06	0.86
WA-PLS component 2	Square root	0.06	0.86
WA-PLS component 3	Square root	0.06	0.88
WA inverse		0.07	0.85
WA-TOL inverse		0.07	0.84
WA inverse	Square root	0.06	0.86
WA-TOL inverse	Square root	0.07	0.82
WA classical		0.07	0.85
WA-TOL classical		0.07	0.84
WA classical	Square root	0.07	0.86
WA-TOL classical	Square root	0.08	0.82

Tables 4.18 to 4.23

Statistical parameters for contemporary data sets using hours inundated per year

Table 4.18 Samples above -1.6 m MHHW using hours inundated per year

Model	Transformation	RMSEP	r^2
WA-PLS component 1		327.02	0.64
WA-PLS component 2		297.24	0.71
WA-PLS component 3		284.35	0.73
WA-PLS component 1	Square root	356.82	0.58
WA-PLS component 2	Square root	319.65	0.66
WA-PLS component 3	Square root	301.10	0.70
WA inverse		326.26	0.64
WA-TOL inverse		483.49	0.28
WA inverse	Square root	356.16	0.58
WA-TOL inverse	Square root	492.99	0.26
WA classical		369.12	0.65
WA-TOL classical		493.79	0.29
WA classical	Square root	422.08	0.59
WA-TOL classical	Square root	505.97	0.27

Table 4.19 Samples above -1.0 m MHHW using hours inundated per year

Model	Transformation	RMSEP	r^2
WA-PLS component 1		236.82	0.69
WA-PLS component 2		208.27	0.76
WA-PLS component 3		196.87	0.78
WA-PLS component 1	Square root	260.21	0.62
WA-PLS component 2	Square root	224.46	0.72
WA-PLS component 3	Square root	209.39	0.76
WA inverse		236.34	0.69
WA-TOL inverse		401.37	0.20
WA inverse	Square root	260.19	0.62
WA-TOL inverse	Square root	409.86	0.17
WA classical		258.95	0.70
WA-TOL classical		405.42	0.20
WA classical	Square root	300.93	0.64
WA-TOL classical	Square root	413.58	0.17

Table 4.20 Samples above -0.5 m MHHW using hours inundated per year

Model	Transformation	RMSEP	r^2
WA-PLS component 1		161.10	0.62
WA-PLS component 2		147.83	0.68
WA-PLS component 3		153.52	0.66
WA-PLS component 1	Square root	168.33	0.58
WA-PLS component 2	Square root	148.56	0.68
WA-PLS component 3	Square root	160.90	0.63
WA inverse		160.79	0.62
WA-TOL inverse		256.03	0.13
WA inverse	Square root	167.77	0.58
WA-TOL inverse	Square root	257.93	0.11
WA classical		180.58	0.64
WA-TOL classical		257.34	0.13
WA classical	Square root	193.95	0.60
WA-TOL classical	Square root	259.96	0.11

Table 4.21 Samples above 0 m MHHW using hours inundated per year

Model	Transformation	RMSEP	r^2
WA-PLS component 1		79.10	0.48
WA-PLS component 2		70.95	0.58
WA-PLS component 3		70.18	0.59
WA-PLS component 1	Square root	80.69	0.46
WA-PLS component 2	Square root	65.82	0.64
WA-PLS component 3	Square root	68.05	0.62
WA inverse		78.97	0.48
WA-TOL inverse		106.75	0.11
WA inverse	Square root	80.70	0.46
WA-TOL inverse	Square root	110.76	0.04
WA classical		89.26	0.52
WA-TOL classical		107.27	0.10
WA classical	Square root	92.36	0.50
WA-TOL classical	Square root	111.52	0.04

Table 4.22 Samples above +0.5 m MHHW using hours inundated per year

Model	Transformation	RMSEP	r^2
WA-PLS component 1		18.98	0.54
WA-PLS component 2		18.38	0.57
WA-PLS component 3		19.18	0.54
WA-PLS component 1	Square root	19.01	0.54
WA-PLS component 2	Square root	17.83	0.59
WA-PLS component 3	Square root	19.05	0.55
WA inverse		18.94	0.54
WA-TOL inverse		19.62	0.51
WA inverse	Square root	19.14	0.53
WA-TOL inverse	Square root	20.16	0.49
WA classical		21.56	0.54
WA-TOL classical		21.98	0.52
WA classical	Square root	22.66	0.53
WA-TOL classical	Square root	23.56	0.48

Table 4.23 Samples above +1.0 m MHHW using hours inundated per year

Model	Transformation	RMSEP	r^2
WA-PLS component 1		4.96	0.90
WA-PLS component 2		4.54	0.92
WA-PLS component 3		4.15	0.94
WA-PLS component 1	Square root	4.67	0.91
WA-PLS component 2	Square root	4.49	0.92
WA-PLS component 3	Square root	4.23	0.93
WA inverse		4.86	0.91
WA-TOL inverse		4.87	0.91
WA inverse	Square root	4.66	0.91
WA-TOL inverse	Square root	4.98	0.90
WA classical		4.94	0.91
WA-TOL classical		4.96	0.91
WA classical	Square root	4.72	0.91
WA-TOL classical	Square root	5.01	0.90

WA and WA-TOL with both inverse and classical deshrinking generate similar results but the best model based upon a low RMSEP and high r^2 is WA-PLS using components 1, 2 and 3. This agrees with Birks (1995) who suggests WA-PLS is an appropriate and robust reconstruction procedure for data spanning an environmental gradient of two or more SD units.

Based upon the r^2 value for the -1.6, -1.0, -0.5, 0, and +0.5 m models, altitude (m) relative to MHHW performs better than hours inundated per year and so hours inundated is disregarded from further analyses of these training sets. For samples above +1.0 m, hours inundated performs slightly better than altitude (m) relative to MHHW with WA-PLS component 3 with no square root transformation providing the best statistical result with a RMSEP of 4.15 and an r^2 of 0.94.

For the training sets -1.6, -1.0 and -0.5 m, a square root transformation of the data using WA-PLS decreases the predictive ability of the model as illustrated by the higher RMSEP and lower r^2 value. For the data sets 0, +0.5 and +1.0 altitude (m) relative to MHHW there appears to be a very slight improvement using a square root transformation for certain components, but these improvements are not significant. RMSEP decreases with smaller training sets, ranging from approximately 0.3 m for the training set -1.6 m MHHW to approximately 0.07 m for samples above +1.0 m MHHW.

In summary, WA-PLS using components 1, 2 and 3 with no data transformation are the best models for the training sets -1.6, -1.0, -0.5, 0 and +0.5 m to predict altitude (m) relative to MHHW. For the training set containing samples above +1.0 m, WA-PLS using components 1, 2 and 3 with no data transformation are the best models to predict both altitude (m) relative to MHHW and hours inundated per year. Scatter plots relating to these models appear in appendix 2.

The scatter plots show that the models are unable to predict samples to occur below their cut off points. For samples above -1.6 m relative to MHHW there is a non-linear relationship for samples found below +1.0 m and the models perform less well for the tidal flat samples. More components improve this relationship, with an increase in r^2 and decrease in RMSEP. The same relationship occurs for the scatter plots obtained for samples above -1.0 m and -0.5 m relative to MHHW. Regression models using samples above 0 m and +0.5 m MHHW suggest that the relationship between the observed and predicted altitude becomes increasingly linear as you approach the salt marsh surface as more samples lie along the 1:1 line. The scatter plots for samples found above +1.0 m, for both altitude (m) relative to MHHW and hours inundated per year are the most accurate models with predicted values very close to the observed.

The r^2 values obtained for the different models are comparable to, and improve upon the r^2 values obtained in other studies (table 4.24).

Table 4.24 r^2 results from other studies

Paper	r^2
Gehrels (2000)	0.59 to 0.80
Gehrels *et al.* (2001)	0.26 to 0.83
Zong and Horton (1999)	0.65 to 0.72
Zong *et al.* (2003)	0.81

4.5 The selection of regression models for the calibration of fossil data

Sections 4.4.3 to 4.4.5 experimented with numerous regression models of the contemporary data using different methods (WA-PLS, WA, WA-TOL and PLS), square root transformations of the biological data and several components. Calibration of the fossil data from Kenai, Kasilof and Girdwood requires the selection of the best regression model or models to estimate relative sea-level changes through time. Different regression models should perform better in certain parts of the environmental range and litho-stratigraphy provides an independent assessment over which model or models are applicable. On this basis, following sections define the models most suitable for the calibration of fossil data.

4.5.1 Calibration of marsh and raised bog sediments

In the modern day Kenai environment diverse raised bog environments occur approximately +1.35 m above MHHW and surface peat (without silt) starts developing in Kenai 2000-10 at +1.15 m above MHHW (appendix 4). Therefore, where peat occurs in the stratigraphy, the +1.0 m MHHW and +1.0 m hours inundated models are acceptable as peat only forms above this elevation, allowing for some variation at the lower end. The scatter plots for these two models (figures 4.12 and 4.13) show very little difference between the three components and so WA-PLS component 1 is appropriate for both environmental variables. They accurately predict altitude (m) relative to MHHW and hours inundated per year for the salt marsh and raised bog samples found in the Kenai contemporary environment from +1.09 to +1.70 m above MHHW (figure 2.4). RMSEP is 0.07 m for altitude (m) relative to MHHW and 4.96 hours for hours inundated per year. It is necessary to convert hours inundated per year back to altitude (m) relative to MHHW to allow quantitative calibrations of the fossil samples (figure 4.14). These models give the highest r^2 (0.85 and 0.90 respectively), lowest RMSEP and lowest sample specific error and so reconstructions are more precise.

4.5.2 Calibration of tidal flat to salt marsh sediments

The +1.0 m models are unsuitable for interpreting changes throughout silt units because of the imposed cut-off value compared to the full elevation range of tidal flat sediments. In the modern day Kenai environment, vegetation is absent at -0.28 m MHHW and scattered *Puccinellia* sp. colonises the mudflat at -0.15 m MHHW. Suitable models include the -0.5 m MHHW or full model, with the -0.5 m model producing smaller sample specific errors due to the removal of non-linear elements of the contemporary data set. Litho-stratigraphy helps indicate which model is most suitable. If the silt contains *in situ* rootlets, the -0.5 m MHHW model is appropriate and more precise, as vegetation does not live below this altitude, again, allowing for some variance at the lower limit. In addition, it has a lower RMSEP than the training set of -1.0 m and a higher r^2 than samples above 0 m MHHW. Figure 4.15 illustrates the relationship between predicted and observed values. WA-PLS component 3 is best as it has more samples lying along the 1:1 line (RMSEP = 0.21, r^2 = 0.84).

If the silt does not contain any rootlets then the full model is the only option, as it is possible that silt deposition occurred below -0.5 m MHHW. The full data set (table 4.5 and figure 4.9) allows the prediction of lower altitudes (m) relative to MHHW, but due to the non-linear relationship between predicted and observed values and the scatter contained within the data set it has a high associated error (RMSEP) of approximately 1.0 m and a low r^2 of 0.65. For the full data set, WA-PLS component 2 is appropriate to calibrate fossil samples as it increases the accuracy and precision of the model compared to components 1 and 3.

4.6 The modern analogue technique

The modern analogue technique (MAT) can reconstruct altitude (m) relative to MHHW and allows identification of fossil samples that have 'poor' modern analogues within the contemporary training set (e.g. Birks, 1995). This is important, as the calibration results using the transfer function may be less accurate where 'poor' modern analogues exist (section 3.6.4).

Figure 4.16 shows the relationship between observed and predicted values using MAT on the contemporary Kenai data. It bases its predictions on the closest match and the weighted mean of the two, five and ten closest dissimilarity coefficients. All models show MAT accurately predicts the observed altitude of contemporary samples found above +1.0 m MHHW, but below this value a non-linear relationship exists.

Using a greater number of dissimilarity coefficients in the weighted mean produces a different relationship below +1.0 m MHHW. For example, figure 4.16 (a) shows that using the closest dissimilarity coefficient, an equal spread exists on either side of the 1:1 line and it can predict down to a depth of approximately -4.5 m MHHW. In comparison, the model using the weighted mean of the ten closest matches (figure 4.16 (d)), predicts samples to have a lower altitude than observed for samples between +1.0 m and -2.0 m MHHW and samples to have a higher altitude than observed for samples below -2.0 m MHHW. The model is unable to predict any sample having a lower altitude than -2.7 m relative to MMHW, even though the lowest observed sample occurs at -5.28 m MHHW. This illustrates that MAT has problems predicting the altitude of tidal flat samples, similar to that observed for the transfer function technique. However, the results obtained also depend on the number of dissimilarity coefficients included in the weighted mean and then there is the added problem in deciding which model performs best in any environmental reconstruction.

Other problems of using MAT to quantitatively reconstruct altitude include the estimation of error terms. Bartlein and Whitlock (1993) use the standard deviation of the mean of the weighted values associated with the ten closest analogues, but they indicate this is likely to underestimate true uncertainty. They also suggest that MAT shows greater short-term variability than reconstructions derived using more statistical techniques due to its reliance on there being a close modern analogue. Given all these factors and additional uncertainties, the transfer function approach (sections 4.4.3 to 4.4.5) offers a better reconstruction of relative sea-level change through time.

Its main advantage is identifying which fossil samples have 'poor' modern analogues when compared to the contemporary data set. However, there is no set method to determine if the lowest dissimilarity found between a fossil sample and a modern sample represents a convincing match and analogue (Birks, 1995). Birks (1995) and Hughes *et al.* (2002) suggest that the extreme 10% of dissimilarities calculated between all modern samples is appropriate to indicate a 'good' analogue. Shane and Anderson (1993) use the extreme 2% and Webb *et al.* (1993) use the extreme 3% to define 'no' analogue situations. Other authors, for example, Whitlock *et al.* (1993) use the first, fifth, and tenth percentile of each unique pairing of the modern samples generated within the MAT program to suggest 'very good', 'good' and 'fair' analogues. Horton (1997) uses the 20th percentile as his cut-off value.

Figure 4.17 shows the cumulative frequency distribution of the minimum dissimilarity coefficient for the 70 contemporary samples and the threshold values used. To assess whether the lowest dissimilarity found between a fossil sample and a modern sample represents a convincing match, the extreme 2.5% and 5% of the dissimilarities calculated between all modern samples represent suitable thresholds. Table 4.25 summarises the values and descriptions used and these descriptions appear in following chapters.

Table 4.25 Thresholds and descriptions of modern analogues

Extreme percentage of data set	Description	Dissimilarity coefficient values
2.5% and less	'poor' analogue	Above 0.885
2.6 to 5%	'close' analogue	0.575 to 0.884
5.1% and above	'good' analogue	Below 0.574

4.7 Summary

This chapter analyses the contemporary data taken from Kenai River Flats and Kenai City Pier. It describes diatom assemblages along the contemporary surface transect and develops quantitative regression models. All techniques highlight the problems associated with the tidal flat samples.

Four regression models are appropriate for the calibration of the fossil data.

Using altitude (m) relative to MHHW:

- The full data set using WA-PLS component 2 - suitable for reconstructing altitude (m) for silt units containing no rootlets

- Samples above -0.5 m using WA-PLS component 3 - suitable for reconstructing altitude for silt units containing herbaceous rootlets
- Samples above +1.0 m using WA-PLS component 1 - suitable for reconstructing altitude for peat units

Using hours inundated per year:

- Samples above +1.0 m using WA-PLS component 1 - suitable for reconstructing altitude for peat units

Over the next three chapters, application of these models to fossil data from Kenai, Girdwood and Kasilof allows the quantification of relative sea-level change through time.

Chapter 5
Results – Kenai

5.1 Introduction

Plafker (1969) suggests approximately 0.5 m co-seismic subsidence accompanied the 1964 earthquake at Kenai but this interpolation was from three observations, at Anchorage, Homer and Nikiski (figure 1.4). The value for Nikiski, 15 km away, was 0.27 m submergence. Strong seismic shaking accompanied co-seismic submergence due to poorly consolidated sediments of Tertiary age (Plafker *et al.*, 1969). In a more recent study limited to the decades leading up to the 1964 event, Zong *et al.* (2003) estimate the magnitude of co-seismic land subsidence at Kenai based on the application of transfer function techniques. They estimate the value to be 0.17 ± 0.12 m based on diatom data (using a smaller contemporary data set than used in chapter 4) and 0.31 ± 0.21 m based on pollen, using a different method to estimate the error term.

Over a longer period, Combellick (1994) and Combellick and Reger (1994) present evidence for buried peat layers at Kenai dating back to 8423-9516 cal yr BP (appendix 3 contains all radiocarbon dates). They suggest that their burial by silt was a result of co-seismic submergence associated with older late Holocene events. However, as there was no investigation of bio-stratigraphy, these changes could result from non-seismic processes, for example on a local scale, river flooding and the infilling of estuaries or on a larger scale, eustatic and isostatic changes.

This chapter presents fossil data from Kenai River Flats, focusing in particular on the core from Kenai 2000-7 (see figure 2.3 for location). Section 5.2 describes the litho-stratigraphy across the marsh and sections 5.3 and 5.4 describe the bio- and chrono-stratigraphy of Kenai 2000-7. Following sections apply statistical techniques to the data from Kenai 2000-7 to allow the reconstruction of relative sea-level change through time. The specific aim is to investigate how the stratigraphy of Kenai River Flats records relative sea- and land-level movements associated with entire earthquake deformation cycles (EDC), in particular the 1964 and possible preceding events, by applying the criteria described by Nelson *et al.* (1996). Section 1.3 reviews the five criteria in detail. This chapter addresses the suddenness, amount and lateral extent of submergence together with any evidence of tsunami deposits. Chapter 8 addresses the synchroneity of submergence, when bringing all three study sites together.

5.2 Litho-stratigraphy of Kenai

A series of cores taken along the contemporary surface transect at Kenai River Flats (figure 2.3) reveals two to three buried peat layers. Figure 5.1 summarises the litho-stratigraphy across the marsh and appendix 4 contains detailed Troels-Smith descriptions.

The upper boundary of the lowest peat and overlying silt varies in depth between 1.0 to 2.5 m below present marsh surface, and it is sharp, apart from in Kenai 2000-7 where it is transitional over 0.05 m. Its thickness ranges from 0.10 m to 1.28 m and it is typically humified herbaceous peat with some *Sphagnum* species and bryophytes. It contains up to three distinct tephras, one likely to be the Hayes tephra (Combellick & Pinney, 1995), dated to 3591-4411 cal yr BP (Riehle, 1985). This peat layer is absent in Kenai 2000-9, probably due to its proximity to the small tidal channel.

In cores Kenai 2000-10 and Kenai 2000-14, a thinner peat layer (typically 0.04 m thick) occurs just above the upper boundary of the lowest peat, separated from it by a thin silt unit. A much thicker intervening clay-silt unit separates the uppermost peat from the lower peats.

The uppermost-buried peat layer is present in Kenai 2000-2 to Kenai 2000-10 with traces of silt found within the peat in Kenai 2000-11 and Kenai 2000-12. The peat ranges in depth from 0.05 to 0.19 m below current marsh surface. It generally thickens towards the landward end of the transect, ranging from 0.08 m by the riverbank to 0.27 m at Kenai 2000-10. It is typically brown herbaceous peat with some *Sphagnum* species and bryophytes. This peat contains up to two distinct tephras. Present day peat accumulation starts along the coring transect at Kenai 2000-7 where there is 0.01 m of silty peat at the surface. At Kenai 2000-16, a floating mat of vegetation occurs from the surface down to a depth of 0.83 m.

This sequence of multiple buried peat layers sharply overlain by silt suggests this area may record relative sea-level changes associated with periods of the EDC model (e.g. Combellick, 1994). Coarser sand layers do not overlie any of the buried peat surfaces, suggesting that there is no evidence for any tsunami deposits.

Using litho-, bio- and chrono-stratigraphical evidence, Zong *et al.* (2003) conclude that the burial of the upper peat layer resulted from co-seismic submergence associated with the 1964 earthquake, dated using caesium-137 (^{137}Cs). Traces of silt found at

Kenai 2000-11 and 12 represent the landward limit of tidal inundation and sedimentation associated with this event. At Kenai 2000-13, the 1964 event coincides with a change from lighter brown *Sphagnum* peat with herbaceous rootlets to herbaceous peat at 0.12 m depth. Diatoms and pollen also record this transition from one freshwater environment to another (Zong *et al.*, 2003).

Further investigations concentrate on Kenai 2000-7, as this is the only location where the upper boundary of the second buried peat layer is transitional over five centimetres. This minimises any effect of sediment erosion, possible sediment mixing and does not bias the sampling design by assuming rapid events. At all other locations along the coring transect this boundary appears sharp. Ideally the bio-stratigraphy of two cores could have been investigated, Kenai 2000-7 with its transitional upper boundary and an additional core with a sharp upper contact. Further litho-stratigraphical investigations are also required using the Russian corer which causes minimal disturbance as stratigraphical boundaries may appear sharper in gouge cores due to the different densities of peat and silt.

5.2.1 Lithology of Kenai 2000-7

Kenai 2000-7 is located approximately 300 m along the contemporary marsh transect and present day vegetation consists of Poaceae, *Carex lyngbyei* and rare *Triglochin maritima* (mid to high marsh). Saline inundation after the 1964 earthquake killed the trees showing through the surface (figure 5.2). The lower peat layer is mottled bryophyte herbaceous peat and occurs at a depth of 1.98 to 1.64 m below present marsh surface. The uppermost peat layer is brown bryophyte herbaceous peat and occurs at a depth of 0.21 to 0.06 m (figure 5.3). Figure 5.4 illustrates and describes the litho-stratigraphy in more detail.

Loss on Ignition

Loss on Ignition (LOI) indicates the amount of organic material contained within the sediment and forms part of the lithological description. Previous studies (e.g. Shennan *et al.*, 1999; Zong *et al.*, 2003) suggest a pre-seismic relative sea-level rise immediately before the 1964 earthquake (sections 1.9 and 1.10). LOI values help to investigate whether there is a minerogenic input into the peat before the peat-silt boundary found at 5.5 cm in Kenai 2000-7 (refer to section 3.4 for method).

Figure 5.5 shows that from 15 to 10 cm the amount of organic material in the bryophyte herbaceous peat is high at approximately 79%. This amount decreases sharply at 9 cm to 53% and then stabilises between 8 and 6 cm at approximately 59%. This suggests increased minerogenic input towards the top of the peat. Within the silt unit, LOI values decrease to 19% before rising again at the surface. It was not possible to calculate LOI values for the second buried peat layer because coring could not collect a large enough volume of sediment.

5.3 Bio-stratigraphy of Kenai 2000-7

Sampling intervals for diatom analysis varied from 1 to 8 cm intervals. Throughout peat units and around peat-silt boundaries, 1 cm intervals allow the identification of relative sea-level changes associated with the EDC model, for example, pre-, co- and post-seismic movements. Throughout thicker silt units, larger sampling intervals allow the identification of broader relative sea-level changes. Investigation of these units were not as detailed because contemporary data from Kenai (chapter 4) suggests any transfer function applied to the silt units are likely to give less precise estimates of predicted altitude (m) relative to MHHW (section 4.4). Other evidence includes the results using cluster analysis where there are no distinct classes below MHHW (section 4.3) and by the tolerances of the diatoms below MHHW occupying large ranges (section 4.4.2). This has implications for the calculation of earthquake recurrence intervals along different parts of the transect. If the land does not recover to developed marsh in-between two earthquakes, no record would exist within the silt.

Figures 5.6 (a) and (b) summarise the lithology, AMS dates and bio-stratigraphy of Kenai 2000-7, showing diatoms that account for at least 2% of all diatom valves counted (diatom count information is in appendix 5). Zones produced during stratigraphically constrained cluster analysis aid the description of diatom changes through the core. Following paragraphs introduce and summarise the main changes in diatom assemblages and present an initial interpretation of sea-level tendencies that will be fully analysed and quantified in later sections of this chapter.

Zone A: 205.5 to 196.5 cm

Polyhalobous diatoms, for example, *Cocconeis peltoides*, *Delphineis surirella* and *Paralia sulcata* dominate at the base of this zone. They decline upwards with an associated increase in oligohalobous and halophobous groups, for example, *Eunotia lunaris*, *Pinnularia lagerstedtii* and *Pinnularia subcapitata.* The change in dominance from polyhalobous to oligohalobous-indifferent species, alongside the change in lithology from silt to peat indicates a negative sea-level tendency and suggests a relative sea-level fall.

Zone B: 196.5 to 180.5 cm

Oligohalobous-indifferent and halophobous diatoms dominate, in particular, *Eunotia lunaris*, *Eunotia pectinalis* and *Eunotia exigua*. *Tabellaria flocculosa* starts to increase towards the top of this zone, indicative of freshwater pools. This suggests a continued negative sea-level tendency (relative sea-level fall) with the development of diverse raised bog and freshwater environments.

Zone C: 180.5 to 165.5 cm

This zone contains three smaller clusters clearly indicated as dashed lines in figure 5.6. *Tabellaria flocculosa* peaks at 178 cm and dominates the first cluster between 180.5 and 175.5 cm, suggesting a continued negative sea-level tendency (relative sea-level fall). The middle cluster, between 175.5 and 170.5 cm shows an increase in polyhalobous, mesohalobous and oligohalobous species, for example, *Cocconeis peltoides*, *Delphineis surirella* and *Navicula cari* var. *cincta*. This indicates a positive sea-level tendency (relative sea-level rise). From 170.5 to 165.5 cm *Eunotia lunaris*, *Eunotia pectinalis*, *Pinnularia brevicostata* and *Eunotia exigua* dominate representing a negative sea-level tendency (relative sea-level fall). These changes occur within the bryophyte herbaceous peat unit and there is no obvious change in lithology.

Zone D: 165.5 to 99.5 cm

Diatom assemblages are significantly different compared to zone C. From 165.5 to 163.5 cm, lithology changes to herbaceous peat with silt. Polyhalobous, mesohalobous and other oligohalobous diatoms increase and halophobous species decline. *Navicula brockmannii* dominates these samples and only small amounts of *Eunotia* species are present. It suggests a positive sea-level tendency and a relative rise in sea level with respect to zone C. From 163.3 to 160.5 cm, lithology changes to grey silt with herbaceous rootlets. All halophobes disappear, *Navicula brockmanii* declines and *Pinnularia lagerstedtii* becomes dominant. From 160.5 to 99.5 cm the number of rootlets contained within the silt declines. There is a gradual decrease in oligohalobous-indifferent taxa and an associated increase in more salt tolerant species, for example *Cocconeis peltoides*, *Delphineis surirella*, *Paralia sulcata* and *Navicula cari* var. *cincta*. Litho-stratigraphy and diatom assemblages indicate a continued positive sea-level tendency and a gradual relative sea-level rise throughout this zone.

Zone E: 99.5 to 21.5 cm

Navicula cari var. *cincta* dominates the lower part of zone E alongside other polyhalobous, mesohalobous and oligohalobous-halophile taxa. Around 55 cm *Navicula cari* var. *cincta* starts to decline and there is an increase in *Delphineis surirella* and *Paralia sulcata*. Salinity groupings suggest a continued positive sea-level tendency and a relative sea-level rise, but it may also represent a change within the tidal flat assemblage as contemporary tidal flat diatoms generally have large tolerances and live over large altitudinal ranges (section 4.4.2). Transfer functions quantitatively reconstruct altitude changes in later sections. At 32.5 cm, polyhalobous species start to decrease together with an associated increase in *Nitzschia obtusa*, *Luticola mutica* and *Pinnularia lagerstedtii*, which becomes more dominant towards the upper part of the zone. Introduction of other oligohalobous-indifferent and halophobous species, for example, *Pinnularia borealis*, *Pinnularia microstauron* and *Pinnularia subcapitata* indicates a negative sea-level tendency and a relative sea-level fall. Litho-stratigraphy illustrates this change by a transition from silt with herbaceous rootlets through to the development of peat.

Zone F: 21.5 to 5.5 cm

The lithological peat-silt boundary determines the upper boundary for zone F, rather than the division produced during cluster analysis that occurs 1 cm lower. Figure 5.6 shows that this zone contains two smaller clusters. From 21.5 to 10.5 cm oligohalobous-indifferent and halophobous species dominate, particularly *Eunotia lunaris*, *Eunotia pectinalis* and *Eunotia exigua*. There are very few polyhalobous, mesohalobous and oligohalobous-halophile taxa suggesting a continued negative sea-level tendency and a relative sea-level fall. At 12.5 cm, *Eunotia exigua* starts to decline. From 10.5 cm, there is an increase in *Nitzschia fruticosa*, *Pinnularia lagerstedtii* and *Pinnularia microstauron* together with the introduction of different polyhalobous, mesohalobous and oligohalobous-halophile species, for example, *Delphineis surirella*, *Paralia sulcata*, *Navicula phyllepta* and *Navicula cari* var. *cincta*. This indicates a positive sea-level tendency and a relative sea-level rise. At 8.5 cm, *Eunotia* species start to increase indicating a slight reversal in this trend. However, they disappear by 6.5 cm and *Nitzschia fruticosa*, *Nitzschia pusilla* and *Pinnularia lagerstedtii* replace them, suggesting a positive sea-level tendency and a relative sea-level rise immediately before the peat-silt boundary.

Zone G: 5.5 cm to surface

At the base of zone G, *Cocconeis peltoides*, *Nitzschia fruticosa* and *Pinnularia lagerstedtii* dominate suggesting a rapid positive sea-level tendency in relation to zone F. Towards the top, mesohalobous diatoms increase and *Navicula phyllepta*, *Navicula protracta* and *Navicula salinarum* dominate alongside *Navicula cari* var. *cincta* and *Nitzschia fruticosa*. The change from silt with occasional herbaceous rootlets to silty peat also indicates a negative sea-level tendency and a relative sea-level fall.

5.4 Chrono-stratigraphy of Kenai 2000-7

Radiocarbon (^{14}C) and caesium-137 (^{137}Cs) dating determines the chronology for Kenai 2000-7. Problems in calibrating the lead-210 (^{210}Pb) measurements make them currently unusable.

Radiocarbon dates are useful in establishing an age for the base of the 1964 peat and the top and base of the second buried peat layer. This is important because if the lower peat layer results from co-seismic submergence it should give an estimate of earthquake recurrence intervals. ^{137}Cs dates the 1964 event together with the start of any pre-seismic signal. The dating of any pre-seismic signal is essential because it may represent a precursor to a major earthquake. Figure 5.7 presents the results.

5.4.1 Radiocarbon results

The NERC Radiocarbon laboratory at East Kilbride AMS dated five bulk peat samples from Kenai 2000-7. Appendix 3 and figure 5.7 (a) shows the calibrated results using the program CALIB 3.4 (refer to section 3.7.2 for calibration method). They suggest the base of the 1964 peat layer (20 cm) dates to 794-1055 cal yr BP and the top of the lowest peat layer dates to approximately 3000 cal yr BP, but there is some discrepancy in the results from this contact. Three bulk peat samples, representing the top of the second peat layer (165 cm), and two from just below representing changes in diatom assemblages (170 and 175 cm), give different ages of 3268-3547, 2472-2843 and 3211-3452 cal yr BP respectively. These changes can only be resolved by re-dating some of the samples using *in situ* marsh macrofossils rather than bulk peat. AMS dates on small bulk peat samples may give older ages compared to those from marsh plant macrofossils as they include organic carbon from plants that died previously and form the accumulating sediment body (e.g. Atwater *et al.*, 1995; Nelson, 1992; Nelson *et al.*, 1995). Alternative explanations include reworking of sediment, deposition of older organic material on the peat surface due to ice processes observed at the site, or multiple small co-seismic events superimposed on one another. The base of the lowest peat layer (198 cm) dates to 6313-6635 cal yr BP.

Figure 5.8 shows the AMS results from this study compared to Combellick and Reger's (1994) radiocarbon dates, recalibrated using the same method (appendix 3). There is a wide scatter within and between both data sets. Combellick and Reger (1994) suggest the top of the lowest peat layer dates to 1099-1387 cal yr BP and its base has an age of 6807-7266 cal yr BP. Re-dating samples can resolve these differences.

5.4.2 ^{137}Cs results

Detectable levels of ^{137}Cs in the environment started in 1954. Maximum concentrations occurred in 1964 after which the Nuclear Test Ban Treaty stopped any further releases (refer to section 1.8.2). Minimum detectable levels of ^{137}Cs are at 5 $Bqkg^{-1}$. Figure 5.7 (b) shows first detectable levels of this radionuclide start at a depth of 8 cm, corresponding to the 1954 horizon. This represents its maximum depth, as it is unclear how much ^{137}Cs migration occurs within salt marsh sediments (section 1.8.2.). ^{137}Cs peaks at 5 cm, directly above the peat-silt boundary suggesting that the change in lithology from peat to silt resulted from co-seismic submergence associated with the 1964 event. Zong *et al.* (2003) also found peak ^{137}Cs concentrations just above the peat-silt boundary and the base of detectable concentrations approximately 3 to 4 cm below.

