Paleocene-Eocene Thermal Maximum (PETM)
Part 2 – Shore-based Data and Analysis

What is shore-based science?

A tremendous amount of science takes place at sea during a drilling expedition. However, most of the detailed investigations must await shore-based sample analyses. Each shipboard scientist prepares a detailed sample request prior to the beginning of the expedition, which is then reviewed by the Co-Chief Scientists and other members of the Shipboard Scientific Party. The shipboard curator, in consultation with the Co-Chief Scientists, develops a detailed sampling plan. During the expedition, samples are collected for all approved sample requests. Near the end of the expedition, the scientists will discuss outstanding scientific issues and decide what further research is required to address the scientific objectives of the expedition, and who will be responsible for each component of the research. The samples are shipped back to the home institutions of the shipboard scientists. In some high-resolution expeditions, a post-cruise sampling party must be organized at the core repository in order to collect the entire suite of requested samples. Results of these shore-based studies are typically published in peer-reviewed journals or special publications.

Shore-Based Data and Exercises

Here we provide some of the shore-based data that have been published from the 9 sites (holes) being investigated (Figure 1). All sites, with the exception of Hole 1220B, have percent carbonate (%carbonate) data across the PETM interval. Percent carbonate is a proxy for dissolution in the deep sea (e.g., movement of the carbonate compensation depth [CCD] higher or lower in the water column as a function of the amount of CO_2 dissolved in seawater).

Much of the calcium carbonate in deep-sea sediments is from calcareous microfossils. These are ancient plankton or bottom-dwelling protists that have hard parts consisting of calcite ($CaCO_3$). In many parts of the deep-sea, marine microfossils are the sediment! The calcareous nannofossils are single-celled photosynthetic algae (Figure 2). These tiny microfossils cover vast areas of the seafloor. Calcareous nannofossils are too small to be routinely separated out of the sediment for isotopic analysis. However, when bulk sediments are analyzed for stable isotopes, it is the calcareous nannofossils that are responsible for most the signal.

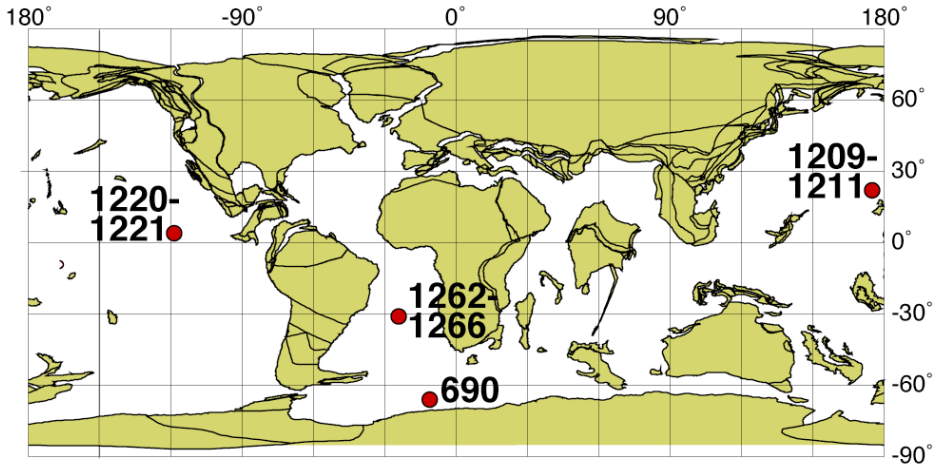

Figure 1. *Plate tectonic reconstruction for 55 Ma (time of the PETM). Locations of sites (holes) discussed here are shown in their backtracked positions (from www.odsn.de).*

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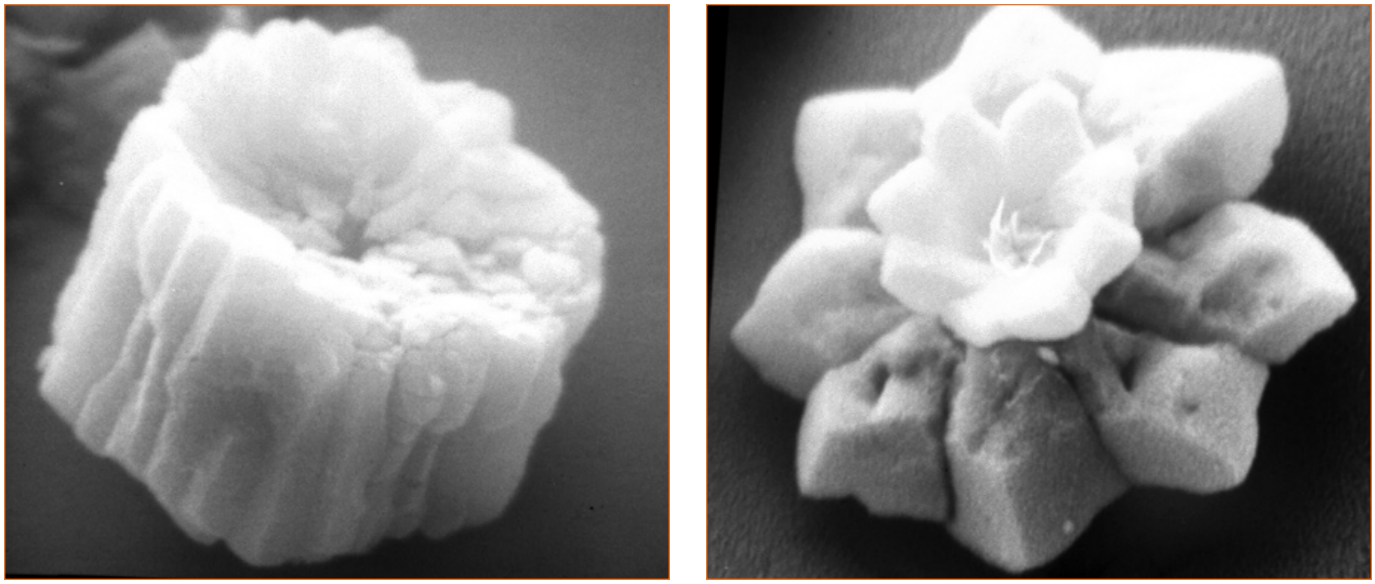

Figure 2. *Late Paleocene calcareous nannofossil Fasciculithus tympaniformis (left) and early to middle Eocene Discoaster kuepperi (right). Scanning electron photomicrographs from http://www.ucl.ac.uk/GeolSci/micropal/calcnanno.html*

The planktic foraminifers are sand-sized single-celled protists (Figure 3). Individual species of planktic foram can be picked out of the sediment and analyzed isotopically. Planktic foraminifera live at different depths in the uppermost water column ranging from the surface mixed layer, to thermocline and sub-thermocline depths. Therefore, different species can be analyzed in order to reconstruct the ancient structure of the upper water column. The oxygen isotopic values of mixed layer species can also be used as a proxy for ancient sea surface temperatures.

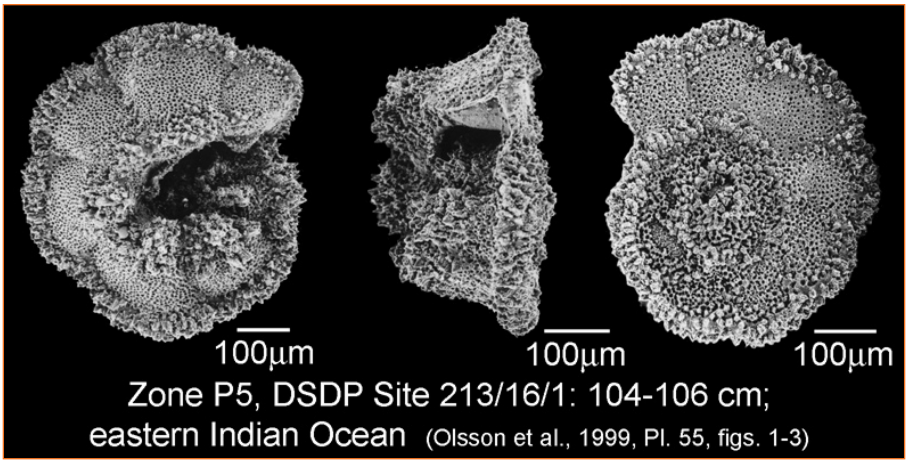

Figure 3. *Three views (umbilical, edge, and spiral views) of Morozovella velascoensis, a species of planktic foraminifer that went extinct at the end of the Paleocene Epoch during the time of the PETM. Scanning electron microscope images from the Atlas of Paleocene Planktonic Foraminifera (R.K. Olsson, C. Hemleben, W.A. Berggren, B.T. Huber, editors, 1999, Smithsonian Contributions to Paleobiology, No. 85). http://portal.chronos.org:80/gridsphere/gridsphere?cid=res_paleocenedb*

Benthic foraminifera live on the seafloor (Figure 4). Their calcite shells can yield isotopic information about deep ocean chemistry and water temperature, as well as ice volume.

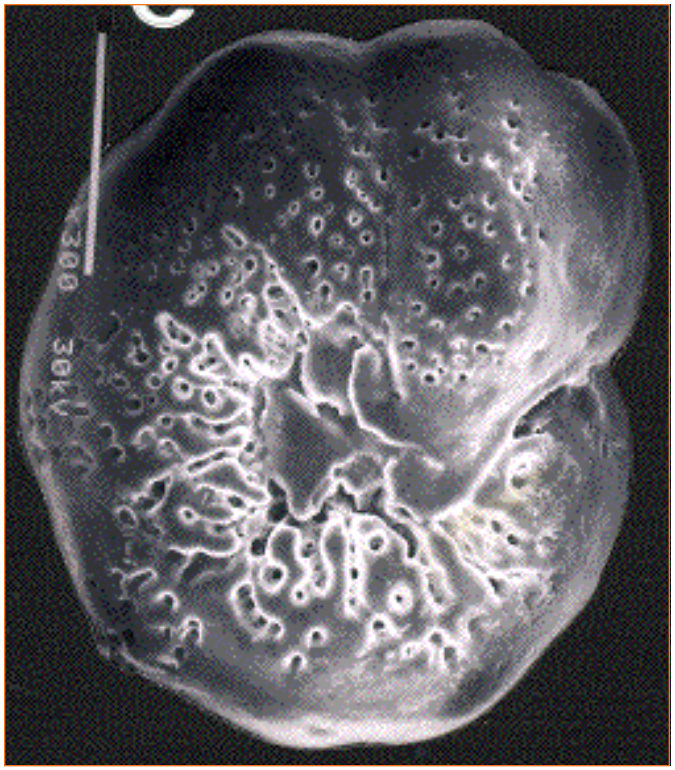

Figure 4. *Gavelinella beccariiformis, a species of benthic foraminifer that went extinct at the onset of the PETM (part of the benthic extinction event, or BEE). Scanning electron microscope image courtesy of Ellen Thomas. http://ethomas.web.wesleyan.edu/ees123/hot-stinky.htm*

Most of the sites also have $\delta^{13}C$ data from planktic foraminifera, bulk sediment, or benthic foraminifera through the PETM interval. Since the world ocean is well mixed on time scales of 1000 years or so, the carbon isotope data is a proxy for biological productivity and carbon burial; major carbon isotope excursions record perturbations in the carbon cycle.

In addition to carbon isotopic and carbonate data, $\delta^{18}O$ data of benthic forams are provided for several of the sites. Because the early Paleogene Period was a time of global warmth and greenhouse climates lacking continental ice sheets, these oxygen isotope data are a proxy for paleotemperatures.

Here is a useful factoid relating changes in $\delta^{18}O$ to changes in paleotemperature:

- ~0.23‰ change in $\delta^{18}O$ = 1°C
- 1‰ change in $\delta^{18}O$ = ~4°C

Note that Site 690 (Hole 690B) has stable isotope data for both planktic foraminifera and benthic foraminifera. This provides a proxy for the surface/upper water column and the deep ocean/lower water column. In addition, there are data for a surface dwelling planktic foraminifer and a deeper (thermocline) dwelling planktic foraminifer. Notice the $\delta^{18}O$ and $\delta^{13}C$ gradients (the difference) between planktic and benthic taxa before the PETM.

1. What is responsible for the $\delta^{18}O$ gradient between planktic and benthic taxa? What is responsible for the $\delta^{13}C$ gradient between planktic and benthic taxa? What happens to these gradients during the PETM?
2. How do $\delta^{18}O$ values of the planktic foraminifera change across the PETM? How do $\delta^{18}O$ values of the benthic foraminifera change across the PETM? What are the similarities and differences between the planktic foram response and benthic foram response?
3. What are similarities and differences in $\delta^{13}C$ between the planktic and benthic forams?
4. Consider the available data for each of the sites (holes) individually. What are the trends in %carbonate data? How does is it compare with the isotope data (if available)? What hypotheses could you advance to explain the observed data?
5. Compare your site with nearby sites. What are the similarities and differences? Can you refine your hypotheses?
6. Now compare all the sites. Assemble a list of shared features. What are the common trends? Do any of the sites standout as being very different from the others? Any distinct patterns as a function of latitude or water depth?
7. Do you have any ideas about why % carbonate values drop off so rapidly? How would you describe the recovery?
8. What ideas do you have about why $\delta^{13}C$ values decreased so rapidly? This is known as the Carbon Isotope Excursion (CIE) in the literature.
9. What ideas do you have about why $\delta^{18}O$ values decreased so rapidly?
10. Benthic foraminifera survived the Cretaceous-Paleogene boundary (K/P boundary; dinosaur and ammonite extinctions), but they suffered a 30-50% loss of species at the PETM. This is known as the Benthic Extinction Event (BEE) in the literature. Any ideas about what may have caused this extinction?

