Bolinas Lagoon Ecosystem Restoration Feasibility Project

Final Public Reports

III Recent (1850-2005) and late Holocene (400-1850) Sedimentation Rates at Bolinas Lagoon

Roger Byrne *et al.*

UC Berkeley

Recent (1850 - 2005) and Late Holocene (AD 400 – AD 1850) Sedimentation Rates at Bolinas Lagoon, Marin County, California

Bolinas Lagoon Inlet - October 5, 2005

A Report Submitted to the
Marin County Open Space District
December 14, 2005
by

Roger Byrne[1] and Liam Reidy[1]
with the assistance of
Dyuti Sengupta[1], Beth Watson[1], Daniel Schmidt[1], Aaron Arthur[2], Matthew Kirby[3], Jena Krause[1], Jennifer Sullivan[1], Josh Borkowski[1], Alex Yiu[1], and Angela Menchaca[4].

[1] Geography Department, University of California, Berkeley, CA 94720.
[2] Earth Science Department, Oregon State University, Corvallis, OR 97331.
[3] Geological Sciences Department, California State University, Fullerton, CA 92834.
[4] Berkeley High School, Berkeley, CA 94704.

Table of Contents

List of Figures (pdf files)

List of Tables

Introduction

Bolinas Lagoon has been the focus of an ongoing debate for at least half a century. Some have argued that destructive land use practices during the period of Mexican and American settlement increased the rate of sediment accumulation to the extent that without direct intervention in the form of dredging the lagoon will become a freshwater marsh or meadow within the next 50 years. Others have claimed that recent sedimentation rates have not been high enough to threaten the lagoon with extinction and that dredging is not needed. As is often the case with protracted debates, the amount of reliable evidence relative to the issue has been limited.

In this report we present new evidence concerning the recent history of the lagoon: evidence that will provide a firmer basis for management than has previously existed. The report consists of two parts. In the first part we present the results of analyses of twenty one short cores recovered from the north basin of Bolinas Lagoon in 2004 and 2005. These cores cover the period of Mexican and American settlement, approximately 1840[1] to the present. In the second part we present data from two longer cores, one taken at the northern edge of the north basin and the other at the southern edge. The northern core represents approximately the last 1000 years and the southern core 1600 years, so collectively they provide a long term perspective on the history of the lagoon prior to significant human impact.

We reconstructed recent sedimentation rates by dating cores with lead 210 and the first appearance of non-native pollen types. The longer term sedimentation rates were reconstructed with Accelerator Mass Spectroscopy (AMS) radiocarbon dates. In addition, several cores were analyzed for particle size variation, pollen content, magnetic susceptibility, water and organic content, pore water salinity, and sediment density (x-radiography). The results of these analyses provide further information regarding the environmental history of the lagoon. Finally, the geochemistry of one well dated core was analyzed with x-ray fluorescence (XRF) in order to identify the origins of the sediments accumulating in the lagoon.

---

[1] All dates in this report are in years AD unless otherwise indicated.

Recent (1850-2005) Sedimentation Rates

Prior to the present study, estimates of recent sedimentation rates at Bolinas Lagoon were primarily based on the US Army Corp of Engineers (USACE) bathymetry surveys (1939, 1968, 1978, 1988, and 1998); a few direct measurements of sediments entering the lagoon (Ritter, 1973); a watershed sediment budget analysis (Tetra Tech, 2002); and the analysis of a single core recovered from the northern end of the lagoon by Bergquist and Byrne in 1976 (Bergquist, 1978). However, none of these studies convincingly answered the question as to the extent to which the lagoon has been "filling in" during the period of Mexican and American settlement.

Coring Strategy

Although initially the intent was to recover a larger number of cores from the lagoon (Figure 1), limitations of time and funding resulted in the primary effort being focused on the north basin (Figure 2). Also, the near surface sediments in the north basin are mostly silts and clays and are therefore more easily cored than the sediments in the southern part of the lagoon which are mostly sand. The presence of important wildlife habitat in the southern part of the lagoon also precluded coring there.

The cores were taken on a grid laid out with one axis parallel to the 1906 fault trace. The grid lines were spaced 200 meters apart and labeled alphabetically and numerically so that cores taken at the intersections of grid lines are labeled with a letter and number, A3, C4, etc. The elevation and location of all cores sites were surveyed in with reference to the new U.S. Coast and Geodetic Survey benchmark on the Pike County Gulch Creek bridge.

Cores were recovered either at high tide from a small plywood raft supported by rubber dinghies or at low tide from plywood sheets laid out directly on the mudflat. The coring device used was a 5 cm diameter Vohnaut piston corer fitted with plastic liners so the sediments could be recovered with minimal disturbance or contamination. All cores were returned to Roger Byrne's Laboratory at UC Berkeley for analysis and storage.

Core Chronologies

The reconstruction of accurate sedimentation rates obviously depends upon reliable core chronologies. For the short cores we used two dating techniques: identification of the first appearance of non-native pollen types whose history of introduction is reasonably well known, and alpha counting of lead 210, a short-lived (22 year half-life), naturally occurring radio-isotope.

Pollen diagrams showing the changing importance of the non-native pollen types in cores A3, C3, F2, and H4 are shown in Figure 3. The generally similar pollen profiles for the four core sites argues against any significant core disturbance whether by bioturbation or tectonic activity. It is true, however, that some minor (<10 cm ?) vertical displacement of pollen in the sediments may have occurred because of bioturbation. A few cores contained bentnose clam (*Macoma nasuta*) shell fragments but in general the cores were relatively free of shell material, an indication that the north basin is not optimum habitat for the mollusks that are locally common in other areas of the lagoon.

Several non-native pollen types are present in the near-surface sediments of the lagoon, including *Erodium cicutarium*, *Rumex acetosella, Plantago lanceolata*, and *Eucalyptus globulus*. The history of these species in the San Francisco Bay area is reasonably well known so we can assign the following dates to their first appearance: *Erodium cicutarium* and *Rumex acetosella* – 1845 +/- 10 years; *Plantago lanceolata* 1870 +/- 10 years; *Eucalyptus globulus* – 1885 +/- 10 years. These "first appearance dates" take into account the fact that there is a lag between the arrival of a species in the area and the first appearance of its pollen in a sediment core.

The establishment of the Baulinas Rancho in the mid -1830's and the subsequent redwood logging that began in 1849 are easily identified in the sediments. In cores from northern part of the north basin *Rumex acetosella* and *Erodium cicutarium* pollen types are typically first encountered in samples taken just below the wood fragments that represent the direct evidence of logging activity. We therefore place the 1850 time horizon just above the first appearance of these pollen types.

Unfortunately, the 1906 earthquake did not coincide with the first appearance of a non-native pollen type. However, it can be approximately located with reference to the first appearance of *Eucalyptus globulus* pollen which is assigned a date of 1885 +/- 10 years. In addition, peaks in *Plantago lanceolata* most likely date to the first few decades of the twentieth century when cattle ranching in the area was well developed. We therefore place the 1906 horizon in the pollen diagrams just above the first appearance of *Eucalyptus* and within the *Plantago lanceolata* peak which is typically broad.

Lead 210 activity levels as measured by alpha counting of samples from cores C3 and H4 are shown in Figure 4. The measurements were made by Flett Research of Winnipeg, Canada. Unfortunately, the amount of lead 210 in the Bolinas sediments is relatively low and there is significant uncertainty therefore in the resulting chronologies. Low lead 210 activity is typical of sites on the west coast of North America because the prevailing winds are westerlies and the Pacific is an insignificant source of lead 210.

The lead 210 chronologies compliment the pollen chronologies in the sense that they provide age estimates for the last 80 years or so, which is the time period for which there are no reliable pollen markers. We should also point out that the lead 210 activity in upper part of the C3 core is significantly less than that in the H4 core. This suggests that there may be an erosional gap at the top of the C3 core. Age-depth curves for C3 and H4 based on the combination of pollen and lead 210 dates are shown in Figures 5a and 5b. Age depth curves for A3 and F2 based on pollen alone are shown in Figures 5c and 5d.

Spatial Variation in Sediment Accumulation

The 21 short cores provide reasonable coverage of the north basin but because of time and financial constraints it was only possible to date 4 of them directly: 2 with pollen and lead 210, and 2 with pollen alone. The chronologies for the 17 undated cores were established by extrapolation of magnetic susceptibility profiles from the dated cores. Four grid line transects showing how this was done are shown in Figures 6a, 6b, 7a, 7b, 8a, 8b, and 9a, 9b. Two versions are shown for each transect. The upper version labeled "a" shows the cores in their true location relative to three tidal datums: mean higher high water (MHHW), mean sea level (MSL), and mean lower low water (MLLW) (the tide gauge data on which these datums are based were kindly made available by PWA). The lower version labeled "b" shows the cores aligned with their core tops set at 0 cm. This version is also labeled with what we interpret to be the 1850 and 1906 time horizons by extrapolation from the dated cores. With some cores the magnetic signal was not easily extrapolated and the assignment of the time horizons may be inaccurate. Further pollen analysis will resolve these issues.

Whole core magnetic susceptibility was determined with a Bartington Magnetic Susceptibility meter. This was done within a few days after recovery while the cores were still in their plastic liners. The core magnetic susceptibility profiles show a complex but still useful pattern of variation within the lagoon.

Of particular interest is the way in which the magnetic susceptibility profiles change along the north west – south east transects; for example, along Transect 4, which is shown in Figure 7. In core H4, which is well dated with pollen and lead 210, the sharp increase in susceptibility at ca. 80 cm is apparently attributable to the 1906 earthquake. Particle size data to be presented later show a short-lived increase in coarse grained sediments at this depth followed by an increase in the percentage of silt+clay. However, as one follows the magnetic susceptibility curves to the north west, i.e., G4, F4, E4, etc., the earthquake signal is less evident and in effect merges with an earlier susceptibility peak that marks the logging activity at the northern end of the lagoon. Core C4 is not directly dated but is close to C3 which is well dated with pollen and lead 210.

The important implication here is that the magnetic susceptibility peaks in the short cores are a reflection of both the logging and earthquake impacts and in the northern part of the lagoon, where the logging activity was concentrated, the earthquake signal is obscured. Paradoxically, at the south end of the north basin, for example at H4, the sedimentation rate indicated for the second half of the nineteenth century is very high but the magnetic susceptibility relatively low.

Site	1906 Depth in core cm	1850 Depth in core cm	Difference cm 1850-1906	Difference cm 1906-2005	Rate mm 1850-1906	Rate mm 1906-2005	Rate mm 1906-2005
A3	55	137	82	55	14	6	9
B3	62	86	24	62	4	6	6
C3	72	106	34	72	6	7	7
D3	96	120	24	96	4	10	8
E3	89	144	55	89	10	9	9
F3	91	134	43	91	8	9	9
G3	72		-72	72		7	
C4	62	89	27	62	5	6	6
D4	82	115	33	82	6	8	7
E4	84	115	31	84	5	8	7
F4	74	118	44	74	8	7	8
G4	72	110	38	72	7	7	7
H4	84	154	70	84	12	8	10
D5	96	120	24	96	4	10	8
E5	67	94	27	67	5	7	6
F5	67	91	24	67	4	7	6
G5	69	94	25	69	4	7	6
H5	84	139	55	84	10	8	9
D2	43	65	22	43	4	4	4
E2	49	80	31	49	5	5	5
F2	32	55	23	32	4	3	4

Table 1. Short core sedimentation rates.

Spatial variations in sedimentation rates based on extrapolations with the magnetic susceptibility transects are shown in Figure 10, Figure 11 and Table 1. The maps represent our current best estimates of 1850-1906 and 1906-2005 sedimentation rates in the northern basin of Bolinas Lagoon. Please note that the spatial variability on the 1850-1906 map is much greater than on the 1906-2005 map and for that reason the contour interval on the former is 1 mm and on the latter 0.5 mm. The numbers next to the core site symbols represent the vertical differences between the 1850, 1906, and 2005 time horizons expressed as sedimentation rates in mm/year. The range of error in these estimates is probably at least +/- 10 percent.

The sediment accumulation maps provide an important perspective on the recent history of Bolinas Lagoon. The 1850-1906 map (Figure 10) clearly shows that the logging impact was largely restricted to the northern and southern margins of the basin. Site H4 near the Pine Gulch Creek Delta has the highest sedimentation rate with 12 mm/year. This high rate may reflect logging in the Pine Gulch Creek watershed but the low magnetic susceptibility signal for this time period may indicate another source; for example, farming on the alluvial lowland west of Pine Gulch Creek Delta. Casa Briones, which was first built in the 1830's, is located less only 500 meters west of the core site. At A3 in the northern part of the lagoon the indicated rate is 10 mm/year. However, at B3, only 200 m from A3, the 1850-1906 rate is only 4 mm/year, and for most of the central part of the north basin between 4 and 7 mm/year. Core E3 is an exception in that it shows an unusually high rate of sediment accumulation (10 mm/year).

The 1906 - 2005 sedimentation rate map (Figure 11) is in several respects different from the 1850 - 1906 map. Sedimentation rates in the northern part of the north basin are generally low and the rates close to Pine Gulch Creek Delta are lower than they were in the earlier period. In contrast, rates are generally high in the deeper central part of the north basin, especially in the area just east of the 1906 fault trace; for example, at D3, E3, and F3. We attribute this to the down-dropping of the eastern part of the lagoon in 1906 and an increased influx of fine grained sediment from the Bolinas Bluffs. On the eastern side of the north basin rates are lower than in the central area, possibly because of the presence there of the main tidal channel. D5 is an exception to the rule with a rate of 10 mm/year. This may be in part due to road construction just to the east of that core site.

An interesting feature of both maps is that the cores on the western side of the 1906 fault trace, for example D2, E2, and F2, show a consistently lower sedimentation rate than adjacent cores to the east of the fault trace. This presumably reflects the greater down-drop on the eastern side during the 1906 event. This possibility is considered further in the following section.

Vertical Displacement during the 1906 Earthquake

One of the expected results of the core analysis is that the thickness of post-1906 sediment east of the fault trace is greater than that to the west (Figure 12). We interpret this to be primarily the result of the vertical displacement and compaction during the 1906 earthquake. Gilbert (1908) on the basis of careful observation of dead marsh plants on Kent Island in 1907 concluded that the downdrop was around 30 cm. The core evidence suggests that the downdrop averaged 45 cm in the north basin immediately to the east of the fault trace.

We estimated the 1906 vertical displacement by subtracting the present elevational differences between core tops east and west of the fault trace and subtracting that value from the elevational differences between the 1906 horizons (Figure 13). The rationale for this methodology is that just prior to the 1906 earthquake the sediment surface at core sites east of the 1906 fault trace, for example: D3, D4, E3, E4, F3, and F4, would have been lower than at core sites west of the trace such as D2, E2, and F2. The vertical displacement estimates shown in Figure 12 average 45 cm which is 50 percent more than Gilbert's 30 cm estimate. We should note, however, that the estimates do not account for compaction or any vertical movement subsequent to 1906 event and therefore may be on the high side. On the other hand, if the lagoon was shallower in 1906 than it is today the amount of down drop may have been greater than indicated. The fact that the largest downdrops are indicated for transect 3, which is the east side transect closest to the fault trace, is reassuring evidence that the spatial pattern shown in Figure 12 is realistic.

The downdrop that took place during the 1906 earthquake was of primary importance for the lagoon in that it increased the tidal prism and to a significant extent counterbalanced the increase in sedimentation that had been brought about by logging and agricultural activities within the watershed. Gilbert's 30 cm estimate was based on his observations of what happened in the saltmarsh area on the north side of Kent Island. This is an area in which the sediments are predominantly sand, and it is not surprising that subsidence was less there than in the north basin where the sediments are mostly silt+clay.

Core Stratigraphy

In order to provide further evidence regarding the recent history of the lagoon, we analyzed the stratigraphy of three well-dated "master cores" (A3, C3, and H4) in some detail. We measured water content, organic content, pore water salinity, and particle size at regularly spaced (usually 5 cm) intervals in each core. The results are shown graphically in Figure 14. Collectively, they provide an important perspective on the effects of redwood logging and the 1906 earthquake, and in general they support the independently derived pollen and lead 210 chronologies.

The pollen/lead 210 chronology for the H4 core places the beginnings of redwood logging at ca. 160 cm and the 1906 earthquake at ca. 90 cm. The logging impact is not clearly evident in this core. The silt+clay percentage does begin to increase at ca. 160 cm depth, but this could also have been the result of farming activity in the area around Casa Briones. At ca. 85 cm there are two changes in core stratigraphy that we attribute to the 1906 earthquake: a sharp increase in magnetic susceptibility, and an irregular and short-lived increase in sand percentages. Also of interest is the prominent pore water salinity spike at 96 cm. This may be high salinity water from the salt marsh that was drowned during the 1906 earthquake. The location of the spike ca. 10 cm below the sand increase could be due to ionic diffusion during the time since the earthquake. Another important aspect of the H4 stratigraphy is the importance of silt+clay from 70 cm to 20 cm. The average silt+clay percentage in this section is ca. 70 percent. The presence of so much fine-grained sediment in the section of the core dating from ca.

1920 to ca. 1980 was unexpected. Geochemical evidence, which we shall present later, indicates that the most likely source is the Monterey shale exposure at the Bolinas Bluffs.

The C3 core location is closer to the center of the north basin than either H4 or A3 and not surprisingly is characterized by finer-grained sediment. The pollen/lead 210 chronology indicates that the start of logging should be evident at ca. 120 cm and the 1906 earthquake at ca. 90 cm. The magnetic susceptibility curve starts to increase at 105 cm and peaks at 80 cm suggesting that at this site the chronology is slightly too old and that the two disturbance signals are superimposed. We assume that the increase in sand percentages between 80 and 75 cm and the salinity peak between 85 and 60 cm both reflect the 1906 earthquake event. The pore water salinity in this core is significantly less than at H4 presumably because of the increased distance from the tidal inlet. The steady decrease in salinity from 65 to 15 cm could be the result of the decrease in tidal prism following the 1906 event. The organic content of the core is less than 8 percent and shows the typical decrease with depth. The water content is much higher in the upper part of the core, as was the case at H4.

The A3 core site is at the lower edge of the saltmarsh at the north end of the lagoon and ca. 5 meters to the east of Wilkins Gulch Creek which drains a small area of Bolinas Ridge. This core clearly shows the effects of redwood logging but the earthquake impact is less evident than at the other two core sites. The pollen chronology suggests that the logging impact should appear at ca. 135 cm and the 1906 earthquake at ca. 80 cm. The magnetic susceptibility curve definitely starts to rise at ca. 135 cm and also shows a broad peak that extends from 120 cm to ca. 85 cm. This section of the core is also characterized by an increase in sand percentages and a corresponding decrease in silt+clay. Insofar as most of the redwood logging took place in the 1850's, it seems likely that at least part of this disturbance is attributable to agricultural activities in the watershed, such as by dairy farming. There is a sharp peak in the percent sand curve at the 99 cm depth which may be equivalent to the sand peaks assigned to the 1906 event in the C3 and H4 cores. If this is the case, the pollen chronology is significantly too old in this section of the core. Above the 99 cm sand peak the silt+clay percentages increase in roughly the same way as at H4 but the magnitude of increase is significantly less. In the upper 40 cm of the core oscillations in the silt+clay and sand percentages indicate short term variations in the depositional environment. The magnetics curve also shows a prominent peak between the 15 and 10 cm depths. According to the Knudsen et al. (1999) report, the uppermost layer of coarse sediment was deposited during the 1998 El Niño flood.

The A3 salinity curve is interestingly different from the C3 and H4 curves in that there is only a minor peak at what is assumed to be the 1906 depth. Much more dramatic is the irregular increase in salinity above 40 cm. This may represent the recent expansion of salt marsh at the core site and the evaporative concentration of salts on the high marsh during the summer. The volumetric water content of the core is consistently around 60 percent and shows very little evidence of compaction. The organic curve is also different from those at other sites in that shows several peaks between 70 and 30 cm and also at the surface. The high values at the surface reflect the recent expansion of salt marsh; the earlier peaks appear to mark local accumulations of organic detritus on what was intertidal mudflat.

Autocompaction

One important natural process that affects the rate of vertical accretion is autocompaction. This process occurs when water is forced out of sediment by the accumulating weight of more recently deposited sediment. Downdrop during earthquakes also causes compaction. The amount of potential compaction in sediments depends upon the initial water content, sediment type, and particle size. Silt+clay, for example, are much more compressible than sand (Bird et al. 2004). The natural breakdown of organic matter can also be a factor but is probably of little significance in the north basin at Bolinas Lagoon where the organic content of sediments is generally less than 8 percent.

The water content of cores H4, C3, and A3 is shown in Figure 14 as a percent of the total volume of the sediments rather than the usual percent wet weight. We have graphed water content this way in order to show the potential for autocompaction. The H4 and C3 water content profiles are similar in that they show the expected pattern of higher percentages (55-60 percent) in the near surface sections of the cores, i.e., above ca. 80 cm, and lower percentages (45-50 percent) below that depth. This indicates that the sediments that are now in the upper part of the cores will autocompact by approximately 20 percent of their volume during the next 100 years or so. The water content curve for A3 is unusually complacent, possibly reflecting its location close to the edge of the lagoon where the thickness of Holocene sediments is not very great.

Short Core Pollen Diagrams

In addition to the pollen diagrams constructed to provide chronological control for the short cores, relatively detailed pollen diagrams were constructed for short cores A3 and H4. These are shown in Figure 15. The selected pollen types included are shown as percentages of the total non-aquatic pollen sum. The objective of the pollen analysis was to provide further paleoenvironmental information about the Bolinas Lagoon environment during the last two hundred years or so. Theoretically, changes in pollen frequencies in the cores should provide further information about changes in upland vegetation and also changes in the extent and composition of fresh and saltwater marshes. Unfortunately, the extraction and counting of Bolinas Lagoon pollen is complicated by the refractory nature of the sediments. As is often the case in estuarine environments, the sediments contain a relatively high concentration of chemically resistant organic material such as charcoal, bacterial residues, wood cellulose, and fungal spores. Obtaining a statistically reliable pollen sum of 400 pollen grains takes several hours of counting.

In the A3 pollen diagram the upland pollen types (i.e., non-aquatic or riparian) show very little change (Figure 15a). Redwood (*Sequoia*) pollen percentages decrease during the second half of the nineteenth century, as might be expected in view of the history of logging in the area. Pine (*Pinus*) pollen decreases to a lesser extent and oak (*Quercus*) shows little change. The native herbaceous pollen types vary irregularly and show no clear response to either logging and grazing impacts or the 1906 earthquake event. The riparian and marsh pollen types are also generally complacent (Figure 15b). An exception is the sharp increase in the Amaranthaceae type (*Salicornia* and *Atriplex*) in the near surface sample which undoubtedly reflects the recent establishment of saltmarsh at the core site. The succession of non-natives has been discussed earlier. Total pollen concentrations in the A3 core vary from 15,000 to over 60,000 grains/cm^3. Concentrations are highest in the pre – Mexican/American period and also during the first few decades of the twentieth century. Relatively low concentrations during the second halves of the nineteenth century and twentieth centuries are probably due to increases in sedimentation rates (logging impact) and the increased water content of the sediments, respectively.

In the H4 diagram the upland pollen types show basically the same trends as in the A3 diagram (Figure 15c). The redwood (*Sequoia*) curve declines steadily in the earlier part of the record and more rapidly after ca. 1920. The reasons for this are not immediately apparent. The pine (*Pinus*) and oak (*Quercus*) curves are both complacent. The most variable herbaceous palynomorph is the unknown monolete spore type. Most likely this represents *Polypodium, Athyrum,* or *Dryopteris.* The monolete spore increase around the middle of the last century is also evident at A3. The riparian and marsh pollen types at H4 show significant changes during the period of record (Figure 15d). Alder pollen (*Alnus*) increases steadily from 10 percent of the non-aquatic total to 30 percent in the surface sample. This increase is apparently attributable to the expansion of alder on the Pine Gulch Creek Delta. The Amaranthaceae pollen type, which here represents *Salicornia* and *Atriplex*, shows a steady decline during the period of American settlement. The freshwater marsh types are also more important prior to 1850. Presumably this reflects the reclamation of marsh for agriculture in the lowland area to the south of Casa Briones.

The North Basin in 1849 – Intertidal or Subtidal?

One important question regarding the size of the tidal prism prior to redwood logging in 1849 is whether or not the north basin was intertidal or subtidal. Rowntree and Bergquist reached different conclusions on this issue. Rowntree (1973) noted the limited extent of tidal channel in the north basin on the 1854 US Coast and Geodetic Survey map and concluded that it was mostly intertidal. Bergquist (1978) questioned the accuracy of the 1854 map on the basis of the stratigraphy of the core he and I took near the Embarcadero in 1976. More specifically, he noted that the 1850 horizon was located at a depth between 115 cm and 120 cm in the core and concluded therefore the core site must have been below MLLW in 1854. Unfortunately, the elevation of the 1976 core site in 1976 was not surveyed precisely but it can be safely assumed to have been below MSL.

The evidence uncovered in this study supports Rowntree's interpretation and confirms the accuracy of the US Coast and Geodetic Survey 1854 map. Especially relevant is the presence of *Cerithidea californica* shells in A3 just 5 cm below the logging horizon. An x-radiograph of this core section is shown in Figure 17. *Cerithidea* is a common gastropod in the lagoon and its main range is within the intertidal zone. Another relevant point is that Bergquist apparently underestimated the amount of subsidence at the 1976 core site between 1849 and 1975. He did acknowledge the 1906 downdrop but did not take into account the effects of sea level rise. If we extrapolate the San Francisco sea level data to Bolinas Lagoon, the rise in sea level during the period 1855 to 1976 was ca. 18 cm (Lyles et al., 1988). This when added to an assumed 30 cm 1906 downdrop reduces the equivalent depth of the 1849 horizon in the 1976 core from ca. 118 cm to ca. 70 cm which is not enough to make the core site subtidal. The broader implication of all this is that the topography of the north basin in 1854 was apparently not very different from what it is today, i.e., largely intertidal.

Also of interest in this context is the USGS Tamalpais Quadrangle of 1897 which was surveyed in 1894 and 1895 and published in 1897. This map is disappointing in that it does not show Kent or McKennan islands, but it does show what can be assumed to be an accurate depiction of the marsh at the north end of the lagoon. This section of the map is reproduced here together with the 1854 US Coast Survey topographic map (T-452) as Figure 16a+b, and with the USACE 1998 infrared aerial photograph as Figure 16c+d. A comparison of the 1854 and 1897 maps shows that the area of marsh did not increase significantly during the second half of the nineteenth century in spite of the logging impact and agricultural activities. Similarly a comparison of the 1897 map and the 1998 aerial photograph shows only a minor expansion of marsh. The area of marsh that is green on the latter image is mostly tule (*Scirpus*) and cattail (*Typha*); the brown area is mostly pickleweed (*Salicornia*).

Short Core Data Compared with the USACE Bathymetry Surveys

The USACE bathymetric surveys of the lagoon theoretically provide a check on the sedimentation rates indicated for the twentieth century sections of the short cores although there are uncertainties regarding the datums the surveys were based on. In order to compare our core results with the bathymetry data we focused on Range 1, the only part of the 1939 survey to include the a significant part of the north basin. Ritter had previously compared the USACE 1939 and 1968 surveys and we reproduce his map and graphic here as Figure 18 (Ritter, 1973). The graphic clearly indicates that a significant amount of sediment had accumulated in the north basin during the 29 years between the two surveys and that the surface elevation in 1968 was ca. 0.5 m or so below mean sea level. Paradoxically, the average core top elevation for our core sites E3, E4, E5, F3, F4, F5, G3, and G4 was also ca. 0.5 m below mean sea level (Figure 19), and the question therefore arose as to why no sediment had accumulated in this part of the lagoon during the period 1968-2005.