5.5 Numerical analysis – calibration of Kenai 2000-7

This section aims to analyse and quantify relative sea-level changes recorded by the bio-stratigraphy of Kenai 2000-7 using the contemporary data set described in chapter 4. Regression models of the contemporary data set suggest Weighted Averaging-Partial Least Squares (WA-PLS) produces the most accurate estimate of predicted altitude (m) relative to MHHW (sections 4.4.3 to 4.4.5). Analyses described in chapter 4 indicate that different regression models perform better in certain parts of the environmental range, therefore, four regression models are suitable for the quantitative calibration of relative sea-level change of the fossil data (see section 4.5 for explanation).

These are:

1. Full contemporary data set using WA-PLS component 2 - suitable for clastic sediments with no rootlets
2. Contemporary samples above -0.5 m MHHW using WA-PLS component 3 - suitable for clastic sediments with rootlets, indicating proximity to the marsh front
3. Contemporary samples above +1.0 m MHHW using WA-PLS component 1 - suitable for all peat layers as modern raised bog environments typically occur above +1.35 m MHHW
4. Contemporary samples above +1.0 m MHHW (hours inundated per year) using WA-PLS component 1 - an alternative model for peat layers. Conversion back to altitude (m) relative to MHHW follows (figure 4.14)

Section 4.5 outlines the use of the lithological constraint summarised above and following sections test this approach against the fossil sequence. Environmental reconstructions use contemporary vegetation data described in table 2.1.

Figure 5.9 shows the calibration results for Kenai 2000-7 using the different models mentioned above (results are in appendix 6). It plots predicted altitude (m relative to MHHW) for each fossil sample, together with its associated error term calculated using the sample specific error generated within WA-PLS (version 1.5; Juggins & ter Braak, 2001). The amount of associated error varies greatly depending on which model is used. Figure 5.9 highlights why specific models perform better in different litho-stratigraphic units.

Table 5.1 shows the accuracy of the calibration models at predicting the altitude of the surface sample. The levelled surface height of Kenai 2000-7 is +1.12 m relative to MHHW. In all cases, the measured value lies within the predicted error terms and suggests that all models are reasonably accurate at reconstructing relative sea-level changes for the fossil data.

Calibration of Kenai 2000-7 using the full data set (figure 5.9) estimates formation of the lower peat layer between +0.38 ± 0.95 m MHHW and +1.35 ± 1.03 m MHHW. In the contemporary Kenai environment, this represents formation in low marsh through to raised bog (table 2.1 and figure 2.4). Deposition of the intervening silt layer occurred between -1.56 ± 1.01 m MHHW and +0.84 ± 0.94 m MHHW, suggesting deposition in unvegetated tidal flat through to low/mid marsh. Formation of the uppermost peat layer occurred between +0.92 ± 0.93 m MHHW and +1.30 ± 0.94 m MHHW, indicating formation in low/mid marsh through to transition into raised bog. The full model predicts the surface height of the core to be +0.31 m above its measured value. Associated error terms are large, ranging from ± 0.93 m to ± 1.06 m throughout the core, making any reconstruction imprecise. However, calibration using the full model is necessary in silt units containing no rootlets and large errors occur because in the contemporary Kenai environment, cluster analysis has difficulty distinguishing any major classes within the mudflat assemblages from approximately -5.3 m to +1.0 m MHHW (section 4.3). Diatoms within this range have large tolerances of approximately 3.0 to 4.0 m and so are present over large altitudes (section 4.4.2) and the different regression models are unable to predict any sample to occur below approximately -4.0 m (sections 4.4.3 to 4.4.5).

Table 5.1 Accuracy of predicted surface height of Kenai 2000-7

Model	Predicted altitude (m) relative to MHHW	Error (±)	Difference between predicted and measured (m)
Full	1.43	0.94	+0.31
above -0.5 m	1.19	0.22	+0.07
above +1.0 m (MHHW)	1.15	0.07	+0.03
above +1.0 m (hours inundated)	1.12	0.04	0

Calibration of Kenai 2000-7 using only contemporary samples above -0.5 m MHHW predicts formation of the lower peat layer between +0.94 ± 0.30 m MHHW and +1.66 ± 0.37 m MHHW representing formation in low/mid marsh through to raised bog environments. Deposition of the intervening silt layer occurred between +0.16 ± 0.48 m MHHW and +1.10 ± 0.25 m MHHW, suggesting deposition in low to mid marsh conditions. Formation of the upper peat unit occurred between +1.13 ± 0.21 m MHHW and +1.59 ± 0.22 m MHHW, equivalent to high marsh to raised bog environments. It predicts the surface height to be +0.07 m above its measured height. This model is more precise than the model using the full data set as associated error terms are smaller ranging from ± 0.21 m to ± 0.48 m throughout the core.

Calibration of Kenai 2000-7 using only contemporary samples found above +1.0 m, relating to both altitude (m) relative to MHHW and hours inundated per year predict formation of the lower peat layer between +1.25 ± 0.06 m MHHW and +1.58 ± 0.13 m MHHW, suggesting formation in high marsh to raised bog conditions. As the two models only include contemporary samples found above +1.0 m MHHW, they are inaccurate at estimating the altitude of samples taken from silt units. However, for comparison, they suggest deposition of the intervening silt layer between +1.08 ± 0.07 m MHHW and +1.26 ± 0.07 m MHHW, indicating deposition in mid to high marsh environments. Both models predict formation of the upper peat between +1.25 ± 0.06 m MHHW and +1.57 ± 0.12 m MHHW, representing formation in high marsh to raised bog environments. The +1.0 hours inundated per year model exactly predicts the surface height of Kenai 2000-7. For the +1.0 m MHHW model, error terms are approximately ± 0.07 m and for the +1.0 hours inundated model, error terms range from ± 0.03 m to ± 0.13 m making them more precise than the other two models.

Other studies using microfossil transfer functions to reconstruct relative sea-level changes typically have error terms around ±0.20 m (e.g. Zong & Horton, 1999). The ±0.04 m and ±0.07 m error terms are a significant improvement on these, but the +1.0 m models are not appropriate for the reconstruction of relative sea-level change through clastic sediments. These must use the -0.5 m or full models.

To reconstruct relative sea-level change through Kenai 2000-7, only one reconstruction is required based on the most suitable calibration model using litho-stratigraphic constraints (section 4.5). Table 5.2 describes the calibration model chosen for different parts of the core. The +1.0 m MHHW and +1.0 hours inundated models produce similar results and so reconstructions use the +1.0 m MHHW model, apart from when the +1.0 hours inundated model produces significantly smaller error terms. This avoids the possibility of introducing more uncertainty when reconverting hours inundated back to altitude (m) relative to MHHW (section 4.5.1).

Table 4.25 summarises the values and terms used to describe results from the modern analogue technique (MAT). Figure 5.10 plots the minimum dissimilarity coefficient for samples in Kenai 2000-7 against depth (cm). It shows two of the fossil samples (2%) have 'poor' modern analogues, 38 (36%) have 'close' modern analogues and 65 (62%) have 'good' modern analogues. The two samples that have 'poor' modern analogues occur at depths of 172 and 175 cm, because these samples contain a mixture of diatoms with broad altitudinal ranges. Their reconstruction using the transfer function approach is possibly less reliable.

Table 5.2 Calibration models used to reconstruct RSL change in different parts of Kenai 2000-7

Depth ranges (cm)	Model used	Reason
205 to 199	-0.5	These samples are found within silt containing rootlets and so the -0.5 m MHHW model is most suitable
198 to 164	+1.0	These samples are within the lower peat unit and so the +1.0 m MHHW model is appropriate
163 to 22	-0.5	These samples are found within the intervening silt unit and as rootlets are present, the -0.5 m model is best
21 to 6	+1.0	These samples are within the upper peat unit and so the +1.0 m MHHW model is appropriate
5 to 2	-0.5	Lithology indicates silt and so the model has to be able to predict below +1.0 m relative to MHHW. As the silt contains rootlets, the -0.5 m model is acceptable
1 to surface	+1.0	Lithology indicates silty peat and so +1.0 hours inundated model is appropriate

Figure 5.11 is a composite diagram illustrating the main changes in predicted altitude (m) relative to MHHW for Kenai 2000-7, calculated using the models specified in table 5.2 (reconstructed values are in appendix 6). Table 5.3 quantitatively describes relative sea-level changes through the core using sea-level tendency (SLT) phases. It includes diatom descriptions (figure 5.6), diatom optima and tolerances ($u \pm t$) of individual diatom taxa (section 4.4.2, figure 4.8 and appendix 1) and environmental reconstructions using table 2.1. These values sometimes differ from reconstructed altitudes because mixing of dominant taxa with numerous other species produce large altitudinal ranges. Section 5.6 examines these changes, testing periods of the earthquake deformation cycle model.

Table 5.3 Description of relative sea-level changes through Kenai 2000-7

SLT Phase	Depth (cm)	Lithology	Brief summary (including optima and tolerance, *u±t* of diatom species)	Sea-level tendency	Quantitative reconstructions	Environmental reconstruction
A	205 to 193.5	Transition from silt with herbaceous rootlets to mottled bryophyte herbaceous peat	Polyhalobous taxa dominate at the base (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Paralia sulcata*, -0.93 ± 1.91 m). Oligohalobous-indifferent and halophobous species increase towards the top (e.g. *Eunotia lunaris*, +1.46 ± 0.40 m; *Eunotia exigua*, +1.49 ± 0.10 m; *Pinnularia subcapitata*, +1.51 ± 0.07 m)	Negative	RSL fall of -1.45 ± 0.34 m from +0.08 ± 0.33 m MHHW to +1.53 ± 0.07 m MHHW	Upper tidal flat/marsh pioneer zone through to raised bog
B	193.5 to 175.5	Bryophyte herbaceous peat	Oligohalobous and halophobous diatoms dominate, e.g. *Eunotia lunaris* (+1.46 ± 0.40 m), *Eunotia pectinalis* (+1.19 ± 1.39 m), *Eunotia exigua* (+1.49 ± 0.10 m) and *Pinnularia subcapitata* (+1.51 ± 0.07 m) with *Tabellaria flocculosa* (+1.32 ± 1.18 m) increasing towards the top	Stable	Ground level stabilises at approximately +1.54 ± 0.07 m MHHW	Raised bog
C	175.5 to 169.5	Bryophyte herbaceous peat	MAT suggests samples from 172 and 175 cm have 'poor' modern analogues and so quantitative reconstructions may be less reliable. From 175.5 to 171.5 cm, halophobes decrease (e.g. *Tabellaria flocculosa*, +1.32 ± 1.18 m) together with the temporary introduction of polyhalobous, mesohalobous and oligohalobous species. They have a broad range of optima and tolerances, e.g. *Cocconeis peltoides* (-1.04 ± 1.75 m), *Delphineis surirella* (-1.13 ± 2.11 m), *Navicula cari* var. *cincta* (+0.20 ± 1.45 m) and *Nitzschia fruticosa* (+1.31 ± 0.16 m). From 171.5 to 169.5 cm the salt tolerant species decline and *Eunotia* species dominate	Positive then negative	RSL rise of +0.21 ± 0.11 m to a new ground height of +1.33 ± 0.07 m MHHW followed by a RSL fall of -0.19 ± 0.10 m, returning to +1.52 ± 0.07 m MHHW	Raised bog and transition into raised bog
D	169.5 to 165.5	Bryophyte herbaceous peat	Oligohalobous-indifferent and halophobous groups dominate e.g. *Eunotia lunaris* (+1.46 ± 0.40 m), *Eunotia pectinalis* (+1.19 ± 1.39 m), *Pinnularia brevicostata* (+1.43 ± 0.13 m), *Eunotia exigua* (+1.49 ± 0.10 m) and *Pinnularia subcapitata* (+1.51 ± 0.07 m). At 166 cm, *Eunotia lunaris* declines and salt tolerant species appear	Stable then positive	Ground level stabilises at approximately +1.52 ± 0.07 m MHHW. At 166 cm, RSL rises by +0.04 ± 0.10 m	Raised bog

E	165.5 to 163.5	Herbaceous peat with silt	Halophobes and *Eunotia* species disappear and polyhalobous, mesohalobous and oligohalobous taxa increase. *Navicula brockmannii* (+1.31 ± 0.19 m) dominates	Positive	RSL rise of +0.20 ± 0.10 m to a new ground height of +1.28 ± 0.07 m MHHW	Transition into raised bog
F	163.5 to 160.5	Silt with herbaceous rootlets	Polyhalobous species continue to increase and *Pinnularia lagerstedtii* (+1.38 ± 0.12 m) dominates	Positive	RSL rise of +0.57 ± 0.40 m to a new ground height of +0.71 ± 0.39 m MHHW	Low marsh
G	160.5 to 32.5	Silt with occasional herbaceous rootlets	This phase contains a mixture of polyhalobous, mesohalobous and oligohalobous diatoms, e.g. *Cocconeis peltoides* (-1.04 ± 1.75 m), *Paralia sulcata* (-0.93 ± 1.91 m), *Navicula cari* var. *cincta* (+0.20 ± 1.45 m), *Nitzschia fruticosa* (+1.31 ± 0.16 m) and *Pinnularia lagerstedtii* (+1.38 ± 0.12 m)	Fluctuating	RSL fluctuates between +0.16 ± 0.48 m MHHW and +1.01 ± 0.23 m MHHW with no general trend	Low to mid marsh
H	32.5 to 21.5	Silt with herbaceous rootlets	Polyhalobous species (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Paralia sulcata*, -0.93 ± 1.91 m) decline and oligohalobous-indifferent taxa increase (e.g. *Pinnularia lagerstedtii*, +1.38 ± 0.12 m). At the top of SLT phase H (22 cm), a single sample suggests a slight reversal but this may be due to local processes, for example, reworking or deposition from ice	Negative	RSL falls by -0.91 ± 0.54 m to a new ground of +1.07 ± 0.25 m MHHW at 23 cm. If the sample at 22 cm represents a RSL change, RSL rises by +0.22 ± 0.36 m to a new ground height of +0.85 ± 0.26 m MHHW	Low to mid marsh
I	21.5 to 11.5	Bryophyte herbaceous peat	LOI values are approximately 79%. Halophobous and oligohalobous-indifferent groups dominate particularly *Eunotia lunaris* (+1.46 ± 0.40 m), *Eunotia pectinalis* (+1.19 ± 1.39 m), *Eunotia exigua* (+1.49 ± 0.10 m) and *Pinnularia subcapitata* (+1.51 ± 0.07 m). Towards the upper part of this phase *Eunotia exigua* starts to decline, with this trend continuing into SLT phase J	Negative	RSL fall of -0.47 ± 0.26 m from +1.07 ± 0.25 m MHHW at 23 cm to a new ground height of +1.54 ± 0.07 m MHHW	Raised bog

J	11.5 to 7.5	Bryophyte herbaceous peat	LOI values decrease from 77% to 53 %. Polyhalobous, mesohalobous and oligohalobous-halophile species increase to 8.5 cm, e.g. *Paralia sulcata* (-0.93 ± 1.91 m) and *Luticola mutica* (+0.92 ± 0.87 m) alongside *Pinnularia lagerstedtii* (+1.38 ± 0.12 m) and *Pinnularia microstauron* (+1.31 ± 0.29 m). Above 8.5 cm halophobes increase once again, particularly *Eunotia exigua* (+1.49 ± 0.10 m). LOI values increase to approximately 59% and detectable levels of ^{137}Cs start at 8 cm (4.97 $Bqkg^{-1}$)	Positive then negative	RSL rise of +0.18 ± 0.10 m to a new ground height of +1.36 ± 0.07 m MHHW, followed by a RSL fall of -0.14 ± 0.10 m to a new ground height of +1.50 ± 0.07 m MHHW	Raised bog
K	7.5 to 5.5	Top 2 cm of bryophyte herbaceous peat unit with sharp upper boundary at 5.5 cm	Halophobes decline and no *Eunotia* species are present by 6 cm. *Nitzschia fruticosa* (+1.31 ± 0.16 m) and *Pinnularia lagerstedtii* (+1.38 ± 0.12 m) dominate with an associated increase in *Cocconeis peltoides* (-1.04 ± 1.75 m) and *Nitzschia obtusa* (+1.14 ± 0.29 m)	Positive	RSL rise of +0.21 ± 0.10 m to a new ground height of +1.29 ± 0.07 m MHHW	Transition to raised bog
L	5.5 to 2.5	Silt with herbaceous rootlets	LOI values fall sharply from 59% to 24%. This phase is characterised by increasing polyhalobous and mesohalobous diatoms, particularly *Cocconeis peltoides* (-1.04 ± 1.75 m) and *Navicula phyllepta* (+0.83 ± 0.68 m). No halophobes are present. Peak ^{137}Cs concentration occurs at 5 cm (26.73 $Bqkg^{-1}$), just above the peat-silt boundary	Positive	RSL rise of +0.28 ± 0.22 m to +0.68 ± 0.23 m. Taking the maximum value produces a new ground height of +0.61 ± 0.22 m MHHW	Low to mid marsh
M	2.5 cm to surface	Transition from silt with herbaceous rootlets to silty peat	LOI values increase to 28%. Mesohalobous diatoms, e.g. *Navicula phyllepta* (+0.83 ± 0.68 m), *Navicula protracta* (+1.08 ± 0.49 m) and *Nitzschia obtusa* (+1.14 ± 0.29 m) dominate together with *Navicula cari* var. *cincta* (+0.20 ± 1.45 m) and *Nitzschia fruticosa* (+1.31 ± 0.16 m). The amount of ^{137}Cs declines within this phase and detectable levels stop at 2 cm	Negative	RSL fall of -0.11 ± 0.21 m to -0.51 ± 0.22 m (depending on value in SLT phase L) to contemporary surface height of +1.12 ± 0.04 m MHHW	Mid to high marsh

5.6 Relative sea- and land-level changes through Kenai 2000-7

This section investigates relative sea-level (RSL) changes described in table 5.3 in chronological order. It tests periods of the EDC model and suggests alternative explanations where appropriate.

In this location, the EDC model could contain up to four main periods (sections 1.3 and 1.9):

1. Rapid co-seismic submergence (sudden relative sea-level rise) during a large magnitude earthquake
2. Rapid post-seismic uplift (relative sea-level fall) immediately following the event on the timescale of decades
3. Slower inter-seismic uplift (relative sea-level fall) on the timescale of centuries
4. Pre-seismic relative sea-level rise immediately before the next co-seismic event

Identification of these four periods, together with the criteria reviewed by Nelson *et al.* (1996) are important when determining if a buried peat layer results from co-seismic submergence or non-seismic changes in relative sea level.

Development of lowest peat - SLT phases A and B

The relative sea-level fall in SLT phase A could represent the inter-seismic period of the EDC model, where strain accumulation at the plate boundary causes land to rise and hence relative sea level to fall. Alternatively, peat formation approximately 6313-6635 cal yr BP could result from non-seismic processes, for example on a global scale, a slowing down in the rate of eustatic sea-level rise approximately 7000 cal yr BP (e.g. Fleming *et al.*, 1998; Peltier, 1998) allowing colonisation of freshwater environments over tidal flats. Locally, it may be a reaction to changing sediment supply, for example, the tidal channel seen in figure 2.3 becoming less active, allowing rapid colonisation by salt marsh plants.

Oscillation in RSL within lowest peat layer - SLT phase C

SLT phase C records an oscillation in relative sea level (approximately 2472-2843 cal yr BP to 3211-3452 cal yr BP) but there is no obvious change in litho-stratigraphy and so it is unknown if it is laterally extensive. It could result from a number of processes and possible hypotheses include:

1. RSL oscillation associated with co-seismic submergence during a small magnitude earthquake, similar to the stratigraphy recorded in Kenai 2000-13 for the 1964 event (figure 5.1, appendix 4) and in core 98-13 (Zong *et al.*, 2003)
2. RSL oscillation associated with non-seismic processes, including eustatic and glacio-isostatic changes
3. RSL oscillation associated with co-seismic submergence superimposed upon a background non-seismic RSL change

Following sections test these hypotheses using the available data.

Hypothesis 1 – The RSL oscillation in SLT phase C results from co-seismic submergence associated with a small magnitude earthquake

As mentioned earlier, the criteria described by Nelson *et al.* (1996) together with the identification of different periods within the EDC model are important when determining if a relative sea-level rise results from co-seismic submergence. Immediately before the event, there is no evidence of a pre-seismic relative sea-level rise. However, with an event so small, it may not affect the raised bog community resulting in no record within the stratigraphy. Possible co-seismic submergence results in a relative sea-level rise of +0.21 ± 0.11 m, suggesting a smaller event or a different spatial pattern of movement than the magnitude 9.2, 1964 earthquake. Immediately after the RSL rise, relative sea-level falls by -0.19 ± 0.10 m representing rapid post-seismic recovery. Identification of possible co- and post-seismic movements are important but lateral extent and suddenness of submergence are unknown.

Co-seismic relative sea-level rise is easier to recognise when peat rapidly submerges into the intertidal area, forming peat-silt couplets in the stratigraphy. However, core 98-13 (Zong *et al.*, 2003) taken from the back marsh area of Kenai records the 1964 event as a change from *Sphagnum* dominated to grass sedge herbaceous peat without any clastic sedimentation. Diatoms show an increase in salt tolerance around the lithological boundary, but halophobes do not return, as *Carex lyngbyei* dominates contemporary vegetation. A core taken from a higher altitude within the raised bog may record diatom changes similar to those observed in SLT phase C without a change in peat lithology.

The hypothesis that the RSL oscillation recorded in SLT phase C resulted from co-seismic movements remains valid. Detailed microfossil analysis at similar depths on other cores along the Kenai transect could test this hypothesis further. In addition, litho-stratigraphic surveys could investigate whether this change merges into a clastic unit in other cores. Figure 5.1 indicates a thicker silt unit in a similar stratigraphic position in three cores, but further surveys are necessary to investigate whether it is laterally extensive and suddenness of submergence. If this does represent co-seismic submergence, its age is indistinguishable from the peat-silt boundary above. This has implications for recurrence intervals and may suggest that large magnitude earthquakes can occur only two to three hundred years apart, rather than the average 600 to 800 years suggested by many authors (section 1.5.4).

Hypothesis 2 - The RSL oscillation in SLT phase C results from non-seismic processes, including eustatic and glacio-isostatic change

Between 7000 and 4000 cal yr BP, models of eustasy predicts a relative sea-level rise of 1.03 $mmyr^{-1}$ to 1.23 $mmyr^{-1}$ with no significant oscillations. This rate slows down to between 0.35 $mmyr^{-1}$ and zero after 4000 cal yr BP (Fleming *et al.*, 1998; Peltier, 1998). In addition, Wiles and Calkin (1994) suggest three major intervals of Holocene glacier expansions in the Kenai Mountains around 3600 cal yr BP, 1350 cal yr BP and the Little Ice Age (650 to 100 cal yr BP). The expansion 3600 cal yr BP is close to the range of dates for the oscillation in SLT phase C. During this period, the mass of ice overlying the Kenai Mountains (figure 2.1 illustrates present day glaciated areas) could isostatically depress the crust resulting in a relative sea-level rise. Following deglaciation, removal of ice could result in isostatic uplift and return the marsh to its previous altitude.

Effects of glacio-isostatic deformation should be rapid in this tectonically active area due to the thin lithosphere. James *et al.* (2000) and Clague and James (2002) investigate postglacial rebound at the northern Cascadia subduction zone and indicate that postglacial rebound was rapid following disappearance of the Cordilleran ice sheet at the end of the Pleistocene, suggesting it was complete by the middle Holocene.

Therefore, a combination of the eustatic sea-level rise together with isostatic adjustments could produce the oscillation in relative sea level observed in SLT phase C. Other non-seismic explanations include a change in the local system, for example, greater activity of the tidal channel allowing increased flooding of the marsh. Investigating the biostratigraphy of cores further away from the tidal channel could test this. The hypothesis that non-seismic processes cause the relative sea-level oscillation in SLT phase C also remains valid.

Hypothesis 3 - The RSL oscillation within SLT phase C results from co-seismic submergence superimposed upon a background non-seismic RSL change

Both hypotheses 1 and 2 are possible explanations of the relative sea-level oscillation observed in SLT phase C, and so the hypothesis that the oscillation results from co-seismic submergence super-imposed upon a non-seismic RSL component remains valid.

All three hypotheses are possible explanations of the relative sea-level oscillation observed in SLT phase C. It could result from co-seismic submergence, non-seismic processes or a combination of them both. Detailed microfossil evidence from other cores taken from Kenai, together with similar analyses from other sites could help to correlate this possible event and help resolve this question. However, it may be impossible to differentiate small co-seismic events from non-seismic change. Nelson *et al.* (1996) suggest changes of more than 1.0 m are more likely to be of co-seismic origin than are changes of less then 0.5 m which are just as likely to be produced from non-seismic causes, for example, barrier breaching. Quantitative transfer functions developed here could lower this threshold, but there still will be a lower limit below which, it will be impossible to distinguish co-seismic from non-seismic events. Chapter 8 investigates this further.

Burial of the lower peat layer - SLT phases D to G

Burial of the lower peat layer dates to approximately 3268-3547 cal yr BP although this date is questionable as Combellick and Reger (1994) date it to 1099-1387 cal yr BP. This event occurs at the transitional boundary between the lowest bryophyte herbaceous peat and overlying silt with herbaceous rootlets. In all other locations along the coring transect this boundary appears sharp, similar to that observed for the 1964 event (appendix 4). Following sections test three possible hypotheses.

Hypothesis 1 - The peat-silt boundary in SLT phases D to G results from co-seismic submergence

According to the four periods of the EDC model and the criteria set out by Nelson *et al.* (1996) co-seismic submergence should produce a large, abrupt change in environment. If this transitional boundary results from RSL changes associated with the EDC model, co-seismic submergence occurs somewhere between SLT phases D and F, between the top of the bryophyte herbaceous peat and the silt with herbaceous rootlets.

The most rapid change in diatom assemblage occurs between SLT phases D and E, where there is a change from dominance by *Eunotia* species to *Navicula brockmanii* (figure 5.6 between diatom zones C and D). A possible pre-seismic relative sea-level rise of +0.04 ± 0.10 m occurs at the top of SLT phase D, where *Eunotia lunaris* declines and salt tolerant species appear. However, there is the possibility that the assemblage at 166 cm results from mixing, as it is not a distinct assemblage when compared to those on either side of it. During burial, diatoms from overlying sediment may mix with assemblages below and chapter 8 considers this in detail. Quantitative reconstructions estimate submergence of +0.20 ± 0.10 m and while these two observations could support a co-seismic explanation, no rapid change to clastic sedimentation and no rapid post-seismic recovery follows, one of the essential elements of the EDC model.

Another possible explanation relating to the EDC model is that SLT phase E represents a pre-seismic relative sea-level rise of +0.20 ± 0.10 m and co-seismic submergence occurs between SLT phases E and F (at 163.5 cm). Quantitative reconstructions suggest a relative sea-level rise of +0.30 ± 0.23 m to +0.57 ± 0.40 m during this phase. However, diatoms indicate a gradual change, implying this relative sea-level rise is not rapid and as mentioned earlier, there is no rapid post-seismic recovery.

In comparison to the 1964 earthquake, the upper boundary of this peat is transitional and no post-seismic uplift is apparent. The peat-silt boundary is laterally extensive (figure 5.1) but suddenness of submergence is questionable. From these differences, it is unlikely that the transitional peat-silt boundary in SLT phases D to G is a result of co-seismic submergence alone, but further investigations of relative sea-level movements around a sharp upper contact of this peat from another coring site could resolve this.

Hypothesis 2 - The peat-silt boundary in SLT phases D to G results from non-seismic processes, including eustatic and glacio-isostatic factors

The change in stratigraphy from well-developed peat to silt with occasional herbaceous rootlets over 5 cm at approximately 3000 cal yr BP suggests a gradual relative sea-level rise. The relationship between eustasy and isostasy is not well constrained in south central Alaska but geophysical modelling can estimate the isostatic component, for example, the ICE-4G and ICE-5GP models proposed by Peltier (2002) predict a current relative sea-level rise of approximately 0.5 ± 0.5 $mmyr^{-1}$.

From 4000 cal yr BP to the present day, Fleming *et al.* (1998) suggests eustatic sea-level rise is still rising at a rate of 0.35 $mmyr^{-1}$ and so it is possible that the relative sea-level change observed in SLT phases D to G results from some combination of eustatic, isostatic and local processes, for example, a change in sediment supply.

Hypothesis 3 - The RSL rise observed during SLT phases D to G results from co-seismic submergence superimposed upon a background non-seismic change

Two of the main arguments against co-seismic submergence are first, the lack of rapid post-seismic uplift and second, relative sea level continuing to rise after the event (figure 5.11). One possible explanation is that co-seismic subsidence is small, 0.20 ± 0.10 m, and post-seismic recovery occurs at a slower rate than the combination of eustatic, isostatic and local relative sea-level change. Therefore, this hypothesis also remains valid.

In summary, it is difficult to conclude whether these relative sea-level changes result from co-seismic submergence, non-seismic RSL rise or a combination of them both. Hypotheses 2 and 3 are more likely than hypothesis 1 but diatom analysis around a sharp boundary at Kenai could help differentiate between these possible explanations. This, alongside correlations with other sites in the area should help investigate the synchroneity of the event and resolve this uncertainty.

Development of the uppermost peat - SLT phases H and I

This general relative sea-level fall may represent the inter-seismic period of the EDC model and results in the development of peat, approximately 794-1055 cal yr BP. Alternatively, it could represent a change in non-seismic processes, for example, eustasy, isostasy and local factors. The reasonably sharp boundary between the silt and peat results from a rapid change in environment allowing salt marsh plants to colonise marine silts quickly, possibly a final pulse of sediment deposition. Other possible explanations include co-seismic uplift similar to that observed for the 1964 event in the Copper River Delta. In this location, peat layers tend to have sharp basal contacts and grade upwards into thicker beds of intertidal silt representing co-seismic uplift followed by inter-seismic submergence (e.g. Plafker *et al.*, 1992). This is unlikely from the evidence presented here, as the sea-level tendency is in one direction only.

Oscillation in RSL within the upper peat - SLT phase J

Within the upper peat layer there is a relative sea-level oscillation between 11.5 and 7.5 cm, similar to that recorded in SLT phase C. The limit of detectable ^{137}Cs occurs at

8 cm depth, indicating these changes occur before 1954. There is no change in litho-stratigraphy and so it is difficult to say whether this oscillation is laterally extensive. This section tests the hypotheses set out under SLT phase C.

Hypothesis 1 - The RSL oscillation within SLT phase J results from co-seismic submergence

Immediately before this possible co-seismic event there is evidence of a pre-seismic relative sea-level rise within SLT phase I, where the percentage of *Eunotia exigua* declines (figure 5.6). This pre-seismic signal does not represent a quantifiable relative sea-level rise but does indicate a change in environment, for example, a change in ground water chemistry. During SLT phase J, quantitative reconstructions suggest co-seismic submergence of +0.18 ± 0.10 m followed by the land returning to its previous altitude, indicating post-seismic recovery. With this being similar to SLT phase C, the bio-stratigraphy compares to Kenai 2000-13 (Zong *et al.*, 2003). The hypothesis that the relative sea-level oscillation observed in SLT phase J results from co-seismic submergence remains valid, as the main periods of the EDC model are identifiable. However, suddenness of submergence and lateral extent of submergence are questionable until further litho-stratigraphic surveys investigate whether this oscillation merges into a silt unit further seaward. For example, figure 5.1 shows a silt unit within the upper peat in Kenai 2000-2.

Hypothesis 2 - The RSL oscillation within SLT phase J results from non-seismic processes, including eustatic and glacio-isostatic changes

A combination of eustatic and isostatic changes may account for the relative sea-level changes observed in SLT phase J. According to Peltier (1998), eustatic sea-level rise stopped 4000 cal yr BP, but according to Fleming *et al.* (1998), it is still ongoing at a slower rate of 0.35 $mmyr^{-1}$. Isostatic adjustments could have taken place during the Little Ice Age, 650 to 100 cal yr BP (Wiles & Calkin, 1994), where advance of the surrounding glaciers in the Kenai Mountains caused depression of the earths crust. Immediately after melting, isostatic uplift returns the land to its previous position. These timings fit in with the radiocarbon result from the base of the peat (794-1055 cal yr BP) and the 1954 horizon at 8 cm depth. Other non-seismic factors include local changes, for example, a change in sediment supply. These mechanisms are also possible explanations for the relative sea-level oscillation observed in SLT phase J.