How do we know how rapid the PETM was, and how long it lasted?

The first estimates of the duration of the P/E event, as well as the rate at which the perturbation occurred, were based on the numerical ages of known paleomagnetic reversals combined with the assumption that sediment accumulated at a constant rate between two geochronological tie-points. For example, in the original paper that defined the event (Kennett and Stott, 1991), the age model was based on the top of magnetic reversal Chron 25N dated at 58.64 Ma (= mega-annums, or million years ago) and determined to occur at 185.2 meters below seafloor (mbsf) in the sediment sequence recovered from ODP Hole 690B. The next available magnetic datum is the bottom of Chron 24N (56.14 Ma) found to occur at 154.62 mbsf. This results in an average sedimentation rate of 1.23 cm per 1000 years between those two tie-points. Armed with this information, the onset of the excursion was estimated to occur in the span of ~10,000 years because the change in benthic foraminiferal $\delta^{13}C$ values was found between two adjacent samples at 170.45 and 170.35 mbsf. The total event (at least in the data set that Kennett and Stott generated) lasted ~270,000 years. However, many things can happen in the span of ~2.5 million years (the span of time between the two magnetic datums) and the assumption of constant sedimentation is not particularly realistic or accurate.

The most significant improvement to the chronology of the P/E event was the discovery that several sediment records spanning the event contain evidence for Milankovitch cycles. Milankovitch cycles occur at astronomically predicted frequencies, and therefore represent a stable “metronome” in sediment sequences (with the big assumption that every cycle is recorded in the sediments – i.e., there are no missing cycles). Röhl et al. (2000) published a new age model for the Hole 690B sediment sequence based on the number of precessional cycles (~21,000 periodicity). The total duration of the event came out to be ~210,000-220,000 years (11 precessional cycles). From these new data we now know that the onset of the climate excursion happened over ~52,000 years, but the most rapid part of the carbon isotope excursion (CIE) occurred in two pulses of ~1000 years or less.

Kennett, J.P., and Stott, L.D., 1991. Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Paleocene, *Nature*, 353:225-229.

Röhl, U., Bralower, T.J., Norris, R.D., and Wefer, G., 2000. New chronology for the late Paleocene thermal maximum and its environmental implications, *Geology*, 28(10):927-930.

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A Note About Depth Scale: mbsf vs. mcd

Figure 5 illustrates the difference between meters below seafloor (mbsf) and meters composite depth (mcd). Part A shows magnetic susceptibility data from three holes at Site 1211 (Holes 1211A, 1211B, and 1211C) on the mbsf (meters below seafloor) depth scale. Note the slight offsets in the magnetic susceptibility between the 3 holes. Part B shows the same records after depth-scale adjustment so that correlative features are aligned ("wiggle matching"). The resulting spliced record on the mcd (meters composite) depth scale is shown in C.
http://www-odp.tamu.edu/publications/198_IR/chap_02/c2_f7.htm#535907

