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

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Abstract

This NEHRP project (#G10AP00075) has successfully developed quantitative diatom-based transfer function models to apply at sites across south-central Alaska to improve the vertical (elevation) precision of geologic estimates of land level changes from great Holocene plate boundary earthquakes. In our paleoseismic studies on Kodiak Island we have 5 critical findings different to those of the key previous study (Gilpin, 1995).

(1) Despite sampling close to the section at Middle Bay described by Gilpin and the core at Anton Larson Bay we did not replicate the evidence of multiple earthquakes;

(2) transects of cores at each site reveal a high degree of heterogeneity in stratigraphy across a marsh and we cannot demonstrate lateral continuity of any earthquake horizon at this stage;

(3) our radiocarbon results are different and indicate more rapid sedimentation at Middle Bay;

(4) our reconstructions of elevation change across stratigraphic contacts are smaller than those suggested by Gilpin;

(5) none of the events we recorded in the marsh stratigraphy would presently fulfil the criteria of Nelson *et al*. (1996) to support a seismic explanation.

There is evidence to suggest possible co-seismic subsidence ~500 BP at both Middle Bay and Anton Larson Bay on Kodiak Island and an earlier event at Anton Larson Bay. However, we require better records of the within-site consistency and between-site correlation of these events. Until we resolve these site-scale records on Kodiak Island, we cannot test current models of the spatial patterns of estimated land level changes for different Holocene plate boundary earthquakes and whether great earthquake ruptures in Alaska are controlled by persistent segment boundaries or whether the rupture areas overlap.

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 late Holocene paleoseismicity, associated land/sea-level movements and tsunami in south-central Alaska from sedimentary sequences in the western sector of the 1964 rupture, on Kodiak Island (Fig. 1). It builds upon previous work undertaken by the principal investigators in Alaska in which we have quantified vertical 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 inter-seismic 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. Recent investigations present evidence for deformation that extended beyond the eastern extent of 1964 rupture during great earthquakes ~900 and ~1500 years ago (Shennan *et al.*, 2009; Shennan *et al.*, 2010). On Kodiak Island, to the west, marsh sediments also indicate co-seismic deformation at ~900 and ~1500 BP (Carver and Plafker, 2008) as well as an older event, equivalent in age to the earthquake dated 2310-1990 BP in upper Cook Inlet (Shennan *et al.*, 2008), and a younger event, ~500 BP, only recorded on Kodiak (Gilpin, 1995). These variable spatial patterns of deformation for each event limit our ability to test models of plate boundary rupture that require spatial data regarding relative land and sea-level data. These models are key to developing predictions of future seismic hazard in Alaska and on other plate boundaries.

This project aims to (a) extend our paleoseismic record beyond Cook Inlet to the southwestern 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 use the 1964 earthquake to provide a well-defined benchmark to assess methods and models that provide reconstructions of earlier events. 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?

1.1 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, in the Cook Inlet, to incrementally larger scales: Cook Inlet to the Gulf of Alaska coast to Kodiak Island.

In our last NEHRP project (Shennan *et al.*, 2010, USGS grant award # G09AP00105) we developed a new modern training set for the eastern Gulf of Alaska, as well as a combined training set for south-central Alaska by combining the Gulf of Alaska and Cook Inlet data. In this project we develop a new Kodiak Island modern training set and test the spatial-scale dependence of different transfer function models by comparing elevation reconstructions for fossil sites on Kodiak using 1) the Kodiak Island modern training set; 2) the Cook Inlet modern training set; 3) the Gulf of Alaska modern training set (Kodiak, Copper River Delta and Cape Suckling), and 4) a new south-central Alaska modern training set that will be the combination of all three.

1.2 Spatial patterns of land level changes (Research Question 2)

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.

On Kodiak Island, marsh sediments record co-seismic deformation in 1964, ~500 BP, ~900 BP, ~1500 BP and ~2100 BP (Carver and Plafker, 2008). The ~500 BP event has only been recorded on Kodiak, whereas all the others correlate with events in Cook Inlet, Prince William Sound and further east for ~900 BP and 1500 BP (Shennan et al., 2009). Our objective is to determine the extent and variation of surface deformation at selected sites on Kodiak Island for multiple late Holocene events. The sites lie across the trough of subsidence in 1964. Collectively these chosen sites should enable us to test different patterns of co-seismic surface deformation, including the limits of deformation and an indication of the locations maximum subsidence. These data will help indicate the persistence of the boundary of the segment that ruptured in 1964.

1.3 Persistence of segment boundaries and earthquake rupture areas (Research Question 3)

Once we have developed new transfer functions we are in a position to evaluate the evidence for whether persistent segment boundaries control great earthquake ruptures in Alaska or whether the rupture areas overlap. For the eastern limit of the 1964 rupture zone, Shennan *et al*. (2009) use the data from all of the sites between Cook Inlet and Icy Bay to contrast different patterns of co-seismic and net deformation for three seismic cycles that generated great earthquakes. Here we aim to reconstruct the pattern and magnitude deformation at the western extent of the 1964 rupture zone during two or three late Holocene events across the trough of subsidence in 1964 to test multiple hypotheses of the persistence of segment boundaries.

2 Field Investigations and Methods

Field investigations took place during July 2010, with extensive coring and sample collection at Middle Bay and Anton Larson Bay on Kodiak Island (Fig. 2; Fig. 3). We also conducted site surveys of Women's Bay and Kalsin Bay. Due to the more complete, yet more complex stratigraphies at Middle Bay and Anton Larson Bay, compared to previous sites, we had to focus on these sites. It was not possible to sample Afognak River, as originally planned, due to the inaccessibility of the site and problems with arranging land access. All collected samples were wrapped in plastic and stored in a fridge at Durham on return to the UK. 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.

3 Results

3.1 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 Kodiak Island modern training set, made up of 46 samples from Middle Bay (Fig. 4; Fig. 5). This 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 Kodiak training set, there is a general trend in the diatom samples relative to elevation (Fig. 5). 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 below SWLIs of 180 are dominated by mesohalobous and oligohalobous-halophilous species. Species distributions in the Kodiak training set are similar to those in Cook Inlet and eastern Gulf of Alaska. The only major difference is the much higher abundances of *Achnanthes delicatula* in the Kodiak training set. The Kodiak training set also extends the environmental gradient to 290 SWLI units, as the highest elevation sample from any site previously was 254 SWLI units.

We investigated the best transfer function to reconstruct elevation for fossil samples by comparing models using this new Kodiak training set with those using the Cook Inlet training set (Hamilton and Shennan, 2005a), as well as combining the three local training sets from Cook Inlet, eastern Gulf of Alaska and Kodiak, into a regional south-central Alaska modern training set. Table 1 shows the summary statistics of WA-PLS regression, and Fig. 7 shows an example of the relationship between observed and predicted SWLIs for the best components of two transfer function models using the Kodiak training set and the combined regional training set.

Model	No. of samples	Bootstrapped r^2	Root mean squared error of prediction
Kodiak – all	46	0.86	23.64
Kodiak >180 SWLI	29	0.80	14.94
Kodiak >225 SWLI	17		
Cook Inlet – all	170	0.67	21.29
Cook Inlet >180 SWLI	145	0.76	8.16
Cook Inlet >225 SWLI	74	0.74	3.12
East Gulf of Alaska – all	56	0.79	32.99
East Gulf of Alaska >100 SWLI	47	0.83	15.09
East Gulf of Alaska >180 SWLI	32	0.85	9.23
East Gulf of Alaska >225 SWLI	9		
Combined – all	276	0.59	33.29
Combined >100 SWLI	255	0.77	17.35
Combined >180 SWLI	206	0.68	11.83
Combined >225 SWLI	100	0.76	6.14

Table 1 Summary statistics for the contemporary training sets using WA-PLS component 2 from C2. The best models are 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)

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. Due to the small size of the East Gulf of Alaska and Kodiak training sets, it is not possible to run the >225 SWLI models, as these do not exceed the minimum sample size. We exclude samples below 100 SWLI units when using the East Gulf of Alaska training set, as in the Gulf of Alaska factors other than elevation were found to control diatom distribution in samples below SWLIs of 100, such as the influence of glacial meltwater from the Copper River Delta (Shennan *et al.*, 2010).

We tested spatial-scale dependence of the different transfer function models by comparing elevation reconstructions for fossil sites using the Kodiak and new regional south-central Alaska modern training sets. We analysed four cores from Middle Bay and Anton Larson Bay, Kodiak Island (MB10-5C, MB10-12, ALB10-4C and ALB10-9), as well as one exposure from each site which cover the 1964 earthquake (MB10-13 and ALB10-4) (Figs. 8-11). Reconstructions based on the full Kodiak modern training set were very similar to those based on the regional south-central Alaska training set. However, it was not possible to produce reliable reconstructions based on a restricted Kodiak training set using only samples >180 SWLI units for example, as the sample size of the training set becomes too small.

We can assess reliability of the reconstructions by using the Modern Analogue Technique (Fig. 12). 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 Kodiak modern training set. This improves significantly when we use the regional south-central Alaska training set including samples from the Cook Inlet and eastern Gulf of Alaska, and the major reason for this is the relatively small sample size of the Kodiak modern training set (it only contains 46 samples compared to 276 samples in the combined training set). The modern Kodiak training set is reasonably internally consistent (maximum MinDC of 67 compared to 122 for the combined south-central Alaska training set), however when only 46 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. We conclude that combining the Kodiak training set with the Cook Inlet and East Gulf of Alaska samples to make a regional training set improves the model performance over using either local training set for reconstructions of elevation change in Kodiak. In the four fossil cores, using the Kodiak modern training set in combination with Cook Inlet and East Gulf of Alaska, lowered the MinDC values in all cases compared to using only the Cook Inlet and East Gulf of Alaska combined (Fig. 12). For core ALB10-4C adding the modern Kodiak samples to the regional training set increased the number of fossil samples having good modern analogues from 20% to 93%. Similarly, for MB10-5C we see an improvement from 18% of fossil samples having a good modern analogue using the Cook Inlet and East Gulf of Alaska modern training set to 65% using the combined modern training set from all sites (Cook, East Gulf and Kodiak).

