ASSESSING THE STRATIGRAPHIC INTEGRITY OF PLANKTIC AND BENTHIC \(^{14}C\) RECORDS IN THE WESTERN PACIFIC FOR \(\Delta^{14}C\) RECONSTRUCTIONS AT THE LAST GLACIAL TERMINATION

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ABSTRACT. There is a growing database of radiocarbon \(({^{14}C})\) reconstructions from biogenic carbonate taken from marine sediment cores being used to investigate changing ocean circulation and carbon cycling at the end of the last great ice age. Reported here are \(^{14}C\) results from a marine core taken in the Makassar Straits of the western equatorial Pacific that was intended to test whether there was evidence of geologic carbon release to the ocean during the glacial termination. A thorough investigation of planktic and benthic \(^{14}C\) ages with stable isotopes and CT-scans revealed extensive burrowing in the upper 2 m of the core that displaced younger sediments downward by more than half a meter into the glacial section of the core. The vertical displacement is evident in both planktic and benthic fossils. However, the extent of displacement and the stratigraphic disturbance became evident only after multiple measurements of different species and genera. A CT-scan prior to sampling would be an effective screening tool to avoid sampling problem cores such as this.

KEYWORDS: isotope analysis, mysterious radiocarbon anomalies.

INTRODUCTION

Considerable effort and expense have been devoted to reconstructions of radiocarbon activity \(\Delta^{14}C\) of biogenic carbonates from marine sediments to evaluate how the global-scale overturning circulation responded to climate changes in the past. This is particularly true for the interval spanning the end of the last glacial maxima and the onset of deglaciation (18–14 kyBP) when the radiocarbon activity of the ocean and atmosphere fell by \(\sim 190\%\) while the production rate of radiocarbon did not decrease correspondingly (Laj et al. 2002; Hain et al. 2014). These contrasting observations led to the term “Mystery Interval” (Broecker and Barker 2007; Broecker 2009). And when considering how to reconcile these two opposing observations, it initially appeared there were only two plausible explanations, both entailing a change in the residence time of waters within the Ocean. The first hypothesis called upon enhanced bottom water stratification and the isolation of an abyssal water mass that accumulated respired metabolic carbon during glaciations (Toggweiler 1999) and then the aged, \(^{14}C\)-depleted abyssal waters were ventilated during the Mystery Interval (Broecker 2009). But after considerable effort, no such isolated abyssal water mass has been documented from glacial age sediment records (Broecker et al. 2004; Broecker and Clark 2010; Hain et al. 2011; Keigwin and Lehman 2015; Zhao et al. 2018). The second hypothesis calls for an enhanced biological pump during glaciations and an overall slow-down of ocean overturning. This would lead to a net accumulation of respired carbon and longer deep-water residence times during glaciations. Then during deglaciation, as ventilation rates increased, the residence time of deep water decreased (Sigman and Boyle 2000; Anderson et al. 2009, 2019; Kwon et al. 2011; Jacobel et al. 2019; Menviel et al. 2018). This hypothesis makes specific predictions about \(\Delta^{14}C\) change in the ocean during the deglaciation. It predicts that the \(\Delta^{14}C\) of deep waters throughout the ocean would increase as older (\(^{14}C\)-depleted) waters from the glacial ocean were replaced by younger
waters at the onset of deglaciation, (Huiskamp and Meissner 2012; Menviel et al. 2018). This hypothesis also predicts that the $\delta^{13}C$ of dissolved inorganic carbon in deep waters would increase as $^{13}C$-depleted respired carbon is replaced by better-ventilated waters (Menviel et al. 2018).

While these ocean circulation hypotheses continue to be investigated, an alternative hypothesis has been put forth that calls upon release of “old” geologic carbon to the ocean and atmosphere during the late glacial and early deglaciation (Stott and Timmermann 2011). Evidence in support of this hypothesis includes large $\Delta^{14}C$ excursions during the last deglaciation (Figure 1). These excursions have been identified in each ocean basin (Stott et al. 2009, 2019a, 2019b; Mangini et al. 2010; Stott and Timmermann 2011; Ronge et al. 2016; Rafter et al. 2018). But there are vast portions of the ocean that have not been explored. Hence, it is not yet clear how extensive these deglacial $\Delta^{14}C$ excursions were and therefore, how much “old” carbon was released to the oceans.

Figure 1 Upper panel is a site location map of the MD98-2164 core and other shallow-intermediate depth cores from previous studies that document benthic $\Delta^{14}C$ excursions at the last glacial termination (lower panel), Table 2.
during the late glacial and early deglaciation. For this reason, efforts are underway to investigate other locations where geologic carbon may have been released to the oceans, including sites in the western equatorial Pacific, which is a geologically active region with numerous hydrothermal and volcanic sources that could contribute $^{14}$C-depleted carbon to the ocean.

In 1998 a coring cruise with the Marion Dufresne set out to obtain a suite of cores in the western Pacific, including sites within the Indonesian Archipelago. The original goal of the endeavor was to investigate the history of the Indonesian Throughflow during the Pleistocene using geochemical tracers to assess whether there was a change in the exchange of waters between the Pacific and Indian Oceans. The exchange of upper ocean waters between the Pacific to the Indian Ocean plays an important role in maintaining continuity in exchange of energy, mass and chemical constituents between ocean basins. For that study a suite of sediment cores was collected from shallow/intermediate water depths between 600 and 1000 m within the Indonesian Archipelago. And because these cores are located in the volcanically active Indonesian region, they are also ideally suited for investigating the history of $\Delta^{14}$C change and the potential role that geologic sources of carbon had on the carbon cycle during the last glacial cycle.