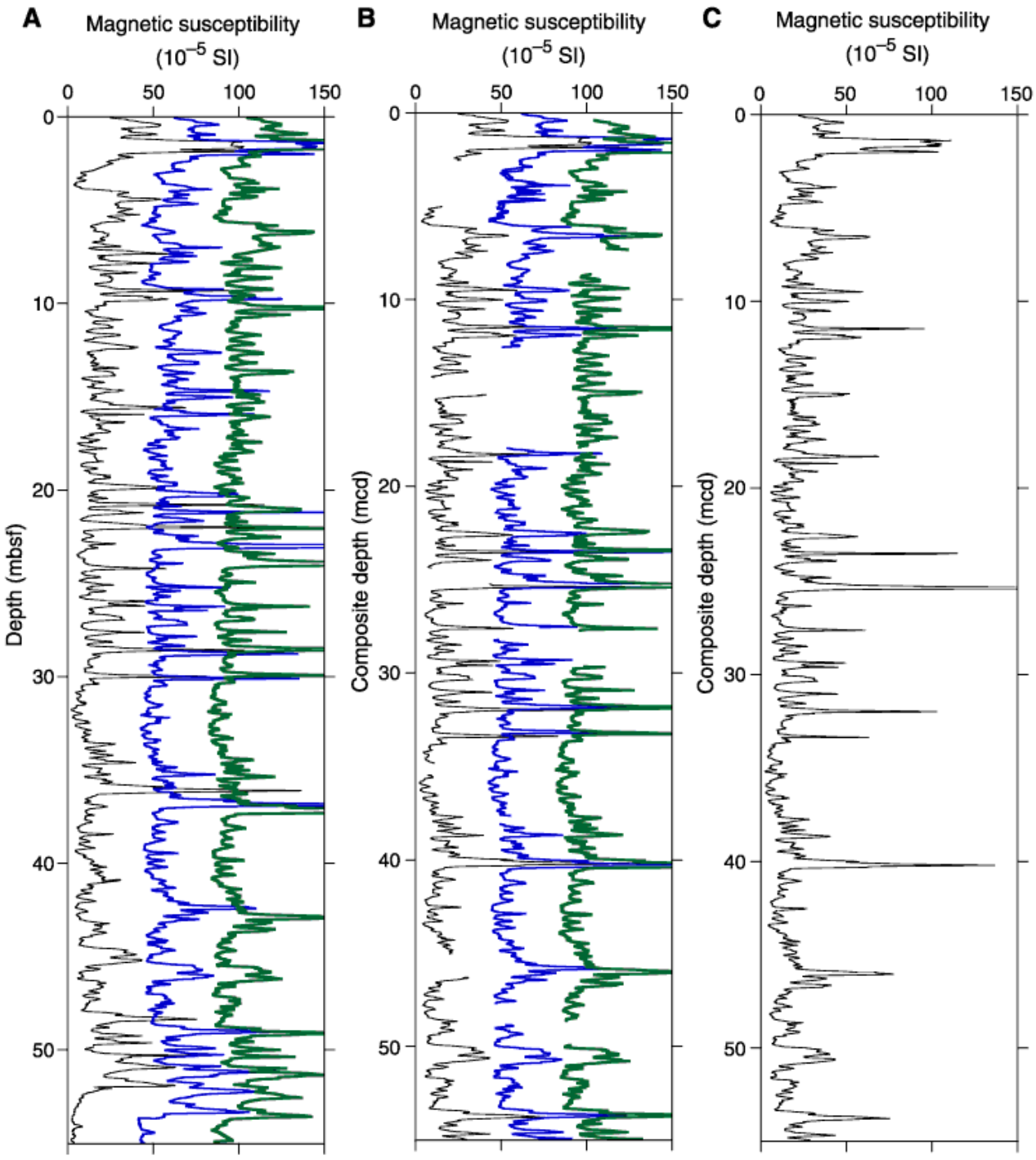
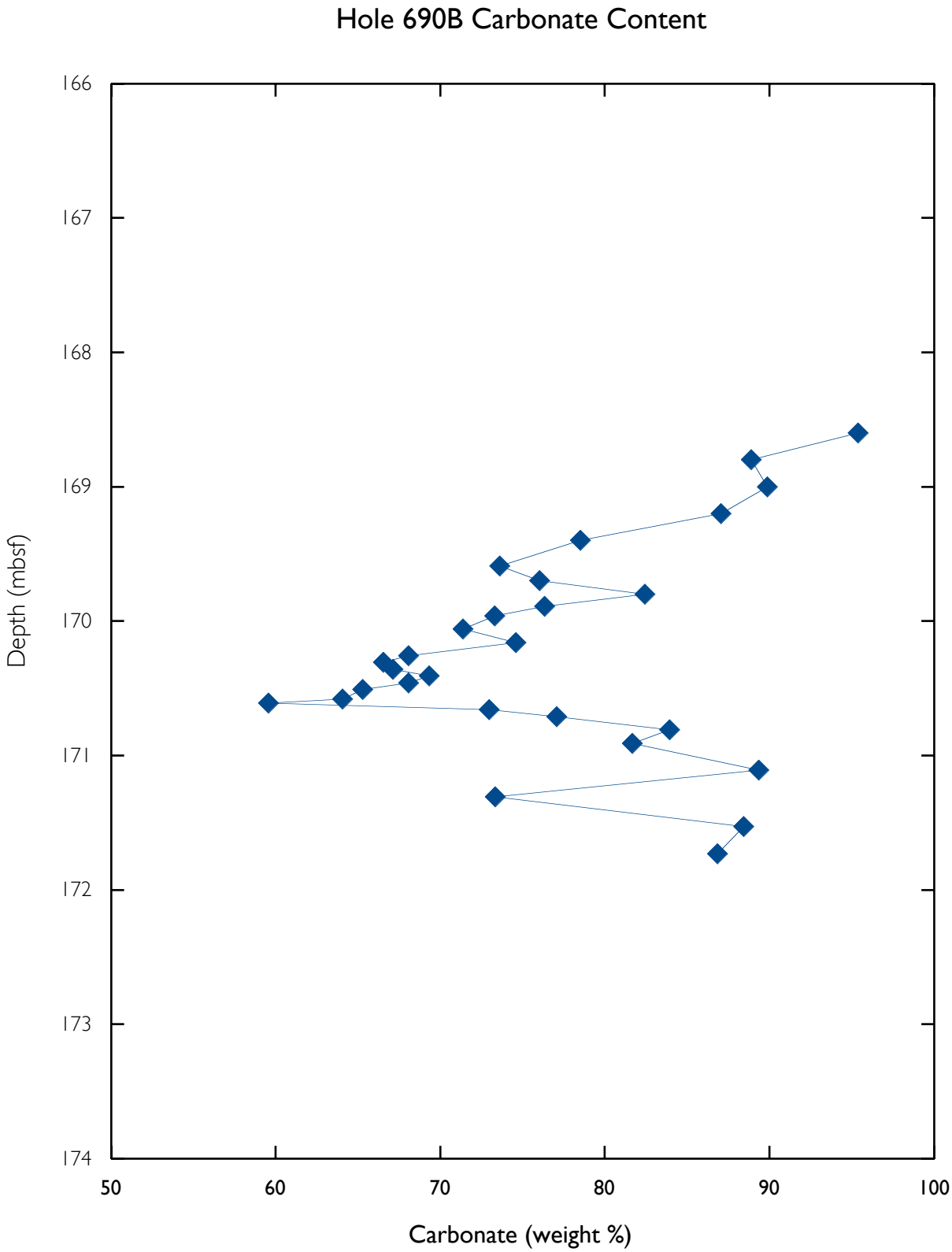
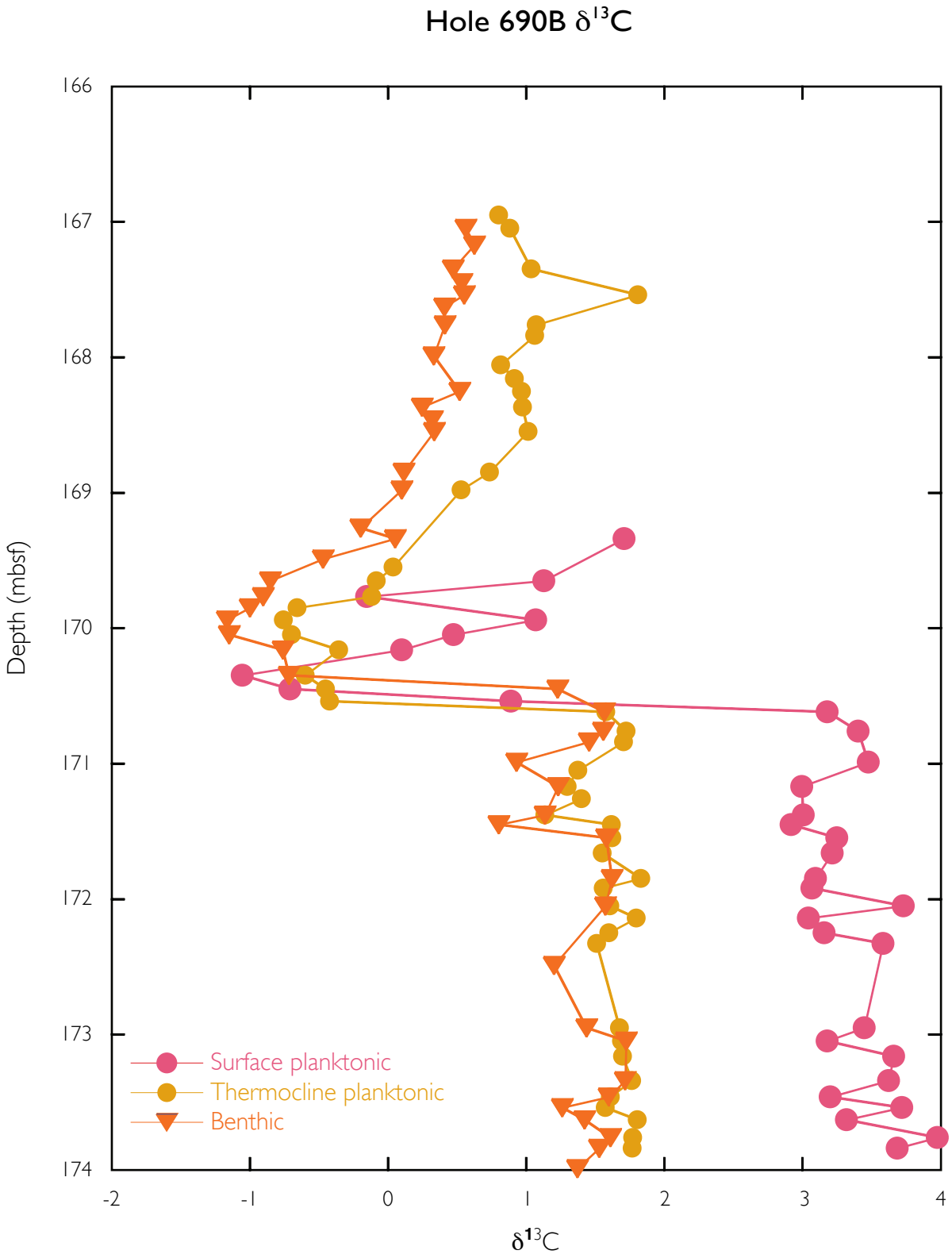
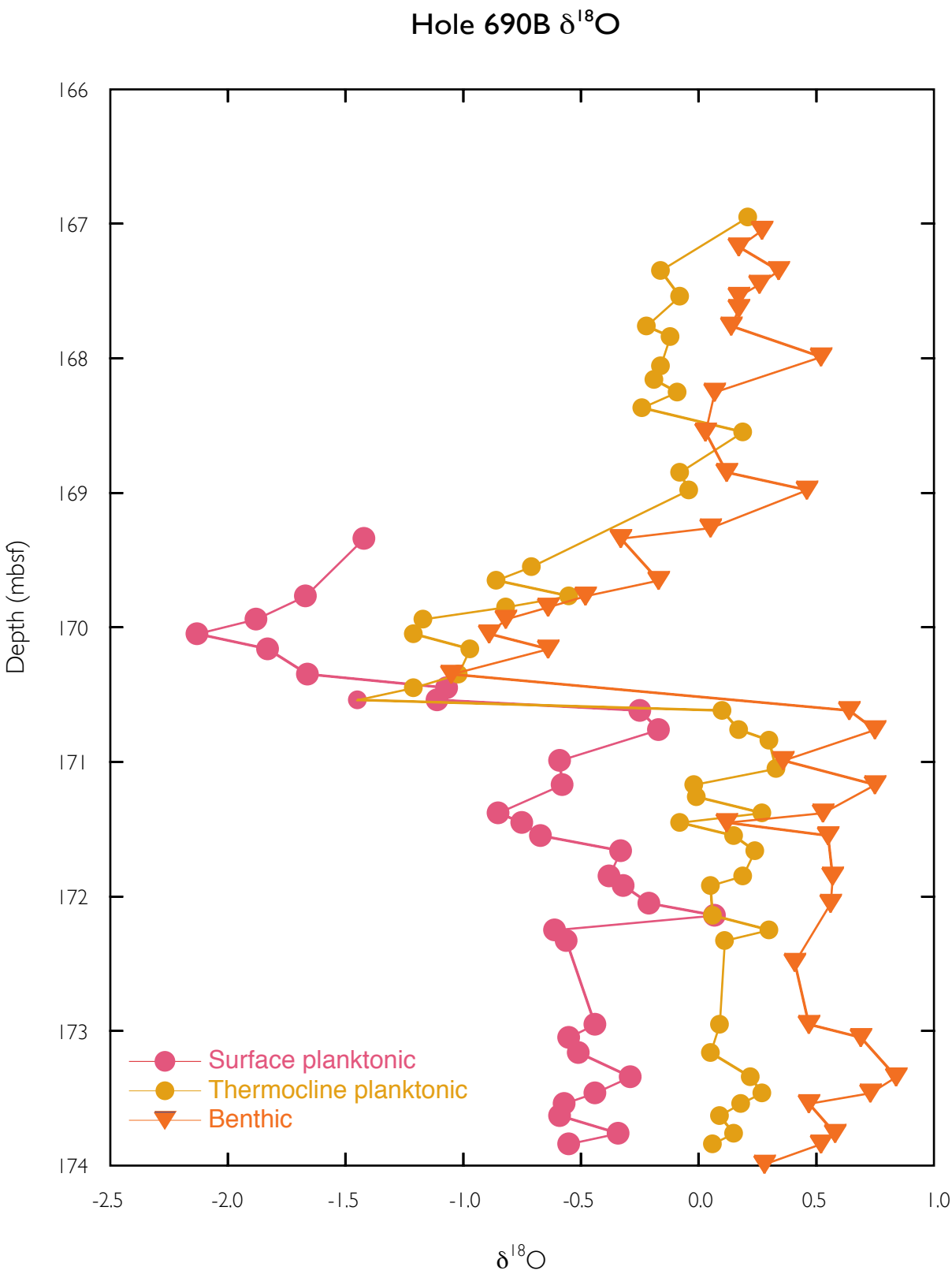
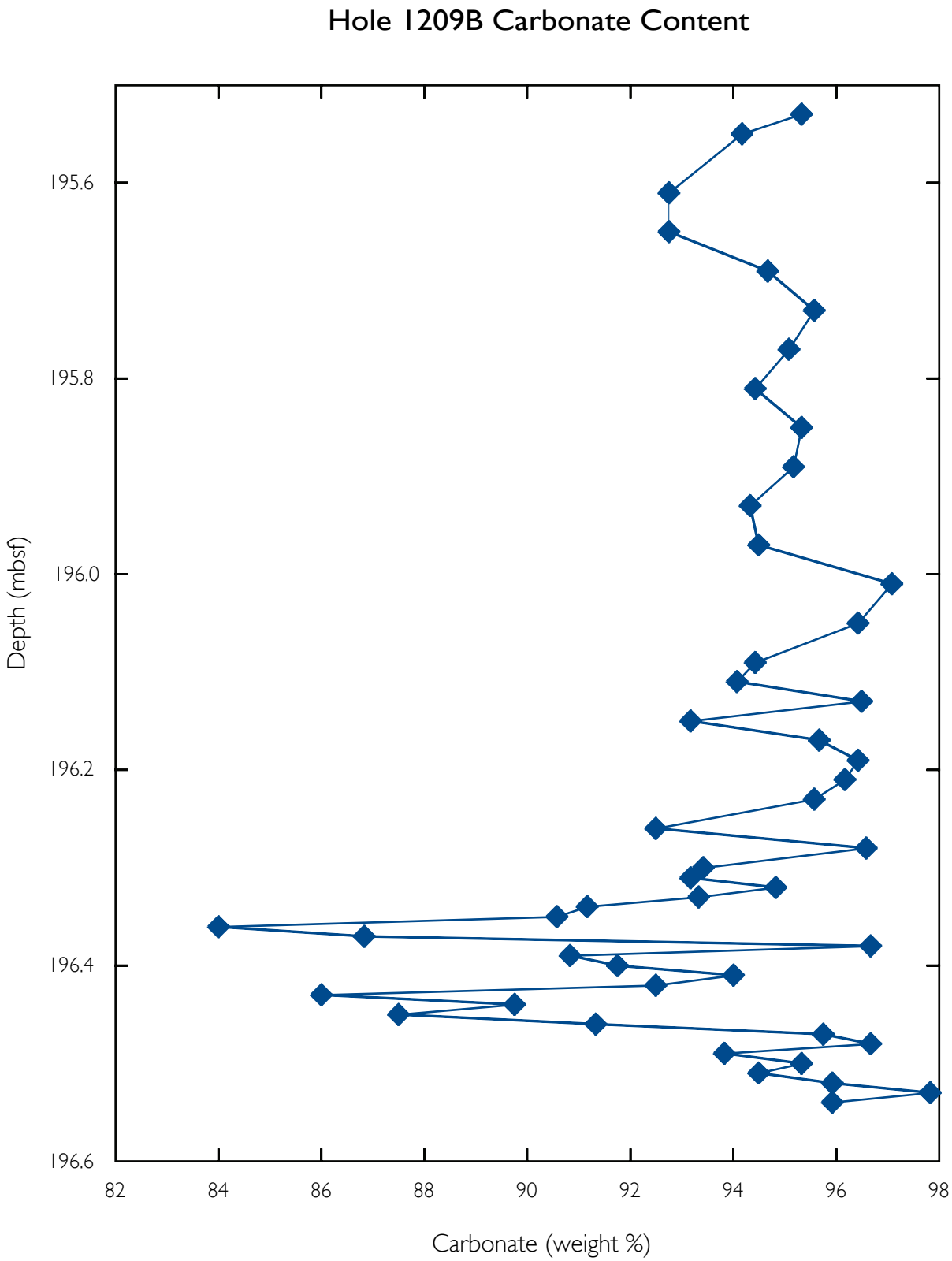


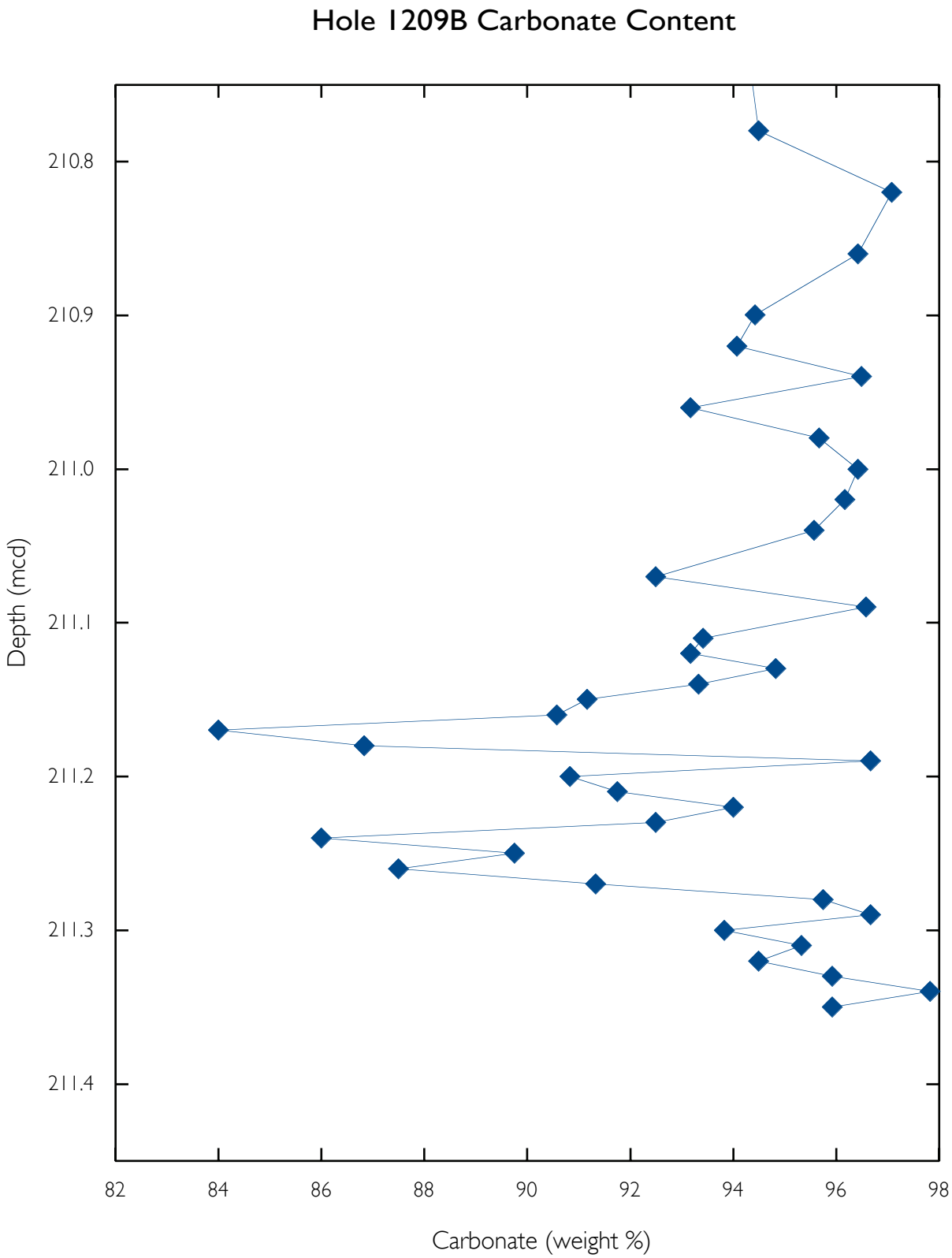
Figure 5. *Magnetic susceptibility data from 3 adjacent holes are used to splice a composite depth scale for Site 1211.*

