Spatial and Temporal Patterns of Deformation Associated with Multiple Late Holocene Earthquakes in Alaska

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Investigators: Ian Shennan, Antony Long, Natasha Barlow and Emma Watcham

Sea Level Research Unit
Department of Geography
University of Durham
Durham
DH1 3LE
United Kingdom

In collaboration with Rod Combellick

Alaska Division of Geological and Geophysical Surveys
Fairbanks, Alaska, USA

Telephone: +44 191 334 1934
Fax: +44 191 334 1801
Email: ian.shennan@durham.ac.uk
URL: http://www.geography.dur.ac.uk

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Ian Shennan, Antony Long, Natasha Barlow and Emma Watcham
Sea Level Research Unit, Department of Geography, University of Durham, Durham, DH1 3LE, UK
Telephone: +44 191 334 1934
Fax: +44 191 334 1801
Email: ian.shennan@durham.ac.uk
URL: http://www.geography.dur.ac.uk

Technical Abstract

This project was formulated around three research questions:

1. Can locally-developed diatom transfer function models from Cook Inlet improve the vertical (elevation) precision of geologic estimates of land level changes from great Holocene plate boundary earthquakes elsewhere in Alaska?
2. How do spatial patterns of estimated land level changes for different Holocene plate boundary earthquakes vary?
3. Are great earthquake ruptures in Alaska controlled by persistent segment boundaries or do the rupture areas overlap?

From a field campaign based out of Cordova and using jet-boat and fixed-wing aircraft we accessed sites in Copper River Delta, at Okalee Spit and the marshes behind the spit, west of Cape Suckling. Intertidal outcrops along a 12km section of Alaganik Slough and the lower part of Pete Dahl Cutoff provided exposures of two peat-silt couplets, with a third revealed by coring. At the mouth of Alaganik Slough we collected modern surface sediment samples from low tide to above high tide level. These modern samples provided the foundation of a local scale Gulf of Alaska diatom transfer function model. Surveys at Oklaee Spit aimed to quantify elevation differences between modern coastal landforms and similar features uplifted in AD1964 and provide fossil cores. Laboratory analyses of modern and fossil diatoms allow us to compare the performance of local modern diatom training sets (Gulf of Alaska) and a regional modern diatom training set (combining the Gulf of Alaska data with our previous data from upper Cook Inlet).

We have successfully addressed the three research questions set out above, and highlight six main conclusions.
(1) Our present Gulf of Alaska modern diatom training set is too small to reflect the range of environments found within large deltas, giving too many poor analogues in fossil reconstructions;
(2) Small marshes, such as those around Cook Inlet, are easier to model, in terms of the relationship between diatom assemblages and elevation, than the marshes at Copper River Delta and Cape Suckling.
(3) Regional diatom datasets reduce reconstruction error terms where there is a good modern analogue.
(4) We can identify different spatial patterns of coseismic deformation during Late Holocene great earthquakes.
(5) In terms of earthquake hazard assessment, comparison of the last four great earthquakes (1964, ~500 BP' ~900 BP, ~1500 BP) show three different modes of plate segmentation and four different spatial extents of surface deformation.
(6) Multi-segment earthquakes ~900 and ~1500 years ago, involving simultaneous rupturing of the megathrust from Cook Inlet in the west to the Pamplona – Malaspina thrust front in the east did not lead to enhanced vertical deformation around Cook Inlet compared to 1964.

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Sea Level Research Unit, Department of Geography, University of Durham, Durham, DH1 3LE, UK
Telephone: +44 191 334 1934
Fax: +44 191 334 1801
Email: ian.shennan@durham.ac.uk
URL: http://www.geography.dur.ac.uk

Non-Technical Abstract

New analyses of sediment cores at Copper River Delta and Cape Suckling reveal land uplift during great earthquakes. We are not at the stage of providing precise measures of uplift for each event due to the complexity of environments found within large deltas. In terms of earthquake hazard assessment in Alaska, comparison of the last four great earthquakes (1964, ~500 BP' ~900 BP, ~1500 BP) show three different modes of plate boundary segmentation and four different spatial patterns of surface deformation.

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1 Context

Future earthquake prediction in the U.S. and minimisation of loss requires geologic evidence to estimate how often, where and what magnitude plate boundary earthquakes have occurred over the Holocene. This project applies temporal and vertical techniques to better understand long term records of Holocene paleoseismicity and associated land/sea-level movements in south-central Alaska from sedimentary sequences in the eastern sector of the 1964 rupture: Cook Inlet, the Copper River Delta and the coast of the Gulf of Alaska, including Cape Suckling and Bering Glacier foreland (Fig. 1). It builds on previous work undertaken by the principal investigators, specifically late Holocene earthquakes and relative sea-level movements in the Pacific Northwest of the USA and Alaska, together with the development of diatom transfer functions to quantify relative land and sea-level changes. Our current investigations quantify ground displacements affecting upper Cook Inlet for seven great earthquakes during the last 4000 years (Hamilton and Shennan, 2005a; Hamilton *et al.*, 2005; Hamilton and Shennan, 2005b; Shennan and Hamilton, 2006). The broader spatial pattern of co-seismic and interseismic deformation beyond upper Cook Inlet is not known for multiple events prior to the 1964 event. Thus, we do not know whether the spatial pattern of deformation observed for each event is the same or different. This limits our ability to test models of plate boundary rupture that require spatial data regarding relative land and sea-level data over multiple events. These models are key to developing predictions of future seismic hazard in Alaska and on other plate boundaries.

1.1 The earthquake deformation cycle in south-central Alaska

Coastal wetlands in the Pacific Northwest are excellent environments for registering late Holocene seismic activity and associated relative sea-level changes due to their low energy depositional setting and their sensitivity to sea-level change. The research status in south-central Alaska, on the Alaska-Aleutian plate boundary, differs to that found in the more intensively studied Cascadia subduction zone. A large (M_w=9.2) and well-documented plate boundary earthquake struck this region on March 27th, 1964. Observations made before and after this event provide important information on pre- and post-seismic land and sea-level movements (Karlstrom, 1964; Plafker, 1965, 1969; Brown *et al.*, 1977; Savage and Plafker, 1991; Plafker *et al.*, 1992; Freymueller *et al.*, 2000; Atwater *et al.*, 2001). No similar data exist for Cascadia where the last great boundary earthquake occurred some 300 years ago (Atwater, 1987, 1992; Atwater *et al.*, 1995; Nelson *et al.*, 1995). The 1964 Alaska earthquake therefore provides a well-defined benchmark to assess methods and models that provide reconstructions of earlier events.

Using the framework of the 1964 event and the established criteria (Nelson *et al.*, 1996), previous research suggests a four phase earthquake deformation cycle (EDC) (as demonstrated in Fig. 2) associated with a series of Holocene earthquakes in south-central Alaska. The research presents a chronology of palaeo-earthquakes from four sites around the Cook Inlet, Girdwood, Anchorage, Kenai and Kasilof (Hamilton and Shennan, 2005a; Hamilton *et al.*, 2005; Hamilton and Shennan, 2005b; Shennan and Hamilton, 2006).

This project aims to (a) extend our paleoseismic record beyond Cook Inlet to the spatial limit of the 1964 rupture, and (b) develop our quantitative methods, based on diatom transfer function models, for application beyond Cook Inlet. Our field and laboratory techniques are now established and capable of resolving quantitative reconstructions of land/sea level changes for Cook Inlet with a precision of ±0.1 m to ±0.3 m. We focus on three main research questions:

1. Can locally-developed diatom transfer function models from Cook Inlet improve the vertical (elevation) precision of geologic estimates of land level changes from great Holocene plate boundary earthquakes elsewhere in Alaska?
2. How do spatial patterns of estimated land level changes for different Holocene plate boundary earthquakes vary?

3. Are great earthquake ruptures in Alaska controlled by persistent segment boundaries or do the rupture areas overlap?

1.2 Local vs regional diatom transfer functions (Research Question 1)

In order to extend the spatial scale of study beyond Cook Inlet we must first establish the applicability of transfer function models developed at the local scale, Cook Inlet, to the regional scale, Copper River Delta and the Gulf of Alaska coast.

In our last NEHRP project (Shennan *et al.*, 2007, USGS grant award # 06HQGR0033) we investigated a sequence at Alaganik Slough on the Copper River Delta, and diatom analyses showed a shift in salinity preferences across the peat-silt boundary at ~600 yrs BP. However, when we used the modern diatom dataset from upper Cook Inlet to reconstruct land/sea-level change, we found little elevation change across the boundary, without the degree of uplift suggested by the lithology or if we were to expect a similar pattern of co-seismic deformation compared to AD1964. The Modern Analogue Technique showed none of the Alaganik Slough fossil samples had a close modern analogue to the Cook Inlet modern training set. This raises the critical question of whether we can use locally-developed diatom transfer models from Cook Inlet to estimate land level changes from earthquakes elsewhere in Alaska.

Therefore in this project we develop a new "Gulf of Alaska modern training set" by collecting new modern samples from the Copper River Delta to combine with the 22 collected from Hartney Bay during our 2007 NEHRP project. This will enable comparison of elevation reconstructions for fossil sites using the Cook Inlet modern training set, Gulf of Alaska modern training set, and a "south-central Alaska modern training set" that is a combination of the two.

1.3 Spatial patterns of land level changes and earthquake rupture areas (Research Questions 2 & 3)

Previous investigations of multiple late Holocene earthquake events in Cook Inlet suggest different spatial patterns of co-seismic subsidence for the 1964, ~900 BP and ~1500 BP great earthquakes (Hamilton and Shennan, 2005a; Hamilton *et al.*, 2005; Hamilton and Shennan, 2005b; Shennan and Hamilton, 2006). One hypothesis to explain these differences is that they record variations in the location, extent or depth of the rupture zone. Testing this hypothesis is important if we are to reduce uncertainties regarding the nature of future earthquake hazard in south central Alaska and improve our understanding of the nature of past earthquake ruptures in this region.

Here we study four additional sites beyond the Cook Inlet to address the issue of spatial variability; two that recorded substantial co-seismic subsidence or uplift during the 1964 earthquake and two towards the periphery of this zone. The chosen sites lie along a transect across the zones of subsidence and uplift (Fig. 3), and enable us to identify the spatial variability and locations of maximum uplift and subsidence along the same transect. Cape Suckling also lies on the boundary with the Yakutat microplate (Fig. 4). The combination of evidence of pre-1964 co-seismic deformation at Copper River Delta and Cape Suckling and of glacio-isostatic change at Bering Glacier foreland allow us to determine whether great earthquake ruptures in Alaska are controlled by persistent segment boundaries or whether the rupture lengths overlap.

2 Field Investigations

Field investigations took place during August 2009, with extensive coring and sample collection at Hope and Bird Point, Turnagain Arm; Alaganik Slough, Copper River Delta; Okalee Spit and Cape Suckling Marsh, Cape Sucking and Tashalich Arm, Bering Glacier. All collected samples were wrapped in plastic and stored in a fridge at Durham on return to the UK.

2.1 Hope and Bird Point, Turnagain Arm, upper Cook Inlet

Previous investigations by Barlow (2010) and further work in August 2009 (Fig. 5) reveals delta sedimentation at Hope dominated by glacial-fluvial outwash from Resurrection and Bear Creeks, with cores from the centre of the marsh mainly consisting of silty-clay with gravel and limited organic matter. The top of the sequence (0 – c.150 cm) at the western end of the marsh (HP-09-8) comprises a silty-clay underlain by a silty-clay with organic laminations, unlike the well-developed pre AD 1964 peat recorded elsewhere in upper Cook Inlet (Hamilton *et al.*, 2005; Shennan *et al.*, 2008). Barlow (2010) suggests the sedimentation at the top of the sequence at Hope is a likely a consequence of rapid development at Hope and nearby Sunrise from AD 1890 to 1940 due to gold mining in the area. Below the disturbed upper sediments, are a series of peat-silt couplets, similar to those at Ocean View and Girdwood (Hamilton *et al.*, 2005; Shennan *et al.*, 2008). We collected samples at 106-156, 251-277, 310-346 and 382-406 cm over the peat-silt boundary of four couplets at HP-09-8.

Due to the lack of horizontally traceable sediments at Hope, we also cored a series of peat-silt couplets at Bird Point where Barlow (2010) records the lateral extent of the upper two couplets, the boundaries of which are dated to be a consequence of the AD 1964 and 900 yr BP earthquakes (Fig. 6). We recorded five peat-silt couplets over c. 5 m at BP-09-1 and collected samples over the lower three peat-silt boundaries to complement the previous work at the site.

2.2 Alaganik Slough, Copper River Delta

Previous work at Alaganik Slough in August 2006, under bank full conditions (Shennan *et al.*, 2007), revealed two peat layers at AS/06/1 (Fig. 7) as documented by Plafker *et al*. (1992). More favourable weather conditions in 2009 allowed us to view the upper peat layer and, in places, the second peat, along the banks of Alaganik Slough from AS/06/1 downstream to the location of our contemporary transect at the mouth of the Slough (Fig. 7). Coring along Alaganik Slough and lower Pete Dahl Slough reveals three peat-silt couplets, which correspond with the couplets recorded by Plafker *et al*. (1992), with an additional previously unrecorded third couplet found at AS/09/3 at ~2.5 m. We collected a series of samples over silt-peat boundaries of the three couplets at the sites in Fig. 7

To calibrate any elevation changes recorded by the fossil diatoms through the peat-silt couplets we collected 46 modern surface samples from the marsh and tidal flat surface at the mouth of Alaganik Slough (Fig. 7). We chose to focus our sampling on the lower part of the delta where freshwater input from the Copper River was likely to have the minimal influence on diatom distribution. We levelled each sample elevation to high tide and converted the elevations relative to MHHW using NOAA data (http://www.co-ops.nos.noaa.gov/) for the tide gauge at Cordova and tidal predictions at Pete Dahl Slough. MHHW allows comparison with the modern samples from Cook Inlet (Hamilton and Shennan, 2005a) and Hartney Bay (Shennan *et al.*, 2007) and therefore development of a combined Gulf of Alaska and Cook Inlet diatom training set.

2.3 Okalee Spit and Cape Suckling Marsh, Cape Suckling

Under our original proposal, we intended to collect a series of modern samples and two pre AD 1964 fossil cores from Cape Suckling Marsh. The collapse of the proposed Bering Glacier field camp meant we were unable to access the helicopter required to core the required sites at the back of the marsh,

which are inaccessible by foot due to large tidal creeks. A series of chartered flights in a small bush plane allowed us to land on the beach at Okalee Spit for a short time around low tide, from which we conducted levelling transects across a series of raised beach berms and dunes that form the spit (Fig. 8). These raised features reflect co-seismic uplift and therefore the measured relative elevation of each beach surface provides estimates of the magnitude of coseismic displacement.

Using a shovel, we were able to collect one fossil section (0 – 50 cm) from the seaward portion of Cape Suckling Marsh, in the lee of Okalee Spit (Fig. 8). We also collected 14 modern samples from the surface of the contemporary beach and back barrier marsh to provide analogues for the fossil diatom assemblages. Due to the limitations of having to work during low tide conditions, it was not possible to level the elevation of the modern samples to repeated high tides and therefore we are able not calculate the elevation of the samples relative to MHHW.

2.4 Tashalich Arm, Bering Glacier

The collapse of the proposed Bering Glacier field camp meant, similarly to Cape Suckling Marsh, we were unable to carry out our intended work around the Bering Glacier foreland. Chartering a floatplane allowed us to land in Vitus Lake, in front of Bering Glacier, for a short period to collect samples from Tashalich Arm. Shennan (2009) documents the presence of an area of Cretaceous rock on the east shore of Tashalich Arm that is becoming exposed following glacial retreat, revealing fossil burrows formed by *Penitella penita*, a low intertidal to shallow subtidal (to 22 m) rock-boring species common on muddy shores around the Gulf of Alaska (Rehder, 1981). From a newly exposed area of rock outcrop we found examples of secondary occupation of *Penitella penita* burrows, both by individuals of the same species and by *Prototheca staminea*. These bivalves are infaunal, typically buried about 0.1 m in gravel/sand/mud substrate and occur from the mid intertidal zone to 10 m depth. Some of the sediments filling the bivalves contain foraminifera and diatoms. Analyses of these may give further detail on relative water depths and hence sea level. We collected three fossil *Prototheaca* found in their growth position from a newly exposed area of rock for radiocarbon dating, to add to the data in Shennan (2009) and provide further constraint on the timing of a early to mid Holocene sea level highstand.

3 Methods

We follow standard procedures, previously reported (Shennan *et al.*, 2003) and reproduced as Appendix A. Laboratory analysis focuses on diatom analysis of the modern and fossil sediments and radiocarbon dating.

4 Results

4.1 Research Question 1 – Can locally-developed diatom transfer function models from Cook Inlet improve the vertical (elevation) precision of geologic estimates of land level changes from great Holocene plate boundary earthquakes elsewhere in Alaska?