In order to clarify this issue, we resurveyed a 600 m section of USACE Range 1 and also generated a Range 1 surface elevation plot from the 1988 USACE bathymetry survey. We did not use the 1978 or 1998 surveys because of concerns about their reliability for this part of the lagoon. The sediment surface elevations along USACE Range 1 in 1939, 1968, 1988, and 2005 are shown in Figure 20 and the average sedimentation rates in Table 2. The results show that the average sedimentation rate between 1939 and 1988 was 14 mm/year and that the rate dropped to 2 mm a year for the period 1988 to the present. These rates are not supported by the short core chronologies. The rates for the two earlier periods appear to be too high and for the later period too low. For example, a backward extrapolation of the 1939 to 1988 rates places the 1906 horizon at ca. 117 cm below NGVD which is ca. 35 cm below the predicted elevation based on the pollen chronology. It is possible that pollen chronology is in error on the young side but it is not likely to be this far off. The H4 lead 210 chronology also suggests the bathymetry sedimentation rates are unreliable. One possible explanation is that the USACE bathymetry surveys were not all tied to the same datum.

Year	mean el. in m rel. to 2005	mean el. in m rel. to MSL	mean el. in m rel. to NGVD	difference in m	difference in years	rate in mm/yr
2005	0.00	-0.42	-0.17			
				0.03	17	2
1988	-0.03	-0.45	-0.20			
				0.28	20	14
1968	-0.31	-0.73	-0.48			
				0.40	29	14
1939	-0.71	-1.13	-0.88			
						x = 11

Table 2. USACE Range 1 elevation differences between the USACE surveys of 1939, 1968, 1988, and a UC survey in 2005. The averages are based upon the first 30 survey stations on the eastern side of the range minus stations located in the tidal channel. NGVD is assumed to be 81 cm above NAVD. The 2005 elevations are tied to the Pike County Gulch benchmark.

In the Bolinas Lagoon Restoration Project Environmental Impact Report it is stated that the USACE assumed that the NGVD of 1929 was equivalent to mean sea level. However, according to NOAA's online benchmark data for the Bolinas Coastguard Station Benchmark (Bolinas Tidal 2) NGVD is 31 cm below MSL (http://www.co-ops.nos.noaa.gov/benchmarks/9414958.html).

Possible Sources of post-1906 Sediments in the North Basin

In order to try and identify the likely source area, or areas, for the fine-grained sediments that accumulated in the north basin after the 1906 earthquake, we analyzed the chemical composition of H4, a well dated short core, and also analyzed surface sediment samples collected in three potential source areas: Pine Gulch Creek Delta, Bolinas Ridge, and the Bolinas Bluffs (Figure 21). Some studies on the geochemistry and mineralogy of the lagoon sediments were carried out in the 1960's by USGS scientists (Ritter, 1969), but these studies focused primarily upon surface sediments.

We collected the Bolinas Ridge and Pine Gulch Creek samples in the intertidal zone and then washed them on a 63 micrometer mesh with distilled water to remove soluble salts and the silts and clays deposited by the tidal circulation. The Bolinas Bluff samples were taken directly from the cliff face. All samples were heated in a furnace at 550°C for one hour to remove organics and ground with a Spex mill prior to pelletizing for XRF analysis. A total of 11 common elements and 24 trace elements were analyzed. Visual inspection of the resulting data showed that 11 elements were potentially useful predictors of sediment source. The rest either showed no clear association with any of the three source areas or were not present in large enough concentrations to be statistically useful. The data for the potentially useful elements were then analyzed with principle components analysis and discriminant function analysis in order to show which of the three source areas the H4 core samples were most likely derived from. The results are shown in Figure 22. They clearly show that most of the post-1906 section of the core, i.e., from 80 cm to 20 cm, consists of material derived from the Monterey Shale exposed in the Bolinas Bluffs. The first principal component, which accounts for 61 percent of the total variance, is negatively loaded on the Pine Gulch Creek samples and positively loaded on the Bolinas Ridge samples; the Bluff samples cluster at close to zero. The discriminant function analysis results show clearly that the H4 samples high in silt+clay are most likely derived from the Bluffs (Figure 23). A cross validation test shows the sample classification to be 79 percent accurate.

We interpret the post-1906 increase in silt+clay deposition at H4 to be result of a combination of several factors. One factor was the collapse of the Bluffs and the resultant increase in easily silt+clay within the intertidal zone. Local accounts indicate that the shaking that occurred during the earthquake caused the Bluffs to collapse to the extent that one could easily walk up from the beach to the Mesa above (Tetra Tech, 2002). This situation was presumably short-lived as wave action would have quickly removed the easily eroded sediment. More important may have been the opening up of the Kent Island and Bolinas tidal channels along the west side of the lagoon as a direct result of the displacement along the fault trace. Flood tide circulation in these channels could then have moved suspended fine silt+clay up into the north basin. Photographic evidence indicates that the Kent Island channel remained active until at least the 1940's. The Bolinas Channel is still active today although during the last three decades it has diminished in size. The grain size and sediment chemistry data for the top 20 cm of the H4 core also show a reduction in silt+clay from the Bolinas Bluffs (Figure 14a).

Variations in Grain Size

In view of the significant variation in grain size in the three master cores (A3, C3, and H4), we also measured grain size in four other cores (D3, C4, D4, and F4). However, grain size variation for these cores was determined not with a laser driven particle size analyzer but by wet sieving. We dried 15 cc samples in an oven, weighed them, and then separated the sand fraction from the silt+clay fraction by washing through a 63 micrometer mesh. The sand remaining on the sieve was then dried and weighed and the silt+clay weight calculated by subtraction from the original dry weight. The results for the three master cores, four sieved cores, plus the grain size data reported by Bergquist (1978) for the core he and I took near the Embarcadero in 1976 (here referred to as core "BB") are shown in Figure 24. The sand and silt+clay fractions for each core are shown as percentages and doubled over in Rorschack fashion to emphasize the changes. The estimated 1850 and 1906 horizons are shown as blue and red lines respectively.

The spatial pattern in grain size shows that the sand percentages are generally high at the northern and southern edges of the basin and low in the central part of the basin. This pattern has been recognized before and is obviously a reflection of the higher energy environments at the northern and southern edges of the basin. At the northern edge two small streams deposit alluvium some of which is washed onto the mudflats at low tide, especially during flood events; at the southern edge both Pine Gulch Creek and the east side tidal channel are sources of relatively coarse sediment.

The temporal variations in grain size are more interesting than the spatial pattern. The results are plotted in a north to south (left to right) sequence in Figure 24. Cores A3, BB, and C3 from the north end of the basin show rather similar profiles with the sand percentages increasing irregularly towards the surface. The BB core was taken in 1976 and therefore lacks the prominent near surface sand increase present in both A3 and C3. We have plotted Bergquist's estimated 1906 horizon with a dashed line because in light of the evidence discussed earlier it is much too high in the core. The second half of the nineteenth century was clearly characterized by relatively high sand percentages in all three cores although the importance of sand relative to silt+clay decreases towards the center of the basin. The high sand percentages are undoubtedly attributable to redwood logging and agricultural activity in the watershed. A post–1906 increase in silt+clay is evident in A3 and C3, and in BB as well if Bergquist's chronology is adjusted downwards. As we discussed earlier, this is presumably due to the enlargement of tidal channels on the west side of the lagoon during the 1906 earthquake. The irregular increase in sand towards the surface at A3 and C3 most likely reflects periodic storm activity and the reduced input of silt+clay from the Bolinas Bluffs.

Cores D3 and C4 are both similar in having very high silt+clay percentages, especially after 1906. This is due to their location in the central part of the north basin, an area too far from streams and tidal channels to receive significant quantities of sand. These cores sites therefore mark a transitional zone in the basin, with areas to the north receiving sand from the small creeks such as Pike County Gulch Creek (Figure 21) and areas to the south receiving sand from Pine Gulch Creek and the east side tidal channel.

Cores D4, F4, and H4 show the much greater importance of sand on the south side of the north basin, especially prior to 1906. In this respect all three cores have "inverted wine glass" sand profiles in contrast to A3, BB, and C3 on the northern side of the basin. The reason for this is not certain but it may due to a period of stronger tidal influence during the nineteenth century. The effects of human activities are most apparent at H4 which, as was discussed before, is the core site closest to Casa Briones. All three cores show an irregular decline in sand percentages after 1906; especially D4 which located closer to the center of the north basin. The smoother nature of the F4 core relative to H4 and D4 is simply an artifact of a coarser sampling interval.

Summary and Conclusions

The short cores analyses have provided a great deal of new evidence regarding the recent history of Bolinas Lagoon. They improve our understanding of spatial and temporal variations in sedimentation rates; the origins of sediments accumulating before and after the 1906 earthquake; the magnitude of downdrop during the 1906 earthquake; and, the potential significance of autocompaction.

1. The reconstructed sedimentation rates for the north basin of Bolinas Lagoon are spatially and temporally variable. The average rate for the period 1850 to 1906 for 21 core sites is 6 mm/year. Above average sedimentation rates of 12 mm/year and 10 mm/year are indicated for H4 near the Pine Gulch Creek delta and A3 near the Embarcadero, respectively. In contrast, the average for the core sites in the central part of the basin is only 6 mm/year. For the period 1906 to 2005 the overall average for 21 core sites is 7 mm/year. High rates for this period are evident in the central part of the north basin on the east side of the fault trace, where the average for core sites D3, D4, E3, E4, F3 and F4 is 9 mm/year.

2. The particle size analysis shows that the during the period 1850-1906 human-induced disturbance such as redwood logging, agricultural activities, and cattle ranching resulted in an increased input of coarse-grained sediment into the lagoon, especially near the Embarcadero and the Pine Gulch Creek Delta. In contrast, during the period 1906-2005 silt+clay rather than sand was the dominant sediment type deposited in the north basin. The source of this fine-grained sediment was the Bolinas Bluffs, as suggested earlier by both Rowntree (1973) and Ritter (1969).

3. A comparison of core stratigraphies on both sides of the 1906 fault trace indicates that the amount of vertical displacement on the east side averaged 45 cm in the deepest area of the north basin. The resulting increase in tidal prism would have more than compensated for the nineteenth century reduction due to redwood logging and agricultural activity.

4. In most of the short cores analyzed stratigraphically the average water content is ca. 70 percent in the upper meter and 50 to 60 percent below that. This indicates that autocompaction will reduce the apparent rate of sediment accretion in the upper meter by ca. 20 percent. In other words, the average rate of 7 mm/year for the period 1906 to 2005 will eventually be reduced to less than 6 mm/year.

Late Holocene (ca. AD 400 to AD 1850[2]) Sedimentation Rates

Research into the longer-term history of Bolinas Lagoon has been limited. In the 1970's Joel Bergquist analyzed several cores from the lagoon as part of his doctoral research at Stanford. His dissertation, which was published as a USGS Open File Report (Bergquist, 1978), is still the most important source of information regarding the longer term history of the lagoon. In the 1990's Knudsen et al. carried out a detailed investigation of the stratigraphy of the extreme north end of the lagoon as part of a NEHRP (National Earthquake Hazards Reduction Program) project (Knudsen et al., 1999). They reported 12 radiocarbon dates from Bolinas Lagoon but unfortunately compaction problems during coring make the dates useless as far as sedimentation rate reconstruction is concerned.

In the discussion that follows we present the results of our analyses of two long cores from the north basin, which we label as L1 and L2. The L1 core was taken close to the H4 short core site and L2 close to the A3 site. Core recovery at H4 was 5.75 m (1.50 m to 7.25 m depths) and at A3 it was 3.12 m. The L1 core has an estimated basal date of AD 400 and the L2 core AD 1100; both cores therefore cover a significant period of time prior to the period of Mexican/American settlement.

Selection of Long Core Sites

We took long cores at the H4 and A3 short core sites to provide longer-term perspectives on sedimentation rates at the northern and southern edges of the north basin where sedimentation rates during the period of Mexican/American settlement were unusually high. According to Bergquist's cross section of the sub-surface stratigraphy of the lagoon (Figure 23 in Bergquist, 1978), the total thickness of Holocene sediments at H4 is ca. 20 m and at A3 ca. 7 m. If we use Atwater's South San Francisco Bay Holocene sea level curve (Figure 6 in Atwater, 1977) as a proxy for Bolinas Lagoon,

---

[2] In our discussion of the long core evidence all dates are expressed in BC/AD notation unless otherwise indicated.

the time of transgression at the two sites would have been ca. 8,000 and 3-4,000 years ago respectively. Greater subsidence at Bolinas relative to San Francisco Bay would make these dates younger.

Core recovery at H4 was complicated by the presence of a dense sand layer between ca. 2 and 3 meters depth. This made manual coring difficult and necessitated the use of a narrow gauge (2.5 cm diameter) Livingston piston corer and a sledge hammer. At A3 the presence of gravel layers in the upper 40 cm made penetration difficult but below that the sediments were soft enough to be recovered with a 5 cm diameter Vohnaut piston corer.

Long Core Chronologies

The L1 core chronology is based on three AMS radiocarbon age determinations on bent nosed clam (*Macoma nasuta*) and cockle (*Clinocardium nuttalli*) shells. The shells were broken and so there is a possibility of some reworking. The age estimates were determined at the Center for Accelerator Mass Spectroscopy (CAMS) at Lawrence Livermore National Laboratory (LLNL) and are shown in Table 3.

Marine shell is not ideal material for radiocarbon dating because of uncertainties regarding the marine reservoir effect. The problem with shell dates along the California coast is that mollusks produce their shells in upwelled water that was last in contact with the atmosphere several hundred years ago and is therefore depleted in radiocarbon. The dates presented in Table 3 are corrected for this reservoir effect using a correction factor based on the radiocarbon dates derived from modern (i.e., pre-bomb) samples of known age. The correction factor (R value) for northern California is 271 +/- 19 years. We should point out, however, that the shells on which the two older dates are based may have been produced during a time of more frequent upwelling (Ingram and Southon, 1996). If this more frequent upwelling affected Bolinas Lagoon it would mean that the dates shown in Table 3 are probably several hundred years too old. Reworking would also artificially increase the age of the horizon in which the shell material was found. Both of these effects produce sedimentation rates that are lower than they should be. In other words, the sedimentation rate reconstructions discussed below are almost certainly minimum estimates.

In addition to providing potential radiocarbon dates, shells can also provide paleoenvironmental information. For example, the bent nosed clam (*Macoma nasuta)* and Nuttall's cockle *(Clinocardium nuttalli)* are both typically found in the intertidal zone. This means that there is probably at least a +/- 1.0 m error factor if a *Macoma* or *Clinocardium* date is used to reconstruct changes in sea level. However, this error does not apply to reconstructed sedimentation rates insofar as they are simply based on the vertical distance between two dates.

Core	Depth m	CAMS#	14C Age years BP	Delta R	Calibrated Age Range (2 sigma)	Median Age
L1	3.73	11432	1315 +/- 35	271 +/- 19	AD 1276-1414	AD 1340
L1	5.93	11433	2025 +/- 45	271 +/- 19	AD 544-749	AD 650
L1	7.25	11434	2265 +/- 35	271 +/- 19	AD 270-513	AD 400

Table 3. Radiocarbon dates on shell samples from Bolinas Lagoon. The global mean reservoir correction is 400 years. The regional correction for northern California (Delta R) is 271 +/- 19. The percent marine carbon in the shell samples is assumed to be 100 percent and the median age estimate has been rounded off to the nearest decade. The calibration was run with CALIB REV 5.0.2 following Stuiver, M., and Reimer, P.J., (1993).

The age - depth curve for L1 shown in Figure 25a is based on the three dates listed in Table 3. The basal date indicates that the 7.25 m core represents approximately the last 1,600 years and that the overall average sedimentation rate was 4.5 mm/year. The average pre - American sedimentation rate was 4.0 mm year. However, this obscures significant short term variability; for example, from AD 400 to AD 650 the average was 5.2 mm/year and from AD 650 to AD 1350 it was 3.1 mm year. This variability was most likely the result of tectonic activity. The 4 mm/year overall average is higher than Bergquist's estimate of 3 mm/year for the late Holocene and significantly higher than my own estimate of 2 mm/year (Byrne, 2002).

The chronology of the lower part of L2 is tentatively based on a radiocarbon date reported by Knudsen et al. (1999) from their 97 BOL D3 core, which was taken at the same location. The date is based on a wood sample from a depth of 1.73 m. Knudsen et al.'s core was taken with a coring device that caused significant compaction and as a result their published depth for the sample dated is not reliable. We re-cored the site with both a Vohnaut Piston Corer and a Russian Peat Corer, neither of which caused any compaction. On the basis of stratigraphic comparisons between the Knudsen et al's core and our cores, we assigned a corrected depth of 2.66 m for the radiocarbon sample which yielded a calibrated median age estimate of AD 1260. The age - depth curve for L2 shown as Figure 25b indicates a pre-American average rate of 2.1 mm/year, which is very close to my estimate of 2.0 mm/year. We should point out, however, that the Knudsen et al. date is based on a wood sample that may have been several hundred years older than the age of the surface it was deposited on, especially if the wood was redwood. This would mean the estimated sedimentation rate would be correspondingly higher.

Long Core Stratigraphies

The magnetic susceptibility data for L1 and H4 are spliced together in Figure 26. The susceptibility values are relatively high in the upper 2 meters and show a sharp increase at what we interpret to be the 1906 horizon. However, below 2 m they are low and show little variation. The only exception is a short spike at the 2.90 m depth. The consistently low values in the lower 5 meters of the core may be due to diagenetic effects. Mineralogical analysis of the sediments will be needed to clarify the issue.

The L1 particle size curves shown in Figure 26 are interesting in several respects. The alternating dominance of silt+clay and sand obviously reflects large scale shifts in the amount energy available for sediment transport in this part of the lagoon. As we indicate in our earlier discussion of the H4 short core, the prominent increase in silt+clay at the 0.8 m depth dates to just after the 1906 earthquake, and we interpret this to reflect increased deposition of fine-grained sediment from the Bolinas Bluffs. If this interpretation is correct similar increases in silt+clay can also be taken as evidence of earthquakes, as for example at 7.00 m (ca. AD 450), at 4.50 m (ca. AD 1080), at 4.18 m (ca. AD 1220), and at 3.40 m (ca. AD 1520).

Another potentially important feature of the L1 particle size data is the prominent sand unit between 2.00 m and 2.80 m. The lower boundary is sharply defined and the upper boundary more gradational. Interpolation between the AD 1350 radiocarbon date at 3.73 m and the AD 1850 horizon at 1.50 m indicates the lower boundary dates to ca. AD 1515 and the upper boundary ca. AD 1740.

The stratigraphy of the L2 core is in several respects different from the stratigraphy of L1. One major difference is the presence of a peaty clay layer between 265 cm and 295 cm. Knudsen et al. (1999) interpreted this to represent a freshwater marsh deposit that formed following the sudden uplift of what had previously been intertidal mudflat and then subsequently down-dropped during another earthquake into the lower intertidal zone and overlain by stream deposited gravelly sand (their Alluvium 2 unit). The radiocarbon date of AD 1260 is based on a piece of wood from the upper part of the peaty mud.

Close interval pollen analysis of this section of the core indicates a different sequence of events (see Figure 27). The pollen diagram shows very high Amaranthaceae percentages (*Salicornia* and *Atriplex*) from 295 cm to 286 cm in the lower part of the peaty section, and an increase in freshwater taxa such as *Typha/Sparganium* and *Myriophyllum* from 285 cm to the top of the peaty section at 265 cm. This sequence indicates a relatively gradual transition from mudflat to saltwater marsh, and from saltwater marsh to a freshwater marsh with local ponding. In other words, the change from mudflat to freshwater marsh was gradual and most likely due to the progressive buildup of sediment rather than uplift. On the other hand, the abrupt change from peaty clay silt to sand at 265 cm may have been due to an earthquake-induced downdrop as Knudsen et al. suggested. The radiocarbon date from near the top of the peaty unit suggests the earthquake occurred shortly after AD 1260.

L1 core stratigraphy also points to a major earthquake at about this time. The sharp increase in silt+clay percentages at the 420 cm depth dates to ca. AD 1220.

The sand unit above the peaty clay silt in L2 is about 35 cm thick (265 cm to ca. 220 cm) and appears to be stratigraphically equivalent to the 1.1 m thick sand unit in L1 (300 cm to 190 cm). This sand unit is present throughout the north basin and was encountered at all the short core sites. The presence of so much sand in the north basin is puzzling in that the present tidal regime is only capable of moving sand to the southern edge of the north basin (Don Danmeier, PWA, personal communication).

One possible explanation is that during the Little Ice Age (ca. AD 1400 – AD 1800) winter storms were more frequent along the California Coast and the strength of the tidal circulation thereby increased. When mid-latitude storm systems cross the California coast with their low pressure centers to the north of Bolinas strong southerly winds significantly increase the amount of water entering the lagoon. Another even more dramatic possibility is that the sand unit was deposited by the tsunami of January 26, 1700. Satake et al. (1996) reported that at 9 pm on this date a magnitude 9 earthquake along the Cascadia subduction zone produced tidal waves that were still over 2-3 m high when they reached Japan 9 hours later. Bernard et al. (1994) modeled the effects of this tsunami at Eureka and Crescent City with the assumption that the waves were 10 m high. We are unaware of any estimate of the size of the waves that reached Bolinas after this earthquake but it seems more than likely they were large enough to transport sand into the northern part of the lagoon. A difficulty with the tsunami hypothesis is that Knudsen et al.'s wood sample from just below the sand unit produced a date of AD 1260. If the date is reliable it indicates that there is an erosional hiatus at that site. More radiocarbon dates are needed to resolve the issue.

Comparison of the Bolinas Earthquake Record with other Paleoseismic Records

One if the important aspects of the Bolinas Long Core earthquake record is that it matches very closely another paleoseismic record from Northern California: the Noyo Canyon turbidite record (Goldfinger et al., 2003). Noyo Canyon is a submarine canyon located just to the west of Punta Arena where the San Andreas fault crosses the coastline and extends out to the edge of the continental shelf. There are 31 turbidites in the Holocene section of Noyo Canyon core 49PC and 6 or 7 of them date to the last 1600 years. The estimated dates of these turbidites correspond remarkably well with the estimated basal dates of the Bolinas silt-clay units (Figure 28). The close correspondence is strong evidence that both paleoseismic records are reliable.

The Amount of Earthquake-Induced Subsidence at Bolinas Lagoon

At H4 it is difficult to estimate the actual amount of earthquake-induced subsidence because the elevation of the sediment surface in AD 400 is not known with certainty. If the core site was several meters below MLLW in AD 400, i.e., the lagoon was much deeper then than it is now, the amount of subsidence needed to accommodate the 7.25 m of sediment that has accumulated since that date is not that great. On the other hand, if the sediment surface in AD 400 was in the lower intertidal zone, say at MLLW (– 0.65 m below MSL), and that relative subsidence due to compaction and sea level rise between then and now was 1.25 m and 2.4 m respectively, the net amount of subsidence would have been 2.7 m. In view of the evidence discussed above for 5 major earthquakes during the last 1600 years, this estimate is not unreasonable.

In the L2 core the base of the freshwater peat unit at the 2.87 m core depth or 2.37 m below MSL can be safely assumed to have been above or close to 1.0 above MSL when the freshwater marsh first developed (estimated date ca. AD 1150). If we assume relative subsidence due to compaction and sea level rise as 0.37 m and 1.28 m, the estimated tectonic subsidence during the period AD 1150 to the present is 1.70 m. This produces a slightly higher annual average than at the H4 site, 2.0 mm/year as compared with 1.7 mm/year, but the two estimates are reasonably close.

Long Core Summary and Conclusions

The results of the long core analyses provide a background against which the significance of recent human impacts can be better assessed. The more important findings can be summarized as follows:

1. At L1 the reconstructed sedimentation rate is 4 mm/year for the period AD 400 to AD 1850; 12 mm/year for the period 1850 to 1906; and, 9 mm/year for the period 1906 to 2005. At L2 the average rate is 2 mm/year for the period 1250 to 1850; 10 mm/year from 1850 to 1906; and 8 mm/year from 1906 to 2006. Sedimentation rates increased during the second half of the nineteenth century at both core sites because of logging and grazing in the watershed. We should note, however, that both L1 and L2 were intentionally taken in areas of unusually high 1850 to 1906 sediment accumulation. The post-1850 sedimentation rate increase in other areas of the north basin was undoubtedly less.

2. The L1 evidence of 5 major earthquakes during last 1600 years correlates well with paleoseismic records in cores from off the northern California coast. The important implication for the present study is that repeated tectonic subsidence is the fundamental reason for the lagoon's continued existence.

3. The sand unit at depths of 2 to 3 meters below the sediment surface throughout the north basin is important evidence of a higher energy environment in the lagoon at sometime during the period AD 1600 to AD 1800. It may have been deposited during a very short lived event, such as the January 26, 1700 tsunami, or it may be the result of more frequent winter storms during the Little Ice Age.

4. No evidence was encountered in the long core analyses that the lagoon closed at any time during the last 1600 years. The pollen of freshwater marsh plants, such as tules and cattails was found in a peaty clay unit in L2 that had been dated by Knudsen at al. (1999) to ca. AD 1260. However, the absence of any similar stratigraphy at equivalent time horizons in the L1 core indicates that the freshwater marsh was restricted to the northern end of the north basin.

Perhaps the most important conclusion to be drawn from this part of the study is that prior to the period of American settlement Bolinas Lagoon was not a deep water lagoon persisting in equilibrium with slowly rising sea level. On the contrary, natural disturbances in the form of earthquakes, and possibly even a major tsunami, have repeatedly disturbed what was a relatively shallow lagoon throughout the period of record. The earthquakes in particular were important in that they caused the tectonic subsidence responsible for the continued existence of the lagoon.

Overall Conclusions

Finally, having reviewed both the short core and long core evidence, it now seems appropriate to reconsider the question raised at beginning of the report, namely: Is Bolinas Lagoon "filling in" at a rate that will lead to its extinction and conversion to freshwater marsh or meadow within the next 50 years?

The answer, almost certainly, is no.

One important implication of the short core analyses is that the logging impact on the lagoon was largely restricted to the northern end of the north basin and the Pine Gulch Creek Delta where sedimentation rates increased to 3 to 5 times the average late Holocene rates. For the rest of the north basin it seems likely that post-1850 rate increases relative to the late Holocene were relatively modest, i.e., 3 times or less. This in turn would explain why in spite of all the disturbance in the watershed during the second half of the nineteenth century the north basin did not fill to the point of becoming a salt or freshwater marsh.

Another important implication of the short core data is that sedimentation rates during the twentieth century were strongly impacted by the 1906 earthquake. The downdrop, which averaged 45 cm in the deeper part of the basin, significantly increased the tidal prism and effectively counterbalanced the increased deposition of the second half of the nineteenth century. The earthquake also opened up the tidal channel on the west side of the lagoon that allowed for an increase in the transport of silt+clay from the Bolinas Bluffs into the north basin. In other words, natural processes of sediment erosion, transport, and deposition were much more important during the last century than was formerly thought to be the case.

The long core evidence also supports the idea that natural processes have controlled the development of the lagoon. If the L1 earthquake record is reliable we can conclude that five major earthquakes have affected the lagoon during the last 1600 years. The indicated mean recurrence interval is ca. 300 years, although the time between the second and third earthquakes was only 130 years!