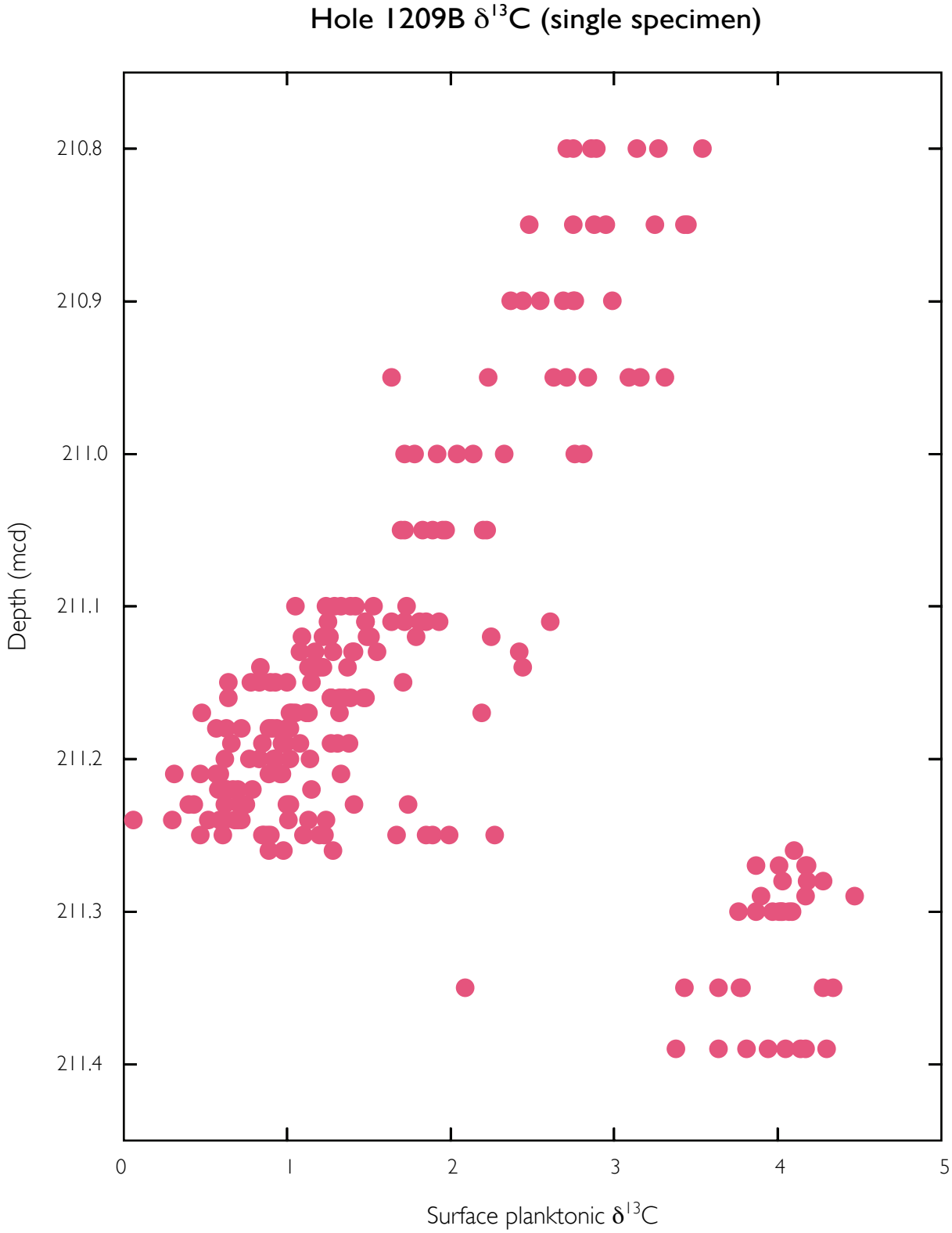

Hole 690B Carbonate Content
Depth (mbsf)
166
167
168
169
170
171
172
173
174
50
60
70
80
90
100
Carbonate (weight %)

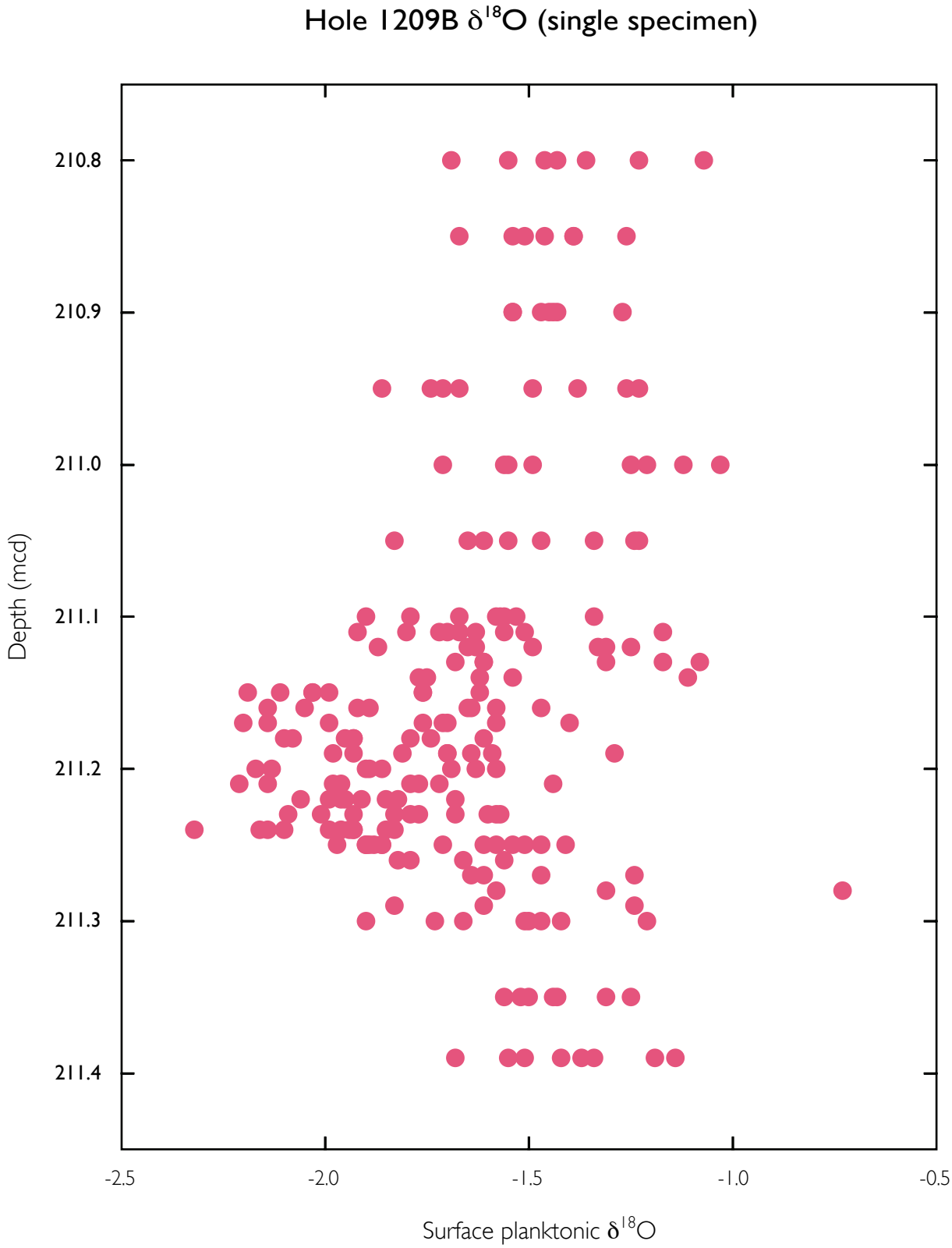

Hole 690B δ13C
Depth (mbsf)
166
167
168
169
170
171
172
173
174
-2
-1
0
1
2
3
4
δ13C
Surface planktonic
Thermocline planktonic
Benthic

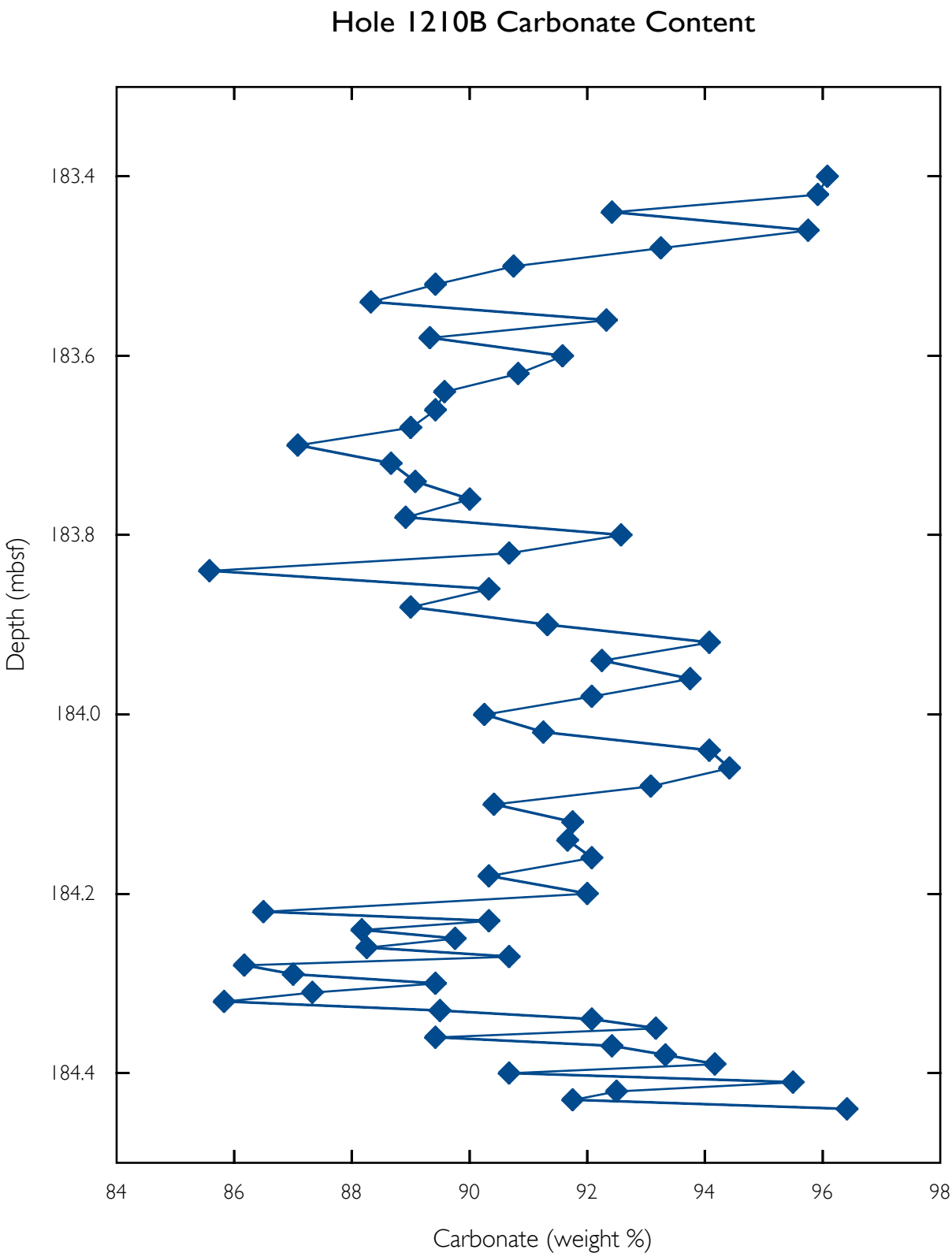

Hole 690B δ18O
Depth (mbsf)
166
167
168
169
170
171
172
173
174
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
δ18O
Surface planktonic
Thermocline planktonic
Benthic