We developed a new Gulf of Alaska modern training set, made up of 34 samples from Alaganik Slough (Fig. 9) and 22 samples from Hartney Bay (Fig. 10, collected in 2006 for our last NEHRP project). Unfortunately, we could not include the samples collected from Cape Suckling in the training set, as we were not able to accurately level the elevation of the samples relative to MHHW (section 2.3). However, a sample number of 56 still exceeds the minimum (25) required to give sample-specific error terms in reconstructing elevation and our experience in Cook Inlet indicates >50 is necessary to

capture a diversity of assemblages and elevations to help minimise poor modern analogues for fossil assemblages.

In this new Gulf of Alaska training set, there is a general trend in the diatom samples relative to elevation (Fig. 11). At the highest elevations, halophobous and oligohalobous-indifferent species dominate samples found above a standardised water level index (SWLI) of 240 (acidic bog). Samples found between SWLIs of 180 and 240 contain species from all halobian classes, with equal abundances of mesohalobous through to halophobous species, and samples between SWLIs of 100 (mean sea level) and 180 are dominated by mesohalobous and oligohalobous-halophilous species. However, it appears that factors other than elevation control diatom distribution in samples below a standardised water level index of 100, with species of all halobian classes present in equal abundances. We speculate that this may reflect their sampling position. The only accessible location for these lowest samples was along the tidal channel itself, rather than the low gradient mudflat. Therefore, the assemblage may have a large proportion of allochthonous species transported down Alaganik Slough. In addition, the diatom species generally have larger tolerances than in Cook Inlet (Fig. 11). There is a notable lack of polyhalobous diatom species in the samples from Alaganik Slough, which likely reflects the influence of the Copper River. Seasonal glacial meltwater in Copper River Delta results in summer salinity values as low as 2 psu (Powers *et al.*, 2002), far fresher than the waters surrounding the contemporary sample sites of Cook Inlet (~20 psu).

We investigated the best transfer function to reconstruct elevation for fossil samples by comparing models using this new Gulf of Alaska training set with those using the Cook Inlet training set (Hamilton and Shennan, 2005a), as well as combining the two local training sets into a regional south-central Alaska modern training set. Table 1 shows the summary statistics of WA-PLS regression, and Fig. 12 shows an example of the relationship between observed and predicted SWLIs for the best components of two transfer function models using the combined regional training set.

Model	No. of samples	Bootstrapped r^2		Root mean squared error of prediction		% change component 2-3
		Comp 2	Comp 3	Comp 2	Comp 3	
Cook Inlet – all	170	**0.672**	0.688	**21.289**	21.260	2.92
Cook Inlet >180 SWLI	145	**0.757**	0.795	**8.162**	7.767	4.84
Cook Inlet >225 SWLI	74	**0.737**	0.766	**3.120**	2.936	2.78
Gulf of Alaska – all	56	**0.792**	0.811	**32.992**	32.027	0.14
Gulf of Alaska >100 SWLI	47	**0.820**	0.831	**15.091**	14.802	2.47
Gulf of Alaska >180 SWLI	32					
Gulf of Alaska >225 SWLI	9					
Combined – all	225	0.636	**0.706**	29.798	**27.607**	7.40
Combined >180 SWLI	177	**0.700**	0.738	**9.861**	9.574	2.92
Combined >225 SWLI	83	0.638	**0.700**	4.125	**3.862**	6.38

Table 1 Summary statistics for the contemporary training sets using WA-PLS components 2 and 3 from C2. Values in bold show the best models, those with the smallest number of 'useful' partial least squares components. To be considered 'useful', a component should give a reduction in prediction error of ≥5% of the RMSEP for the simplest one-component model (ter Braak and Juggins, 1993; Birks, 1998)

The Gulf of Alaska model (all 56 samples) has the highest RMSEP of all the models, and it does not successfully predict the elevations of samples below a standardised water level index of 100 (Fig. 12). Therefore, in order to improve the predictive capabilities of the transfer function, we exclude samples below 100 SWLI units when using the Gulf of Alaska training set.

We include the statistics for models using the full modern data sets as well as models containing only samples above SWLIs of 180 and 225, as Hamilton and Shennan (2005a) showed different regression models perform better in different parts of the environmental range. Peat only forms in environments above a SWLI of 230, so using samples with a SWLI above 225 is most accurate for reconstructing changes through peat units, and similarly it is best to use samples above a SWLI of 180 for interpreting changes through silt units with the presence of rootlets. Unfortunately due to the relatively small size of the Gulf of Alaska training set, it is not possible to run the Gulf of Alaska >180 and >225 SWLI models. The combined south-central Alaska models >180 and >225 are also heavily influenced by the Cook Inlet samples relative to those from the Gulf of Alaska.

We tested spatial-scale dependence of the different transfer function models by comparing elevation reconstructions for fossil sites using both the local Cook Inlet and Gulf of Alaska modern training sets, and the regional combined training set. Here we propose the optimum training set to use for reconstruction, with conclusions regarding the magnitude of rupture detailed in section 4.2. We analysed four cores from the Gulf of Alaska from Alaganik Slough (AS/09/3 and AS/09/4 collected in 2009, and AS/06/1 collected in 2006) and Cape Suckling (CS/05/2 collected 2005). The lithostratigraphy of the Alaganik Slough cores is the same, with silt overlain by freshwater peat. CS/05/2 is similar although with a 6 cm sand layer between the peat and silt units. All four silt-peat couplets record uplift of the marsh surface. The base of the peats in AS/09/3, AS/09/4 and CS/05/2 date to ~900 yr BP, and AS/06/1 to ~660 yr BP, suggesting an hiatus following presumed coseismic uplift ~900 yr BP. Diatom analyses show similar assemblages in terms of the main species present and their overall trends (Fig. 13 - Fig. 16).

The transfer function software will always produce a reconstructed elevation, so it is essential to consider both the statistical and ecological reliability of the reconstructions. Figures. 13-16 illustrate numerous unacceptable reconstructions, mainly due to a poor fit between fossil samples and those in the modern dataset – the so-called poor modern analogue situation. The model reconstructions (Figs. 13-16) simply highlight the different results obtained by using different modern training sets, for example, the large difference in the reconstructions when samples with a SWLI below 100 are excluded from the Gulf of Alaska training set. This is a much larger effect than when samples with a SWLI below 180 are excluded from the Cook Inlet training set.

We can assess reliability of the reconstructions by using the Modern Analogue Technique. We use the minimum dissimilarity coefficient (MinDC) and take the largest MinDC value calculated between all modern samples as a cut-off for each fossil sample between a ‘good’ and ‘poor’ analogue in the modern training set. Applying this approach to the four fossil cores shows no fossil samples have a close modern analogue using the Gulf of Alaska modern training set. For AS/09/3, AS/09/4 and CS/05/2, this improves when we use the combined regional training set, with two-thirds of fossil samples having good modern analogues (Fig. 17).

In our last NEHRP project we reported results of our first attempt to quantify elevation change in the Copper River Delta using core AS/06/1 and the Cook Inlet modern training set (Shennan *et al.*, 2007). No fossil samples had a close modern analogue and we concluded that we could not accurately reconstruct elevation change at this site using the Cook Inlet modern diatom data, due the difference in contemporary environments between the sample locations. We speculated that using a modern diatom dataset from the Gulf of Alaska region would improve the transfer function model. However, it appears that the transfer function model using the Gulf of Alaska modern training set does not improve the vertical (elevation) accuracy and precision of geologic estimates of land level changes in this area.

One of the major reasons for this may be the relatively small sample size of the Gulf of Alaska modern training set; it only contains 56 samples (47 with a SWLI >100) compared to the Cook Inlet training set of 170 samples (145 with a SWLI >180). The modern Gulf of Alaska training set is reasonably

internally consistent (maximum MinDC of 85 compared to 122 for Cook Inlet), however when only 47 samples are used in the transfer function for fossil reconstructions, this may not be enough to cover the possible range of environments that occurred in the past. Consequently, it is hard to compare the viability of using the small Gulf of Alaska modern training set against the much larger Cook Inlet training set. We can only make conclusions regarding the accuracy of reconstructions from the two training sets when they are of more comparable size, or at least a threshold sample number is reached in the Gulf of Alaska. Until this point, we propose that the combined regional training set improves the model performance over using either local training set for reconstructions of elevation change in the Gulf of Alaska. If we consider the dominant diatom species in the silt-peat couplet of AS/06/1 as an example (Table 2), including modern samples from the Gulf of Alaska improves the non-analogue situation and maximum abundances of species in the modern dataset over using the Cook Inlet training set alone.

Diatom species	Max fossil	Max modern		
		Gulf of Alaska >100 SWLI	Cook Inlet >180 SWLI	Combined >180 SWLI
Diploneis ovalis	38.91	13.75	31.58	31.58
Pinnularia microstauron	17.58	1.25	17.85	17.85
Pinnularia subcapitata	15.89	0.44	21.55	21.55
Navicula cari var. *cincta*	14.34	55.72	89.71	89.71
Pinnularia viridis	11.72	**0.40**	0	0.40
Caloneis bacillum	11.60	**5.38**	1.88	5.38
Rhopalodia gibba	10.12	1.00	5.42	5.42
Navicula pupula	9.30	0.50	9.20	9.20
Nitzschia frustulum	8.80	**14.93**	5.63	14.93
Rhopalodia gibberula	8.71	0	0	0

Table 2 Most abundant diatom species in core AS/06/1 and their maximum abundances in the Gulf of Alaska, Cook Inlet and Combined training sets. Numbers in bold indicate where the local Gulf of Alaska training set is better than the Cook Inlet. In all cases the combined training set is either the same or better than either local one.

We also tested the different transfer function models in the Cook Inlet by comparing elevation reconstructions for a fossil site (Bird Point) for which we have existing data (Barlow, 2010). Elevation reconstructions for core BP/08/6 suggest co-seismic subsidence for both peats G (~900 yr BP) and H (1964 AD) (Fig. 18), and we compared the reconstructions using the Cook Inlet modern training set and the combined south-central Alaska training set. We found virtually no difference in the reconstructions across peat G (co-seismic subsidence of 1.34 ± 0.32 m using the Cook Inlet modern training set and 1.36 ± 0.38 m using the combined training set), but there is a larger difference across peat H (1.19 ± 0.33 m of subsidence using the Cook Inlet training set compared to 1.32 ± 0.39 m using the combined training set). Again, this supports the earlier results from the Gulf of Alaska, that patterns of elevation change differ slightly between reconstructions using local and regional modern training sets, and that regional transfer models can improve the precision of elevation reconstructions.

Our comparison of modern training sets and a range of transfer function models from Cook Inlet, from Gulf of Alaska, and their combination as a regional training set gives the following conclusions at this stage:
(1) The Gulf of Alaska training set is too small to reflect the range of environments found within large deltas, giving too many poor analogues in fossil reconstructions;
(2) Small marshes, such as those around Cook Inlet, are easier to model, in terms of the relationship between diatom assemblages and elevation – as shown above using the results from Bird Point;

(3) Similarities between the Cook Inlet and Gulf of Alaska data sets and their combination as a regional dataset give promising results, but these require further validation. We shall undertake this during our 2010-2011 NEHRP Project (grant award # G10AP00075) using samples collected on Kodiak Island;
(4) Regional datasets potentially reduce reconstruction error terms where there is a good modern analogue.

4.2 Research Question 2 – How do spatial patterns of estimated land level changes for different Holocene plate boundary earthquakes vary?

Until we can test further the local and regional modern training set approaches using our new data from Kodiak Island we follow the approach outlined by Hamilton and Shennan (2005), but using the combined south central Alaska modern data set. In the following sections we use the core lithology to define the appropriate transfer function model: >180 SWLI for fossil samples from silt with in situ rootlets and >225 SWLI for fossil samples from peat layers.

Reconstructions from two peat-silt couplets at Bird Point (BP/09/1) address our first objective of this question to determine the extent and variation of surface deformation around upper Cook Inlet for multiple late Holocene events. Radiocarbon dates from the top of each peat layer indicate peat growth ended ~1500, ~2100 and ~2600 yr BP (Table 3). These three earthquake events are in addition to the ~900 BP and 1964 AD events recorded in BP/08/6 that we discuss above.

Peats 1 and 2 in core BP/09/1 are overlain by silt with intertidal diatoms (Fig. 19), and represent co-seismic subsidence. The diatom assemblages of the two peat-silt couplets are very similar in terms of main species present and overall trends. Reconstructions of relative sea-level change from the transfer function suggest co-seismic subsidence of ~0.8 ± 0.5 m for peat 1 (1500 yr BP) and ~1.15 ± 0.4 m for peat 2 (2100 yr BP) (Fig. 20). This is slightly less subsidence than recorded in 1964 (~1.3 m) and 900 yr BP (~1.4 m), but is of comparable magnitude to subsidence recorded for the same events at Girdwood and Ocean View.

Site	Lab code (Beta-)	Stratigraphic context	Laboratory reported ^{14}C age ±1σ	Calibrated age BP Median age followed by minimum and maximum ages of 95% range		
BP/09/1/1*	266420	Top of peat 'F'	1580 ± 40	1467	1415	1519
BP/09/1/2*	266421	Top of peat 'E'	2170 ± 40	2197	2118	2304
BP/09/1/3*	266422	Top of peat 'D'	2580 ± 40	2722	2618	2757
HP/09/8*	226423	Top of 4th peat 'E'	2040 ± 40	1999	1933	2053
AS/09/3/1*	266415	Base of peat 1	880 ± 40	794	735	824
AS/09/3/2*	266416	Base of peat 2	1480 ± 40	1365	1329	1400
AS/09/4*	266417	Base of peat 1	930 ± 40	849	795	886
AS/09/5*	266418	Base of peat 3	2020 ± 40	1972	1901	2004
AS/09/8*	266419	Base of peat 2	1430 ± 40	1331	1299	1350
YK/2	239243	Base of peat	920 ± 40	844	791	908
YK/5-1	239245	3cm above base of peat	920 ± 40	844	791	908
YK/5-2	242795	Base of peat	970 ± 40	863	799	867
TA/09/SH/1*	266424	Paired molluscs *Prototheca staminea*	5510 ± 40	6309	6279	6342

Table 3 Radiocarbon dates taken in 2009 for all sites: Bird Point (BP), Hope (HP), Alaganik Slough (AS), Yakataga (YK) and Tashlalich Arm (TA). Those marked with * were dated under this project; other dates are reported in Shennan (2009).

The reconstructions from Bird Point complete our investigations of surface deformation around the upper Cook Inlet, which are summarised in Table 4.

Age[a]	Site and core	Girdwood peat	Coseismic land elevation change (m)
AD 1964	Girdwood-1	H	-1.51 ± 0.32
	Girdwood-33		-1.48 ± 0.30
	Girdwood-34		-1.34 ± 0.32
	Girdwood-99		-1.00 ± 0.28
	Bird Point		-1.33 ± 0.46
	Ocean View-4		-0.67 ± 0.43[b]
	Ocean View-15		-0.71 ± 0.31
	Kenai-3		-0.45 ± 0.28
	Kenai-7		-0.73 ± 0.24
	Kenai-8		-0.30 ± 0.28
	Kenai-13		-0.09 ± 0.13
	Kasilof		None recorded
~900 BP	Girdwood-1	G	-1.50 ± 0.34
	Girdwood-2		-1.59 ± 0.30
	Bird Point		-1.38 ± 0.41
	Ocean View-15		-0.23 ± 0.32[b]
	Kenai		None recorded
	Kasilof		None recorded
~1500 BP	Girdwood-2	F	-1.42 ± 0.29
	Bird Point		-0.79 ± 0.53
	Ocean View-2		-0.99 ± 0.32[b]
	Ocean View-23		-0.43 ± 0.30
	Kenai-5		-1.20 ± 0.27
	Kenai-15		-1.11 ± 0.27
	Kenai-7		Sediment mixing
	Kasilof-1		-0.70 ± 0.23
~2100 BP	Girdwood-1	E	-1.20 ± 0.34
	Girdwood-2		-0.79 ± 0.29
	Girdwood-3		No tidal submergence
	Bird Point		-1.15 ± 0.41
	Hope		To be calibrated
	Ocean View[c]		None recorded
	Kenai		None recorded
	Kasilof		None recorded
~2500 BP	Girdwood-1	D	-1.42 ± 0.34
	Girdwood-2		-1.48 ± 0.42
	Bird Point		To be calibrated
	Kenai		None recorded
	Kasilof		None recorded
~3300 BP	Girdwood-1	A	-1.36 ± 0.30
	Girdwood-2		-1.60 ± 0.32
	Kenai		None recorded
	Kasilof		None recorded
~3800 BP	Girdwood-06	Y	-0.70 ± 0.30
	Kenai		None recorded
	Kasilof		None recorded

Table 4 Summary of coseismic subsidence and ages of great earthquakes recorded in marsh sequences around upper Cook Inlet. Reconstructions from Bird Point are described in this report, and all other values come from Shennan and Hamilton (2006). Notes: [a] approximate age used for ease of reference in text; [b] fossil samples have poor analogues within modern diatom assemblages; [c] no sediment was sampled older than 2100 yr BP from Ocean View.

