Late Holocene earthquakes in Kodiak Island, Alaska and implications for plate segmentation

External Grant Award # G12AP20084

Investigators: Ian Shennan, Natasha Barlow, Ed Garrett and Frank Davies

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

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

Start date: September 1st 2012
End date: August 31st 2013

Key words: Paleoseismology, Recurrence interval, Surface deformation

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number **G12AP20084**. *The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.*

© I Shennan, N Barlow, E Garrett and F Davies 2013

Abstract

This project has applied quantitative diatom-based transfer function models at sites on Kodiak Island to improve the vertical (elevation) precision of geologic estimates of land level changes from great Holocene plate boundary earthquakes. Through detailed analysis of cores and outcrops we conclude:
(1) There is good evidence for coseismic submergence across Kalsin Bay and Middle Bay within the last few hundred years.
(2) A precise age for this earthquake and correlation with other sites across Kodiak awaits the results of further modelling (Shennan *et al*., in prep).
(3) Some peat-silt couplets that appear to record submergence more likely result from sedimentation changes within freshwater environments.
(4) Diatom analysis, or an alternative biological proxy method of environmental reconstruction, is essential to identify and quantify submergence.
(5) Previous evidence of significant uplift across short distances at Kalsin Bay is proven incorrect.
(6) While we have sediment sequences extend back to ~2500 cal yr BP there is not yet a clear correlation with earthquakes recorded in upper Cook Inlet, Copper River Delta and Katalla.
(8) The hypothesis of persistent segment boundaries remains open to debate but we have identified previously unknown sediment sequences, at Kalsin Bay and Anton Larson Bay to test this further.

1 Context

This project set out to undertake new field and laboratory investigations and subsequent data analyses to examine geologic evidence of Holocene ground displacements in Kodiak Island, Alaska, associated with past subduction zone earthquakes. It builds on previous work undertaken by the principal investigators in Kodiak, elsewhere in Alaska and the Pacific Northwest, together with the development of diatom transfer functions to quantify relative land and sea-level changes. Our published investigations quantify vertical ground displacements affecting upper Cook Inlet for seven great earthquakes during the last 4000 years. Beyond upper Cook Inlet the broader spatial pattern of co-seismic and interseismic deformation is not known for most of these events and is poorly quantified for all except 1964. Thus, we do not yet know whether the spatial pattern of vertical deformation observed for each event is the same or different. This limits our ability to test models of plate boundary rupture and segmentation 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.

We set out three research questions:

1. Can we quantify geologic estimates of land level changes from great Holocene plate boundary earthquakes and complete earthquake cycles across a series of sites on Kodiak Island?

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?

and anticipated the following deliverables:

1 Collection of cores or sampling of exposed sections to examine possible earthquake horizons at sites on Kodiak Island
2 Analysis of fossil diatom samples from samples collected
3 Application of transfer function models to improve geological estimates of land level changes in Kodiak Island
4 Analysis of AMS dated in situ macrofossils to provide a chronology of late Holocene great earthquakes
5 Evaluation of the patterns of pre-1964 co-seismic deformations across the western limit of the 1964 zone of rupture
6 Presentation of results at scientific meetings
7 Submission of results to an international refereed journal.

2 Summary of deliverables

Following preliminary surveys of Anton Larson Bay, Womens Bay, Middle Bay, Kalsin Bay, Isthmus Bay and some small marshes along the road network we chose to concentrate on the sites at Kalsin Bay, Kalsin Pond and Middle Bay (Figure 1). These sites contain the most extensive sediment sequences and allow us to test the hypotheses outlined by Gilpin (1995), which is a key paleoseismic record for Kodiak Island. We used both outcrops and hand driven cores to determine the lateral continuity of sediment layers prior to selecting which samples to return to Durham. We follow standard laboratory procedures for diatom analyses, previously reported (Shennan *et al.*, 2003), and describe the results in the following sections. Our transfer function model reconstructions use the dataset

described in our recent paper, that includes data and results from Kodiak (Watcham *et al.*, 2013). Laboratory analysis focuses on diatom analysis of the modern and fossil sediments and radiocarbon dating. We obtained 21 new AMS radiocarbon dating results from samples collected at Kalsin Bay, Kalsin Pond and Middle Bay. We discuss these data and their correlation with the broader region of the 1964 rupture zone. We presented preliminary findings at GSA 2012 and will present papers at SSA 2014 and IGCP 588 2014. We shall submit a paper to a journal late 2013.

3 Results

3.1 Research Question 1. Can we quantify geologic estimates of land level changes from great Holocene plate boundary earthquakes and complete earthquake cycles across a series of sites on Kodiak Island?

For the diatom analyses presented, we use primarily quantitative methods using transfer function approaches, developed and successfully applied at other sites in south central Alaska (Hamilton and Shennan, 2005, Watcham *et al.*, 2013). For the transfer function models we use a regional-scale modern training set collected from a wide range of marshes across ~1000 km of south central Alaska in order to seek the best fit between fossil and modern diatom assemblages. We use three models, constrained by the lithology of the Holocene sediment sequence; one for peat sediment, a second for organic silt units and silt units with visible plant rootlets, and a third for silt units with no rootlets (Hamilton and Shennan, 2005). We assess goodness of fit between each fossil sample and the modern dataset with a dissimilarity coefficient, using the 20th percentile of the dissimilarity values for the modern samples as the cut-off between 'close' and 'poor' modern analogues for fossil samples, and the 5th percentile as the threshold for defining 'good' modern analogues. For reconstruction of the elevation at which the fossil sediment was laid down, termed paleomarsh surface elevation, we present sample-specific 95.4 % error terms.

In all of the diatom diagrams we show only those species >10% of the assemblage. We classify each species according to their optimal elevation in the modern data set, dark blue = ~tidal flat elevations; mid blue = tidal marsh; light blue = upper marsh to freshwater; black cross-hatch = insufficient abundance of species sent in modern data set. This classification scheme is an aid to summarise the assemblage changes but does not take into account the elevation range of each species. In contrast, the transfer function models do account for these ranges. The right-hand graph shows the changes in paleomarsh surface elevation (PMSE), with 95% confidence limits. We do not show the PMSE reconstructions for the coarse layers that occur directly above the peat contact and are overlain by more fine grained sediment. These coarse layers likely indicate tsunami deposition. For clarity, we do not show the goodness of fit between each fossil sample and the modern data.

Table 1 shows the results of the radiocarbon dated samples from Kalsin Bay and Middle Bay.

3.1.1 Kalsin Bay

Our survey of ground levels and sediment stratigraphy (Figure 2) shows a marked contrast with the details reported by Gilpin (1995). We do not see the ~3.5 m difference (Figure 3) in ground elevation between Kalsin Pond and the marsh transect. Indeed, Kalsin Pond becomes tidal during highest tides. Water level in the pond, measured as -0.13 m MHHW on May 24, 2013, is controlled by the sill of the culvert beneath the road. The pond was created during construction of the new road after the 1964 earthquake. Prior to then it was a tidal marsh to freshwater bog on the margin of the estuary and, therefore, we can consider Kalsin Pond as part of the same sedimentary system as the rest of Kalsin Bay and not as evidence for significant differential uplift over a short distance.

At the site scale we see one peat-silt couplet that we can trace across most cores (Figure 5). It typically occurs between 70 and 90 cm below ground surface, and always below the Katmai tephra.