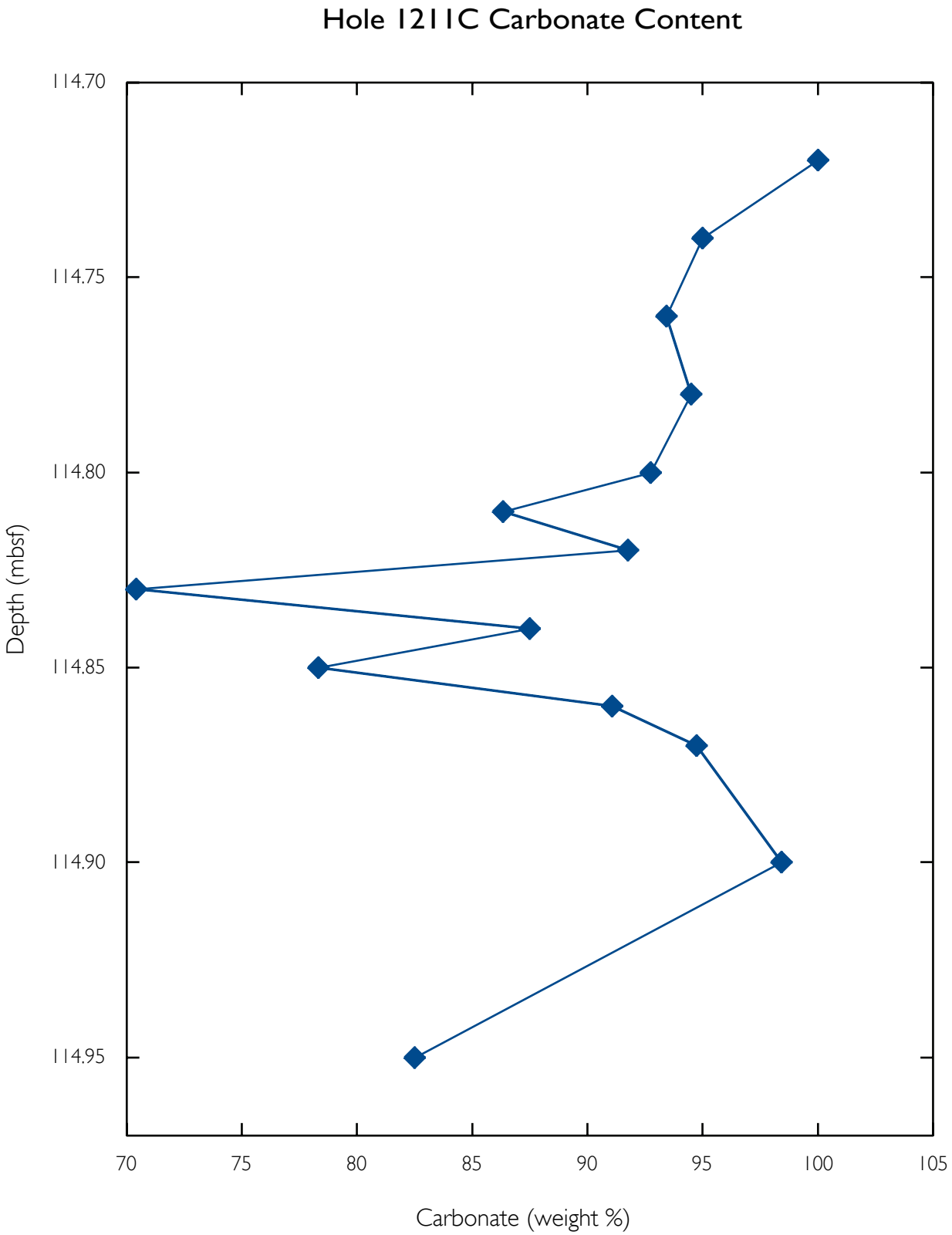

Hole 1209B Carbonate Content
Depth (mbsf)
195.6
195.8
196.0
196.2
196.4
196.6
82
84
86
88
90
92
94
96
98
Carbonate (weight %)

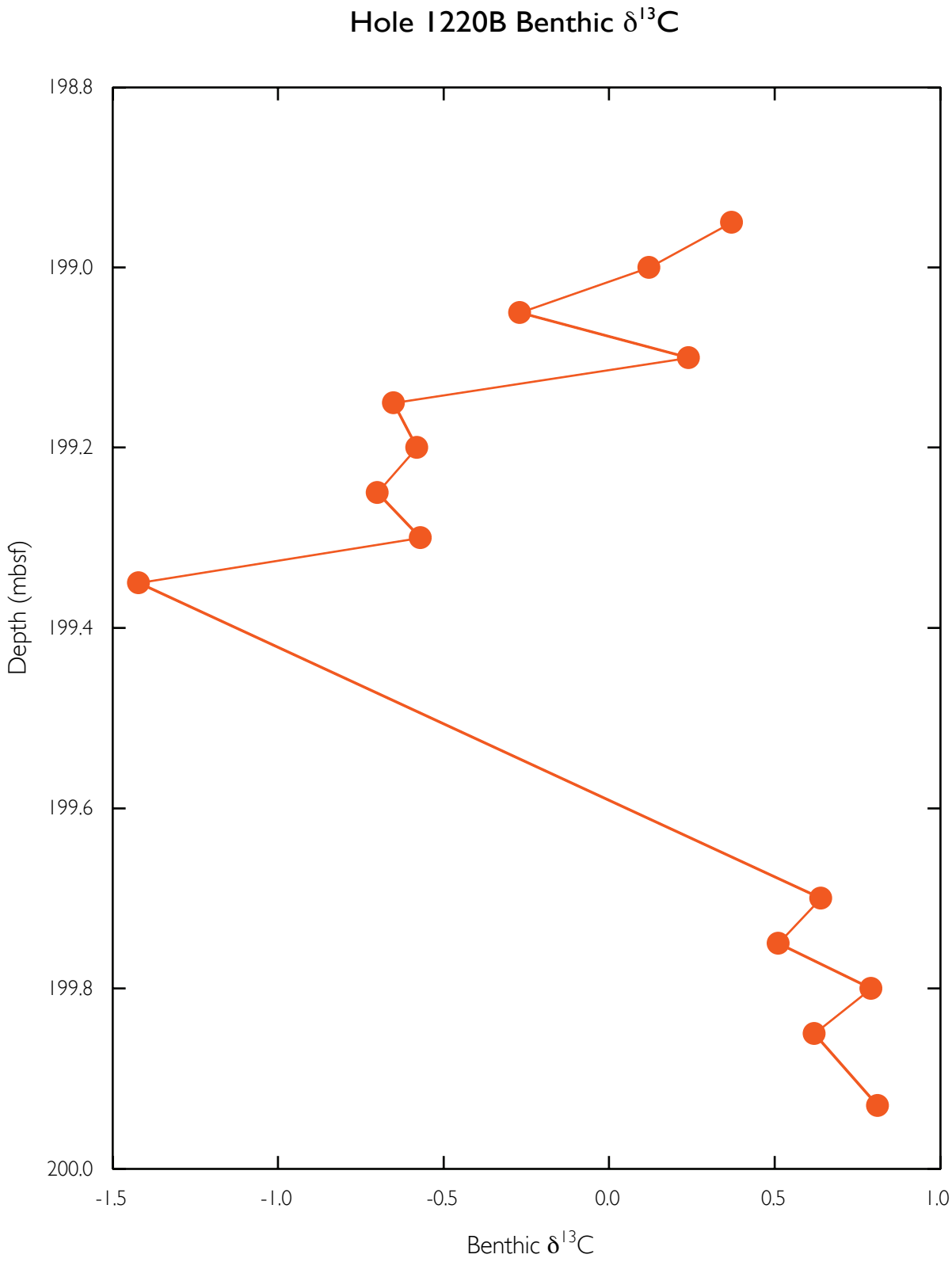

Hole 1209B Carbonate Content
Depth (mcd)
210.8
210.9
211.0
211.1
211.2
211.3
211.4
82
84
86
88
90
92
94
96
98
Carbonate (weight %)

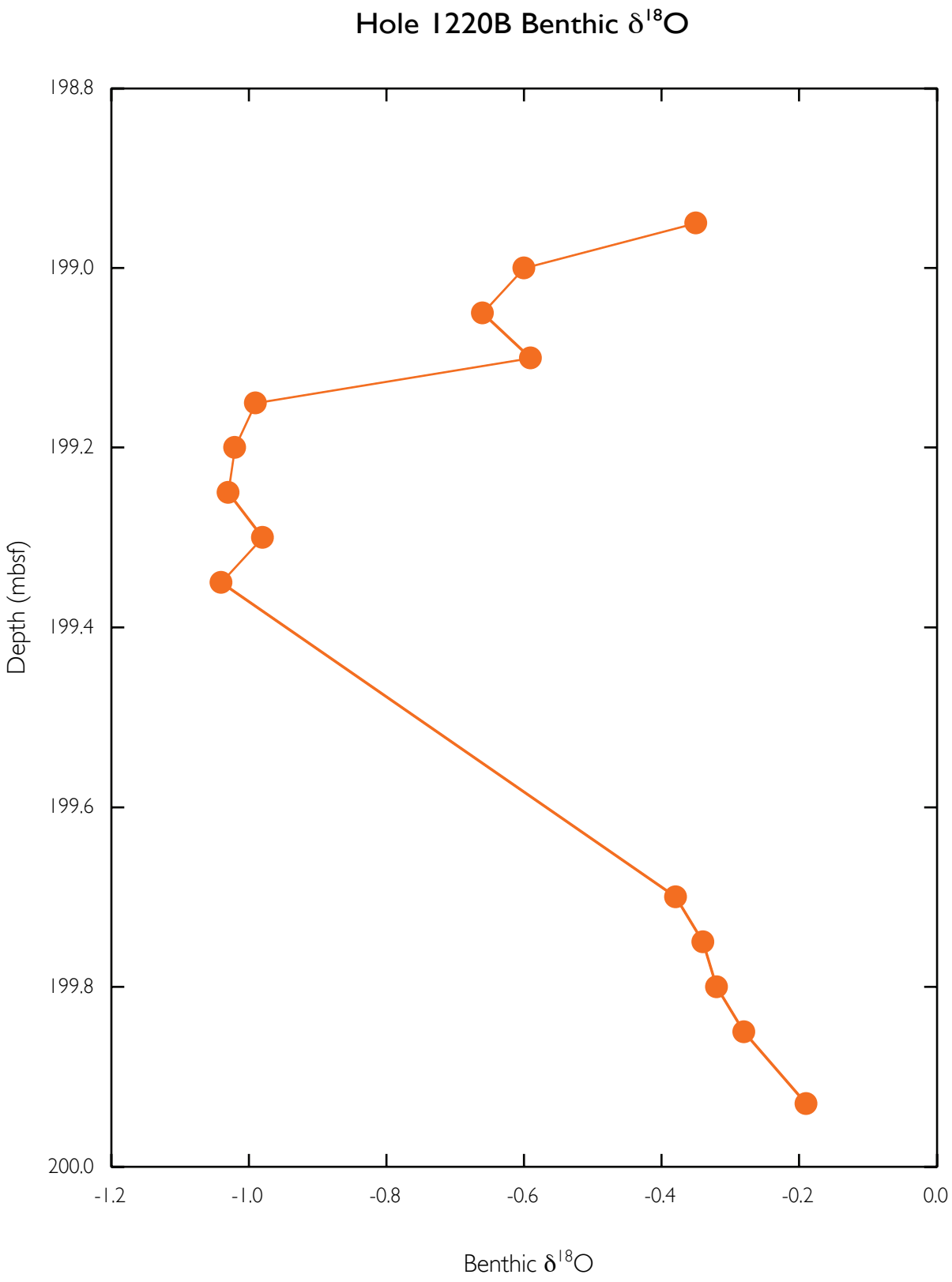

Hole 1209B δ13C (single specimen)
Depth (mcd)
210.8
210.9
211.0
211.1
211.2
211.3
211.4
0
1
2
3
4
5
Surface planktonic δ13C