Our comparison of modern training sets and a range of transfer function models from Kodiak, Cook Inlet, East Gulf of Alaska, and their combination as a regional training set gives the following conclusions at this stage:
(1) The Kodiak training set is currently too small to give good analogues in fossil reconstructions;
(2) Adding the modern samples from Kodiak into the regional training set significantly increases the number of fossil samples with close modern analogues.
(3) The regional dataset potentially reduces reconstruction error terms where there is a good modern analogue.

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

We use the regional south-central Alaska modern data set to reconstruct elevation for fossil samples from the six cores from Middle Bay and Anton Larson Bay. We restrict the modern training set used in the transfer function to samples above 100 SWLI units, as below this factors other than elevation appear to control diatom distribution (particularly at Copper River Delta and Kenai). For example, the input of glacial meltwater into the Copper River Delta significantly affects diatom distribution in samples below a SWLI of 100 (Shennan *et al.*, 2010). We consider our reconstructions of elevation change as provisional until we can test the modern training set further.

We report 13 radiocarbon dates from Middle Bay and Anton Larson Bay (Table 2). The only previously reported dates from these sites come from Gilpin (1995) and Carver and Plafker (2008), but these differ significantly. Based on salt marsh investigations at sixteen sites across Kodiak Island, Gilpin (1995) identified three palaeoseismic events from clusters of radiocarbon dates at ~500 yr BP, ~800 yr BP and ~1300 yr BP. He reported abrupt vegetation and salinity changes associated with the 500 yr and 1300 yr BP events at most sites, but did not find evidence for the 500 yr BP event at Anton Larson Bay, or for the 1300 yr BP event at Middle Bay. The 800 yr event was dated at Middle Bay, but was not associated with a definitive change in diatom environment indicative of land-level change. Gilpin interpreted this event horizon as evidence of rapid inundation associated with a tsunami from a distant source (most likely to be a rupture of the Prince William Sound segment).

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		
MB10/5C 107cm	287207	Top of peat	410 ± 40	470	320	520
MB10/5C 124cm	287208	Middle of peat	330 ± 40	390	310	480
MB10/5C 135cm	299877	Base of peat 1	240 ± 30	290	0	420
MB10/12 70cm	295548	Top of peat 2	270 ± 30	320	0	440
MB10/12 83cm	295549	Middle of peat 2	210 ± 30	180	0	310
MB10/12 90cm	295550	Top of peat 1	320 ± 30	390	310	470
MB10/12 93cm	295551	Base of peat 1	420 ± 30	490	330	520
MB10/8 130cm	299878	Top of peat	330 ± 30	390	310	470
MB10/8 153.5cm	299879	Base of peat	700 ± 30	660	560	690
ALB10/4 78.5cm	287205	Top of peat 2	370 ± 40	430	320	500
ALB10/4 117cm	295546	Base of peat 2	1320 ± 30	1260	1180	1300
ALB10/4 146cm	287206	Top of peat 1	2260 ± 40	2240	2150	2350
ALB10/9 57cm	295547	Top of peat	180 ± 30	180	0	300

Table 2 Radiocarbon dates taken in 2010 from Middle Bay (MB) and Anton Larson Bay (ALB).

At all sites we observe bryophyte peat overlain by salt marsh *Triglochin* peat and intertidal silt. In MB10-5C we observe one peat-silt couplet, dating to 520-320 cal yr BP, which fits with the maximum dates for an event reported by Gilpin (1995) in Middle Bay and neighbouring Kalsin Bay at 695-509 cal yr BP. However, there is no significant change in the diatom assemblage across the stratigraphic boundary and the transfer function reconstruction does not show an elevation change (Fig. 8, Fig. 13). We interpret the 1 cm thick silt layer at 116 cm, with the lowest reconstructed elevation, to be an ice-rafted tidal flat block, a phenomenon that we observe on the contemporary marsh.

By contrast, the peat-silt couplet in MB10-12 is younger, dating to 320 cal yr BP (440-0 cal yr BP) and elevation reconstructions from the transfer function suggest slight subsidence across the boundary of

~0.2 m (Fig. 13). We do not find evidence for the 800 yr BP and 1300 yr BP events at Middle Bay within the depth of the cores taken.

At Anton Larson Bay (core ALB10-4C) the top peat-silt couplet dates to the same range as that in MB10-5C between 500-320 cal yr BP. There is a transition in the diatom assemblage from entirely freshwater species in the peat to a mixed marine, brackish and freshwater assemblage in the overlying silts (Fig. 10). Reconstructions from the transfer function suggest slight co-seismic subsidence of ~0.2 m (Fig. 14). There is an additional lower transition from freshwater species to mixed marine, brackish and freshwater species at 118 cm, which dates to 1300-1180 cal yr BP. Although the stratigraphy is the reverse of the couplet above, with bryophyte peat overlying silt, the diatom assemblages across the two boundaries are very similar in terms of main species present and overall trends. The date on the transition also corresponds exactly in age to the event identified at Anton Larson Bay by Gilpin at 1290-1178 cal yr BP, but in our sequence, the sediment shows an up-core change from silt to peat, not the reverse.

We observe one peat-silt couplet in a second core from Anton Larson Bay, ALB10-9, but it is not associated with a change in the diatom assemblage and we do not find evidence for palaeoearthquakes in this core.

In addition to assessing the evidence for palaeoearthquakes, we also investigated the 1964 event (MB10-13 and ALB10-4). A layer of tsunami sand overlain by silt with intertidal diatoms is preserved between the modern peat mat and the underlying peat, whose lower bound is the 1912 Katmai tephra deposit. Reconstructions of elevation change from the transfer function suggest co-seismic subsidence of ~0.6 ± 0.4 m for Middle Bay and ~1.0 ± 0.5 m for Anton Larson Bay. This is slightly less subsidence than suggested by Plafker (1969) of between 1.3 and 1.8 m for eastern Kodiak Island.

Our analysis of fossil cores from Middle Bay and Anton Larson Bay give the following conclusions:
(1) We have limited evidence from Middle Bay and Anton Larson Bay for the ~500 yr BP event previously identified by Gilpin (1995). We cannot refute the idea of an earthquake occurring at ~500 yr BP due to archaeological evidence from the Afognak River, northeast of Kodiak, of settlements being abandoned at this time (Hutchinson and Cowell, 2001; Saltonstall and Carver, 2002). However, our diatom analysis and transfer function reconstructions suggest that any co-seismic land level change on the main island was of a much smaller magnitude than Gilpin proposed.
(2) We did not find evidence for an event at ~800 yr BP at either site.
(3) We find evidence for an older event Anton Larson Bay, which dates to 1300-1180 cal yr BP, associated with only slight submergence. This requires further investigation to test against the criteria for a supporting co-seismic cause (Nelson *et al.*, 1996).
(4) Our reconstructions of co-seismic subsidence associated with the 1964 event are at the lower end of the range proposed by Plafker (1969).

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

Fig. 15 illustrates our current working hypotheses regarding plate segmentation, built upon our investigations at the eastern boundary of the 1964 rupture zone and correlation with published records from Kodiak Island. While we have found evidence to suggest possible co-seismic subsidence ~500 BP at both Middle Bay and Anton Larson Bay on Kodiak Island and an earlier event at Anton Larson Bay, we require better records of the within-site consistency and between-site correlation of these events. Until we resolve these site-scale records on Kodiak Island, we cannot test current models of the spatial patterns of estimated land level changes for different Holocene plate boundary earthquakes and determine whether great earthquake ruptures in Alaska are controlled by persistent segment boundaries or whether the rupture areas overlap.

4 *Conclusions*

We have addressed the three research questions set out above, and highlight four main conclusions.
(1) The Kodiak modern training set is small, but when combined with samples from Cook Inlet and eastern Gulf of Alaska, the regional data set covers a longer environmental gradient and reconstruction error terms are reduced.
(2) We can identify different spatial patterns of co-seismic deformation during late Holocene great earthquakes in south-central Alaska.
(3) We find limited evidence for possible earthquakes ~500 yr BP at Middle Bay and Anton Larson Bay and ~1300 yr BP at Anton Larson Bay.
(4) In terms of earthquake hazard assessment, comparison of the last four great earthquakes (1964, ~500 BP, ~900 BP, ~1500 BP) suggest three different modes of plate segmentation and spatial extents of surface deformation.

5 *Appendix A*

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

5.1 Microfossil analysis

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). C2 (version 1.5; Juggins, 2007) allows plotting of results and the halobian classification system divides the diatom species into five categories of salt tolerance (Table 3).

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) and brackish (mesohalobous) 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 3 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 earthquake deformation cycle 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.

5.2 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. Calibrated ages are reported as the range between the calculated minimum and maximum value, with the median age marked on figures.

5.3 Numerical techniques

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

5.3.2 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.