Table 1: Radiocarbon samples

Site, Core and depth	Laboratory number	Stratigraphic context	Material dated	Measured age	13C/12C	Convential radiocarbon age	2 sigma calibated age
Kalsin Bay 2013 core 5							
KB13/5 77cm	357771	Base of peat below Katmai tephra	Herbaceous macrofossil leaves/stems	NA	NA	130 +/- 40 BP	Cal AD 1670 to 1780 (Cal BP 280 to 170)/Cal AD 1800 to 1950 (Cal BP 160 to 0)/Cal AD 1950 to post 1950 (Cal BP 0 to post 1950)
KB13/5 92cm	356266	Top of peat, contact A	Herbaceous macrofossil leaves/stems	20 +/- 30 BP	-25.8 o/oo	10 +/- 30 BP	
KB13/5 110cm	357772	Within silt-peat	Herbaceous macrofossil leaves/stems	NA	NA	730 +/- 30 BP	Cal AD 1260 to 1290 (Cal BP 690 to 660)
KB13/5 116cm	357408	Top of peat, contact B	Herbaceous macrofossil leaves/stems	NA	NA	200 +/- 30 BP	Cal AD 1650 to 1680 (Cal BP 300 to 260)/Cal AD 1730 to 1810 (Cal BP 220 to 140)/Cal AD 1930 to post 1950 (Cal BP 20 to post 1950)
KB13/5 131.5cm	356268	Top of peat, contact C	Herbaceous macrofossil leaves/stems	1090 +/- 30 BP	-26.5 o/oo	1070 +/- 30 BP	Cal AD 900 to 920 (Cal BP 1060 to 1030)/Cal AD 940 to 1020 (Cal BP 1010 to 930)
KB13/5 184cm	356269	Base of organic sequence	Herbaceous macrofossil leaves/stems	2480 +/- 30 BP	-26.4 o/oo	2460 +/- 30 BP	Cal BC 760 to 680 (Cal BP 2710 to 2630)/Cal BC 670 to 410 (Cal BP 2620 to 2360)
Kalsin Bay 2013 core 17							
KB13/17 101cm	357409	Top of peat, contact A	Herbaceous macrofossil leaves/stems	180 +/- 30 BP	-26.9 o/oo	150 +/- 30 BP	Cal AD 1670 to 1780 (Cal BP 280 to 170)/Cal AD 1800 to 1890 (Cal BP 160 to 60)/Cal AD 1910 to 1950 (Cal BP 40 to 0)/Cal AD 1950 to post 1950 (Cal BP 0 to post 1950)
Kalsin Bay 2013 core 22							
KB13/22 72cm	356271	Top of peat, contact A	Herbaceous macrofossil leaves/stems	130 +/- 30 BP	-27.4 o/oo	90 +/- 30 BP	Cal AD 1680 to 1730 (Cal BP 270 to 220)/Cal AD 1810 to 1930 (Cal BP 140 to 20)/Cal AD Post 1950
Kalsin Bay 2013 core 27							
KB13/27 67cm	357773	Base of peat below Katmai tephra	Herbaceous macrofossil leaves/stems	NA	NA	103.7 +/- 0.3 pMC	
KB13/27 89cm	357774	Top of peat, contact A	Herbaceous macrofossil leaves/stems	520 +/- 30 BP	-29.3 o/oo	450 +/- 30 BP	Cal AD 1420 to 1460 (Cal BP 530 to 490)
KB13/27 109cm	357775	Base of organic sequence	Herbaceous macrofossil leaves/stems	810 +/- 30 BP	-27.4 o/oo	770 +/- 30 BP	Cal AD 1220 to 1280 (Cal BP 730 to 670)
Kalsin Bay 2013 core 29							
KB13/29 56cm	357776	Base of peat below Katmai tephra	Herbaceous macrofossil leaves/stems	103.3 +/- 0.3 pMC	-26.9 o/oo	103.7 +/- 0.3 pMC	
KB13/29 69.5cm	356272	Top of peat, contact A	Herbaceous macrofossil leaves/stems	630 +/- 30 BP	-27.3 o/oo	590 +/- 30 BP	Cal AD 1300 to 1370 (Cal BP 650 to 580)/Cal AD 1380 to 1410 (Cal BP 570 to 540)
KB13/29 83.5cm	357410	Top of peat, contact B	Herbaceous macrofossil leaves/stems	100.5 +/- 0.3 pMC	-31.7 o/oo	101.9 +/- 0.3 pMC	

KB13/29 179cm	356274	Top of peat, contact C	Herbaceous macrofossil leaves/stems	2090 +/- 30 BP	-28.4 o/oo	2030 +/- 30 BP	Cal BC 110 Cal AD 30 (Cal BP 2060 to 1920)/Cal AD 40 to 50 (Cal BP 1910 to 1900)
KB13/29 185cm	356275	Base of organic sequence	Herbaceous macrofossil leaves/stems	2140 +/- 30 BP	-28.6 o/oo	2080 +/- 30 BP	Cal BC 180 to 40 (Cal BP 2130 to 1990)/Cal BC 10 to 0 (Cal BP 1960 to 1950)
Middle Bay 2013 outcrop 1							
MB13/1 82cm	356276	Top of peat, contact A	Single flattened stem	200 +/- 30 BP	-27.3 o/oo	160 +/- 30 BP	Cal AD 1660 to 1710 (Cal BP 290 to 240)/Cal AD 1720 to 1830 (Cal BP 230 to 120)/Cal AD 1830 to 1890 (Cal BP 120 to 60)/Cal AD 1910 to post 1950 (Cal BP 40 to post 1950)
MB13/1 88cm	357821	Top of peat, contact B	Herbaceous macrofossil leaves/stems	240 +/- 30 BP	-26.2 o/oo	220 +/- 30 BP	Cal AD 1640 to 1680 (Cal BP 310 to 270)/Cal AD 1740 to 1760 (Cal BP 210 to 190)/Cal AD 1760 to 1800 (Cal BP 190 to 150)/Cal AD 1940 to post 1950 (Cal BP 10 to post 1950)
MB13/1 119cm	357411	Top of peat, contact C	Herbaceous macrofossil leaves/stems	NA	NA	450 +/- 30 BP	Cal AD 1420 to 1460 (Cal BP 530 to 490)
MB13/1 143cm	356279	Base of organic sequence	Herbaceous macrofossil leaves/stems	710 +/- 30 BP	-27.6 o/oo	670 +/- 30 BP	Cal AD 1280 to 1320 (Cal BP 670 to 630)/Cal AD 1350 to 1390 (Cal BP 600 to 560)
Middle Bay 2013 outcrop 1							
MB13/4 91cm	356280	Top of peat, contact A	2 Carex leaves	110 +/- 30 BP	-29.5 o/oo	40 +/- 30 BP	

We refer to this couplet as Contact A. The couplet typically comprises peat abruptly overlain by fine to coarse sand and a fining-up sequence to silt then organic silt and then peat (Figure 5). Most cores end on buried gravel that prevented further penetration, but in two locations we obtained deeper sequences. Around core 5 we could trace up to two additional contacts across ~100 m. At core 29 we also found two additional contacts but we could not trace these in more than one other core.

Many of the cores contained thin, 1 to 2 cm thick layers of mixed sediment, from fine sand to medium angular gravel that were not traced between cores. We reported numerous similar layers from Middle Bay in our previous report (Shennan *et al.*, 2011) and we interpret these as winter ice-rafted sediment. These occur across all the Kodiak marshes we have studied and we previously reported them from Cook Inlet marshes (Hamilton *et al.*, 2005).

Figure 5 to 8 show consistent evidence of marsh submergence represented by contact A at cores 5, 17, 18, 22, 25, 27 and 29, widely spread across the marsh. At all sites, except 25, elevation change is in the order of 0.5 ± 0.5 m subsidence. The greater estimate of subsidence at core 25 results from the abundance of *Diploneis interrupta*, for which we have no modern analogue at the percentages seen in figure 7.

With rapid submergence, there is always the possibility of erosion of the top of the peat, so each of the ages for the top contact of a peat is a maximum age for the event. A radiocarbon plateau makes it difficult to obtain a precise age for contact A, with many calibrated ages ranging the seventeenth century to present (Table 1). In order to constrain the age better we are now developing a Bayesian model using the approach outlined by Lienkaemper and Bronk Ramsey (2009) and successfully applied to locations in the Prince William Sound segment of the subduction zone (Shennan *et al.*, In Press). This analysis (Shennan *et al.,* in prep.) will include previously published radiocarbon ages from Kodiak (Carver and Plafker, 2008) and our earlier results (Shennan *et al.*, 2011). Visual comparison suggests that ages for contact A at Kalsin Bay are younger than those suggested, 533-437 cal yr BP, for the latest rupture of the Kodiak segment (Carver and Plafker, 2008) but we caution against this conclusion until we complete further analyses.

The ages with bomb-spike radiocarbon, for three samples from core 27 and 29, indicate intrusion of young carbon to sediment layers beneath the distinctive Katmai tephra. We observed no root penetration through the tephra at any of the cores. We suggest that these samples indicate intrusion of modern carbon through a process of marsh floatation. This has been described at a number of locations in Europe, most commonly associated with an apparently out of sequence minerogenic unit, given the original German term, “inner sedimentation” or “klappklei” (Figure 9). The process occurs at present on the east coast of the Jade Bay (Behre, 2004). Following flooding of a peat area, whether by barrier breakdown or human interaction, high water levels cause the peat to fracture along a weak horizon, with the upper layers floating, allowing sediment to be deposited along the fracture during the period of high water. Such fractures and sediments extend >100 m (Figure 9). Locations 27 and 29 are both close, <10 m, to the edge of Kalsin Pond and we suggest that following construction of the new road and culvert after the 1964 earthquake, the new watertable allowed intermittent fracturing and floatation of the surface layer and intrusion of modern organic sediment from the pond, into the sediment sequence.

None of the peat-silt contacts from greater depths, contacts B and C at core 5 and B and C at core 29, show any change in paleomarsh surface elevation (figures 5 and 8), even though they have sharp contacts and in some cases a thin, coarse sediment layer that may indicate tsunami sedimentation.

3.1.2 Middle Bay

Erosion along the intertidal reach of Salt Creek meant that we are able to enhance the straigraphic survey that we previously constructed using hand driven cores (Shennan *et al.*, 2011) with a series of outcrop sections (Figure 10). We selected two outcrops for detailed sampling, diatom analysis (Figure 11) and radiocarbon dating (Table 1).

At outcrop 1, only contact A records subsidence. Contact B shows no change in paleomarsh surface elevation, while the diatom data show contact C as clastic deposition above peat in an increasingly freshwater system (Figure 11). This may indicate backswamp sedimentation as the coast prograded. Contact A at outcrop 4, which is upstream of outcrop 1 and at a higher elevation (Figure 10), also reveals clastic deposition above peat in a freshwater environment, with no indication of submergence or enhanced tidal input (Figure 11).

These results indicate the importance of using microfossil analyses to identify marsh submergence. Lithology alone is not sufficient.