Hypothesis 3 - The RSL oscillation within SLT phase J results from co-seismic submergence super-imposed upon non-seismic relative sea-level change
Hypotheses 1 and 2 are possible explanations for the relative sea-level oscillation observed in SLT phase J, therefore a combination of the two is also viable. It may represent small co-seismic submergence superimposed upon some background non-seismic change, whether eustatic, isostatic or local, for example, migration of the tidal channel and a change in marsh sedimentary processes.

The relative sea-level oscillation identified in SLT phase J is very similar to that in SLT phase C. It may result from small co-seismic submergence, non-seismic RSL change or a combination of both. As the relative sea-level changes are so small, it is difficult to say which hypothesis is most likely. Detailed microfossil work on other cores from Kenai together with other sites in the area could test these hypotheses further and chapter 8 investigates this in detail.

RSL changes associated with the 1964 event – SLT phases K to M
This section investigates relative sea-level changes associated with the 1964 earthquake in detail and compares the results to previous work in the area (e.g. Zong *et al.*, 2003). ^{137}Cs confirms the burial of the upper peat layer resulted from co-seismic submergence associated with the 1964 event (figure 5.7b and section 5.4.2).

Pre-seismic relative sea-level rise - SLT phase K
A pre-seismic RSL rise of +0.21 ± 0.10 m starts within the peat (7.5 cm), directly below the peat-silt boundary. ^{137}Cs data indicate that this period started approximately 10 years before the 1964 event (figure 5.7b and section 5.4.2). Evidence suggests it is not a result of mixing because it has a distinct diatom assemblage (figure 5.6). *Gomphonema olivaceum* and *Nitzschia fonticola* are not present in the underlying peat or overlying silt. There are also no *Eunotia* species above 7 cm and *Pinnularia lagerstedtii* increases immediately below the peat-silt boundary. In addition, loss on ignition values (figure 5.5 and section 5.2.1) support an increase in minerogenic input towards the top of the peat.

Zong *et al.* (2003) also found a pre-seismic relative sea-level rise that started around the beginning of the 1950's at Kenai. Using a smaller data set and the transfer function method of Weighted Averaging-Tolerance Downweighted (r^2=0.81), they calculate the rise to be +0.16 ± 0.09 m using diatom transfer functions and +0.16 ± 0.11 m using pollen transfer functions. However, there is an inconsistency in their calculation of associated error terms when estimating pre- and co-seismic changes at Kenai and Girdwood by Zong *et al.* (2003). Values given in the text are smaller than those shown on diagrams. Even taking the smallest value in the text the calculation of sea- and land-level movements erroneously uses the mean error term of the two data points rather than ^{2} + error term 2^{2}) as shown in section 3.6.2. Therefore, real error terms are greater than the terms quoted in table 3 of Zong *et al.* (2003), for example, co-seismic submergence at Girdwood 98-33 derived from diatom data should be 1.98 ± 0.32 m rather than 1.98 ± 0.23 m.

None of the tide gauges operating before the earthquake (Seward and Kodiak Island) record a pre-seismic relative sea-level rise (Savage & Plafker, 1991). A discussion of possible alternative mechanisms of this change occurs in Zong *et al.* (2003) and Long and Shennan (1998). They include non-seismic causes such as sediment mixing resulting from bioturbation, freeze thaw and the first tidal flooding after the earthquake. However, if this were the case, diatom assemblages are likely to be a mixture of the ones on either side. Other causes may include El Nino and fluctuations in isostatic rebound or changes in eustasy, but Long and Shennan (1998) suggest it results from a reduction in inter-seismic strain accumulation. Chapter 8 discusses all of the pre-seismic periods and possible alternative explanations in detail.

Co-seismic submergence - SLT phase L

Evidence to suggest co-seismic submergence includes a laterally extensive upper boundary between the peat and overlying silt with herbaceous rootlets (figure 5.1), a dramatic decrease in LOI values (figure 5.5) and a rapid change in diatom assemblages (figure 5.6). The peat-silt boundary is not very sharp but Mulholland (2002) suggests that abrupt contacts may result from compaction over timescales of decades to thousands of years. ^{137}Cs confirms the rapid relative sea-level rise observed in SLT phase L results from the 1964 event (figure 5.7). Diatom transfer functions suggest the amount of co-seismic submergence to take place at Kenai was between +0.28 ± 0.22 m and +0.68 ± 0.23 m. The value depends on whether you compare the level at the top of the peat with the first assemblage from the silt unit or from a few centimetres above the contact to make allowance for rapid sedimentation and recovery during and immediately after the event. Both Shennan *et al.* (1996) and Zong *et al.* (2003) suggest calculation of the amount of subsidence equals the maximum difference estimated from the marsh top and the minimum value indicated in the overlying minerogenic sequence. This may over estimate the value if it refers to a single sample that is an outlier in the model and chapter 8 investigates this in detail.

Both of these values are comparable to the estimates of Plafker (1965, 1969) and Zong *et al.* (2003). Zong *et al.* (2003) estimate the magnitude of co-seismic land subsidence at Kenai to be 0.17 ± 0.12 m based on diatom transfer functions to 0.31 ± 0.21 m based on pollen transfer functions. Plafker (1965, 1969) suggests 0.5 m co-seismic subsidence accompanied the 1964 event at Kenai, interpolated from three observations at Anchorage, Homer and Nikiski. The measured value at Nikiski (15 km away) was 0.27 m submergence (Plafker, 1969), which is extremely close to the lower reconstructed value using the transfer function approach.

Post-seismic recovery of the land - SLT phase M

Post-seismic recovery occurs in SLT phase M and has been rapid on the Holocene timescale, with redevelopment of silty peat at the surface, only 36 years after the event. Quantitative reconstructions record -0.11 ± 0.21 m to -0.51 ± 0.22 m post-seismic uplift (RSL fall) together with sediment accumulation depending on the amount of co-seismic submergence estimated in SLT phase L. This suggests 39 to 75% recovery has occurred during this period. From 1964 to 1995, GPS, tide gauge and levelling measurements suggest 0.20 m post-seismic uplift has occurred at Kenai relative to the Seward tide gauge (Cohen & Freymueller, 1997).

Relative sea-level movements surrounding the 1964 event agree with periods of the EDC model. Transfer functions quantify pre-seismic, co-seismic and post-seismic changes around the peat-silt boundary. These movements allow comparisons between this event and older ones affecting the Kenai area.

5.7 Summary of relative sea-level changes at Kenai

The stratigraphy of Kenai records up to four co-seismic events, with the uppermost being a result of co-seismic submergence associated with the 1964 earthquake. Table 5.4 summarises them and gives each an event name to facilitate comparisons with the other sites in chapter 8.

The stratigraphy of Kenai 2000-7 clearly records the 1964 event by the burial of the uppermost peat layer (KE-4). Immediately before the event, there is a pre-seismic signal evident from diatom changes in the upper few centimetres of peat, LOI values indicating an increase in minerogenic input and quantitative transfer functions suggesting a relative sea-level rise. ^{137}Cs dates this period to start around 1954.

Table 5.4 Summary of possible events at Kenai

+ve values represent a relative sea-level rise whereas –ve values suggest a relative sea-level fall

SLT phase	Description	Event name	EDC related	Date at contact (cal yr BP)	Pre-seismic RSL change (m)	Co-seismic RSL change (m)	Sharpness of boundary (Troels-Smith)	Lateral extent	Post/inter-seismic recovery (m) and sediment accumulation
K to M	Upper peat-silt boundary of uppermost peat	KE-4	Yes	1964 AD	+0.21 ± 0.10	+0.28 ± 0.22 to +0.68 ± 0.23	2	>400 m	-0.11 ± 0.21 to -0.51 ± 0.22
J	Oscillation in RSL within upper peat	KE-3	?	1954 AD to 794-1055	*Eunotia exigua* declines	+0.18 ± 0.10	No change in lithology	Not investigated	-0.14 ± 0.10
D to G	Upper peat-silt boundary of lowest peat	KE-2	?	3268-3547	+0.04 ± 0.10 to +0.20 ± 0.10	+0.20 ± 0.10 to +0.57 ± 0.40	0, but sharper in other cores	>700 m	No rapid RSL fall
C	Oscillation in RSL within lowest peat	KE-1	?	2472-2843 to 3211-3452	Not identified	+0.21 ± 0.11	No change in lithology	Not investigated	-0.19 ± 0.10

The litho-stratigraphic boundary fulfils four out of the five criteria described by Nelson *et al.* (1996). The peat-silt boundary is laterally extensive, represents a sudden, large submergence event and observations at the time record it as being synchronous over a large area (figure 1.4). Estimates of pre-seismic, co-seismic and post-seismic movements obtained in this study compare well to those from earlier studies (e.g. Zong *et al.*, 2003).

The RSL oscillations within SLT phases C (KE-1) and J (KE-3) are of similar magnitude but because the relative sea-level changes are so small, it is difficult to discriminate between co-seismic submergence associated with a small magnitude earthquake or non-seismic RSL changes. As they coincide with glacier expansions in the surrounding Kenai Mountains, effects of glacio-isostasy seem the simplest explanation. Chapter 8 compares these changes to similar oscillations at other sites and investigates them in detail.

The lowest transitional peat-silt boundary in SLT phases D to G (KE-2) record a similar magnitude relative sea-level rise when compared to the 1964 event. However, as the stratigraphic boundary is transitional and because there is no rapid post-seismic recovery, it is likely to result from co-seismic submergence superimposed upon non-seismic changes or purely from non-seismic changes in relative sea level.

Chapter 6
Results – Girdwood

6.1 Introduction

This chapter presents fossil results from seven buried peat layers at Girdwood. The uppermost results from co-seismic submergence associated with the 1964 earthquake, dated using ^{137}Cs (Zong *et al.*, 2003). Plafker *et al.* (1969) suggest 1.5 m regional subsidence and up to 0.9 m local subsidence of unconsolidated sediment accompanied this event at Girdwood. Detailed microfossil work (Shennan *et al.*, 1999; Zong *et al.*, 2003) investigates the associated pre-seismic and co-seismic movements. Below this layer, Combellick (e.g. 1991, 1993, 1994) describes five buried peat layers, each thought to be the result of sudden co-seismic subsidence associated with older late Holocene earthquakes. The buried peat layers are laterally extensive and have sharp upper boundaries separating them from overlying silt, following the criteria described by Nelson *et al.* (1996). Combellick (1994) radiocarbon dates them to have ages of 730-900, 1170-1360, 1930-2120, 2730-2850 and 3370-4090 cal yr BP.

This chapter follows the same format as chapter 5. Sections 6.2 and 6.3 describe the litho- and chrono-stratigraphy of the marsh, setting the general context for the seven peat-silt couplets found and sampled at varying depths below the present day marsh surface. Following sections describe the litho-, bio- and chrono-stratigraphy of each individual peat layer in detail with the application of statistical techniques allowing the reconstruction of relative sea-level (RSL) change through time. This chapter aims to investigate how the stratigraphy of Girdwood records relative sea- and land-level movements associated with multiple earthquake deformation cycles (EDC).

6.2 Litho-stratigraphy of Girdwood

The litho-stratigraphy of Girdwood marsh comprises multiple peat-silt couplets found at varying depths below present day marsh surface. Most are laterally extensive and all have sharp upper boundaries and transitional lower boundaries. The peat and organic layers vary in thickness with the thickest being 0.48 m in G-01-3 and the thinnest being three distinct layers of herbaceous rootlets in G-01-1B. Figure 6.1 summarises the litho-stratigraphy across the marsh, appendix 4 contains detailed Troels-Smith descriptions and figure 6.2 shows the sampling locations.

The bank section at Girdwood contains two extensive peat layers, the upper buried in 1964 and the lower buried approximately 557-1056 cal yr BP (Combellick & Reger, 1994) although radiocarbon dates from this study disagree with this age. Sampling of the bank section took place at G-800 (comparable to G-01-3 in figure 6.1) in May 2000 using a mixture of monolith tins and tubing depending on the amount of sediment required.

Coring across the marsh surface was extremely difficult due to the compact nature of the sediment. However, in May 2001 it was possible to core below the tidal flats. After plotting the stratigraphy, sampling took place at two sites, G-01-1 and G-01-9 (figures 6.1 and 6.2) because of the volume of sediment required and ease of sampling without potential contamination. The sampling of these deeper peat layers used a variety of monolith tins, Russian and gouge corers. Monolith tins were best where the peat layers were close to the surface and accessible, gouge corers were best through the consolidated silt units and Russian corers were used through the deeper buried peat layers to allow sampling of a greater volume of sediment for dating. Following sections describe the stratigraphy of individual peat-silt couplets in detail.

6.3 Chrono-stratigraphy of Girdwood

Caesium-137 (^{137}Cs) and radiocarbon (^{14}C) analyses allow the dating of multiple buried peat layers at Girdwood. Zong *et al.* (2003) provide detailed radionuclide measurements on the upper peat. Peak ^{137}Cs concentrations occur at the peat-silt boundary, proving that the change in stratigraphy resulted from co-seismic submergence associated with the 1964 earthquake. Any pre-seismic relative sea-level rise before this event started in the early 1950's (Zong *et al.*, 2003).

Sixteen AMS dates (NERC, allocation number 935 0901) allow the dating of the top, any pre-seismic signal and base of the older buried peat layers (appendix 3). All were bulk peat samples apart from the top of G-01-1A, where numerous seeds of *Menyanthes trifoliata* allowed the dating of macrofossils. Figure 6.3 shows the calibrated AMS dates for G-800, G-01-1 and G-01-9 using the calibration method described in section 3.7.2. The results are not straightforward as there are numerous age reversals throughout the sequence, for example, in G-800 the base of the upper peat appears older than the top of the lower peat.

Figure 6.4 compares the radiocarbon results from this study to those of Combellick (1991) and Combellick and Reger (1994) recalibrated using the same method (appendix 3). There is a wide amount of scatter between and within each data set and there are some major differences. For example, Combellick and Reger (1994) date the top of the lower peat layer in G-800 to approximately 800 cal yr BP, whereas the AMS date in this study dates it to 1182-1345 cal yr BP. Following sections describe these dating problems in detail but they cannot be resolved until *in situ* macrofossils from the same cores are re-dated. Following sections review each individual peat layer in detail, starting with G-800, G-01-1 and then G-01-9.

6.4 Bank section – G-800

This section describes Girdwood G-800 in more detail from the surface down through the upper peat to down below the second peat layer. It is equivalent to G-01-3 in figure 6.1. The upper peat layer is visible along the entire marsh front with its upper boundary varying in depth from approximately 0.30 m to 1.00 m below present day marsh surface which consists of low growing *Carex lyngbyei* and *Triglochin maritima*. Ghost forests visible on the surface today are rooted in this peat. All depths relate to the top of the bank section, which is approximately 0.34 m below the general level of the vegetated marsh. At the sampling site, the upper peat layer is brown herbaceous peat and occurs at a depth of 0.69 to 1.12 m (figure 6.5a). From 0.82 to 0.91 m it contains a small amount of silt. Subsequent tidal erosion exposed a section in September 2002 (site name G-02-2), approximately 50 m away from G-800 (figure 6.2). This shows a more clearly defined silt layer within the upper peat (figure 6.5b and appendix 4).

Approximately 1.0 m below the top of this peat is the lower peat layer (figure 6.5a), dated six times by Combellick and Reger (1994) to have an age of 557-1056 cal yr BP. This layer is also laterally extensive but was only visible in May 2000 due to the ever-changing thickness of tidal silt at the marsh front. The lower peat layer is herbaceous peat and occurs at a depth of 1.79 to 1.88 m. Coarse sand layers do not overlie any of the buried peat surfaces suggesting no tsunami evidence.

6.4.1 Bio-stratigraphy of G-800

Sampling intervals for diatom analysis varied depending on stratigraphy. Throughout the lowest peat layer, sampling took place at 1 cm intervals because no previous studies have investigated the microfossils contained within it. Sampling intervals increased to 8 cm through the intervening silt layer, as less detail is required from this section of the core when looking at relative sea-level changes associated with major earthquakes as the main evidence occurs around peat-silt boundaries. Through the upper peat, sampling intervals varied from 2 to 4 cm, with 1 cm intervals taken around the 1964 boundary. Sampling intervals increased to 8 cm through the uppermost silt to the present day surface. Detailed microfossil analysis of the 1964 event, undertaken by Shennan *et al.* (1999) and Zong *et al.* (2003) concentrate only on the few centimetres surrounding the upper peat-silt boundary. The present study significantly extends current knowledge by investigating in detail relative sea-level changes throughout a complete earthquake deformation cycle, including two co-seismic submergence events.

Figure 6.6 shows the lithology of the section, AMS dates and summarises the bio-stratigraphy of Girdwood G-800, from the surface down to a depth of 195 cm. It shows diatoms that account for at least 2% total diatom valves at each level along with summary salinity classes. Zones produced during stratigraphically constrained cluster analysis aid the description of diatom changes through the core. Following paragraphs introduce and summarise the main changes in diatom assemblages and present an initial interpretation of sea-level tendencies that will be fully analysed and quantified in later sections. Diatom count information for Girdwood G-800 is in appendix 5.

Zone A: 194.5 to 185.5 cm

Oligohalobous-indifferent diatoms dominate zone A, particularly *Pinnularia lagerstedtii*. The decline in polyhalobous diatoms towards the top of this zone, together with a gradual change in lithology from silt to peat indicates a gradual negative sea-level tendency and suggests a relative sea-level fall.

Zone B: 185.5 to 178.5 cm

Halophobous diatoms, for example, *Eunotia exigua* and *Pinnularia subcapitata* increase to a peak at 181 to 182 cm suggesting a continued negative sea-level tendency (relative sea-level fall). However, above 180.5 cm they start to decline together with an increase in oligohalobous-indifferent species, in particular, *Navicula variostriata* and *Nitzschia pusilla*. At the very top of zone B, polyhalobous species increase (e.g. *Delphineis surirella*). These changes above 180.5 cm suggest a positive sea-level tendency (relative sea-level rise) within the top few centimetres of the lower peat layer. The boundary between zone B and zone C is a sharp contact between this peat layer and overlying silt with herbaceous rootlets.

Zone C: 178.5 to 164 cm

Diatom assemblages are significantly different compared to zone B. Polyhalobous diatoms dominate especially, *Actinoptychus senarius*, *Delphineis surirella*, *Odentella aurita* and *Paralia sulcata*. The change in diatom assemblages, alongside the rapid change in lithology from freshwater peat to silt with herbaceous rootlets represents a sudden positive sea-level tendency (relative sea-level rise). Towards the top of this zone, polyhalobous diatoms decrease slightly with an associated increase in mesohalobous and oligohalobous species suggesting the start of a negative sea-level tendency (relative sea-level fall).

Zone D: 164 to 124 cm

The lithology of zone D is silt with herbaceous rootlets. Polyhalobous diatoms, for example, *Delphineis surirella* and *Paralia sulcata* dominate. However, they continue to decline throughout this zone together with an increase in mesohalobous and oligohalobous species, particularly *Nitzschia fruticosa*. This suggests the negative sea-level tendency (relative sea-level fall) started in zone C continues throughout zone D.

Zone E: 124 to 111 cm

Polyhalobous diatoms (e.g. *Delphineis surirella* and *Paralia sulcata*) continue to decline and mesohalobous and oligohalobous species dominate, for example, *Navicula protracta, Navicula cari* var. *cincta* and *Nitzschia fruticosa*. The negative sea-level tendency (relative sea-level fall) continues through zone E.

Zone F: 111 to 102 cm

Zone F contains two smaller clusters indicated by the dendrogram and illustrated on figure 6.4 as dashed lines. The lower cluster from 111 to 107 cm shows an increase in oligohalobous-indifferent diatoms, for example, *Nitzschia palustris*, *Pinnularia subsolaris* and *Stauroneis anceps* together with a general decline in polyhalobous, mesohalobous and oligohalobous-halophile species. The second cluster from 107 to 102 cm indicates a continued decline of the more salt tolerant species and the introduction of halophobes for example, *Eunotia exigua*. The general trend of decreasing salt tolerant diatoms and the introduction of halophobous species, together with the change in lithology from silt with herbaceous rootlets to freshwater peat suggests a continued negative sea-level tendency (relative sea-level fall).

Zone G: 102 to 68.5 cm

In the absence of any lithological evidence of local channel migration the bio-stratigraphy of zone G suggests a complex pattern of relative sea-level movements within the upper peat layer. It contains three smaller clusters (indicated by the dendrogram) illustrated by dashed lines on figure 6.6.

Oligohalobous-indifferent and halophobous diatoms dominate the lowest cluster from 102 to 94 cm, for example, *Achnanthes minutissima*, *Eunotia lunaris* and *Eunotia exigua*. Halophobes peak at 100 cm, suggesting a continued negative sea-level tendency (relative sea-level fall) followed by a slight positive sea-level tendency (relative sea-level rise). Within the second cluster from 94 to 82 cm, halophobes continue to decline to a low at 84 cm. There is an associated increase in more salt tolerant species, for example, *Delphineis surirella*, *Nitzschia obtusa*, *Luticola mutica*, *Navicula brockmannii* and *Pinnularia lagerstedtii*. This suggests a positive sea-level tendency (relative sea-level rise) and accompanies an increase in silt content. The third cluster ranges from 82 to 68.5 cm. At the base of this cluster, halophobes increase to a peak at 76 cm, for example, *Eunotia exigua* and *Pinnularia subcapitata*. This suggests a negative sea-level tendency (relative sea-level fall). However, above 76 cm halophobes decline and more salt tolerant diatoms increase, for example, *Nitzschia obtusa*, *Navicula begeri and Pinnularia lagerstedtii*. This suggests a positive sea-level tendency (relative sea-level rise) within the upper few centimetres of the peat. The boundary between this zone and zone H is a sharp contact between the peat layer and silt deposited top.

Zone H: 68.5 to 12 cm

At the base of this zone, there is a sudden change in diatom assemblage compared to zone G. Polyhalobous diatoms, for example, *Actinoptychus senarius*, *Cocconeis peltoides*, *Delphineis surirella*, *Odentella aurita* and *Paralia sulcata* dominate. This change, together with the sharp contact between the peat and silt with herbaceous rootlets indicates a rapid positive sea-level tendency (relative sea-level rise).

Between 67 and 44 cm oligohalobous diatoms increase, for example, *Nitzschia fruticosa*. The one sample at 40 cm suggests a slight reversal in this trend with polyhalobous species dominating once again. Above 40 cm, polyhalobous diatoms decline and there is a general increase in mesohalobous and oligohalobous species, for example, *Navicula protracta*, *Navicula cari* var. *cincta*, *Nitzschia fruticosa* and *Nitzschia pusilla*. Salinity groupings suggest a general negative sea-level tendency (relative sea-level fall) within the upper silt layer and later sections quantify these changes.

Zone I: 12 cm to ground surface

Throughout this zone, there is decrease in polyhalobous species and an increase in oligohalobous-indifferent species, in particular, *Achnanthes minutissima* and *Nitzschia pusilla*. This suggests a continued negative sea-level tendency (relative sea-level fall) to the present day.

6.4.2 Chrono-stratigraphy of G-800

Caesium-137 (^{137}Cs) and radiocarbon (^{14}C) dating determine the chrono-stratigraphy of G-800. Zong *et al.* (2003) measured ^{137}Cs concentrations from two cores at Girdwood, 98-33 and 98-34. They show maximum concentrations occur at the upper peat-silt boundary suggesting the rapid relative sea-level rise resulted from co-seismic submergence associated with the 1964 event. The 1954 horizon occurs approximately 5 cm below.

Figure 6.3 shows the AMS results for the buried peats in G-800 (appendix 3). Radiocarbon dating of the base of the upper peat (109 cm) gives an age of 1350-1517 cal yr BP. The top of the second peat layer (179 cm) dates to 1182-1345 cal yr BP, a couple of centimetres below at 181 cm is dated to 1294-1505 cal yr BP and its base (190 cm) dates to 3572-3820 cal yr BP. The dates of the second peat layer are in sequence but the base of the upper peat appears older than it should be. There is also the discrepancy of the date of the second peat layer when compared to dates of Combellick (1991) and Combellick and Reger (1994) who date it six times to approximately 800 cal yr BP. In addition, a tephra found beneath the base of the uppermost peat layer may be the Augustine tephra, deposited approximately 500 cal yr BP (Beget, pers com). Re-dating *in situ* macrofossils from the same core could help solve these discrepancies.

6.4.3 Numerical analysis of G-800

This section aims to analyse and quantify relative sea-level changes recorded by the bio-stratigraphy of Girdwood G-800 using the contemporary data set from Kenai described in section 4.5. Contemporary data from Kenai offers the best transition from tidal flat through to the vegetated marsh surface whereas at Girdwood, there is no such transition because of the 1 m high cliff section separating the two. It follows the same logic as explained for the Kenai fossil data in section 5.5.

In addition, there is the complication of the difference in tidal range between Girdwood and Kenai. At Kenai, the tidal range is approximately 6 m whereas at Girdwood it is approximately 10 m. A similar zonation of contemporary diatoms should occur at both sites, but because of the larger tidal range at Girdwood, some up scaling of the contemporary Kenai data may be required. No scaling is applied when calibrating the transfer function model as the method chosen directly affects the results obtained. It will not change the trend of relative sea level between samples but it may change its magnitude. Section 6.4.4 considers this in more detail and upscaling occurs in the discussion of results (section 6.4.5).

Figure 6.7 shows the calibration results for Girdwood G-800 using the different models outlined in section 4.5. It plots predicted altitude (m relative to MHHW) for each fossil sample, together with its associated error term calculated using the sample specific error generated within WA-PLS (version 1.5; Juggins & ter Braak, 2001). Reconstructed values are in appendix 6 and tables 6.1 to 6.3 summarise the results. The amount of associated error varies greatly depending on which model is used and as with Kenai 2000-7, highlights why litho-stratigraphy is required to select the best model. Environments indicated by the altitude reconstructions are from table 2.1.

Table 6.1 Summary of calibration results for G-800 using the full model (all contemporary samples against altitude (m) relative to MHHW)

Lithological unit	**Altitude reconstruction (m)**	**Environment indicated by the altitude reconstructions**
Lower peat	+0.47 ± 0.94 m MHHW to +1.29 ± 0.94 m MHHW	Low marsh through to the transition zone into raised bog
Intervening silt	-2.17 ± 1.08 m MHHW to +0.93 ± 0.94 m MHHW	Unvegetated mudflat through to low/mid marsh
Upper peat	+0.43 ± 0.94 m MHHW to +1.26 ± 0.93 m MHHW	Low to high marsh
Upper silt	-2.11 ± 1.00 m MHHW to a surface altitude of +1.06 ± 0.93 m MHHW	Unvegetated mudflat through to mid marsh

Table 6.2 Summary of calibration results for G-800 using the -0.5 m model (contemporary samples above -0.5 m MHHW against altitude (m) relative to MHHW)

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Lower peat	+0.92 ± 0.25 m MHHW to +1.33 ± 0.23 m MHHW	Low/mid marsh through to transition into raised bog
Intervening silt	-0.10 ± 0.43 m MHHW to +1.07 ± 0.22 m MHHW	Upper tidal flat/marsh pioneer zone through to mid marsh
Upper peat	+0.87 ± 0.23 m MHHW to +1.44 ± 0.21 m MHHW	Low/mid marsh to raised bog
Upper silt	-0.24 ± 0.32 m MHHW to a surface altitude of +1.19 ± 0.22 m MHHW	Unvegetated mudflat through to high marsh

Table 6.3 Summary of calibration results for G-800 using the two +1.0 models (contemporary samples above +1.0 m MHHW against altitude (m) relative to MHHW and hours inundated per year)

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Lower peat	+1.23 ± 0.06 m MHHW to +1.37 ± 0.08 m MHHW	High marsh to diverse raised bog
Intervening silt	Approximately +1.12 ± 0.07 m MHHW	Mid to high marsh
Upper peat	+1.14 ± 0.04 m MHHW to +1.47 ± 0.07 m MHHW	High marsh to diverse raised bog
Upper silt	Approximately +1.11 ± 0.07 m MHHW, increasing to +1.31 ± 0.07 m MHHW at the surface	Mid marsh through to transition zone into raised bog

As with the Kenai fossil data, the four calibration models perform differently in certain parts of the core. Reconstruction of relative sea level only requires one model, chosen using the established litho-stratigraphic constraints (see sections 4.5 and 5.5). Table 6.4 describes the calibration model chosen for different parts of G-800. It only considers the +1.0 m MHHW model, rather than both the +1.0 m MHHW and +1.0 hours inundated models because they produce such similar results.

Table 6.4 Calibration models used to reconstruct RSL change in different parts of G-800

Depth ranges (cm)	Model used	Reason
194 to 189 178 to 116 68 to 0	-0.5	Lithology indicates silt with rootlets. The -0.5 m model is appropriate and more precise as modern day samples taken from Kenai suggest no vegetation occurs below -0.28 m MHHW
188 to 179 112 to 69	+1.0	Lithology indicates peat and so the +1.0 m MHHW model is appropriate

Figure 6.8 shows the results from the modern analogue technique (MAT). In summary, MAT indicates one fossil sample (2%) has a 'poor' modern analogue, 22 (43%) have 'close' modern analogues and 28 (55%) have 'good' modern analogues (see section 4.6 for discussion of critical values). Only the surface sample from G-800 has a 'poor' modern analogue compared to the contemporary data set from Kenai because of its dominance by *Achnanthes minutissima* and *Nitzschia pusilla*. Both species have comparable percentages in the contemporary data set, but they do not occur in the same assemblage. In reality, this may not be a problem as they both have similar optima and tolerances (figure 4.8 and appendix 1). One possible explanation is that the surface assemblage results from mixing of sediment from ice blocks deposited on the marsh surface (figure 2.12).

The transfer function (-0.5 m model) predicts the surface height of G-800 to be +1.19 ± 0.22 m MHHW. At the time of sampling, levelling the surface altitude of G-800 was not possible due to adverse weather conditions. One year later, the sampling site had a levelled surface height of +0.98 m MHHW but alteration due to erosion and sedimentation at the marsh front could affect this reading. However, it does lie within the error term of the predicted altitude and indicates that even though the surface sample does not have a good modern analogue, the transfer function is reasonably accurate.

Figure 6.9 is a composite diagram illustrating the main changes in predicted altitude (m) relative to MHHW for Girdwood G-800 (individual results are in appendix 6), drawn using table 6.4 (with no scaling to account for differences in tidal range between

Girdwood and Kenai). The contemporary surface sample (highlighted in red) has a 'poor' modern analogue, identified using figure 6.8 but this reconstruction does not appear to be inaccurate as its approximate levelled height lies within its error term. Table 6.5 quantitatively describes the main changes in relative sea level with the help of sea-level tendency (SLT) phases. Diatom descriptions are in figure 6.6, section 4.4.2, figure 4.8 and appendix 1 describe the optima and tolerances of diatom species and environmental reconstructions are from table 2.1. It also includes the scaling of relative sea-level changes, explained in the next section.

6.4.4 The question of scaling

The height axis for quantitative reconstruction using the transfer function approach relates to Kenai where the tidal range (difference between MHHW and MLLW) is 6.08 m, whereas at Sunrise, 12 km west of Girdwood, it is 10.18 m (refer to section 4.2.1; data from NOAA Tide Tables, http://co-ops.nos.noaa.gov). The limited amount of contemporary data at Girdwood only allows an upscaling of a linear ratio between the two tidal ranges that is similar to the scaling applied by Zong *et al.* (2003).

Table 6.6 Calculation of scaling factor

Location of nearest station with predictions	Tidal range (m) (MHHW-MLLW)	Scaling factor between observed & predicted	Actual tidal range (m) at sites
Kenai City Pier	6.08	1.09 (figure 4.1b)	6.08 x 1.09 = 6.64
Sunrise	10.18	0.83 (figure 4.2 a & b)	10.18 x 0.83 = 8.45

Using table 6.6 the best estimate for the ratio between the tidal ranges is the difference between the actual tidal ranges using observational data. This is the ratio 6.64:8.45, resulting in a scaling factor of 1.27 m. Application of this ratio to the results occurs in table 6.5 and in the discussion of relative sea-level changes throughout the sequence (section 6.4.5) but not to individual samples.