Two key points arise from the comparisons of cosesimic subsidence around Upper Cook Inlet (Table 4). First, in the region of greatest subsidence in 1964, upper Turnagain Arm, we see no evidence of significantly greater subsidence during any late Holocene earthquakes. Second, the pattern of subsidence varies slightly, with the more peripheral sites, Ocean View, Kenai and Kasilof, showing no evidence of subsidence for earthquakes ~2100 BP and earlier. Our limited data from Hope (Table 3 and 4) suggests coseismic subsidence petered out between Hope and Anchorage.

We consider our reconstructions of coseismic uplift from Alaganik Slough and the marsh west of Cape Suckling as provisional until we can test the modern training set further, as outlined in section 4.1. We currently only have quantitative reconstructions of uplift for the penultimate earthquake, ~900 BP. At Alaganik Slough, we see the clearest signal, ~0.25 m uplift, at the most seaward site, diminishing landward (Fig. 21). This reflects the same spatial pattern observed in 1964, which was sufficient to reverse temporarily the drainage for several days. At Cape Suckling marsh the reconstructions show a greater uplift ~900 BP compared to 1964 (Fig. 22). In contrast to the reconstructions of subsidence around Cook Inlet, our reconstructions of uplift are difficult to compare to observations in 1964. The contours of uplift in 1964 are only extrapolated across Alaganik Slough (Plafker, 1969) and we had previously noted the differences between the uplift at the rocky headland of Cape Suckling compared to the marsh to the west (Shennan *et al.*, 2009; Shennan and Hamilton, 2010). Barnacles at Cape Suckling record 4-5 m uplift in 1964 (Plafker, 1969). In contrast, air photographs show pre-1964 intertidal marsh and mudflat in the lee of Okalee Spit. Four metres uplift would raise these intertidal marshes significantly present above high tide. Our surveys of Oklaee Spit (Fig. 8), suggest much less uplift. We interpret ridge 1 as the equivalent of the mid-tide beach berm, uplifted in 1964, and now vegetated with low dune developed (Fig. 8). Transects 1, 2 and 3 show ~1-1.5 m difference in elevation (dashed lines in Fig. 8). Note, the small dune shown in transect 1. Transect 4 crosses ridge 2, and onto the marsh behind. Ridge 2 appears on pre-1964 air photographs, with forested dunes already present. The break in slope in the lee of the dune ridge, is ~1 m above the present marsh level. All these morphological features suggest less uplift than shown by the barnacles at the rocky headland of Cape Suckling and the lines of driftwood survey by Plafker (1969).

Even so, our reconstructions of uplift in 1964 from the marsh at Cape Suckling are still lower than our morphological surveys, which require further consideration. In addition to our qualifications regarding the modern training set providing suitable analogues for the palaeoenvironments in large wetlands like those of the Copper River Delta and the Bering River system in the lee of Okalee Spit to the west of Cape Suckling, we note two further possible influences. First, ground shaking during a great earthquake and coseismic uplift, causing dewatering of uplifted marshes may both cause sediment compaction. Therefore, marshes may record less than the true amount of regional uplift. It is uncertain whether ground shaking and liquefaction could lead to metre-scale surficial subsidence across the marsh and spit. For comparison, in 1964 there was ~0.9 m localised subsidence due to sediment compaction at Girdwood (Plafker et al., 1969) and more than 2 m localised subsidence at some sites during the 1899 Yakutat earthquake (Plafker and Thatcher, 2008). Second, we can speculate that the silt-peat boundary may not represent the earthquake horizon. In large wetlands we can envisage a rapid adjustment of sedimentation patterns in the days and weeks after uplift. This could lead to rapid clastic sedimentation up to high tide level, prior to colonization by plants that eventually lead to peat formation. This would still produce a sharp contact in the lithology, but would give a poor estimate of the amount of coseismic uplift. This hypothesis requires future testing.

The date from the *in situ* bivalves at Tashalich Arm (Table 3) show relative sea-level was above present ~6200 BP, fitting within the range of previous samples that reveal a sea-level highstand from ~9200 to at least 5000 cal BP. This provides a background trend of relative sea-level change, driven by glacio-isostasy and long term tectonic uplift (see discussion by Shennan, 2009).

4.3 Research Question 3 – Are great earthquake ruptures in Alaska controlled by persistent segment boundaries or do the rupture areas overlap?

Fig. 23 illustrates our current working hypotheses regarding plate segmentation. Our FY2010-11 Project (grant award # G10AP00075) will consider the southwestern boundary of the 1964 rupture zone and the single segment rupture ~500 BP. Here we summarise the evidence towards the eastern boundary of the 1964 rupture zone and a transect from the zone of subsidence around upper Cook Inlet. We have four key findings:

- Variation in the northwestern extent of subsidence around upper Cook Inlet: ~900 BP subsidence ended between Anchorage and Kenai. ~1500 BP subsidence at Kenai and Kasilof was greater than in 1964, suggesting the zone of subsidence extended further. ~2100 BP subsidence ended between Hope and Anchorage (the data for earlier events are too restricted to draw further conclusions).
- Greater uplift in Cape Suckling marsh ~900 BP than 1964 suggests the zone of uplift extended further east, and we correlate the uplifted sequences along the Yakataga coast to the same earthquake. We make a similar argument for the ~1500 BP earthquake (Shennan *et al.*, 2009).
- Away from the limits of uplift and subsidence, sites such Alaganik Slough, Bird Point and Girdwood show no coseismic deformation of significantly greater magnitude than in 1964. These observations favour the multi-segment rather than the multi-segment with enhanced vertical deformation hypothesis (Fig. 23b)
- In terms of earthquake hazard assessment, comparison of the last four great earthquakes (1964, ~500 BP' ~900 BP, ~1500 BP) show three different modes of plate segmentation and four different spatial extents of surface deformation.

5 Conclusions

We have successfully addressed the three research questions set out above, and highlight six main conclusions.

(1) Our present Gulf of Alaska modern diatom training set is too small to reflect the range of environments found within large deltas, giving too many poor analogues in fossil reconstructions;

(2) Small marshes, such as those around Cook Inlet, are easier to model, in terms of the relationship between diatom assemblages and elevation.

(3) Regional diatom datasets reduce reconstruction error terms where there is a good modern analogue.

(4) We can identify different spatial patterns of coseismic deformation during Late Holocene great earthquakes.

(5) In terms of earthquake hazard assessment, comparison of the last four great earthquakes (1964, ~500 BP' ~900 BP, ~1500 BP) show three different modes of plate segmentation and four different spatial extents of surface deformation.

(6) Multi-segment earthquakes ~900 and ~1500 years ago, involving simultaneous rupturing of the megathrust from Cook Inlet in the west to the Pamplona – Malaspina thrust front in the east did not lead to enhanced vertical deformation around Cook Inlet compared to 1964.

6 Appendix A

See our previous report (Shennan *et al.*, 2003) for bibliographic details of references cited only in this appendix.

6.1 Microfossil analysis

Analysis of the surface samples from Alaganik Slough allows development of a modern data set, ranging from tidal flat through to raised bog environments to compare to our published data (Hamilton and Shennan, 2005a). Sampling intervals of fossil cores varied from 0.5 to 2 cm.

Preparation of diatom samples followed standard laboratory methods (Palmer and Abbott, 1986) with a minimum count of 250 diatom valves possible for most samples. 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 plotting of results and the halobian classification system divides the diatom species into five categories of salt tolerance (Table 4).

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 (polyhalobous class) and brackish (mesohalobous class) groups usually dominate tidal flat environments and freshwater groups tolerant of different degrees of saline inundation (oligohalobous-halophile and oligohalobous-indifferent classes) become dominant through the transition from salt marsh to freshwater marsh (e.g. Zong *et al*., 2003). Salt-intolerant species (halophobous class) characterise the most landward communities, including acidic bog above the level of the highest tides. 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 (2001), 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.

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

Table 5 The halobian classification scheme (Hemphill-Haley, 1993)

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) defines 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.

6.2 Radiocarbon dating

In situ macrofossils were used for AMS radiocarbon dating. CALIB 5.0.1 (Stuiver & Reimer, 1993) calibrates the radiocarbon results to calendar years before present using the atmospheric decadal data set (file INTCAL04.14C, Reimer et al., 2004) and the 95% probability distribution method. In addition we recalibrated the ages reported in Hamilton and Shennan (2005a) using the INTCAL04.14C

data set to allow comparison with the dates reported for this project. Calibrated ages are reported as the range between the calculated minimum and maximum value, with the median age marked on figures.

6.3 Numerical techniques

6.3.1 Transfer function

Numerical techniques establish the relationship between contemporary diatom data and elevation (m) relative to MHHW and allow comparisons between the contemporary data set and every fossil sample analysed. These provide quantitative estimates of relative sea-level change throughout the entire profile, rather than just at stratigraphic boundaries.

Contemporary distribution of diatoms from tidal flat to freshwater environments allows development of a transfer function to reconstruct the magnitude of relative land and sea-level changes. 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 for a fossil sample using a modern training set. 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. CANOCO (version 4.5; ter Braak & Smilauer, 2002) 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). 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), all available within the software package C2 (Juggins, 2003).

Statistical parameters produced during regression and calibration includes 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 of Prediction (RMSEP) measures the predictive abilities of the training set and is calculated by a method called bootstrapping (ter Braak & Juggins, 1993).

When calculating a relative sea-level change between two fossil samples, the change in elevation is simply the difference between the two reconstructed values and calculation of the associated error term uses the formula (Preuss, 1979): $\sqrt{(\text{error term } 1^2 + \text{error term } 2^2)}$

6.3.2 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. Birks, 1995; Edwards & Horton, 2000; Zong *et al*., 2003). The computer program C2 (Juggins, 2003) models the full contemporary diatom data set against each fossil data set and determines the minimum dissimilarity coefficient for each fossil sample.

7 Figures

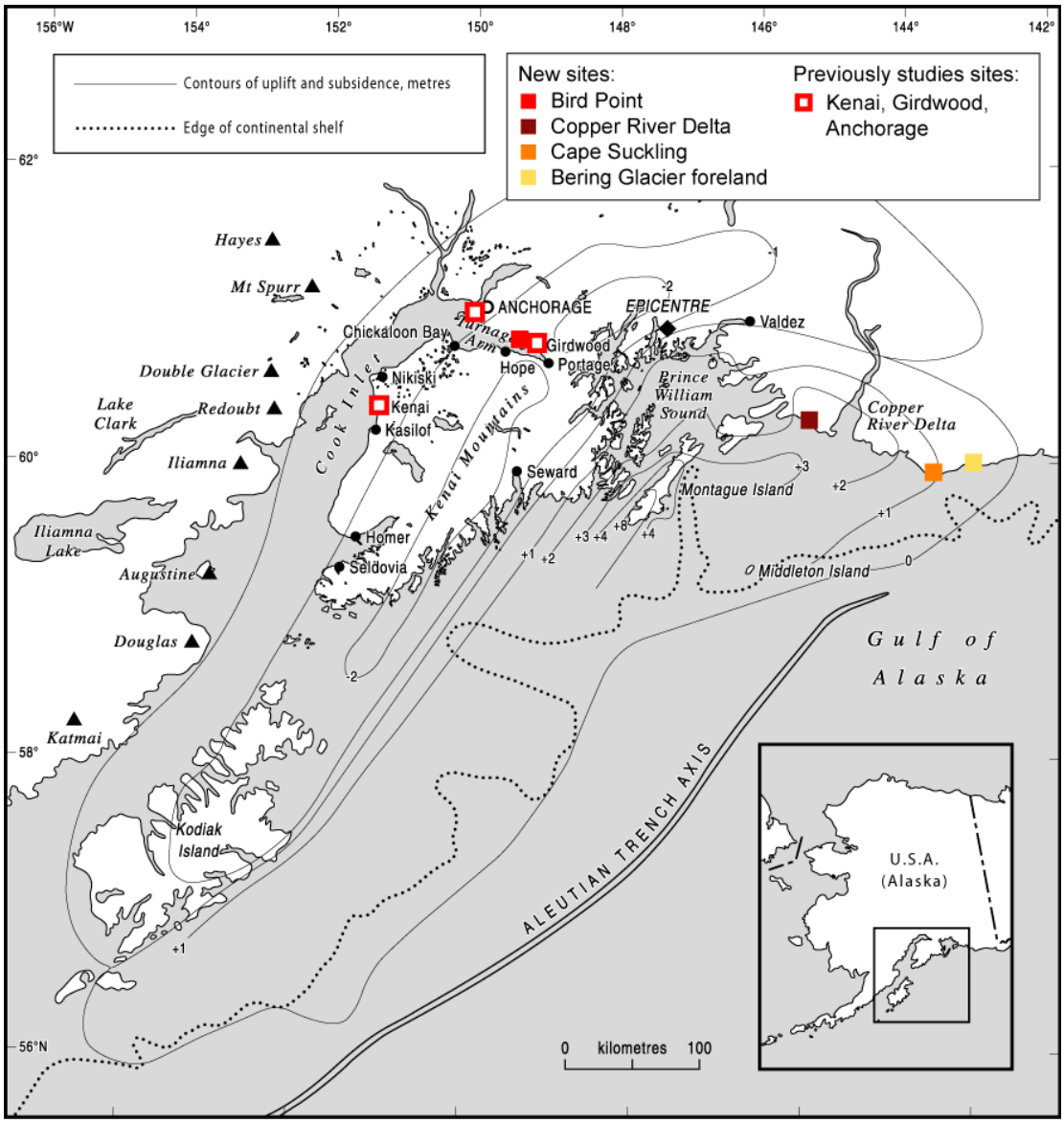


Fig. 1. Location of field sites. Contours show vertical deformation caused by the 1964 earthquake (excluding local subsidence caused by sediment compaction), Plafker *et al*. (1992)

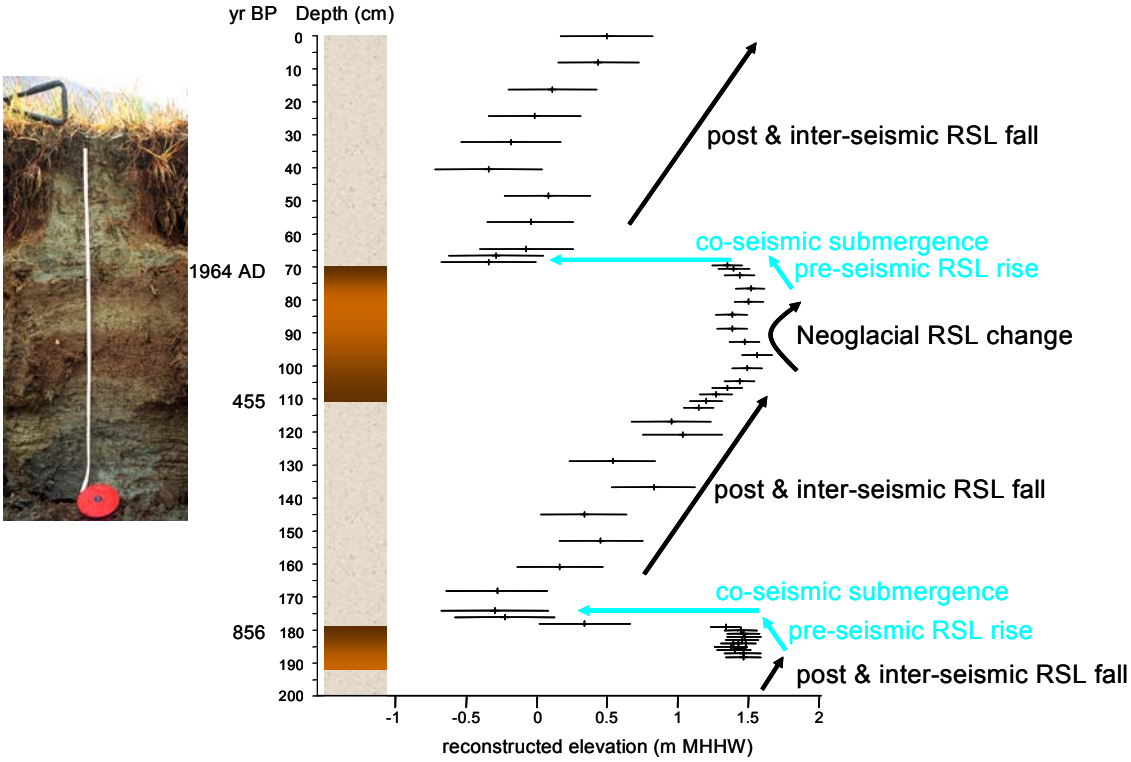


Fig. 2. Reconstruction of relative sea-level change for Girdwood, showing the four phases of the earthquake deformation cycle. The neoglacial RSL change in the pre-1964 AD peat is in addition to the tectonically driven RSL changes shown through the rest of the peat-silt couplets.