Finally, we should point out that if we extrapolate the average twentieth century north basin sedimentation rate of 7 mm/year to 2050, an additional 32 cm of sediment will accumulate. However, if we subtract from this 12 cm for sea level rise[3] and 7 cm for autocompaction, the net increase in sediment surface elevation relative to tidal datums will be only 13 cm. This will not be enough to convert the north basin into a freshwater marsh.

---

[3] This estimate is derived from the IPCC predictions as shown in Figure 10 of Byrne (2002).

References

Atwater, B. F., Hedel, C. W., and Helley, E. J. (1977). Late Quaternary depositional history, Holocene sea-level changes, and vertical crustal movement, southern San Francisco Bay, California. U.S. Geological Survey Professional Paper 1014. Washington D.C.

Bergquist J. R. (1978). Depositional history and fault related studies, Bolinas Lagoon, California. U.S. Geological Survey Open-File Report 78-802, 164 pp.

Bernard, E.N., Mader, C., Curtis, G. and Satake, K. (1994). Tsunami Inundation Model Study of Eureka and Crescent City, California. NOAA Tech. Memo. ERL PMEL-103, 80 pp.

Bird, M.I., Fifield, L.K., Chua, S., and Goh, B. (2004). Calculating Sediment Compaction for Radiocarbon Dating of Intertidal Sediments. *Radiocarbon*, **46**, 421-435.

Byrne, A.R. (2002). Comments on the Bolinas Restoration Project. Draft Environmental Impact Statement (DEIS), Environmental Impact Report (EIR), Draft Feasibility Report (DFR) and Their Technical Appendices. 27pp.

Goldfinger C., Hans Nelson, C., and Johnson, J.E. (2003). Holocene Earthquake Records from the from the Cascadia subduction zone and northern San Andreas Fault based on precise dating of offshore turbidites. *Annual Review of Earth and Planetary Sciences* Vol. **31**: 555-577.

Ingram, B.L. and Southon, J. R. (1996). Reservoir ages in Eastern Pacific coastal and estuarine waters. *Radiocarbon* **38**, 573-582.

Knudsen, K. L., Witter R. C., Garrison-Laney, C. E., Baldwin, J. N., and Carver, G. A. (1999). Evidence for earthquake-induced, rapid subsidence in estuarine sediment along the northern San Andreas Fault. Final Technical Report submitted to the

U.S. Geological Survey National Earthquake Hazards Reduction Program in June 1999.

Lawson, A. C. (Chairman) (1908). The California earthquake of April 18, 1906. Report of the State Earthquake Investigation Commission, Volume 1. Carnegie Institute of Washington Publication.

Lyles, S. D., Hickman, L. E. and Debaugh, H. A. (1988). Sea level variations for the United States, 1855-1986. United States Department of Commerce NOAA Technical Report.

Niemi, T. M. (2002). Determination of a high resolution paleoearthquake chronology for the northern San Andreas Fault at the Vedanta Marsh Site, Marin County, CA. Progress report submitted to the U.S. Geological Survey National Earthquake Hazards Reduction Program.
http://erpweb. er.usgs.gov/reports/annsum/vol43/nc/01HQGR0194.htm

Ritter, J. R. (1969). Preliminary studies of sedimentation and hydrology in Bolinas Lagoon, Bolinas, California, May 1967-1968.

Ritter, J. R. (1969). Measurement of Water Flow and Suspended Sediment Load, Bolinas Lagoon, Bolinas, California. USGS Professional Paper 650-B: 189-193. Washington D.C.

Ritter, J.R. (1973). Bolinas Lagoon, Marin County, California, summary of sedimentation and hydrology, 1967-1969. US Geological Survey Water-Resources Investigations 19-73. Washington D.C.

Rowntree, R. A. (1973). Morphological change in a California estuary: sedimentation and marsh invasion at Bolinas Lagoon. Unpublished Phd thesis, Geography Department, University of California, Berkeley.

Satake, K., Shimazaki, K., Tsuji, Y, and Ueda, K., (1996). Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700: Nature, v. 379, p. 246-249.

Stuiver, M. & Reimer, P. J. (1993). Extended 14 C data base and revised CALIB 3.0 14 C age calibration program. *Radiocarbon* **35**, 215-230.

Tetra Tech (2002). Bolinas Lagoon Watershed Study Input Sediment Budget. In Volume II Technical Appendices. Bolinas Lagoon Ecosystem Restoration Project. USACE San Francisco District and Marin County Open Space District.

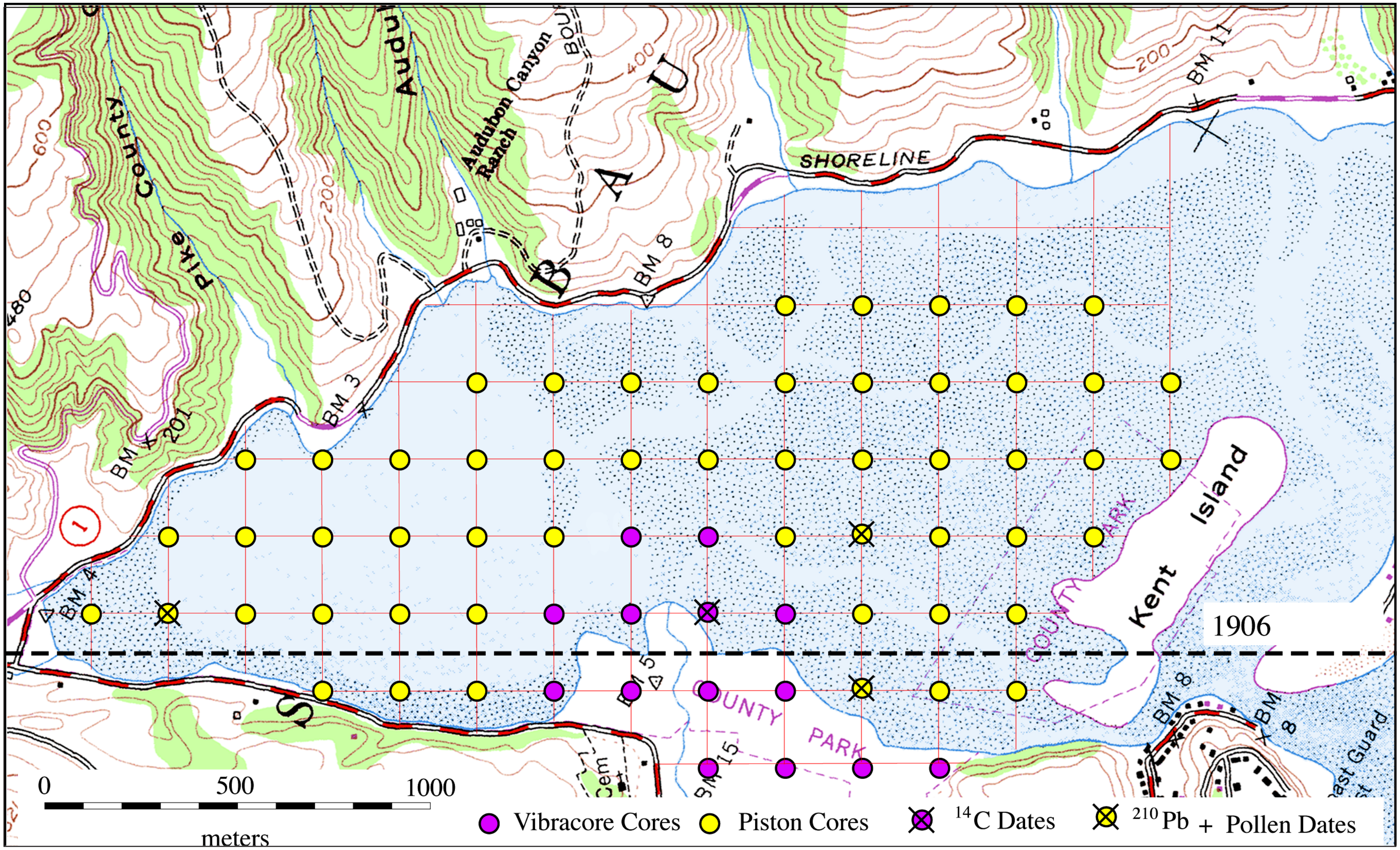

Figure 1. Proposed Coring Sites

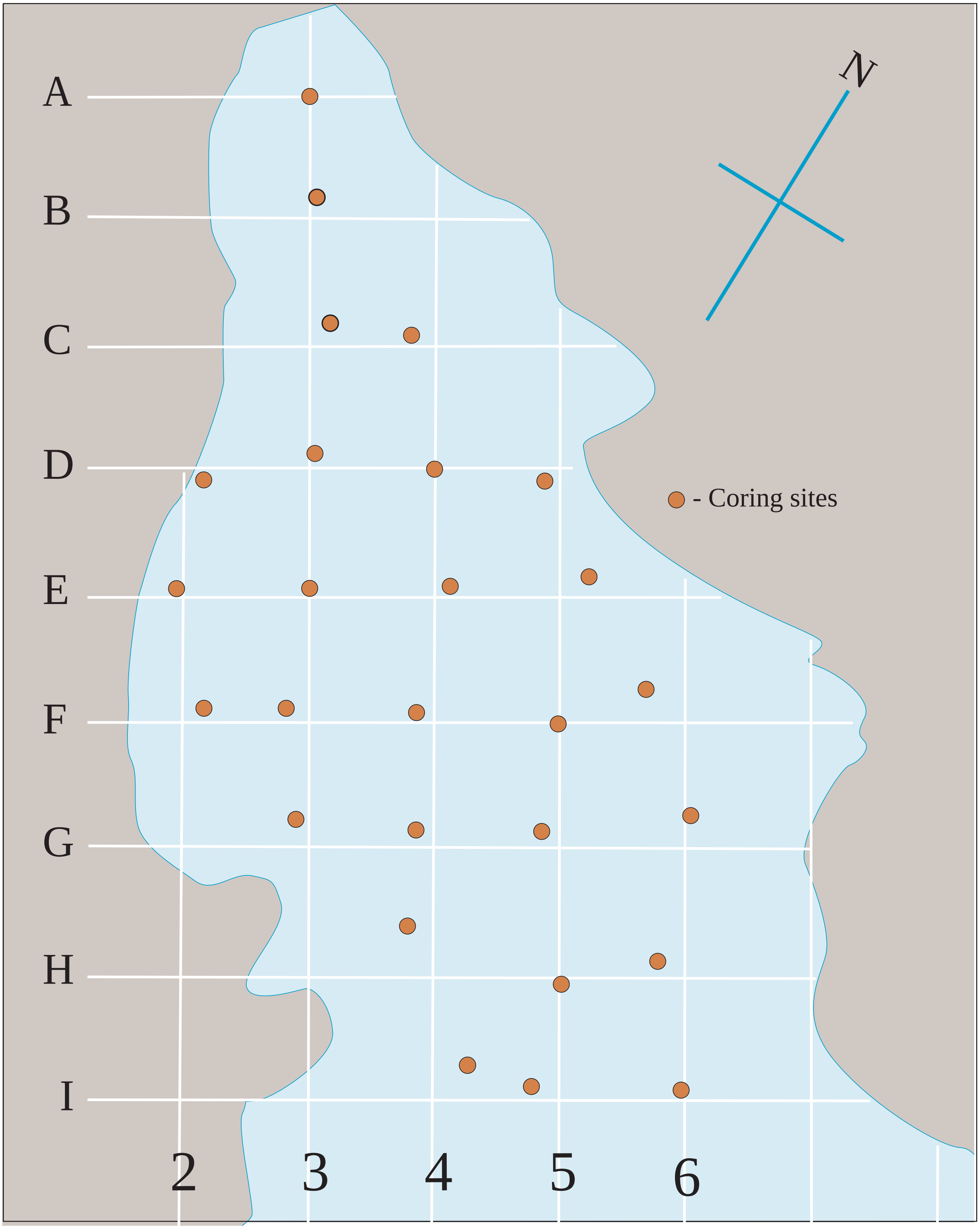

Figure 2. Actual Core Sites

Core A3, Bolinas Lagoon Marin County, California

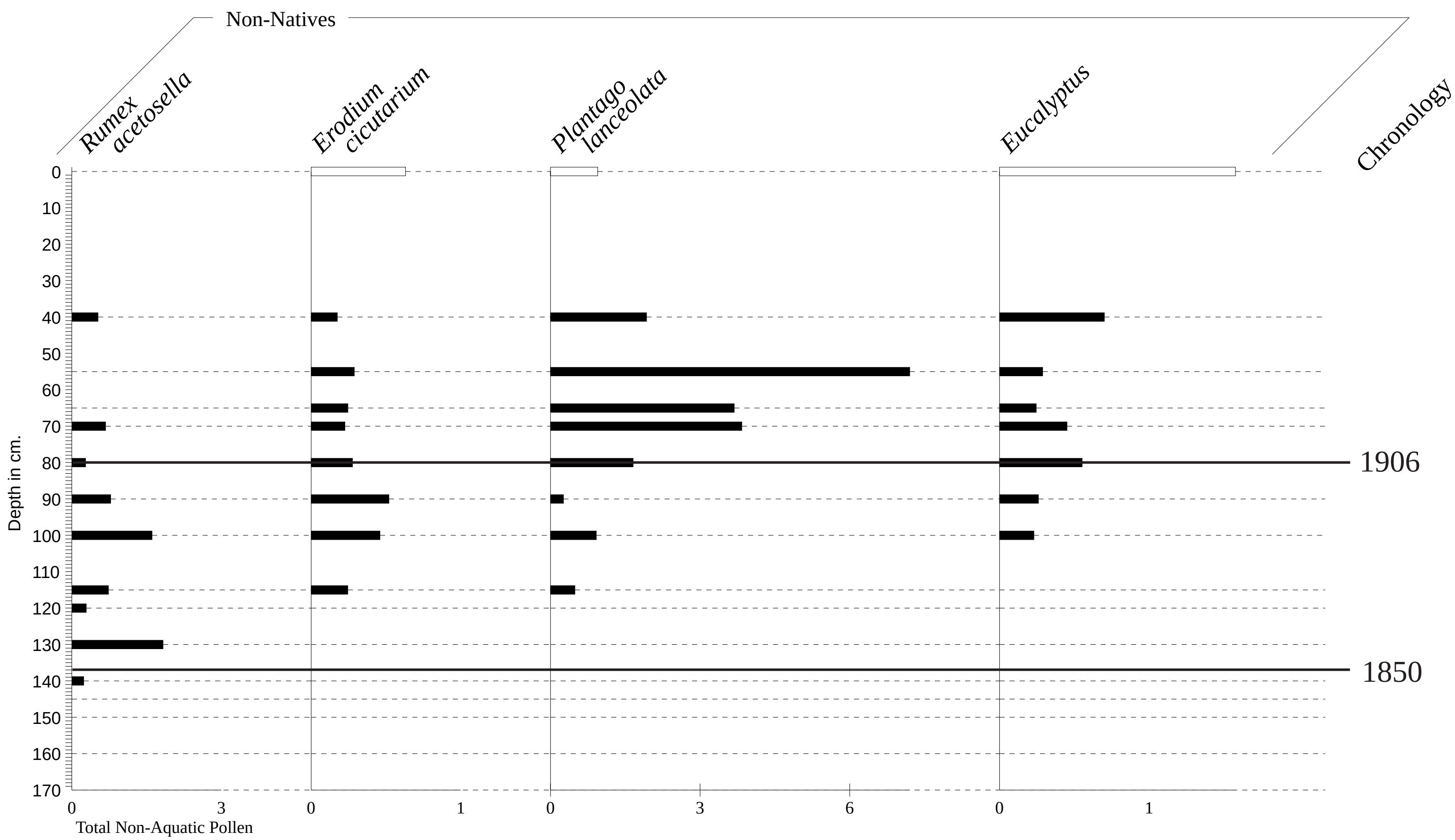

Figure 3a. First Appearance of non-native pollen types and approximate location of 1850 and 1906 horizons in A3.

Core C3, Bolinas Lagoon Marin County, California

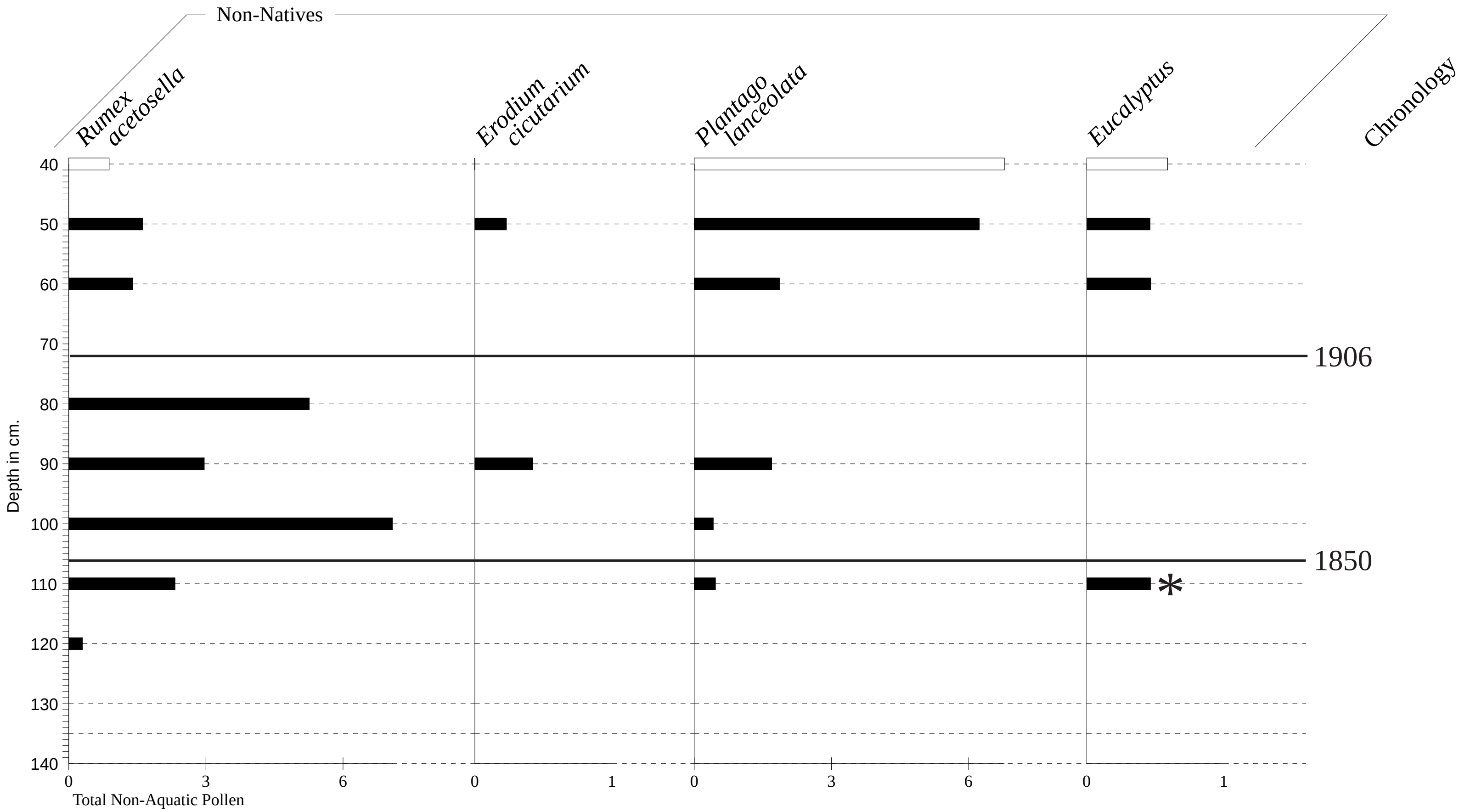

Figure 3b. First Appearance of non-native pollen types and approximate location of 1850 and 1906 horizons in C3.

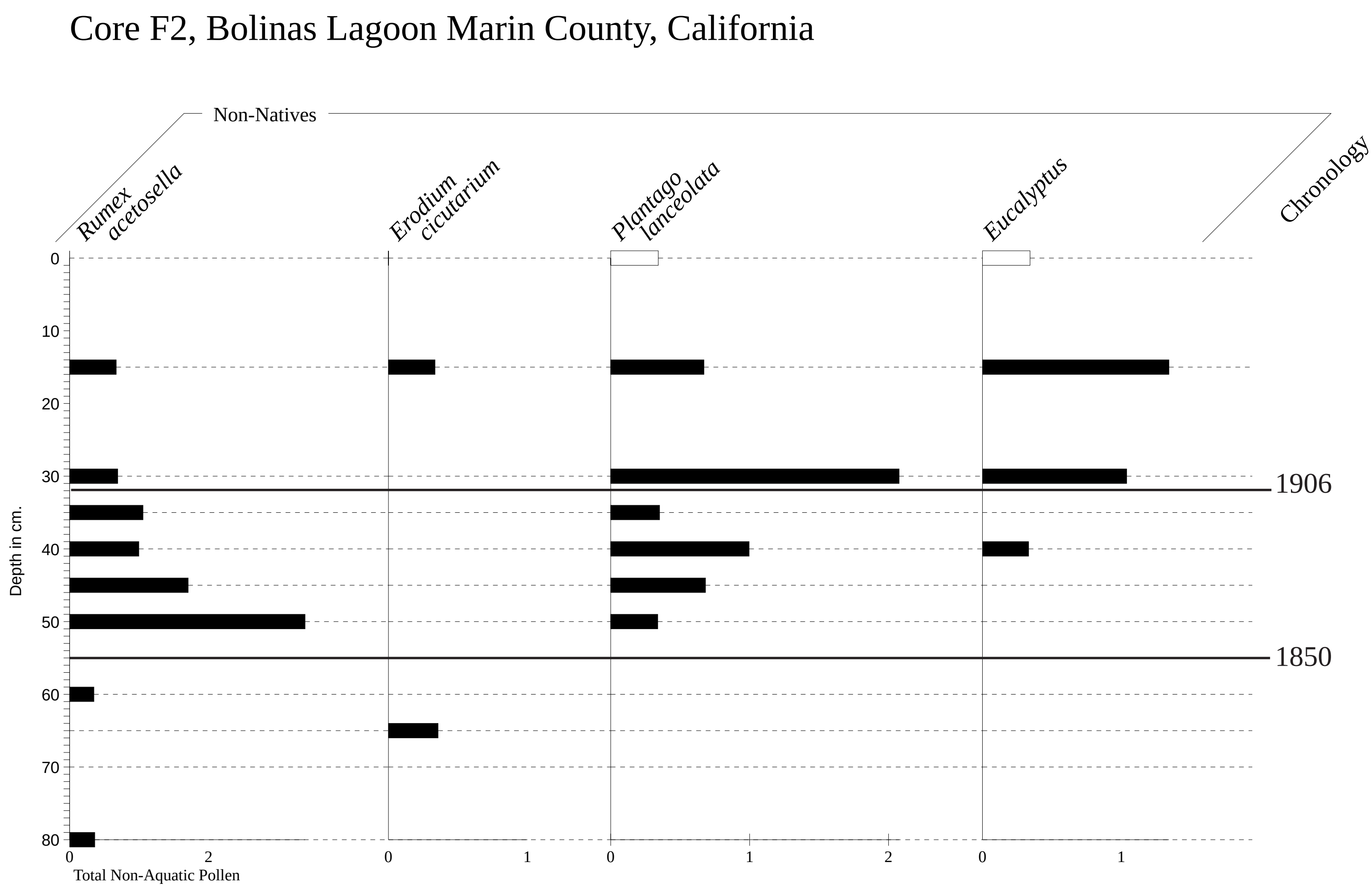

Figure 3c. First Appearance of non-native pollen types and approximate location of 1850 and 1906 horizons in F2.

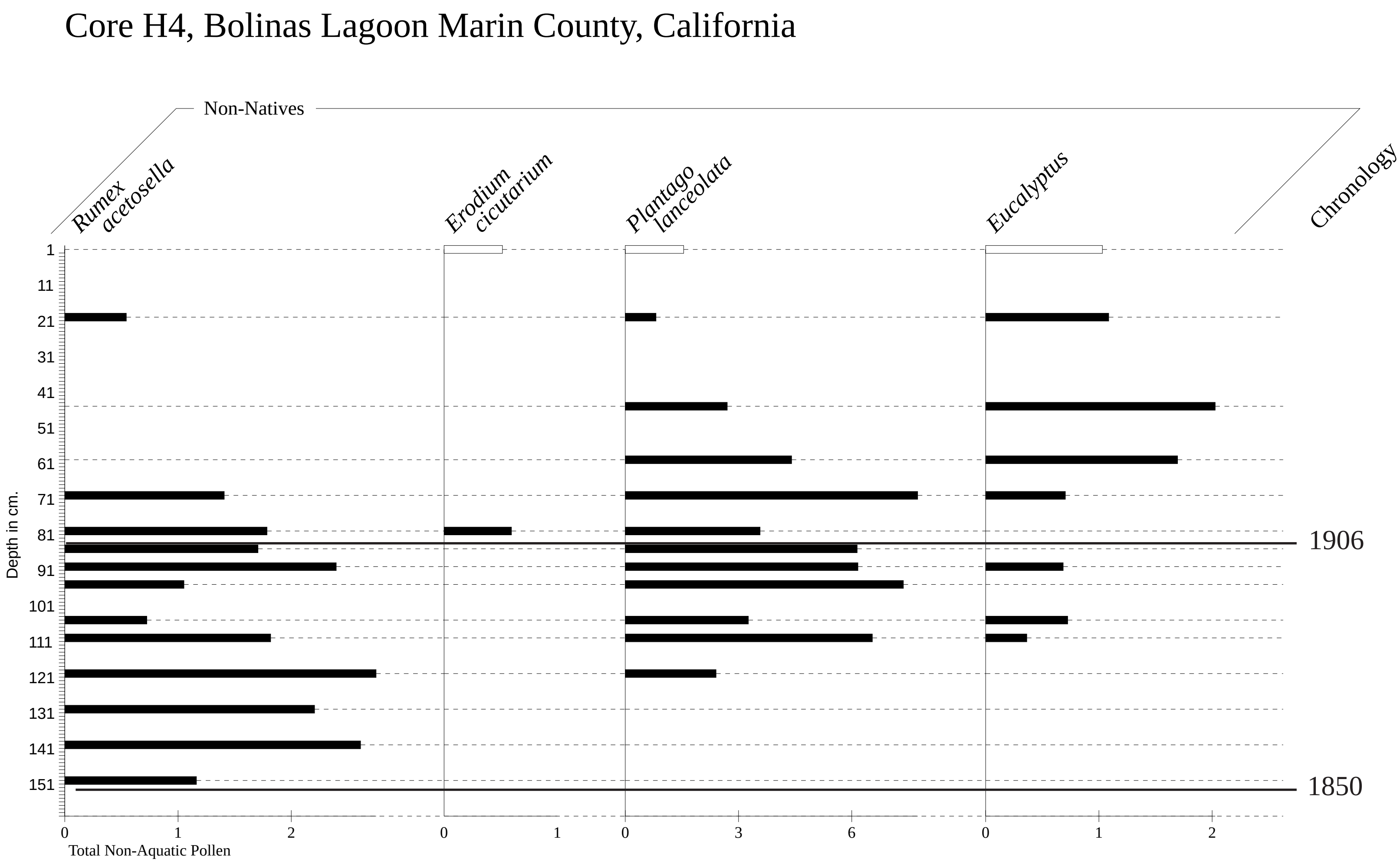

Figure 3d. First Appearance of non-native pollen types and approximate location of 1850 and 1906 horizons in H4.