Table 6.5 Description of relative sea-level changes through G-800

SLT Phase	Depth (cm)	Lithology	Brief summary (including optima and tolerance, *u*±*t* of diatom species)	Sea-level tendency	Quantitative reconstructions (no scaling)	Quantitative reconstructions (with scaling)	Environmental reconstruction
A	194.5 to 187.5	Gradual transition from silt with herbaceous rootlets to herbaceous peat	A mixture of polyhalobous, mesohalobous and oligohalobous diatoms dominate SLT phase A (figure 6.6), for example, *Paralia sulcata* (-0.93 ± 1.91 m), *Nitzschia obtusa* (+1.14 ± 0.29 m), *Navicula begeri* (+1.27 ± 0.15 m) and *Pinnularia lagerstedtii* (+1.38 ± 0.12 m)	Negative	RSL fall of -0.27 ± 0.24 m from +1.02 ± 0.23 m MHHW to +1.29 ± 0.07 m MHHW	RSL fall of -0.34 ± 0.30 m	Mid marsh through to transition zone into raised bog
B	187.5 to 180.5	Herbaceous peat	Polyhalobous species decline (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Paralia sulcata*, -0.93 ± 1.91 m), oligohalobous-indifferent species dominate (e.g. *Nitzschia obtusa*, +1.14 ± 0.29 m; *Nitzschia pusilla*, +1.36 ± 0.19 m; *Pinnularia lagerstedtii*, +1.38 ± 0.12 m) and halophobes are introduced (e.g. *Eunotia exigua*, +1.49 ± 0.10 m)	Negative	RSL fall of -0.08 ± 0.11 m to a new ground height of +1.37 ± 0.08 m MHHW	RSL fall of -0.10 ± 0.13 m	Raised bog
C	180.5 to 178.5	Upper 2 cm of herbaceous peat. Sharp upper contact with overlying silt	Some oligohalobous-indifferent diatoms and all halophobes decline, for example, *Pinnularia lagerstedtii* (+1.38 ± 0.12 m) and *Eunotia exigua* (+1.49 ± 0.10 m). This is accompanied by an increase in more salt tolerant species (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Navicula variostriata*, +1.35 ± 0.32 m; *Nitzschia pusilla*, +1.36 ± 0.19 m) indicating greater tidal inundation	Positive	RSL rise of +0.10 ± 0.11 m to a new ground height of +1.27 ± 0.07 m MHHW	RSL rise of +0.13 ± 0.13 m	Raised bog to transition zone into raised bog

D	178.5 to 175	Silt with herbaceous rootlets	SLT phase D is characterised by a dramatic increase in polyhalobous diatoms, for example, *Actinoptychus senarius* (-1.31 ± 1.90 m), *Delphineis surirella* (-1.13 ± 2.11 m) and *Paralia sulcata* (-0.93 ± 1.91 m). No halophobes are present	Positive	RSL rise between +0.86 ± 0.36 m and +1.37 ± 0.44 m to a new ground height of either +0.41 ± 0.35 m MHHW or -0.10 ± 0.43 m MHHW	Maximum RSL rise of +1.74 ± 0.56 m	Upper tidal flat/marsh pioneer zone to low marsh
E	175 to 94	Silt with herbaceous rootlets to herbaceous peat	Polyhalobous species decline (e.g. *Delphineis surirella*, -1.13 ± 2.11 m) and mesohalobous and oligohalobous species increase (e.g. *Navicula protracta*, +1.08 ± 0.49 m; *Navicula cari* var. *cincta*, +0.20 ± 1.45 m; *Nitzschia fruticosa*, +1.31 ± 0.16 m). Introduction of halophobous species (e.g. *Eunotia exigua*, +1.49 ± 0.10 m) occurs at the base of the upper peat	Negative	RSL fall of -1.57 ± 0.44 m to a new ground height of +1.47 ± 0.07 m MHHW	RSL fall of -1.99 ± 0.56 m	Upper tidal flat/marsh pioneer zone to raised bog
F	94 to 74	Herbaceous peat	From 91 to 82 cm, there is an increase in silt content, a decrease in halophobes (e.g. *Eunotia exigua*, +1.49 ± 0.10 m) and an increase in more salt tolerant species (e.g. *Nitzschia obtusa*, +1.14 ± 0.29 m; *Nitzschia pusilla*, +1.36 ± 0.19 m; *Pinnularia lagerstedtii*, +1.38 ± 0.12 m). Above 82 cm, halophobes increase once again (e.g. *Eunotia exigua*, +1.49 ± 0.10 m; *Pinnularia subcapitata*, +1.51 ± 0.07 m)	Positive then negative	RSL rise of +0.17 ± 0.10 m to a new ground height of +1.30 ± 0.07 m MHHW followed by a RSL fall of -0.14 ± 0.10 m to a new ground height of +1.44 ± 0.07 m MHHW	RSL rise of +0.22 ± 0.13 m followed by RSL fall of -0.18 ± 0.13 m	Raised bog to transition zone into raised bog

G	74 to 68.5	Top few cm's of herbaceous peat. Sharp upper contact between peat and overlying silt	Halophobes decrease (e.g. *Eunotia exigua*, +1.49 ± 0.10 m; *Pinnularia subcapitata*, +1.51 ± 0.07 m) and salt tolerant diatoms increase. Dominant taxa include *Paralia sulcata* (-0.93 ± 1.91 m), *Nitzschia obtusa* (+1.14 ± 0.29 m), *Pinnularia lagerstedtii* (+1.38 ± 0.12 m) and *Eunotia exigua* (+1.49 ± 0.10 m)	Positive	RSL rise of +0.13 ± 0.10 m to a ground height of +1.31 ± 0.07 m MHHW	RSL rise of +0.17 ± 0.13 m	Transition zone into raised bog
H	68.5 to 67	Silt with herbaceous rootlets	Diatom assemblages show a rapid change to dominance by polyhalobous species, for example, *Actinoptychus senarius* (-1.31 ± 1.90 m), *Cocconeis peltoides* (-1.04 ± 1.75 m), *Delphineis surirella* (-1.13 ± 2.11 m) and *Paralia sulcata* (-0.93 ± 1.91 m)	Positive	RSL rise of +1.55 ± 0.33 m to a new ground height of -0.24 ± 0.32 m MHHW	RSL rise of +1.97 ± 0.42 m	Unvegetated mudflat/marsh pioneer zone
I	67 to surface	Silt with herbaceous rootlets	Polyhalobous species generally decline towards the surface (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Paralia sulcata* -0.93 ± 1.91 m) and oligohalobous taxa increase (e.g. *Achnanthes minutissima*, +1.44 ± 0.16 m; *Nitzschia pusilla*, +1.36 ± 0.19 m) There is a slight reversal at 40 cm but error terms overlap	Negative	General RSL fall of -1.43 ± 0.39 m to a surface altitude of +1.19 ± 0.22 m MHHW	RSL fall of -1.82 ± 0.50 m	Upper tidal flat/ marsh pioneer zone to high marsh

6.4.5 Relative sea- and land-level changes through G-800

Following sections interpret the relative sea-level changes described in table 6.5 in chronological order, testing periods of the EDC model and where appropriate suggesting alternative mechanisms.

Development of the lower peat - SLT phases A and B

This phase could represent the inter-seismic period of the EDC model where strain accumulation at the plate boundary gradually causes land to rise and relative sea level to fall. Alternatively, it could represent a change in non-seismic processes, for example a slowing down in the rate of eustatic sea-level rise approximately 4000 cal yr BP (Fleming *et al.*, 1998; Peltier, 1998), isostatic adjustments or local processes such as a change in sedimentary conditions. Peat development started approximately 3572-3820 cal yr BP.

RSL changes associated with the penultimate event – SLT phases C to E

RSL changes surrounding the burial of the lower peat layer conform to periods of the EDC model. There is some discrepancy over the age of its burial, with Combellick and Reger (1994) suggesting its burial approximately 800 cal yr BP and an AMS date from this study indicating burial 1182-1345 cal yr BP (figure 6.3 and appendix 3).

Pre-seismic RSL rise associated with the penultimate event - SLT phase C

This phase occurs within the upper two centimetres of the lower peat layer with diatom assemblages suggesting a positive sea-level tendency. Quantitative reconstructions suggest a relative sea-level rise of +0.10 ± 0.11 m from a ground level of +1.37 ± 0.08 m MHHW to +1.27 ± 0.07 m MHHW. Applying the scaling factor of 1.27 m produces a pre-seismic relative sea-level rise of +0.13 ± 0.13 m. Evidence to suggest these assemblages are not a result of mixing includes an increase in *Navicula variostriata* and *Nitzschia pusilla* within this phase. These species only occur in small numbers in the above silt.

Co-seismic submergence associated with the penultimate event - SLT phase D

Evidence suggesting co-seismic submergence includes a laterally extensive buried peat layer with a sharp upper boundary together with polyhalobous diatoms dominating the overlying silt. This indicates a sudden change from a freshwater peat environment to one regularly inundated by the tide and fulfils three of the five criteria suggested by Nelson *et al.* (1996). There is no evidence of any tsunami deposit and chapter 8 investigates synchroneity of submergence when bringing all three sites together.

Quantitative reconstructions indicate a rapid relative sea-level rise of +1.37 ± 0.44 m to a new ground height of -0.10 ± 0.43 m MHHW, assuming the first altitude reconstruction within the silt unit is due to mixing (chapter 8 investigates this further). Applying the scaling factor produces co-seismic submergence of +1.74 ± 0.56 m.

Post-seismic recovery of the land - SLT phase E

Rapid relative sea-level fall follows co-seismic submergence in SLT phase D allowing development of the upper peat approximately 1350-1517 cal yr BP, although this date is questionable when compared to dates of Combellick (1991) and Combellick and Reger (1994) who suggest that this upper peat started to form approximately 500 cal yr BP. Quantitative reconstructions indicate a relative sea-level fall of -1.57 ± 0.44 m to a new ground height of +1.47 ± 0.07 m MHHW, representing post-seismic and inter-seismic recovery of the land combined with sediment accumulation. Applying the scaling factor to this value suggests -1.99 ± 0.56 m recovery. A comparison between the rate of uplift for this event and that since the 1964 earthquake is impossible because there is an age reversal between the top of the lowest peat and the base of the 1964 peat.

Other possible hypotheses to explain the rapid relative sea-level changes around the lower peat-silt boundary include non-seismic processes. However, as tendencies and magnitudes are directly comparable to the 1964 event (see later) and fulfil three out of the five criteria suggested by Nelson *et al.* (1996), they are likely to represent co-seismic submergence associated with the penultimate event to affect Girdwood.

RSL oscillation within the upper peat unit - SLT phase F

There is an oscillation in relative sea level below the pre-seismic signal of the 1964 earthquake occurring between 1954 AD and 1350-1517 cal yr BP. Quantitative reconstructions suggest a relative sea-level rise of +0.17 ± 0.10 m to a new ground height of +1.30 ± 0.07 m MHHW. Applying the scaling factor to this produces a value of +0.22 ± 0.13 m. Following this rise, relative sea-level falls by -0.14 ± 0.10 m (-0.18 ± 0.13 m with scaling factor) and the ground surface returns more or less to its previous altitude. This is directly comparable to the relative sea-level rise (+0.18 ± 0.10 m) observed below the 1964 event in Kenai 2000-7 (section 5.6 - SLT phase J, event KE-3). Following sections test the same hypotheses as in section 5.6.

Possible hypotheses include:

1. RSL oscillation associated with co-seismic submergence of a small magnitude earthquake
2. RSL oscillation associated with non-seismic processes, for example, the combination of eustatic and glacio-isostatic changes
3. RSL oscillation associated with co-seismic submergence superimposed upon a background non-seismic RSL change

Hypothesis 1 - The RSL oscillation within SLT phase F results from co-seismic submergence

Lateral extent, amount and suddenness of submergence (Nelson *et al.*, 1996) together with the identification of pre-seismic, co-seismic and post-seismic relative sea-level movements are important when deciding if SLT phase F records an episode of co-seismic submergence. Immediately before the event, there is no evidence of a pre-seismic relative sea-level rise. After possible co-seismic submergence of +0.17 ± 0.10 m (+0.22 ± 0.13 m with scaling factor), the land returns to its previous altitude, suggesting recovery of the same magnitude. This oscillation corresponds to a slight increase in silt content between 0.91 and 0.82 m. The hypothesis that the relative sea-level oscillation observed in SLT phase F results from co-seismic submergence remains valid, although to fulfil the criteria of Nelson *et al.* (1996) further investigation of other cores is required to see if it becomes a sharp peat-silt boundary. It is similar to the change recorded in Kenai 98-13 for the 1964 event (Zong *et al.*, 2003) and chapter 8 considers possible small co-seismic events in detail.

Hypothesis 2 - The RSL oscillation within SLT phase F results from non-seismic processes, including eustatic and glacio-isostatic changes

A combination of eustatic, isostatic and local processes could account for the relative sea-level oscillation observed in SLT phase F. Similar to the changes in Kenai 2000-7, isostatic adjustments could have taken place during the Little Ice Age, 650 to 100 cal yr BP. Advance of the surrounding glaciers in Portage Valley and adjacent mountains reached their maximum extent before 140 cal yr BP (Crossen, 1992) causing depression of the earths crust. Following melting, isostatic uplift returns the land to its previous position and these responses would be rapid due to its proximity to the subduction zone. Other non-seismic factors include local changes, for example, a change in sedimentary processes, but as this relative sea-level rise corresponds to the relative sea-level rise at Kenai, it is likely to be a response to a regional or global factor. This hypothesis also remains valid.

Hypothesis 3 - The RSL oscillation within SLT phase F results from co-seismic submergence superimposed upon a non-seismic RSL change

As both hypotheses 1 and 2 are possible explanations of the relative sea-level oscillation observed in SLT phase F, some combination of both is also possible. It may represent small co-seismic submergence superimposed upon some background non-seismic RSL change, whether eustatic, isostatic or local, for example, migration of the tidal channel or a change in marsh sedimentary processes.

In summary, the relative sea-level oscillation observed in SLT phase F could result from co-seismic submergence, non-seismic changes or a combination of both but as the relative sea-level changes are so small, it is difficult to distinguish between them. Given that the event occurs at both Kenai and Girdwood, it is unlikely that local scale processes are the cause and chapter 8 investigates this further.

Quantitative changes associated with the 1964 event – SLT phases G to I

Identification of pre-, co- and post-seismic periods of the EDC model occurs at or around the upper peat-silt boundary. ^{137}Cs relates this peat-silt boundary to the 1964 earthquake (Zong *et al.*, 2003) and following sections examine these relative sea-level changes in detail.

Pre-seismic relative sea-level rise - SLT phase G

Quantitative reconstructions indicate an increase in tidal inundation immediately before the 1964 earthquake with a relative sea-level rise of +0.13 ± 0.10 m to a new ground height of +1.31 ± 0.07 m MHHW. Applying the scaling factor to this result suggests a relative sea-level rise of +0.17 ± 0.13 m. It is unlikely that these diatom assemblages are a result of mixing at the peat-silt boundary because species such as *Nitzschia obtusa*, *Navicula brockmannii* and *Pinnularia lagerstedtii* increase and do not occur in the overlying silt.

Three other exposures of the 1964 peat at Girdwood record the same trend (Shennan *et al.*, 1999; Zong *et al.,* 2003). Zong *et al.* (2003) suggest this change started around the beginning of the 1950's (using ^{137}Cs) and calculated a relative sea-level rise of +0.16 ± 0.13 using diatom transfer functions and +0.15 ± 0.11 m using pollen transfer functions. As mentioned in chapter 5, their error term calculations are erroneous but the reconstructed results are very similar to those obtained in this study. In addition, there is also observational data indicating a relative sea-level rise before the event. Karlstrom (1964) reports that storm tides that did not flood the marsh surface before

1953 began depositing a thin surface silt layer that became progressively thicker. Chapter 8 investigates other possible mechanisms.

Co-seismic submergence associated with the 1964 event - SLT phase H

Evidence suggesting co-seismic submergence includes a laterally extensive sharp boundary between the peat and overlying silt with herbaceous rootlets together with diatom assemblages showing a rapid change to dominance by polyhalobous species. ^{137}Cs dates this contact to 1964 (Zong *et al.*, 2003) and quantitative reconstructions indicate a positive sea-level tendency of +1.55 ± 0.33 m to a new ground level of -0.24 ± 0.32 m MHHW. Applying the scaling factor to this figure suggests the magnitude of co-seismic submergence would be +1.97 ± 0.42 m. This is of the same magnitude as the sum of regional subsidence, ~1.5 m, and local subsidence of unconsolidated sediment, up to ~0.9 m (Plafker *et al.,* 1969). No tsunami affected the Turnagain Arm during this event and as it was synchronous over a large area, it fulfils four out of the five criteria described by Nelson *et al.* (1996).

These figures also compare favourably with the results of Zong *et al.* (2003) who estimate co-seismic submergence between +1.59 ± 0.22 m and +1.98 ± 0.23 m using diatom transfer functions and greater than +1.07 ± 0.42 m using pollen transfer functions.

Post-seismic recovery - SLT phase I

Immediately after the 1964 earthquake, rapid uplift of the land and sedimentation occurs and this is continuing to the present day (e.g. Atwater *et al.*, 2001; Bartsch-Winkler, 1988; Bartsch-Winkler & Schmoll, 1992; Brown *et al.*, 1977; Combellick, 1997; Cohen, 1996, 1998; Plafker *et al.*, 1992). Repeated levelling at Girdwood by Brown *et al.* (1977) suggests a cumulative uplift of approximately 2 cm from 1964 to 1965, 12 cm from 1964 to 1968 and 40 cm from 1964 to 1975. Quantitative reconstructions using the microfossil data suggest -1.43 ± 0.39 m recovery by 2000 (-1.82 ± 0.50 m when scaled) suggesting most recovery occurs in the post-seismic period of the EDC model.

6.4.6 Summary of G-800

The stratigraphy of G-800 records up to three episodes of co-seismic submergence. Table 6.7 compares and summarises them, giving each an event name for use in chapter 8 when bringing all three sites together.

The uppermost peat-silt boundary (GW-8) relates to co-seismic submergence associated with the 1964 event and figures obtained from this study are similar to both observational data (e.g. Plafker *et al.*, 1969) and those estimated previously from fossil data by the transfer function method (e.g. Zong *et al.*, 2003). Quantitative reconstructions clearly identify four periods of the EDC model, inter-seismic, pre-seismic, co-seismic and post-seismic movements. The peat-silt boundary is laterally extensive and represents large, sudden submergence of the peat into the intertidal zone, fulfilling four out of the five criteria of Nelson *et al.* (1996). Synchroneity of submergence occurred over a large area (figure 1.4) and no tsunami affected the Turnagain Arm.

The oscillation in relative sea level below the 1964 event (GW-7) is directly comparable to that found in Kenai 2000-7 (section 5.6) suggesting that the oscillation is due to regional or global factors, rather than local processes. It could result from a small co-seismic event, non-seismic relative sea-level change or a combination of them both but as the relative sea-level changes are so small, it is difficult to differentiate between them (chapter 8 investigates these small events in detail). Given there is observational data of glacier oscillations during this period, non-seismic explanations seem the simplest as there is no clear evidence of this change being laterally extensive, and it is difficult establishing whether it follows the five criteria of Nelson *et al.* (1996).

The laterally extensive lower peat-silt boundary (GW-6) records the penultimate great earthquake to affect Girdwood and it is directly comparable to the 1964 event in sea-level tendencies and magnitude. Before the event, there is a pre-seismic relative sea-level rise, followed by large, sudden co-seismic submergence. Immediately after, relative sea-level falls, indicating the post-and inter-seismic periods of the EDC model together with sediment accumulation. There is no evidence of any tsunami deposit and there is some discrepancy over the age of its burial. AMS dating of *in situ* macrofossils rather than bulk peat samples could resolve this. The above interpretation of G-800 fulfils three out of the five criteria described by Nelson *et al.* (1996) and chapter 8 investigates synchroneity of submergence when bringing all three sites together.

Table 6.7 Summary of possible events in G-800

+ve signs represent a relative sea-level rise and –ve signs represent a relative sea-level fall

Values in brackets are scaled due to the difference in tidal range between Girdwood and Kenai

SLT Phase	Description	Event name	EDC related	Date at contact (cal yr BP)	Pre-seismic RSL change (m)	Co-seismic RSL change (m)	Sharpness of boundary (Troels-Smith)	Lateral extent	Post/inter-seismic recovery (m) and sediment accumulation
G to I	1964 earthquake	GW-8	Yes	1964 AD	$+0.13 \pm 0.10$ $(+0.17 \pm 0.13)$	$+1.55 \pm 0.33$ $(+1.97 \pm 0.42)$	4	>1 km	-1.43 ± 0.39 (-1.82 ± 0.50)
F	Oscillation within upper peat	GW-7	?	1954 AD to 1350-1517	Not identified	$+0.17 \pm 0.10$ $(+0.22 \pm 0.13)$	Increase in silt content	>50 m	-0.14 ± 0.10 (-0.18 ± 0.13)
C to E	Penultimate event	GW-6	Yes	1182-1345 (or ~800)	$+0.10 \pm 0.11$ $(+0.13 \pm 0.13)$	$+1.37 \pm 0.44$ $(+1.74 \pm 0.56)$	4	>1 km	-1.57 ± 0.44 (-1.99 ± 0.56)

Following sections now consider individual peat-silt boundaries found in cores G-01-1 and G-01-9 (see figure 6.2 for location of sampling sites). The principal aim in studying these individual peat-silt boundaries is to establish if they were buried by co-seismic submergence, and if so, what magnitude.

6.5 G-01-1A

G-01-1A occurs towards the top of G-01-1 (figure 6.1) and it is laterally extensive for at least 10 m on either side of the sampling site. The bryophyte peat layer is 0.24 m thick with numerous seeds of *Menyanthes trifoliata*, a perennial bog plant within the top few centimetres. Figure 6.10 describes the litho-stratigraphy in more detail, with depths relating to the top of the monolith. The sharp peat-silt boundary occurs approximately 4.90 m below current marsh surface and there is no evidence of any tsunami deposit.

6.5.1 Bio- and chrono-stratigraphy of G-01-1A

Preservation of diatoms throughout G-01-1A is very poor and so information on diatom changes through the peat-silt sequence is scarce. However, diatom data combined with pollen data (counted by Ian Shennan) allow an initial interpretation of relative sea-level movements (count summary is in appendix 5). Figures 6.11(a) and (b) show the changes in diatoms and pollen through G-01-1A, lithology and AMS dates.

Lithology changes from silt with herbaceous rootlets through to bryophyte peat at the base of this sequence. Cyperaceae, Poaceae and other marsh plants, for example, *Potentilla egedii* and *Triglochin maritima* dominate the assemblage at 39 cm but as peat develops, these species decline with *Sphagnum* species and *Myrica gale* increasing to a peak at 22 cm. This suggests a negative sea-level tendency (relative sea-level fall) throughout the peat. Within the top 2 cm of bryophyte peat, *Sphagnum* species and *Myrica gale* decrease together with an increase in more salt tolerant plants, for example *Potentilla egedii* and *Triglochin maritima*, suggesting a positive sea-level tendency (relative sea-level rise) immediately before the peat-silt boundary. Polyhalobous diatoms, for example *Delphineis surirella* and *Paralia sulcata* dominate the overlying silt (figure 6.11(a), zone b), indicating a rapid change from raised bog to one regularly inundated by the tide.

AMS dating of *Menyanthes trifoliata* seeds dates the top of the peat layer (20 cm) to 1951-2305 cal yr BP and a bulk peat sample dates the base (42 cm) to 3564-3864 cal yr BP (figures 6.3, 6.11 and appendix 3).

6.5.2 Numerical analysis – calibration of G-01-1A

Due to the lack of fossil diatom data, numerical analysis of G-01-1A only provides an estimate of ground height relative to m MHHW for samples found in the silt on either side of the peat. Calibration of the pollen data was not possible due to the lack of a contemporary pollen data set. Figure 6.12 shows the results of the four calibration models, individual reconstructions are in appendix 6 and tables 6.8 to 6.10 summarise the results. They highlight why the litho-stratigraphic constraint provides a logical method of deciding the best model (section 4.5). Environments indicated by the altitude reconstructions are from table 2.1.

Table 6.8 Summary of calibration results for G-01-1A using the full model

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Underlying silt	+0.17 ± 1.00 m MHHW to +0.56 ± 0.99 m MHHW	Low marsh
Overlying silt	-1.53 ± 0.98 m MHHW to -0.72 ± 0.98 m MHHW	Unvegetated mudflat

Table 6.9 Summary of calibration results for G-01-1A using the -0.5 m model

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Underlying silt	+0.87 ± 0.23 m MHHW to +1.20 ± 0.22 m MHHW	Low/mid to high marsh
Overlying silt	-0.12 ± 0.33 m MHHW to +0.02 ± 0.32 m MHHW	Upper tidal flat/marsh pioneer zone

Table 6.10 Summary of calibration results for G-01-1A using the two +1.0 m models

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Underlying silt	+1.15 ± 0.04 m MHHW to +1.29 ± 0.07 m MHHW	High marsh through to transition into raised bog
Overlying silt	Approximately +1.09 ± 0.03 m MHHW	Mid marsh

Table 6.11 describes the calibration models used to quantitatively reconstruct relative sea-level changes through G-01-1A following the litho-stratigraphic criteria explained in section 4.5. As the results using the +1.0 m MHHW and +1.0 hours inundated models are so similar, following sections only consider the +1.0 m MHHW model.

Table 6.11 Calibration models used to reconstruct RSL change in G-01-1A

Depth ranges (cm)	Model used	Reason
46 to 44 19 to 17	-0.5	Lithology indicates silt containing rootlets and so the -0.5 m model is appropriate
41	+1.0	Lithology indicates organic silty peat and so the +1.0 m MHHW model is most suitable

Figure 6.13 shows the results using MAT. It indicates four fossil samples (67%) have 'close' modern analogues and two (33%) have 'good' modern analogues within the contemporary Kenai data set, suggesting calibration results are reliable. Figure 6.14 shows the composite diagram of relative sea-level changes through G-01-1A, drawn using the models specified in table 6.11 (with no scaling, appendix 6).

6.5.3 Relative sea- and land-level changes through G-01-1A

As diatom data is scarce, these results provide a best estimate of quantitative changes through G-01-1A. At the base, there is a negative sea-level tendency from the underlying silt through to the development of peat. At Kenai, modern raised bog environments typically occur between +1.35 m MHHW and +1.57 m MHHW. The sharp upper contact of the peat with the overlying silt, together with dominance by polyhalobous diatoms, for example, *Delphineis surirella* (-1.13 ± 2.11 m), *Gyrosigma wansbeckii* (-1.38 ± 1.64 m) and *Paralia sulcata* (-0.93 ± 1.91 m) suggest a rapid positive sea-level tendency (relative sea-level rise). Reconstructed values estimate the new ground height to be -0.12 ± 0.33 m MHHW, representing upper tidal flat/marsh pioneer zone vegetation. Assuming peat forms at a similar altitude to that observed at Kenai, estimates of relative sea-level rise are between +1.47 ± 0.34 m and +1.69 ± 0.34 m (+1.87 ± 0.43 m to +2.15 ± 0.43 m with scaling factor).

6.5.4 Summary of G-01-1A

Relative sea-level movements through G-01-1A follow periods of the EDC model. The transition from tidal flat through to raised bog at the base of this sequence suggests a negative sea-level tendency and records the inter-seismic period of the EDC model. Immediately before the sharp peat-silt boundary, there is a pre-seismic relative sea-level rise evident from pollen analysis, followed by rapid co-seismic submergence approximately 1951-2305 cal yr BP. Following the event, diatoms suggest the start of a post-seismic period with a slight relative sea-level fall. The peat-silt boundary is also laterally extensive with evidence fulfilling three out of the five criteria set out by Nelson *et al.* (1996). There is no evidence of any tsunami deposit and chapter 8 investigates synchroneity. Comparisons to the 1964 (GW-8) and penultimate event (GW-6) recorded in G-800, indicate a similar amount of co-seismic submergence.

6.6 G-01-1C

The sharp peat-silt boundary in G-01-1C is located 0.64 m below the upper peat-silt boundary in G-01-1A and is approximately 5.55 m below contemporary marsh surface (figure 6.1). The 0.11 m thick peat layer contains abundant herbaceous rootlets, there is no evidence of any tsunami deposit and depths relate to the top of its monolith. Figure 6.15 illustrates the litho-stratigraphy of G-01-1C in more detail.

6.6.1 Bio- and chrono-stratigraphy of G-01-1C

Sampling intervals for diatom analysis varied from 1 to 2 cm through the peat layer and overlying silt. Figure 6.16 summarises the bio-stratigraphy of G-01-1C showing diatoms that account for at least 2% of all diatom valves counted, lithology and AMS dates (diatom count summary is in appendix 5). Zones produced during stratigraphically constrained cluster analysis aid in the description of diatom changes.

Zone A: 25.5 to 22 cm

Oligohalobous-indifferent diatoms dominate the silt unit in zone A, for example, *Cymbella ventricosa*, *Pinnularia borealis* and *Pinnularia mesolepta*. Normally, polyhalobous and mesohalobous species would dominate silt units but the slight increase in halophobous species, together with the change in stratigraphy from silt to peat suggests a negative sea-level tendency (relative sea-level fall).

Zone B: 22 to 12.5 cm

A mixture of mesohalobous, oligohalobous and halophobous diatoms dominate zone B, for example, *Hantzschia virgata*, *Nitzschia obtusa*, *Nitzschia pusilla*, *Eunotia exigua* and *Pinnularia subcapitata*. This suggests a negative sea-level tendency (relative sea-level fall) compared to zone A. Halophobous and oligohalobous-indifferent species peak at 14 cm, after which they start to decline. An increase in polyhalobous and mesohalobous diatoms, for example, *Delphineis surirella* and *Paralia sulcata* accompanies this change. This indicates a positive sea-level tendency (relative sea-level rise) immediately below the peat-silt boundary. The upper boundary of this zone represents a sudden change from herbaceous peat to silt containing no herbaceous rootlets.

Zone C: 12.5 to 10 cm

Polyhalobous diatoms dominate zone C, for example, *Actinoptychus senarius*, *Cocconeis peltoides*, *Delphineis surirella* and *Paralia sulcata*. The sudden change in diatom species, alongside the sharp boundary in-between the peat and silt suggests a rapid positive sea-level tendency (relative sea-level rise).

AMS dating of three bulk peat samples from G-01-1C suggests its formation approximately 3000 to 4000 cal yr BP (figures 6.3, 6.16 and appendix 3). The top of the peat (13 cm) dates to 3480-3827 cal yr BP, a sample from 14 cm dates to 2889-3207 cal yr BP and the base (23 cm) dates to 3689-3961 cal yr BP. The age reversal within this sequence requires re-dating of samples using *in situ* macrofossils.

6.6.2 Numerical analysis – calibration of G-01-1C

This section aims to analyse and quantify relative sea-level changes recorded by the bio-stratigraphy in figure 6.16 using the Kenai contemporary data. Figure 6.17 shows the calibration results using the full, -0.5 m, +1.0 m MHHW and +1.0 hours inundated models, individual values are in appendix 6 and tables 6.12 to 6.14 summarise the results. It emphasises how different the results are when using different calibration models and why the litho-stratigraphic constraint is suitable (section 4.5). The environments indicated by the altitude reconstructions are from table 2.1.

Table 6.12 Summary of calibration results for G-01-1C using the full model

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	+0.28 ± 1.11 m MHHW to +1.38 ± 0.95 m MHHW	Low marsh to raised bog
Overlying silt	-1.65 ± 0.99 m MHHW to -1.83 ± 0.99 m MHHW	Unvegetated mudflat

Table 6.13 Summary of calibration results for G-01-1C using the -0.5 m model

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	+1.29 ± 0.30 m MHHW to +1.49 ± 0.24 m MHHW	Transition zone into raised bog through to diverse raised bog
Overlying silt	+0.01 ± 0.38 m MHHW to +0.10 ± 0.38 m MHHW	Upper tidal flat/marsh pioneer zone

Table 6.14 Summary of calibration results for G-01-1C using the two +1.0 m models

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	+1.35 ± 0.16 m MHHW to +1.47 ± 0.09 m MHHW	Diverse raised bog environments
Overlying silt	+1.09 ± 0.03 m MHHW to +1.11 ± 0.07 m MHHW	Mid marsh

Table 6.15 shows the calibration models chosen to reconstruct relative sea level in different parts of G-01-1C using the litho-stratigraphic constraint (section 4.5). As the +1.0 m MHHW and +1.0 hours inundated models are so similar, following sections only consider the +1.0 m MHHW model.

Table 6.15 Calibration models used to reconstruct RSL change in different parts of G-01-1C

Depth ranges (cm)	Model used	Reason
25	-0.5	Lithology indicates silt containing rootlets and so the -0.5 m model is suitable
23 to 13	+1.0	Lithology indicates peat with abundant herbaceous rootlets. Therefore, the +1.0 m MHHW model is appropriate
12 to 10	Full	Lithology indicates silt with no rootlets. The full model is most appropriate as there is the possibility that deposition occurred below the limit of vegetation

Figure 6.18 shows the results from MAT. It suggests two fossil samples (15%) have 'poor' modern analogues, two (15%) have 'close' modern analogues and nine (70%) have 'good' modern analogues within the contemporary Kenai data set. The 'poor' analogue situations occur at 23 and 25 cm depth, at the regressive contact between the silt and peat. Reconstructions based on these samples may be less reliable.