6 Figures

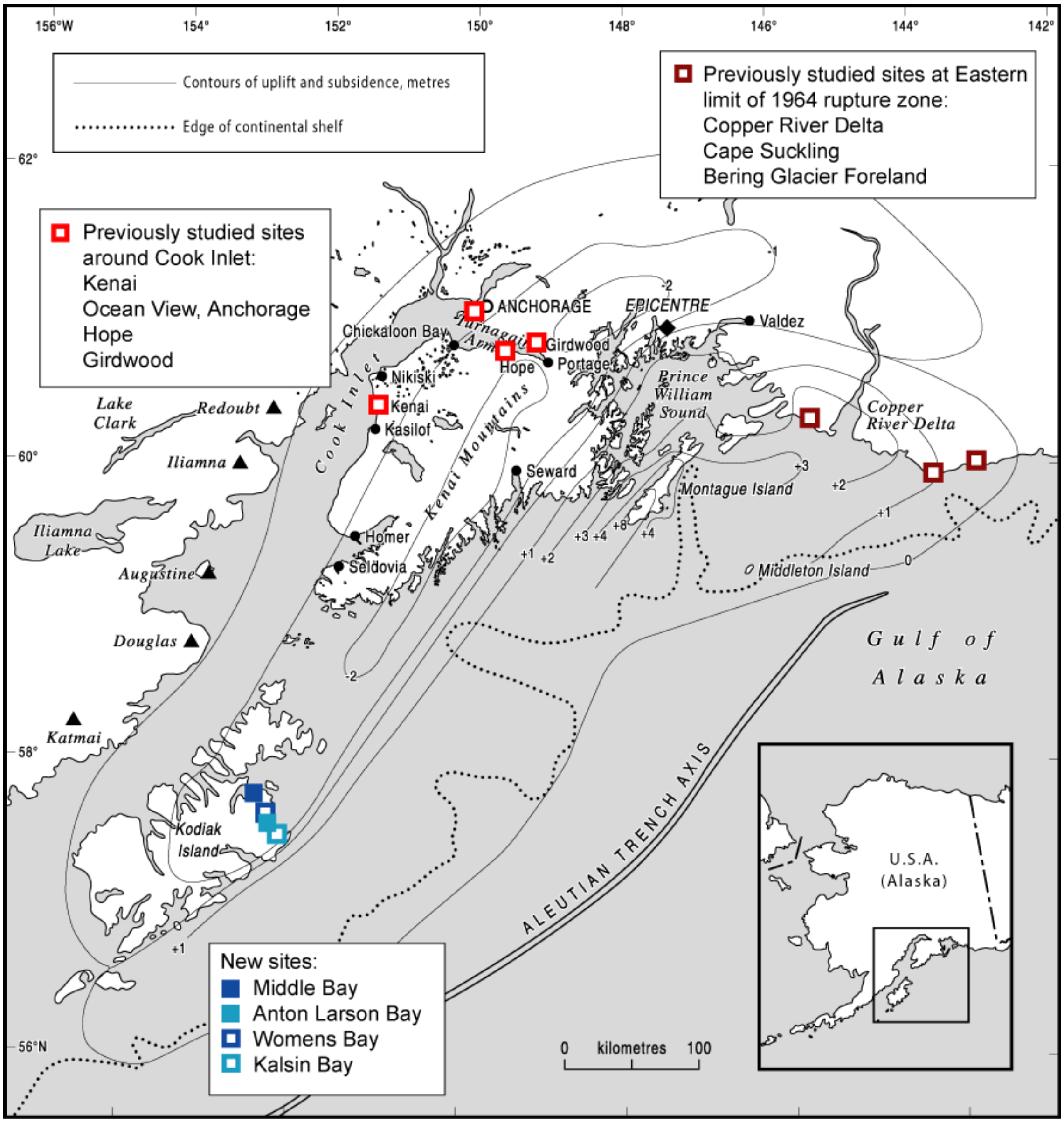

Fig. 1. Location of field sites. Contours show vertical deformation caused by the 1964 earthquake (excluding local subsidence caused by sediment compaction), Plafker *et al.* (1992)