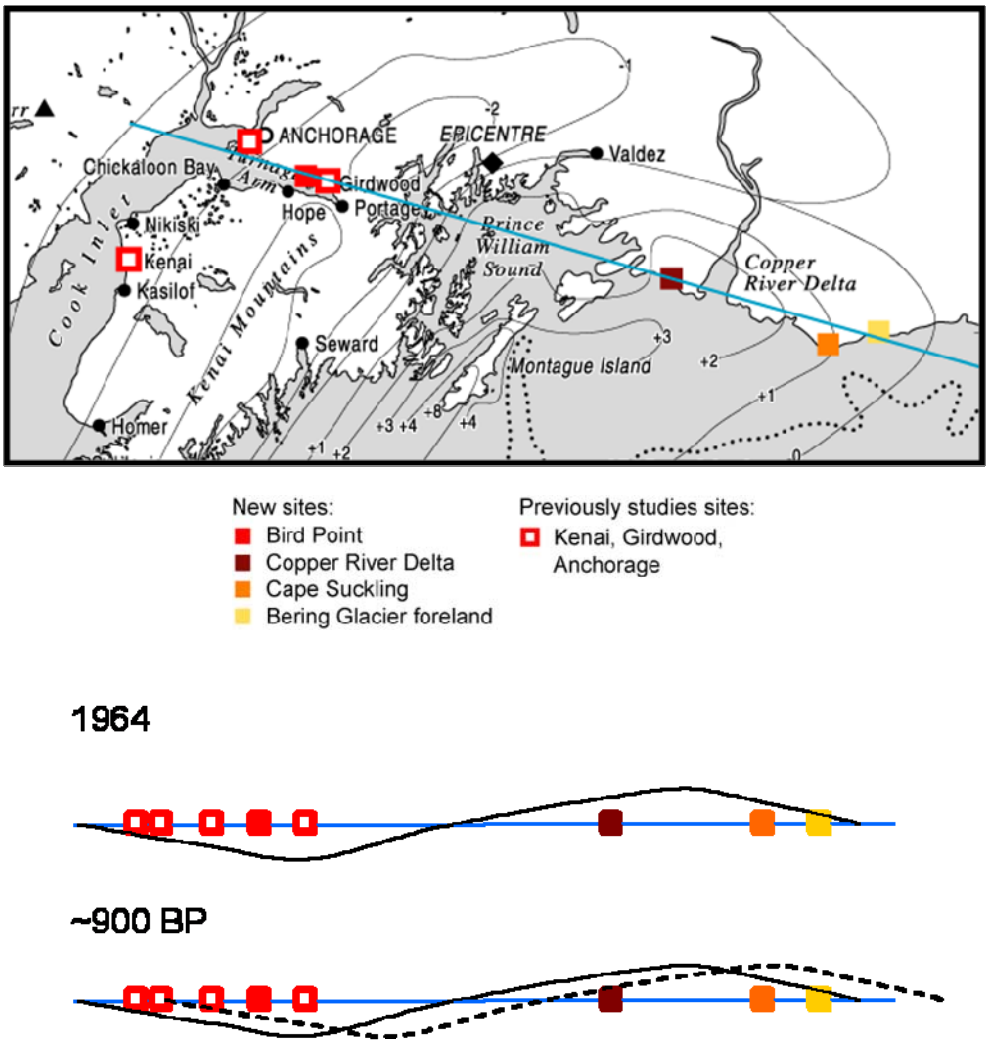


Fig. 3. Study sites in the Cook Inlet and coast of the Gulf of Alaska, lying along a transect (blue line) across the zones of subsidence and uplift associated with the 1964 earthquake. The lower graphs show schematic patterns of surface deformation recorded at the study sites, for the 1964 earthquake (solid black line) and a speculative hypothesis (dashed line) for the ~900 yr BP earthquake.

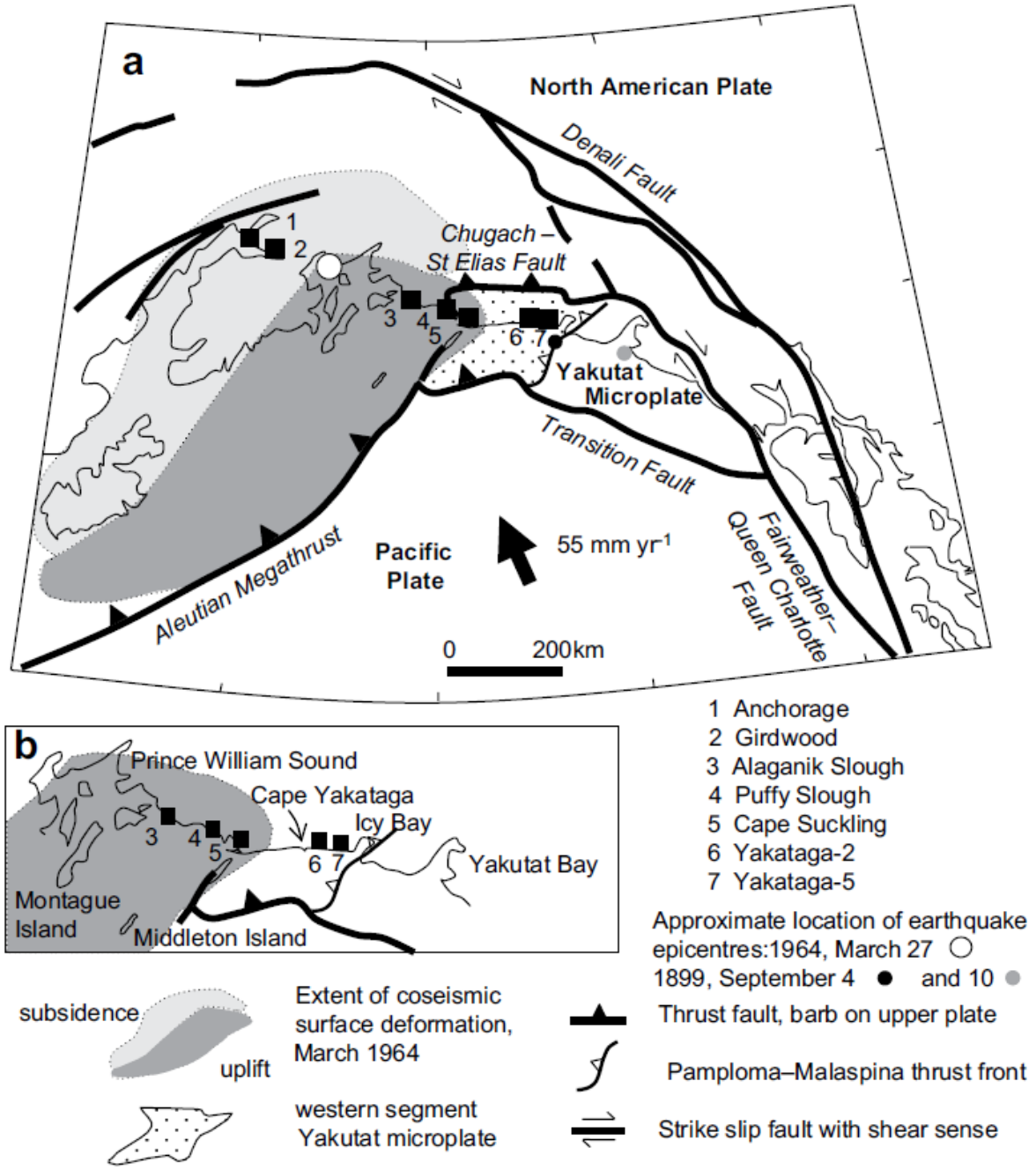


Fig. 4. (a) Tectonic setting of the eastern sector of the Aleutian megathrust and Yakutat microplate, and the extent of coseismic deformation in the 1964 earthquake; (b) Sites along the Gulf of Alaska coast (Shennan *et al.*, 2009)

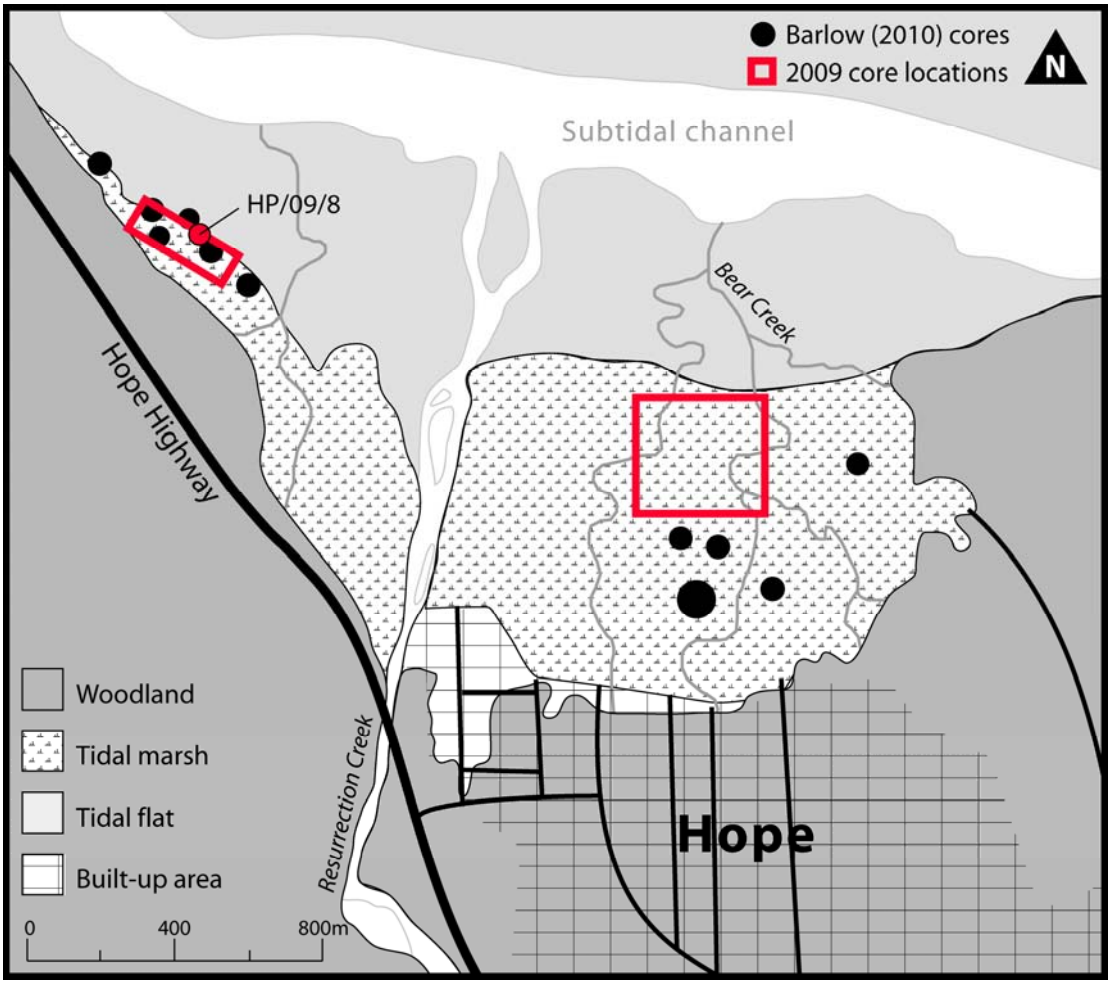


Fig. 5. Location of previous coring sites at Hope, upper Cook Inlet, by Barlow (2010) and areas targeted for further coring under this project in August 2009 (in red). HP/09/8 is the core where samples were collected for laboratory analysis.

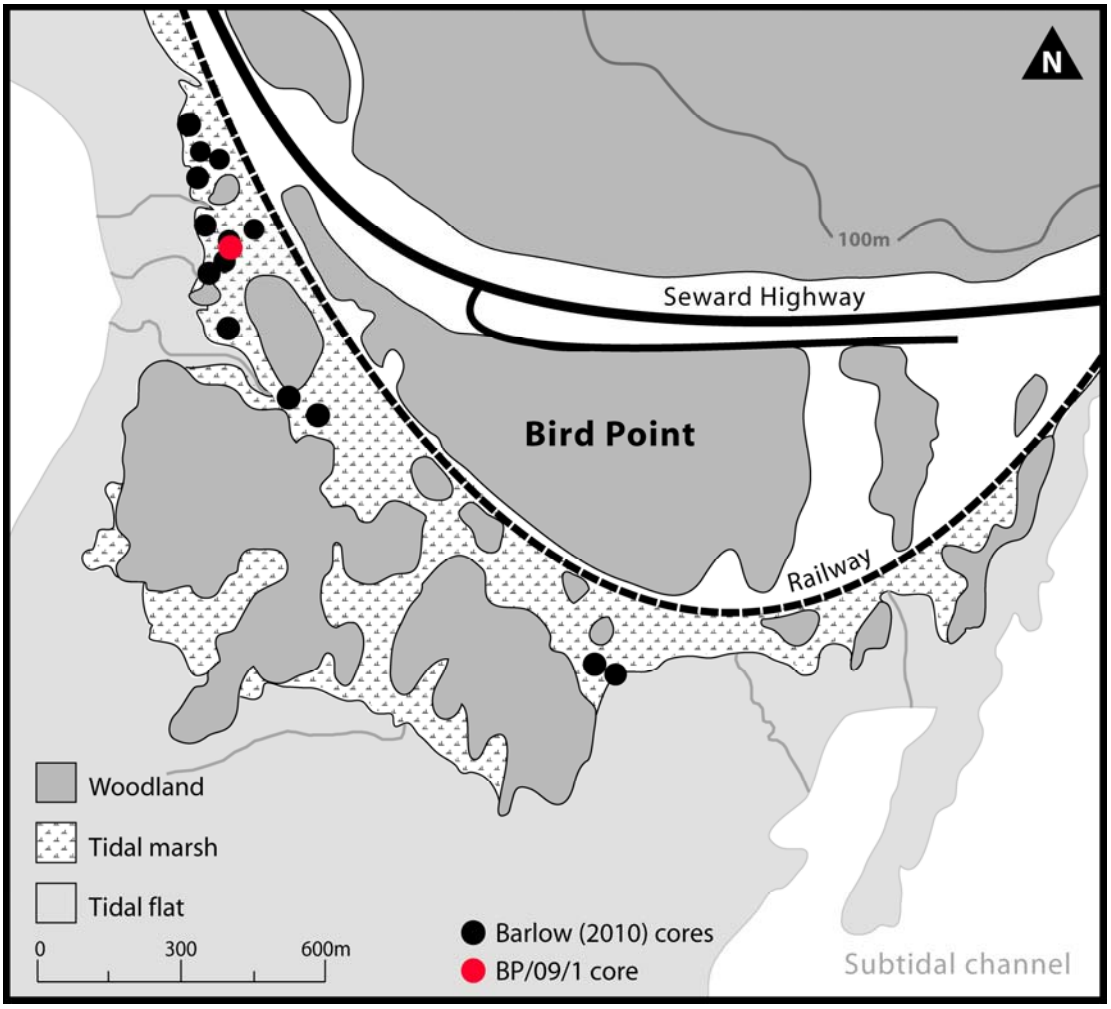


Fig. 6. Location of previous coring sites at Bird Point, upper Cook Inlet, by Barlow (2010) and location of BP/09/1 (in red) where sediments were collected for laboratory analysis under this project.