Figure 6.19 is a composite diagram illustrating changes in predicted altitude (m) relative to MHHW for G-01-1C, drawn using the models described in table 6.15 (values are unscaled, appendix 6). Highlighted samples have 'poor' modern analogues, identified using figure 6.18. Table 6.16 quantitatively describes these changes using diatom data from figure 6.16, optima and tolerance of diatom species from figure 4.8 and appendix 1 with environmental reconstructions from table 2.1.

6.6.3 Relative sea- and land-level changes through G-01-1C

Quantitative reconstructions of relative sea-level change through G-01-1C suggest the peat-silt boundary may result from co-seismic submergence associated with a large earthquake. SLT phases A and B record a relative sea-level fall during the inter-seismic period of the EDC model, where strain accumulation at the plate boundary results in relative land uplift. Immediately before the event, there is a possible pre-seismic relative sea-level rise (SLT phase C) of +0.06 ± 0.14 m.

Table 6.16 Description of relative sea-level changes through G-01-1C

SLT Phase	Depth (cm)	Lithology	Brief summary (including optima and tolerance, *u*±*t* of diatom species)	Sea-level tendency	Quantitative reconstructions (no scaling)	Quantitative reconstructions (with scaling)	Environmental reconstruction
A	25 to 22	Transition from silt with herbaceous rootlets to herbaceous peat	Oligohalobous-indifferent diatoms dominate throughout SLT phase A, for example, *Pinnularia microstauron* (+1.31 ± 0.29 m). Halophobes increase slightly towards the top, for example, *Pinnularia subcapitata* (+1.51 ± 0.07 m) and *Tabellaria fenestrata* (+1.35 ± 0.70 m)	Negative	RSL fall of -0.30 ± 0.36 m to a new ground height of +1.47 ± 0.09 m MHHW	RSL fall of -0.38 ± 0.45 m	High marsh to raised bog
B	22 to 13.5	Herbaceous peat	Halophobous taxa dominate this phase (e.g. *Eunotia exigua*, +1.49 ± 0.10 m; *Pinnularia subcapitata*, +1.51 ± 0.07 m)	Stable	RSL is stable with the land lying at approximately +1.44 ± 0.09 m MHHW	RSL is stable at approximately +1.83 ± 0.11 m MHHW	Raised bog
C	13.5 to 12.5	Top 1 cm of herbaceous peat. Sharp upper contact with overlying silt	Halophobes decline (e.g. *Eunotia exigua*, +1.49 ± 0.10 m) and more salt tolerant species increase (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Paralia sulcata*, -0.93 ± 1.91 m; *Nitzschia obtusa*, +1.14 ± 0.29 m)	Positive or mixing	RSL rise of +0.06 ± 0.14 m to a new ground height of +1.39 ± 0.12 m MHHW	RSL rise of +0.08 ± 0.18 m	Raised bog
D	12.5 to 9.5	Grey silt with no rootlets	SLT phase D is characterised by a rapid increase in polyhalobous species, for example, *Actinoptychus senarius* (-1.31 ± 1.90 m), *Cocconeis peltoides* (-1.04 ± 1.75 m), *Delphineis surirella* (-1.13 ± 2.11 m) and *Paralia sulcata* (-0.93 ± 1.91 m)	Positive	Using the full model, RSL rises by +3.22 ± 1.00 m to a new ground height of -1.83 ± 0.99 m MHHW. Using the -0.5 model, RSL rises by +1.38 ± 0.40 m to a new ground height of +0.01 ± 0.38 m MHHW	Using the full model, RSL rises by +4.09 ± 1.27 m. Using the -0.5 model, RSL rises by +1.75 ± 0.50 m.	Unvegetated mudflat to upper tidal flat/marsh pioneer zone

Application of the scaling factor produces a pre-seismic relative sea-level rise of +0.08 ± 0.18 m. However, diatom evidence suggests that this assemblage may also be the result of mixing.

Evidence from the peat-silt boundary in G-01-1C fulfils three of the five criteria described by Nelson *et al.* (1996). It is laterally extensive and the sharp upper boundary suggests sudden, large submergence of a freshwater environment into the intertidal zone. Therefore, the rapid change from peat to silt in SLT phase D indicates rapid co-seismic submergence approximately 3480-3827 cal yr BP. As the overlying silt contains no rootlets the full model is best, but this represents the maximum amount of submergence associated with this event. Quantitative reconstructions indicate a relative sea-level rise of +3.22 ± 1.00 m. Applying the scaling factor to this value represents co-seismic submergence of +4.09 ± 1.27 m. This estimate is far larger than for any other event at Girdwood, but using the full model affects this reconstruction. As discussed in section 4.4.3 the full model contains many limitations due to the lack of trend over a large altitudinal range. The -0.5 m model estimates co-seismic submergence to be +1.38 ± 0.40 m (+1.75 ± 0.50 m with scaling). Submergence of this magnitude compares directly to that experienced in 1964 at Girdwood (GW-8).

6.6.4 Summary of G-01-1C

In summary, relative sea- and land-level changes through G-01-1C record periods of the EDC model and tendencies are directly comparable to the 1964 event. Using the full model, the magnitude of co-seismic submergence appears larger, suggesting a larger earthquake or a different pattern of deformation. However, the -0.5 m model produces co-seismic submergence that is directly comparable to the amount experienced in 1964.

6.7 G-01-1E

The sharp peat-silt boundary in G-01-1E occurs 0.89 m below the upper peat-silt boundary in G-01-1A and is 5.80 m below contemporary marsh surface. The herbaceous peat layer is 0.12 m thick, there is no evidence of any tsunami deposit and figure 6.20 illustrates the litho-stratigraphy in more detail. Depths relate to the peat-silt boundary in G-01-1A because sampling took place from an open exposure of this peat that formed a shelf on the side of a channel.

6.7.1 Bio- and chrono-stratigraphy of G-01-1E

Sampling intervals for diatom analysis varied from 1 to 4 cm (diatom count information is in appendix 5). Figure 6.21 summarises the bio-stratigraphy of G-01-1E, showing diatoms that account for at least 2% of all diatom valves counted, lithology and AMS dates. Following sections describe the bio-stratigraphy using zones produced during stratigraphically constrained cluster analysis.

Zone A: 101.5 to 89.5 cm

A mixture of polyhalobous, mesohalobous and oligohalobous diatoms dominate the assemblage at 101 cm, for example, *Delphineis surirella* and *Nitzschia fruticosa*. Above this level, polyhalobous, mesohalobous and oligohalobous-halophile diatoms decline, together with an associated increase in oligohalobous-indifferent and halophobous species. Dominant taxa include *Cymbella ventricosa*, *Frustulia vulgaris*, *Nitzschia palustris* and *Pinnularia mesolepta*. Halophobous diatoms (e.g. *Eunotia exigua* and *Tabellaria fenestrata*) peak at 91 cm. The change from polyhalobous diatoms through to halophobous species, together with the change in lithology from silt to peat suggests a negative sea-level tendency (relative sea-level fall). At 90 cm, halophobous and oligohalobous-indifferent diatoms decrease and polyhalobous species increase, suggesting a positive sea-level tendency (relative sea-level rise) at the top of this zone, 1 cm below the peat-silt boundary. The increase in silt between 96.5 and 93.5 cm does not significantly alter diatom assemblages but later sections quantify this.

Zone B: 89.5 to 69.5 cm

Halophobous diatoms dominate the base of this zone, in particular, *Tabellaria fenestrata* and *Tabellaria flocculosa*, indicating a negative sea-level tendency (relative sea-level fall) compared to zone A. Above 88 cm, they start to decline together with the introduction of oligohalobous, mesohalobous and polyhalobous diatoms. This suggests a gradual positive sea-level tendency (relative sea-level rise) towards the top. Changes in bio-stratigraphy record a negative sea-level tendency across the stratigraphic boundary but normally, the sudden change from peat to silt at 88.5 cm would represent a rapid positive sea-level tendency.

Two AMS dates from G-01-1E dates the top of the peat (89 cm) to 3212-3634 cal yr BP and its base (98 cm) to 3724-4076 cal yr BP (figures 6.3 and appendix 3).

6.7.2 Numerical analysis – calibration of G-01-1E

This section aims to analyse and quantify relative sea-level changes recorded by the bio-stratigraphy in figure 6.21 using the Kenai contemporary data. Figure 6.22 shows the calibration results using the full, -0.5 m, +1.0 m MHHW and +1.0 hours inundated models and emphasises why a litho-stratigraphic criteria is needed to decide the best model. Individual results are in appendix 6, tables 6.17 to 6.19 summarise the results with environments indicated by the altitude reconstructions from table 2.1.

Table 6.17 Summary of calibration results for G-01-1E using the full model

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	-0.17 ± 0.96 m MHHW to +1.01 ± 0.99 m MHHW	Upper tidal flat/marsh pioneer zone through to mid marsh
Overlying silt	+0.59 ± 0.96 m MHHW to +1.29 ± 0.94 m MHHW	Low marsh through to transition into raised bog

Table 6.18 Summary of calibration results for G-01-1E using the -0.5 m model

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	+0.92 ± 0.27 m MHHW to +1.46 ± 0.29 m MHHW	Low/mid marsh to raised bog
Overlying silt	+1.58 ± 0.38 m MHHW, decreasing to +1.11 ± 0.33 m MHHW	Diverse raised bog through to mid marsh

Table 6.19 Summary of calibration results for G-01-1E using the two +1.0 m models

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	+1.27 ± 0.07 m MHHW to +1.48 ± 0.07 m MHHW	Transition into raised bog through to fully developed raised bog
Overlying silt	+1.55 ± 0.13 m MHHW to +1.41 ± 0.11 m MHHW	Raised bog

Table 6.20 shows the calibration models chosen to reconstruct relative sea level in different parts of G-01-1E using the established litho-stratigraphic criteria (section 4.5).

Table 6.20 Calibration models used to reconstruct RSL change in G-01-1E

Depth ranges (cm)	Model used	Reason
101 70 to 88	-0.5	Lithology indicates silt containing rootlets and so the -0.5 m model is appropriate
89 to 99	+1.0	Lithology indicates peat and so the +1.0 m MHHW model is most suitable

Figure 6.23 illustrates the results using MAT. It suggests three of the fossil samples (20%) have 'poor' modern analogues, ten (67%) have 'close' modern analogues and only two (13%) have 'good' modern analogues when compared to the contemporary Kenai data. A problem arises from silt containing freshwater diatoms, particularly, *Tabellaria* species that live in contemporary raised bog conditions at Kenai. No contemporary Kenai environment is similar.

Figure 6.24 is a composite diagram of relative sea-level change through G-01-1E drawn using the models specified in table 6.20 (with no scaling, appendix 6). Samples highlighted in red have 'poor' modern analogues, identified using figure 6.23. Table 6.21 quantitatively describes these results using diatom data from figure 6.21, species optima and tolerances from figure 4.8 and appendix 1 and environmental reconstructions from table 2.1.

6.7.3 Relative sea- and land-level changes through G-01-1E

Relative sea-level movements surrounding the peat-silt boundary in G-01-1E are confusing in that they do not fit with the pattern observed in other peat-silt couplets or with the EDC model. The relative sea-level fall recorded in SLT phase A may represent the inter-seismic period of the EDC model where strain accumulation at the plate boundary results in relative land uplift.

Table 6.21 Description of relative sea-level changes through G-01-1E

SLT Phase	Depth (cm)	Lithology	Brief summary (including optima and tolerance, *u±t* of diatom species)	Sea-level tendency	Quantitative reconstructions (no scaling)	Quantitative reconstructions (with scaling)	Environmental reconstruction
A	101 to 98	Transition from silt with herbaceous rootlets to herbaceous peat	Polyhalobous species dominate at the base of SLT phase A (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Paralia sulcata*, -0.93 ± 1.91 m) and oligohalobous-indifferent taxa dominate at the top	Negative	RSL fall of -0.71 ± 0.29 m to a ground height of +1.45 ± 0.09 m MHHW	RSL fall of -0.90 ± 0.38 m	Low marsh to raised bog
B	98 to 88.5	Herbaceous peat	Oligohalobous-indifferent diatoms dominate throughout this phase with halophobous diatoms increasing towards the top (e.g. *Tabellaria fenestrata*, +1.35 ± 0.70 m; *Tabellaria flocculosa*, +1.32 ± 1.18 m). Polyhalobous species increase slightly at 90 cm (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Paralia sulcata*, -0.93 ± 1.91 m)	Stable	Reconstructed altitudes range from +1.34 ± 0.07 m MHHW to +1.48 ± 0.07 m MHHW	RSL is stable	Raised bog
C	88.5 to 69.5	Silt with herbaceous rootlets	Halophobes dominate the diatom assemblage immediately above the peat-silt contact, particularly, *Tabellaria flocculosa* (+1.32 ± 1.18 m) and *Tabellaria fenestrata* (+1.35 ± 0.70 m). Above 86 cm halophobes decline and more salt tolerant species increase, for example, *Nitzschia obtusa* (+1.14 ± 0.29 m) and *Pinnularia lagerstedtii* (+1.38 ± 0.12 m)	Negative followed by positive	Initial RSL fall of -0.10 ± 0.39 to a new ground height of +1.58 ± 0.38 m MHHW followed by RSL rise of +0.47 ± 0.50 m to a new ground height of +1.11 ± 0.33 m MHHW	Initial RSL fall of -0.13 ± 0.49 m followed by RSL rise of +0.60 ± 0.64 m	Raised bog through to mid marsh

The sharp boundary in-between the peat and silt at 88.5 cm, dating to approximately 3212-3634 cal yr BP, usually indicates a rapid relative sea-level rise. Within the overlying silt, SLT phase C records an initial relative sea-level fall of -0.10 ± 0.39 m followed by a relative sea-level rise of +0.47 ± 0.50 m (with scaling, this is equivalent to a RSL fall of -0.13 ± 0.49 m followed by a RSL rise of +0.60 ± 0.64 m). *Tabellaria* species dominate the silt, but in the contemporary Kenai environment they are indicative of freshwater pools found towards the upper limits of the contemporary Kenai transect. It is hard to envisage a contemporary environment where freshwater diatoms are living in silt and until we find a similar contemporary assemblage, it is difficult to establish whether this peat-silt boundary results from co-seismic submergence. We have searched for such an assemblage, but to date, nothing similar exists. These assemblages are very similar to those found at the base of G-01-1C (figure 6.16), at 159 cm in G-01-1F (figure 6.26) and in the overlying silt of G-01-9 (figure 6.31). Section 6.10.2 investigates these assemblages further.

6.7.4 Summary of G-01-1E

To summarise, the litho-stratigraphy of G-01-1E is the same as other buried peats in G-01-1 but the diatom assemblages surrounding the peat-silt boundary are different. It is laterally extensive and on visual inspection indicates a large, rapid submergence event. A possible inter-seismic period is identifiable before the major change in stratigraphy from peat to silt but because the diatoms contained within the overlying silt are halophobes rather than marine, it indicates that this stratigraphic boundary probably does not result from co-seismic submergence. It more likely results from non-seismic processes, such as a glacial outburst flood or a change in the hydro-dynamics of the estuary but its origin is inconclusive.

6.8 G-01-1F

The sharp peat-silt boundary in G-01-1F occurs 1.47 m below the upper peat-silt boundary in G-01-1A (to which measurements refer) and is 6.38 m below present marsh surface. The peat layer is 0.13 m thick and there is no evidence of any tsunami deposit. Figure 6.25 illustrates the litho-stratigraphy of G-01-1F in more detail.

6.8.1 Bio- and chrono-stratigraphy of G-01-1F

Sampling intervals for diatom analysis varied from 1 to 4 cm. Figure 6.26 summarises the bio-stratigraphy of G-01-1F showing diatoms that account for at least 2% of all diatom valves counted, lithology and AMS dates (diatom count summary is in appendix 5). Zones produced during stratigraphically constrained cluster analysis aid in the description of diatom changes.

Zone A: 167.5 to 161 cm

Polyhalobous, mesohalobous and oligohalobous diatoms dominate the base of zone A, for example, *Paralia sulcata* and *Navicula salinarum*. Towards the top, oligohalobous-indifferent species increase together with the introduction of halophobous taxa suggesting a slight negative sea-level tendency (relative sea-level fall).

Zone B: 161 to 158 cm

Halophobous diatoms, in particular, *Tabellaria flocculosa* dominate zone B, peaking at 159 cm. This suggests a continued negative sea-level tendency at the transition from silt to peat. This one assemblage is similar to those found in the overlying silt in G-01-1E (figure 6.21).

Zone C: 158 to 146.5 cm

Zone C occurs within the herbaceous/bryophyte peat layer. Oligohalobous indifferent diatoms dominate, for example, *Nitzschia fruticosa* and *Nitzschia pusilla*. Halophobous diatoms (e.g. *Eunotia exigua*, *Pinnularia subcapitata* and *Tabellaria flocculosa*) peak at 153 and 148 cm, indicating a negative sea-level tendency (relative sea-level fall). Polyhalobous species (e.g. *Cocconeis peltoides* and *Paralia sulcata*) start to increase at 151 cm suggesting a positive sea-level tendency (relative sea-level rise) towards the top of the peat. The sudden change in lithology from peat to silt with herbaceous rootlets marks the top of this zone.

Zone D: 146.5 to 144 cm

There is a sudden change in diatom assemblages compared to zone C. Polyhalobous diatoms dominate, for example, *Cocconeis peltoides*, *Delphineis surirella* and *Paralia sulcata*, and the more salt intolerant species decline. This change in bio-stratigraphy, together with the sudden change from peat to silt with herbaceous rootlets represents a rapid positive sea-level tendency (relative sea-level rise).

Radiocarbon dates from G-01-1F are problematic as they show age reversals. The top of the peat (147 cm) dates to 4298-4784 cal yr BP, 153 cm dates to 3212-3464 cal yr BP and its base (157 cm) dates to 4254-4525 cal yr BP (figure 6.3 and appendix 3). Re-dating *in situ* macrofossils can help solve these problems.

6.8.2 Numerical analysis – calibration of G-01-F

This section aims to analyse and quantify relative sea-level changes recorded by the bio-stratigraphy of G-01-1F using the Kenai contemporary data. Figure 6.27 shows the calibration results using the full, -0.5 m, +1.0 m MHHW and +1.0 hours inundated models, individual results are in appendix 6 and tables 6.22 to 6.24 summarise them.

Table 6.22 Summary of calibration results for G-01-1F using the full model

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	+0.60 ± 0.96 m MHHW to +1.12 ± 0.94 m MHHW	Low to mid/high marsh
Overlying silt	-1.47 ± 0.97 m MHHW to -0.24 ± 0.95 m MHHW	Unvegetated mudflat through to upper tidal flat/marsh pioneer zone

Table 6.23 Summary of calibration results for G-01-1F using the -0.5 m model

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	+1.08 ± 0.23 m MHHW to +1.50 ± 0.23 m MHHW	Mid marsh through to diverse raised bog
Overlying silt	+0.58 ± 0.27 m MHHW, decreasing to +0.02 ± 0.32 m MHHW	Low marsh through to upper tidal flat/marsh pioneer zone

Table 6.24 Summary of calibration results for G-01-1F using the two +1.0 m models

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	+1.26 ± 0.06 m MHHW to +1.47 ± 0.07 m MHHW	High marsh through to diverse raised bog
Overlying silt	+1.23 ± 0.07 m MHHW, decreasing to +1.08 ± 0.03 m MHHW	High to mid marsh

Table 6.25 shows the calibration models most suitable for reconstructing RSL change in different parts of G-01-1F, based on the established litho-stratigraphic criteria (section 4.5).

Table 6.25 Calibration models used to reconstruct RSL change in G-01-1F

Depth ranges (cm)	Model used	Reason
163 to 167 144 to 146	-0.5	Lithology indicates silt containing herbaceous rootlets and so the -0.5 m model is most suitable
147 to159	+1.0	Lithology indicates peat and so the +1.0 m MHHW model is appropriate

Figure 6.28 shows the results from MAT. It suggests seven fossil samples (54%) have 'close' modern analogues and six (46%) have 'good' modern analogues. Therefore, calibration results should provide reliable reconstructed altitudes.

Figure 6.29 represents relative sea-level changes through G-01-1F drawn using table 6.25 (with no scaling, appendix 6). Table 6.26 quantitatively describes these changes using diatom data in figure 6.26, species optima and tolerances in figure 4.8 and appendix 1 and environmental reconstructions from table 2.1.

6.8.3 Relative sea- and land-level changes through G-01-1F

SLT phase A records a relative sea-level fall that represents the inter-seismic period of the EDC model where strain accumulation at the plate boundary results in relative land uplift. At the top of SLT phase B, immediately before the peat-silt boundary, there is a possible pre-seismic relative sea-level rise of +0.12 ± 0.09 m (+0.15 ± 0.13 m with scaling). The boundary between SLT phases B and C is a rapid stratigraphic change between peat and overlying silt with herbaceous rootlets. The sudden change from raised bog to one regularly inundated by the tide indicates co-seismic submergence of +1.33 ± 0.33 m (+1.69 ± 0.42 m with scaling) approximately 4298-4784 cal yr BP. The peat-silt boundary is also laterally extensive and so it fulfils three out of the five criteria set out by Nelson *et al.* (1996). Chapter 8 investigates synchroneity of submergence.

Table 6.26 Description of relative sea-level changes through G-01-1F

SLT Phase	Depth (cm)	Lithology	Brief summary (including optima and tolerance, *u±t* of diatom species)	Sea-level tendency	Quantitative reconstructions (no scaling)	Quantitative reconstructions (with scaling)	Environmental reconstruction
A	167.5 to 158	Transition from silt with herbaceous rootlets to silty peat	Polyhalobous diatoms decline (e.g. *Paralia sulcata*, -0.93 ± 1.91 m; *Cocconeis peltoides*, -1.04 ± 1.75 m) and halophobous taxa increase at 159 cm (e.g. *Tabellaria flocculosa*, +1.32 ± 1.18 m). This occurs at the transition into silty peat and so may represent redeposition	Negative	RSL fall of -0.63 ± 0.24 m to a ground height of +1.46 ± 0.08 m MHHW	RSL fall of -0.80 ± 0.31 m	Low/mid marsh to raised bog
B	158 to 146.5	Silty peat to bryophyte peat. Sharp upper contact with overlying silt	Oligohalobous-indifferent diatoms dominate throughout this phase (e.g. *Nitzschia fruticosa*, +1.31 ± 0.16 m; *Nitzschia pusilla*, +1.36 ± 0.19 m). Halophobe diatoms (e.g. *Tabellaria flocculosa*, +1.32 ± 1.18 m) peak at 153 cm and 148 cm but decline within the top 2 cm of peat. Polyhalobous diatoms start to increase at 151 cm (e.g. *Cocconeis peltoides*, -1.04 ± 1.75 m; *Delphineis surirella*, -1.13 ± 2.11 m)	Oscillating	RSL is oscillating between +1.30 ± 0.07 m MHHW and +1.47 ± 0.08 m MHHW. Above 153 cm, RSL generally rises by +0.12 ± 0.09 m to a new ground height of +1.35 ± 0.07 m MHHW	RSL is oscillating followed by a RSL rise of +0.15 ± 0.13 m	Raised bog and transition into raised bog
C	146.5 to 143.5	Silt with herbaceous rootlets	Polyhalobous diatoms (e.g. *Cocconeis peltoides*, -1.04 ± 1.75 m; *Delphineis surirella*, -1.13 ± 2.11 m; *Paralia sulcata*, -0.93 ± 1.91 m) dominate SLT phase C	Positive	RSL rise of +1.33 ± 0.33 m to a ground height of +0.02 ± 0.32 m MHHW	RSL rise of +1.69 ± 0.42 m	Upper tidal flat/marsh pioneer zone

6.8.4 Summary of G-01-1F

Quantitative reconstructions of G-01-1F suggest the peat-silt boundary results from co-seismic submergence. The figures are slightly less than those estimated for the 1964 event in G-800, indicating that the earthquake was slightly smaller in magnitude or had a different pattern of deformation.

6.9 G-01-9

The sampling site for G-01-9 was a bank section exposed at the far western side of Girdwood marsh during low tide (figure 6.2). Combellick and Reger (1994) found four buried peat layers with sharp upper contacts at this site and dated the top of the peat studied here to 1823-2114 cal yr BP. We only sampled one of these peat layers because it was the only one fully exposed and the bank section was too dangerous to clean. The 0.10 m thick herbaceous peat layer has a sharp upper boundary with the overlying silt, which occurs approximately 3.97 m below present marsh surface. Figure 6.30 illustrates the litho-stratigraphy of G-01-9 in more detail with depths relating to the top of the monolith. There is no evidence of any tsunami deposit.

6.9.1 Bio- and chrono-stratigraphy of G-01-9

Sampling intervals for diatom analysis varied from 1 to 3 cm. Figure 6.31 summarises the bio-stratigraphy of G-01-9 showing diatoms that account for at least 2% of all diatom valves counted, lithology and AMS dates (diatom count summary is in appendix 5). Following sections describe zones produced during stratigraphically constrained cluster analysis.

Zone A: 21.5 to 15.5 cm

Throughout this zone, there is a decrease in polyhalobous, mesohalobous and oligohalobous-halophile species (e.g. *Navicula cari* var. *cincta*) and an increase in oligohalobous-indifferent and halophobous diatoms (e.g. *Eunotia lunaris* and *Pinnularia lagerstedtii*). These changes, alongside the transition from silt to peat suggest a negative sea-level tendency (relative sea-level fall).

Zone B: 15.5 to 10.5 cm

Oligohalobous-indifferent and halophobous diatoms dominate zone B (e.g. *Pinnularia mesolepta, Eunotia exigua* and *Tabellaria fenestrata*). Halophobes peak at 11 cm suggesting a continued negative sea-level tendency (relative sea-level fall). The top of this zone is 1 cm below the sharp peat-silt boundary.

Zone C: 10.5 to 5.5 cm

Salt tolerant species increase slightly at the base of this zone (e.g. *Nitzschia obtusa*) but halophobous and oligohalobous-indifferent diatoms continue to dominate in the overlying silt (e.g. *Tabellaria flocculosa*). The peat-silt boundary occurs at 9.5 cm.

Radiocarbon dating of the top (10 cm) and base (19 cm) of the peat in G-01-9 give ages of 1903-2144 cal yr BP and 2745-2917 cal yr BP respectively (figure 6.3 and appendix 3). The age of burial corresponds to that of Combellick and Reger (1994) who dated the top to 1823-2114 cal yr BP but they date the top of a lower peat with a gradational upper contact (found 1.33 m below) to 2479-2847 cal yr BP.

6.9.2 Numerical analysis – calibration of G-01-9

This section aims to analyse and quantify relative sea-level changes recorded by the bio-stratigraphy of G-01-9 using the Kenai contemporary data. Figure 6.32 shows calibration results using the full, -0.5 m, +1.0 m MHHW and +1.0 hours inundated models and emphasises why a litho-stratigraphic constraint is required when choosing the most appropriate model (section 4.5). Reconstructed values are in appendix 6 and tables 6.27 to 6.29 summarise the results with the environments indicated by the altitude reconstructions from table 2.1.

Table 6.30 shows the most suitable calibration model used to reconstruct relative sea level change for G-01-9 based on the established litho-stratigraphic criteria (section 4.5).

Figure 6.33 shows the results using MAT. It indicates five samples (56%) have 'poor' modern analogues, two (22%) have 'close' modern analogues and two (22%) have 'good' modern analogues within the Kenai contemporary data set. The main reason for this 'poor' analogue situation is silt containing freshwater diatoms and so reconstructions using this data may contain a degree of error. As noted in earlier sections, no similar Kenai contemporary assemblage exists.

Figure 6.34 is a composite diagram representing relative sea-level changes through G-01-9, drawn using the models specified in table 6.30 (with no scaling, appendix 6). Table 6.31 quantitatively describes these changes in detail using diatom data from figure 6.31, species optima and tolerances from figure 4.8 and appendix 1 and environmental reconstructions from table 2.1.

Table 6.27 Summary of calibration results for G-01-9 using the full model

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	+0.42 ± 0.97 m MHHW to +1.02 ± 0.94 m MHHW	Low to mid marsh
Overlying silt	+0.68 ± 1.01 m MHHW to -0.50 ± 1.11 m MHHW	Low marsh to unvegetated mudflat

Table 6.28 Summary of calibration results for G-01-9 using the -0.5 m model

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	+1.18 ± 0.22 m MHHW to +1.58 ± 0.27 m MHHW	High marsh through to diverse raised bog
Overlying silt	+1.39 ± 0.29 m MHHW, decreasing to +1.16 ± 0.35 m MHHW	Raised bog through to high marsh

Table 6.29 Summary of calibration results for G-01-9 using the two +1.0 m models

Lithological unit	Altitude reconstruction (m)	Environment indicated by the altitude reconstructions
Peat	+1.23 ± 0.06 m MHHW to +1.53 ± 0.12 m MHHW	High marsh through to diverse raised bog
Overlying silt	+1.44 ± 0.11 m MHHW to +1.49 ± 0.08 m MHHW	Raised bog

Table 6.30 Calibration models used to reconstruct RSL change in G-01-9

Depth ranges (cm)	Model used	Reason
21 9 to 6	-0.5	Lithology indicates silt containing herbaceous rootlets and so the -0.5 m model is most suitable
19 to 10	+1.0	Lithology indicates peat and so the +1.0 m MHHW model is appropriate

Table 6.31 Description of relative sea-level changes through G-01-9

SLT Phase	Depth (cm)	Lithology	Brief summary (including optima and tolerance, *u±t* of diatom species)	Sea-level tendency	Quantitative reconstructions (no scaling)	Quantitative reconstructions (with scaling)	Environmental reconstruction
A	21.5 to 12.5	Transition from silt with herbaceous rootlets to herbaceous peat	Oligohalobous-indifferent diatoms dominate SLT phase A (e.g. *Nitzschia pusilla*, +1.36 ± 0.19 m; *Pinnularia lagerstedtii*, +1.38 ± 0.12 m). Salt tolerant diatoms decrease (e.g. *Navicula cari* var. *cincta*, +0.20 ± 1.45 m) and halophobous species increase towards the top (e.g. *Pinnularia subcapitata*, +1.51 ± 0.07 m)	Negative	RSL fall of -0.43 ± 0.23 m to a new ground height of +1.52 ± 0.08 m MHHW	RSL fall of -0.55 ± 0.30 m	Mid marsh to raised bog
B	12.5 to 9.5	Herbaceous peat	Oligohalobous-indifferent taxa (e.g. *Eunotia lunaris*, +1.46 ± 0.40 m; *Pinnularia lagerstedtii*, +1.38 ± 0.12 m) and halophobous species dominate (e.g. *Eunotia exigua*, +1.49 ± 0.10 m; *Tabellaria flocculosa*, +1.32 ± 1.18 m). Polyhalobous species increase slightly (e.g. *Paralia sulcata*, -0.93 ± 1.91 m)	Positive	RSL rise of +0.10 ± 0.11 m to a new ground height of +1.42 ± 0.07 m MHHW	RSL rise of +0.13 ± 0.13 m	Raised bog
C	9.5 to 5.5	Silt with herbaceous rootlets	Oligohalobous-indifferent and halophobous species dominate the silt unit, particularly *Tabellaria flocculosa* (+1.32 ± 1.18 m). Halophobes decline towards the top	Positive	RSL rise of +0.26 ± 0.36 m to a new ground height of +1.16 ± 0.35 m MHHW	RSL rise of +0.33 ± 0.45 m	Raised bog to high marsh

6.9.3 Relative sea- and land-level movements of G-01-9

SLT phase A indicates a relative sea-level fall through the transition from silt to peat which could represent the inter-seismic period of the EDC model where strain accumulation at the plate boundary results in relative land uplift. Towards the top of the peat unit, SLT phase B records a relative sea-level rise of +0.10 ± 0.11 m, which could suggest a pre-seismic relative sea-level rise. Applying the scaling factor to this value produces a relative sea-level rise of +0.13 ± 0.13 m.

SLT phase C is very similar to that found above the peat-silt boundary in G-01-1E. Across the laterally extensive peat-silt boundary (1903-2144 cal yr BP), quantitative reconstructions indicate a relative sea-level rise of +0.26 ± 0.36 m (+0.33 ± 0.45 m with scaling). The sharp peat-silt boundary normally indicates a rapid change from raised bog through to an environment regularly inundated by the tide. However, halophobous diatoms dominate the overlying silt.