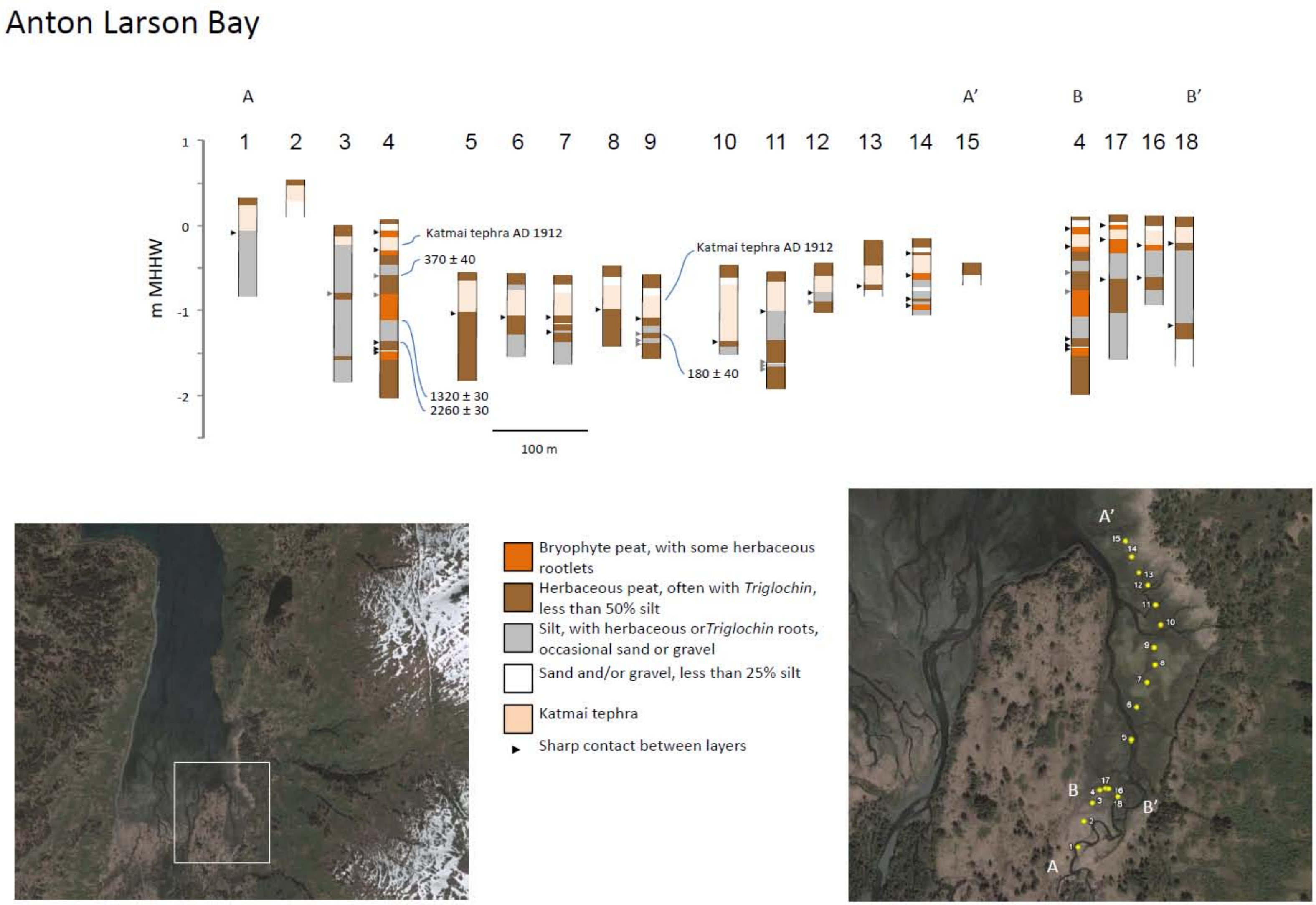

Fig. 2. Coring transects from Anton Larson Bay, Kodiak Island

Middle Bay coring transects

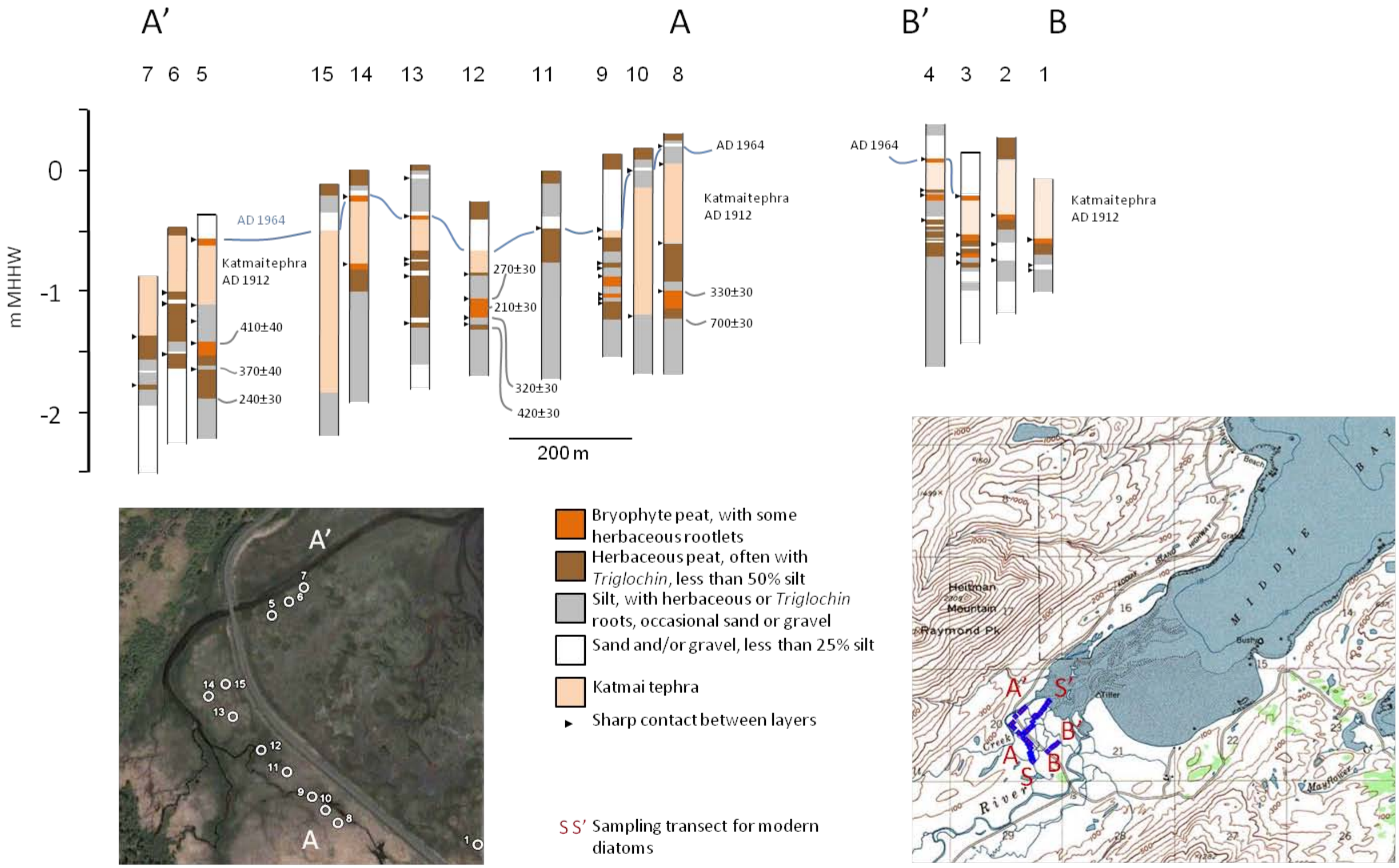

Fig. 3. Coring transects from Middle Bay, Kodiak Island

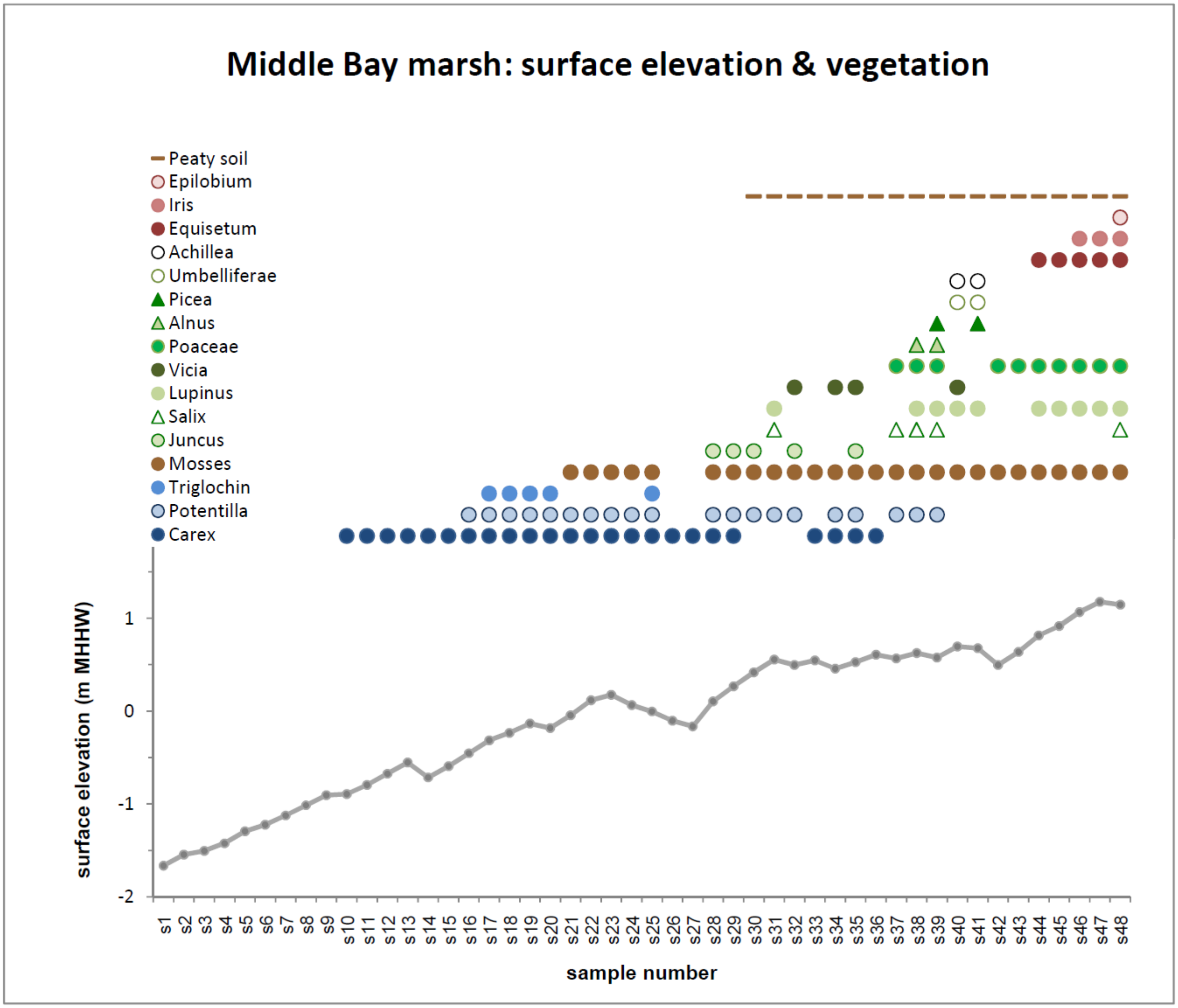

Fig. 4. Contemporary sampling transect across Middle Bay, showing surface elevation and vegetation

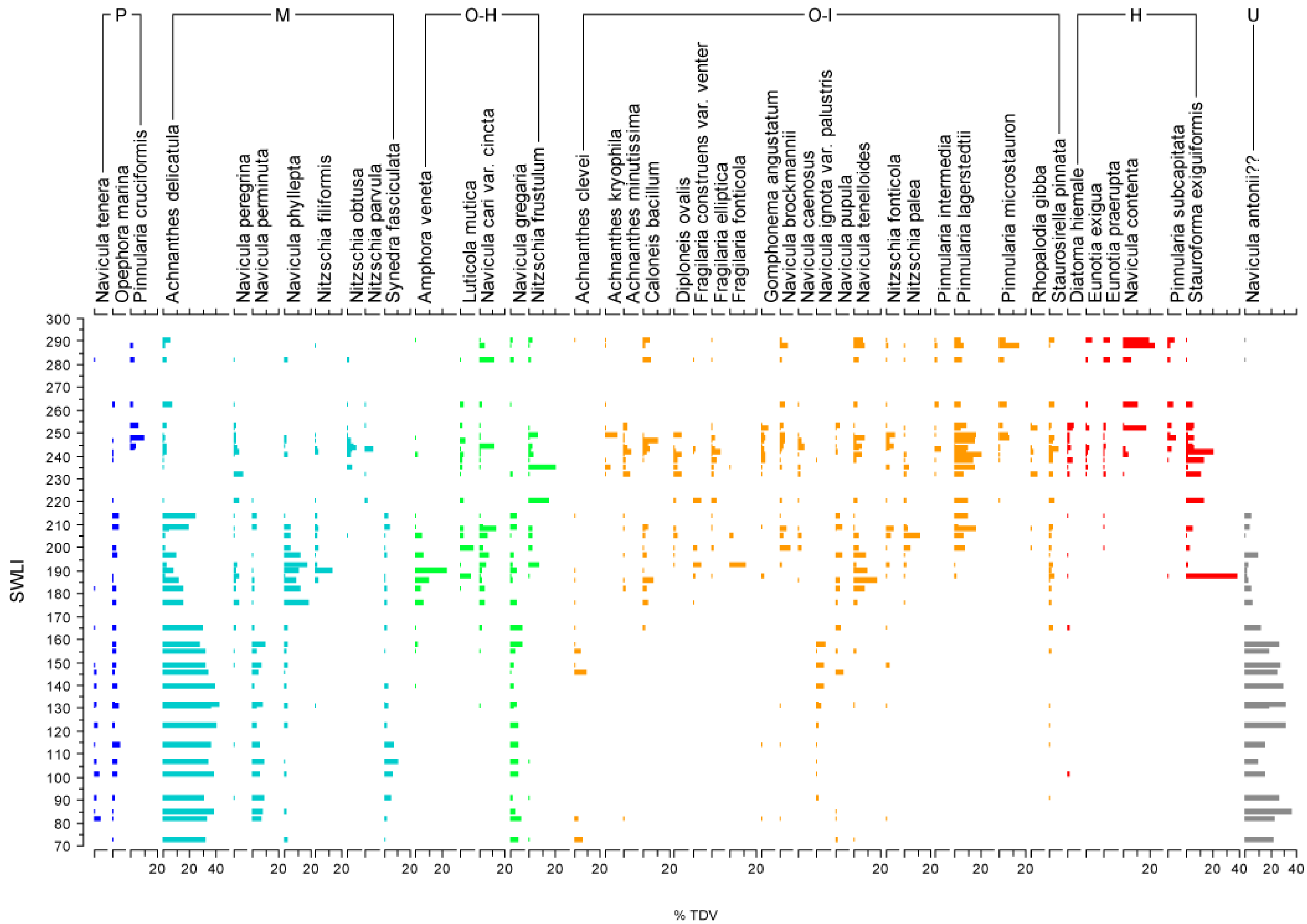

Fig. 5. Summary diatom data for modern samples from Middle Bay plotted against SWLI value, showing species >5% of total count. Samples are ordered by elevation (Standardised Water Level Index, where 100 = mean sea level and 200 = mean higher high water)diatom classification: P – polyhalobous; M – mesohalobous; O-H – oligohalobous-halophilous; O-I – oligohalobous-indifferent; H – halophobous; U - unknown