The radiocarbon ages from outcrop 1 (Table 1) indicate that contact A is likely recording the same event as that recorded widely across Kalsin Bay. Our estimate for subsidence is slightly less than the 0.5 ± 0.5 m at Kalsin Bay.

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

The findings raise important questions regarding the extent of spatial deformations during late Holocene earthquakes. First, the only substantive evidence we have found at both Kalsin Bay and Middle Bay relates to a recent earthquake, represented by contact A. We aim to constrain the age by using Bayesian modelling as outline above, but it is clear that this event is younger than the penultimate great earthquake recorded around Cook Inlet and Copper River Delta (Shennan *et al.*, In Press, Carver and Plafker, 2008). This event at Middle Bay and Kalsin Bay created less subsidence than in 1964, yet appears to have generated a tsunami.

The deeper sequences recorded at Kalsin Bay cores 5 and 29, and in some of the cores adjacent to them, record for the first time, estuarine sedimentation extending back 2000 to 2500 cal yr BP. These cover the time interval of three great earthquakes recorded in upper Cook Inlet, Copper River Delta and Katalla (Shennan *et al.*, In Press, Carver and Plafker, 2008). We presently have insufficient data to determine whether these produce coseismic land motions in Kodiak.

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

The results outlined in sections 3.1 and 3.2 demonstrate that we cannot confirm that the segmentation model for the 1964 earthquake applies to previous great earthquakes. We have proven the existence of sedimentation at Kalsin Bay of a suitable age range to test this hypothesis further.

4 Conclusions

We have addressed the three research questions set out above, and highlight five main conclusions.
(1) There is good evidence for coseismic submergence across Kalsin Bay and Middle Bay within the last few hundred years.
(2) A precise age for this earthquake and correlation with other sites across Kodiak awaits the results of further modelling (Shennan *et al*., in prep).
(3) Some peat-silt couplets that appear to record submergence more likely result from sedimentation changes within freshwater environments.

(4) Diatom analysis, or an alternative biological proxy, is essential to identify and quantify submergence.
(5) Previous evidence of significant uplift across short distances at Kalsin Bay is proven incorrect.
(6) While we have sediment sequences that extend back to ~2500 cal yr BP, there is not yet a clear correlation with earthquakes recorded in upper Cook Inlet, Copper River Delta and Katalla.
(7) The hypothesis of persistent segment boundaries remains open to debate, yet there are previously unknown sediment sequences at Anton Larson Bay (Shennan *et al.*, 2011) and Kalsin Bay available to test this further

Acknowledgements: Gary and Deborah Carver for logistical support and discussions.

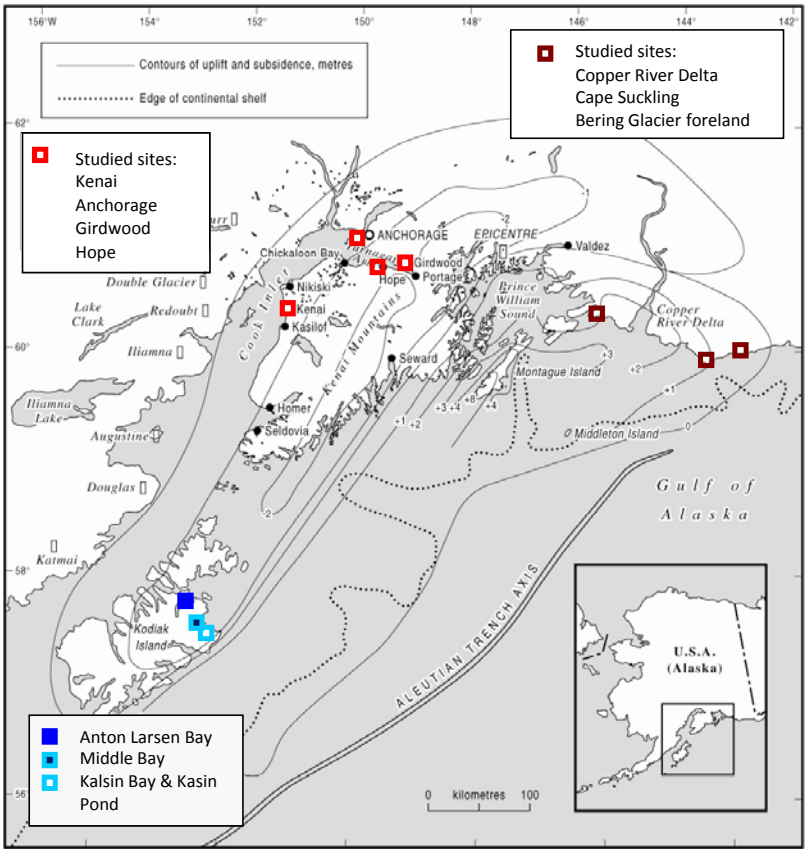
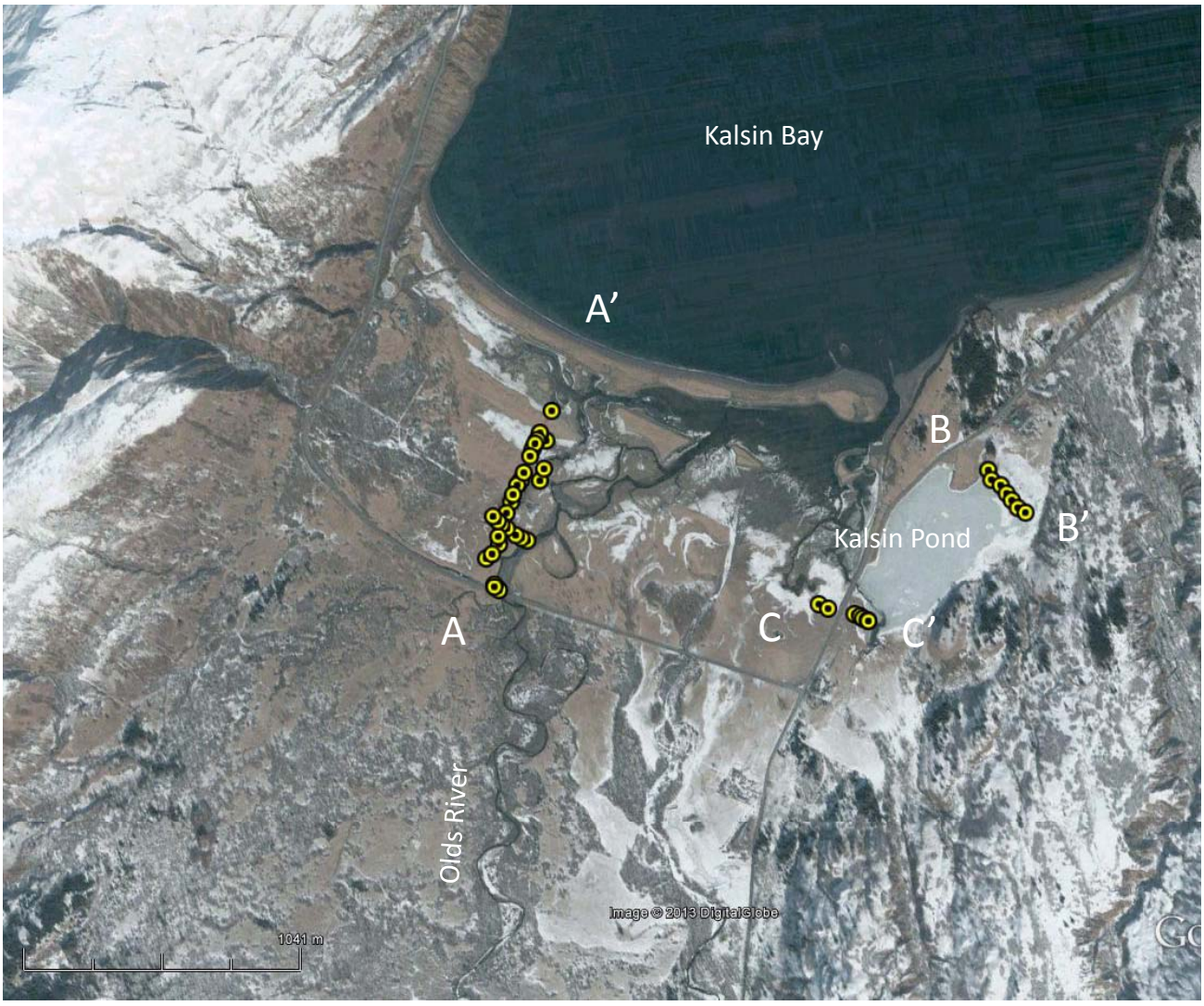