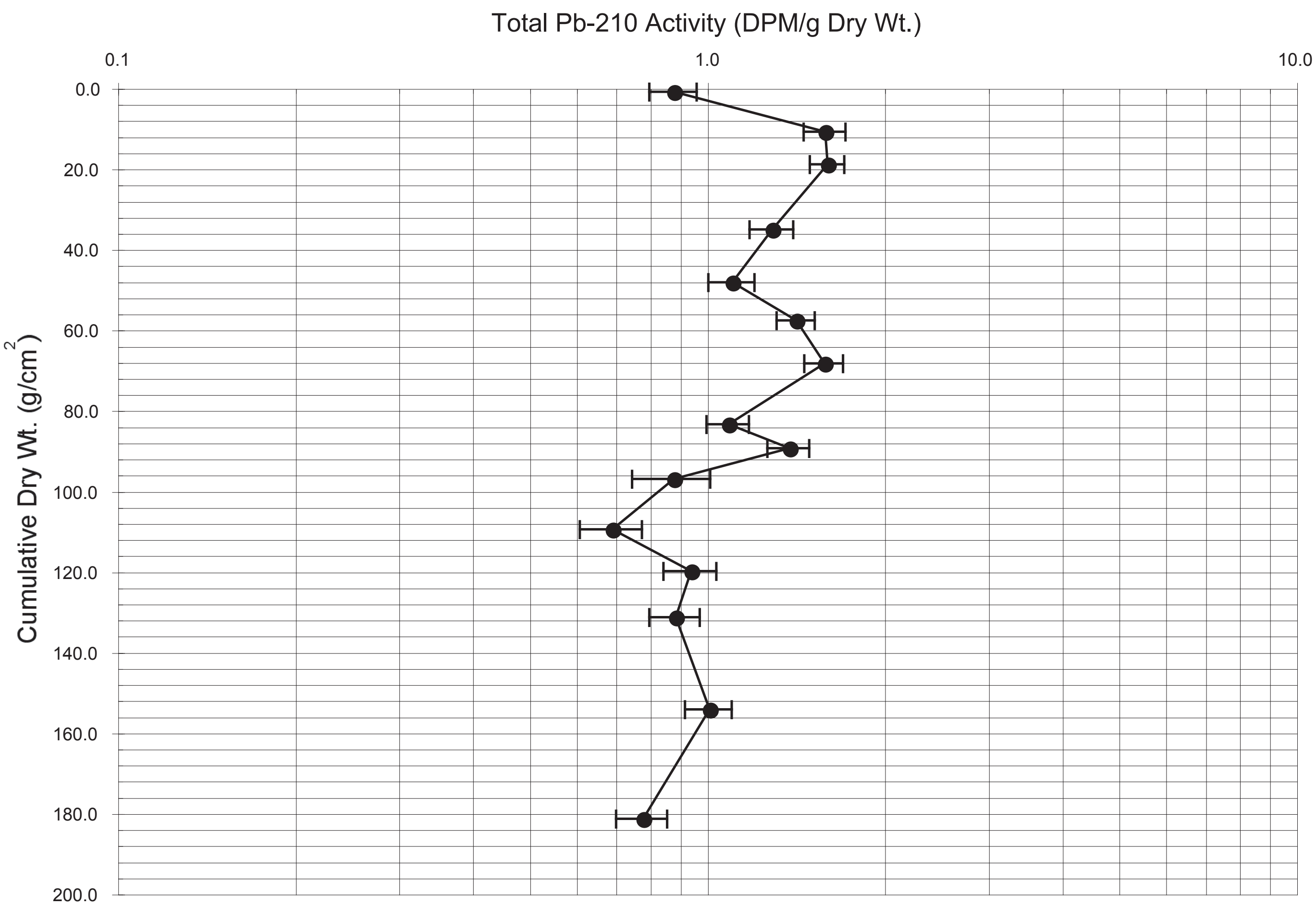

Figure 4a. Total Pb-210 Activity Core C3

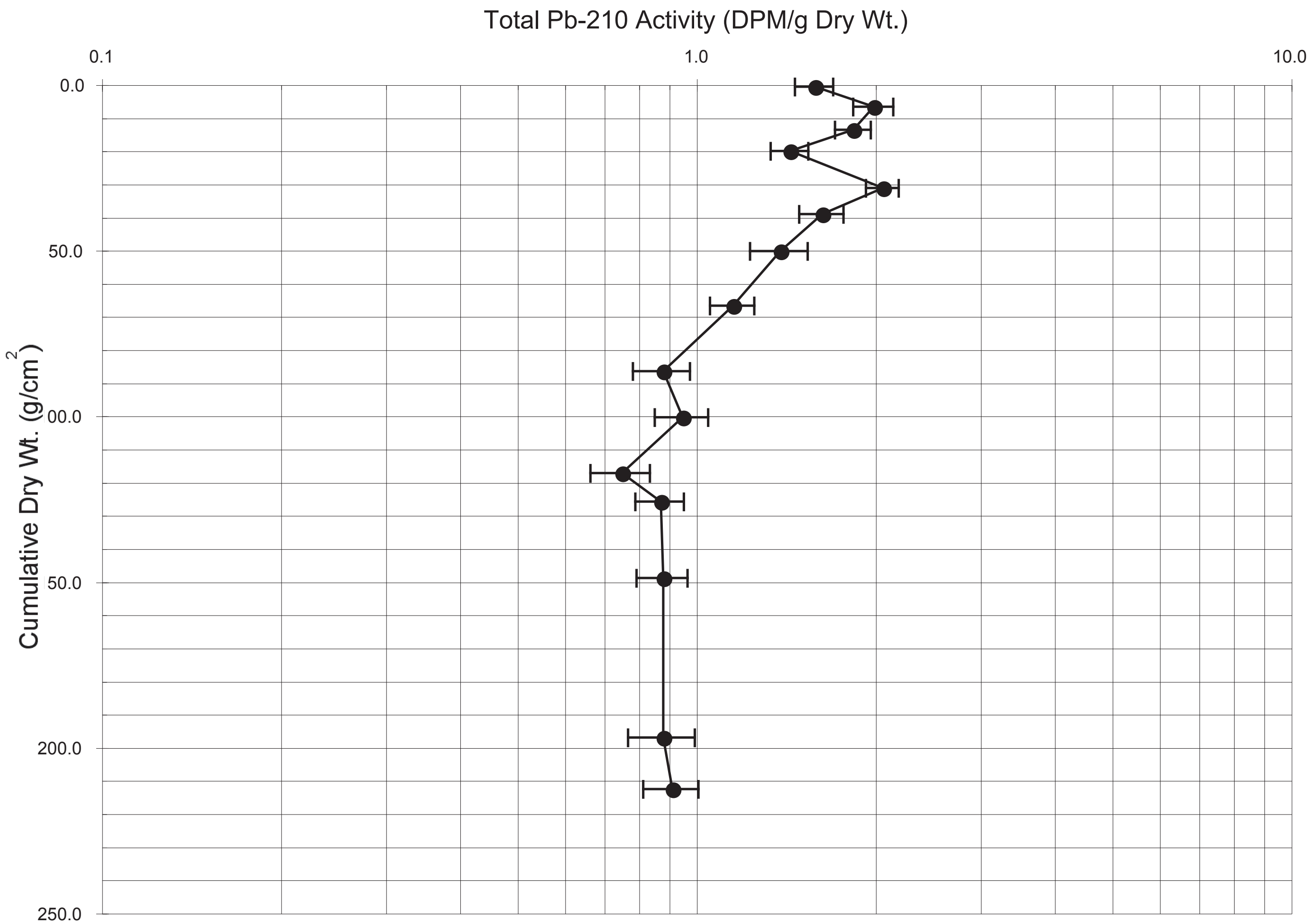

Figure 4b. Total Pb-210 Activity Core H4.

Bolinas Core A3 Age-Depth

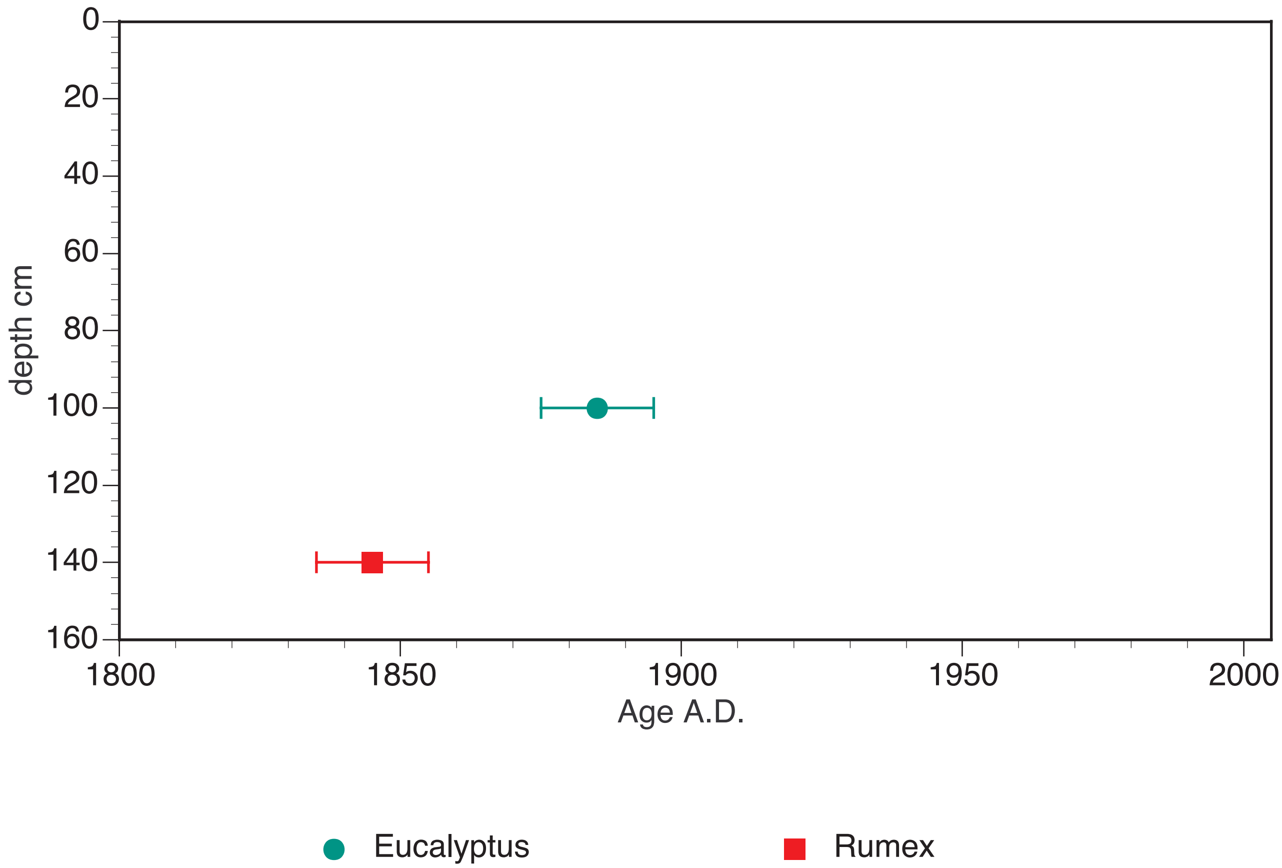

Figure 5a. Age-Depth Curve Core A3

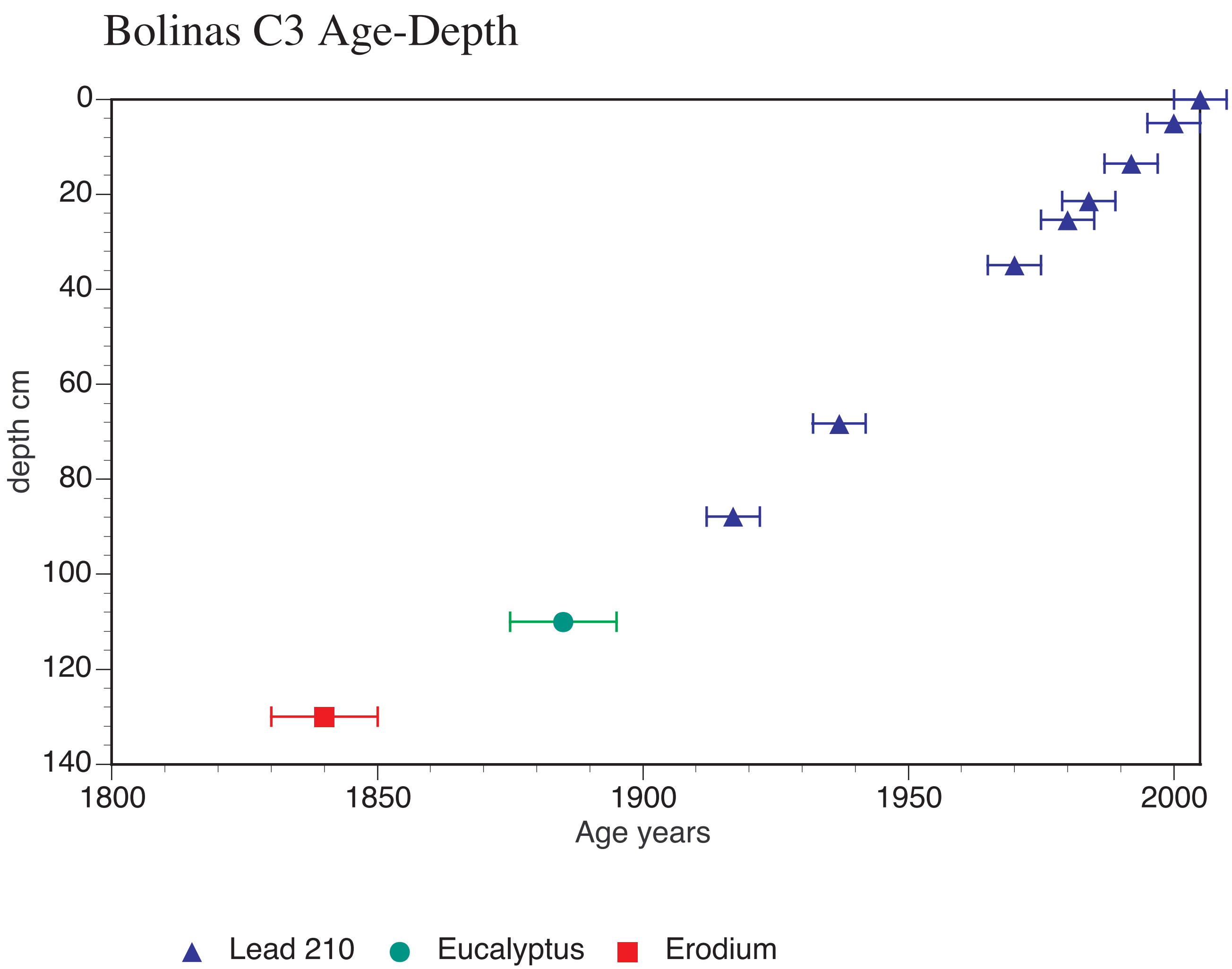

Figure 5b. Age-Depth Curve Core C3.

Bolinas Core F2 Age-Depth

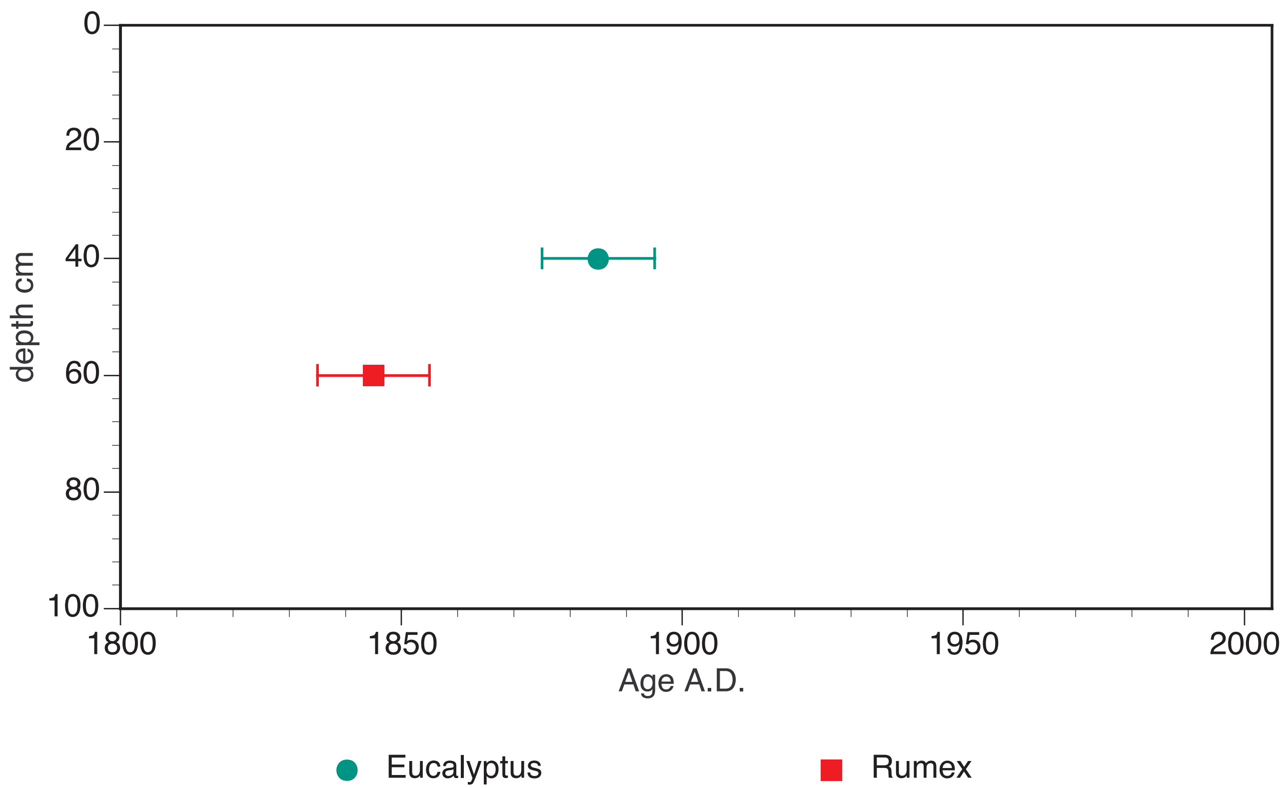

Figure 5c. Age-Depth Curve Core F2.

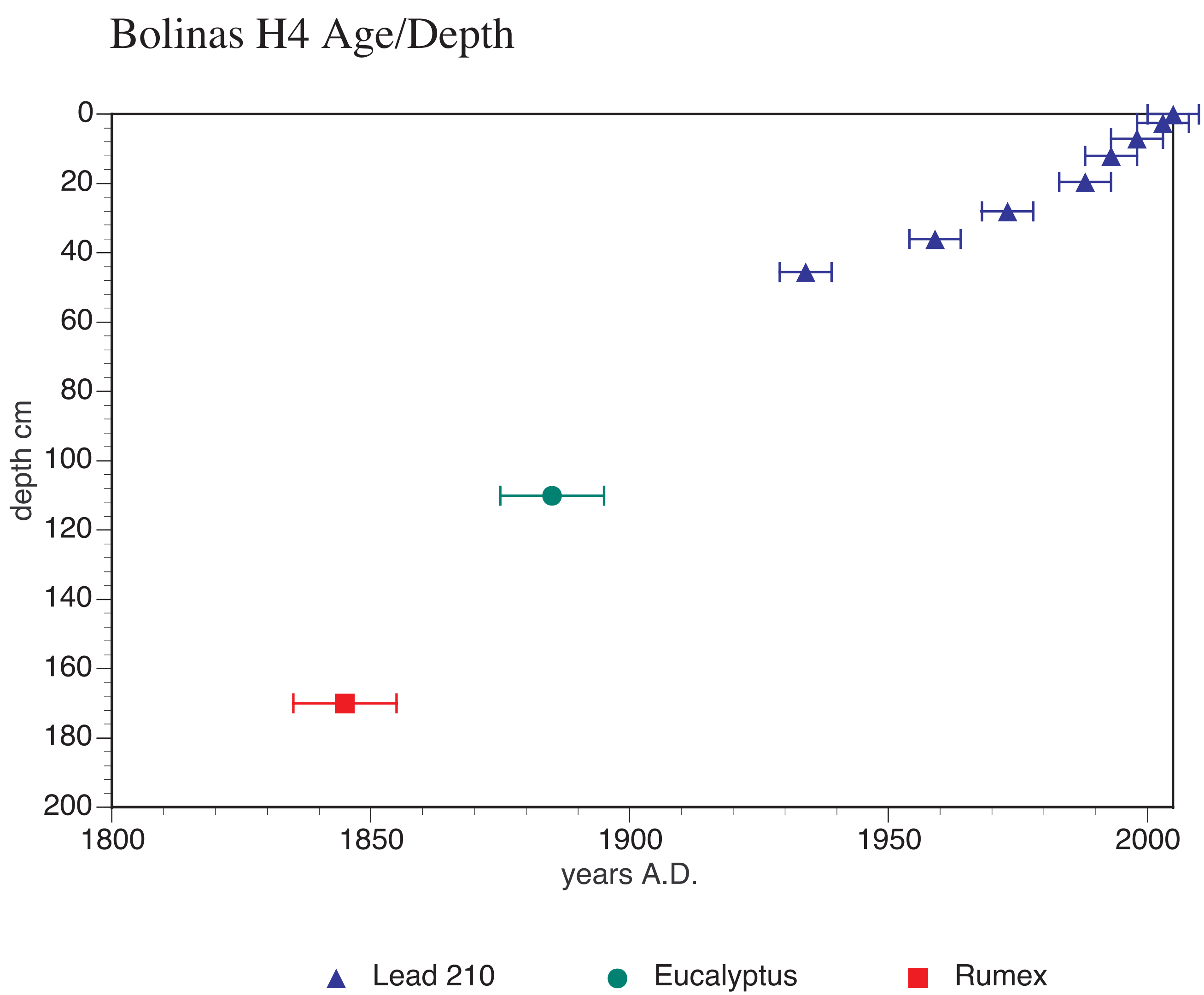

Figure 5d. Age-Depth Curve Core H4

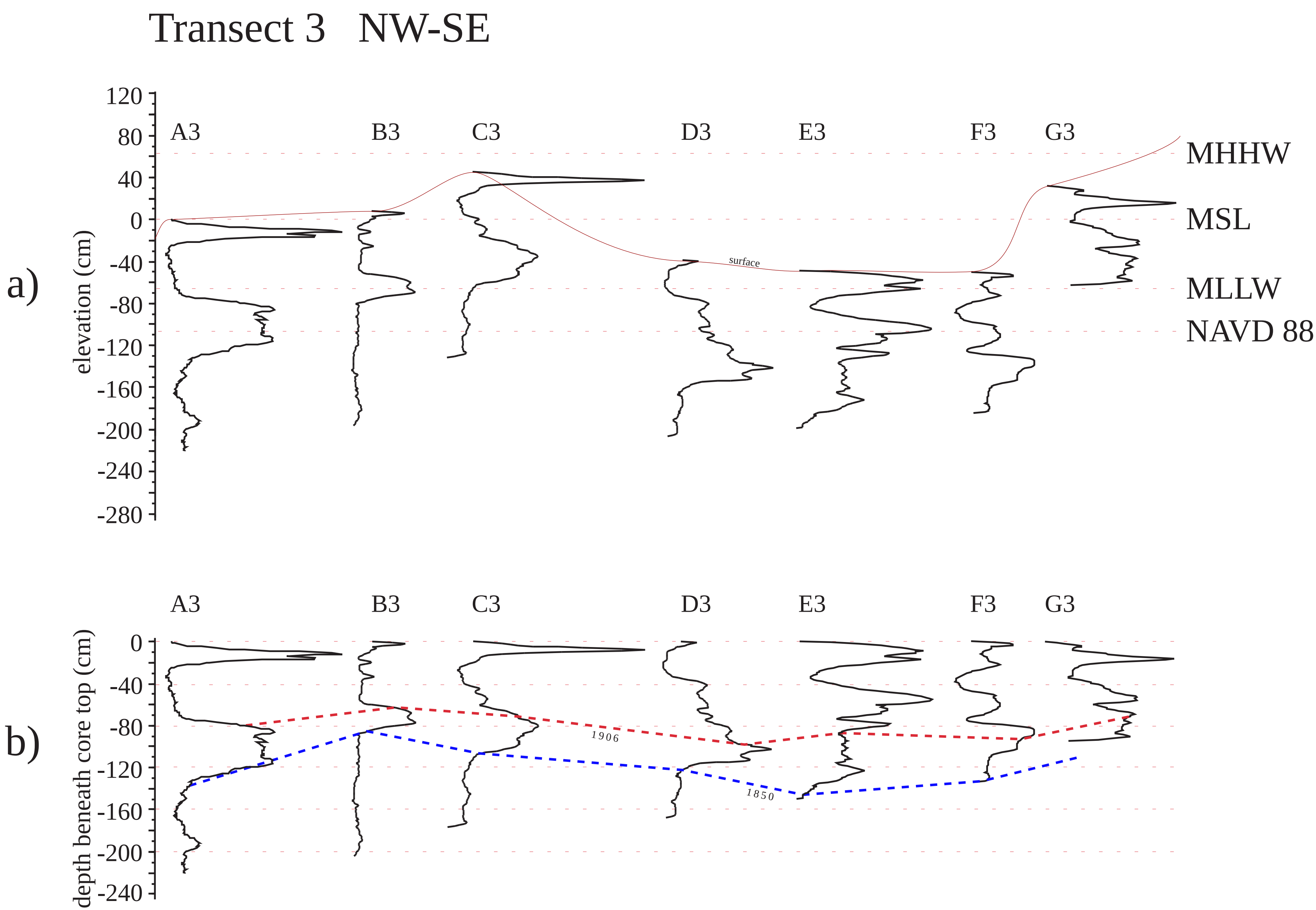

Figure 6a, 6b. Magnetic Susceptibility Profiles Transect 3.