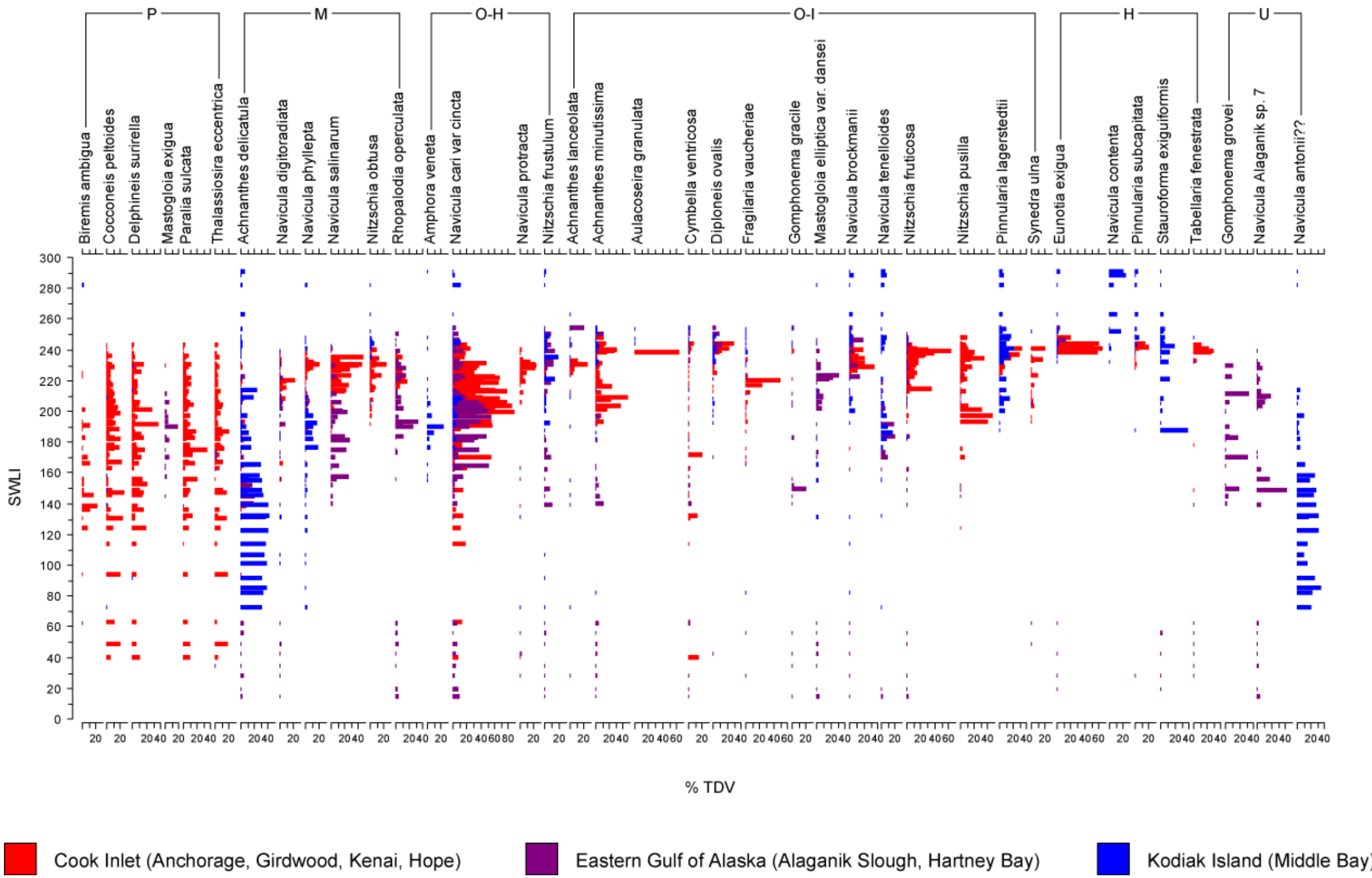

Fig. 6. Modern diatom data (≥20% total diatom valves counted) for upper Cook Inlet, eastern Gulf of Alaska and Kodiak Island. Samples are ordered by elevation (Standardised Water Level Index, where 100 = mean sea level and 200 = mean higher high water). Summary diatom classification: P – polyhalobous; M – mesohalobous; O-H – oligohalobous-halophilous; O-I – oligohalobous-indifferent; H – halophobous; U - unknown

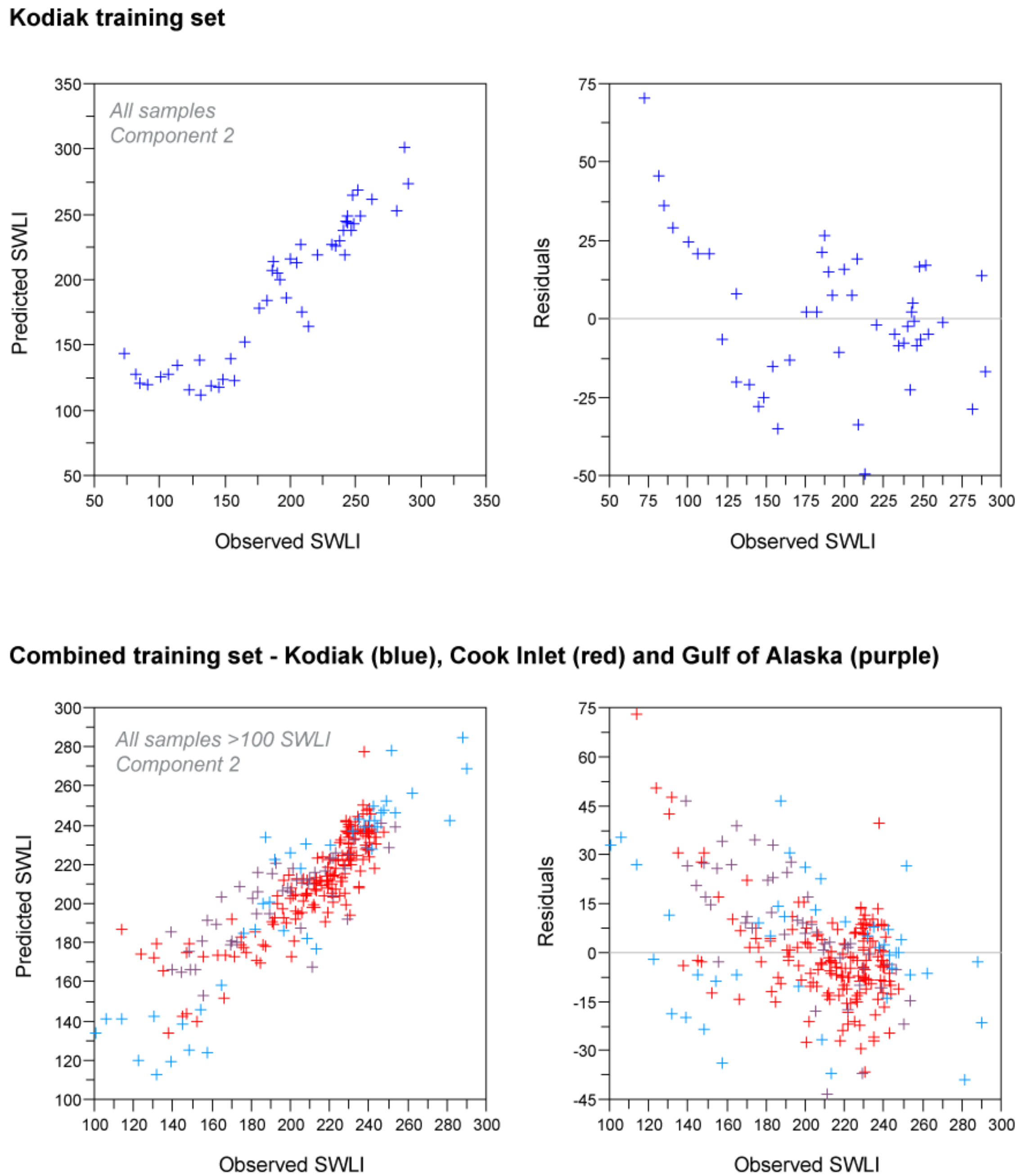

Fig. 7. Observed against predicted Standardised Water Level Index (SWLI) values for the Kodiak Island modern training set and the south-central Alaska modern training set, which combines the upper Cook Inlet (Hamilton and Shennan, 2005a) and eastern Gulf of Alaska (Shennan *et al.*, 2010) modern training sets with the Kodiak samples.