6.9.4 Summary of G-01-9

Relative sea-level changes around the peat-silt boundary in G-01-9 are similar to those recorded in G-01-1E and section 6.10.2 considers possible explanations in detail. Inter-seismic and pre-seismic periods are identifiable before the peat-silt boundary, but it is unlikely that co-seismic submergence is responsible for the burial of the peat layer. If this were the case, the overlying silt would contain marine diatoms. Its burial is more likely due to a non-seismic process such as changes in the hydro-dynamics of the estuary.

6.10 Summary of Girdwood events

Multiple buried peat-silt couplets at Girdwood record a history of great earthquakes to affect the upper Cook Inlet area and table 6.32 summarises each one. Section 6.10.1 investigates evidence of co-seismic submergence where as section 6.10.2 investigates the peat-silt boundaries in G-01-1E and G-01-9, where the overlying silt contains freshwater diatoms. Events are given names to facilitate comparisons between sites in chapter 8.

Table 6.32 Summary of possible events at Girdwood

All values are scaled with +ve signs suggesting a relative sea-level rise and –ve signs suggesting a relative sea-level fall

Description	Event name	EDC related	Date at contact (cal yr BP)	Pre-seismic RSL change (m)	Co-seismic RSL change (m)	Sharpness of boundary (Troels-Smith)	Lateral extent	Post/inter-seismic recovery (m) and sediment accumulation
G-800 1964 event	GW-8	Yes	1964 AD	+0.17 ± 0.13	+1.97 ± 0.42	4	>1 km	-1.82 ± 0.50
G-800 oscillation in upper peat	GW-7	?	1954 AD to 1350-1517	Not identified	+0.22 ± 0.13	Increase in silt content	>50 m	-0.18 ± 0.13
G-800 lower peat-silt boundary	GW-6	Yes	1182-1345 (or ~800)	+0.13 ± 0.13	+1.74 ± 0.56	4	>1 km	-1.99 ± 0.56
G-01-1A	GW-4	Yes	1951-2305	Yes, in pollen changes	+1.87 ± 0.43 to +2.15 ± 0.43	4	>50 m	Not investigated
G-01-1C	GW-3	Yes	3480-3827	+0.08 ± 0.18 (may be mixing)	+1.75 ± 0.50 to +4.09 ± 1.27	4	>50 m	Not investigated
G-01-1E	GW-2	No	3212-3634	No	-0.13 ± 0.49	4	>50 m	Not investigated
G-01-1F	GW-1	Yes	4298-4784	+0.15 ± 0.13	+1.69 ± 0.42	4	>50 m	Not investigated
G-01-9	GW-5	No	1903-2144	+0.13 ± 0.13	+0.33 ± 0.45	4	>200 m	Not investigated

6.10.1 Evidence of great earthquakes to affect Girdwood

The two peat silt boundaries in G-800, the 1964 (GW-8) event and penultimate event (GW-6) record characteristic relative sea-level movements associated with the EDC model and fulfil at least three out of the five criteria described by Nelson *et al.* (1996). In addition, the relative sea-level oscillation in SLT phase F (GW-7) may be the result of small co-seismic submergence. At greater depths below the marsh surface, similar relative sea-level movements surround the peat layers in G-01-1A (GW-4), G-01-1C (GW-3) and G-01-1F (GW-1). Table 6.32 compares relative sea-level movements for each peat-silt boundary.

Table 6.32 shows the magnitudes of pre- and co-seismic movements are similar for four events (GW-8, GW-6, GW-4, GW-1) indicating a similar size earthquake. If they were synchronous at other sites, it would suggest the same spatial pattern of deformation (see chapter 8). The estimate of co-seismic submergence is greater in G-01-1C (GW-3), but this could reflect the use of the full model rather than the -0.5 m model to reconstruct altitude in overlying silt units. It was not possible to quantitatively estimate the magnitude of pre-seismic relative sea-level rise in G-01-1A due to the absence of diatoms within the peat unit and lack of a contemporary pollen data set.

Other possible explanations for these relative sea-level movements include changes in eustatic sea-level rise, isostatic adjustments and local processes. Models of eustatic sea-level rise indicate a slow down in the release of water to the oceans approximately 4000 cal yr BP. Between 7000 and 4000 cal yr BP eustatic relative sea-level rise was between 1.03 $mmyr^{-1}$ and 1.23 $mmyr^{-1}$, and from 4000 cal yr BP to the present day it was between 0.35 $mmyr^{-1}$ and zero (Fleming *et al.*, 1998; Peltier, 1998). The slow down, at approximately 4000 cal yr BP could account for the formation of peat in some of the peat-silt couplets rather than post-seismic and inter-seismic uplift of the land.

Changes in hyrdo- and glacio-isostatic processes, for example, advance of surrounding glaciers could also account for some of the relative sea-level movements (e.g. GW-7). However, the fluctuations would be smaller and more gradual than the rapid movements observed for most of the peat-silt boundaries at Girdwood. Other possible explanations include variations in local processes. As the direction and magnitude of relative sea-level changes are similar to the 1964 event, it seems likely that these peat-silt boundaries represent evidence of great historic earthquakes to affect the Girdwood area. It is difficult to advance earthquake recurrence intervals using the AMS dates from this study due to the large number of age reversals through the sequence but chapter 8 considers this further.

6.10.2 Unsolved problems

The peat-silt boundaries in G-01-1E (GW-2) and G-01-9 (GW-5) differ to those summarised in section 6.10.1. The lithology is the same with both having sharp upper boundaries between underlying peat and overlying silt, but the silt contains halophobous diatoms, in particular, *Tabellaria* species. In the contemporary Kenai environment, these species live in standing water in raised bog conditions with organic sedimentation at the highest elevations in the sampled transect. Any quantitative reconstruction based on diatom assemblages therefore suggests that the change from peat to silt indicates a relative sea-level fall, rather than a relative sea-level rise. A similar assemblage also occurs in the underlying silt of G-01-1F, at 159 cm. There are a number of hypotheses surrounding the formation of these peat-silt contacts including co-seismic and non-seismic RSL changes. They are unlikely to be co-seismic in origin as the overlying silt should contain marine diatoms but until we find an equivalent contemporary assemblage, their formation remains a mystery. If they are not a result of co-seismic submergence, then this has implications for deducing earthquake recurrence intervals in the area and shows that these cannot be calculated using litho-stratigraphy alone. Bio-stratigraphical evidence is also required.

Chapter 7
Results – Kasilof

7.1 Introduction

This chapter presents fossil results from three buried peat layers within the bank section at Kasilof. During the 1964 earthquake, Plafker (1969) estimates 0.5 m submergence at this site, similar to that at Kenai, with this value extrapolated from three data points at Anchorage, Nikiski and Homer. Previous work includes Combellick (1994), Combellick and Reger (1994) and Combellick and Pinney (1995). These studies concentrate on the radiocarbon dating of three buried peat layers interpreted as recording possible co-seismic events and prominent tephras within the bank section. No previous detailed microfossil work exists at this site.

This chapter follows the same format as chapters 5 and 6. Sections 7.2 and 7.3 describe the litho- and chrono-stratigraphy with following sections describing in detail the bio-stratigraphy of the bank section. Application of quantitative techniques allows the reconstruction of relative sea-level change through time. Its particular aim is to investigate how the stratigraphy of Kasilof records relative sea- and land-level movements associated with entire earthquake deformation cycles (EDC).

7.2 Litho-stratigraphy of Kasilof

The litho-stratigraphy of Kasilof marsh comprises multiple peat-silt couplets found at varying depths below present day marsh surface. Figures 7.1 (a) and (b) summarise the litho-stratigraphy of the bank section close to the sampling site of Combellick and Reger (1994).

The bank section at Kasilof reveals three laterally extensive peat layers. The lowest peat layer occurs 1.09 m below present marsh surface and is 0.99 m thick. It is bryophyte peat with distinct wood layers at three locations: 1.00 to 1.05 m, 1.38 m and 1.85 m. It also contains two distinct tephras, at 1.11 m and at 1.34 to 1.38 m. Mineralogical studies and dating of the upper tephra at 1.11 m suggests it is the Hayes tephra deposited 3591-4411 cal yr BP (Combellick & Pinney, 1995; Riehle, 1985; Riehle *et al.*, 1990). The middle fibrous peat layer occurs 0.96 m below present marsh surface and is 0.06 m thick. The 0.14 m thick upper herbaceous peat layer occurs 0.54 m below present marsh surface and has two small tephras at 0.62 m and 0.67 m. No evidence for any tsunami deposit exists immediately above any of the buried peat layers. All three peat layers occur in two other cores taken further inland, but investigations of litho-stratigraphy across the marsh was limited due to frozen ground.

Sampling of the three peat layers within the bank section took place using monolith tins and tubing. This allowed the collection of a greater volume of sediment without any risk of contamination. Section 7.4 considers the lowest two peat layers, known as KS-01-1 and sampled in 2001. Section 7.5 looks at the uppermost peat, known as KS-3 and sampled in 2000. The top of KS-01-1 corresponds to the base of KS-3.

7.3 Chrono-stratigraphy of Kasilof

Caesium-137 (^{137}Cs) and radiocarbon (^{14}C) dating determines the chrono-stratigraphy of the Kasilof bank section.

Nine AMS dates on bulk peat samples give the ages shown in figure 7.2 (appendix 3). Dates from this study suggest the uppermost peat has a modern radiocarbon age and dates from 3-310 cal yr BP (54 cm) to 655-727 cal yr BP (68 cm). There are a number of age reversals within the middle peat but it formed approximately 1300 to 1400 cal yr BP. The lowest peat has an age of 1878-2038 cal yr BP at the top (109 cm), 1353-1521 cal yr BP 4 cm below (113 cm) and an age of 6310-6525 cal yr BP at the base (208 cm).

Figures 7.2 and 7.3 show AMS results from this study against those of Combellick and Reger (1994). Figure 7.3 shows that the relationship contains less scatter when compared to the results from Kenai (figure 5.8) and Girdwood (figure 6.4) with the two prominent tephras providing additional dating control. Both data sets suggest the top of the uppermost peat has a modern radiocarbon age. There are some differences between the age of the top of the middle peat layer, with AMS dates from this study indicating it dates to approximately 1300-1400 cal yr BP and Combellick and Reger (1994) suggesting it dates to 1009-1304 cal yr BP. Assuming the AMS date for the top of the lowest peat layer contains error, both data sets reveal similar ages for its top (approximately 1400 cal yr BP) and base (approximately 6000 cal yr BP).

^{137}Cs measurements (figure 7.4) indicate that burial of the upper peat layer was not a result of co-seismic submergence associated with the 1964 event, as detectable levels do not exist on either side of the peat-silt boundary. Very little of the radionuclide is present throughout the upper part of the silt, but the 1964 horizon is likely to be around 16.5 cm, as this is the only location where detectable levels of the radionuclide occur. Sampling at smaller intervals could possibly locate the 1964 horizon.

7.4 KS-01-1

KS-01-1 includes the middle and lowest buried peat layers (figure 7.1a). The middle peat (0.96 to 1.02 m) has an age of approximately 1300 to 1400 cal yr BP and the lowest peat (1.09 to 2.08 m) has an age of approximately 1400 to 6000 cal yr BP and contains two prominent tephras.

7.4.1 Bio-stratigraphy of KS-01-1

Sampling intervals for diatom analysis varied from 1 to 4 cm, depending on location within the core. Sampling took place at larger intervals through the silts and the thicker lowest peat layer with smaller intervals around peat-silt boundaries. There were no diatoms preserved in samples 123 to 116 cm. Figure 7.5 shows the lithology of the section, AMS dates and summarises the bio-stratigraphy of KS-01-1 from 214 to 54 cm. It shows diatoms that account for at least 2% total diatom valves at each level along with summary salinity classes (diatom count information is in appendix 5). Zones produced during stratigraphically constrained cluster analysis aid the description of the diatom changes through the core.

Zone A: 214.5 to 208.5 cm

The lithology of this zone is compacted clay with fine rootlets containing polyhalobous diatoms, in particular, *Delphineis surirella* and *Paralia sulcata.* The change from silt through to the base of bryophyte peat suggests a negative sea-level tendency (relative sea-level fall).

Zone B: 208.5 to 201.5 cm

Declining polyhalobous diatoms (e.g. *Actinoptychus senarius* and *Cocconeis peltoides*) together with increasing oligohalobous-indifferent and halophobous species (e.g. *Eunotia lunaris*, *Navicula pupula*, *Pinnularia gentilis* and *Eunotia exigua*) indicates a continued negative sea-level tendency (relative sea-level fall). This change corresponds to the development of bryophyte peat.

Zone C: 201.5 to 146 cm

Pinnularia brevicostata peaks at the base of zone C. Above this, *Eunotia exigua* dominates alongside smaller amounts of *Achnanthes minutissima*, *Eunotia lunaris* and *Eunotia pectinalis*. Dominance by halophobes suggests a continued negative sea-level tendency (relative sea-level fall).

Zone D: 146 to 112.5 cm

Diatoms were absent between 123.5 and 115.5 cm and so no description is possible for this part of the zone. Oligohalobous-indifferent and halophobous diatoms dominate the remainder of zone D, for example, *Cymbella ventricosa*, *Pinnularia microstauron*, *Eunotia exigua* and *Tabellaria fenestrata*, suggesting relative sea level is stable.

Zone E: 112.5 to 108.5 cm

Zone E occurs in the top 4 cm of the lowest peat layer before a sharp upper boundary with the overlying silt. The stratigraphic boundary rather than a division on the dendrogram determines the top of this zone. Halophobous species decrease (e.g. *Eunotia exigua*, *Pinnularia subcapitata* and *Tabellaria fenestrata*) and polyhalobous, mesohalobous and oligohalobous-halophile taxa increase. Dominant species include *Nitzschia obtusa*, *Navicula pusilla* and *Pinnularia lagerstedtii*. The gradual increase in salt tolerant diatoms indicates a positive sea-level tendency (relative sea-level rise) immediately before the lowest peat-silt boundary.

Zone F: 108.5 to 104.5 cm

There is a sudden change in diatom assemblage compared to zone E, with dominance by polyhalobous species such as *Cocconeis peltoides*, *Delphineis surirella*, *Diploneis smithii* and *Paralia sulcata*. The rapid change from bryophyte peat to silt with herbaceous rootlets, together with dominance by polyhalobous taxa suggests a rapid positive sea-level tendency (relative sea-level rise).

Zone G: 104.5 to 95.5 cm

Throughout this zone, there is a transitional change from silt to fibrous peat, with its top being a sharp boundary between the middle peat and overlying silt. Polyhalobous taxa decrease (e.g. *Delphineis surirella* and *Paralia sulcata*) and oligohalobous-indifferent species dominate. Dominant species include *Nitzschia obtusa*, *Navicula begeri*, *Nitzschia pusilla* and *Pinnularia lagerstedtii*. Halophobes (*Eunotia exigua* and *Tabellaria fenestrata*) increase between 101 and 98 cm. These changes suggest a gradual negative sea-level tendency (relative sea-level fall). Towards the top of the peat, halophobes decrease and salt tolerant taxa increase, for example, *Navicula cryptocephala*, *Nitzschia fruticosa* and *Nitzschia pusilla*. This suggests a slight positive sea-level tendency (relative sea-level rise) immediately before the middle peat-silt boundary.

Zone H: 95.5 to 77 cm

The lithology of zone H is silt with herbaceous rootlets. Polyhalobous and mesohalobous diatoms dominate the assemblage at 95 cm, for example, *Cocconeis peltoides*, *Delphineis surirella*, *Paralia sulcata*, *Navicula peregrina* and *Nitzschia sigma*. This could suggest a rapid positive sea-level tendency (relative sea-level rise) compared to zone G, but as it only occurs in one sample it is probably an outlier against a general trend that starts in zone H. Above 94.5 cm, there is a rapid change back to dominance by oligohalobous-indifferent taxa such as *Nitzschia fruticosa*, *Nitzschia pusilla* and *Pinnularia lagerstedtii*. From 92.5 to 77 cm, oligohalobous-indifferent diatoms decline and polyhalobous and mesohalobous diatoms increase, for example, *Paralia sulcata*, *Nitzschia obtusa*, *Rhopalodia operculata* and *Navicula cari* var. *cincta*. This represents a gradual positive sea-level tendency (relative sea-level rise) towards the top of this zone.

Zone I: 77 to 53.5 cm

A mixture of polyhalobous, mesohalobous and oligohalobous-halophile diatoms dominate zone I. From 77 to 58 cm, polyhalobous species increase, for example, *Cocconeis peltoides*, *Delphineis surirella*, *Odentella aurita* and *Paralia sulcata*. This suggests a positive sea-level tendency (relative sea-level rise) compared to zone H. From 58 to 53.5 cm polyhalobous species decrease and mesohalobous and oligohalobous species dominate, such as *Caloneis westii*, *Navicula phyllepta*, *Navicula cari* var. *cincta* and *Navicula cryptocephala*. This indicates a negative sea-level tendency (relative sea-level fall) towards the top of this zone.

7.4.2 Numerical analysis – calibration of KS-01-1

This section aims to analyse and quantify relative sea-level changes recorded by the bio-stratigraphy of KS-01-1 using the contemporary data set from Kenai described in section 4.4. It follows the same logic explained for the Kenai fossil data in section 5.5 and the Girdwood fossil data throughout chapter 6. As the sampling site is only 17 km south of Kenai, we assume the same tidal range.

Figure 7.6 shows the calibration results for KS-01-1 using the four regression models (see section 4.5 for explanation). It plots predicted altitude (m relative to MHHW) for each fossil sample, together with its associated error term calculated using the sample specific error generated within WA-PLS (version 1.5; Juggins & ter Braak, 2001). Reconstructed values are in appendix 6 and tables 7.1 to 7.3 summarise the results highlighting why the litho-stratigraphic constraint is required to select the most appropriate model (section 4.5). Environments indicated by the altitude reconstructions are from table 2.1.

Table 7.1 Summary of calibration results for KS-01-1 using the full model

Lithological unit	Altitude reconstruction (m)	Environment indicated by altitude reconstruction
Lowest peat	+0.17 ± 0.96 m MHHW to +1.46 ± 0.94 m MHHW	Low marsh through to raised bog
Intervening silt	-1.39 ± 1.12 m MHHW to +0.86 ± 0.93 m MHHW	Unvegetated mudflat through to low/mid marsh
Middle peat	+0.75 ± 0.93 m MHHW to +1.50 ± 0.93 m MHHW	Low marsh through to raised bog
Upper silt	-1.47 ± 0.96 m MHHW to +0.89 ± 0.93 m MHHW	Unvegetated mudflat through to low/mid marsh

Table 7.2 Summary of calibration results for KS-01-1 using the -0.5 m model

Lithological unit	Altitude reconstruction (m)	Environment indicated by altitude reconstruction
Lowest peat	+0.91 ± 0.22 m MHHW to +1.60 ± 0.23 m MHHW	Low/mid marsh through to raised bog
Intervening silt	+0.33 ± 0.29 m MHHW to +1.06 ± 0.21 m MHHW	Low to mid marsh
Middle peat	+1.00 ± 0.23 m MHHW to +1.37 ± 0.21 m MHHW	Mid marsh through to raised bog
Upper silt	-0.28 ± 0.32 m MHHW to +1.10 ± 0.22 m MHHW	Unvegetated mudflat through to mid marsh

Table 7.3 Summary of calibration results for KS-01-1 using the two +1.0 m models

Lithological unit	Altitude reconstruction (m)	Environment indicated by altitude reconstruction
Lowest peat	+1.22 ± 0.06 m MHHW to +1.57 ± 0.12 m MHHW	High marsh through to raised bog
Intervening silt	+1.09 ± 0.03 m MHHW to +1.28 ± 0.07 m MHHW	Mid marsh through to transition into raised bog
Middle peat	+1.22 ± 0.05 m MHHW to +1.35 ± 0.07 m MHHW	High marsh through to diverse raised bog
Upper silt	+1.08 ± 0.03 m MHHW to +1.29 ± 0.07 m MHHW	Mid marsh through to transition into raised bog

Table 7.4 shows the calibration model chosen for different parts of KS-01-1, based on the established litho-stratigraphic criteria described in section 4.5. As the results using the +1.0 m MHHW and +1.0 hours inundated models are so similar, following sections only consider the +1.0 m MHHW model.

Table 7.4 Calibration models used to reconstruct RSL change in different parts of KS-01-1

Depth ranges (cm)	Model used	Reason
67 to 54	Full	Lithology suggests silt with rare plant fragments. As it is unknown whether these are *in situ*, it is possible that deposition occurred below the limit of vegetation
95 to 69 108 to 103 214 to 209	-0.5	Lithology indicates silt with rootlets. Therefore, the -0.5 m model is appropriate and more precise as modern day samples taken from Kenai suggest that no vegetation occurs below -0.28 m MHHW
102 to 96 208 to 109	+1.0	Lithology indicates peat and so the +1.0 m MHHW model is appropriate

Figure 7.7 shows the results from MAT. It suggests that only two samples, 202 and 205 cm (3%) have 'poor' modern analogues when compared to the contemporary

Kenai data. 31 samples (44%) have 'close' modern analogues and 37 (53%) have 'good' modern analogues. Therefore, most quantitative reconstructions should be reliable.

Figure 7.8 is a composite diagram illustrating the main changes in predicted altitude relative to MHHW for KS-01-1, drawn using the models specified in table 7.4 (appendix 6). Highlighted samples have 'poor' modern analogues, identified using MAT (figure 7.7), indicating these reconstructions may be less reliable. Table 7.5 quantitatively describes these changes through the core using sea-level tendency (SLT) phases, diatom data from figure 7.5, diatom optima and tolerances from figure 4.8 and appendix 1 and environmental reconstructions from table 2.1.

7.4.3 Relative sea- and land-level changes through KS-01-1

This section examines the relative sea-level changes described in table 7.5 through KS-01-1 in chronological order, testing periods of the EDC model.

Development of the lowest peat layer - SLT phases A and B

Development of peat approximately 6310-6525 cal yr BP agrees with radiocarbon dates from Combellick and Reger (1994). The relative sea-level fall could result from the inter-seismic period of the EDC model where strain accumulation at the plate boundary gradually uplifts the land. Alternatively, it could result from a change in non-seismic processes, for example, eustatic sea-level rise, isostatic adjustments or local changes.

Figure 7.5 shows a slight increase in polyhalobous diatoms from 188 to 172 cm within the lower peat layer and quantitatively this represents a relative sea-level rise of only $+0.05 \pm 0.10$ m. The magnitude is a lot smaller than the RSL oscillations described from Kenai and Girdwood but it could record a small co-seismic submergence event. Until more detailed microfossil analysis is undertaken and until this change is traced through other cores merging into a peat-silt couplet, it remains inconclusive. As the RSL change is so small, following sections do not consider it further.

Table 7.5 Description of relative sea-level changes through KS-01-1

SLT Phase	Depth (cm)	Lithology	Brief summary (including optima and tolerance, *u±t* of diatom species)	Sea-level tendency	Quantitative reconstructions	Environmental reconstruction
A	214.5 to 194	Gradual change from silt with herbaceous rootlets to bryophyte peat	Polyhalobous species (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Paralia sulcata*, -0.93 ± 1.91 m) dominate at the base. Halophobous species, particularly *Eunotia exigua* (+1.49 ± 0.10 m) increase towards the top	Negative	RSL fall of -1.42 ± 0.42 m to a new ground height of +1.54 ± 0.07 m MHHW	Upper tidal flat/marsh pioneer zone through to diverse raised bog
B	194 to 113.5	Bryophyte peat	Diatom assemblages are similar throughout this phase. Oligohalobous-indifferent and halophobous diatoms dominate, for example, *Eunotia lunaris* (+1.46 ± 0.40 m) and *Eunotia exigua* (+1.49 ± 0.10 m). Halophobes decline slightly towards the top	Stable	Reconstructed altitudes range from +1.48 ± 0.07 m MHHW to +1.54 ± 0.07 m MHHW, giving a mean altitude of +1.51 ± 0.07 m MHHW	Raised bog
C	113.5 to 108.5	Top 5 cm of bryophyte peat. Sharp upper contact with overlying silt	Halophobes decline (e.g. *Eunotia exigua*, +1.49 ± 0.10 m) and polyhalobous and mesohalobous taxa increase (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Paralia sulcata*, -0.93 ± 1.91 m; *Nitzschia obtusa*, +1.14 ± 0.29 m). The most dominant species is *Pinnularia lagerstedtii* (+1.38 ± 0.12 m)	Positive	RSL rise of +0.21 ± 0.10 m to a new ground height of +1.27 ± 0.07 m MHHW	Raised bog to transition zone into raised bog
D	108.5 to 106.5	Silt with herbaceous rootlets	Polyhalobous species dominate SLT phase D (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Diploneis smithii*, -2.33 ± 1.15 m; *Paralia sulcata*, -0.93 ± 1.91 m)	Positive	Rapid RSL rise of +0.94 ± 0.30 m to a new ground height of +0.33 ± 0.29 m MHHW	Low marsh
E	106.5 to 98.5	Gradual transition from silt with herbaceous rootlets to fibrous peat	Polyhalobous species decline (e.g. *Delphineis surirella*, -1.13 ± 2.11 m; *Diploneis smithii*, -2.33 ± 1.15 m; *Paralia sulcata*, -0.93 ± 1.91 m) and oligohalobous-indifferent and halophobous species increase (e.g. *Navicula begeri*, +1.27 ± 0.15 m; *Nitzschia pusilla*, +1.36 ± 0.19 m; *Pinnularia lagerstedtii*, +1.38 ± 0.12 m; *Eunotia exigua*, +1.49 ± 0.10 m)	Negative	RSL fall of -1.02 ± 0.30 m to a new ground height of +1.35 ± 0.07 m MHHW	Low marsh to raised bog

F	98.5 to 95.5	Upper 3 cm of fibrous peat. Sharp upper contact with overlying silt	Salt tolerant species increase. Dominant diatom species include *Nitzschia obtusa* (+1.14 ± 0.29 m), *Navicula cryptocephala* (+0.17 ± 1.13 m), *Navicula begeri* (+1.27 ± 0.15 m) and *Nitzschia pusilla* (+1.36 ± 0.19 m). However, this phase could be the result of mixing	Positive or mixing	RSL rise of +0.08 ± 0.10 m to a new altitude of +1.27 ± 0.07 m MHHW	Raised bog to transition zone into raised bog
G	95.5 to 58	Silt with herbaceous rootlets through to silt with rare plant fragments	A mixture of oligohalobous, mesohalobous and polyhalobous diatoms dominate SLT phase G, with polyhalobous species generally increasing towards the top. At the base, dominant diatom species include *Nitzschia fruticosa* (+1.31 ± 0.16 m), *Nitzschia pusilla* (+1.36 ± 0.19 m) and *Pinnularia lagerstedtii* (+1.38 ± 0.12 m). At the top, dominant diatom species include *Delphineis surirella* (-1.13 ± 2.11 m), *Paralia sulcata* (-0.93 ± 1.91 m), *Caloneis westii* (-0.32 ± 0.76 m) and *Navicula cari* var. *cincta* (+0.20 ± 1.45 m)	Generally positive	General RSL rise of +2.74 ± 0.96 m to a new ground height of -1.47 ± 0.96 m MHHW, although using the full model may overestimate this value. Using the -0.5 model, RSL rises by +1.55 ± 0.33 m to a new ground height of -0.28 ± 0.32 m MHHW. There are a number of oscillations such as the initial RSL rise immediately above the peat-silt boundary of +0.75 ± 0.26 m but this may be an outlier	Transition zone into raised bog through to unvegetated mudflat
H	58 to 53.5	Silt with rare plant fragments	Polyhalobous species decrease slightly and mesohalobous and oligohalobous taxa increase. Dominant species include *Navicula phyllepta* (+0.83 ± 0.68 m), *Navicula cari* var. *cincta* (+0.20 ± 1.45 m) and *Nitzschia fruticosa* (+1.31 ± 0.16 m)	Negative	RSL fall of -1.71 ± 1.35 m to a new ground height of +0.24 ± 0.95 m MHHW	Low marsh

Pre-seismic RSL rise before the lowest peat-silt boundary – SLT phase C

A pre-seismic relative sea-level rise of +0.21 ± 0.10 m occurs within the top 5 cm of the lowest bryophyte peat. Evidence suggests the diatom assemblages are not a result of mixing because halophobes gradually decline (e.g. *Frustulia rhomboides*, +1.51 ± 0.06 m; *Pinnularia subcapitata*, +1.51 ± 0.07 m; *Tabellaria fenestrata*, +1.35 ± 0.70 m) and species such as *Nitzschia obtusa* (+1.14 ± 0.29 m), *Navicula pusilla* (+0.72 ± 2.96 m) and *Navicula variostriata* (+1.35 ± 0.32 m) are not found in samples on either side of this phase. Chapter 8 investigates possible mechanisms for any pre-seismic relative sea-level rise.

Co-seismic submergence – SLT phase D

The sharp peat-silt boundary at 108.5 cm, together with dominance by polyhalobous species in the overlying silt represents a large, rapid change in environment from raised bog through to one regularly inundated by the tide. Quantitative reconstructions indicate a sudden relative sea-level rise of +0.94 ± 0.30 m caused by co-seismic submergence approximately 1353-1521 to 1878-2038 cal yr BP (figure 7.2 and appendix 3).

Post- and inter-seismic recovery – SLT phase E

Immediately after the co-seismic event in SLT phase D, diatom assemblages suggest a negative sea-level tendency with quantitative reconstructions indicating a relative sea-level fall of -1.02 ± 0.30 m. This phase is likely to represent rapid post-seismic and inter-seismic uplift of the land together with sediment accumulation allowing re-development of freshwater peat.

Identification of inter-seismic, pre-seismic, co-seismic and post-seismic relative sea-level movements together with the peat-silt boundary being laterally extensive and indicating a large, rapid relative sea-level rise suggests the lowest peat-silt boundary results from co-seismic submergence approximately 1353-1521 cal yr BP to 1878-2038 cal yr BP (figure 7.2, appendix 3). It fulfils three out of the five criteria described by Nelson *et al.* (1996) and there is no evidence of any tsunami deposit. Chapter 8 investigates synchroneity of submergence when bringing all three sites together. It is unlikely that non-seismic processes could produce similar relative sea-level changes, in both tendency and magnitude.

RSL rise across the middle peat-silt boundary – SLT phases F and G

Relative sea-level movements surrounding the burial of the middle peat do not strictly follow periods of the EDC model. The testing of three hypotheses helps in deciding whether the peat-silt boundary results from co-seismic submergence approximately 1393-1531 cal yr BP (figure 7.2 and appendix 3). These are:

1. RSL rise associated with rapid co-seismic submergence
2. RSL rise associated with non-seismic processes, including eustatic and glacio-isostatic changes
3. RSL rise associated with co-seismic submergence superimposed upon a gradual non-seismic RSL change

Following sections investigate these three hypotheses using the available data.

Hypothesis 1 - The middle peat-silt boundary results from co-seismic submergence

A possible pre-seismic relative sea-level rise of +0.08 ± 0.10 m occurs within the top 3 cm of the middle peat before the sharp peat-silt boundary (SLT phase F). However, a distinct diatom assemblage does not exist within this phase, suggesting it could be a result of diatoms mixing from the overlying silt with those found in the underlying peat. The sudden change in lithology from fibrous peat to silt with herbaceous rootlets at 95.5 cm, together with dominance by polyhalobous diatoms at 95 cm represents a rapid relative sea-level rise of +0.75 ± 0.26 m (SLT phase G). This could record rapid co-seismic submergence associated with a large earthquake approximately 1300 cal yr BP. As the peat-silt boundary is laterally extensive, it fulfils three of the five criteria suggested by Nelson *et al.* (1996) and chapter 8 investigates synchroneity of submergence when bringing data from all three sites together. Immediately following the event, quantitative reconstructions indicate a rapid relative sea-level fall of -0.58 ± 0.33 m possibly representing post-seismic uplift of the land but this trend does not continue long term. From this evidence, it appears that the middle peat-silt boundary from the bank section at Kasilof could result from co-seismic submergence. However, the dramatic relative sea-level rise only occurs in one sample at 95 cm depth, with rapid rebound only 1 cm above, indicating that the sample from 95 cm may be outlier. Following sections consider possible non-seismic causes.