Figure 1: Location map



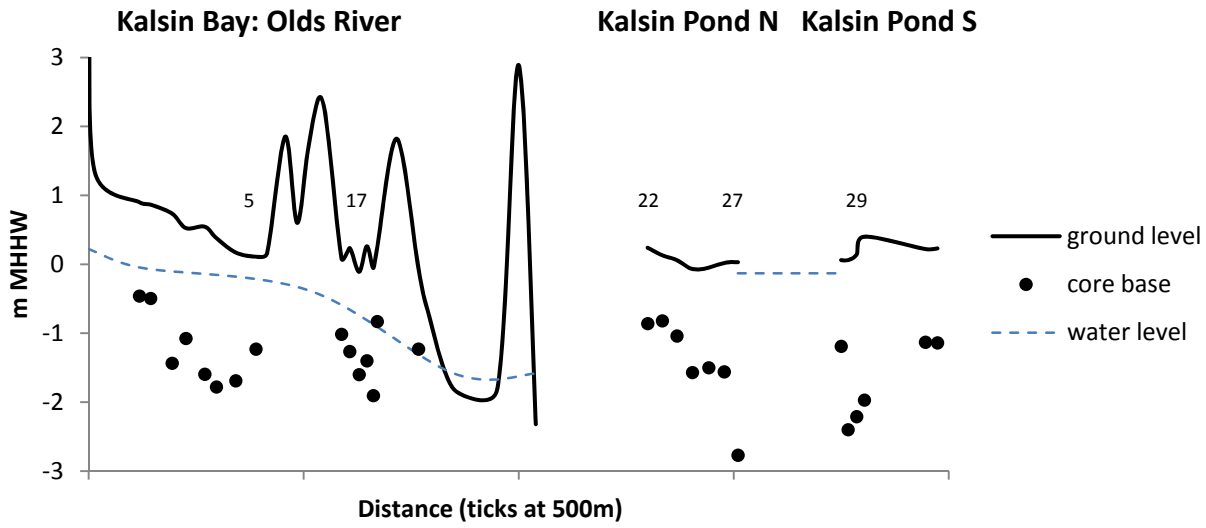


Figure 2: Kalsin Bay field site. Yellow dots are core locations, letters indicate surface transects shown in lower figure. A – A' extends from the road to the modern storm ridge.

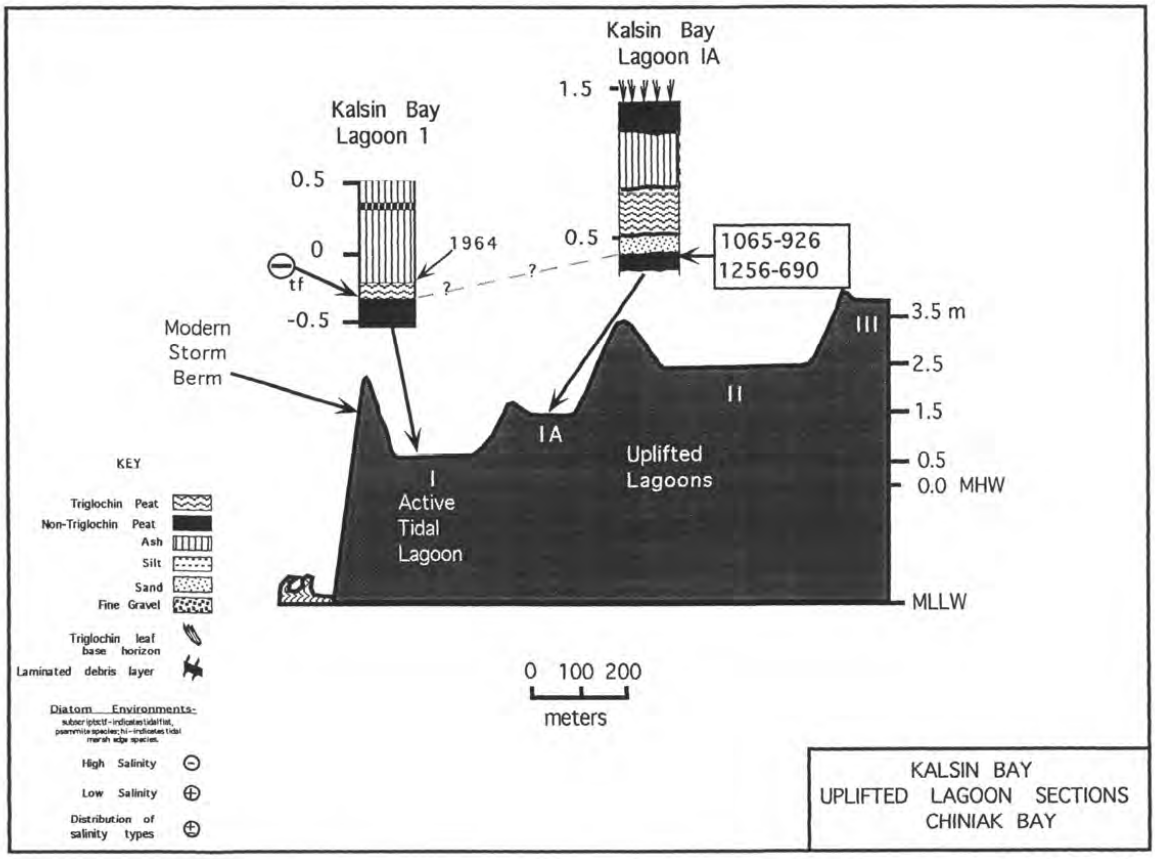


FIGURE A7

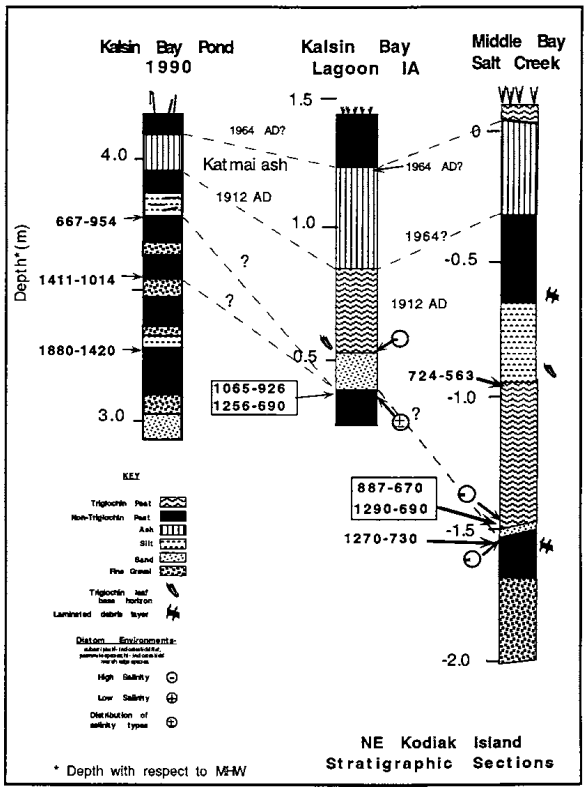


Figure A6

Figure 3: Gilpin (1995, figures A6 and A7) Stratigraphy of Kalsin Bay, Kalsin Pond and Middle Bay. Elevations relative to MHW, which is ~0.3m lower than MHHW, the datum used in this report