Transect 4 NW-SE

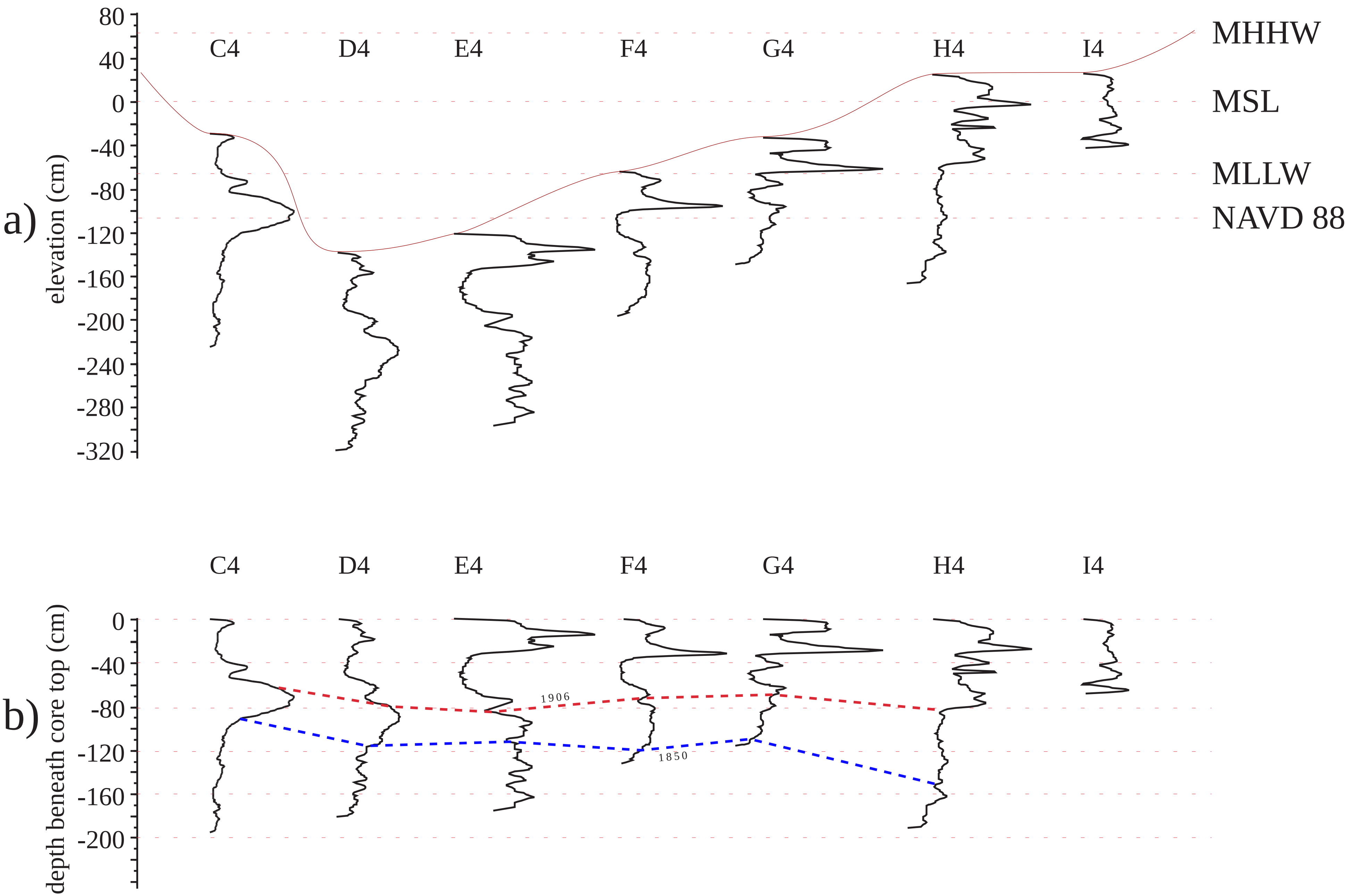

Figure 71, 7b. Magnetic Susceptibility Profiles Transect 4.

Transect C

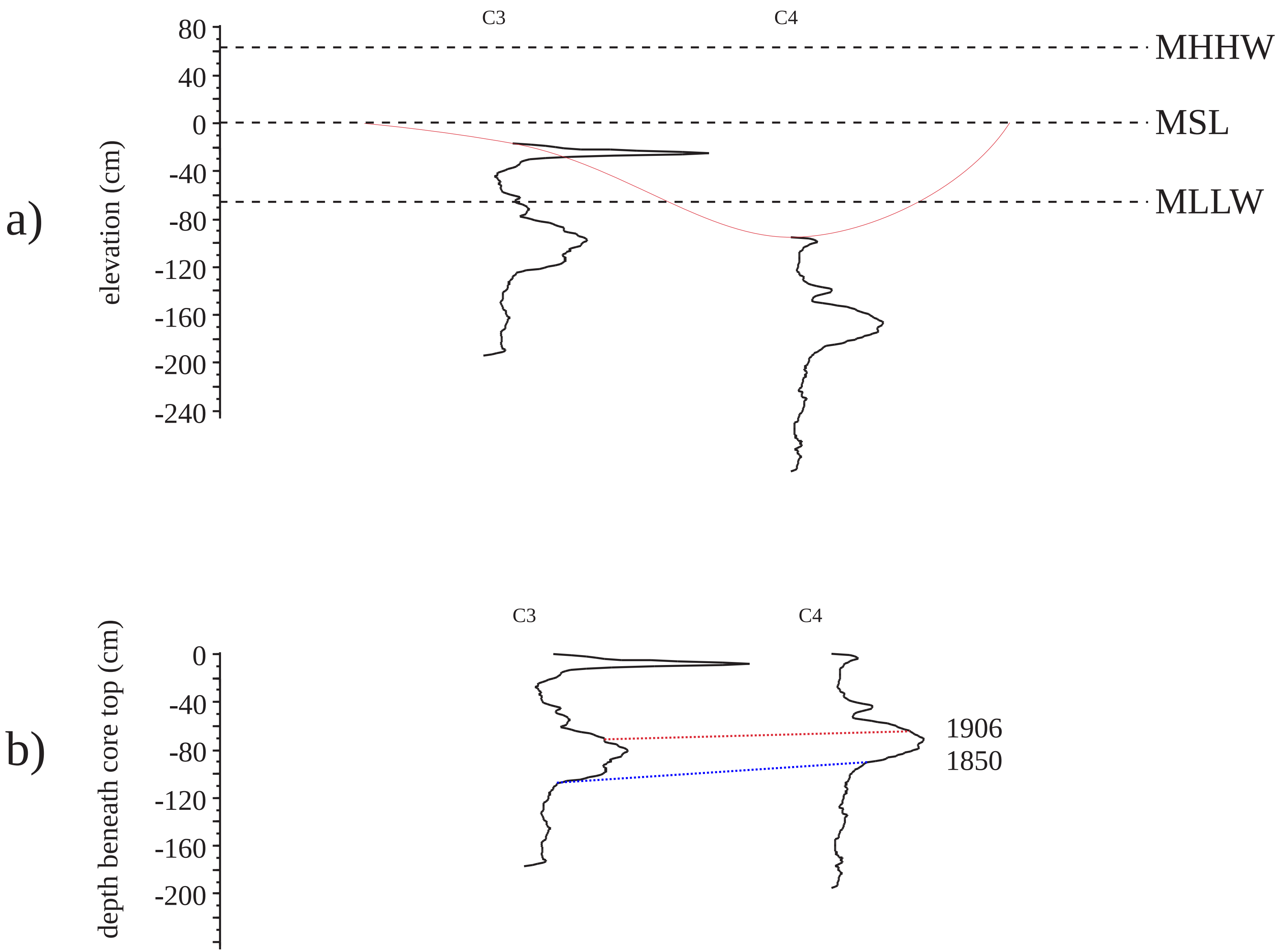

Figure 8a, 8b. Magnetic Susceptibility Profiles for Transect C.

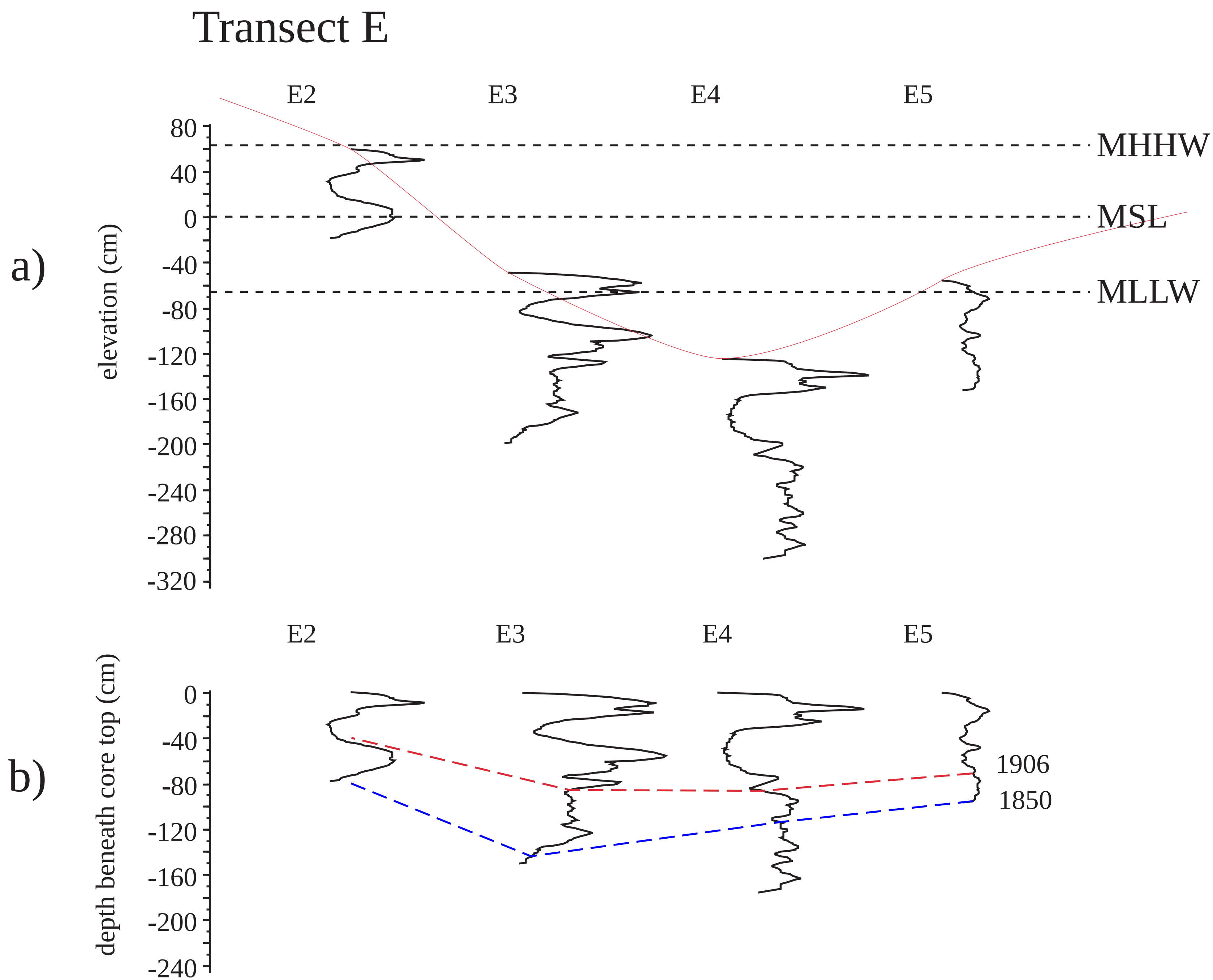

Figure 9a, 9b. Magnetic Susceptibility Profiles for Transect E.

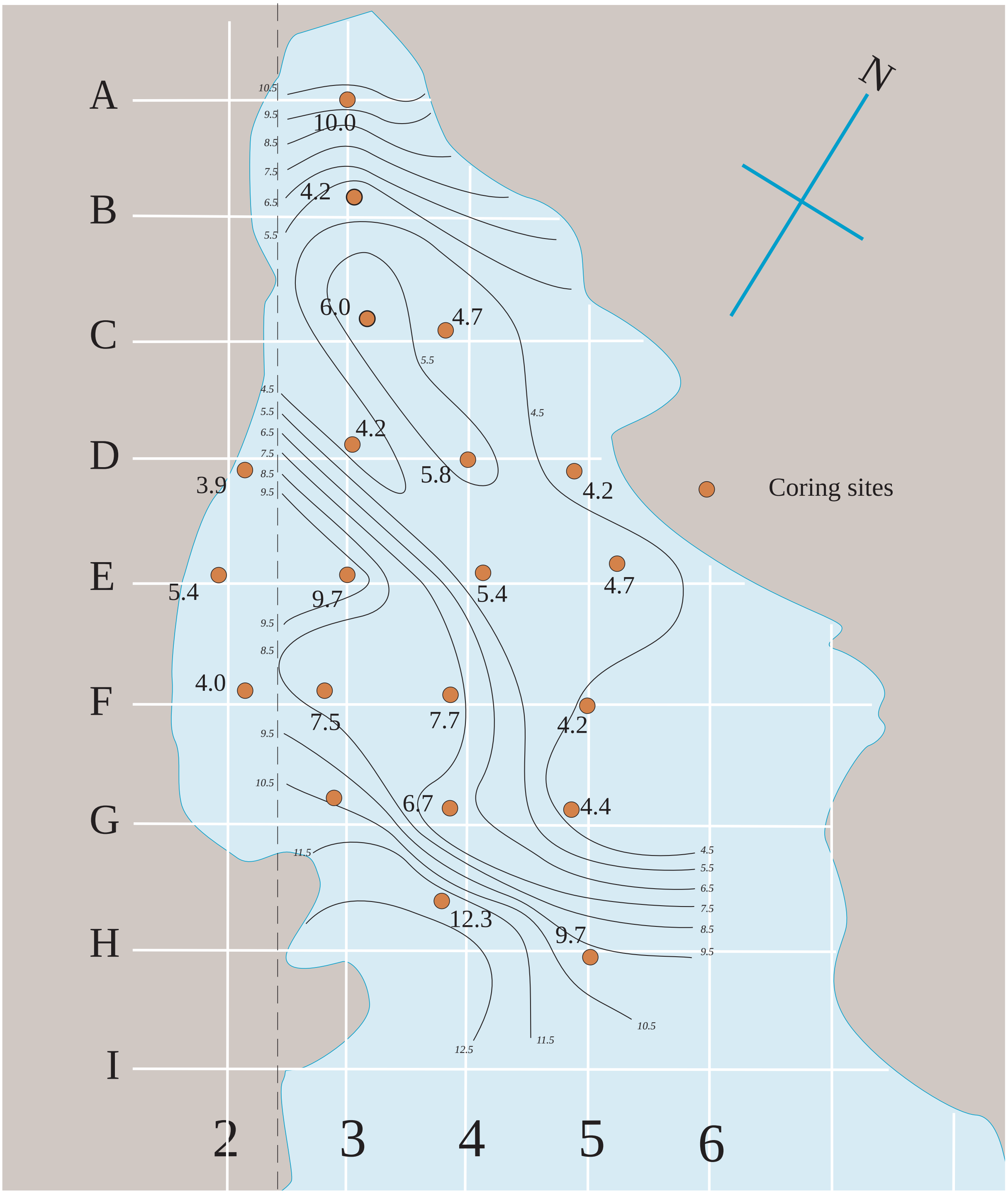

Figure 10. North Basin Sedimentation Rates (mm/year) 1850-1906.

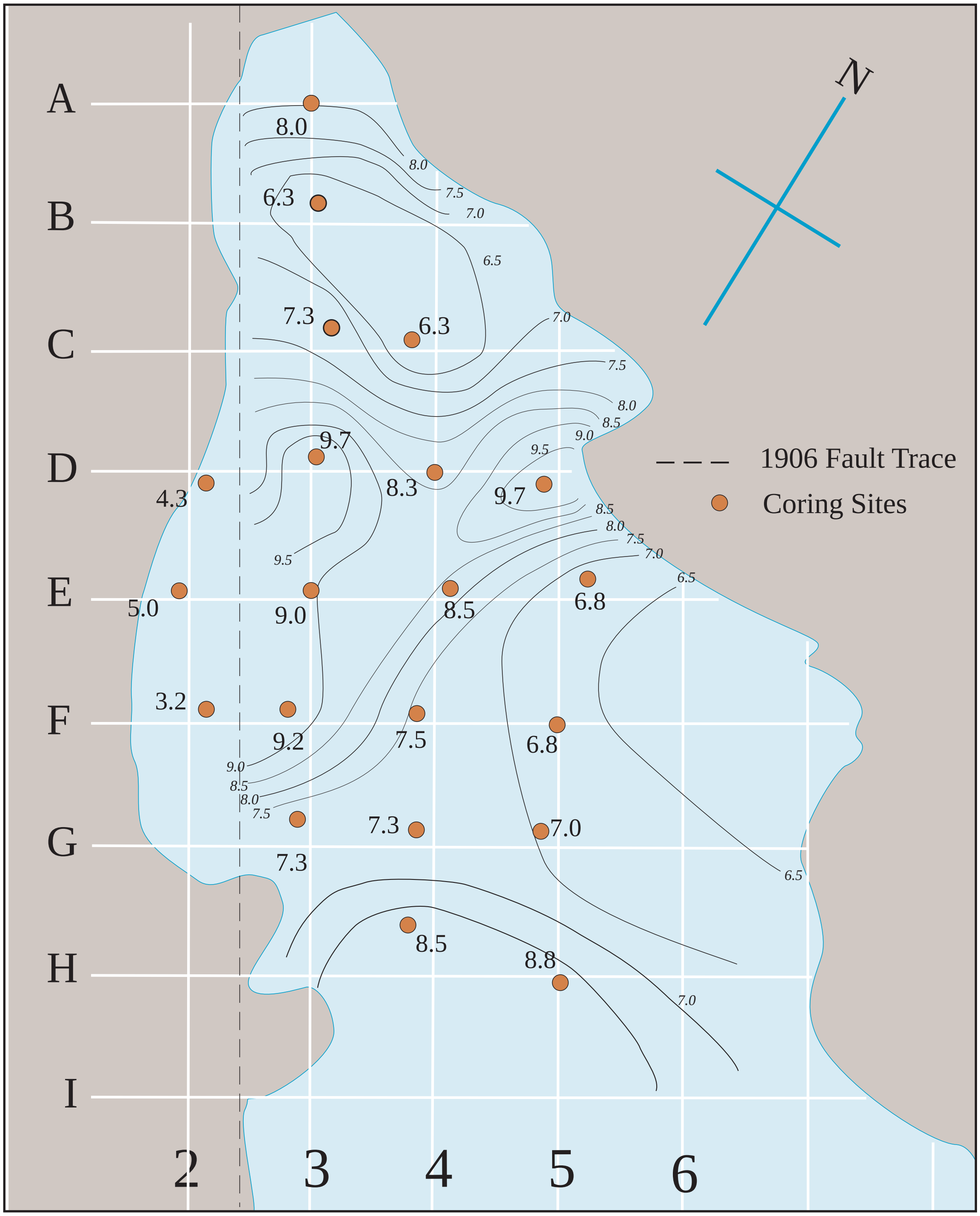

Figure 11. North Basin Sedimentation Rates (mm/year) 1906-2005.

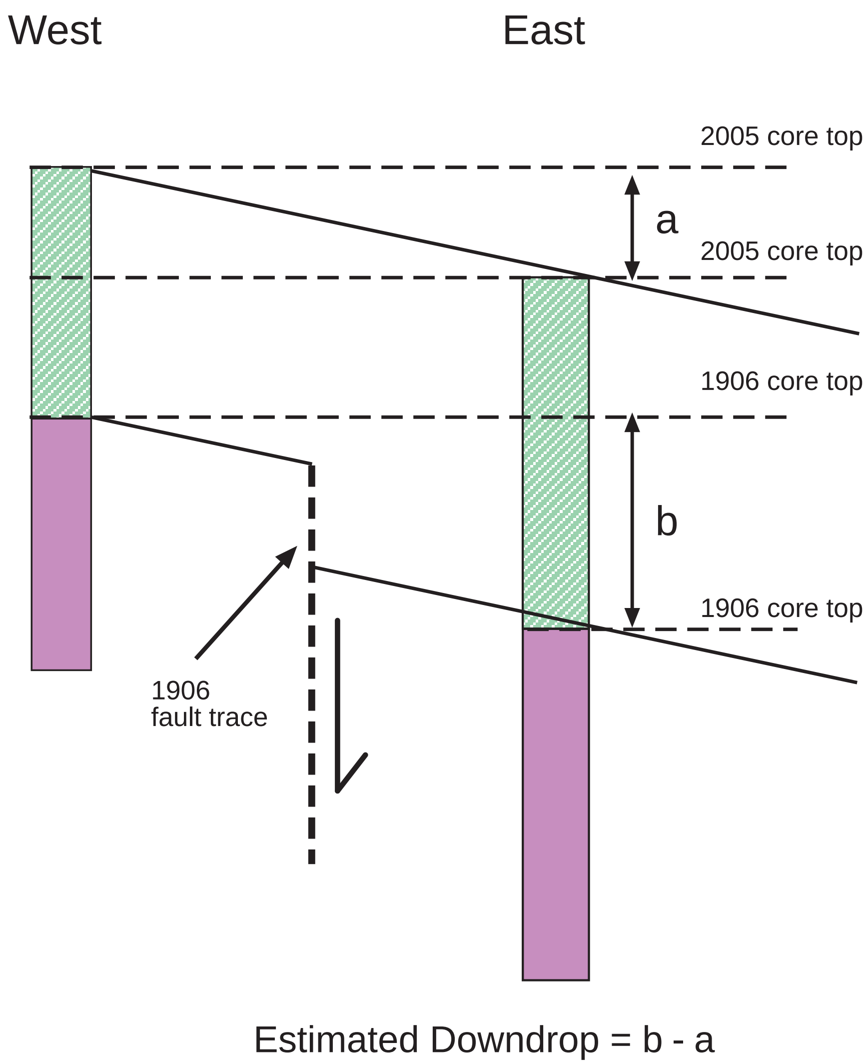

Figure 12. Method of Estimating 1906 Downdrop.

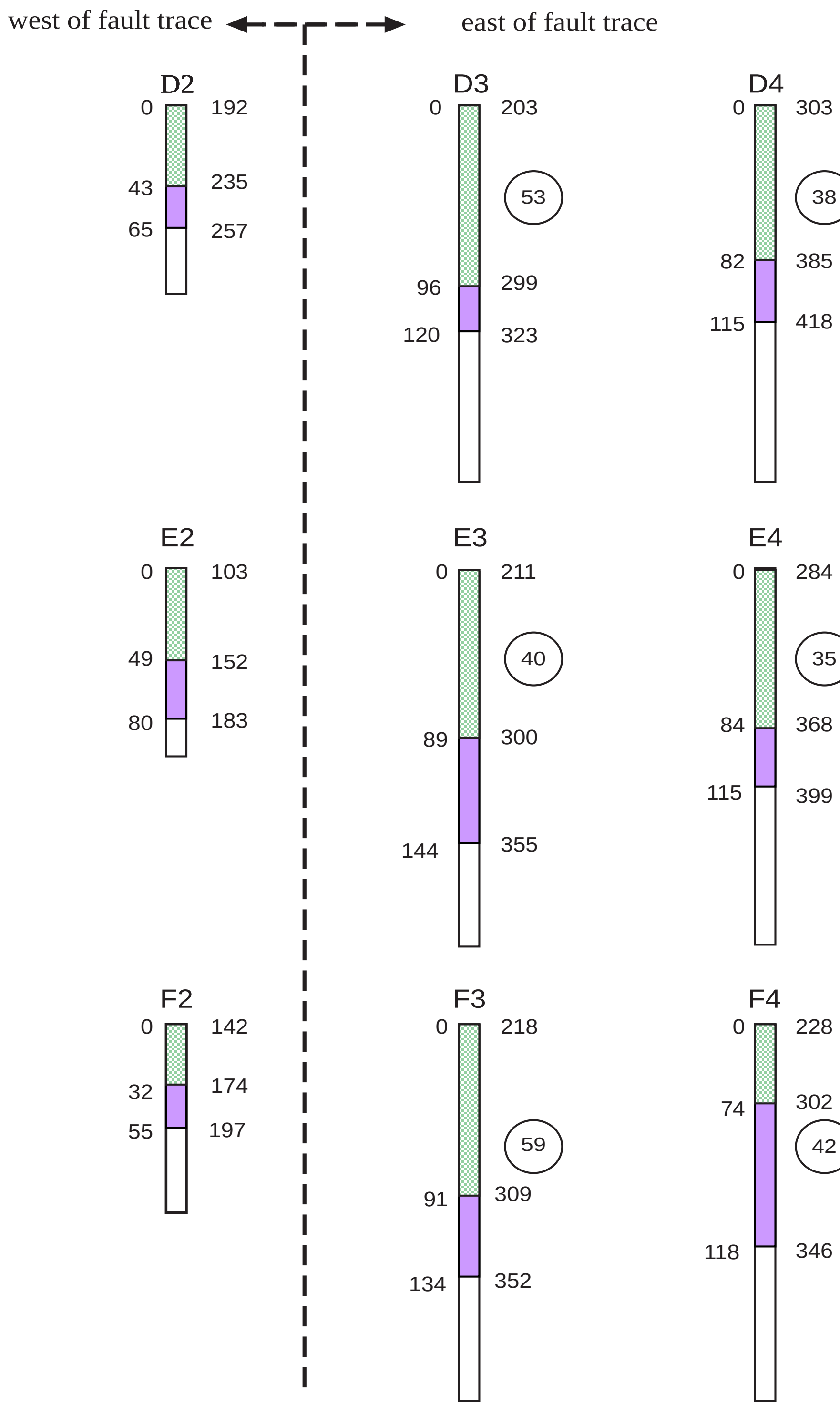

Figure 13. 1906 Downdrop Estimates

The numbers to the left of the cores represents depth below core top in cm and the numbers to the right the depth below the Pike County Gulch Creek benchmark. The green fill represents the thickness of sediment accumulated since 1906 and the purple the fill from 1850-1906. The number in the circle shows the estimated downdrop during the 1906 earthquake in cm.

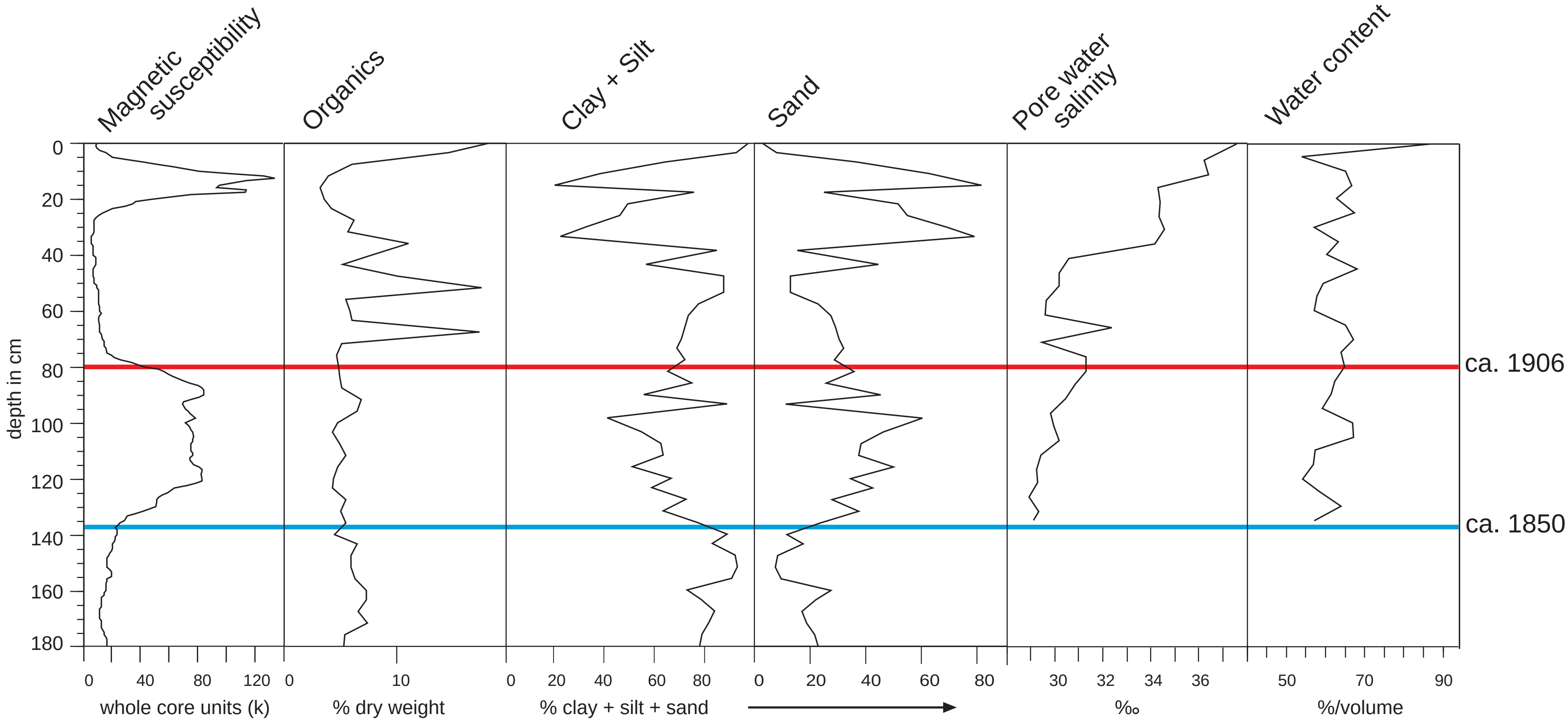

Figure 14a. Core A3 Stratigraphy.