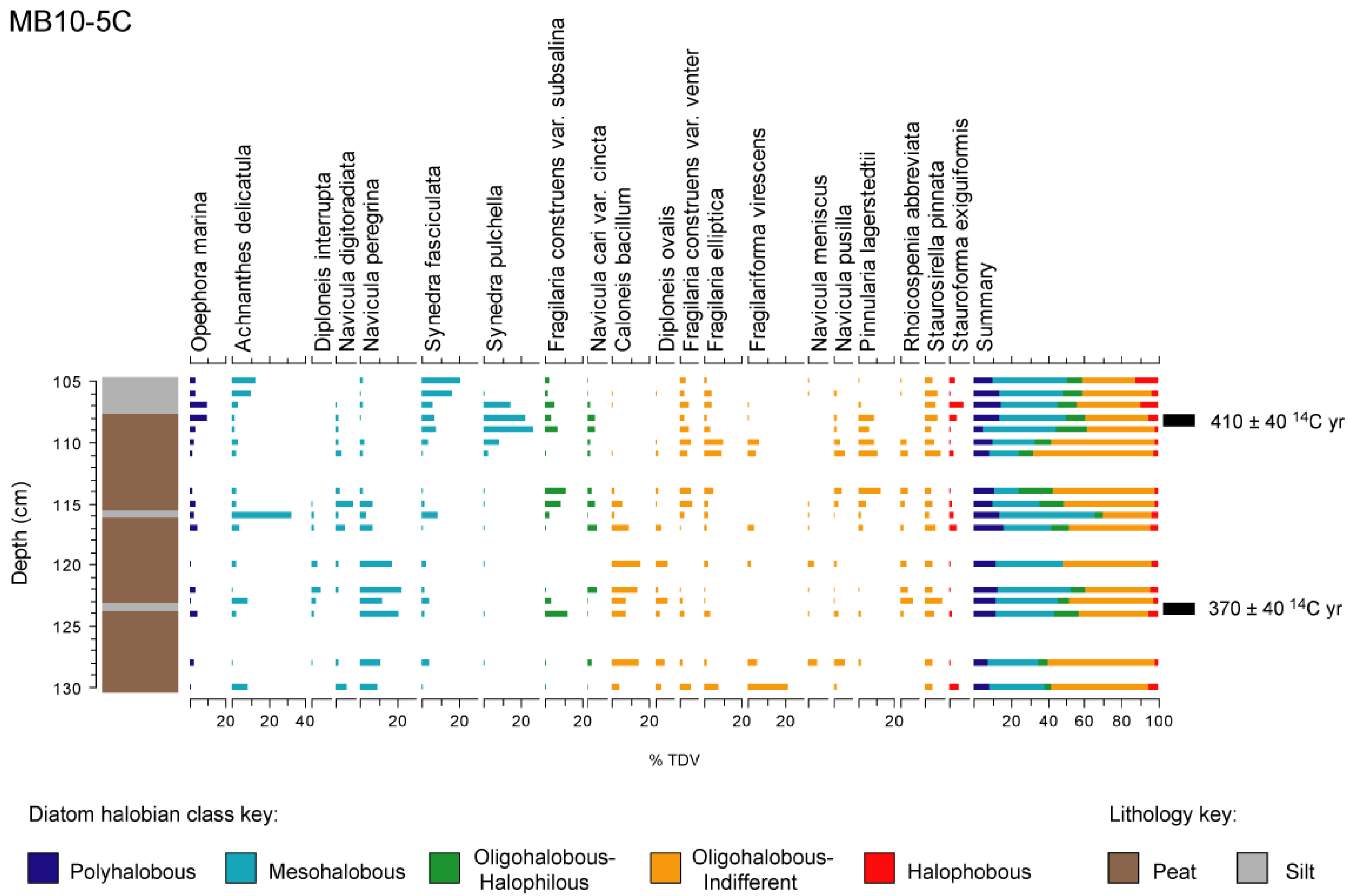

Fig. 8. Summary diatom data for MB10-5C. Diatoms are expressed as % total valves counted, showing species >5% total count. The key refers to Figs. 8-11.

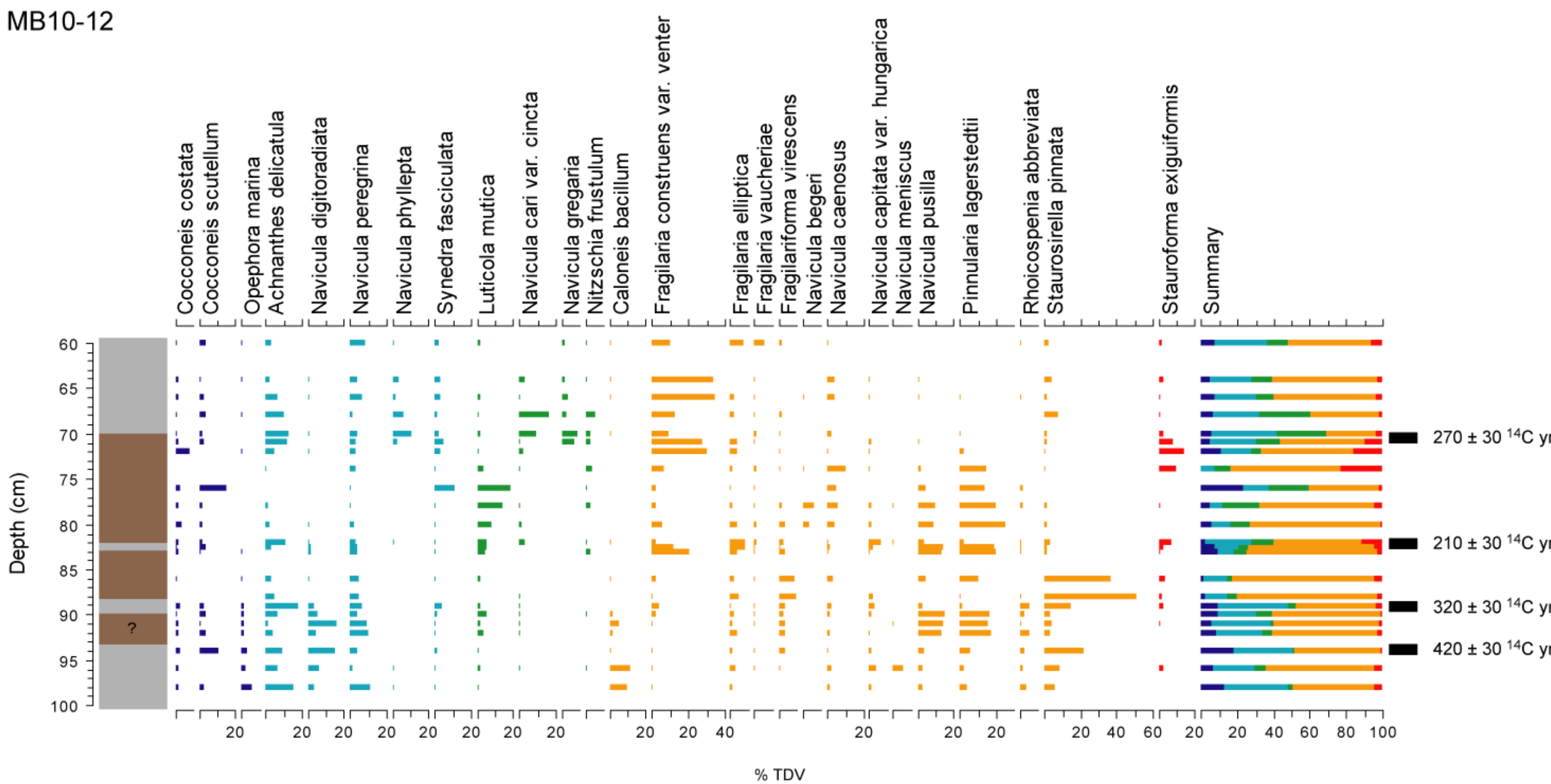

Fig. 9. Summary diatom data for MB10-12. Diatoms are expressed as % total valves counted, showing species >5% total count

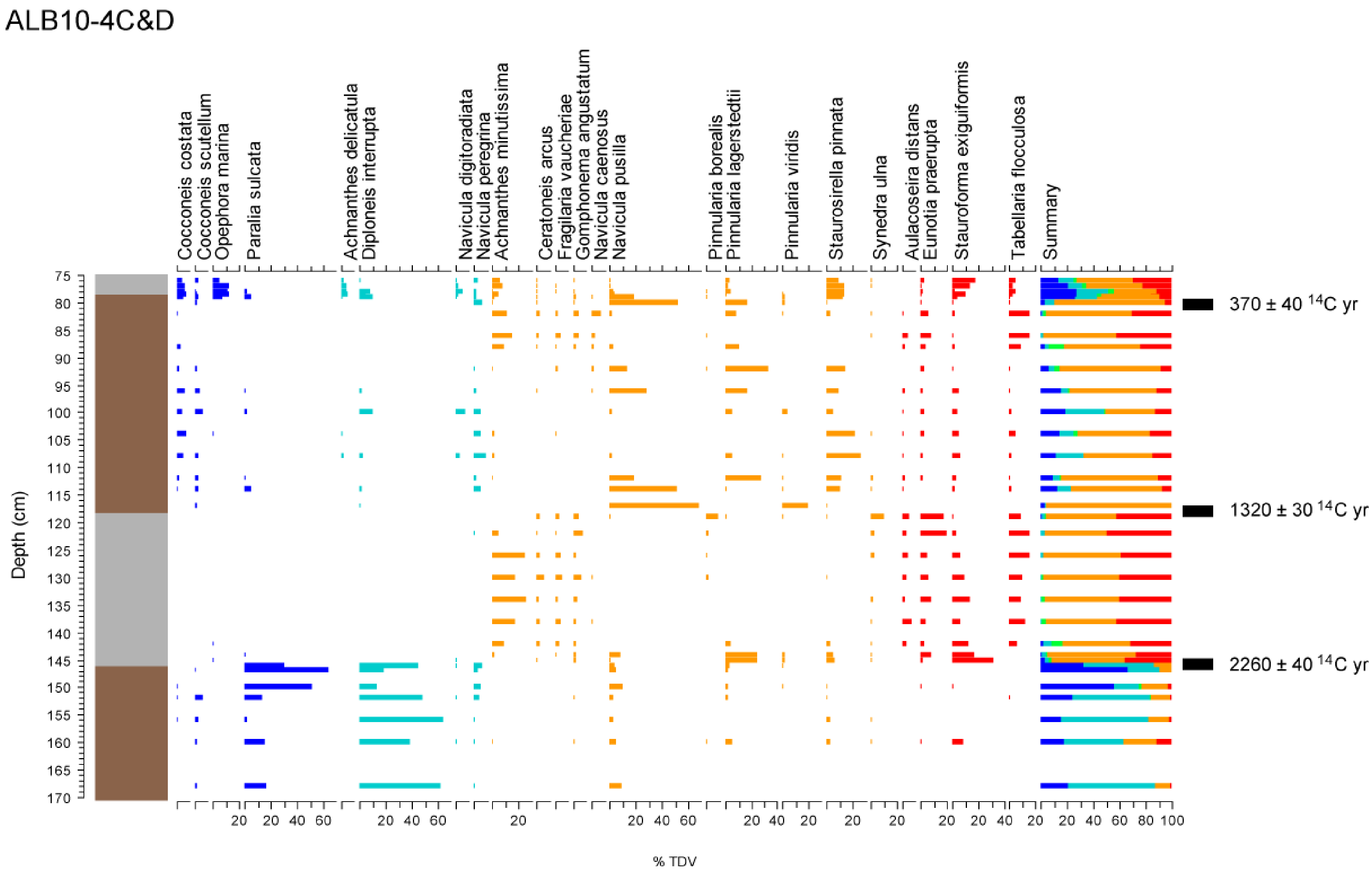

Fig. 10. Summary diatom data for ALB10-4C&D. Diatoms are expressed as % total valves counted, showing species >5% total count