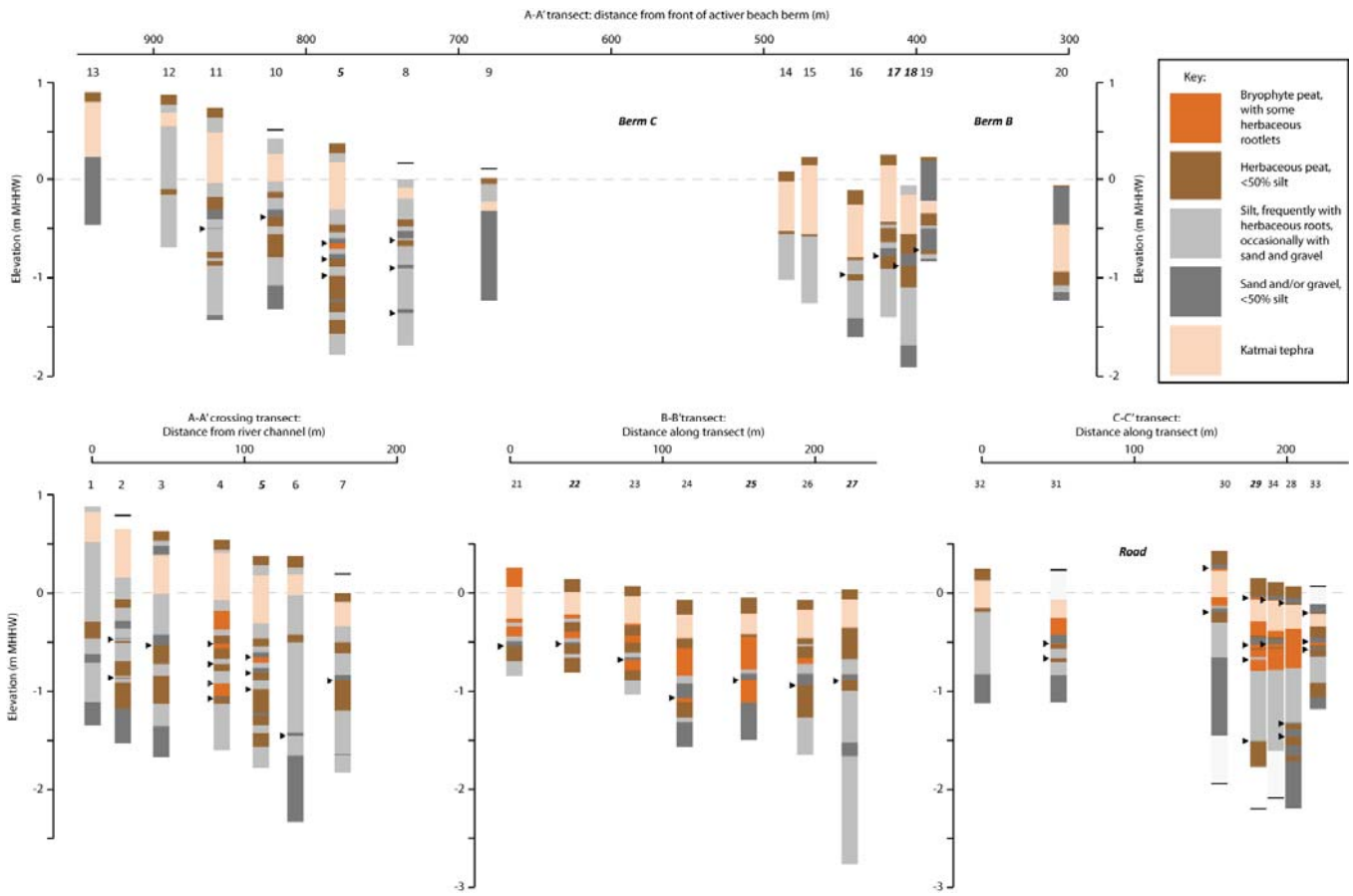


Figure 4: Upper – Stratigraphic cross section from cores drilled in 2013
Lower: Kalsin Bay core 5, contact A. Note: surface smears not removed at this stage