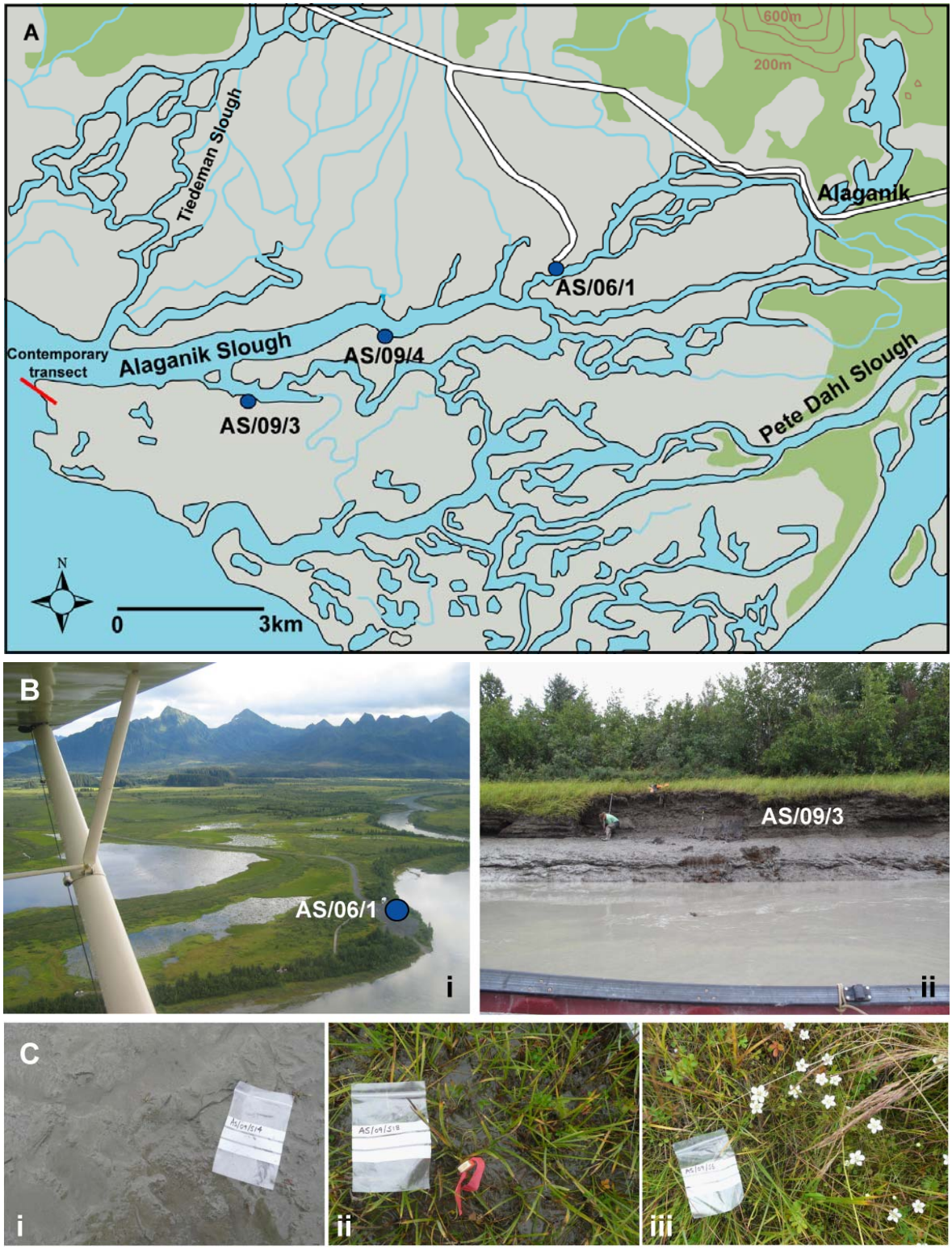
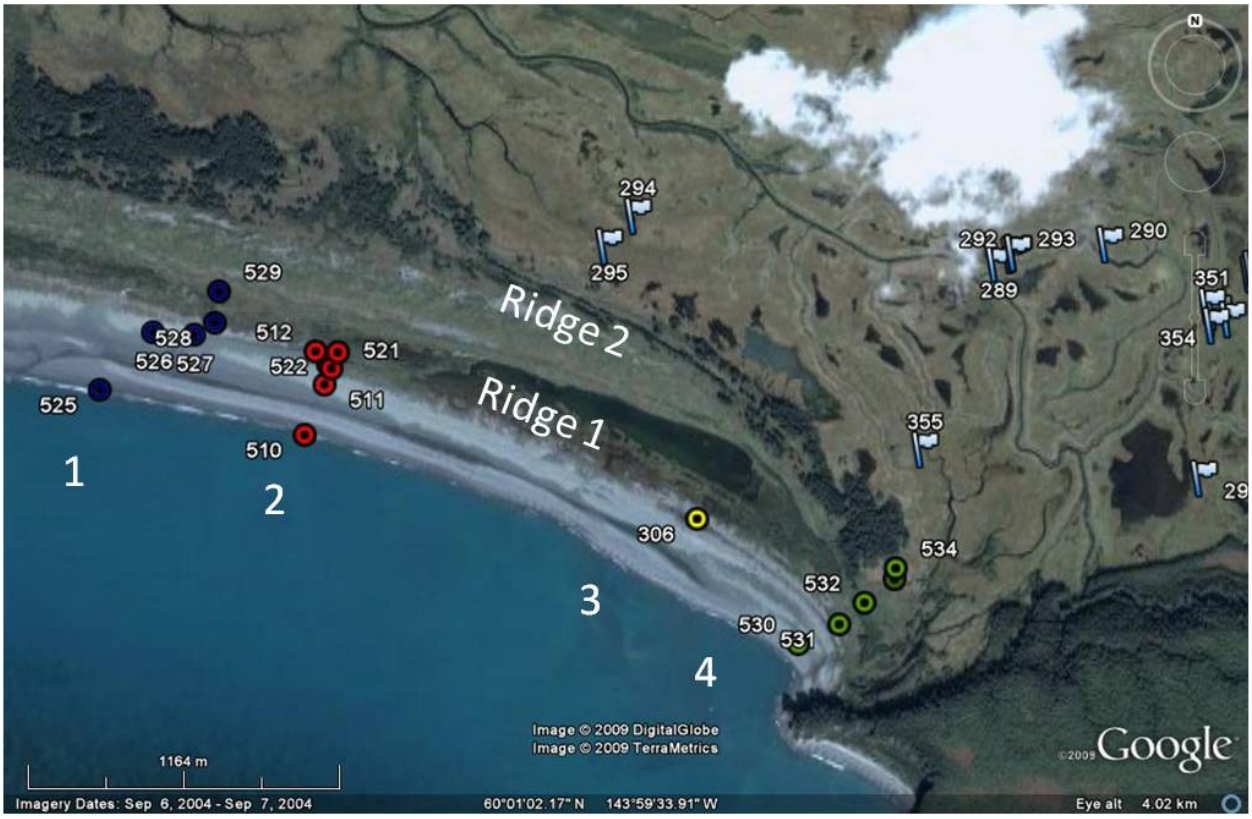


Fig. 7. Alaganik Slough, Copper River Delta, (a) location map of coring sites and contemporary sampling transect; (b) photographs of the fossil coring sites AS/06/1 and AS/09/3; (c) photographs of the contemporary sedimentary environments along the transect from which the 46 samples were collected: i – mud flat, ii – low marsh, iii – high marsh



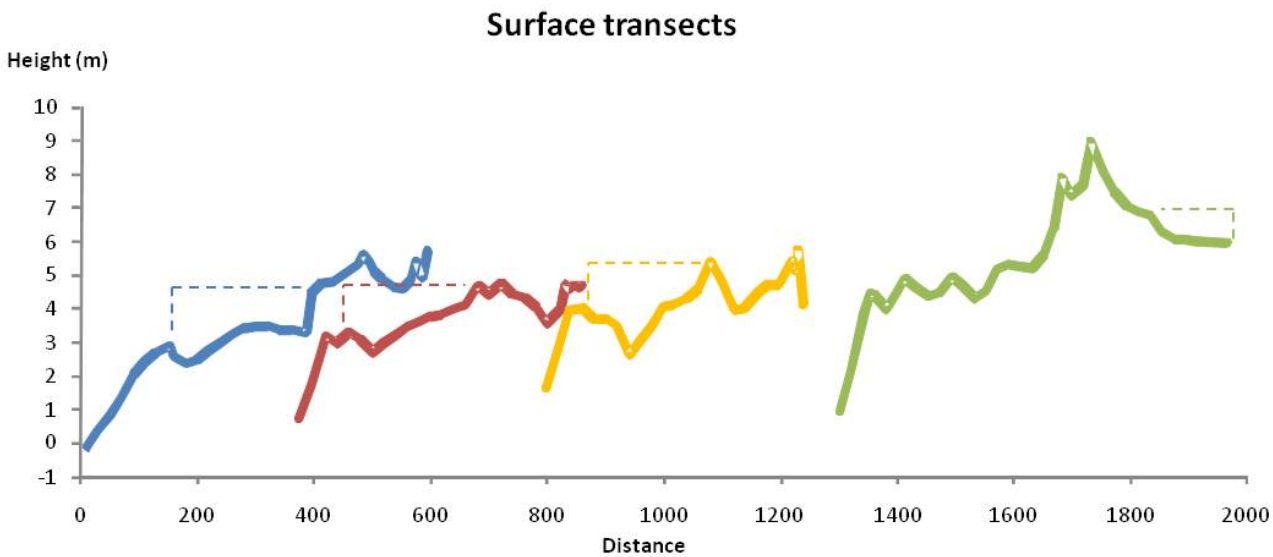


Fig. 8. Raised beaches at Okalee Spit and levelling transects across the beach berms and dunes that form the spit. We took one 50 cm fossil core from Cape Suckling Marsh, in the lee of Okalee Spit at location 534. The dotted lines on the surface transects represent the difference in altitude between the modern day beach and the uplifted equivalent.

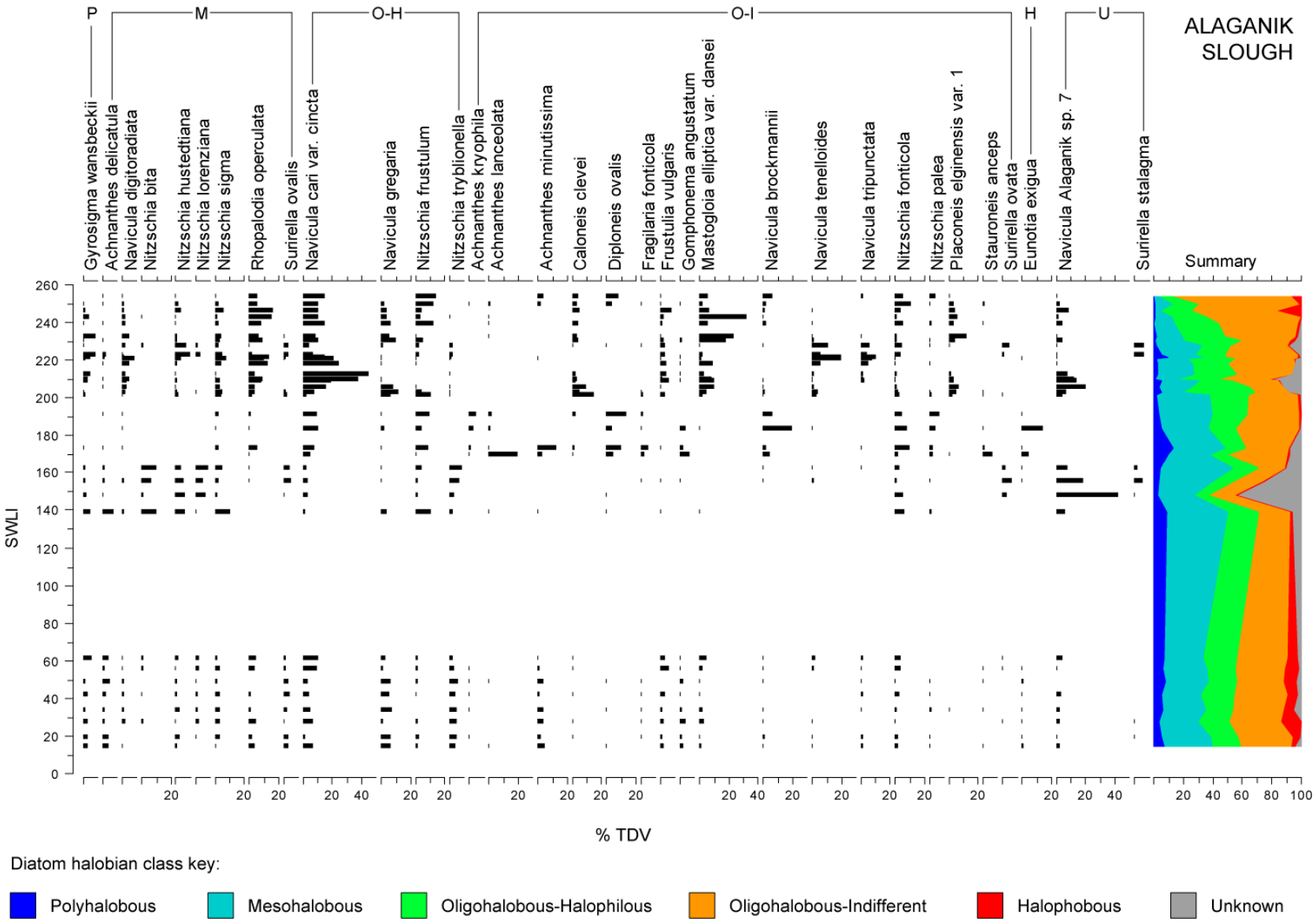


Fig. 9. Summary diatom data for modern samples from Alaganik Slough plotted against SWLI value, showing species >5% of total count. Note 100 SWLI units is mean sea level and 200 SWLI units is mean higher high water.

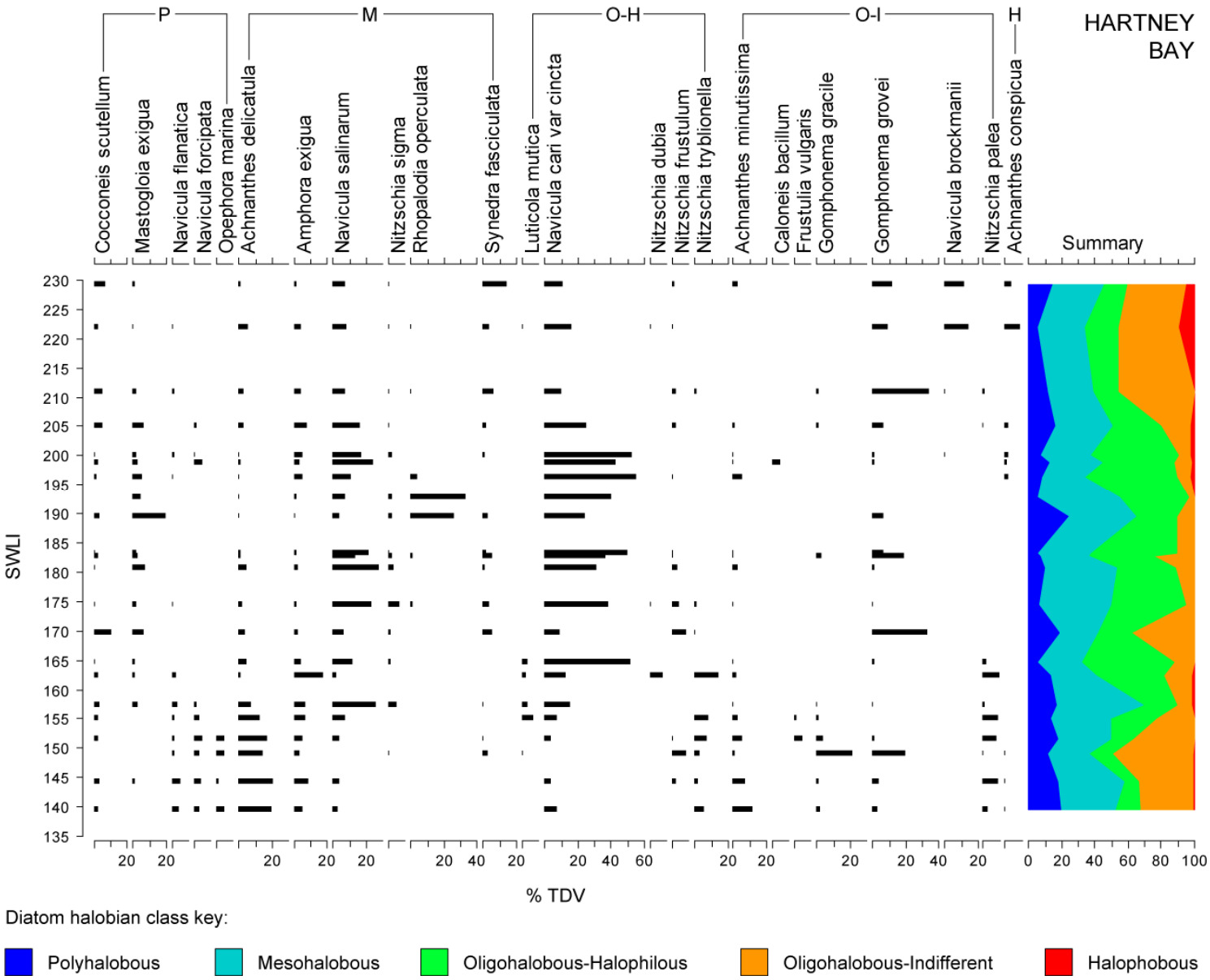


Fig. 10. Summary diatom data for modern samples from Hartney Bay plotted against SWLI value, showing species >5% of total count