Core C3 Stratigraphy

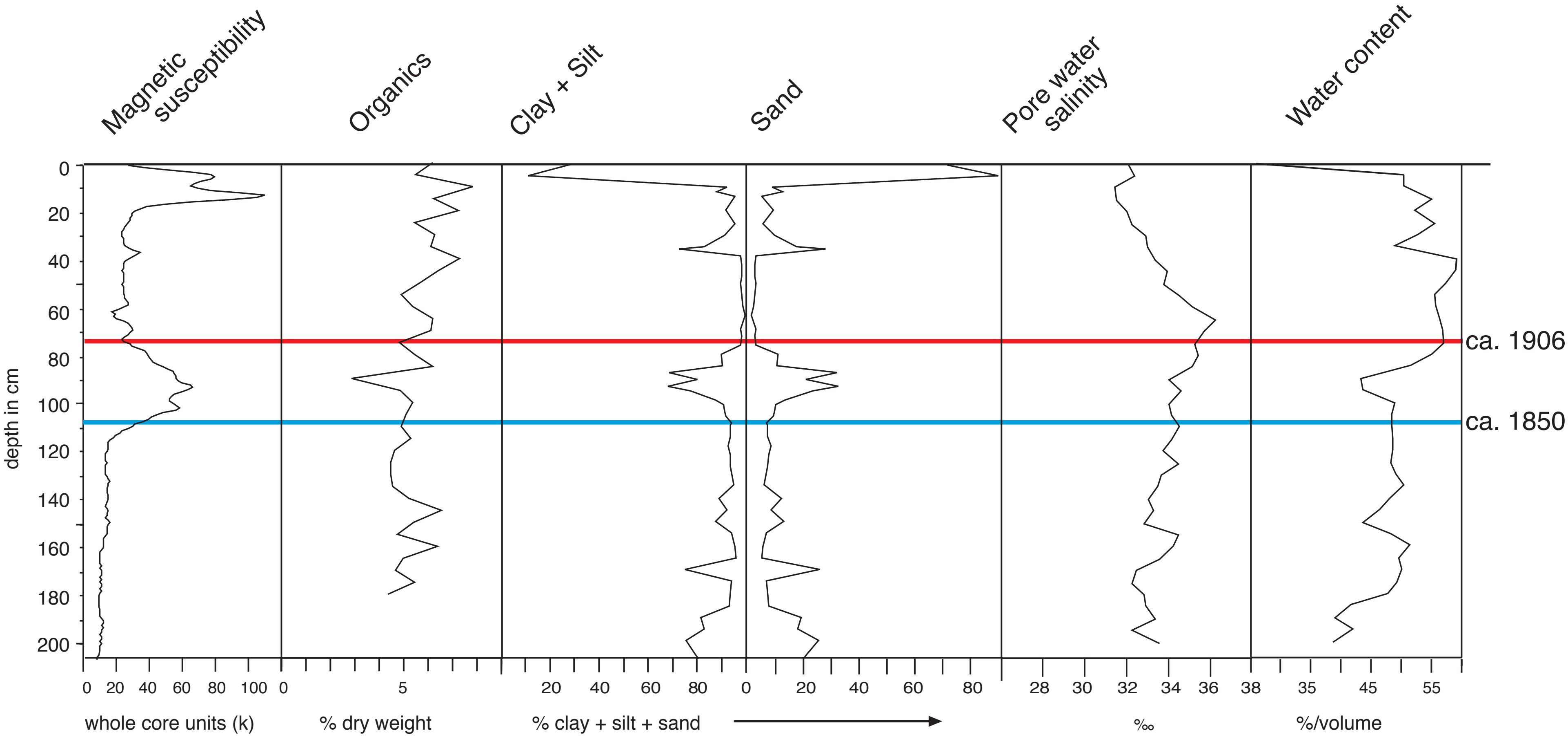

Figure 14b. Core C3 Stratigraphy

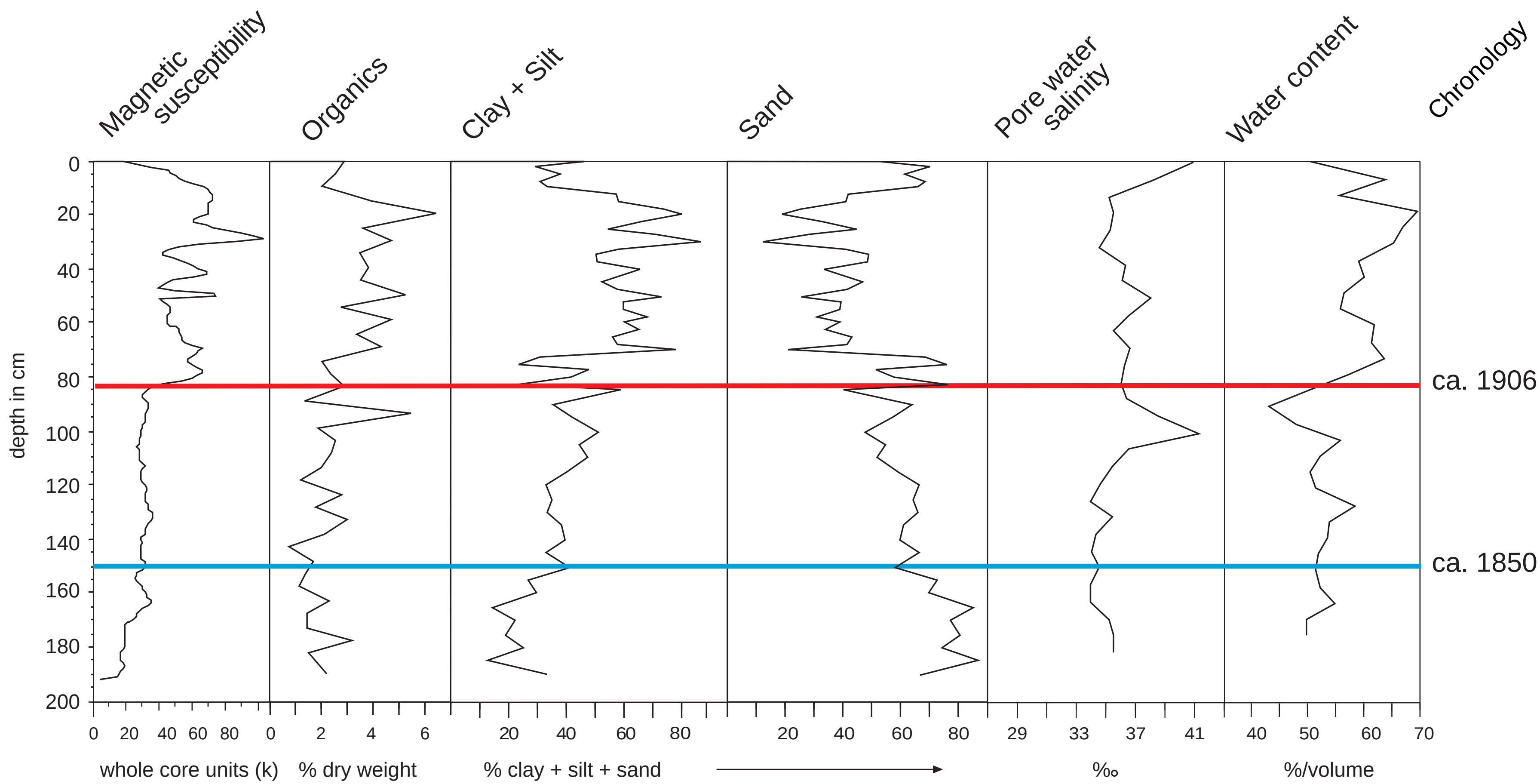

Figure 14c. Core H4 Stratigraphy.

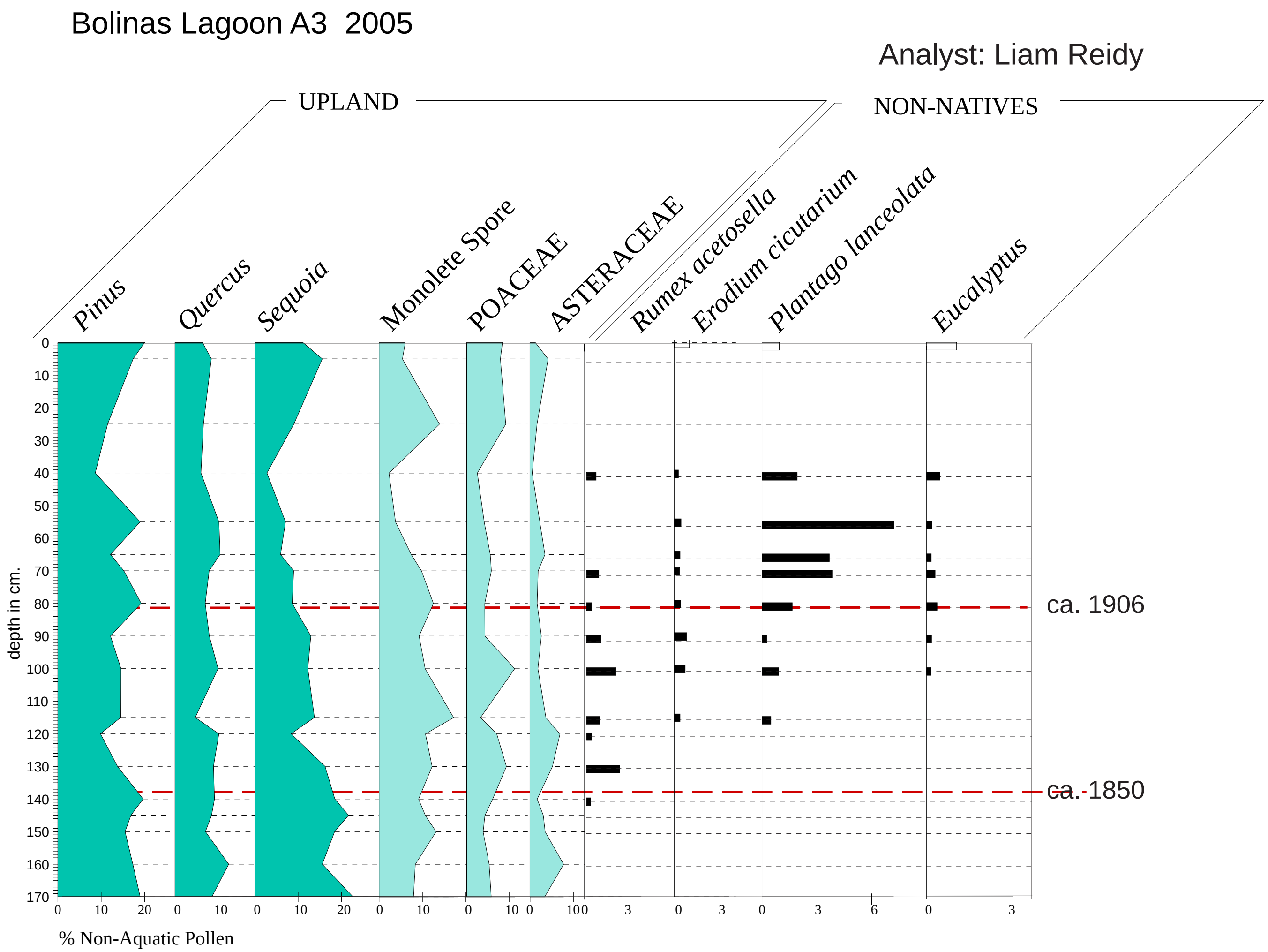

Figure 15a. Core A3 Upland Pollen.

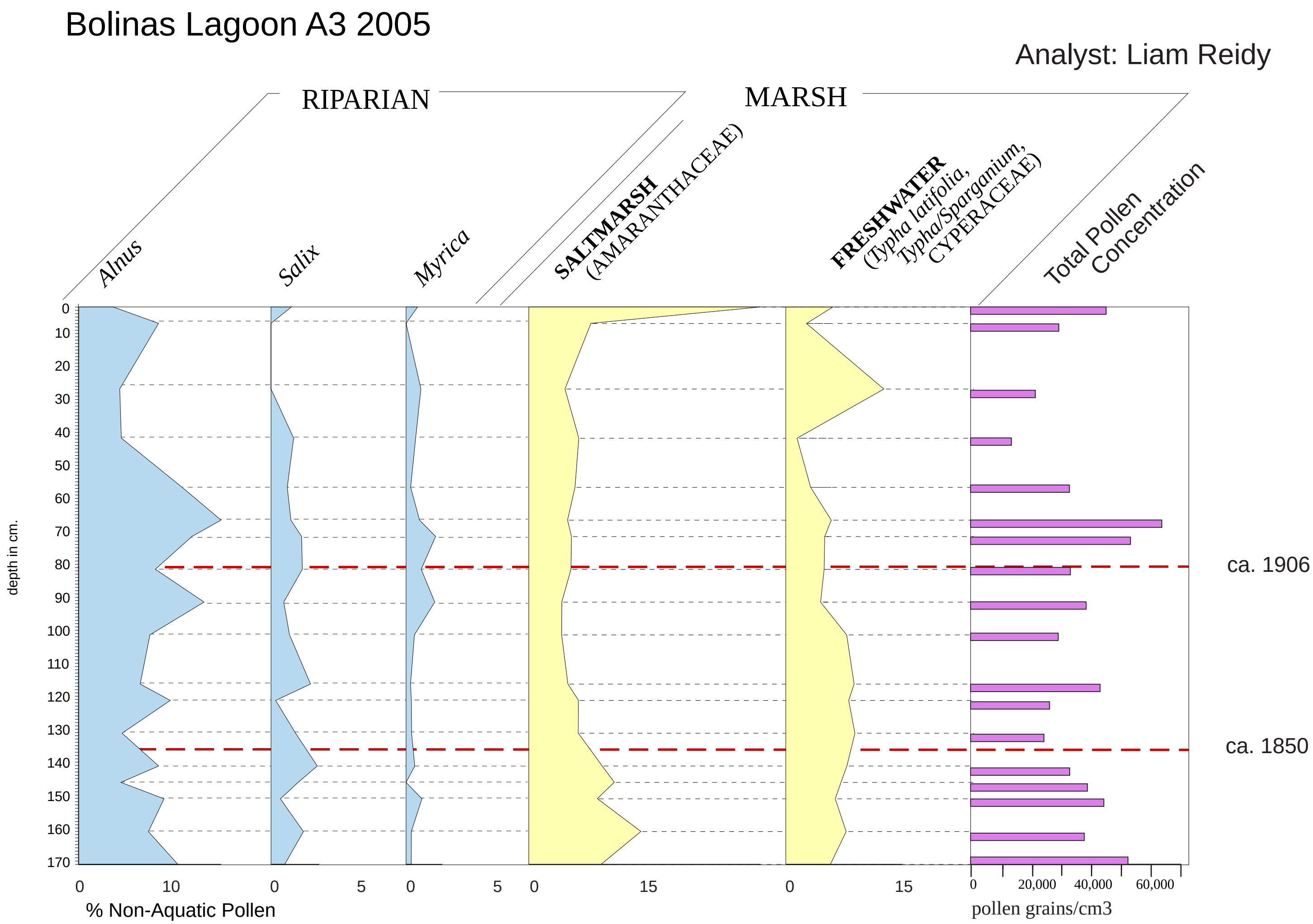

Figure 15b. A3 Riparian and Marsh Pollen.

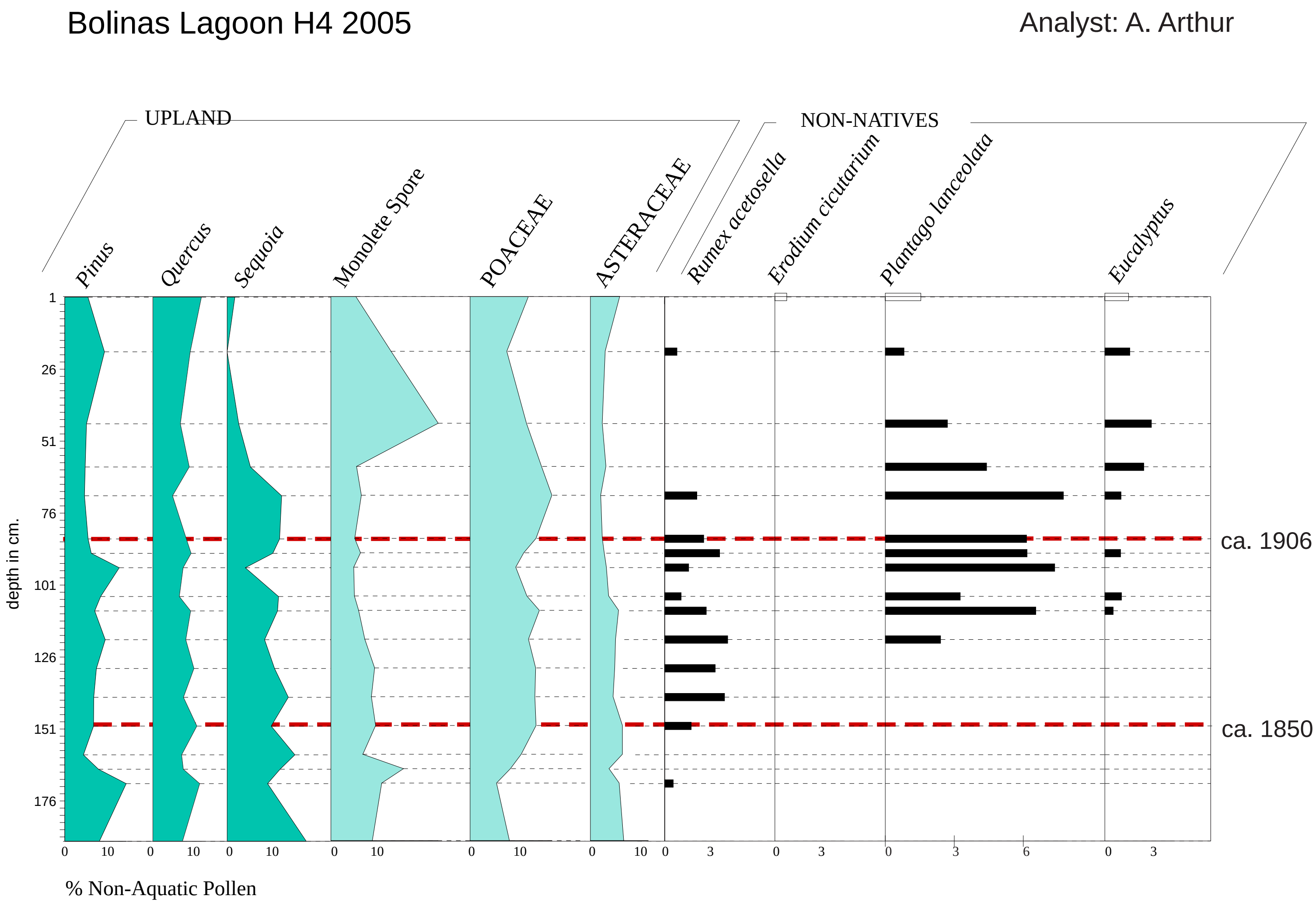

Figure 15c. Core H4 Upland Pollen.

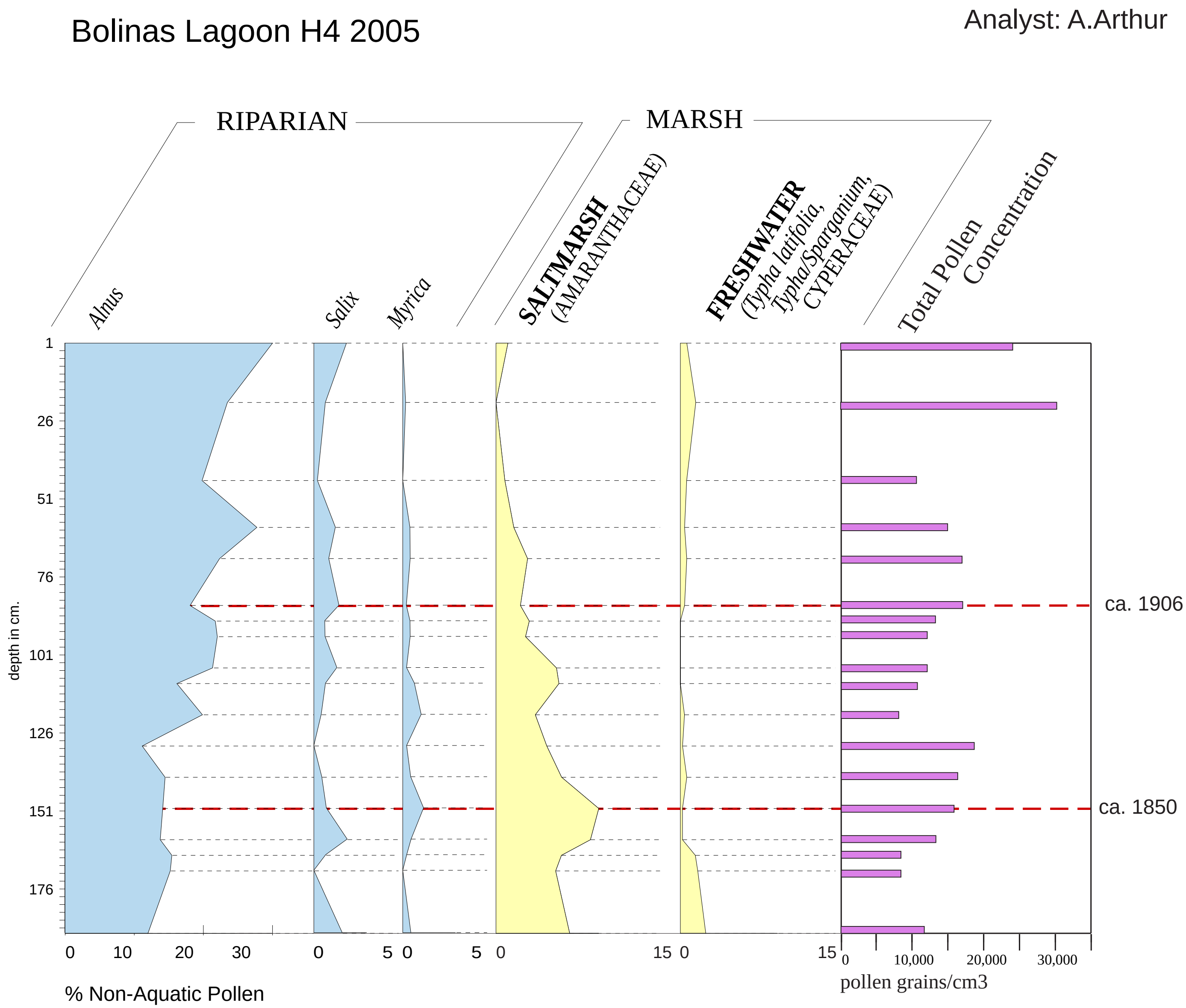

Figure 15d. Core H4 Marsh and Riparian Pollen.

Figure 16a and 16b. US Coast and Geodetic Survey Map 1854
and USGS Topographic Map 1897.

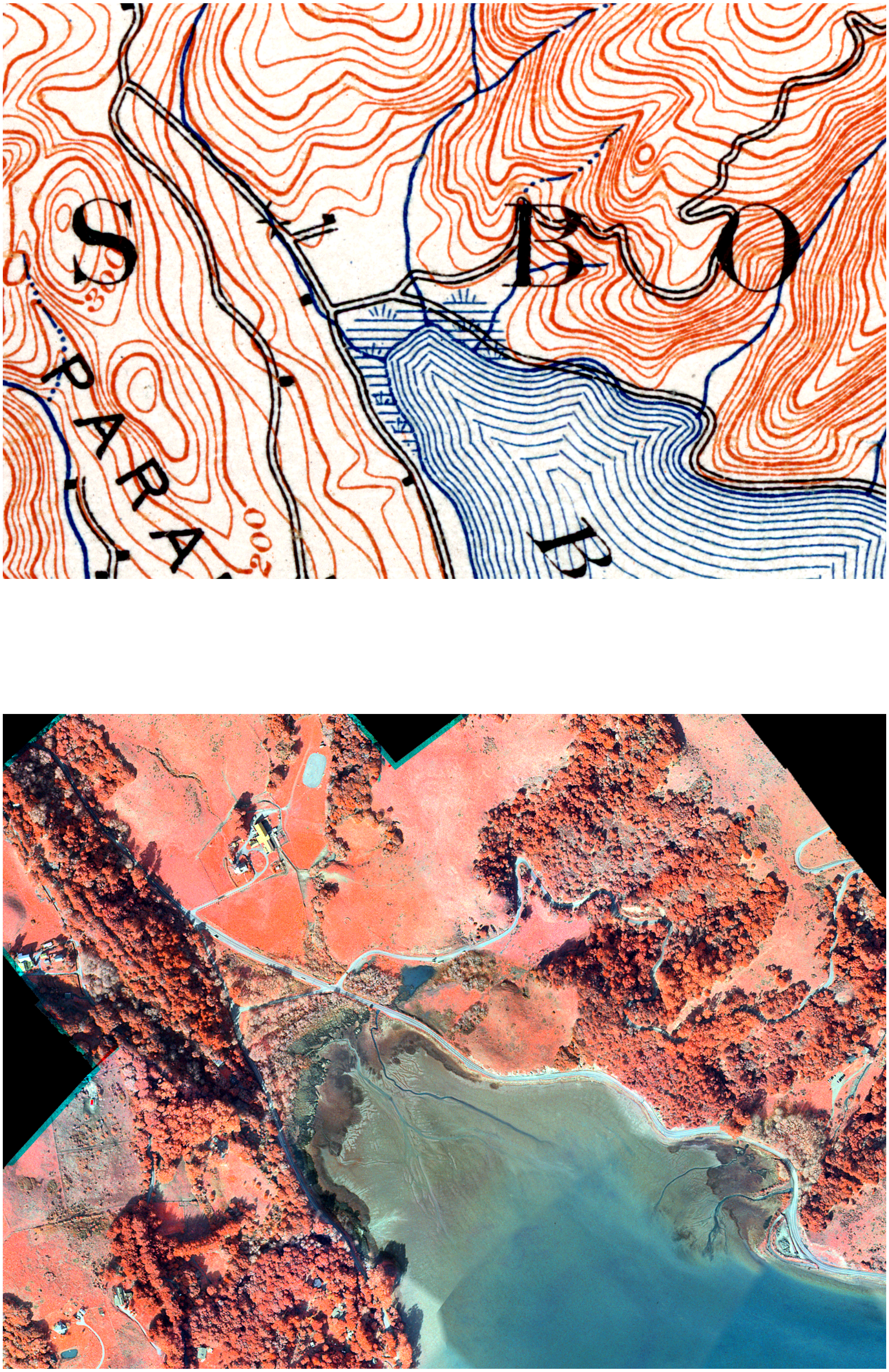

Figure 16c and 16d. USGS topographic map 1897 and USACE infrared aerial photograph 1998.