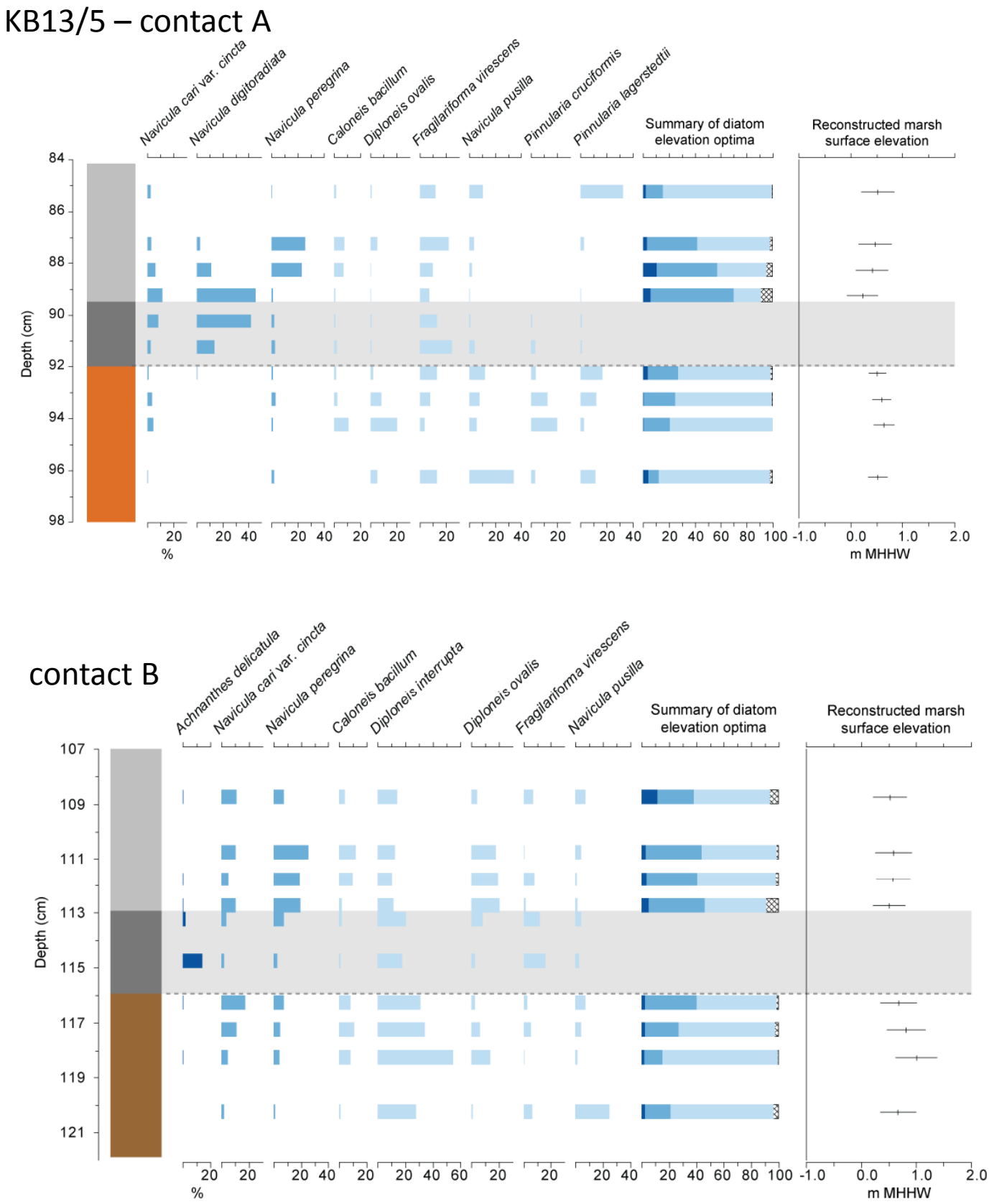


Figure 5: Kalsin Bay core 5 - Diatoms and PMSE reconstructions

KB13/5 – contact C

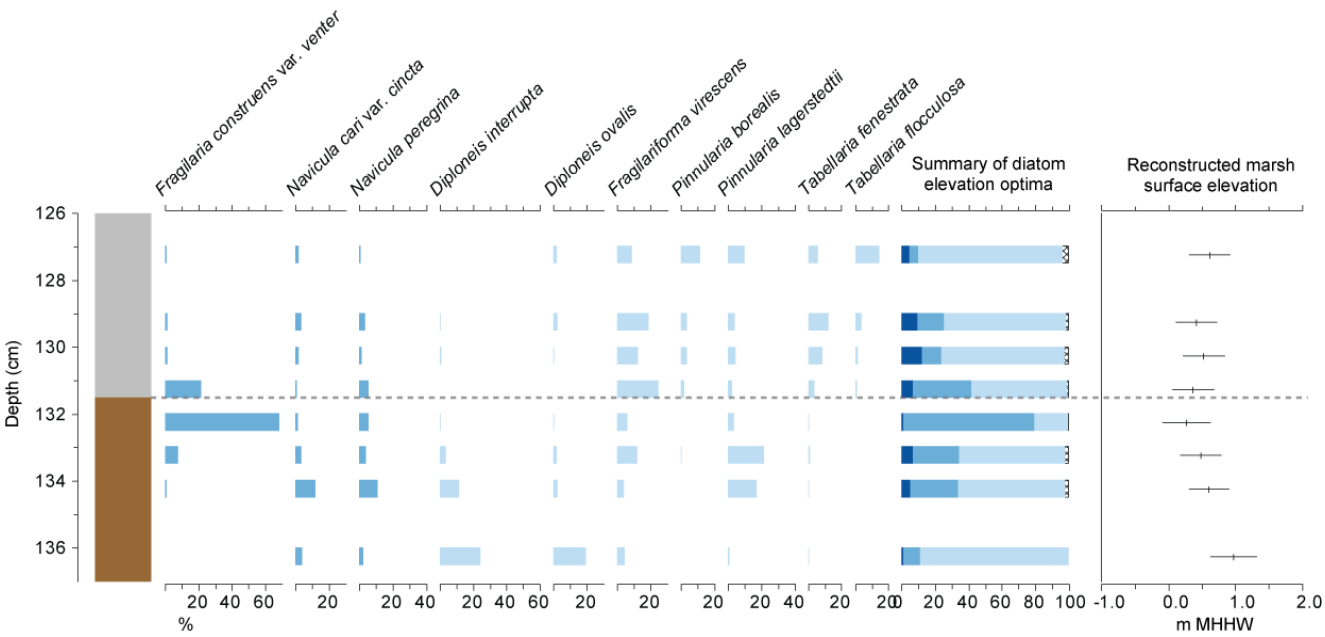


Figure 5 continued: Kalsin Bay core 5 - Diatoms and PMSE reconstructions

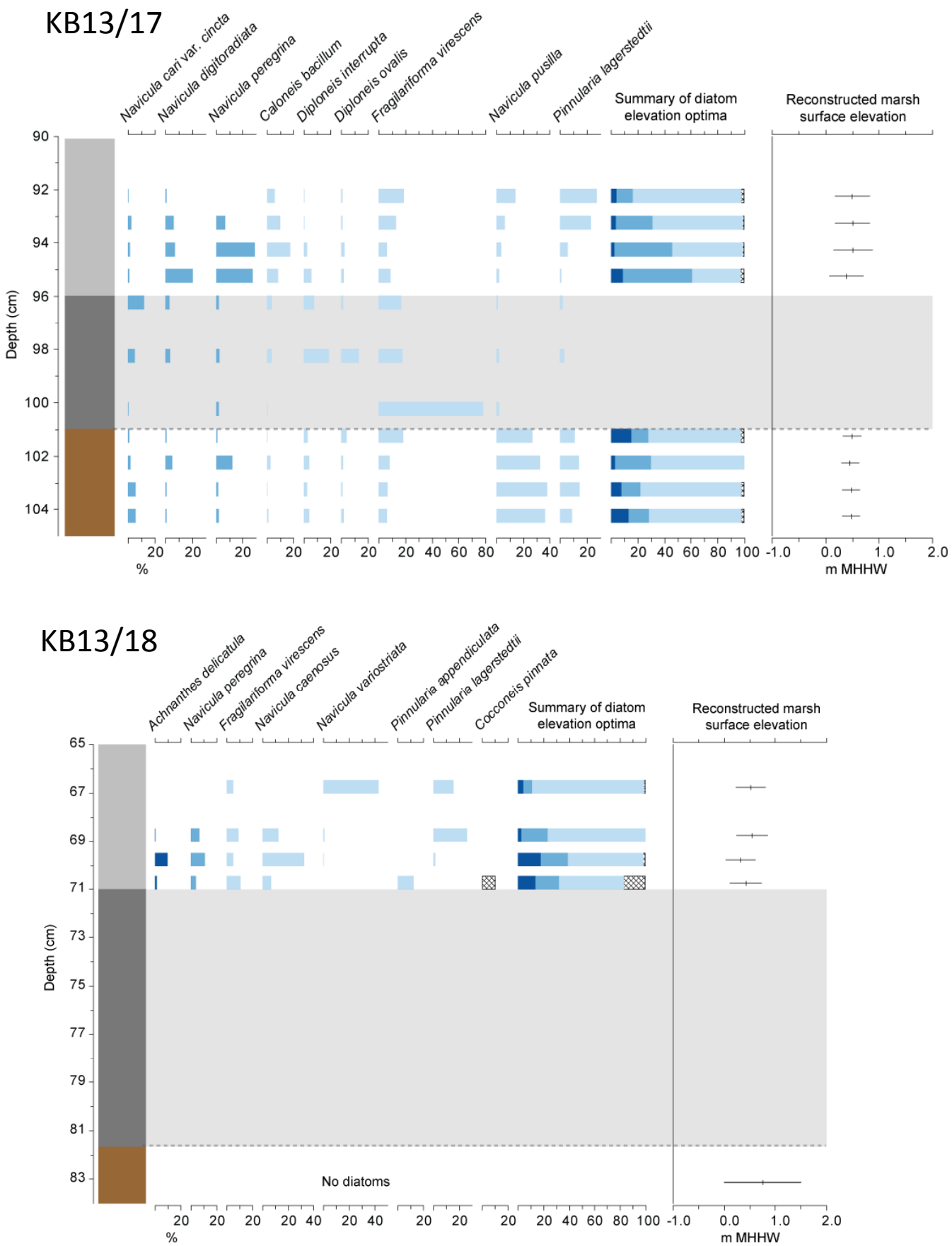


Figure 6 : Kalsin Bay cores 17 and 18 (15m apart) 5 - Diatoms and PMSE reconstructions. In absence of diatoms at base of core 18, PMSE inferred from stratigraphy and comparison with reconstructed elevation of herbaceous peat in other cores

Figure 7 : Kalsin Bay – transect at North of Kalsin Pond cores 22 and 25 - Diatoms and PMSE reconstructions.

KB13/27

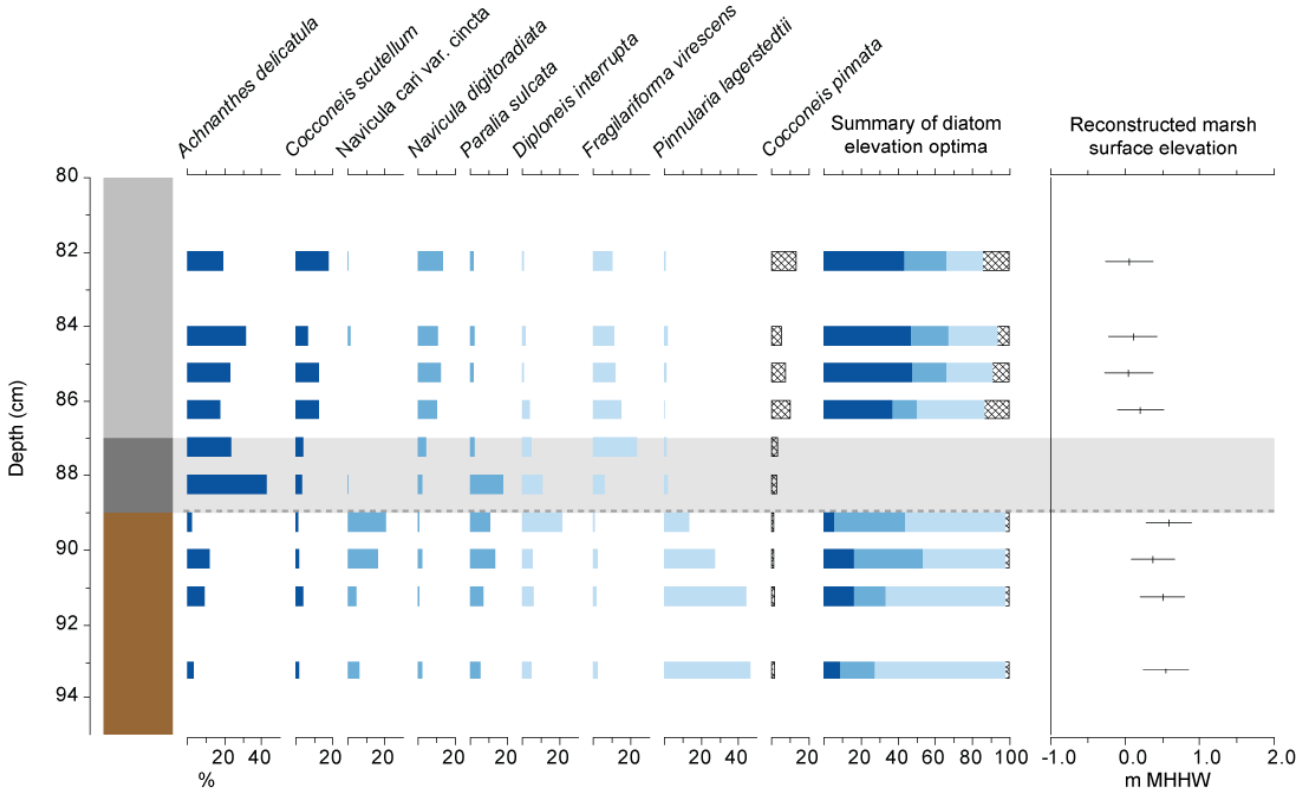
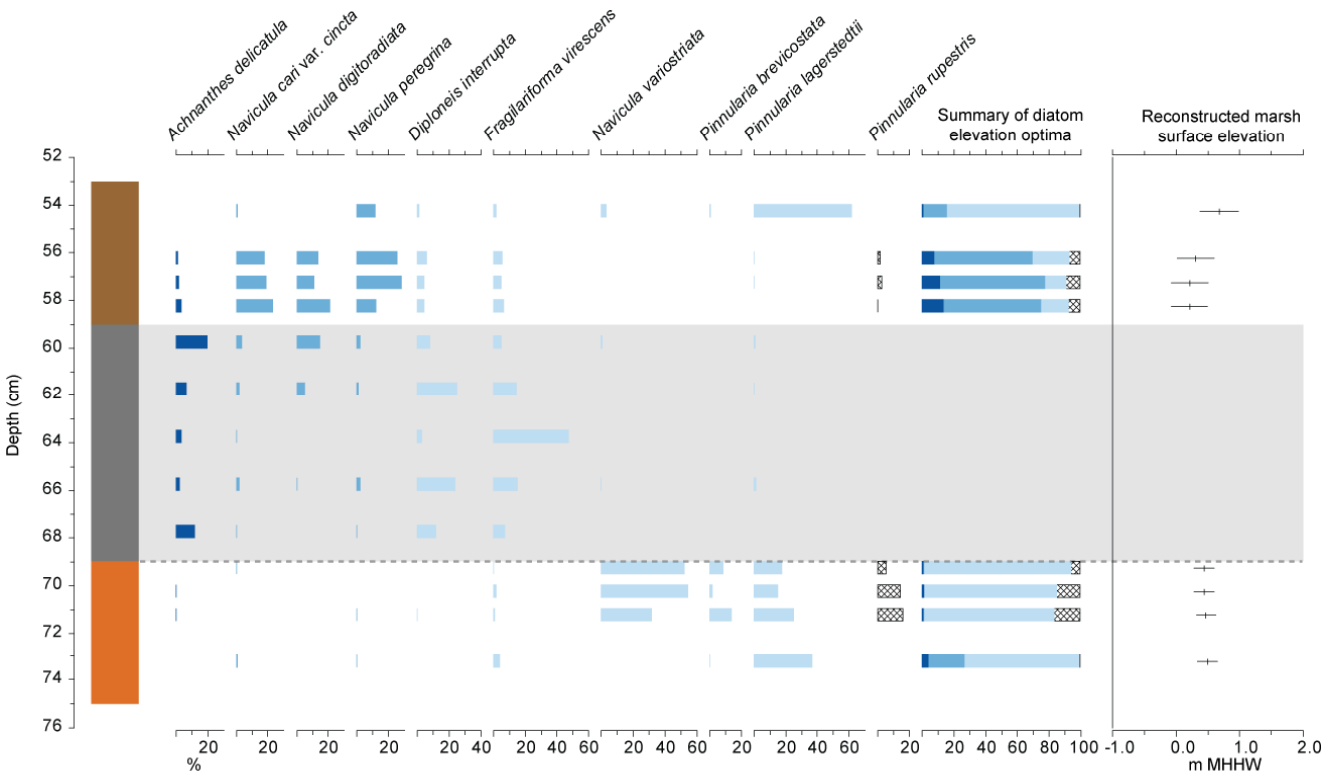


Figure 7 continued : Kalsin Bay – transect at North of Kalsin Pond core 27 - Diatoms and PMSE reconstructions.