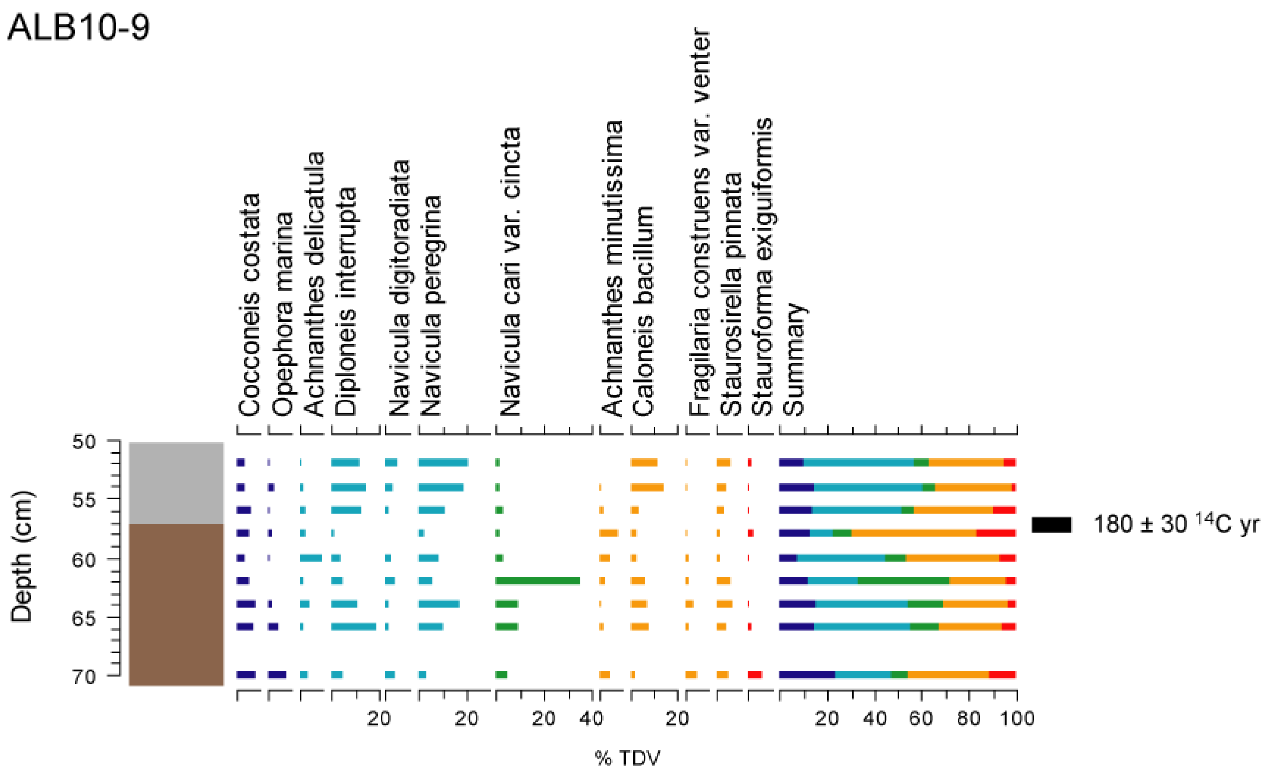

Fig. 11. Summary diatom data for ALB10-9. Diatoms are expressed as % total valves counted, showing species >5% total count

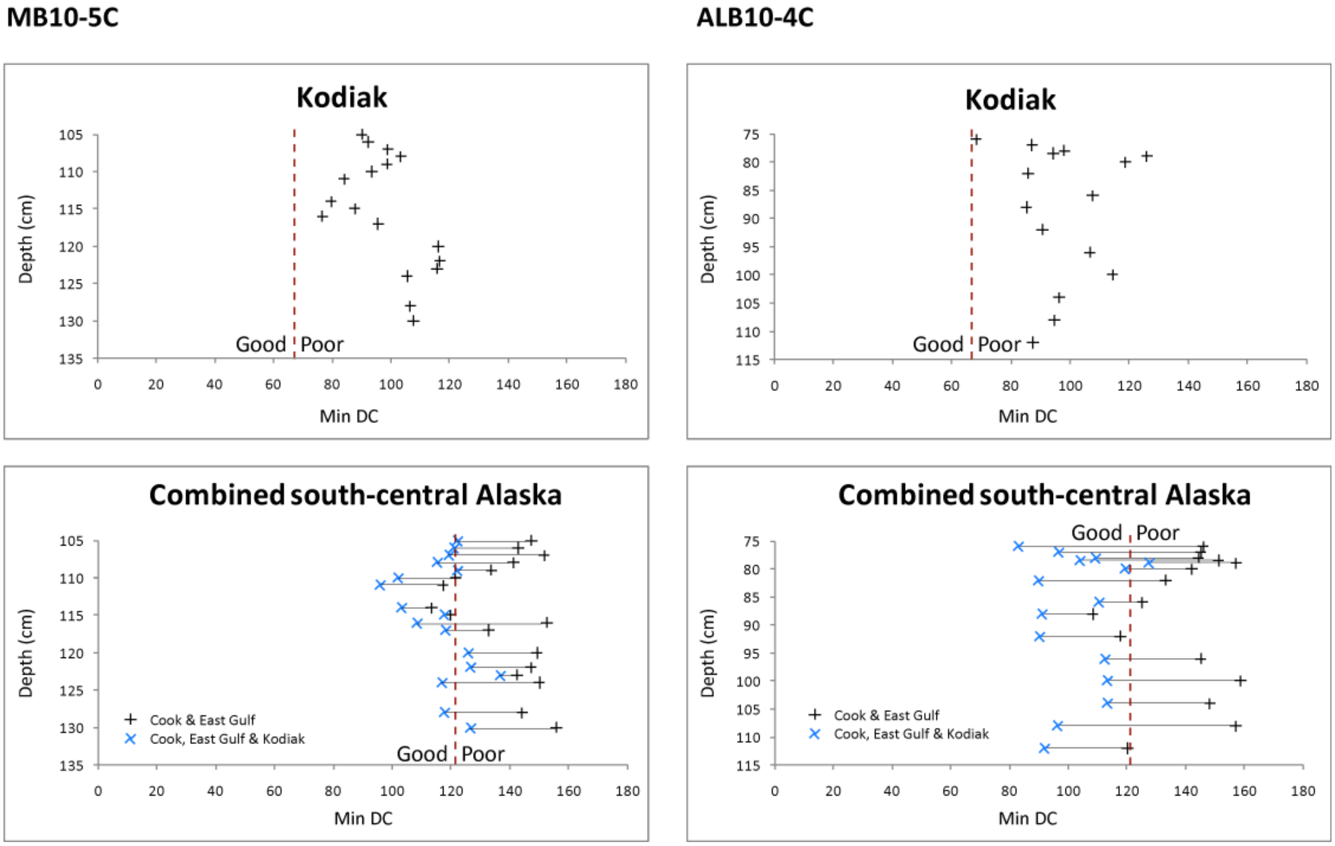

Fig. 12. Comparison of the minimum dissimilarity coefficient (MinDC) for each fossil sample from MB10-5C and ALB10-4 between the Kodiak (top), combined Cook Inlet and East Gulf of Alaska (bottom, black crosses), and combined Cook Inlet, East Gulf of Alaska and Kodiak (bottom, blue crosses) transfer function models. The threshold marked between good and poor analogues is the largest MinDC value of the modern training set.