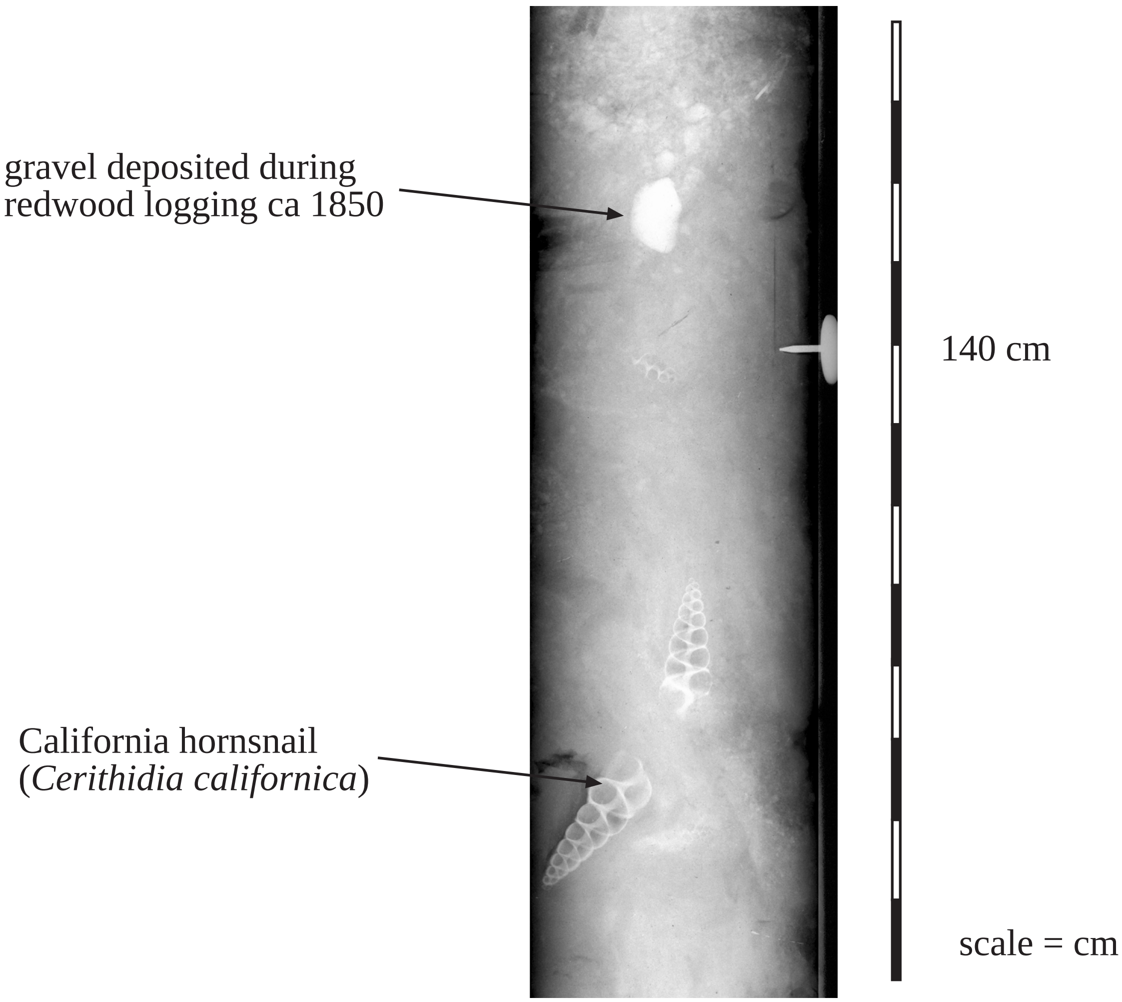

Figure 17. X-Radiograph of Bolinas L2 Core.

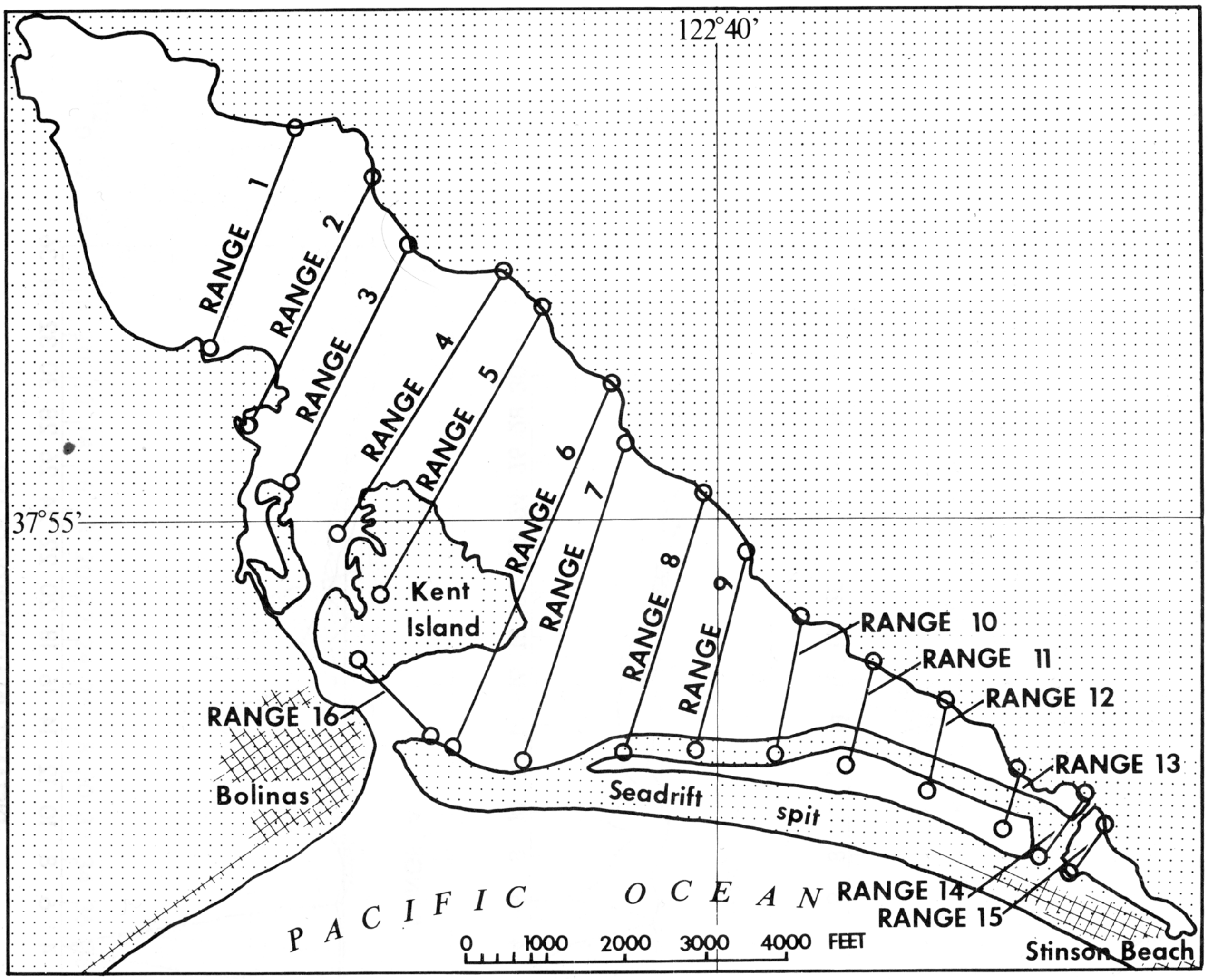

Figure 18a.. USACE Bathymetry Range Lines 1939 (Ritter, 1973).

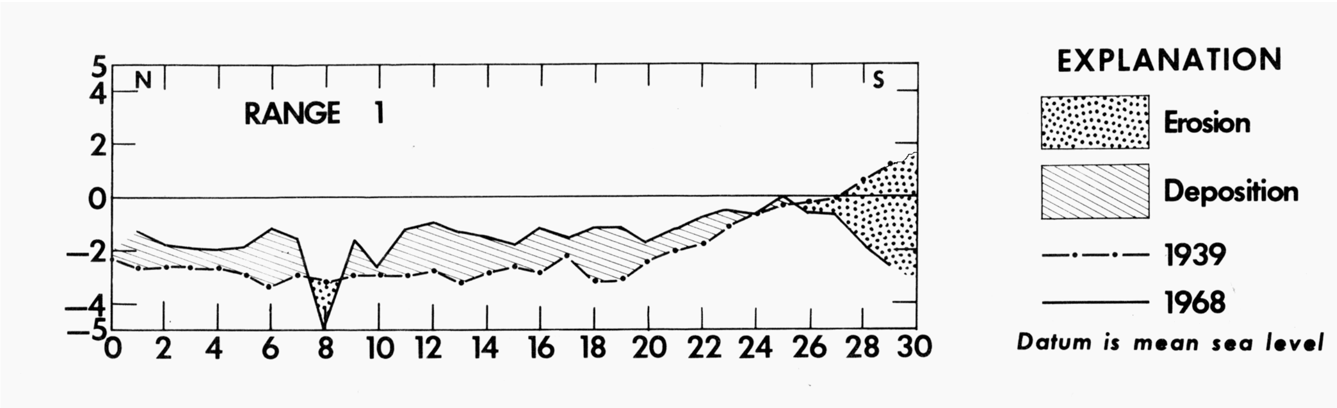

Figure 18b. USACE 1939 and 1968 Range 1 Profiles (Ritter, 1973).

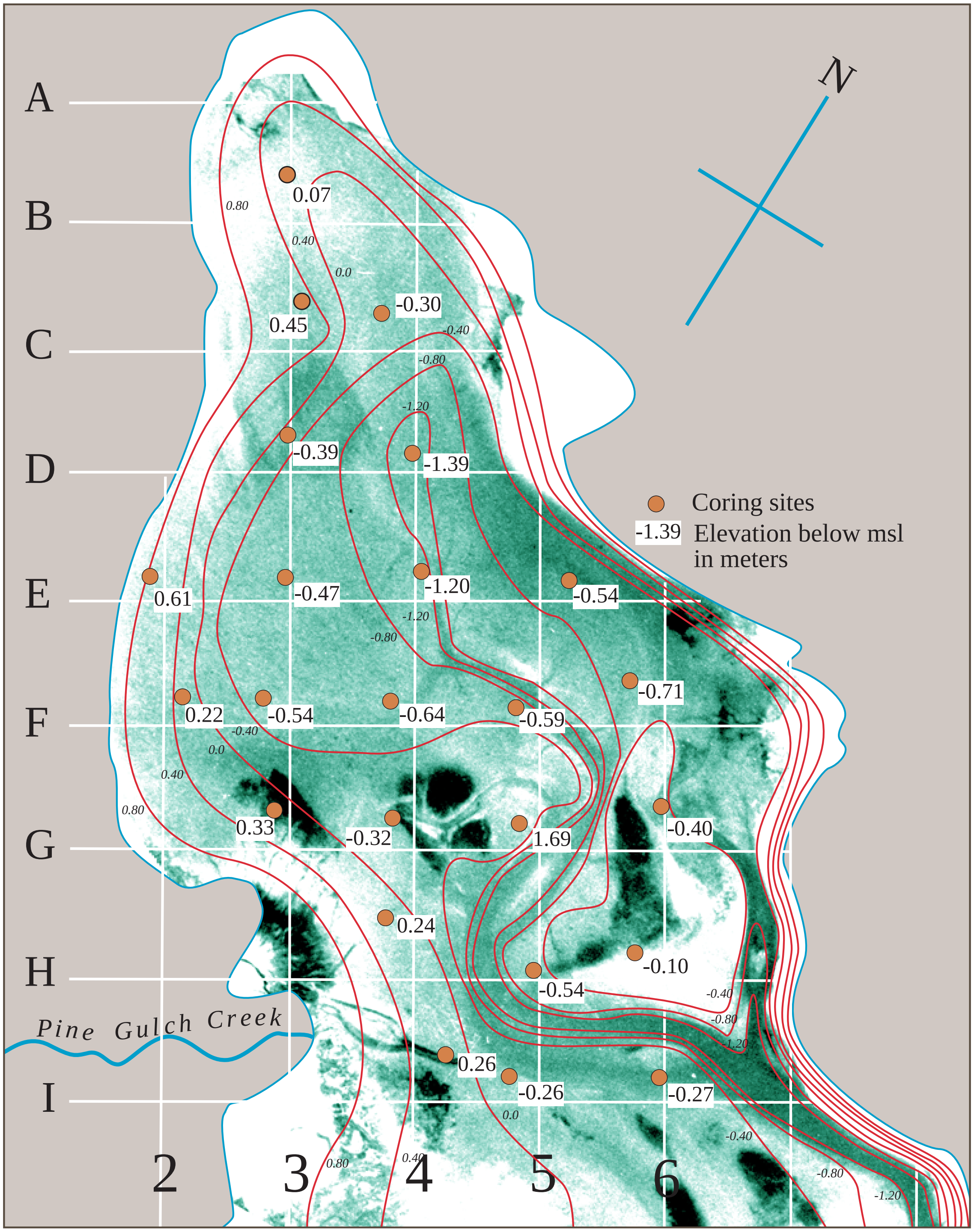

Figure 19. North Basin 2004 Bathymetry with a 1998 USGS Aerial Photograph in the background.

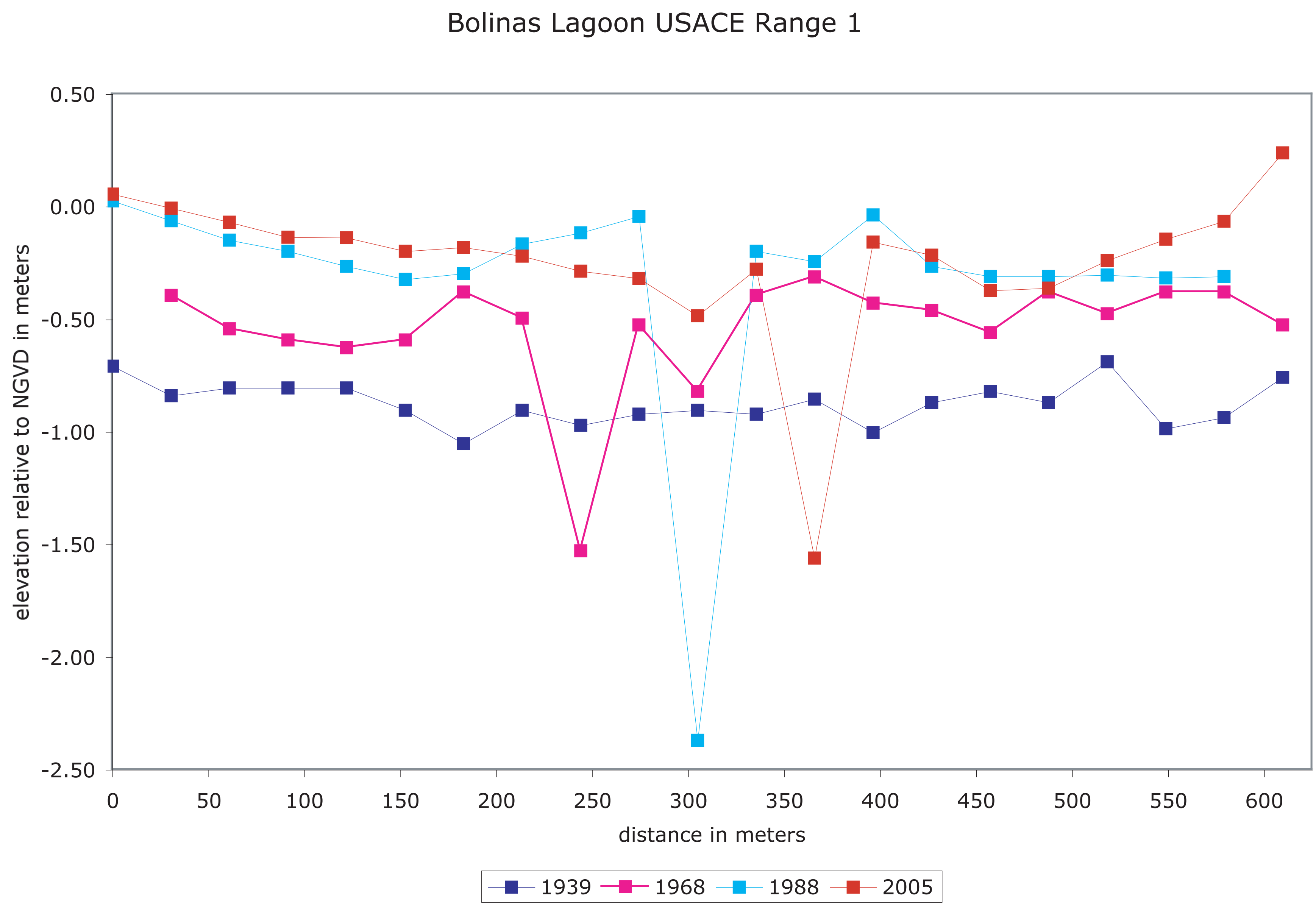

Figure 20. USACE Range 1 Profiles. NGVD = - 0.25 m below MSL

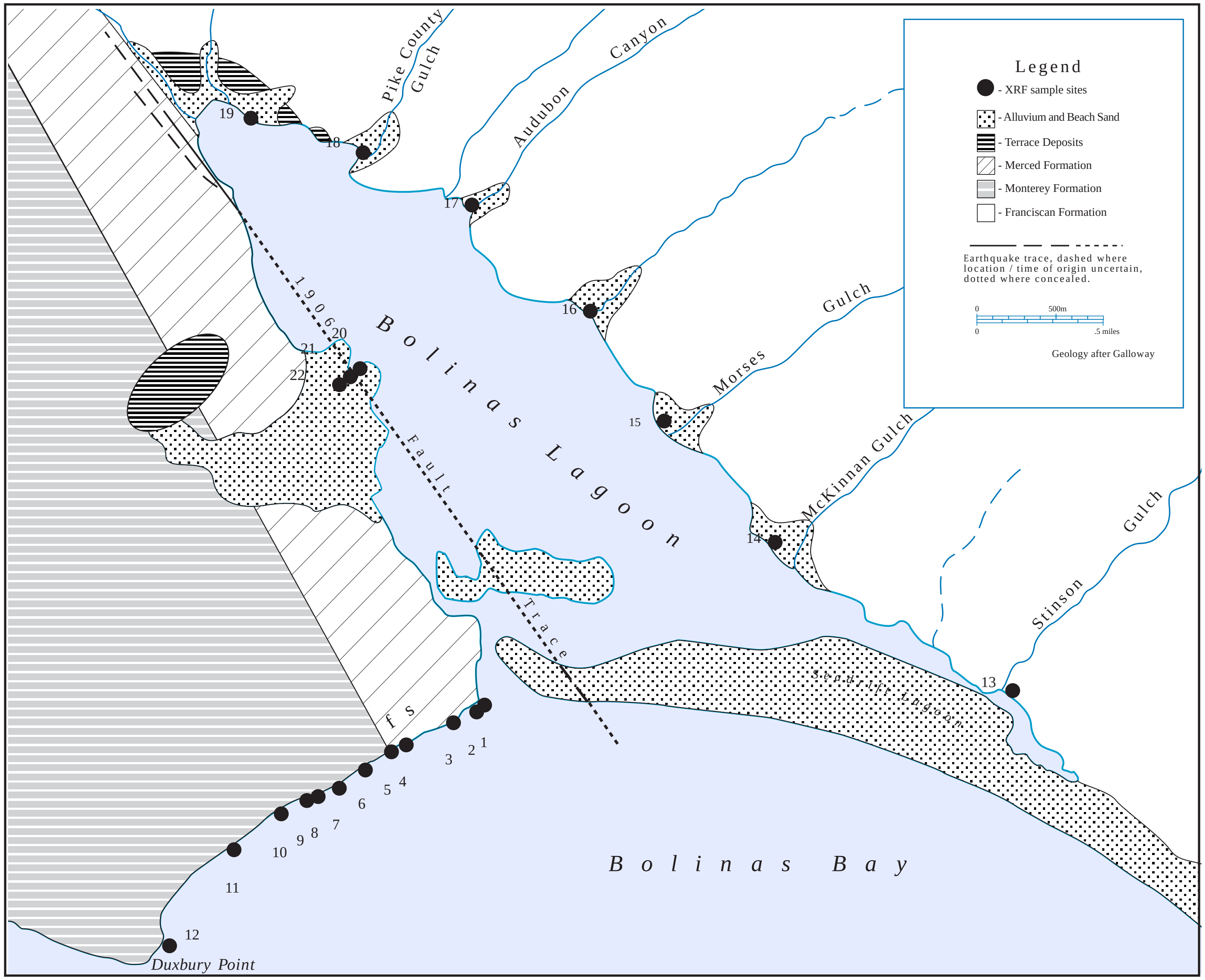

Figure 21. XRF surface sample locations.

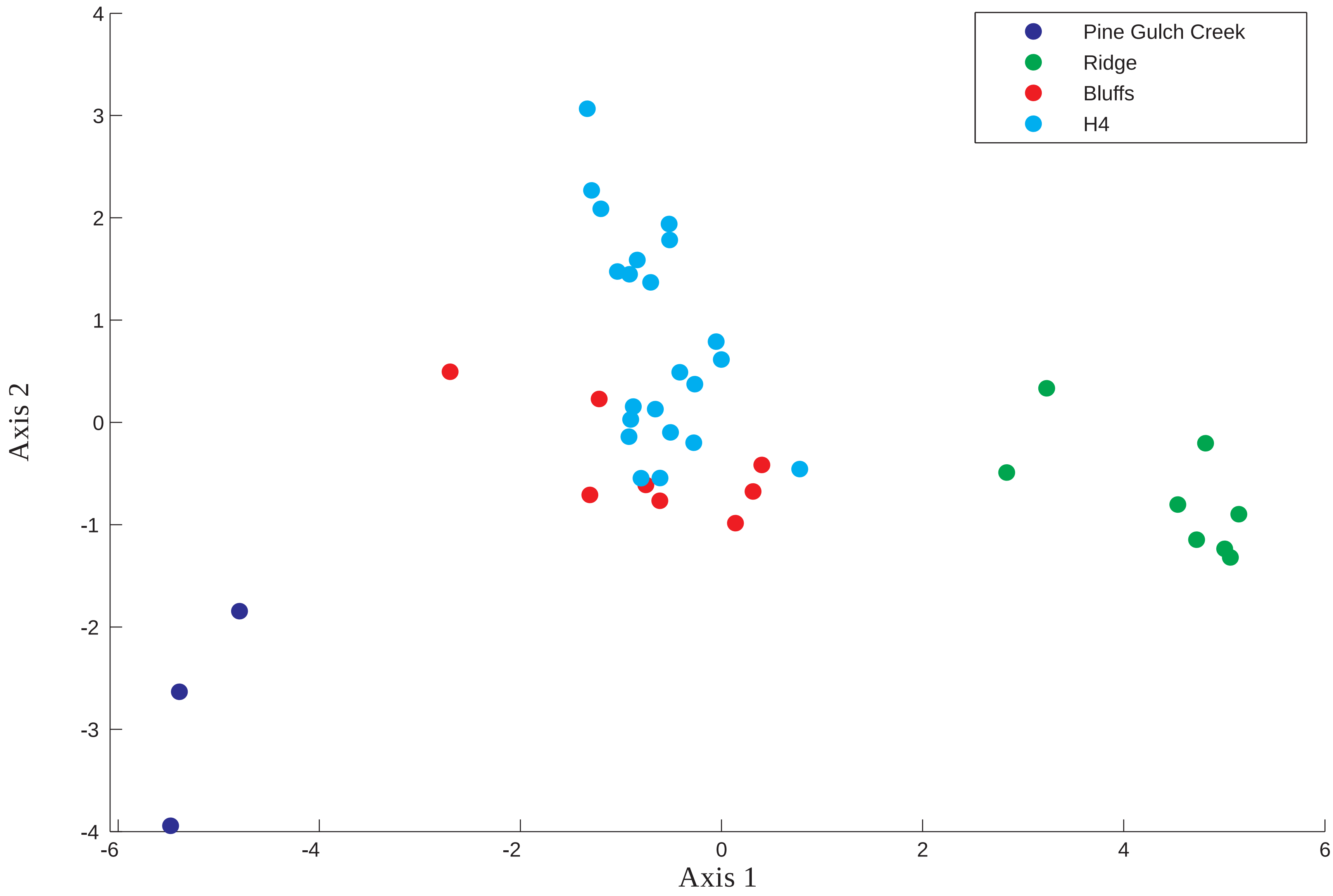

Figure 22. Principal Components Analysis of Bolinas Lagoon XRF Samples.

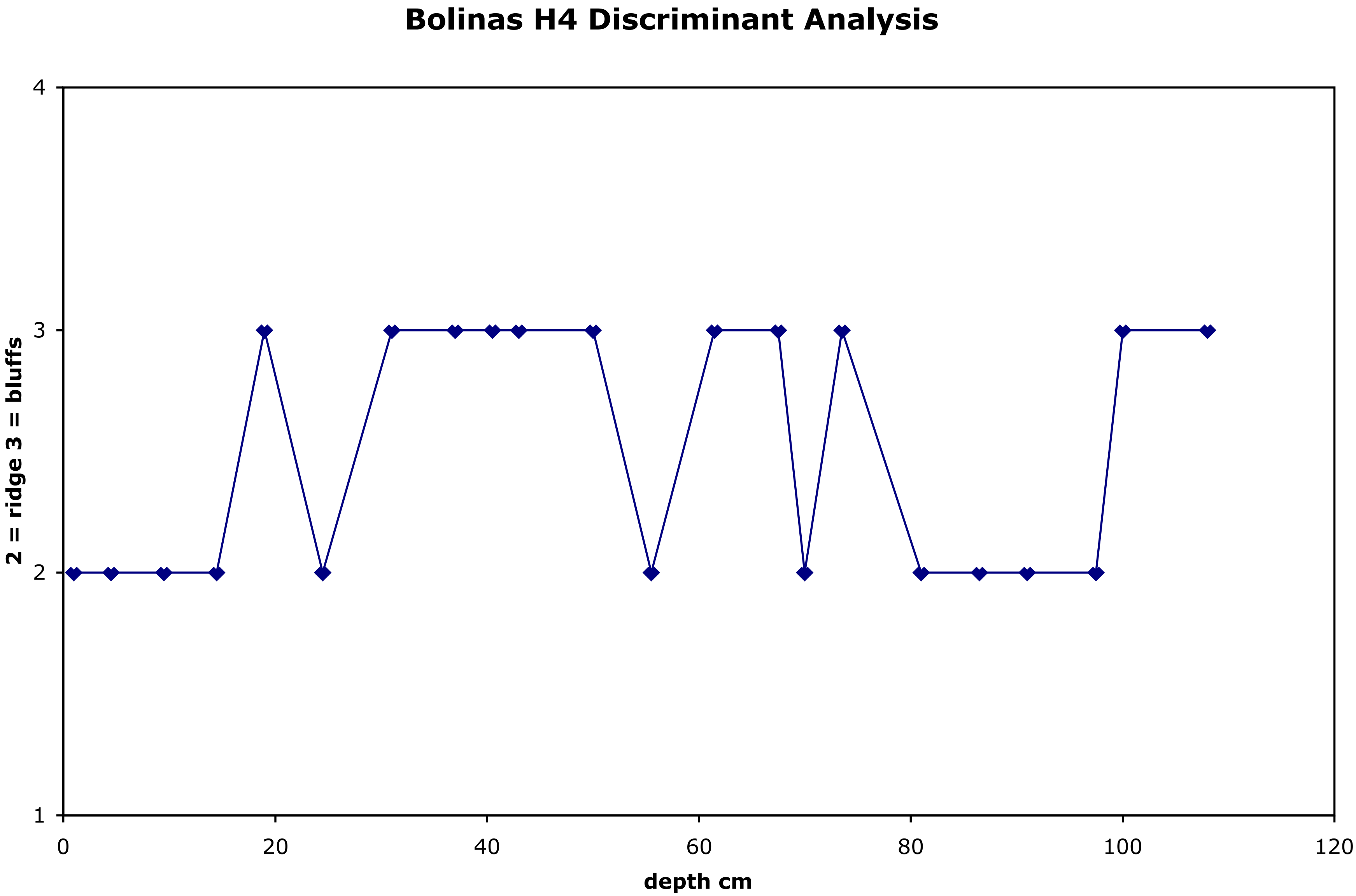

Figure 23. Core H4 discriminant function analysis results.