KB13/29 – contact A



KB13/29 – contact B

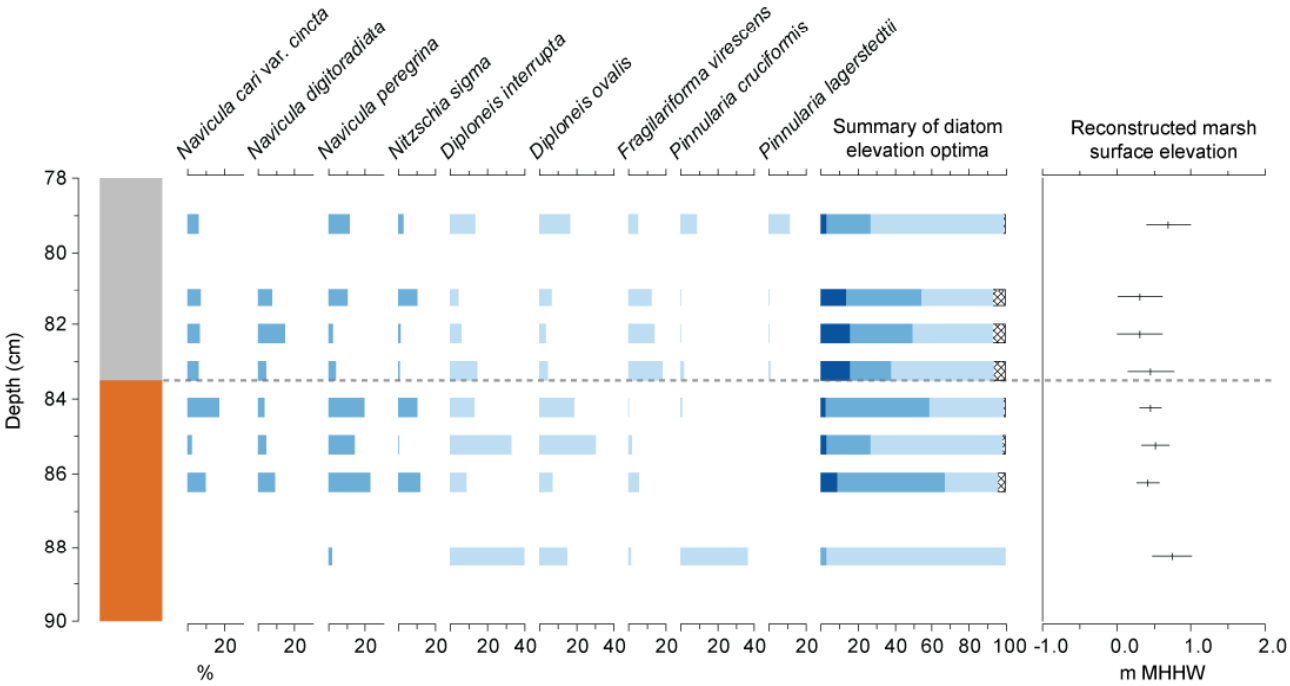


Figure 8 : Kalsin Bay – transect at South of Kalsin Pond core 29 - Diatoms and PMSE reconstructions.

KB13/29 – contact C

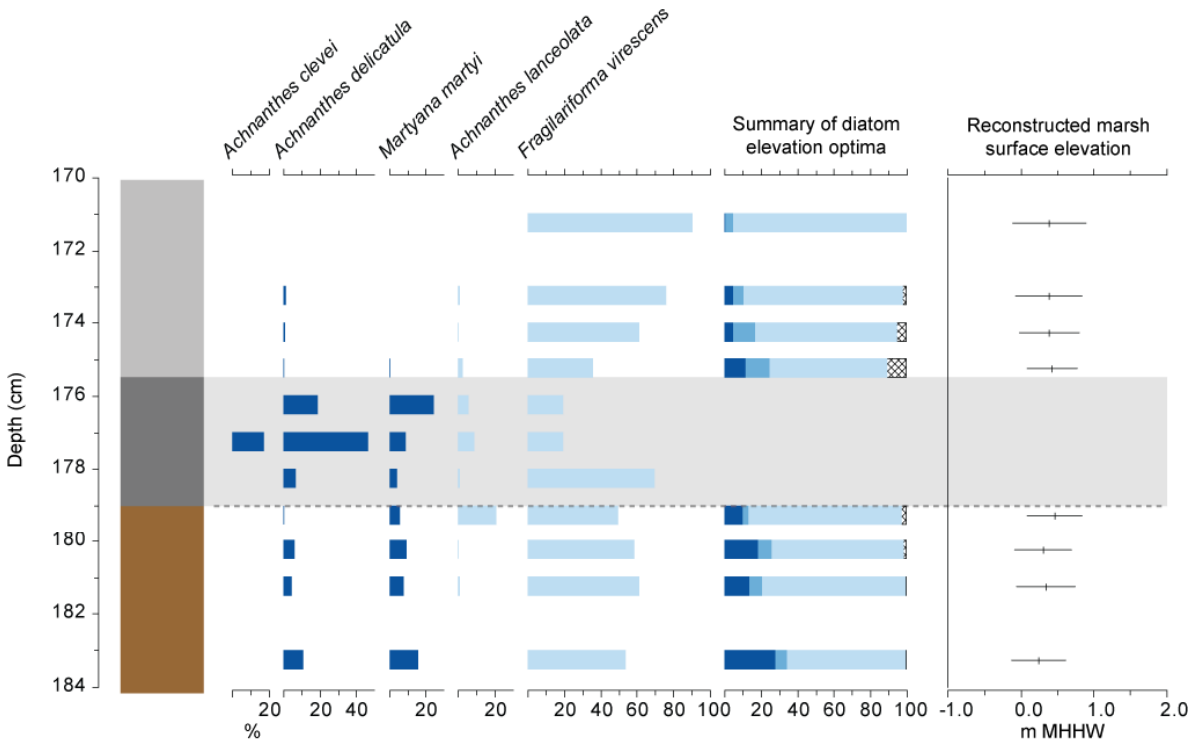


Figure 8 continued : Kalsin Bay – transect at South of Kalsin Pond core 29 - Diatoms and PMSE reconstructions.

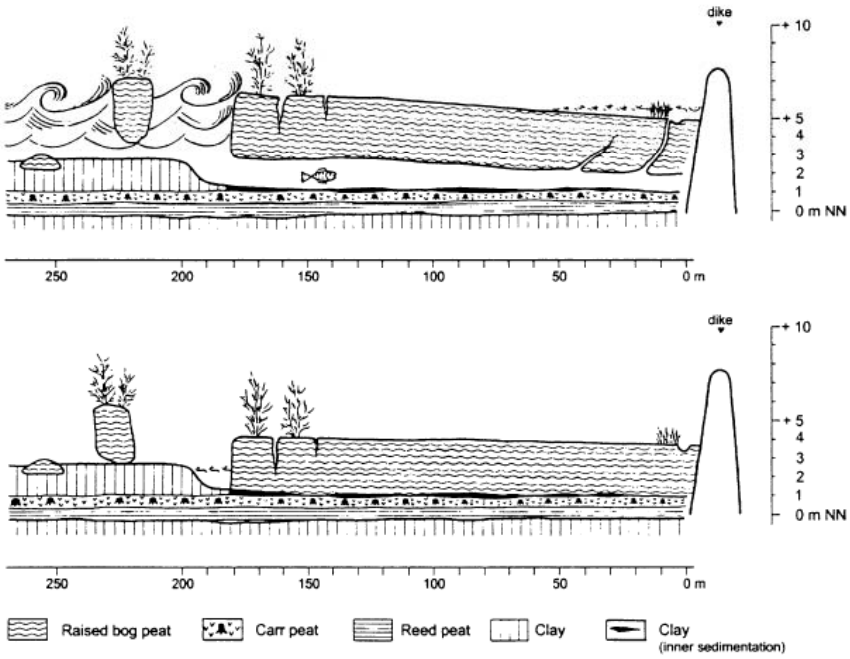
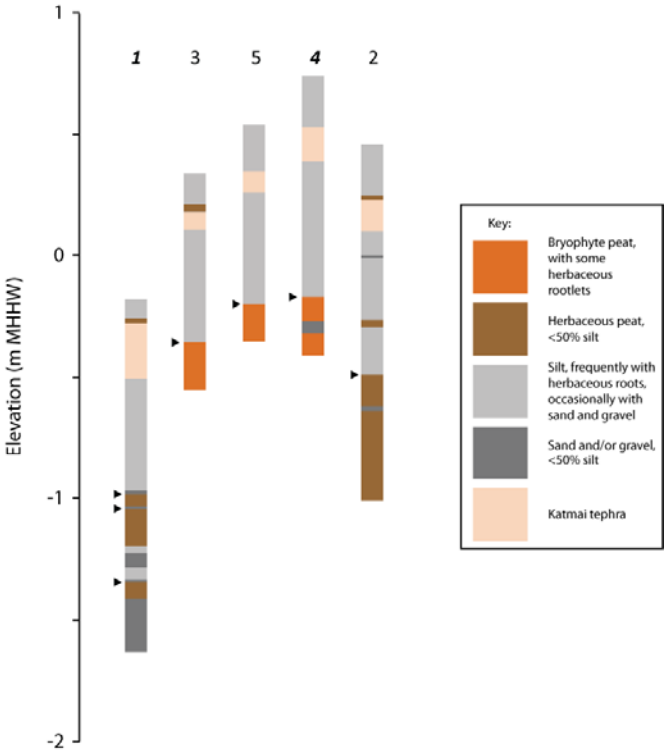