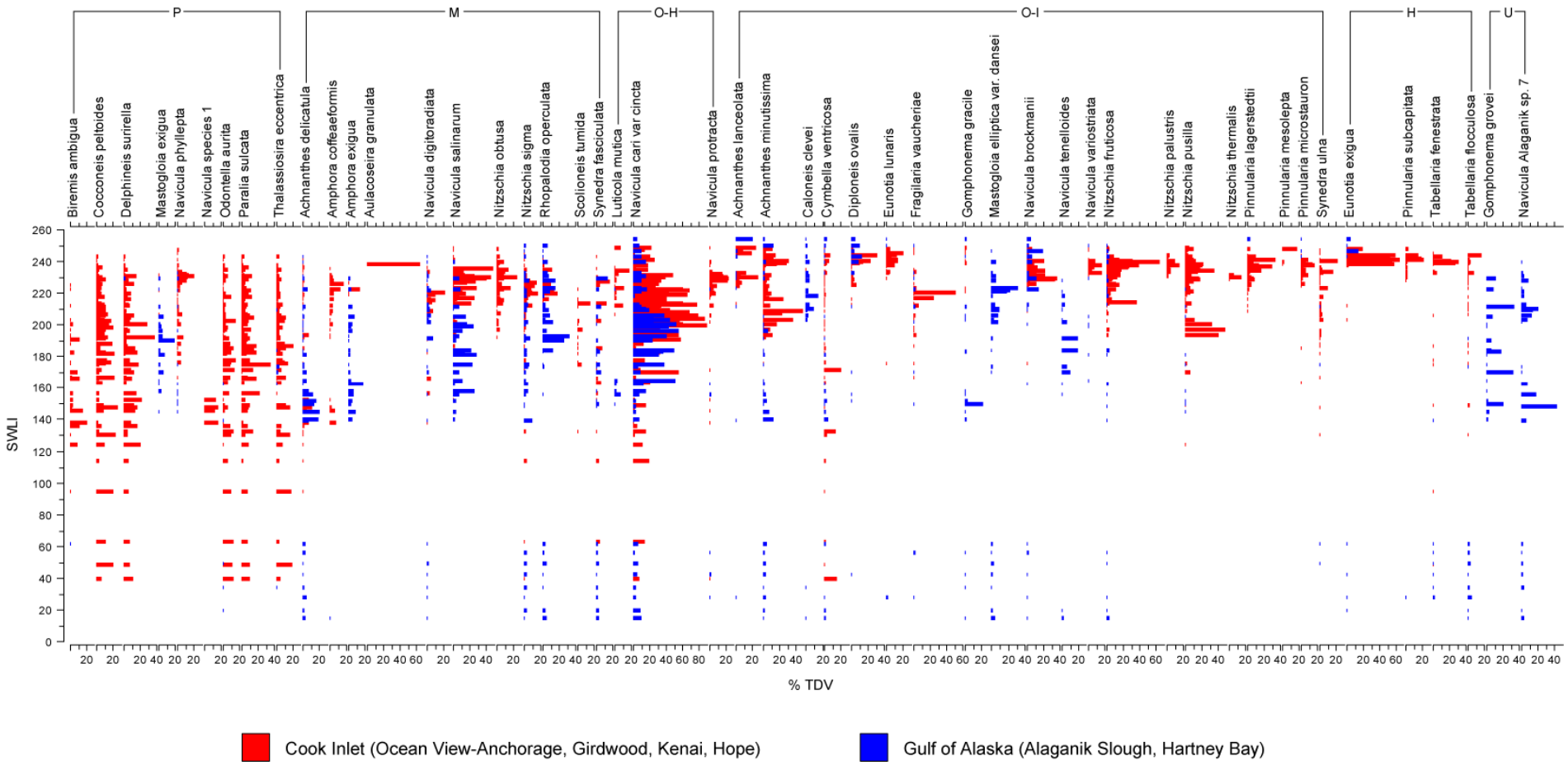


Fig. 11. Modern diatom data (≥15% total diatom valves counted) for upper Cook Inlet and the Gulf of Alaska. Samples are ordered by elevation (Standardised Water Level Index, where 100 = mean sea level and 200 = mean higher high water). Summary diatom classification: P – polyhalobous; M – mesohalobous; O-H – oligohalobous-halophilous; O-I – oligohalobous-indifferent; H – halophobous; U - unknown

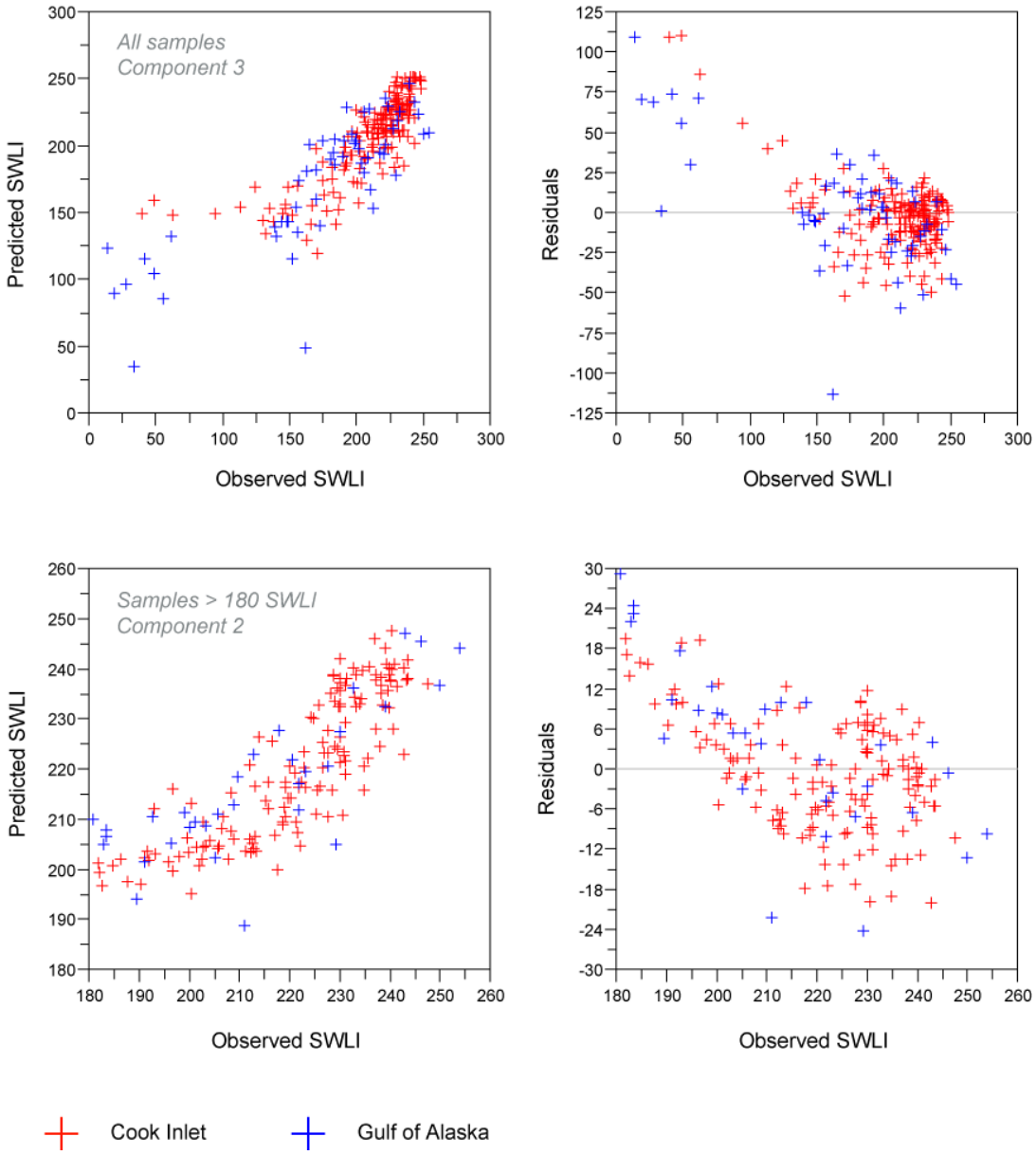


Fig. 12. Observed against predicted Standardised Water Level Index (SWLI) values for the combined upper Cook Inlet (Hamilton and Shennan, 2005a) and Gulf of Alaska modern training sets for two transfer function models

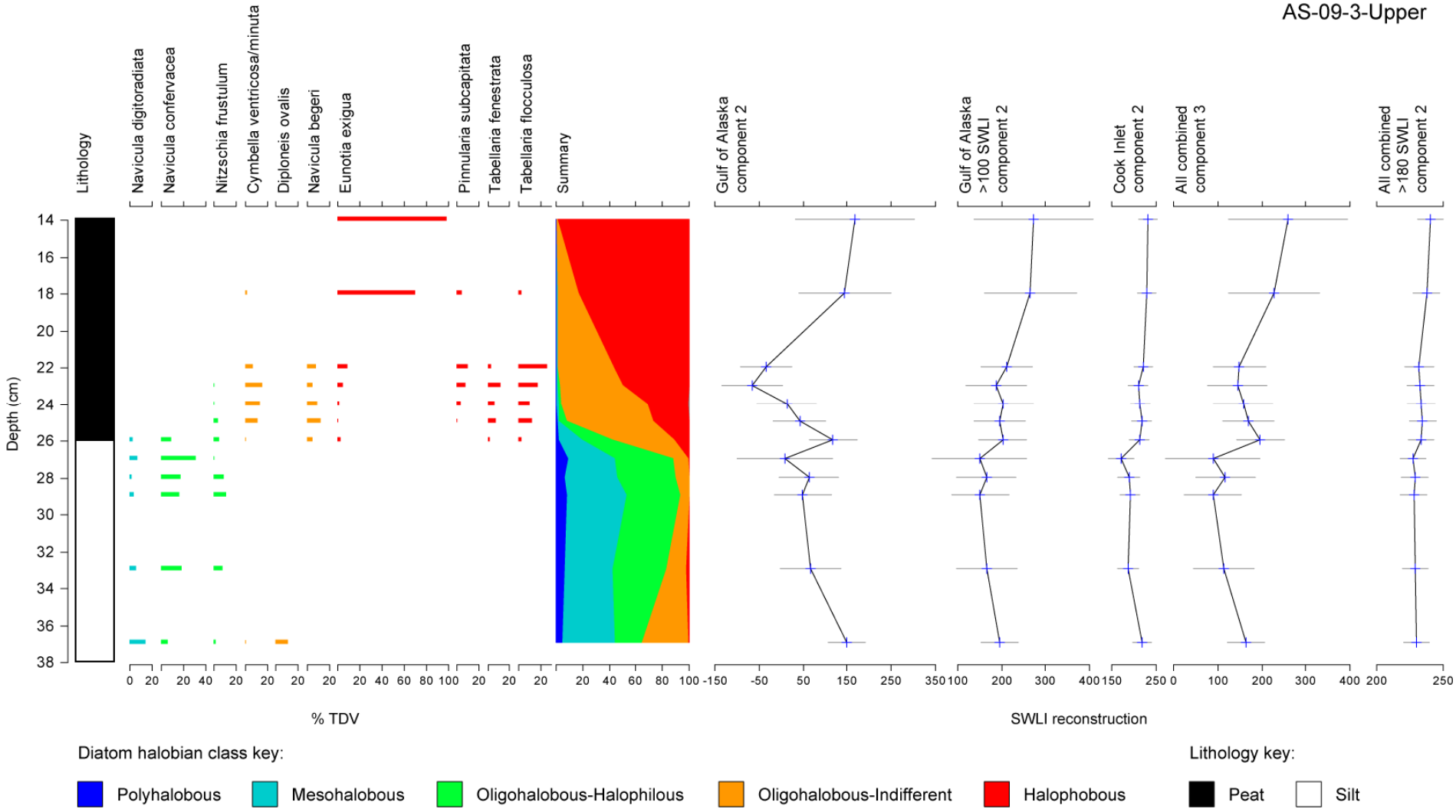


Fig. 13. Summary diatom data for AS/09/3 upper peat and SWLI reconstructions using different modern training sets. Diatoms are expressed as % total valves counted, showing the 10 most abundant species

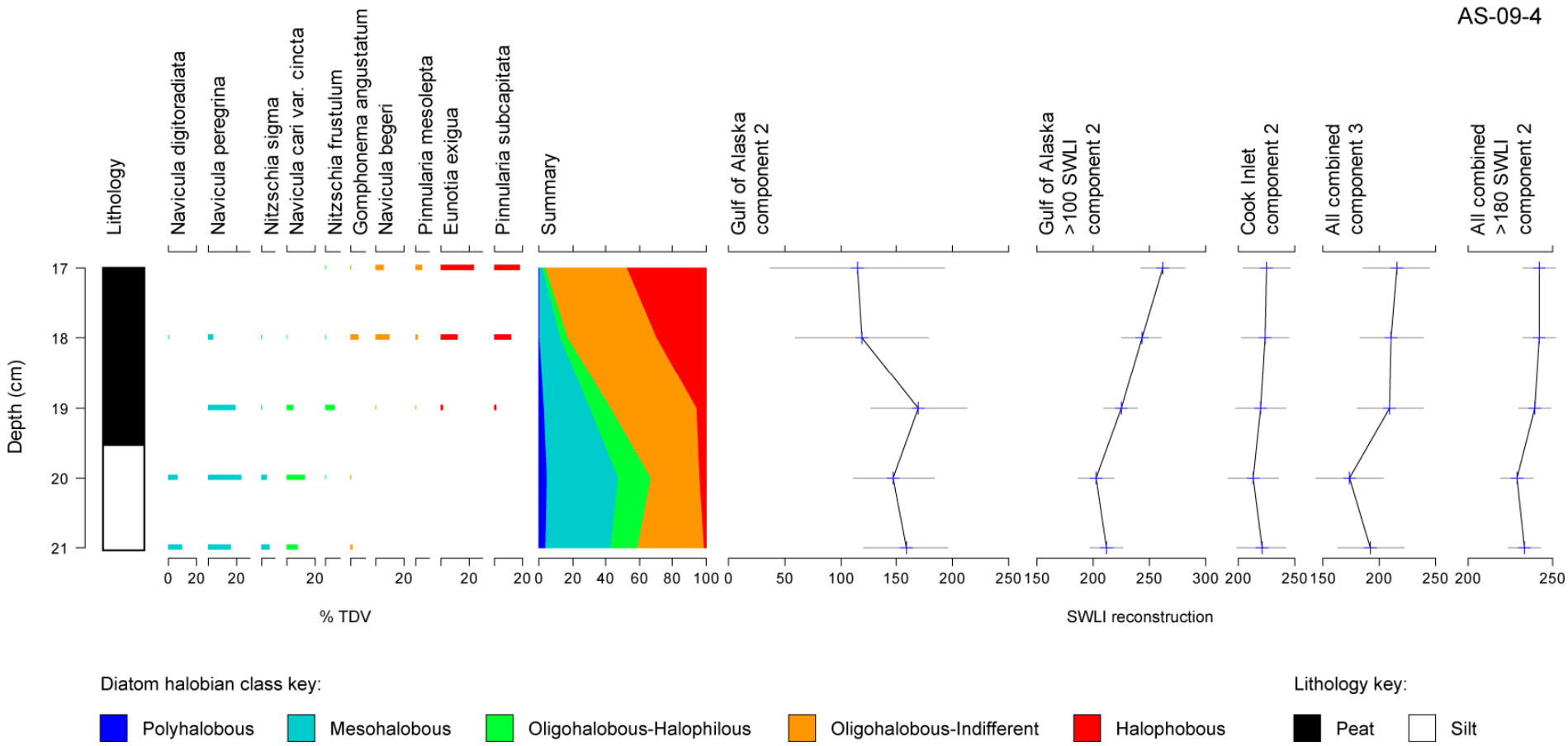


Fig. 14. Summary diatom data for AS/09/4 and SWLI reconstructions using different modern training sets. Diatoms are expressed as % total valves counted, showing the 10 most abundant species