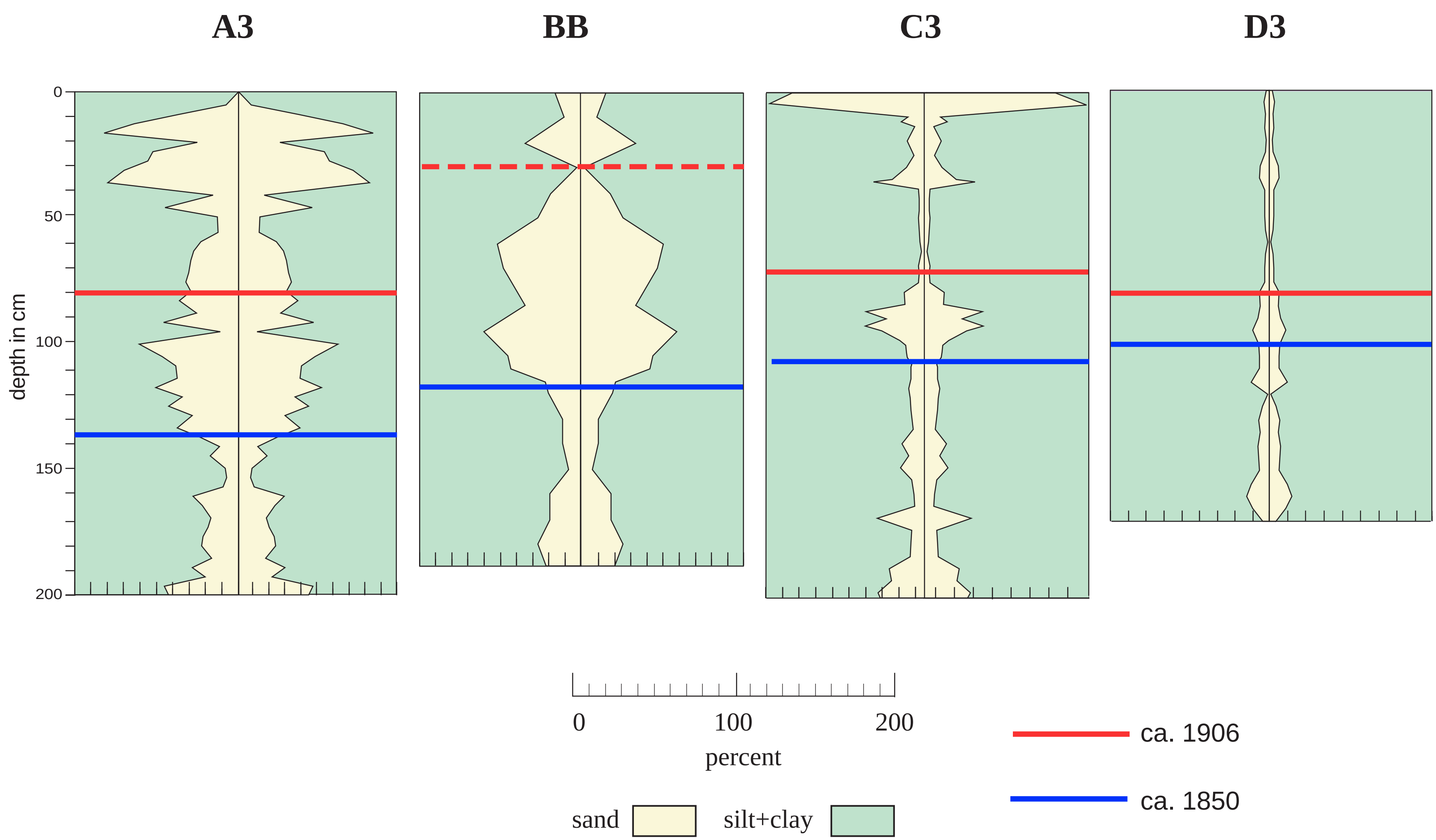

Figure 24a. Grain size variation Transect 3

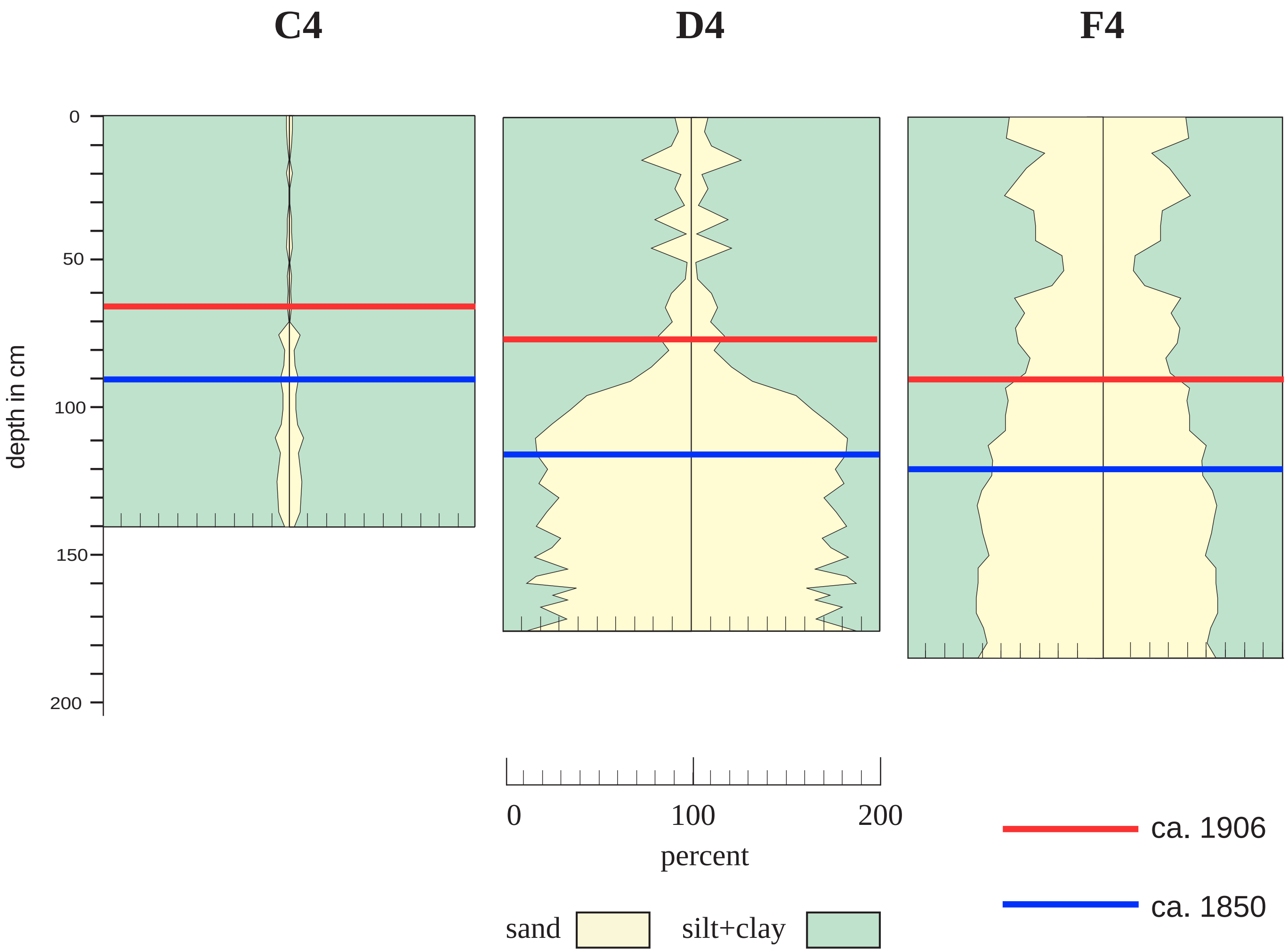

Figure 24b. Grain size variation Transect 4.

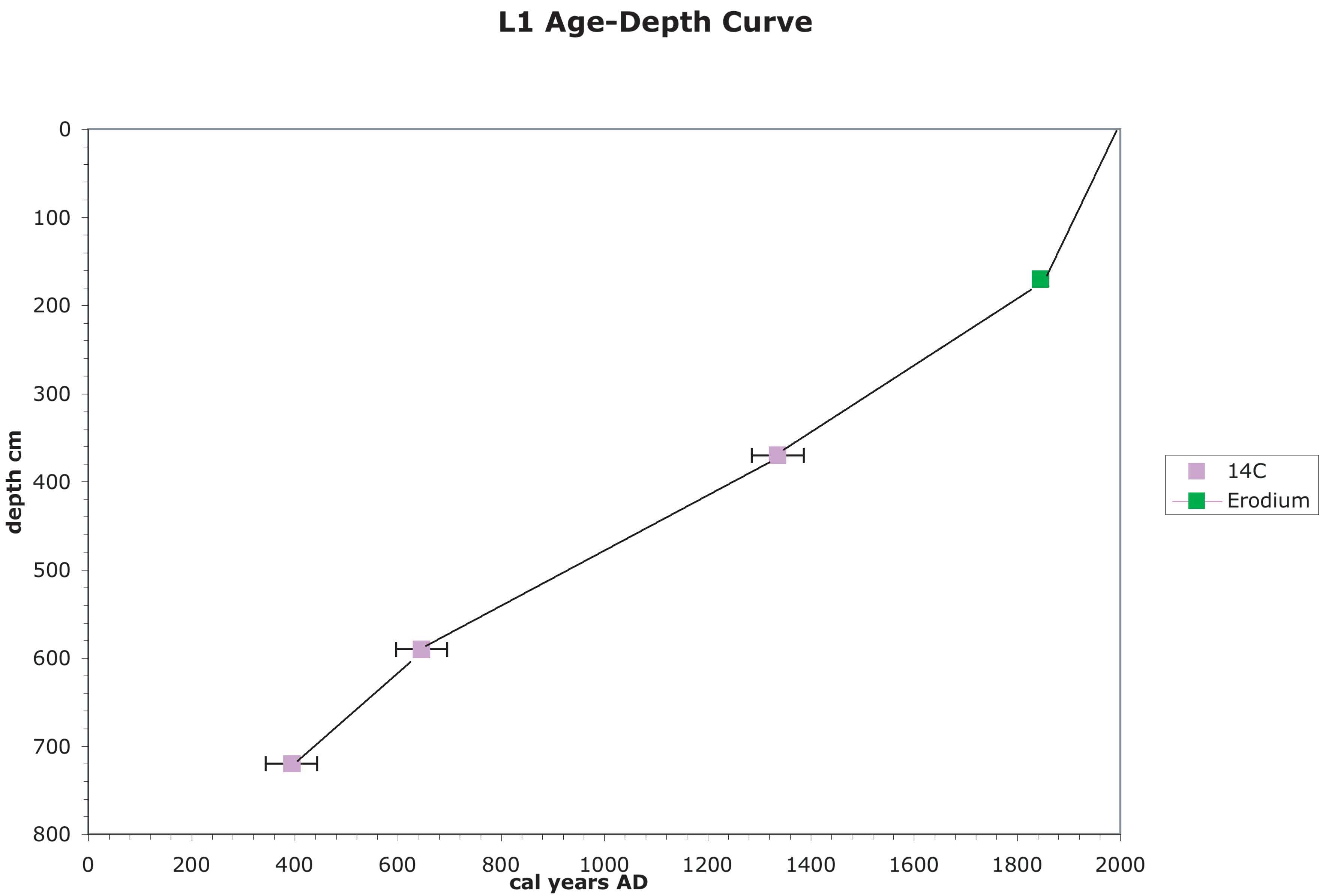

Figure 25a. L1 Age-Depth Curve.

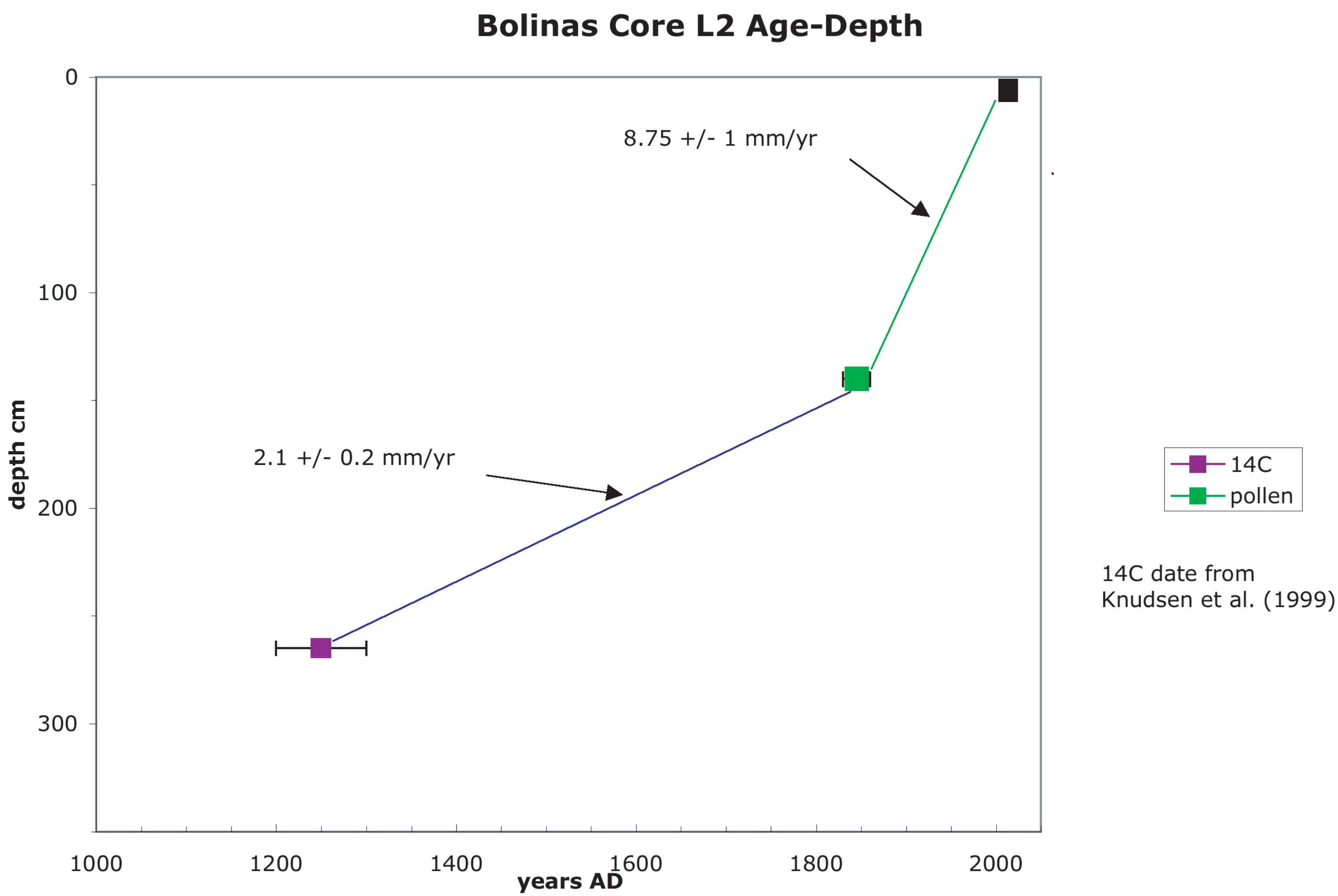

Figure 25b. L2 Age-Depth.

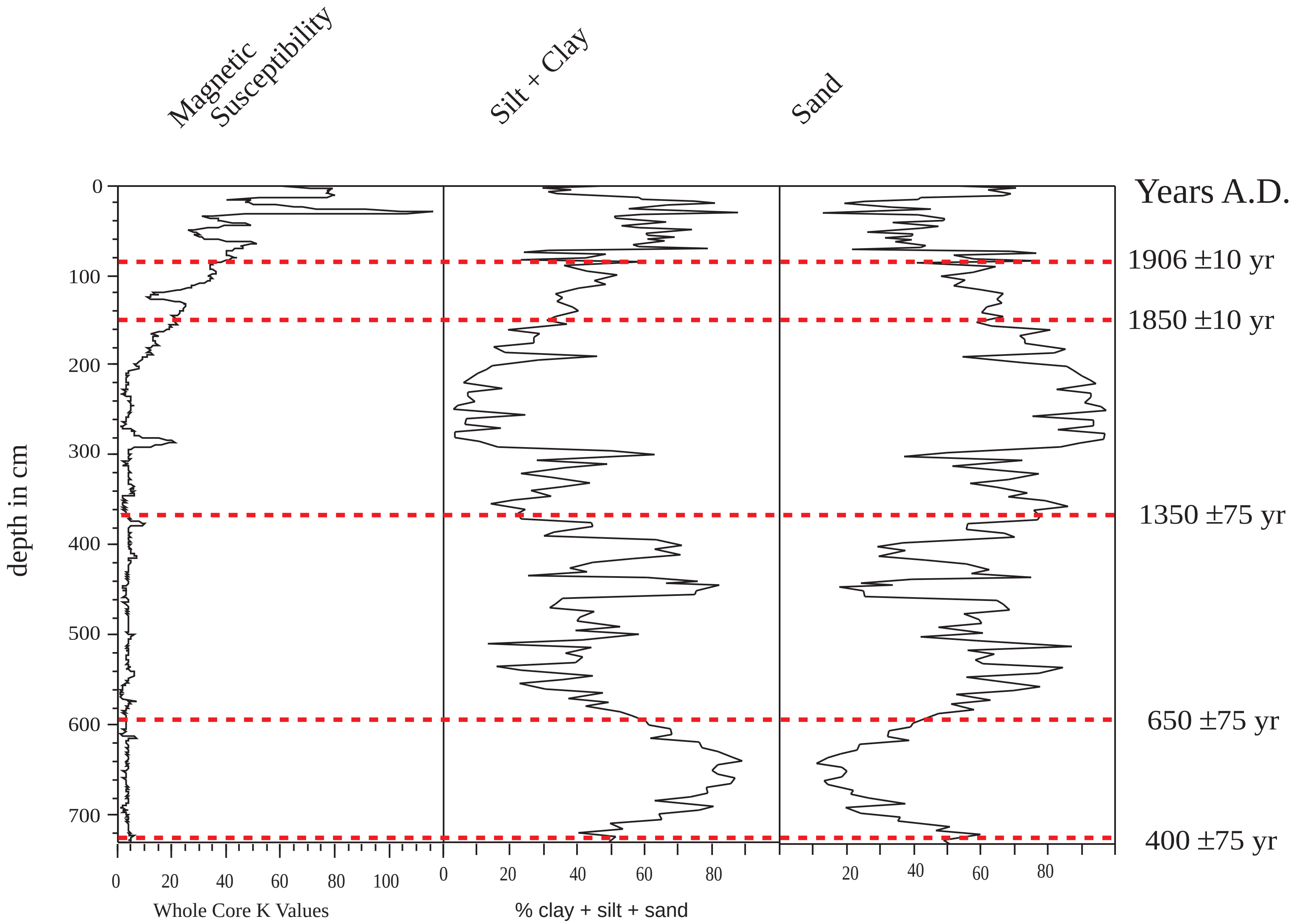

Figure 25a. Core L1 Magnetic Susceptibiloity and Grain Size.

Bolinas Lagoon L2 Core, Marin County

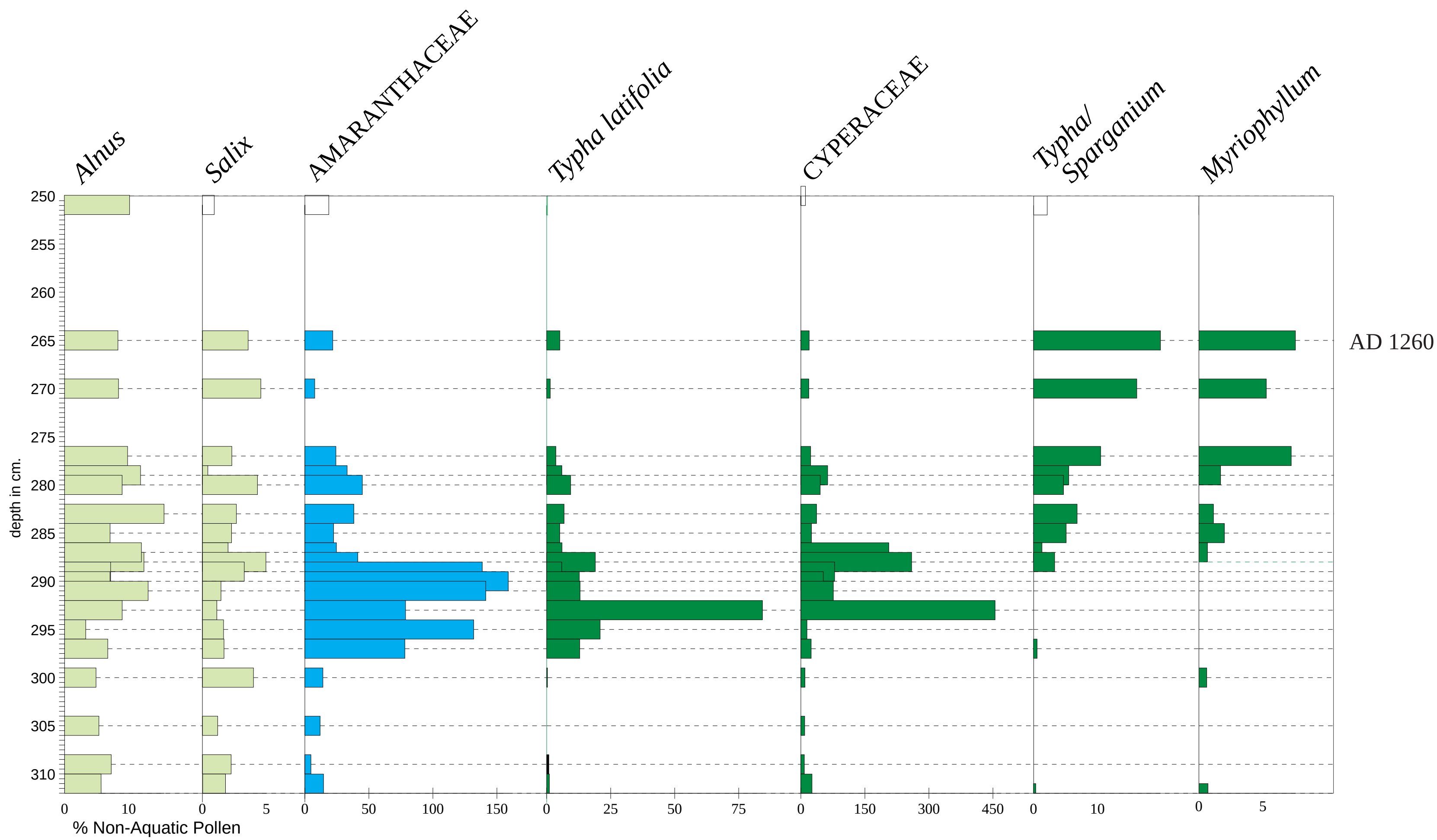

Figure 27. Pollen content of peat section in Core L2.

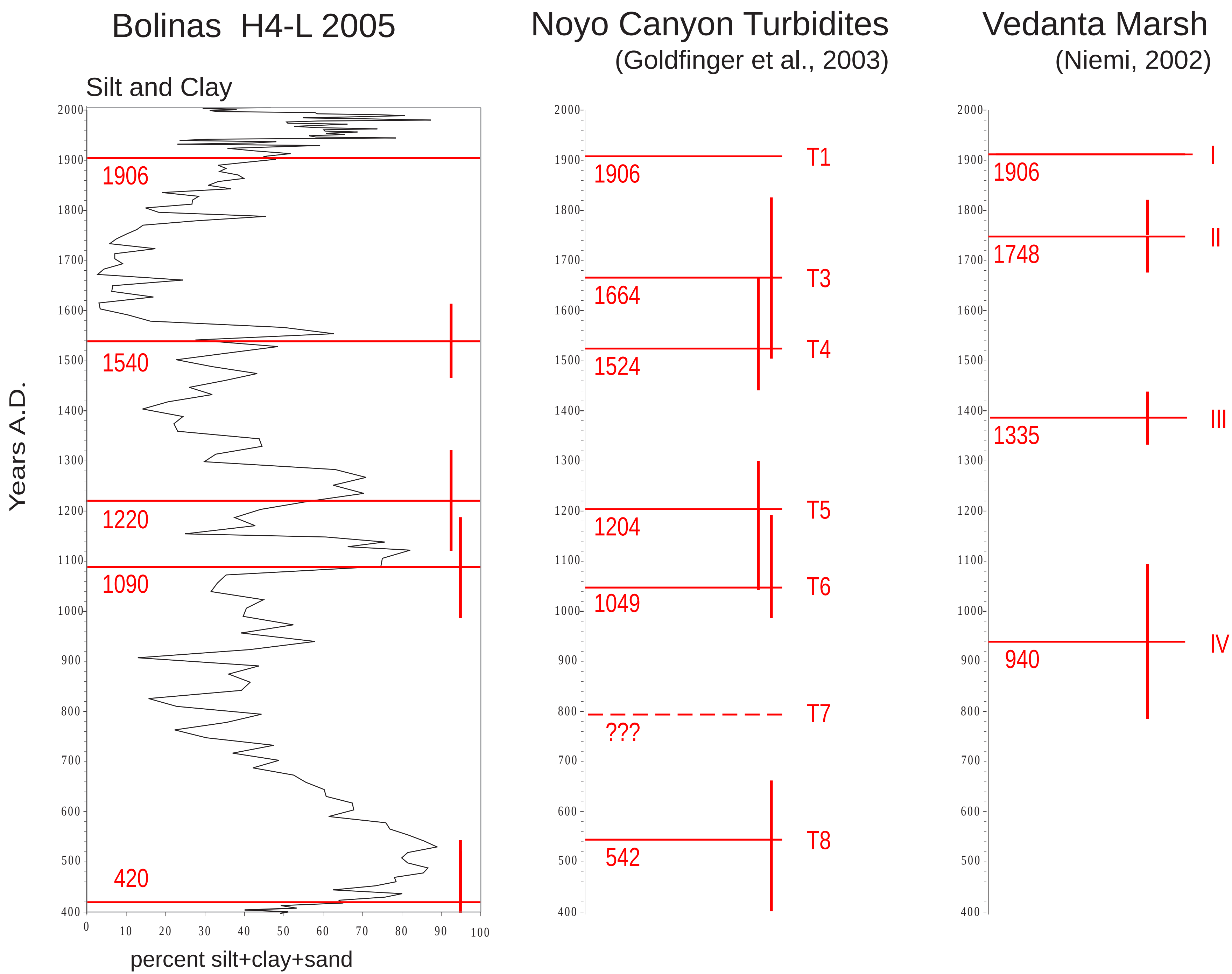

Figure 28. Paleoseismic comparisons.