Fig. 16. Fragmentation of the Sehestedter Moor and deposition of intercalated clay (formation of *Klappklei*). Above: peat floating at high-tide storm surge. Below: normal situation.

Figure 9: Illustration of the process of “inner sedimentation” or “klappklei”, from Behre (2004)

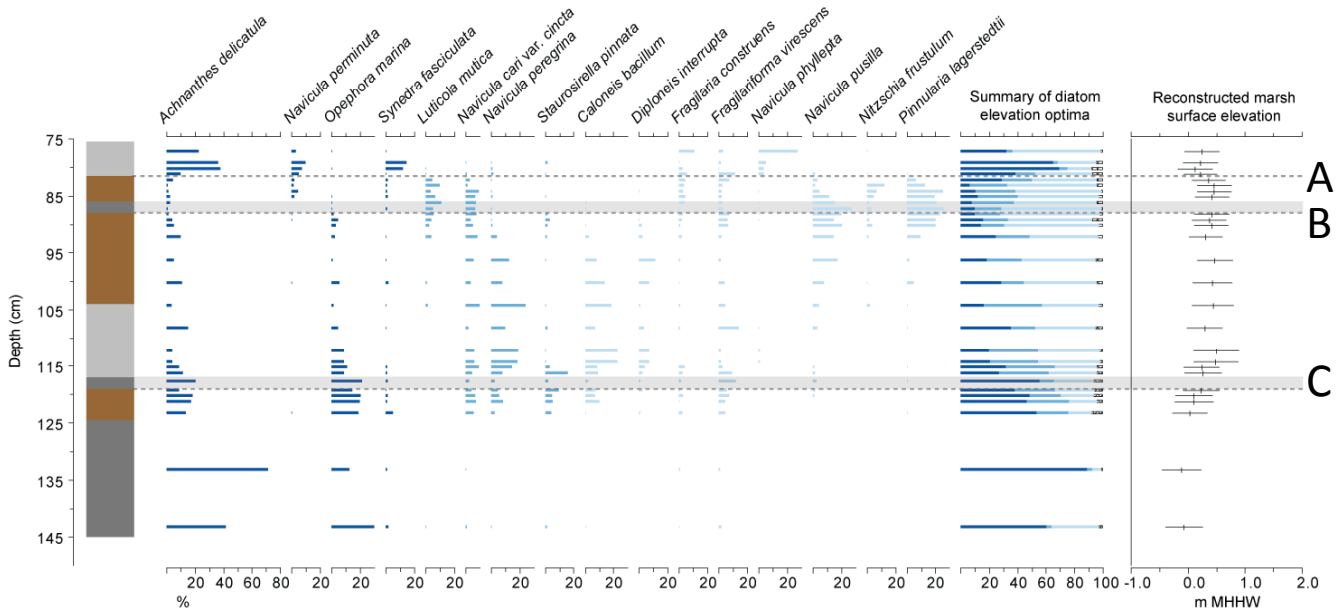


Outcrop 1

Outcrop 4

Figure 10: Middle Bay; Site map, showing outcrop locations; stratigraphy of outcrops and photographs of sampled outcrop locations. Borehole data reported in Shennan *et al.,* 2011.

MB13/1 – complete outcrop



MB13/4 – complete outcrop

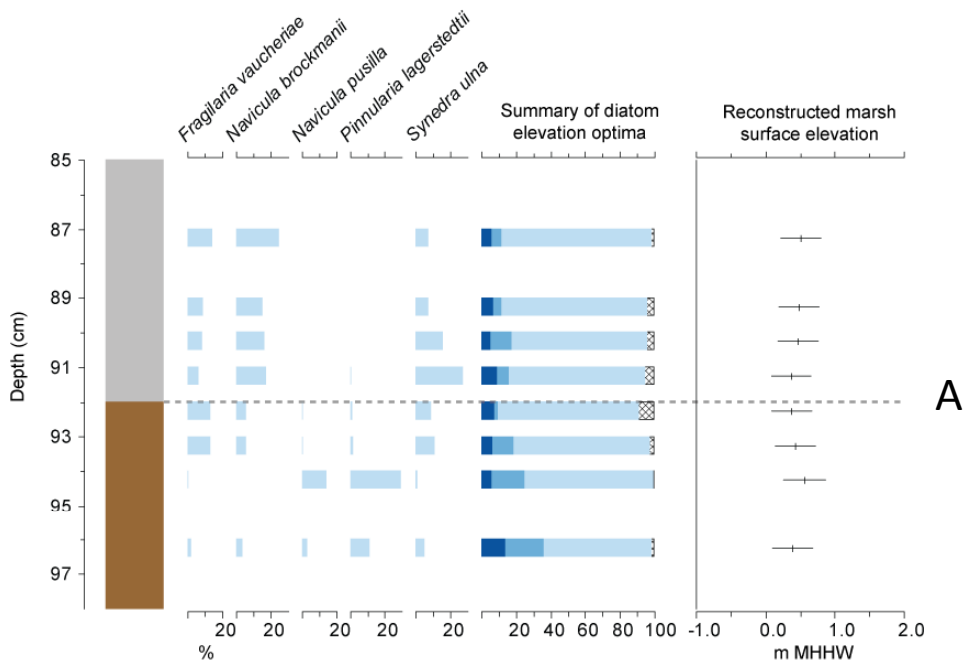


Figure 11 : Middle Bay – outcrop 1 and 4 - Diatoms and PMSE reconstructions.

5 References

Behre, K.-E., 2004. Coastal development, sea-level change and settlement history during the later Holocene in the Clay District of Lower Saxony (Niedersachsen), northern Germany, *Quaternary International,* 112**,** 37-53.

Carver, G. & Plafker, G., 2008. Paleoseismicity and Neotectonics of the Aleutian Subduction Zone - An Overview. *in Active tectonics and seismic potential of Alaska*, pp. 43-63, eds. Freymueller, J. T., Haeussler, P. J., Wesson, R. & Ekstrom, G. American Geophysical Union, Washington.

Gilpin, L.M., 1995. Holocene paleoseismicity and coastal tectonics of the Kodiak Islands, Alaska, PhD, University of California Santa Cruz, Santa Cruz.

Hamilton, S. & Shennan, I., 2005. Late Holocene relative sea-level changes and the earthquake deformation cycle around upper Cook Inlet, Alaska, *Quaternary Science Reviews,* 24**,** 1479-1498.

Hamilton, S., Shennan, I., Combellick, R., Mulholland, J. & Noble, C., 2005. Evidence for two great earthquakes at Anchorage, Alaska and implications for multiple great earthquakes through the Holocene, *Quaternary Science Reviews,* 24**,** 2050-2068.

Lienkaemper, J.J. & Bronk Ramsey, C., 2009. OxCal: Versatile tool for developing paleoearthquake chronolgies - A primer, *Seismological Research Letters,* 80**,** 431-434.

Shennan, I., Bruhn, R.L., Barlow, N.L.M., Good, K. & Hocking, E.P., In Press. Late Holocene great earthquakes in the eastern part of the Aleutian megathrust *Quaternary Science Reviews*.

Shennan, I., Hamilton, S. & Long, A., 2003. Late Holocene paleoseismicity and associated land/sea level change in the greater Anchorage area. *in US Geological Survey, Department of the Interior, Award no 02HQGR0075*, pp. 90.

Shennan, I., Long, A., Barlow, N. & Watcham, E.P., 2011. Spatial and Temporal Patterns of Deformation Associated with Multiple Late Holocene Earthquakes in Kodiak Island, Alaska, pp. 27U.S. Geological Survey (USGS), Department of the Interior, award number G109AP00075.

Watcham, E.P., Shennan, I. & Barlow, N.L.M., 2013. Scale considerations in using diatoms as indicators of sea-level change: lessons from Alaska, *Journal of Quaternary Science,* 28**,** 165-179.