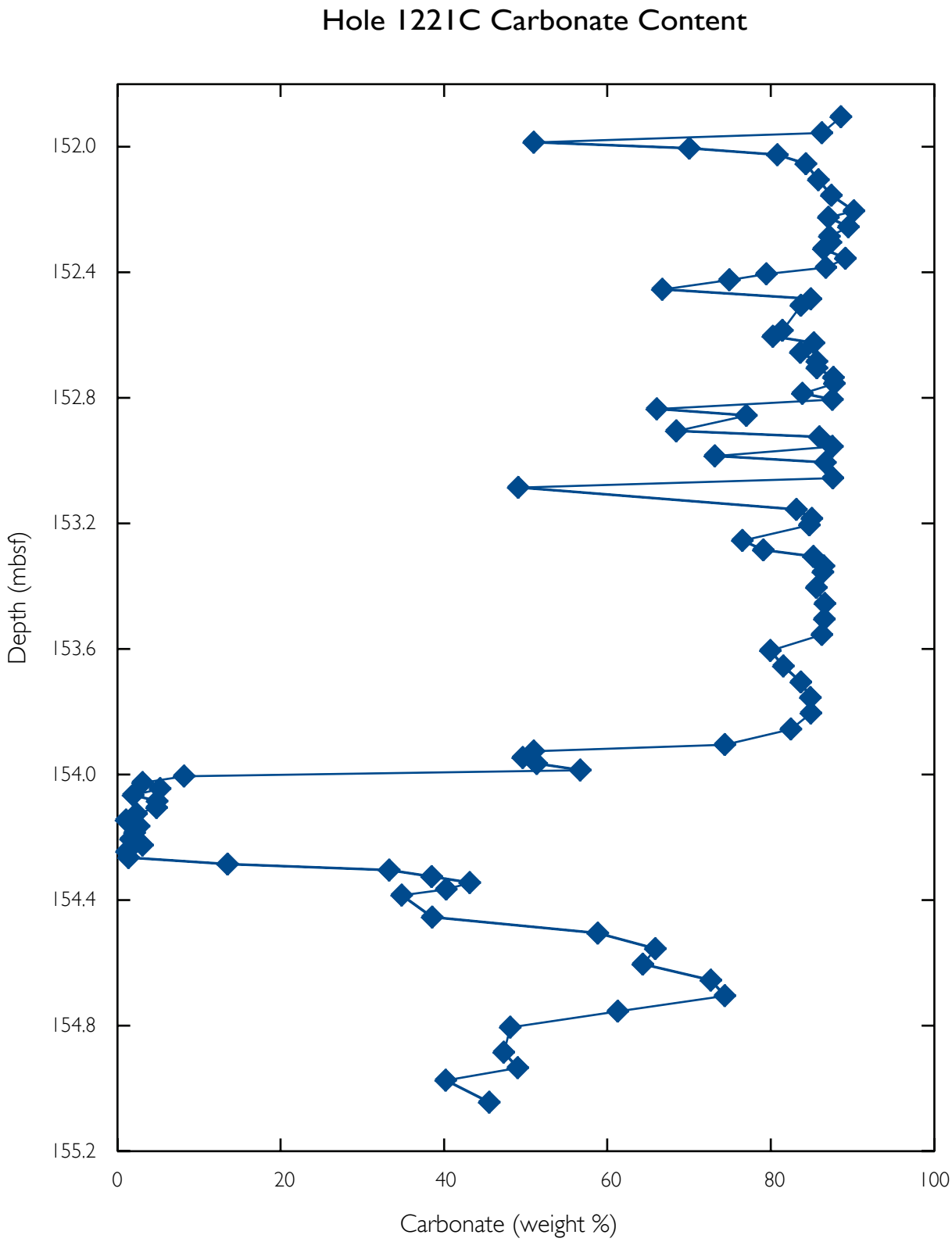

Hole 1209B δ18O (single specimen)
Depth (mcd)
210.8
210.9
211.0
211.1
211.2
211.3
211.4
-2.5
-2.0
-1.5
-1.0
-0.5
Surface planktonic δ18O

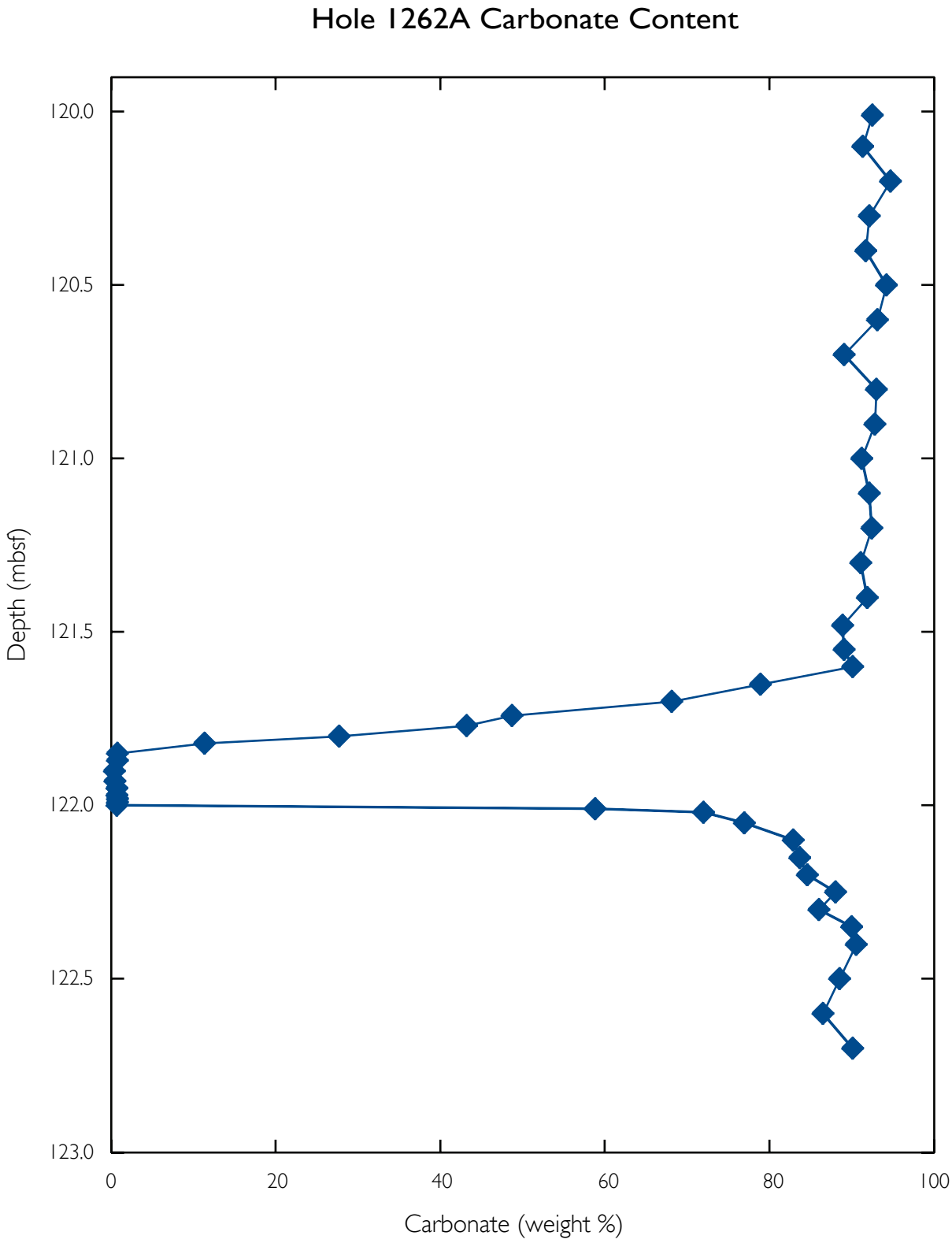

Hole 1210B Carbonate Content
Depth (mbsf)
183.4
183.6
183.8
184.0
184.2
184.4
84
86
88
90
92
94
96
98
Carbonate (weight %)

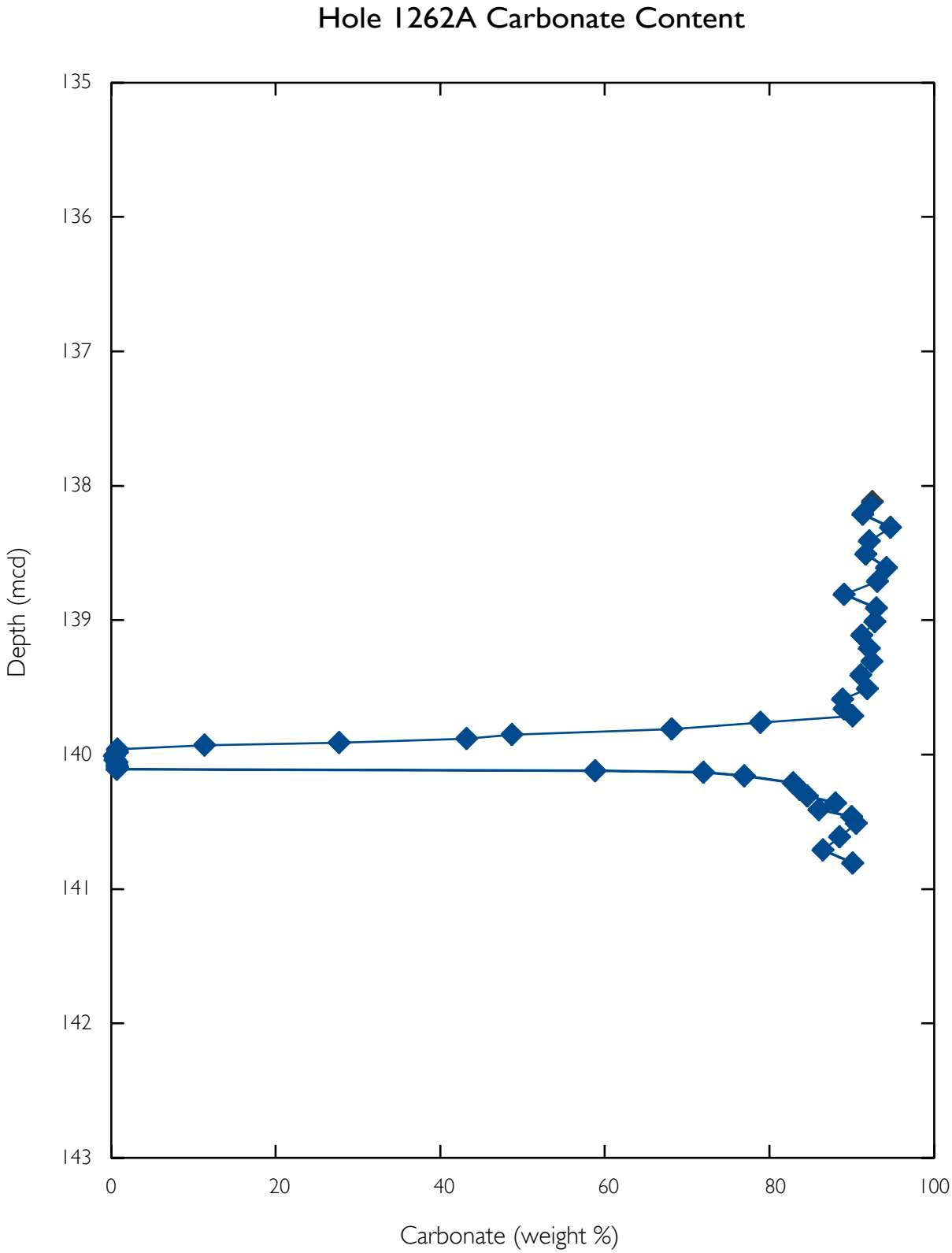

Hole 1211C Carbonate Content
Depth (mbsf)
114.70
114.75
114.80
114.85
114.90
114.95
70
75
80
85
90
95
100
105
Carbonate (weight %)

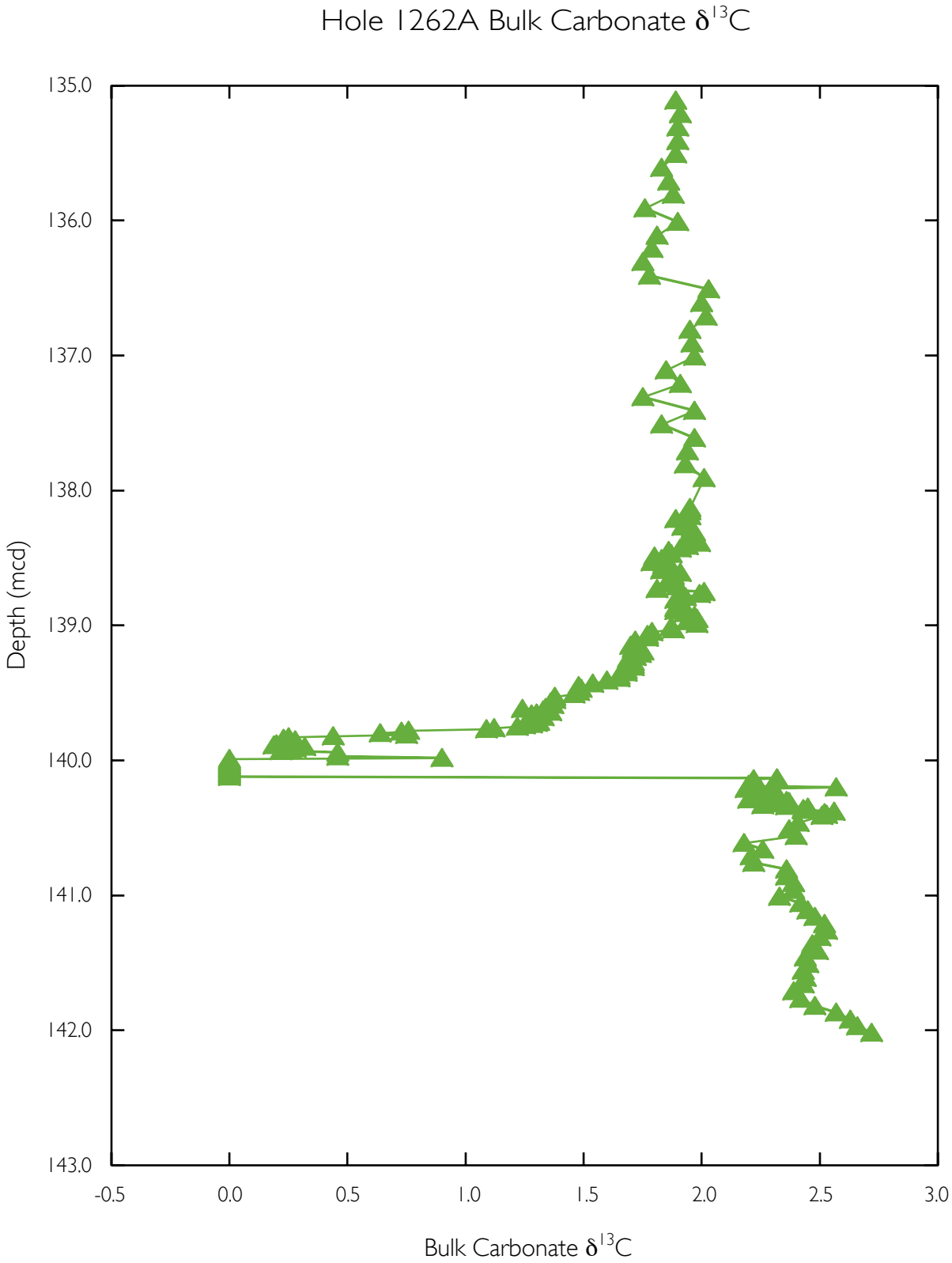

Hole 1220B Benthic δ13C
198.8
199.0
199.2
199.4
199.6
199.8
200.0
Depth (mbsf)
-1.5
-1.0
-0.5
0.0
0.5
1.0
Benthic δ13C