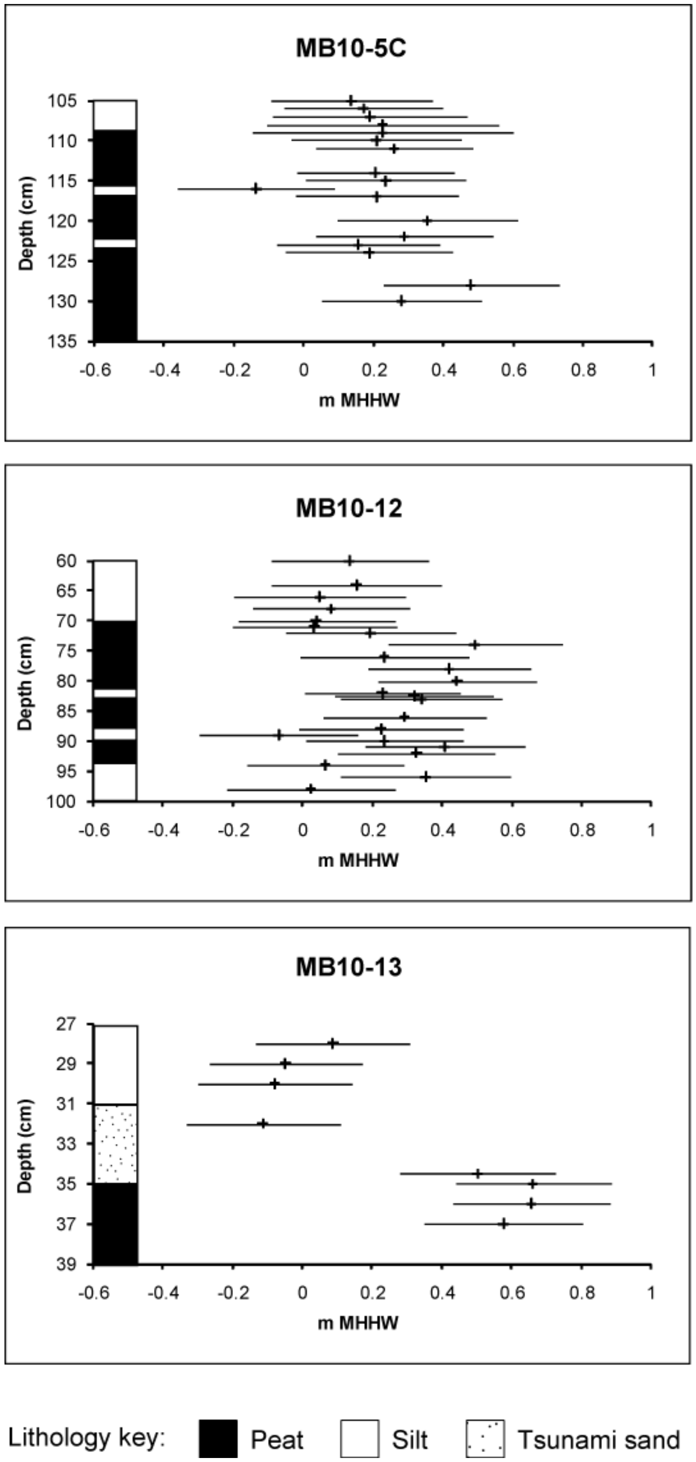

Fig. 13. Elevation reconstructions at Middle Bay ±1 standard error, using the combined south-central Alaska modern training set (excluding samples <100 SWLI units).

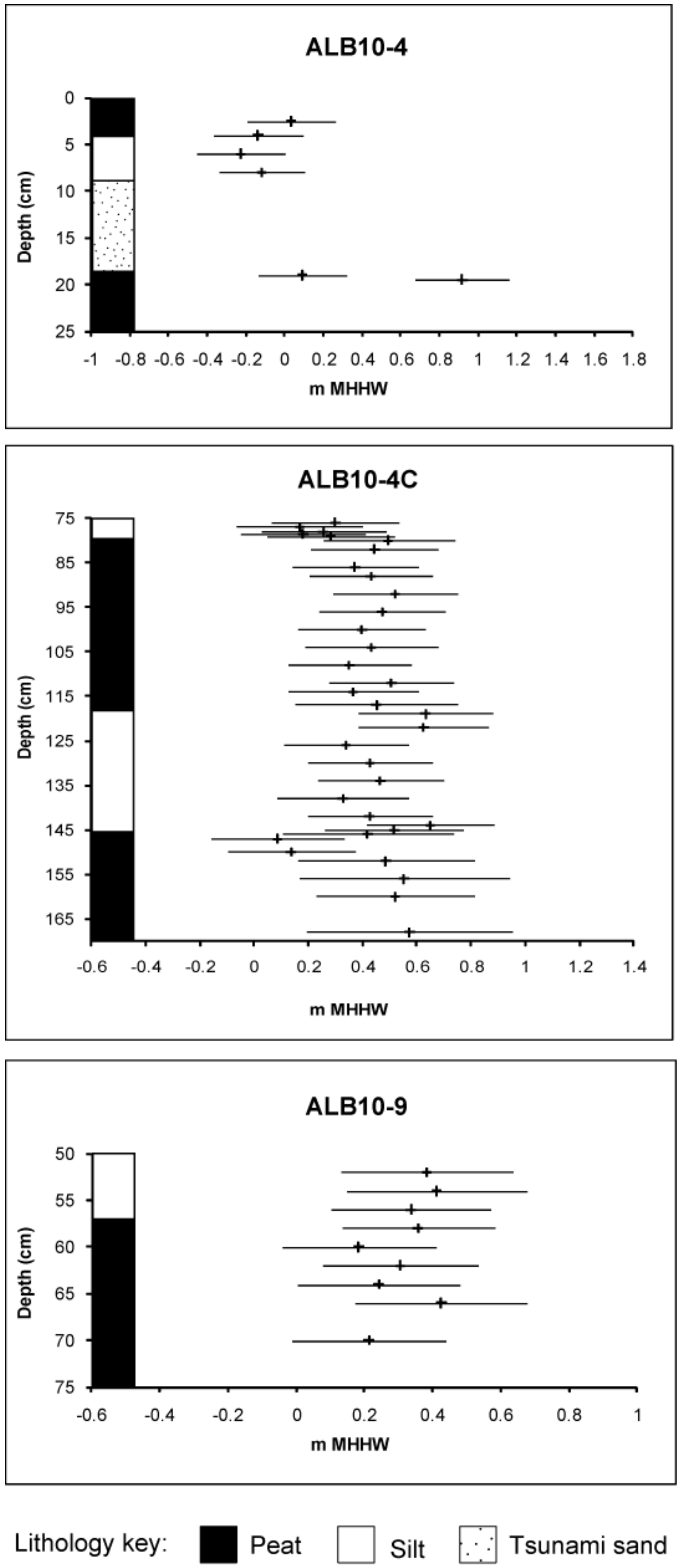

Fig. 14. Elevation reconstructions at Anton Larson Bay ±1 standard error, using the combined south-central Alaska modern training set (excluding samples <100 SWLI units).

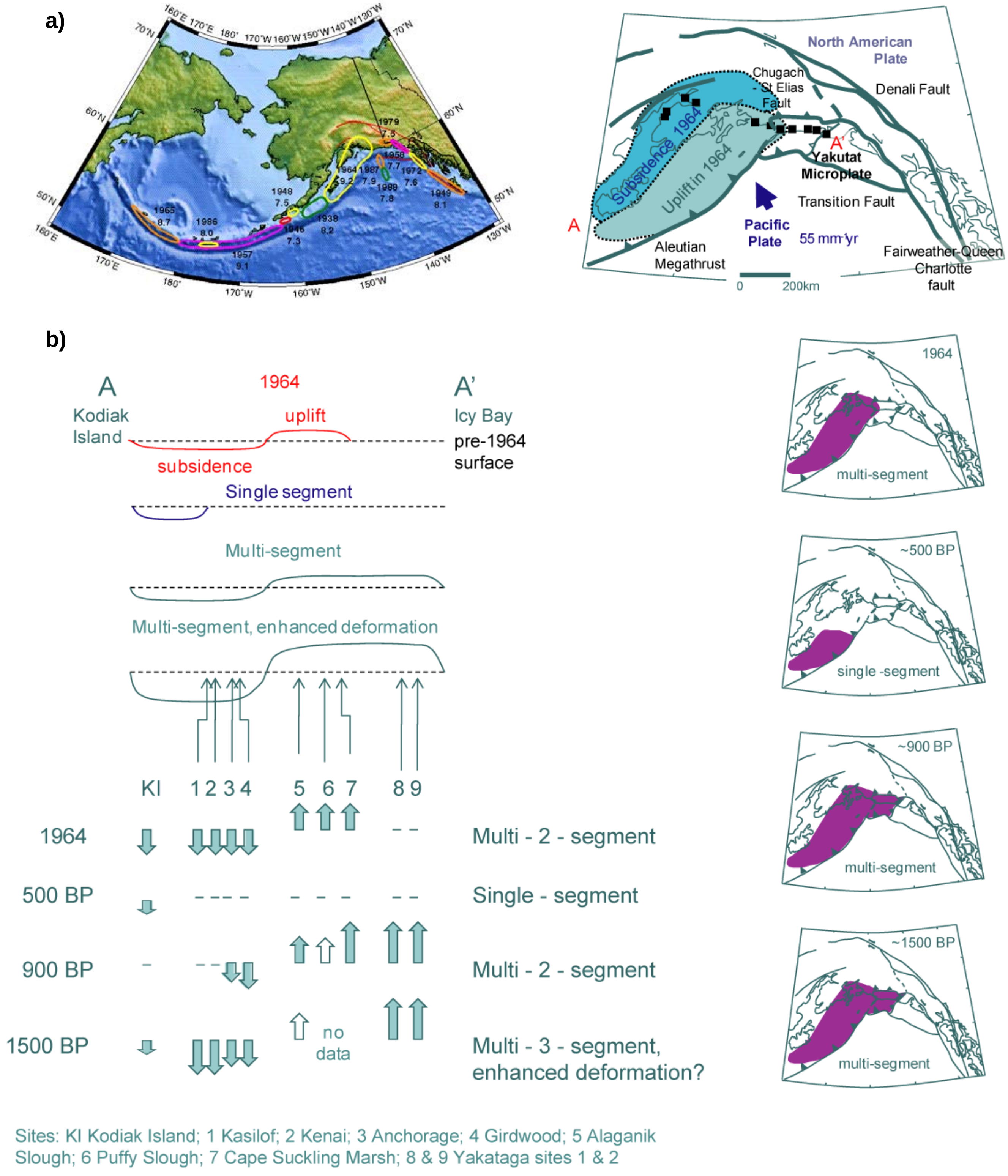

Fig. 15. Comparisons of patterns of deformation and segment ruptures for 1964 and three late Holocene great earthquakes. (a) Segments of the Aleutian megathrust that have ruptured since 1900 AD (modified after Nishenko and Jacob, 1990); (b) Hypotheses of single and multiple-segment rupturing. Large arrows indicate where uplift/subsidence was greater than in 1964 and open arrows indicate where there is no quantitative estimate.

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