Hypothesis 2 – The middle peat-silt boundary results from non-seismic RSL changes

If the reconstructed altitude of the sample at 95 cm were not present, quantitative reconstructions would suggest a gradual rise in relative sea level from 98.5 cm (in the peat) to 58 cm (in the silt), combining SLT phases F and G (figure 7.8). The formation of the middle peat-silt boundary by non-seismic causes include eustatic and isostatic processes, for example, Wiles and Calkin (1994) suggest glacier expansions in the Kenai mountains approximately 1350 cal yr BP, which corresponds to the date at the top of the peat. Other possibilities include a change in local processes such as a variation in the hydro-dynamics of the estuary. A shift in the meandering river system seems a likely explanation as figure 2.8 clearly shows that the river has meandered all over its valley in the past.

Hypothesis 3 – The middle peat-silt boundary results from co-seismic submergence superimposed upon a non-seismic RSL change

Both hypotheses 1 and 2 are possible explanations of the relative sea-level changes surrounding the middle peat-silt boundary at Kasilof. Throughout the silt units in SLT phases G and H, lithology changes from silt with herbaceous rootlets through to silt with rare plant fragments and so the full model is best when reconstructing altitude for some samples. Larger magnitude relative sea-level changes together with larger error terms (typically ±0.96 m) are likely when using the full model rather than the -0.5 m model. However, quantitative reconstructions do show that if the peat-silt boundary resulted from co-seismic submergence, no longer-term recovery of the land occurs. This suggests that immediately after the event, a change in eustatic sea-level rise, isostatic processes or local conditions were greater than post- and inter-seismic uplift of the land. Possible contributing factors include glacier expansions around 1350 cal yr BP (Wiles & Calkin, 1994).

Relative sea-level changes surrounding the burial of the middle peat-silt boundary are complicated. It could result from the EDC model with identification of possible inter-seismic, pre-seismic, co-seismic and post-seismic periods. However, it is unlikely that microfossil evidence would only record a large co-seismic submergence event in one sample, suggesting that the sample immediately above the peat-silt boundary (at 95 cm) is an outlier. This being the case, the middle peat-silt boundary probably results from non-seismic processes, such as a change in the meandering river system.

7.5 KS-3 the uppermost peat layer through to present day mash surface

Figure 7.1(b) describes the litho-stratigraphy of KS-3 in detail. The surface vegetation consists of low growing *Triglochin maritima*, Poaceae and *Carex lyngbyei*, and the peat layer dates from approximately 3-310 to 655-727 cal yr BP (figure 7.2 and appendix 3). ^{137}Cs suggests its burial before 1954 as there are no detectable amounts of this radionuclide around the peat-silt boundary (figure 7.4).

7.5.1 Bio-stratigraphy of KS-3

Sampling intervals for diatom analysis varied from 1 cm through the peat layer to 4 cm through the overlying silt unit. Figure 7.9 shows the lithology of the section, AMS dates and summarises the bio-stratigraphy of KS-3, from the surface down to a depth of 71 cm. It shows diatoms that account for at least 2% total diatom valves at each level along with summary salinity classes (diatom count information is in appendix 5). Zones produced during stratigraphically constrained cluster analysis aid the description of the diatom changes through the core. Following paragraphs introduce and summarise the main changes in diatom assemblages and present an initial interpretation of sea-level tendencies that will be fully analysed and quantified in later sections.

Zone A: 71.5 to 68.5 cm

The lithology of zone A is grey clay-silt with herbaceous rootlets, with less rootlets towards the base. Polyhalobous and mesohalobous diatoms dominate particularly *Caloneis westii* and *Navicula peregrina*. Towards the top of this zone, they start to decline, together with an increase in oligohalobous-indifferent species (e.g. *Cymbella ventricosa*) suggesting a negative sea-level tendency and a relative sea-level fall.

Zone B: 68.5 to 64.5 cm

Oligohalobous-indifferent species continue to increase together with the introduction of halophobes. Dominant species include *Cymbella ventricosa*, *Eunotia lunaris* and *Pinnularia gentilis.* This change, alongside the transition from silt to peat indicates a continued negative sea-level tendency (relative sea-level fall).

Zone C: 64.5 to 55.5 cm

Halophobous and oligohalobous-indifferent diatoms dominate zone C, in particular, *Eunotia lunaris*, *Eunotia pectinalis* and *Eunotia exigua* that peaks at 60 cm. *Tabellaria fenestrata* and *Tabellaria flocculosa* peak at 59 and 58 cm respectively. This suggests a continued negative sea-level tendency (relative sea-level fall) to 58 cm. Above this level, halophobes decline slightly, indicating a possible positive sea-level tendency (relative sea-level rise) towards the top of this zone.

Zone D: 55.5 to 53.5 cm

This zone occurs within the top 2 cm of the herbaceous peat layer with its upper boundary being a sharp contact between the peat and overlying silt with herbaceous rootlets. *Eunotia exigua* dominates, suggesting a negative sea-level tendency (relative sea-level fall) compared to zone C. However, the introduction of small amounts of polyhalobous, mesohalobous and oligohalobous taxa also suggests a positive sea-level tendency (relative sea-level rise) compared to zone C. Later sections quantify these changes.

Zone E: 53.5 to 50 cm

The lithology of this zone is clay silt with rootlets. Oligohalobous-indifferent diatoms peak at the base of this zone, for example, *Navicula begeri*, *Navicula brockmanii* and *Pinnularia lagerstedtii*. Very few halophobes are present with polyhalobous species increasing towards the top, for example, *Cocconeis peltoides* and *Paralia sulcata*. This indicates a positive sea-level tendency (relative sea-level rise) compared to zone D.

Zone F: 50 to 30 cm

A mixture of polyhalobous, mesohalobous and oligohalobous diatoms dominate zone F, for example, *Paralia sulcata*, *Navicula protracta*, *Navicula salinarum*, *Navicula cari* var. *cincta* and *Nitzschia fruticosa*. Relative sea level appears stable, as there are no major changes in diatom assemblage.

Zone G: 30 cm to surface

Diatom assemblages in zone G are very similar to those in zone F. A mixture of polyhalobous, mesohalobous and oligohalobous diatoms dominate, with polyhalobous taxa increasing towards the top (e.g. *Cocconeis peltoides*, *Delphineis surirella*, *Odentella aurita* and *Paralia sulcata*). This suggests a slight positive sea-level tendency (relative sea-level rise) towards the surface.

7.5.2 Numerical analysis – calibration of KS-3

This section aims to analyse and quantify relative sea-level changes recorded by the bio-stratigraphy of KS-3 using the established method.

Figure 7.10 shows the calibration results for KS-3 using the four regression models outlined in section 4.5. It plots predicted altitude (m relative to MHHW) for each fossil sample, together with its associated error term calculated using the sample specific error generated within WA-PLS (version 1.5; Juggins & ter Braak, 2001). Reconstructed values are in appendix 6 and tables 7.6 to 7.8 summarise the results showing that the amount of associated error varies greatly depending on which model is used. Environments indicated by the altitude reconstruction are from table 2.1.

Table 7.6 Summary of calibration results for KS-3 using the full model

Lithological unit	Altitude reconstruction (m)	Environment indicated by altitude reconstruction
Upper peat	+0.77 ± 0.99 m MHHW to +1.34 ± 0.93 m MHHW	Low marsh through to raised bog
Overlying silt	+1.05 ± 0.93 m MHHW, decreasing to -1.37 ± 0.94 m MHHW	Mid marsh through to unvegetated tidal flat

Table 7.7 Summary of calibration results for KS-3 using the -0.5 m model

Lithological unit	Altitude reconstruction (m)	Environment indicated by altitude reconstruction
Upper peat	+1.27 ± 0.22 m MHHW to +1.70 ± 0.26 m MHHW	Transition into raised bog through to diverse raised bog
Overlying silt	+1.17 ± 0.22 m MHHW, decreasing to +0.01 ± 0.27 m MHHW	High marsh through to the upper tidal flat/marsh pioneer zone

Table 7.8 Summary of calibration results for KS-3 using the two +1.0 m models

Lithological unit	Altitude reconstruction (m)	Environment indicated by altitude reconstruction
Upper peat	+1.29 ± 0.07 m MHHW to +1.58 ± 0.13 m MHHW	Transition zone into raised bog through to diverse raised bog
Overlying silt	+1.30 ± 0.07 m MHHW to +1.09 ± 0.03 m MHHW	Transition zone into raised bog environments through to mid marsh

Quantitative reconstruction of relative sea-level change through KS-3 only requires one model, chosen using the litho-stratigraphic constraints described in section 4.5. Table 7.9 shows the model chosen for different parts of the core. As the results using the +1.0 m MHHW and +1.0 hours inundated models are so similar, this section only considers the +1.0 m MHHW model.

Table 7.9 Calibration models used to reconstruct RSL change in different parts of KS-3

Depth ranges (cm)	Model used	Reason
69 to 72 53 to 0	-0.5	Lithology indicates silt with rootlets. Therefore, the -0.5 m model is appropriate and more precise as modern day samples taken from Kenai suggest that no vegetation occurs below -0.28 m MHHW
54 to 68	+1.0	Lithology indicates peat and so the +1.0 m MHHW model is appropriate

Figure 7.11 shows the results from MAT. Only one assemblage from 65 cm depth has a 'poor' modern analogue due to its dominance by *Pinnularia brevicostata* and *Pinnularia gentilis*. It indicates that 3% of the fossil samples have 'poor' modern analogues, 11 (33%) have 'close' modern analogues and 21 (64%) have 'good' modern analogues within the contemporary Kenai training set. Therefore, most quantitative reconstructions are reliable.

Figure 7.12 is a composite diagram illustrating the main changes in predicted altitude (m) relative to MHHW for KS-3, drawn using the models specified in table 7.9 (values from the transfer function are in appendix 6). The highlighted sample has a 'poor' modern analogue, identified using figure 7.11 and so this reconstruction may be less reliable. Table 7.10 quantitatively describes these changes using sea-level tendency (SLT) phases, diatom descriptions from figure 7.9, diatom optima and tolerances from figure 4.8 and appendix 1 and environmental reconstructions from table 2.1.

Table 7.10 Description of relative sea-level changes through KS-3

SLT Phase	Depth (cm)	Lithology	Brief summary (including optima and tolerance, *u±t* of diatom species)	Sea-level tendency	Quantitative reconstructions	Environmental reconstruction
A	71.5 to 63.5	Gradual transition from silt with herbaceous rootlets to herbaceous peat	Polyhalobous and mesohalobous species decline (e.g. *Cocconeis peltoides*, -1.04 ± 1.75 m; *Paralia sulcata*, -0.93 ± 1.91 m; *Caloneis westii*, -0.32 ± 0.76 m) and halophobous species increase (e.g. *Eunotia exigua*, +1.49 ± 0.10 m; *Pinnularia subcapitata*, +1.51 ± 0.07 m)	Negative	RSL fall of -2.01 ± 0.49 m to a new ground height of +1.54 ± 0.07 m MHHW	Unvegetated mudflat through to raised bog
B	63.5 to 54.5	Herbaceous peat	Oligohalobous-indifferent and halophobous taxa dominate SLT phase B, especially *Eunotia lunaris* (+1.46 ± 0.40 m), *Eunotia pectinalis* (+1.19 ± 1.39 m) and *Eunotia exigua* (+1.49 ± 0.10 m). There is a peak of *Tabellaria fenestrata* (+1.35 ± 0.70 m) at 59 cm, followed by a peak of *Tabellaria flocculosa* (+1.32 ± 1.18 m) at 58 cm	Stable	RSL fluctuates between +1.52 ± 0.07 m MHHW and +1.55 ± 0.07 m MHHW	Raised bog
C	54.5 to 53.5	Top 1 cm of herbaceous peat unit. Sharp upper contact with overlying silt	*Eunotia exigua* (+1.49 ± 0.10 m) dominates but there is also the introduction of more salt tolerant species, for example, *Paralia sulcata* (-0.93 ± 1.91 m) and *Nitzschia obtusa* (+1.14 ± 0.29 m)	Positive or mixing	RSL rise of +0.07 ± 0.10 m to a new ground height of +1.45 ± 0.07 m MHHW	Raised bog
D	53.5 to 46	Clay-silt with herbaceous rootlets	Halophobes decline (e.g. *Eunotia exigua*, +1.49 ± 0.10 m; *Tabellaria flocculosa*, +1.32 ± 1.18 m) and polyhalobous species increase (e.g. *Cocconeis peltoides*, -1.04 ± 1.75 m; *Paralia sulcata*, -0.93 ± 1.91 m)	Positive	RSL rise of +0.92 ± 0.25 m to a new ground height of +0.53 ± 0.24 m MHHW	Low marsh
E	46 to 34	Clay-silt with herbaceous rootlets	Polyhalobous species decrease (e.g. *Cocconeis peltoides*, -1.04 ± 1.75 m) and oligohalobous-halophile species increase (e.g. *Rhopalodia operculata*, +0.86 ± 0.25 m; *Navicula cari* var. *cincta*, +0.20 ± 1.45 m)	Negative	RSL fall of -0.41 ± 0.33 m to a new ground height of +0.94 ± 0.23 m MHHW	Low to mid marsh
F	34 cm to surface	Clay-silt with herbaceous rootlets	Polyhalobous diatoms increase, for example, *Cocconeis peltoides* (-1.04 ± 1.75 m) and *Paralia sulcata* (-0.93 ± 1.91 m)	Positive	RSL rise of +0.90 ± 0.35 m to a surface altitude of +0.04 ± 0.26 m MHHW	Upper tidal flat/ marsh pioneer zone

7.5.3 Relative sea- and land-level changes through KS-3

This section investigates the relative sea-level changes described in table 7.10 in chronological order. It tests periods of the EDC model and suggests alternative explanations where appropriate.

Development of the uppermost peat - SLT phases A and B

Development of the uppermost peat in SLT phases A and B (approximately 655-727 cal yr BP) continue from SLT phases G and H in KS-01-1. The relative sea-level fall could result from inter-seismic uplift of the land during the EDC model or a changing balance between eustatic sea-level rise, isostatic adjustments and local processes.

Burial of the uppermost peat – SLT phases C to F

Relative sea-level movements surrounding the burial of the uppermost peat are not as straight forward as those surrounding the lowest peat in KS-01-1. The testing of three hypotheses helps in deciding whether the peat-silt boundary results from co-seismic submergence approximately 3-310 cal yr BP.

Hypothesis 1 - The upper peat-silt boundary in KS-3 results from co-seismic submergence

As outlined in chapters 5 and 6, the criteria of Nelson *et al.* (1996) together with the identification of pre-seismic, co-seismic and post-seismic relative sea-level movements are important when deciding if a peat-silt boundary results from co-seismic submergence. In the upper few centimetres of the peat (SLT phase C), quantitative reconstructions indicate a relative sea-level rise of +0.07 ± 0.10 m. This could represent a pre-seismic relative sea-level rise or mixing at the peat-silt boundary.

The laterally extensive sharp contact between the peat and overlying silt with herbaceous rootlets suggests a large, sudden change from a freshwater environment to one regularly inundated by the tide. Quantitative reconstructions indicate a relative sea-level rise of +0.92 ± 0.25 m (SLT phase D) over five centimetres. This rapid relative sea-level rise appears gradual because of dominance by oligohalobous-indifferent species (e.g. *Navicula begeri*, +1.27 ± 0.15 m; *Navicula brockmannii*, +1.31 ± 0.19 m; *Pinnularia lagerstedtii*, +1.38 ± 0.12 m) immediately above the peat-silt contact. However, these assemblages could result from other processes such as mixing during rapid sedimentation following the event. Immediately after the event (SLT phases E and F), quantitative reconstructions indicate that no rapid post-seismic or inter-seismic uplift of the land occurs.

The apparent gradual burial of the peat, together with the lack of any post-seismic or inter-seismic uplift indicates that the upper peat-silt boundary in KS-3 may not result from co-seismic submergence alone. Following hypotheses test whether it could result from non-seismic processes.

Hypothesis 2 - The upper peat-silt boundary in KS-3 results from non-seismic RSL changes

Non-seismic processes such as eustatic sea-level rise and isostatic adjustments could account for the peat-silt boundary in KS-3, but it is hard to envisage these changes having such a large magnitude and being so sudden. An alternative explanation is a rapid change in the dynamics of the meandering river system with valley infilling and effects of channel migration. This could explain the change from peat to silt together with the lack of any post- or inter-seismic recovery.

Hypothesis 3 - The upper peat-silt boundary in KS-3 results from co-seismic submergence superimposed upon a non-seismic RSL change

The rapid change from peat to silt with herbaceous rootlets could suggest co-seismic submergence of +0.92 ± 0.25 m (SLT phase D). The apparent gradual change in relative sea level could represent mixing at the boundary or re-deposition of diatoms by ice. However, the lack of any long-term post-seismic or inter-seismic uplift of the land indicates that co-seismic submergence may be superimposed upon a background non-seismic relative sea-level rise.

In summary, the peat-silt boundary in KS-3 could result from co-seismic submergence superimposed upon a background non-seismic RSL change. However, a simpler explanation is that it results from changes in the meandering river system. Bio-stratigraphical investigations of other cores from Kasilof, together with other cores from different sites in the area could help solve this uncertainty and investigate how this peat-silt boundary relates to the oscillation in relative sea level observed before the 1964 event at Kenai and Girdwood.

The bank section at Kasilof does not record evidence of the 1964 event, as this horizon is located somewhere within the overlying silt layer. As explained in previous chapters, there is a problem in getting detailed relative sea-level changes through silt units because the diatoms show large tolerances (section 4.4.2). Sampling further inland may detect any submergence associated with this event because freshwater diatoms are more sensitive to altitudinal change. Alternatively, no co-seismic submergence took place at Kasilof during the 1964 event.

7.6 Summary of Kasilof

The three buried peat layers in the bank section at Kasilof may result from relative sea-level changes associated with the EDC model. Table 7.11 summarises the results and gives each event a name to make comparisons easier when merging all three sites together in chapter 8.

The three peat layers within the bank section at Kasilof reveal different relative sea-level movements around each peat-silt boundary. The third and lowest peat layer (KS-1) resulted from co-seismic submergence as clear pre-seismic, co-seismic and post-seismic movements are identifiable around the stratigraphic boundary. It fulfils three of the five criteria described by Nelson *et al.* (1996) as the peat-silt boundary is laterally extensive and shows a large, sudden relative sea-level rise. There is no evidence of any tsunami deposit and chapter 8 investigates synchroneity of submergence when bringing all three sites together.

The burial of the middle (KS-2) and uppermost (KS-3) peat layers possibly result from co-seismic submergence combined with non-seismic relative sea-level change. However, a simpler explanation is that they result from a change in the meandering river system and are only locally significant. Investigation of other cores from Kasilof, together with correlation from other sites could help resolve this.

This study adds to and improves upon existing knowledge (e.g. Combellick, 1994; Combellick & Reger, 1994). Results from this site suggest that not all peat-silt boundaries result from co-seismic submergence and not all relative sea-level movements follow patterns of the EDC model. Radionuclide dating indicates that the uppermost peat layer was buried before the 1964 earthquake and the section studied shows no evidence for the estimated 0.50 m co-seismic submergence during the 1964 event.

Table 7.11 Summary of possible events at Kasilof

+ve values represent a relative sea-level rise whereas –ve values represent a relative sea-level fall

SLT phase	Description	Event	EDC related	Date at contact (cal yr BP)	Pre-seismic RSL change (m)	Co-seismic RSL change (m)	Sharpness of boundary (Troels-Smith)	Lateral extent	Post/inter-seismic recovery (m) and sediment accumulation
C to F (KS-3)	Uppermost peat	KS-3	?	3-310	+0.07 ± 0.10 or mixing	+0.92 ± 0.25	4	>100 m	No rapid RSL fall
F to H (KS-01-1)	Middle peat	KS-2	?	1393-1531	+0.08 ± 0.10 or mixing	+0.75 ± 0.26	4	>100 m	No rapid RSL fall
C to E (KS-01-1)	Lowest peat	KS-1	Yes	1353-1521 to 1878-2038	+0.21 ± 0.10	+0.94 ± 0.30	4	>100 m	-1.02 ± 0.30

Chapter 8
Discussion and Conclusions

8.1 Introduction

The results presented in the preceding chapters represent the first study to undertake high resolution microfossil analyses of complete and multiple earthquake deformation cycles in Alaska. The comprehensive contemporary diatom data set from Kenai allows the quantification of relative land- and sea-level changes for these cycles and enables discrimination of co-seismic from non-seismic processes. This chapter brings together the data from the three study sites to address the main objectives previously set out in chapter 1:

1. To understand the spatial and temporal variation of late Holocene relative sea- and land-level movements associated with great earthquakes (magnitude>8.0)
2. To understand non-seismic controls on relative sea level through the late Holocene

Chapter 1.11 outlines six hypotheses that together address these objectives. This chapter investigates these hypotheses in the following six sections using table 8.1 that summarises possible earthquakes recorded at Kenai, Girdwood and Kasilof, using results from chapters 4 to 7. The final objective is to put the seismic and non-seismic components into context, investigate broader implications and identify areas for future research.

8.2 Records of multiple co-seismic events in the marsh stratigraphy around the upper Cook Inlet

Bio- and litho-stratigraphical evidence from Kenai, Girdwood and Kasilof record at least three possible episodes of co-seismic submergence associated with the earthquake deformation cycle (EDC) at each site. Table 8.1 shows that some are clearer than others based on the framework set out by Nelson *et al.* (1996) who suggest that the suddenness (indicated by sharpness of boundary), amount and lateral extent of submergence are important when identifying peat-silt couplets of co-seismic origin. Their two other criteria are synchroneity of submergence (section 8.5) together with evidence of any tsunami deposit. No tsunami affected the upper Cook Inlet in 1964

Table 8.1 Summary of events at Kenai, Girdwood and Kasilof

Values for Girdwood are scaled and +ve signs represent a RSL rise and -ve signs represent a RSL fall

Site	Event	EDC related	Date at contact (cal yr BP)	Pre-seismic RSL change (m)	Co-seismic RSL change (m)	Sharpness of boundary (Troels-Smith)	Lateral extent	Post/inter-seismic recovery (m) and sediment accumulation
Kenai	KE-4	Yes	1964 AD	+0.21 ± 0.10	+0.28 ± 0.22 to +0.68 ± 0.23	2	>400 m	-0.11 ± 0.21 to -0.51 ± 0.22
	KE-3	?	1954 AD to 794-1055	*Eunotia exigua* declines	+0.18 ± 0.10	No change in lithology	Not investigated	-0.14 ± 0.10
	KE-2	?	3268-3547	+0.04 ± 0.10 to +0.20 ± 0.10	+0.20 ± 0.10 to +0.57 ± 0.40	0, but sharper in other cores	>700 m	No rapid RSL fall
	KE-1	?	2472-2843 to 3211-3452	Not identified	+0.21 ± 0.11	No change in lithology	Not investigated	-0.19 ± 0.10
Girdwood	GW-8	Yes	1964 AD	+0.17 ± 0.13	+1.97 ± 0.42	4	>1 km	-1.82 ± 0.50
	GW-7	?	1954 AD to 1350-1517	Not identified	+0.22 ± 0.13	Increase in silt content	> 50 m	-0.18 ± 0.13
	GW-6	Yes	1182-1345	+0.13 ± 0.13	+1.74 ± 0.56	4	>1 km	-1.99 ± 0.56
	GW-4	Yes	1951-2305	Yes, in pollen changes	+1.87 ± 0.43 to +2.15 ± 0.43	4	> 50 m	Not investigated
	GW-3	Yes	3480-3827	+0.08 ± 0.18 or mixing	+1.75 ± 0.50 to +4.09 ± 1.27	4	> 50 m	Not investigated
	GW-2	No	3212-3634	No	-0.13 ± 0.49	4	> 50 m	Not investigated
	GW-1	Yes	4298-4784	+0.15 ± 0.13	+1.69 ± 0.42	4	> 50 m	Not investigated
	GW-5	No	1903-2144	+0.13 ± 0.13	+0.33 ± 0.45	4	>200 m	Not investigated
Kasilof	KS-3	?	3-310	+0.07 ± 0.10 or mixing	+0.92 ± 0.25	4	>100 m	No rapid RSL fall
	KS-2	?	1393-1531	+0.08 ± 0.10 or mixing	+0.75 ± 0.26	4	>100 m	No rapid RSL fall
	KS-1	Yes	1353-1521 to 1878-2038	+0.21 ± 0.10	+0.94 ± 0.30	4	>100 m	-1.02 ± 0.30

and there is no evidence to suggest that a tsunami accompanied any other late Holocene event (chapters 5 to 7).

Quantitative reconstructions using diatom data also identify the four different periods of the EDC model suggested by Shennan *et al.* (1999). This model includes inter-seismic, pre-seismic, co-seismic and post-seismic movements combined with the effects of non-seismic sea-level change and sediment accumulation between co-seismic events. Table 8.1 summarises the magnitude of these periods using the quantitative transfer function approach and indicates the degree of confidence for co-seismic origin of each submergence event (column labelled EDC related). It shows only one definite co-seismic event at Kenai (KE-4), five at Girdwood (GW-8, GW-6, GW-4, GW-3, GW-1) and one at Kasilof (KS-1). This has implications for the calculation of earthquake recurrence intervals where previous analyses used no microfossil evidence (e.g. Combellick, 1994). Within each site, most definite events are of similar magnitude to the 1964 earthquake and section 8.6 makes further comparisons. The others, marked by a question mark, may result from co-seismic submergence, but some do not fulfil the criteria suggested by Nelson *et al.* (1996) and three events (KE-2, KS-2, KS-3) record no RSL fall following burial of the peat layer indicating no post-seismic uplift (Shennan *et al.*, 1999). Section 8.3 further tests the validity of the four-phase EDC model.

This raises issues for further consideration. First, the point at which small magnitude co-seismic relative sea-level changes become indistinguishable from those caused by any combination of non-seismic processes. Second, the method chosen to define the magnitude of a co-seismic event from across a peat-silt boundary. Neither of these two are unique to this study. For example, Shennan *et al.* (1996, 1998) suggest a lower limit of approximately 0.5 m at which co-seismic and non-seismic events become indistinguishable. To address the second issue, they determined the magnitude of each by ignoring the reconstructed RSL from the first 1 to 2 cm above a peat-silt boundary where they argued that there was evidence of sediment mixing or rapid deposition. Nelson *et al.* (1998) also found it difficult to distinguish peat-silt boundaries formed by seismic or hydrodynamic causes for more than three out of ten possible events identified in southern Oregon, USA. Following paragraphs consider both of these topics further.

Identifying small co-seismic from non-seismic events

The oscillations in relative sea level below the 1964 peat-silt boundary at Kenai and Girdwood (KE-3 and GW-7, table 8.1) may represent small co-seismic submergence but it is difficult distinguishing these relative sea-level changes from non-seismic processes. As it occurs at two sites, it is likely to result from a regional or global factor, rather than local changes. Chapters 5 and 6 suggest that the advance and retreat of glaciers during the Little Ice Age may be a cause. Other authors make similar arguments for different time periods in non-seismic areas, for example, Dawson *et al.* (2002) and Firth and Stewart (2000) present evidence of glacio-isostatic adjustments in Scotland during the Younger Dryas.

Both Kenai and Girdwood record a relative sea-level rise of approximately 0.2 m and a subsequent sea-level fall of a similar magnitude, but neither shows any pre-seismic relative sea-level rise. There is no change in litho-stratigraphy at Kenai but there is an increase in silt content at Girdwood (figure 6.5 (a) and (b) and appendix 4).

For comparison of a co-seismic event represented by no clastic deposition within a stratigraphic sequence, Zong *et al.* (2003) calculated that approximately 0.15 m submergence accompanied the 1964 event at Kenai 98-13 in the raised bog environment. When looking at this core alone, the microfossil and litho-stratigraphic evidence appear no different to a small non-seismic change in sea level and are comparable to the oscillations found at Girdwood (GW-7) and Kenai (KE-1 and KE-3). It is only after investigation of other cores of the same event at the site, can changes in the raised bog be linked to the 1964 earthquake.

Similarities between these different events suggest that where magnitudes are less than 0.5 m, and may be as small as 0.2 m, it is difficult to confirm co-seismic submergence unless the event develops into a peat-silt boundary, further along the stratigraphic section. Two or more cores or exposures should be sampled for litho-, bio- and chrono-stratigraphical analyses that then indicate suddenness of submergence over tens or hundreds of metres together with a quantifiable amount of submergence.

Determination of magnitude of RSL change across a peat-silt boundary

Figure 8.1 highlights a key issue in interpreting RSL movements surrounding peat-silt boundaries. Sediment reworking immediately after the earthquake may be evident in the lower part of the clastic unit producing a mixed diatom assemblage and an intermediate reconstructed altitude (type A, figure 8.1). In accounting for this, numerous authors (e.g. Shennan *et al.*, 1996; Zong *et al.*, 2003) suggest the amount of co-seismic subsidence equals the maximum difference estimated from the marsh top and the minimum value indicated in the lower part of the overlying minerogenic sequence. However, this would overestimate the subsidence if sediment reworking results in transport of tidal flat sediments from lower altitudes onto the submerged marsh surface (type B, figure 8.1). A good example is the 1964 event at Kenai. Reconstructed values for this event (KE-4, table 8.1, figure 5.11) suggest the elevation of the overlying silt ranges from +1.01 ± 0.21 m MHHW to +0.61 ± 0.22 m MHHW in the 3 cm above the peat-silt contact, representing a RSL rise of +0.28 ± 0.22 m or +0.68 ± 0.23 m. Alternatively, with no sediment reworking recovery from the minimum value could indicate rapid post-seismic uplift. The only unbiased way to test this is to analyse multiple records of the same event at one site. Zong *et al.* (2003) calculated co-seismic submergence for the 1964 event at three other sites at Kenai to have an average value of 0.17 ± 0.12 m using diatom data and 0.31 ± 0.21 m using pollen data (note their incorrect calculation of the error term discussed in chapter 5). These observations suggest that the smaller estimate for KE-4 is more reliable and is close to the recorded value of submergence, approximately 0.27 m at Nikiski 15 km away (Plafker, 1969). Where there is evidence of sediment mixing, changes in reconstructed relative sea level (figure 8.1) can only be resolved by looking at multiple cores from the same site.

Tsunami deposits can also affect relative sea-level reconstructions around peat-silt boundaries. Typically, they would consist of coarse sand sheets that thin, fine upwards and rise in altitude towards the land (Nelson *et al.*, 1996). Bio-stratigraphic and litho-stratigraphic investigations of the sediment (e.g. Dawson *et al.*, 1996; Hemphill-Haley, 1995a) help distinguish these deposits from normal post-seismic sedimentation. None of the evidence presented in this thesis suggest a tsunami origin for any post-seismic sedimentation.

8.3 A test of the four-phase EDC model

From studying the stratigraphic evidence of the 1964 earthquake at Girdwood, Shennan *et al.* (1999) propose an EDC model with up to four main periods (sections 1.3 and 1.9):

1. Rapid co-seismic submergence (sudden relative sea-level rise) during a large magnitude earthquake (magnitude>8)
2. Rapid post-seismic uplift (relative sea-level fall) immediately following the event on the timescale of decades
3. Slower inter-seismic uplift (relative sea-level fall) on the timescale of centuries
4. Pre-seismic relative sea-level rise immediately before the next co-seismic event

Identification of these four periods is important when determining if a buried peat layer results from co-seismic submergence or non-seismic changes in addition to the criteria reviewed in Nelson *et al.* (1996). This section appraises the four-phase EDC model with reference to the summary data in table 8.1.

For the seven definite co-seismic events (table 8.1, KE-4, GW-8, GW-6, GW-4, GW-3, GW-1 and KS-1) all have a quantifiable pre-seismic RSL rise and co-seismic submergence and four of them record quantifiable post-seismic and inter-seismic RSL fall together with the effects of sediment accumulation (KE-4, GW-8, GW-6 and KS-1). Post- and inter-seismic periods were not studied above three peat-silt boundaries at Girdwood (GW-4, GW-3 and GW-1) because the principal aim in studying these individual peat-silt boundaries was to establish if they were buried by co-seismic submergence, and if so, of what magnitude. In all cases, it is difficult to differentiate between post-seismic RSL fall, inter-seismic RSL fall and sedimentation because of the possibility of sediment mixing, lack of knowledge on sedimentation rates and lack of chronology through clastic units. However, observations from the 1964 event (e.g. Brown *et al.*, 1977) indicate that post- and inter-seismic periods are separate and there is nothing in the fossil record to suggest otherwise. These results suggest that the four-phase EDC model remains valid. In contrast, the lack of key elements of this model indicates that for some burial events co-seismic and non-seismic explanations remain equally valid. For example, KE-2, KS-2 and KS-3 record no rapid or continued RSL fall in the post- and inter-seismic periods, suggesting no relative uplift contrary to the EDC model.