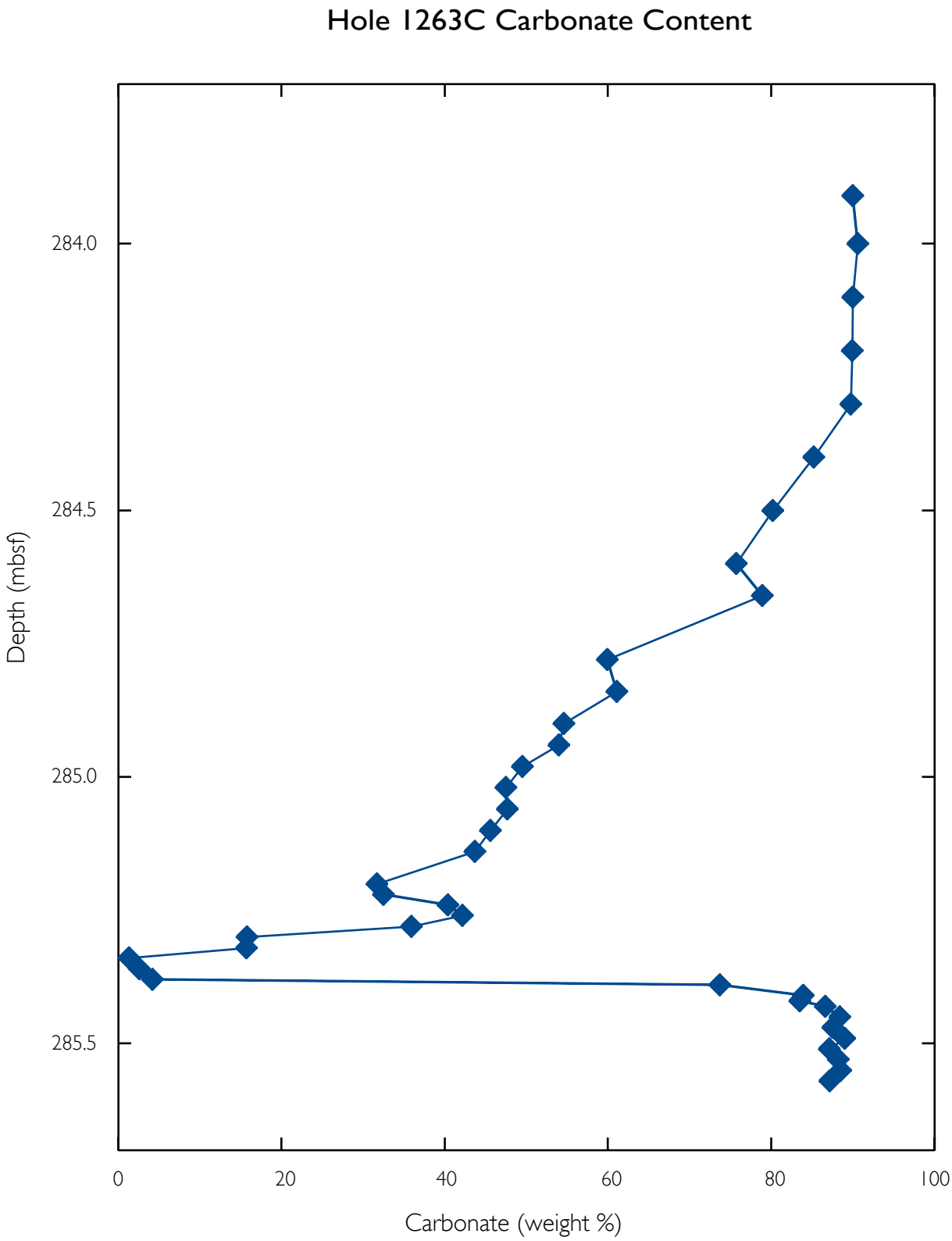

Hole 1220B Benthic δ18O
198.8
199.0
199.2
199.4
199.6
199.8
200.0
Depth (mbsf)
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
Benthic δ18O

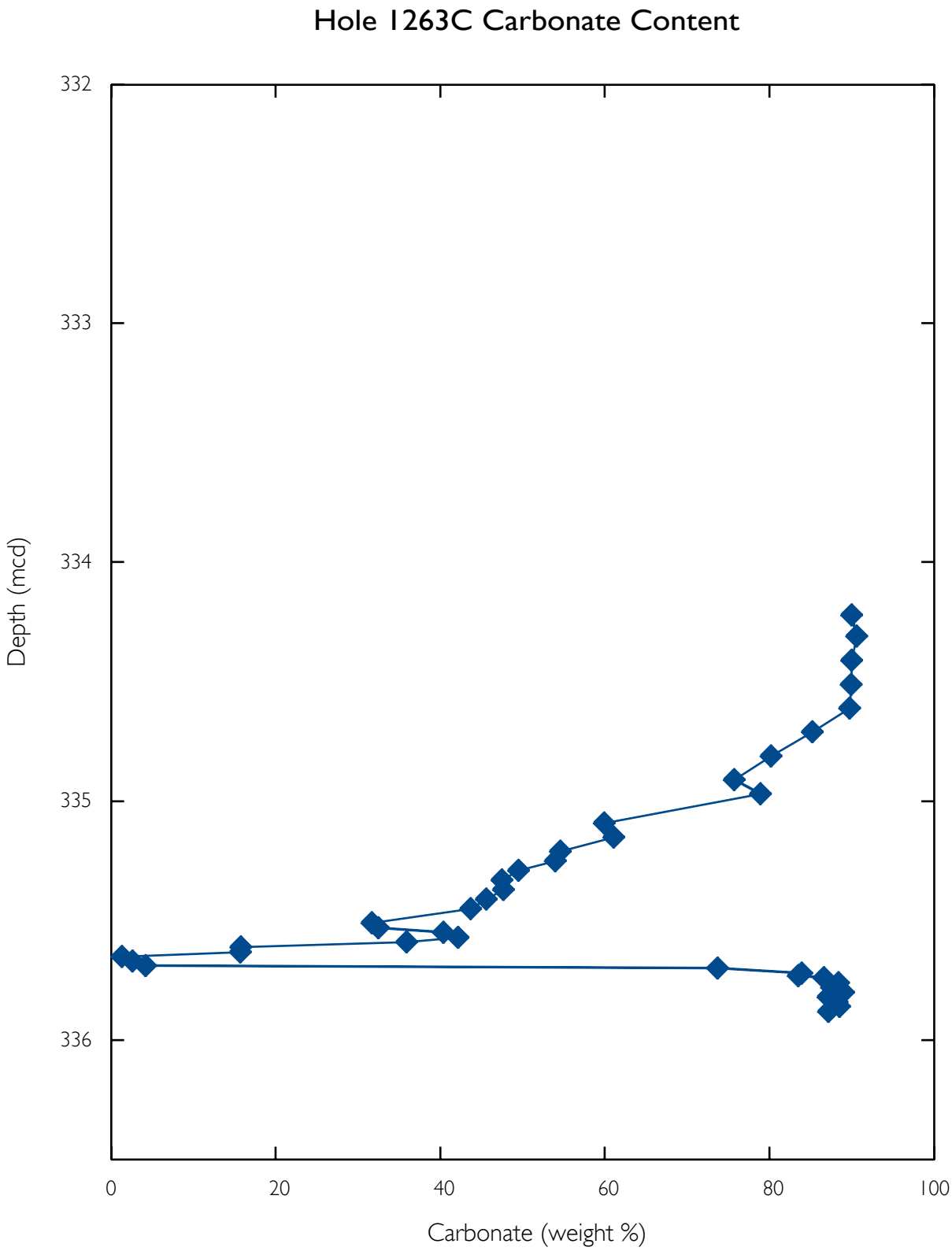

Hole 1221C Carbonate Content
Depth (mbsf)
152.0
152.4
152.8
153.2
153.6
154.0
154.4
154.8
155.2
0
20
40
60
80
100
Carbonate (weight %)

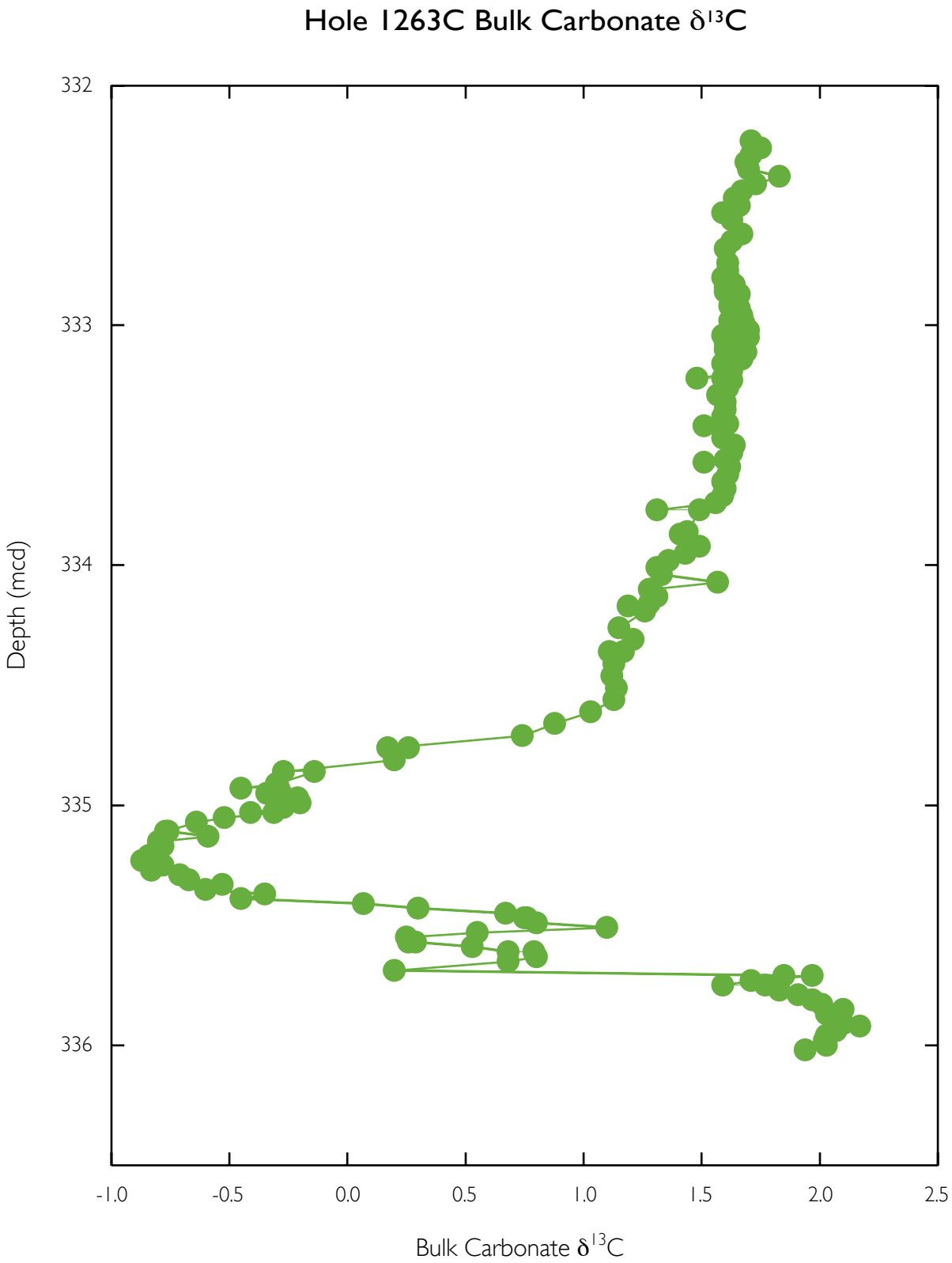

Hole 1262A Carbonate Content
Depth (mbsf)
120.0
120.5
121.0
121.5
122.0
122.5
123.0
0
20
40
60
80
100
Carbonate (weight %)