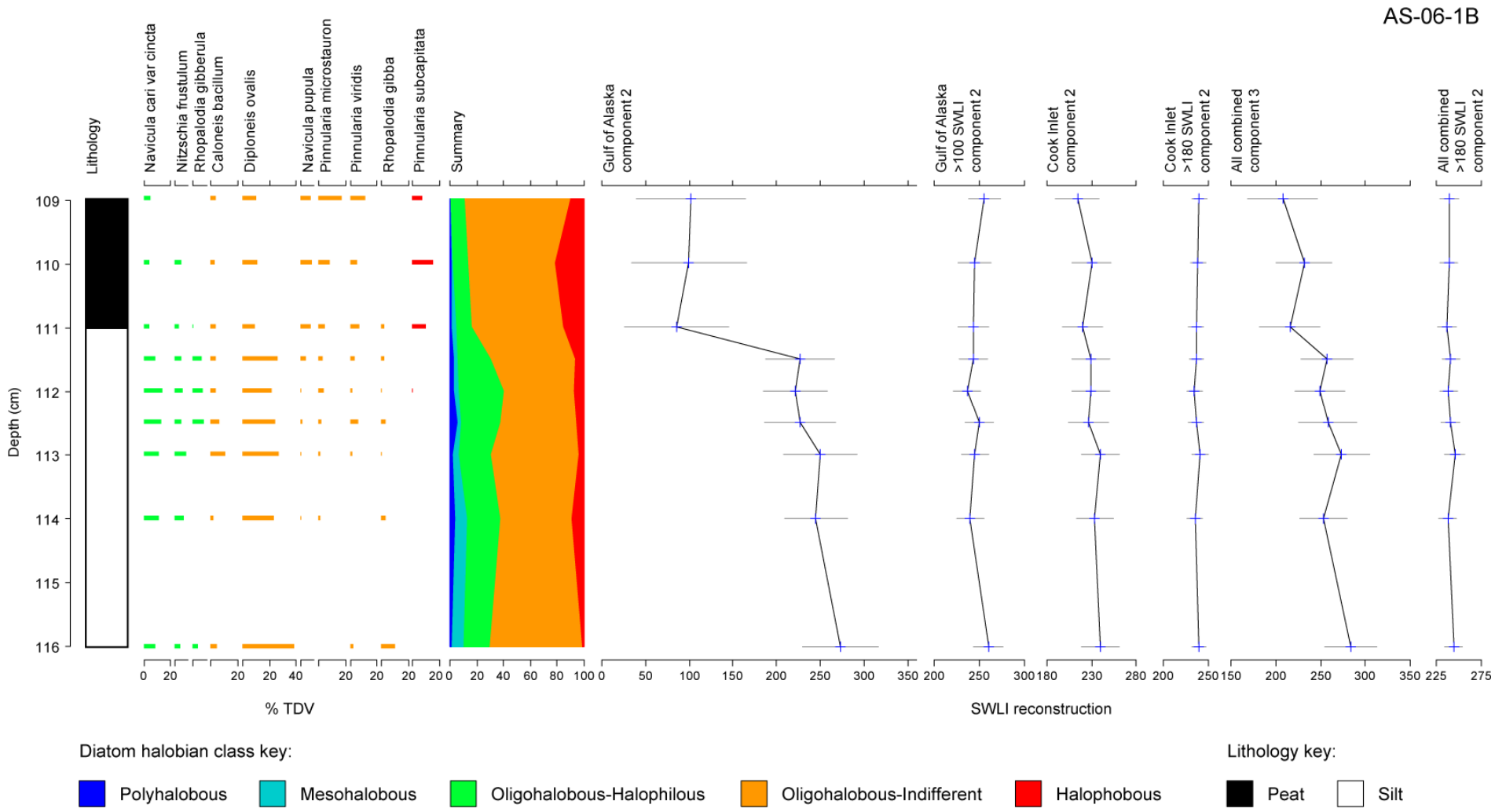


Fig. 15. Summary diatom data for AS/06/1B and SWLI reconstructions using different modern training sets. Diatoms are expressed as % total valves counted, showing the 10 most abundant species

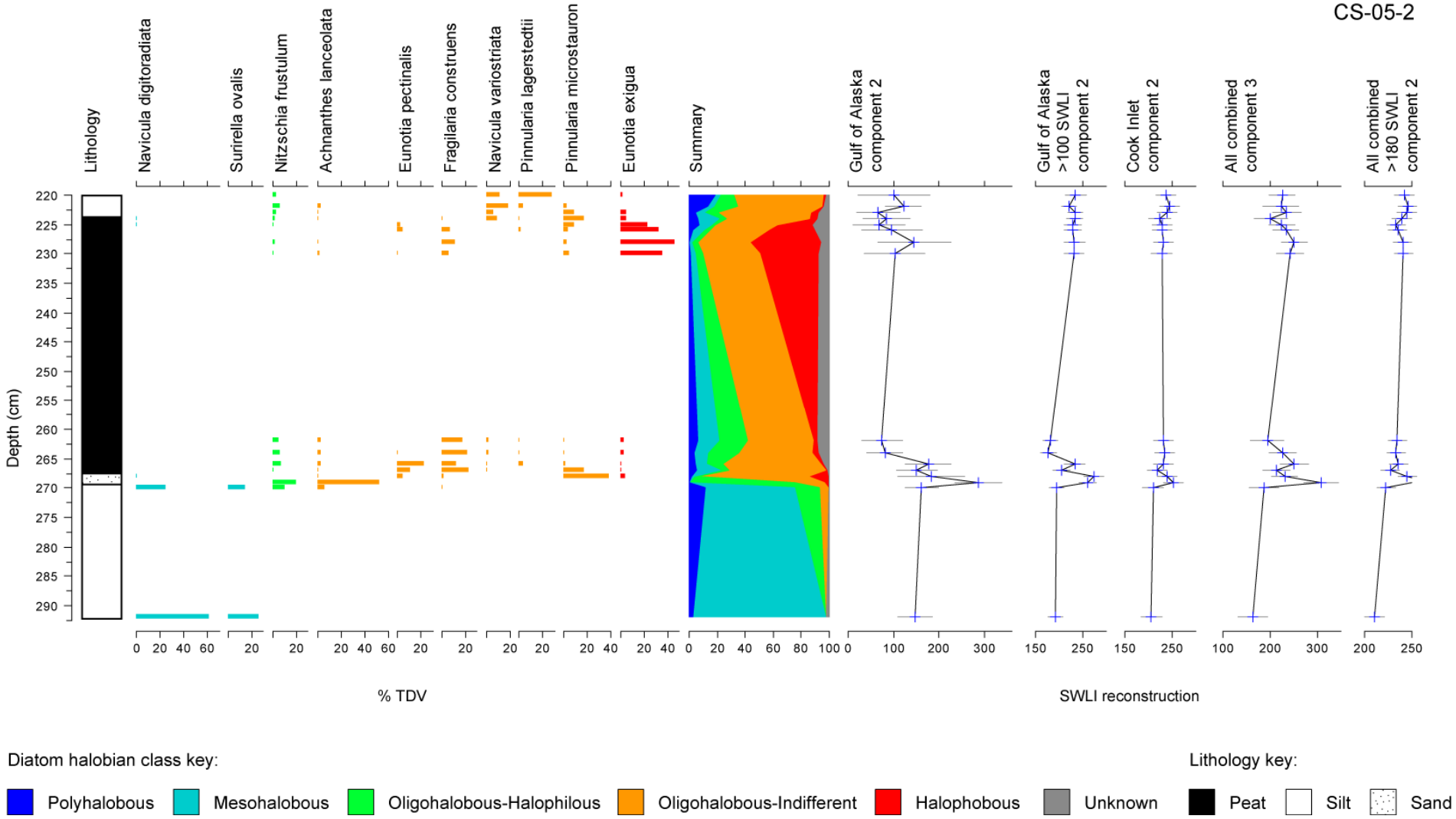


Fig. 16. Summary diatom data for CS/05/2 and SWLI reconstructions using different modern training sets. Diatoms are expressed as % total valves counted, showing the 10 most abundant species.

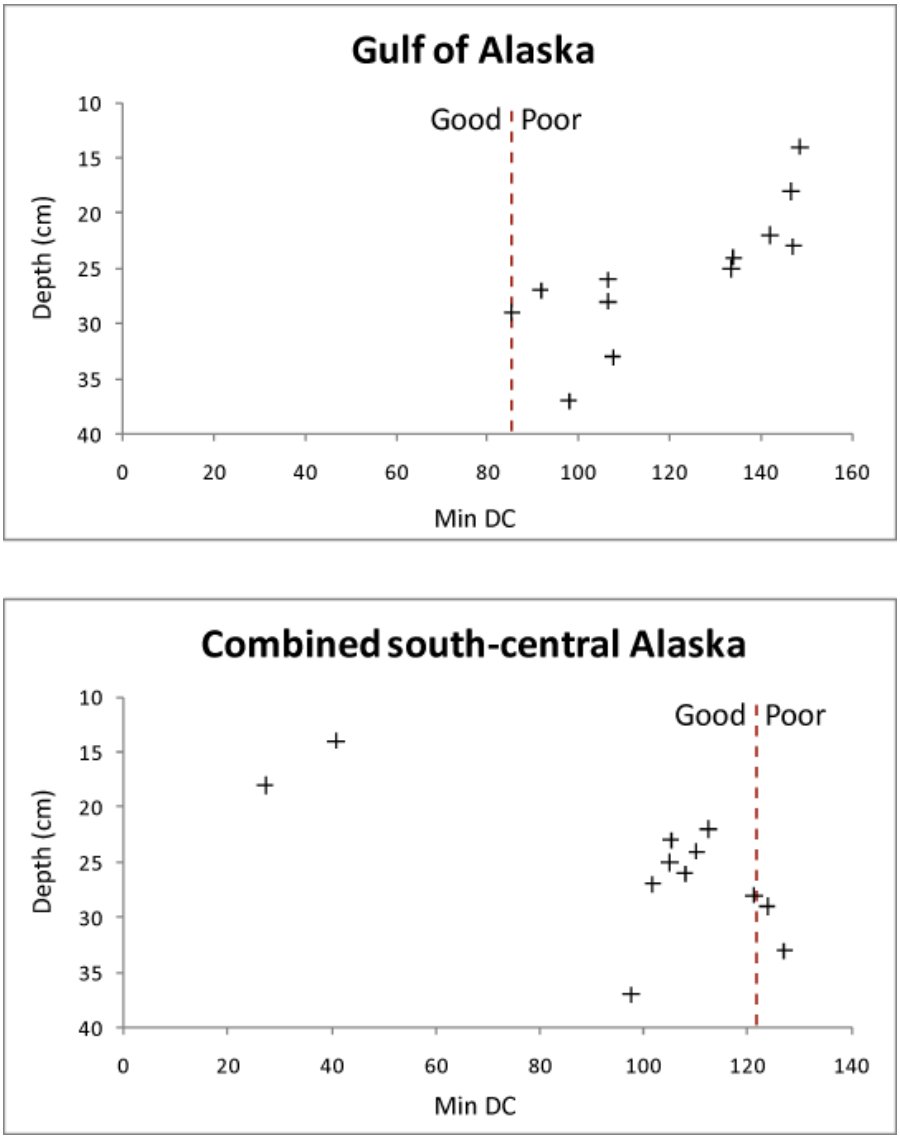


Fig. 17. Comparison of the minimum dissimilarity coefficient (MinDC) for each fossil sample from AS/09/3 between the local and regional transfer function models, with the threshold marked between good and poor analogues.

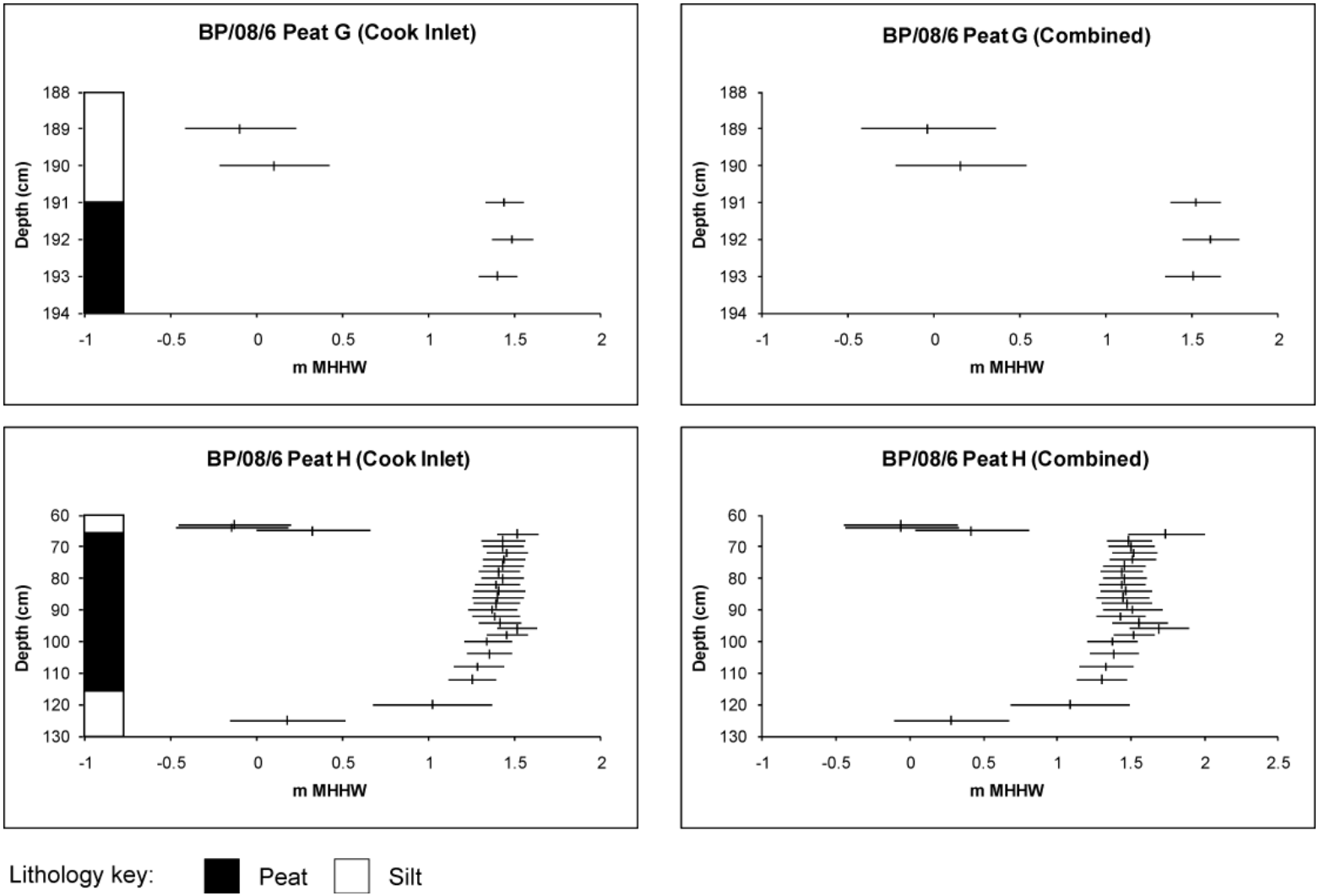


Fig. 18. Reconstructions of relative elevation ±1 standard error at Bird Point, core BP/08/6, from transfer functions using (a) Cook Inlet modern training set, and (b) combined Cook Inlet and Gulf of Alaska modern training set. The tops of peats G and H date to ~900 yr BP and 1964 AD respectively

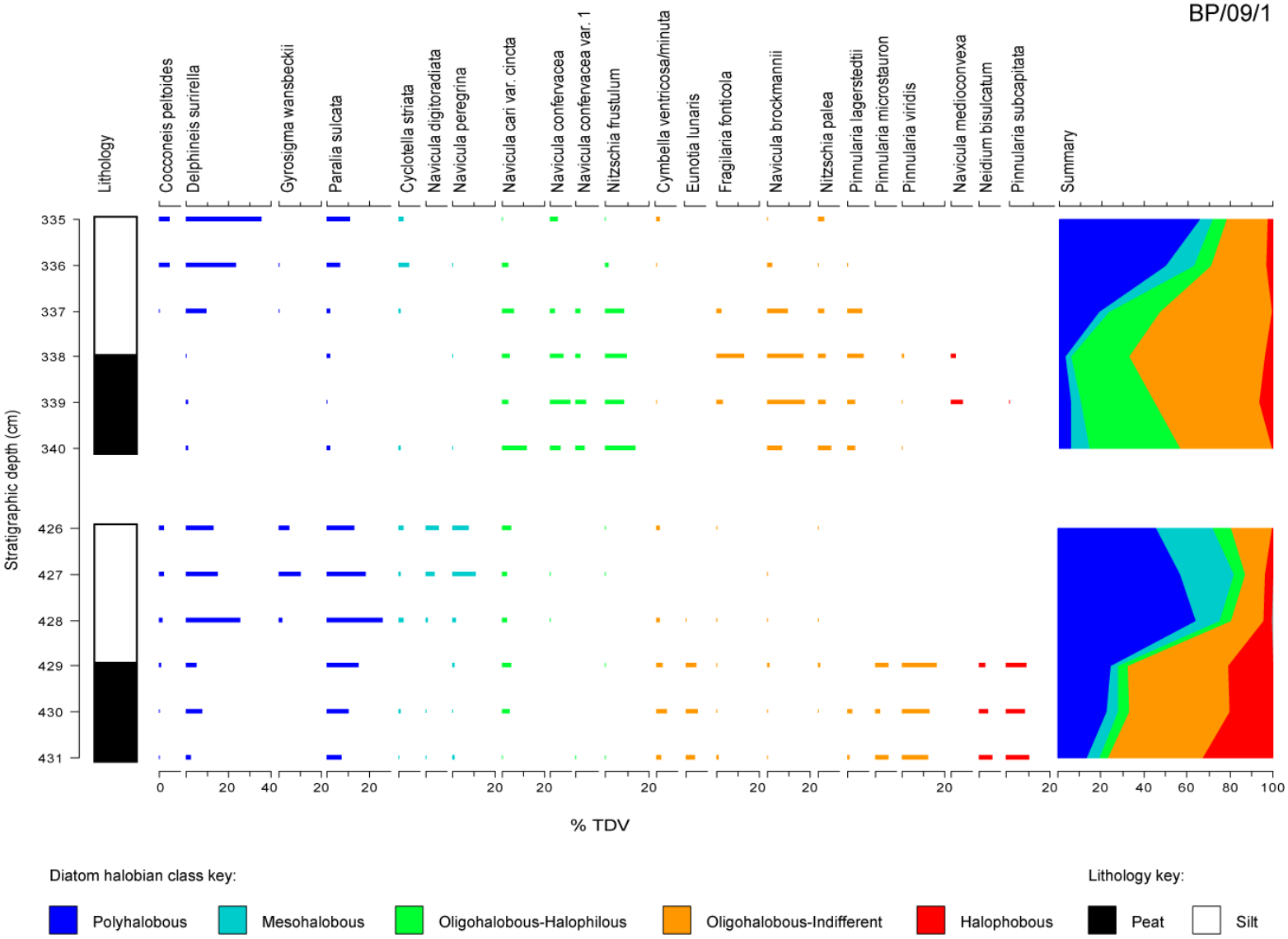


Fig. 19. Summary diatom data for BP/09/1 peats 1 and 2. Diatoms are expressed as % total valves counted, showing species >5%