Relative sea-level movements surrounding the peat-silt boundaries in GW-2 and GW-5 are confusing, as they do not follow patterns of the EDC model. The overlying silt contains freshwater diatoms, in particular, *Tabellaria* species. Co-seismic submergence would lower the marsh surface into the intertidal zone resulting in deposition of a silt containing marine diatoms. Therefore, the most probable explanation is non-seismic burial, for example, a glacial outburst flood or river flooding leading to a longer-term change in sedimentation pattern. However, until a similar modern diatom assemblage is found in clastic sedimentation, it is difficult to say with any certainty under what conditions these sediments were deposited.

Improving the contemporary diatom training set would be beneficial to quantifying more precisely relative sea-level changes through the entire EDC. While the present transfer function performs exceptionally well in vegetated marsh and bog environments the error terms from tidal flat reconstructions are much larger. It is unknown how river discharge and winter ice affect the contemporary tidal flat diatom assemblages at Kenai River. Investigating contemporary surface diatoms at an open site may help improve the resolution from tidal flat environments. Zong *et al.* (2003) analysed the contemporary tidal flat to marsh transition at Portage (figure 1.4) but found poor matching analogues with the fossil diatom samples. This may result from the large discharge of freshwater from melting glaciers around the head of Turnagain Arm. Girdwood is unsuitable for a continuous contemporary diatom transect due to the ~1 m cliff at the marsh front. A possible alternative exists at Ocean View (Anchorage) where the transition from tidal flat to vegetated salt marsh is gradual and it is not greatly influenced by river discharge. Such a training set from Ocean View, where the tidal range is in excess of 10 m, would improve the scaling factor applied to fossil data to account for the differences in tidal range between sites within the upper Cook Inlet.

8.4 Pre-seismic relative sea-level rise as a precursor to a major earthquake

Shennan *et al.* (1998, 1999) and Zong *et al.* (2003) record a pre-seismic relative sea-level rise before episodes of co-seismic submergence in the Pacific Northwest of the USA and before the 1964 event in Alaska (section 1.9). Tide gauge records before the 1964 earthquake are available from Women's Bay (Kodiak Island) and Seward (Kenai Peninsula). Both locations experienced co-seismic submergence associated with the 1964 earthquake (figure 1.4) but the tide gauge measurements did not register any quantifiable pre-seismic relative sea-level rise (Savage & Plafker, 1991). One explanation is that there is differential movement between sites, for example, Cohen and Freymueller (2001) use GPS measurements to establish a different direction and rate of present day movement between Seward and Anchorage against sites along the western Kenai Peninsula. The most direct support for pre-seismic relative sea-level rise is from Karlstrom (1964) who observed that at Girdwood, storm tides that did not flood the marsh surface before 1953 began depositing a thin surface layer of silt that became progressively thicker each year. This date corresponds to the start of the pre-seismic signal identified from the microfossil data at Girdwood, dated using ^{137}Cs (Zong *et al.*, 2003).

Similar pre-seismic relative sea-level changes occur before all possible co-seismic events studied in this thesis, apart from the oscillations within peat layers (KE-3, KE-1 and GW-7 as discussed in section 8.2). Most pre-seismic signals have a distinct diatom assemblage that differs from a mixture of diatoms found in the underlying peat together with those from the overlying silt, although exceptions occur in GW-3, KS-2 and KS-3. Quantitative reconstructions suggest possible pre-seismic RSL rise ranges from +0.07 ± 0.10 m in KS-3 (although as mentioned earlier, this may be due to mixing at the peat-silt boundary) to +0.21 ± 0.10 m in KE-4 and KS-1. Results from this study also show no apparent relationship between magnitude of pre-seismic relative sea-level rise against magnitude of co-seismic submergence (figure 8.2).

The only reliable method of dating pre-seismic relative sea-level rise occurs for the 1964 event, where detection of ^{137}Cs in sediment allows a chronology back to 1954 (section 1.8.2). For other late Holocene events, the signal also occurs over a few centimetres of sediment accumulation. Although AMS dating has not helped due to the large number of age reversals through the sequence, it is unlikely to identify age differences in the order of decades. Overall, there is no evidence from this study to suggest that the pre-seismic signal occurs over a period of months as suggested by a number of studies (table 1.2). Shennan *et al.* (1999) and Zong *et al.* (2003) also indicate that a pre-seismic relative sea-level rise starts several years to a decade before the co-seismic event in 1964. These observations are important as they may represent a pre-cursor to a major earthquake.

Other possible explanations for observed pre-seismic changes

If the RSL rise does not form part of the EDC model, other possible explanations include a temporary change in sea level due to the El Nino Southern Oscillation (ENSO). ENSO can cause higher water levels along the west coast of the USA and Alaska, for example, the 1997-1998 El Nino caused a short-lived sea-level rise during the winter of approximately 0.20 m at Seldovia and Seward, Alaska (data from http://pmel.noaa.gov). Any effect before the 1964 event would be as short lived and the magnitude would be even smaller as the only El Nino as large as the 1997-1998 occurred in 1940-1942. Observations at Girdwood by Karlstrom (1964) suggest that the relative sea-level rise started in 1953 corresponds to an El Nino peak but it could not account for continued flooding of the marsh surface between 1954 and 1957 when

El Nino was weak. The short-term effect could not account for a relative sea-level rise over the period of several years to a decade and it is hard to envisage how such a process could occur before every peat-silt boundary. Other possibilities include sediment mixing around boundaries due to the flow or percolation of water (e.g. Battarbee, 1986), diatoms burrowing through the sediment column (e.g. Hay *et al.*, 1993), tidal inundation and the effects of ice.

Mulholland (2002) took an experimental approach to investigate any pre-seismic relative sea-level rise. Blocks of salt marsh sediment were extracted and transplanted into the tidal flat at Kenai, Alaska and Cowpen Marsh, UK, and sediment allowed to accumulate for up to nine months, including a very severe winter. This simulated co-seismic submergence and investigated whether mixing from any cause, including bioturbation and effects of ice, could account for the pre-seismic signal using computer modelling. Mulholland (2002) found that bioturbation is limited to a few millimetres and so it cannot account for a pre-seismic signal over a few centimetres. Bio-stratigraphical evidence from this thesis and from Zong *et al.* (2003) suggest that most pre-seismic signals have their own discrete diatom assemblages representing a transitional environment rather than a mix of the overlying and underlying assemblages. The Mulholland (2002) results offer very strong support for pre-seismic relative sea-level rise as a real component of the EDC model.

During an additional field season in April 2002, the marshes at Kenai and Girdwood were still experiencing winter conditions (section 2.7). Coverage by ice could potentially influence diatom distribution, both along the contemporary diatom transect and in fossil sequences. Due to safety constraints, no comprehensive sampling of the ice could occur and so it is unknown whether the sediment contained within the ice contains diatoms. To account for this when sampling contemporary diatom assemblages the top 1 cm of sediment was taken to allow for seasonal / annual diatom blooms and trends, including coverage by ice. In addition, when preparing fossil diatom samples, 1 cm slices account for the same considerations. When evaluating the EDC model, the role of ice may have two potentially important effects:

1. Whether it could account for the pre-seismic signal
2. Whether it could influence the registration of any co-seismic event

Ice and the pre-seismic signal

The increase in marine diatoms and relative decrease in freshwater diatoms in any pre-seismic signal could result from the mixing of diatoms during winter months. Observations in April 2002 suggest four potential processes:

1. The build up of ice on the tidal flat could potentially disturb all tidal flat sediments. However, this could not explain a pre-seismic signal contained within fully developed peat units or that recorded by pollen data (Zong *et al.*, 2003). To date, no study has investigated co-seismic events recorded within silt units.

2. The deposition of sediment from melted ice blocks is concentrated at the marsh front. This could potentially deposit diatoms onto the marsh surface that will be incorporated into the annual accumulation. However, the sediment at the marsh front is organic silt rather than fully developed peat from which this and previous studies record pre-seismic relative sea-level rise.

3. The freeze-thaw process as a mixing process. Evidence to refute this hypothesis includes the pre-seismic signal having a distinct diatom assemblage compared to the diatoms contained within the overlying silt and underlying peat. The pre-seismic signal also appears to occur over decades rather than months as it affects diatom assemblages over a couple of centimetres or more. Other evidence includes the work of Mulholland (2002) reviewed earlier in this section.

4. The melting of ice lenses and discontinuous permafrost could potentially contribute to localised submergence of the marsh surface. However, observations of the marsh surface at the three sites over five years during this and associated projects reveal no evidence to support this hypothesis. Small scale morphological features such as salt pans and shallow pools showed little change and appear to be long-term marsh features.

Ice and the registration of a co-seismic event

If large co-seismic submergence occurs whilst the mudflat and marsh surface is frozen then it could potentially affect the registration of the event within the stratigraphy. The next high tide would deposit silt onto the frozen surface. Once thawed tidal sedimentation would revert to the normal pattern but it is possible that the coincidence of frozen ground and co-seismic submergence produces a different diatom assemblage. This remains a hypothesis to test and it may be another explanation for the mixed assemblages found at the base of some silt units directly above the co-seismic peat-silt contact as discussed in section 8.2 and figure 8.1.

Mechanisms and broader perspective

If it does form part of the EDC model and occurs over several years to a decade, possible mechanisms of pre-seismic RSL rise include aseismic slip (e.g. Dragert *et al.*, 2001; Miller *et al.*, 2002). For example, tide gauge data in Japan (Katsumata *et al.*, 2002) record several centimetres of aseismic subsidence during a five year period before the 1994 Hokkaido-Toho-Oki earthquake (magnitude 8.3). Other possible mechanisms include certain seismic quiescence models (e.g. Kato *et al.*, 1997; Wyss *et al.*, 1981; Dieterich & Okubu, 1996) and section 1.10 reviews these processes. Both produce a reduction of uplift caused by inter-seismic strain accumulation (e.g. Long & Shennan, 1998). Pre-seismic RSL rise does appear to be a common feature and seismological models developed on observational data need to take account of these late Holocene relative sea-level movements.

8.5 Chronology of events

Numerous papers use radiocarbon dating to estimate recurrence intervals of great earthquakes (e.g. Atwater *et al.*, 1995; Plafker *et al.*, 1992; Combellick, 1994). Combellick (1994) suggests five main periods of co-seismic submergence around the upper Cook Inlet (figure 1.4), with a maximum of nine possible events in the past 5000 cal yr BP including:

1. The 1964 event
2. Evidence from five sites around the upper Cook Inlet suggesting co-seismic subsidence 700 to 900 cal yr BP
3. Evidence for one or two regional co-seismic subsidence events during 1100 to 2300 cal yr BP
4. Evidence from Portage and Girdwood indicating one to four events during 2400 to 3000 cal yr BP
5. Correlation between a subsidence event at Girdwood to an uplift event on Middleton Island representing a regional event 3400 to 4000 cal yr BP

New evidence from this thesis permits a reassessment of these five main periods although following figures do not include the 1964 event. Figure 8.3 (a) shows calibrated radiocarbon dates from this study from the top of peat layers and dates from the start of any pre-seismic signal, indicted by microfossil analysis (appendix 3). It highlights some of the problems associated with these dates due to the large number of age reversals through the sequence. Figure 8.3 (b) shows the best estimate for the age of burial for each peat layer using their stratigraphic position as one option for addressing the apparent age reversals. This could be resolved by redating *in situ* macrofossils for each event. Only then will it be possible to establish if co-seismic events are synchronous across the area of study. Even so, a scatter of dates will still occur due to the limitations of the radiocarbon method. The AMS results from this study (table 8.2) show the possible time intervals for separate co-seismic events (including relative sea-level oscillations KE-3, KE-1, GW-7) in the last 4000 years with these periods highlighted in figure 8.3 (b).

Table 8.2 Timing of possible co-seismic periods based on results from this study

Date cal yr BP	Maximum number of events	Evidence from
1964 AD	1	GW-8, KE-4
1954 AD to 310	1	GW-7?, KE-3?, KS-3
1182-1521	2	GW-6, KS-2, KS-1
1951-2305	1	GW-4
2472-3207	1	GW-3, KE-2
3211-3634	1	GW-1, KE-1

Between 1182-1521 cal yr BP the stratigraphy records one definite event at Girdwood (GW-6) and Kasilof (KS-1), another possible event at Kasilof (KS-2) but none at Kenai. At Kenai, this age falls within the clastic unit separating the two main peat layers and either this submergence event did not affect Kenai or the stratigraphy does not record it as a peat layer submerged into the intertidal zone at the sampling site. At two different sampling sites along the Kenai River, Combellick and Reger (1994) dated the top of a peat layer to 931-1407 cal yr BP and 1099-1387 cal yr BP indicating that this submergence event may have affected the area. Alternatively, the AMS age for the lower peat at Kenai-2000-7 may be in error but re-dating *in situ* macrofossils is required to resolve this.

These estimates (table 8.2) of possible co-seismic periods differ from those of Combellick (1994). Figure 8.4 combines the results from figure 8.3 (b) with data from Ocean View (Hamilton *et al.*, 2001) and re-calibrated dates of Combellick (1991) and Combellick and Reger (1994) from different sites around the Cook Inlet (see figure 2.1 for location). Offsets within sites indicate samples taken from different sections or cores from the same marsh. Figure 8.4 (a) shows the broad time zones suggested from the results in this study (table 8.2) as grey shaded areas and figure 8.4 (b) shows the broad time zones suggested by Combellick (1994). They only roughly correspond to one another and differ over the event dated by Combellick (1991) and Combellick and Reger (1994) approximately 800 cal yr BP. No dates from this study indicate a submergence event in this time period, but at Girdwood, the sample dated 1182-1345 cal yr BP (GW-6) comes from the same lithological unit. Therefore, the dashed line in figure 8.4 (a) indicates an apparent single, widespread event whose age cannot be resolved with present evidence to a period smaller than 700-1521 cal yr BP.

The scatter of ages in figure 8.4 highlights some of the problems associated with using radiocarbon dating to estimate regionally synchronous co-seismic events. Numerous authors (e.g. Combellick, 1994; Nelson *et al.*, 1996; Shennan *et al.*, 1998) question the use of conventional radiocarbon dates on bulk peat samples up to 5 cm thick as used in the majority of studies. Such dates generally give older ages than plant macrofossils dated by AMS as they include organic carbon from plants that died previously and from the accumulating sediment body (Atwater *et al.*, 1995; Nelson, 1992; Nelson *et al.*, 1995). As the AMS dates on 0.5 to 1 cm thick bulk peat samples in this study have so many reversals within each sequence, the limitation of incorporated older carbon still applies. Re-dating *in situ* macrofossils rather than bulk peat samples could resolve these dating issues but until then, it is difficult to say whether events are synchronous at different sites.

Despite these limitations, results from this study have some important implications for earthquake recurrence intervals. Some of the peat layers observed in stratigraphic sequence in the same borehole or exposure have very similar ages. For example, KS-1 and KS-2, and the middle samples from GW-1 and GW-3 suggest that multiple events may have occurred within 200 or 300 years of each other or less. This indicates that the average earthquake recurrence interval for this area, approximately 600 to 800 years (Combellick, 1991, 1994, 1997; Combellick & Reger, 1994; Plafker *et al.*, 1992; Plafker & Rubin, 1992) hides the fact that intervals between events may be significantly shorter and has potential significance for future planning and building regulations.

The two events highlighted by red squares (figure 8.4) represent dates obtained from the top of the peats for events GW-2 and GW-5 (table 8.1). Microfossils in the overlying silt, particularly, *Tabellaria* species, indicate a freshwater environment, and so these peat-silt boundaries are different to the others. They lie within the time bands of submergence events suggested by Combellick (1994) and so question whether these and other non-seismic events have been included in calculation of recurrence intervals.

Other problems relating to the synchroneity of events and estimation of recurrence intervals occurs when tidal flats do not recover back to developed marsh in-between two co-seismic events (e.g. a possible event 1182-1521 cal yr BP recorded at Girdwood and Kasilof, but in the clastic unit along the transect of cores at Kenai). As seen in chapters 4 through 7, quantitative transfer functions are less precise at reconstructing relative sea- and land-level changes through silt units, making identification of periods within the EDC model difficult in silt units alone.

8.6 Is the 1964 event a good model for other late Holocene events?

This section considers whether the 1964 earthquake is typical of other late Holocene events in terms of the pattern and magnitude of sea- and land-level changes and therefore whether it is useful as a model to understand these repeated events. The alternative is that each event differs significantly in terms of pattern and magnitude of displacement and hence inferred movement along different sections of the plate boundary.

Within the error terms of the RSL reconstructions (table 8.1), the magnitude of submergence is generally similar for all late Holocene events when compared to the 1964 earthquake. The mean estimate for the 1964 event at Girdwood is slightly larger than the mean values for most of the others (table 8.1) and this may explain why some are not recorded in the stratigraphy at Kenai, where relative sea-level changes associated with the 1964 event were quite small. The one exception is event KS-1 / GW-6 where the magnitude of co-seismic submergence at Kasilof is 0.94 ± 0.30 m. Combellick and Reger (1994) may have identified this event at Kenai, but ages from KE-2000-7 suggest that this event falls within the thick clastic unit between the two main peats, as discussed in section 8.5. The large amount of submergence at Kasilof compared to the 1964 event may suggest a different pattern of deformation and perhaps a different fracture zone along the plate boundary.

8.7 Importance of seismic compared to non-seismic controls on RSL

This section aims to investigate the balance between seismic and non-seismic controls on relative sea level. The following equation shows their relationship at time τ and location φ (Shennan & Horton, 2002):

$$\Delta\xi_{rsl}(\tau,\varphi) = \Delta\xi_{eus}(\tau) + \Delta\xi_{iso}(\tau,\varphi) + \Delta\xi_{local}(\tau,\varphi) + \Delta\xi_{tect}(\tau,\varphi) \qquad \text{(Equation 1)}$$

where $\Delta\xi_{eus}(\tau)$ is the eustatic function over time, $\Delta\xi_{iso}(\tau,\varphi)$ is the total glacio-isostatic and hydro-isostatic load contributions, $\Delta\xi_{local}(\tau,\varphi)$ is the effect of local processes and $\Delta\xi_{tect}(\tau,\varphi)$ is the combination of pre-seismic, co-seismic, post-seismic and inter-seismic movements. It shows that if pre-seismic and co-seismic submergence equals post- and inter-seismic uplift the tectonic component is zero over the long term and relative sea-level changes are equal to the balance between eustasy, isostasy and local factors. Local processes are equivalent to (Shennan & Horton, 2002):

$$\Delta\xi_{local}(\tau,\varphi) = \Delta\xi_{tide}(\tau,\varphi) + \Delta\xi_{sed}(\tau,\varphi) \qquad \text{(Equation 2)}$$

where $\Delta\xi_{tide}(\tau,\varphi)$ is the effect of changing tidal regimes over time and $\Delta\xi_{sed}(\tau,\varphi)$ is the effect of sediment consolidation. Sediment consolidation can occur under two scenarios. The first is due to ground shaking during an earthquake and the second is the effect of loading on top of buried sediments.

Figure 8.5 shows a schematic model of co-seismic submergence, post- and inter-seismic uplift, sediment accumulation and marsh burial. It suggests that the occurrence of multiple peat-silt couplets below present marsh surface can occur under three different conditions. Without any background sea-level change, post- and inter-seismic uplift must be less than co-seismic subsidence (A). If co-seismic submergence equals post-and inter-seismic uplift, different peat layers would be super-imposed on top of one another (B). Where there is non-seismic sea-level rise, inter-seismic uplift can be less than (C) or equal co-seismic submergence (D).

Not shown in figure 8.5 is the scenario where post- and inter-seismic uplift is greater than co-seismic submergence resulting in long term uplift. With no non-seismic sea-level rise, this leads to emergence of marshes above present and oxidation of peat. This is not observed and so not considered further. With non-seismic sea-level rise a variation of scenario D occurs where $\Delta\xi_{int}(\tau)$ is less than the sum of $\Delta\xi_{cos}(\tau)$ and $\Delta\xi_{rsl}(\tau)$ allowing preservation of buried peat layers.

The following equation represents the changes between two events at a single location:

$$\Delta\xi_{int}(\tau) = \Delta\xi_{rsl}(\tau) + \Delta\xi_{cos}(\tau) - \Delta\xi_{sed}(\tau) - \xi_{peat}(\tau) \qquad \text{(Equation 3)}$$

where $\Delta\xi_{int}(\tau)$ represents post- and inter-seismic uplift, $\Delta\xi_{rsl}(\tau)$ is non-seismic sea-level change over the time period in question, $\Delta\xi_{cos}(\tau)$ equals co-seismic submergence accompanying an earthquake, $\Delta\xi_{sed}(\tau)$ is sedimentation between the tops of two peat layers and $\xi_{peat}(\tau)$ is the difference in the formation height of the top of the first buried peat ($\xi_{peat1}(\tau)$) and the formation height of the top of the second buried peat ($\xi_{peat2}(\tau)$).

Figure 8.6 plots the age of buried peat layers against depth below contemporary marsh surface using radiocarbon dates from this study and recalibrated dates from Combellick (1991) and Combellick and Reger (1994). As well as data from Kenai, Girdwood and Kasilof, it includes data from Ocean View (Hamilton *et al.*, 2001), Portage and Chickaloon Bay (Combellick & Reger, 1994). Figure 8.6 also includes two general sea-level curves. Curve 1 is based on an estimate for eustatic sea-level rise by Fleming *et al.* (1998), of 1.03 $mmyr^{-1}$ with no significant oscillations between 7000 and 4000 cal yr BP, and a slower rate of 0.35 mm yr^{-1} between 4000 cal yr BP and the present day. Curve 2 is based on the ICE-4G and ICE-5GP models proposed by Peltier (2002) that predict current relative sea-level rise of approximately 0.5 ± 0.5 $mmyr^{-1}$ in south central Alaska due to glacio-isostatic adjustments (GIA).

In this area, numerous authors assume glacio- and hydro-isostatic effects from the LGM were complete by approximately 7000 cal yr BP (e.g. Combellick, 1994). The main reason behind this assumption is its proximity to the Alaska-Aleutian subduction zone, where the mantle has a lower viscosity and the lithosphere is thinner than in areas located further away. Others make comparable arguments in the Pacific Northwest of the USA and Canada to suggest postglacial rebound was complete by the early Holocene (e.g. Matthews *et al.*, 1970; Clague *et al.*, 1982; Williams & Roberts, 1989). In contrast, RSL data indicates ongoing isostatic rebound from central Washington down to central Oregon equal to approximately 0.25 ± 0.02 $mmyr^{-1}$ 100 km^{-1} (Long & Shennan, 1998). Until better modelling of the area occurs, this factor remains unknown. For south central Alaska, other evidence to suggest absence of longer-term uplift following deglaciation includes the submerged glacial cirques along the south coast of the Kenai Peninsula (Plafker & Rubin, 1967). Given the present evidence, the two general sea-level curves form the starting point for further analysis, on the assumption that they represent reasonable estimates of non-seismic relative sea-level change ($\Delta\xi_{rsl}(\tau)$).

Two groupings become apparent from figure 8.6. With $\Delta\xi_{rsl}(\tau)>0$, i.e. non-seismic relative sea-level rise, scenarios C or D apply (figure 8.5). Data from Kenai and Kasilof plot very close to curves 1 and 2, suggesting that net sedimentation at these sites equals non-seismic sea-level rise (figure 8.5, scenario D). If this were not the case, the observations would plot below the background curves. Therefore, relative sea-level changes equate to:

$$\Delta\xi_{rsl}(\tau) = \Delta\xi_{sed}(\tau) \qquad \text{(Equation 4)}$$

and

$$\Delta\xi_{int}(\tau) = \Delta\xi_{cos}(\tau) \qquad \text{(Equation 5)}$$

This agrees with the findings of Long and Shennan (1998) in the Pacific Northwest of the USA who suggest that negligible permanent deformation occurs during an earthquake cycle. Kelsey *et al.* (1994) also indicate that permanent deformation averaged over many earthquake cycles is low, ranging between 1 and 8%.

The second grouping includes Portage, Girdwood, Ocean View and Chickaloon Bay, all of which lie along the shore of Turnagain Arm. These sites do not follow either pattern of non-seismic relative sea-level change as indicated by curves 1 and 2 as buried peat layers are significantly deeper below present marsh surface. At these sites relative sea level equates to (figure 8.5, scenario C):

$$\Delta\xi_{rsl}(\tau) < \Delta\xi_{sed}(\tau) \qquad \text{(Equation 6)}$$

therefore

$$\Delta\xi_{int}(\tau) < \Delta\xi_{cos}(\tau) \qquad \text{(Equation 7)}$$

over the long term. Solving equation 3, using 0.5 ± 0.5 mmyr^{-1} as the background sea-level change (Peltier, 2002) estimates the relative magnitudes of co-seismic against post- and inter-seismic movements (table 8.3). Estimates of age, relative sea-level changes and sediment accumulation for pairs of events at Girdwood suggest 70 to 90% recovery of co-seismic submergence during post- and inter-seismic uplift (table

8.3). However, large error terms, when taking into account the age ranges, are associated with these calculations and would increase the range of estimates to 50 to 100% recovery. Therefore, at present, it is difficult to establish whether all events have the same amount of recovery.

Table 8.3 Amount of recovery during post- and inter-seismic periods at Girdwood

Events	$\Delta\xi_{rsl}(\tau)$ (m)	$\xi_{peat}(\tau)$ (m)	$\Delta\xi_{sed}(\tau)$ (m)	$\Delta\xi_{cos}(\tau)$ (m)	$\Delta\xi_{int}(\tau)$ (m)	$\Delta\xi_{int}(\tau)$ / $\Delta\xi_{cos}(\tau)$ x 100 % recovery
GW-6 and GW-8	0.65	0.04	1.1	1.74	1.33	76
GW-4 and GW-5	0.04	0.11	0.64	1.65	1.16	70
GW-3 and GW-4	0.47	0.09	0.57	1.75	1.56	89

Inherent in these calculations is the amount of consolidation that occurs due to ground shaking during an earthquake and by the accumulation of sediment on top of older sediment. During the 1964 event, Plafker *et al.* (1969) estimate up to 0.9 m of local compaction at Girdwood as an unknown thickness of unconsolidated material lies beneath the marsh. This represents approximately 40% of the 2.4 m total submergence. Similar effects for previous events would mean that the value for percentage recovery quoted above (table 8.3) could be a significant under-estimate. With such a scenario, post- and inter-seismic uplift is much closer to the amount of co-seismic subsidence and the extra submergence is the result of sediment consolidation. Over numerous EDC cycles, sediment consolidation may have a dramatic effect and could be a significant factor in explaining the plot of the Turnagain Arm data below the predicted eustatic (curve 1) and GIA RSL (curve 2) models. To get a precise measure of consolidation during an event, sea-level index points are required on till or bedrock, so that the effects of consolidation are kept to a minimum.

Another possible explanation for the difference between the Turnagain Arm sites and Kenai/Kasilof is the difference in tidal range through time. A number of studies model increases in tidal range over the Holocene, for example, Gehrels *et al.* (1995) and Scott and Greenberg (1983) in the Bay of Fundy/Gulf of Maine and Austin (1991) in the North Sea. Shennan and Horton (2002) also modelled increases in tidal range over the past 3000-4000 cal yr BP, particularly within the large estuaries along the east coast of England. For the Humber, they suggest a 2.5 m reduction in the height of mean high tide above mean tide level. A similar effect, upscaled for the larger tidal range in the Turnagain Arm would give a comparable figure of 3.5 to 4.0 m. This would bring the values in figure 8.6 for sites around the Turnagain Arm closer to curves 1 and 2, suggesting that the magnitude of post- and inter-seismic uplift equals co-seismic submergence. This is an important hypothesis that future modelling studies can test.

8.8 Summary and areas for future research

The novelty of this research is the successful analysis of multiple co-seismic events at three sites around the upper Cook Inlet, including the analysis of at least one complete EDC cycle at each site. Quantitative transfer functions allow reconstruction of relative sea-level changes through the four-phase EDC model and together with the criteria of Nelson *et al.* (1996) provide a level of confidence in interpreting a peat-silt boundary as representing co-seismic submergence. The analyses described in preceding sections provide a more robust separation of co-seismic and non-seismic processes than Shennan *et al.* (1996, 1998) in which the quantitative methods only worked well at one site. One immediate advance would be the application of the transfer function approach to data collected by Shennan *et al.* (1996, 1998) from Johns River (Washington) and Netarts Bay (Oregon) to enable a quantitative reconstruction of relative sea-level change through numerous EDC cycles in the Pacific Northwest. Future analyses from Alaska and comparable subduction zone environments should aim to include the criteria of Nelson *et al.* (1996) along with quantitative reconstructions through complete cycles.

This study describes five definite late Holocene co-seismic events at Girdwood and one each at Kenai and Kasilof, with further possible events at all three sites. Three of these are not observed as sharp peat-silt boundaries and may be interpreted as glacio-isostatic response to ice sheet advance and retreat. The most recent RSL oscillations at Girdwood and Kenai coincide with evidence of glacier movements during the Little Ice Age. This hypothesis requires further testing, but if the correlation is firmly established, it provides an excellent set of observations to test models of earth rheology in areas of thin lithosphere. Such areas are not usually considered in the global models (e.g. Peltier, 1998, 2002).

A key element of this thesis is the identification and quantification of pre-seismic relative sea-level rise before all those events attributed to co-seismic submergence. The magnitude of pre-seismic relative sea-level rise, up to +0.21 ± 0.10 m, shows no correlation to the magnitude of co-seismic submergence. The change typically occurs over 1 to 5 cm of sediment and is dated at Kenai and Girdwood (for the 1964 earthquake) to start approximately 10 years before the event. This is strong evidence to suggest it represents a precursor to a large event and independent work elsewhere describe possible mechanisms for this phenomenon (section 1.10).

The precise chronology of events in Alaska remains problematic. Conventional radiocarbon dates on bulk peat samples 1 to 5 cm thick and AMS dates on bulk peat samples ~0.5 cm thick give numerous age reversals around peat-silt boundaries due to possible sediment mixing. Until extensive dating of *in situ* macrofossils takes place, it is difficult to advance earthquake recurrence intervals. Peat-silt boundaries produced by non-seismic processes, for example, the two identified at Girdwood where the overlying silt is characterised by halophobe diatoms further complicate the calculation of earthquake recurrence intervals. Nevertheless, there are six periods of co-seismic submergence, including 1964, in the last 4000 years spaced at irregular intervals.

Quantitative reconstructions suggest that at each site, submergence resulting from most co-seismic events studied are of similar magnitude to the 1964 earthquake. One limitation is that contemporary tidal flat diatom assemblages from Kenai vary little over a large altitudinal range and so the transfer function approach has difficulty reconstructing altitudes for some fossil tidal flat samples. Possible explanations include the effect of the Kenai River and the action of ice over the winter months. Examination of contemporary tidal flat samples from Ocean View, Anchorage and Girdwood may help solve this difficulty and investigate whether the lack of distinct tidal flat assemblages at Kenai is a local phenomena or a regional trend. An alternative approach is to consider other microfossil groups. Shennan *et al.* (1999) report some success in using foraminifera and thecamoebians but initial investigations at Kenai (Hamilton, 1998) show their preservation is poor. Zong *et al.* (2003) obtain good results using pollen from peat layers, but the interpretation uses qualitative methods, while Hughes *et al.* (2002) apply a pollen transfer function to comparable sediments in the Pacific Northwest. Similarly Roe *et al.* (2002) demonstrate the use of testate amoebae. Both pollen and testate amoebae could be particularly useful where diatoms are poorly preserved, such as in the peat at G-01-1A.

From investigations at only three sites it is not possible to identify whether pre-1964 events affected the same area and hence location and length of the rupture zone. To do this, and to investigate patterns of co-seismic uplift, further regional work is required around Prince William Sound, Kodiak Island and Copper River Delta. In addition, long-term patterns of relative sea-level change show significant differences between sites around Turnagain Arm compared to Kenai and Kasilof. At Kenai and Kasilof, there is negligible permanent deformation over multiple earthquake deformation cycles but this is not the case at sites around Turnagain Arm. Before attributing this to only partial recovery between events, other factors deserve further attention, especially sediment consolidation, tidal range change through time and improvements in GIA modelling taking into account local ice sheet reconstructions.

Identification of a pre-seismic relative sea-level rise and the ability to quantify changes throughout a whole EDC presents an innovative challenge to the geophysical and seismological modelling communities to validate their models. These modelling studies currently depend upon tide gauge and GPS observations over the last 50 years, or in most cases a significantly shorter period. Integration of these modelling approaches with the palaeo-environmental evidence from multiple events and through complete earthquake deformation cycles offers a tremendous opportunity to advance understanding of great earthquakes in subduction zone locations around the world including Alaska, Chile, Japan and the Pacific Northwest of the USA and Canada.

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