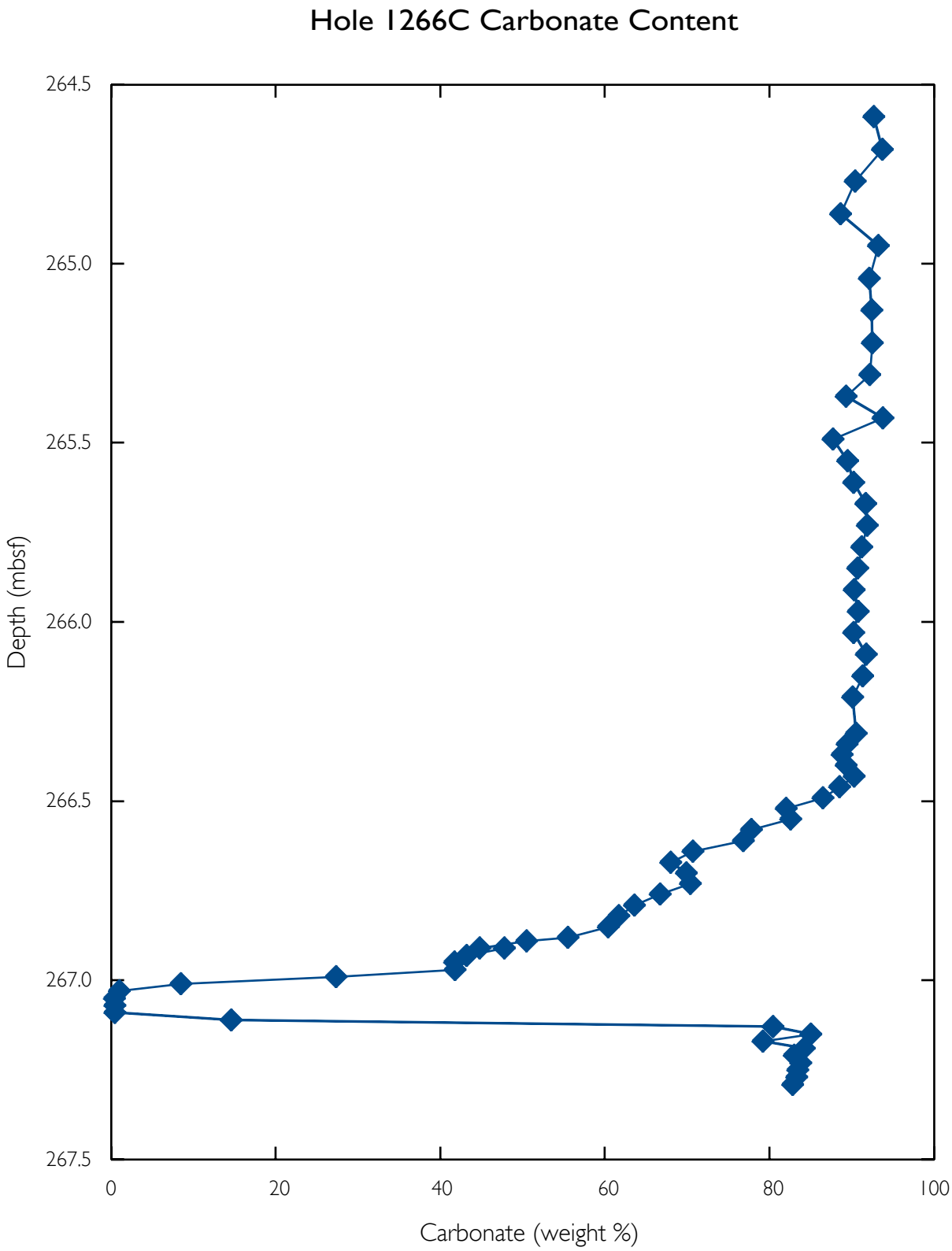

Hole 1262A Carbonate Content
Depth (mcd)
135
136
137
138
139
140
141
142
143
0
20
40
60
80
100
Carbonate (weight %)

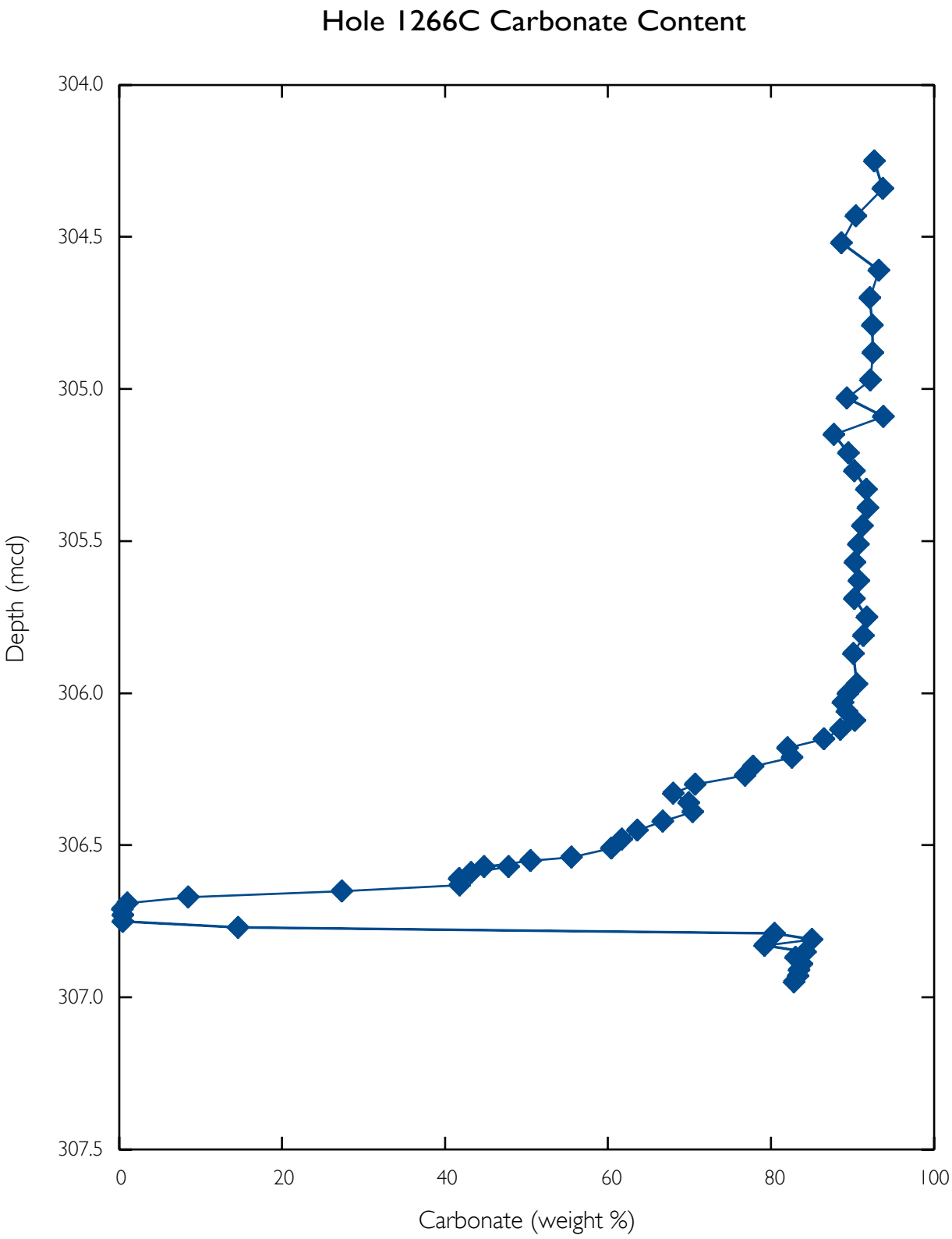

Hole 1262A Bulk Carbonate δ13C
Depth (mcd)
135.0
136.0
137.0
138.0
139.0
140.0
141.0
142.0
143.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Bulk Carbonate δ13C

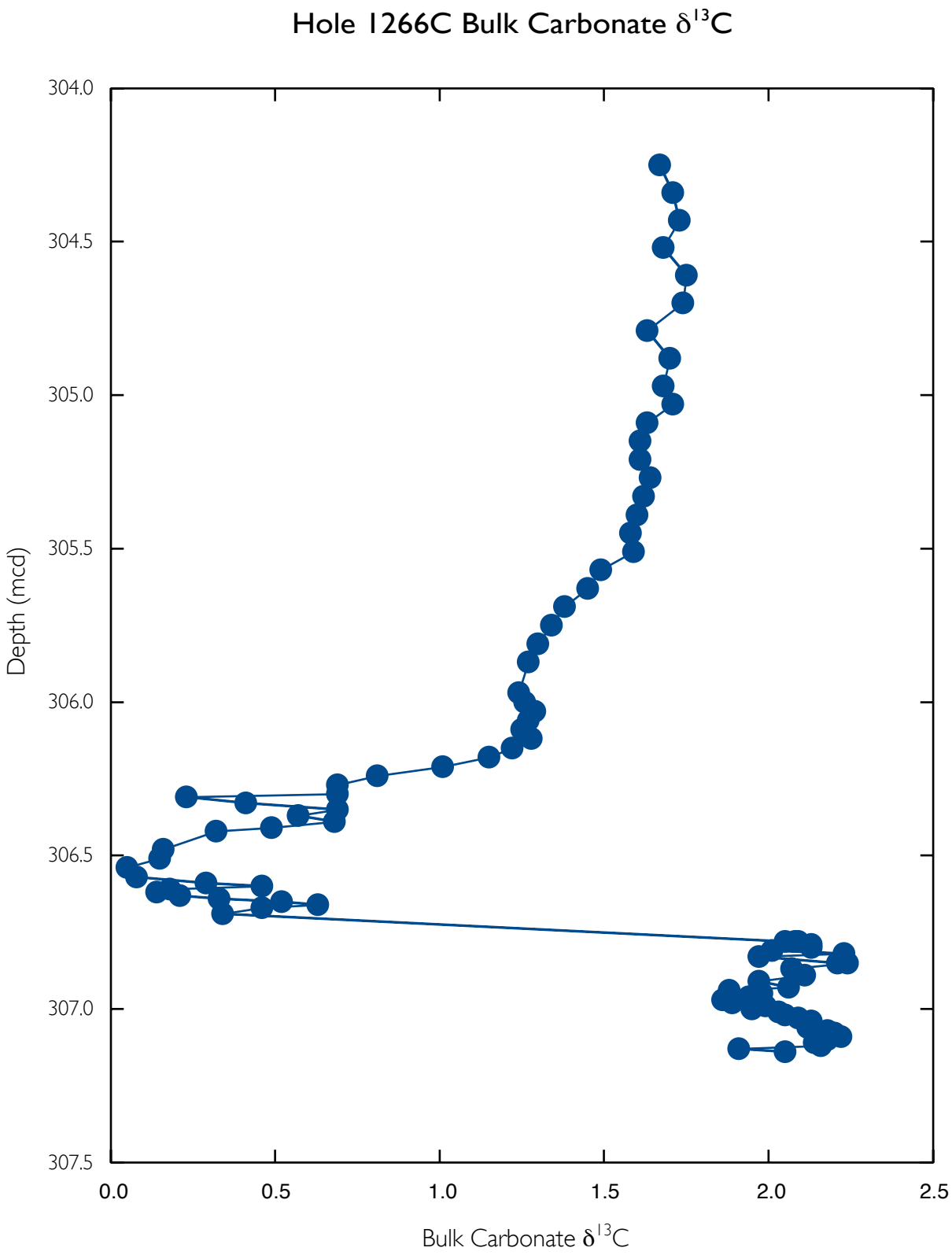

Hole 1263C Carbonate Content
Depth (mbsf)
284.0
284.5
285.0
285.5
0
20
40
60
80
100
Carbonate (weight %)


Hole 1263C Carbonate Content
Depth (mcd)
332
333
334
335
336
0
20
40
60
80
100
Carbonate (weight %)


Hole 1263C Bulk Carbonate δ13C
Depth (mcd)
332
333
334
335
336
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
Bulk Carbonate δ13C


Hole 1266C Carbonate Content
Depth (mbsf)
264.5
265.0
265.5
266.0
266.5
267.0
267.5
0
20
40
60
80
100
Carbonate (weight %)


Hole 1266C Carbonate Content
Depth (mcd)
304.0
304.5
305.0
305.5
306.0
306.5
307.0
307.5
0
20
40
60
80
100
Carbonate (weight %)


Hole 1266C Bulk Carbonate δ13C
Depth (mcd)
304.0
304.5
305.0
305.5
306.0
306.5
307.0
307.5
0.0
0.5
1.0
1.5
2.0
2.5
Bulk Carbonate δ13C