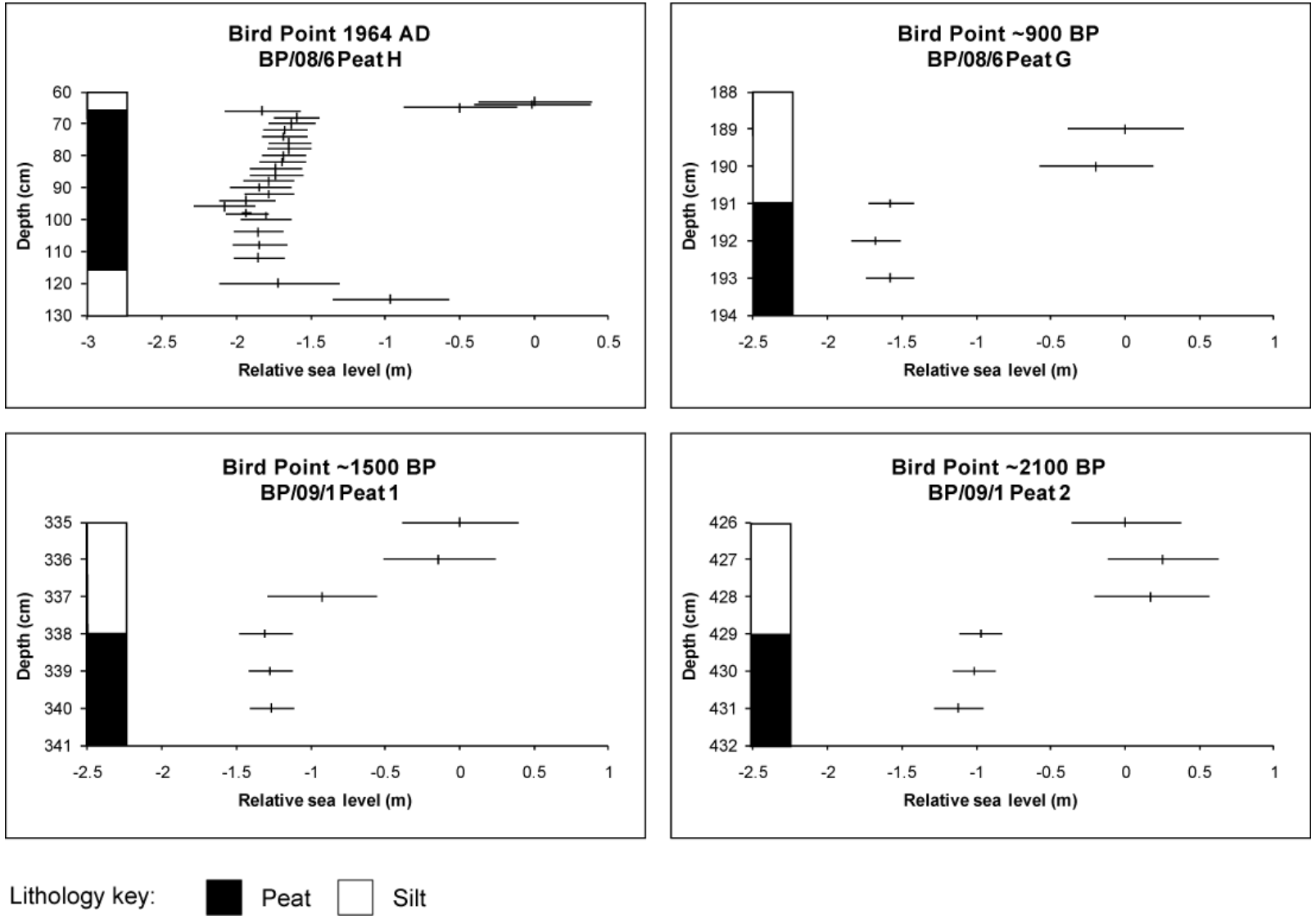


Fig. 20. Relative sea level reconstructions at Bird Point ±1 standard error, using the combined Cook Inlet and Gulf of Alaska modern training set. In each graph, zero refers to the top of the section of core within the graph to highlight the magnitude of relative sea level rise across the peat-silt boundary.

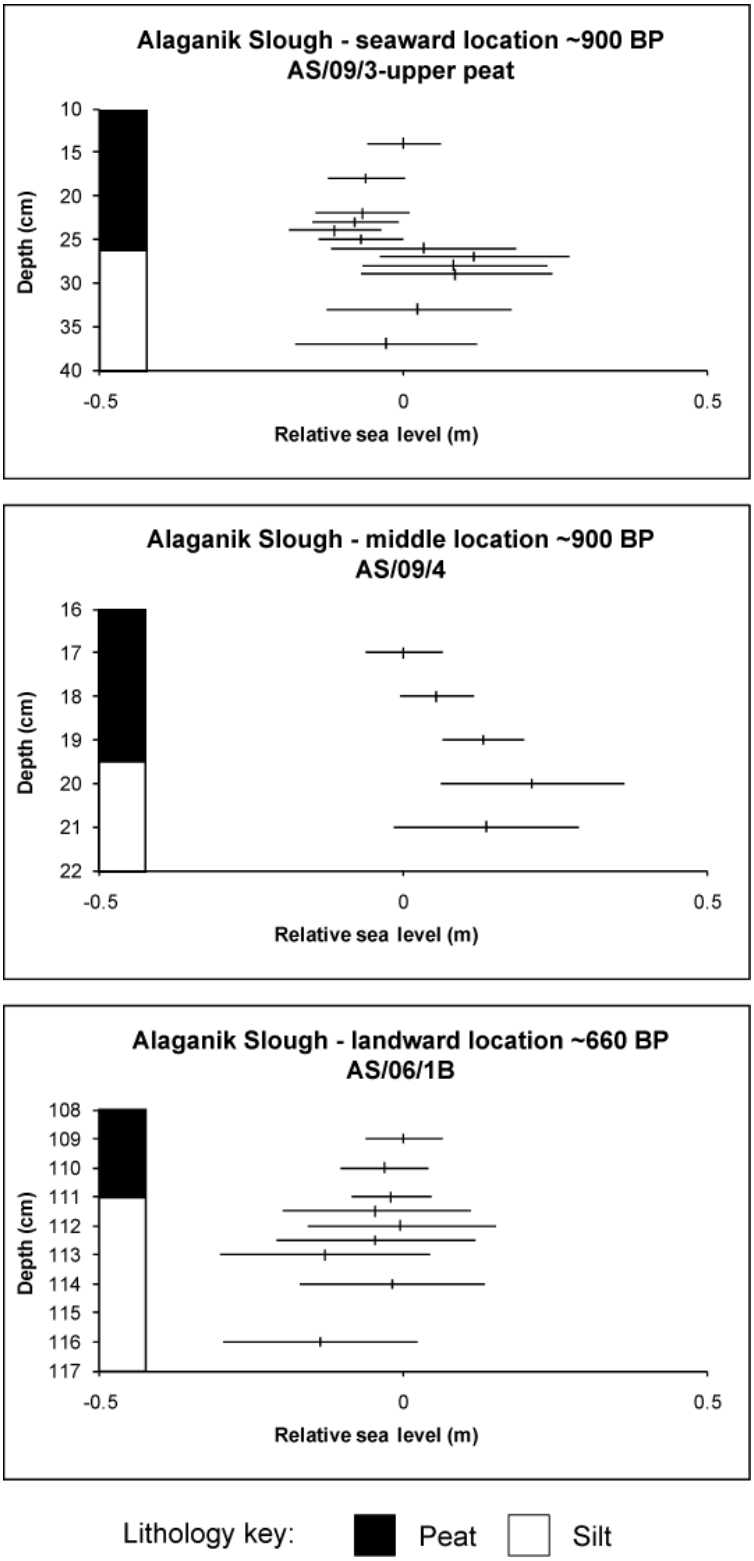


Fig. 21. Relative sea level reconstructions at Alaganik Slough ±1 standard error, using the combined Cook Inlet and Gulf of Alaska modern training set. In each graph, zero refers to the top of the section of core within the graph to highlight the magnitude of relative sea level rise across the peat-silt boundary.

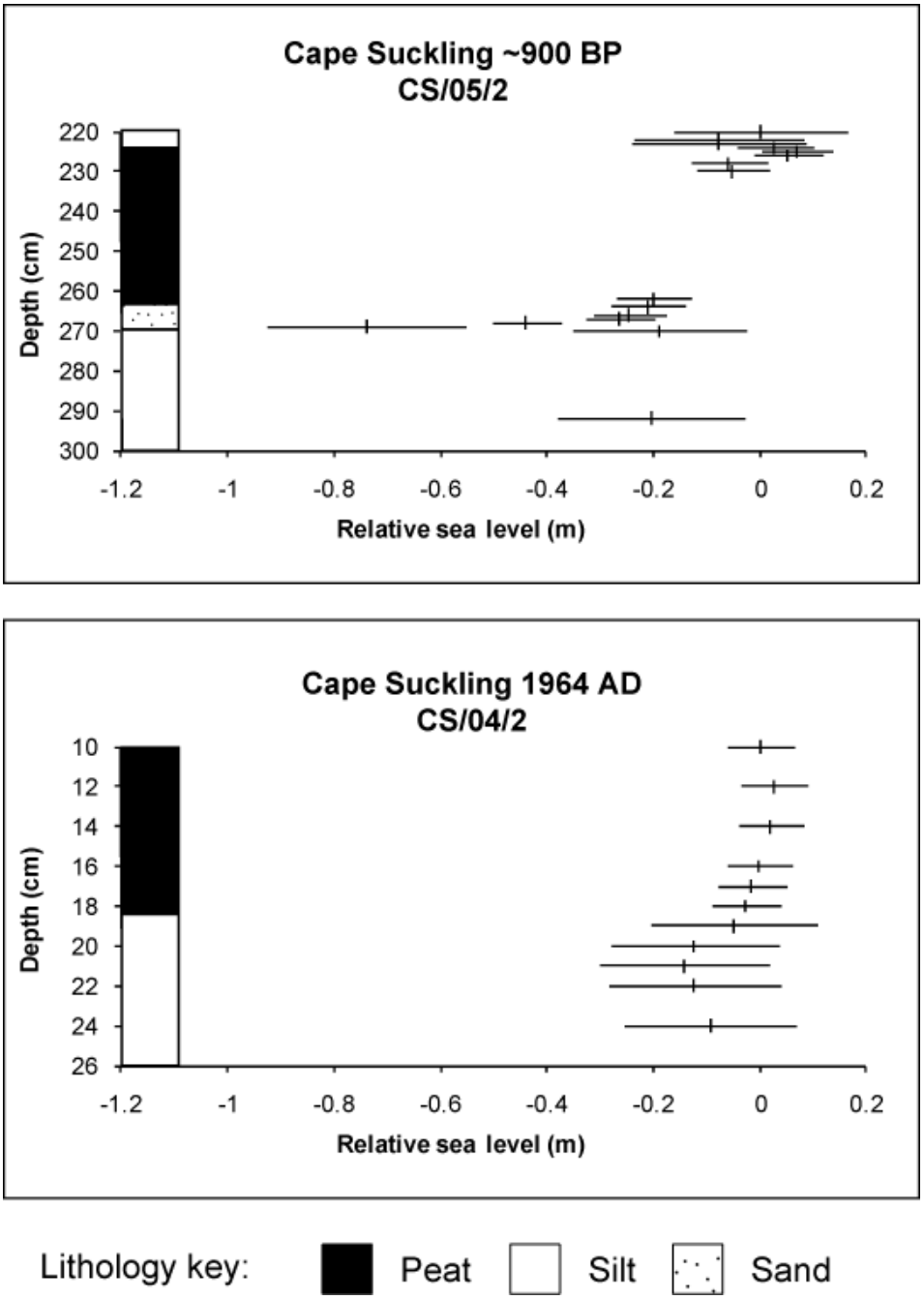


Fig. 22. Relative sea level reconstructions at Cape Suckling ±1 standard error, using the combined Cook Inlet and Gulf of Alaska modern training set. In each graph, zero refers to the top of the section of core within the graph to highlight the magnitude of relative sea level rise across the peat-silt boundary.

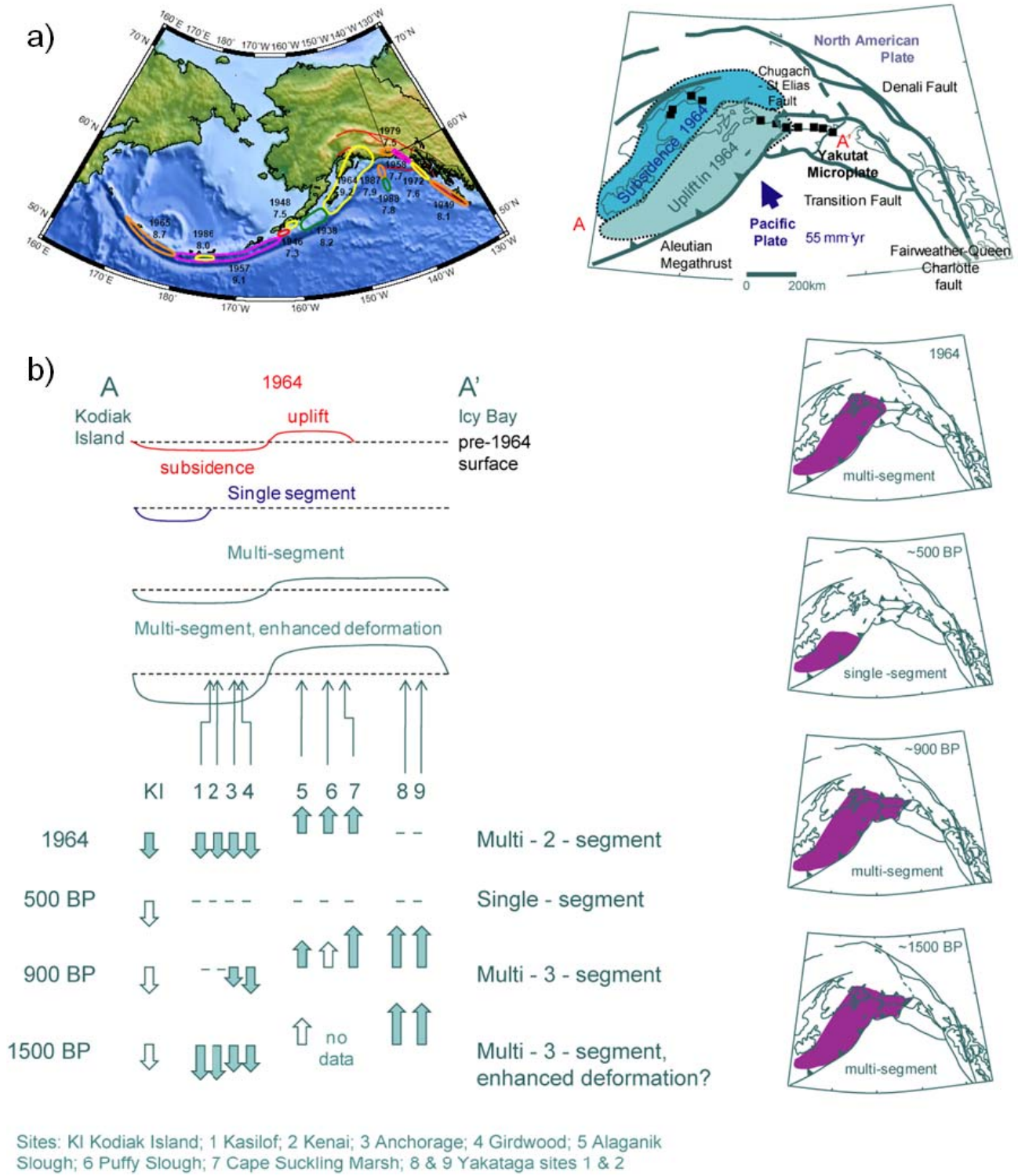


Fig. 23. Comparisons of patterns of deformation and segment ruptures for 1964 and three late Holocene great earthquakes. (a) Segments of the Aleutian megathrust that have ruptured since 1900 AD (modified after Nishenko and Jacob, 1990); (b) Hypotheses of single and multiple-segment rupturing. Large arrows indicate where uplift/subsidence was greater than in 1964 and open arrows indicate where there is no quantitative estimate.

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