Studies of marine sediments typically begin by developing a stable oxygen isotope stratigraphy from planktic or benthic foraminiferal calcite taken from discrete horizons in a core. The downcore stable isotope values are then compared to well-established marine composite records (standard curves) of planktic or benthic $\delta^{18}$O that have been chronologically aligned to U/Th dated speleothem $\delta^{18}$O records or ice core records (Lisiecki and Stern 2016). But comparing a sediment core’s stable isotope stratigraphy to a standard curve leaves uncertainty about a core’s stratigraphic continuity or integrity. This is because sediment disturbances, missing sediments (hiatuses) may be undetectable from these comparisons alone. Radiocarbon data of biogenic constituents such as foraminifera may be a useful tool for evaluating a core’s stratigraphic integrity. At the same time, these are costly measurements and when the purpose of making the $^{14}$C measurements is to explore whether there was a radiocarbon anomaly at the glacial termination, it is also possible that what may appear to be a $^{14}$C excursion is in fact, an artifact of core disturbance. This becomes clear only after developing a stable isotope stratigraphy and making numerous $^{14}$C measurements. In the present study an example is presented that illustrates how important it is to thoroughly investigate whether the stratigraphy of a core has been disrupted by post depositional processes such as large burrowing, which can displace sediments.

STUDY SITE AND METHODS

In 1998 core MD9821-64 was collected in the Makkassar Strait (Figure 1) (6.64°S, 119.42°E; 719 m water depth). The core was split into two halves. One half was used for sampling, the other archived. Sediment samples were taken at 5-cm intervals. Each sample was disaggregated in a buffered sodium hexametaphosphate solution and then washed over a $>63 \mu$m screen to remove the fines. The $>63 \mu$m fraction was then dried at low temperature. The $\delta$18O and $\delta$13C was measured on a Micromass Isoprime dual inlet mass spectrometer with carbonate device located at the University of Southern California in April 2010. A standard
calcite (Ultiss) was measured in the same system along with the foraminiferal samples. Average precision for these standards was <0.15‰ for both oxygen and carbon. All stable isotope results are reported in ‰ relative to VPDB standard. Single specimens of G. ruber and Globigerinoides sacculifer (>250 mm, no final sac) were also analyzed from 4 samples (11 cm, 181 cm, 191 cm and 195 cm). These specimens were cleaned using the same method as the multi-specimen samples. The Ultiss standard was run with these samples at weights similar to that of the single specimens (~20 μg). The precision for these small standard samples was also <0.15‰.

Between December 2009 and July 2010 planktic and benthic foraminifera were picked for radiocarbon analysis to assess whether there were changes in the surface to intermediate depth 14C age difference at the last glacial termination. Similar studies using cores from the eastern equatorial Pacific have documented large benthic-planktic (B-P) 14C age increases at the last glacial termination (Stott et al. 2009). Using the stable isotope stratigraphy as a guide, samples were selected at 10–20-cm intervals, starting from the 3-cm interval down to the δ18O maxima at 199 cm. In some samples the benthic foraminifer Oridorsalis sp were large enough to be analyzed individually. Bivalve shells and Gastropod specimens were also analyzed from several intervals. These samples were cleaned in the same way as the stable isotope samples. After cleaning and weighing the samples were submitted to the Keck Carbon Cycle AMS Laboratory at the University of California Irvine. The 14C ages are summarized in Table 1 in the chronologic order in which they were analyzed.

In August 2010 the top two sections of the core (half round tubes) were passed through a computed tomography scan (CT-scan) that combines X-ray measurements taken at different angles to produce a cross-sectional visualization of the internal structures of the core. This technique visualizes relative differences in sediment density and thus, is useful for characterizing core disturbances created by burrowing organisms.

RESULTS AND DISCUSSION

The initial suite of G. ruber δ18O measurements (Figure 2) document two interglacial to glacial transitions corresponding to marine isotope stages 1 and 2 (0–200 cm) and stages 4 and 5 (750–900 cm). The magnitude of change between the warm interglacial stage 1 and the colder glacial stage 2 is ~2‰ and very close to other G. ruber δ18O records developed from higher deposition rate cores from the western Pacific (Stott et al. 2002, 2004, 2007; Saikku et al. 2009). There is no indication of a break in the glacial to interglacial δ18O stratigraphy except a sample at 141 cm that has a slightly higher δ18O value than the sample at 161 cm. The stable isotope stratigraphy indicates the last glacial maximum occurs at ~199 cm. Using the 199 cm sample as a chronologic datum implies an average sedimentation rate of ~10 cm/kyr for the top 2 m of the core. With these results in hand it appeared appropriate to proceed with the second phase of the study, to develop planktic and benthic 14C ages to investigate whether there was increased benthic-planktic 14C age differences at the glacial termination as seen in other shallow-intermediate depth cores (see Table 2).

An initial suite of 14C measurements was conducted on multi-specimens of the planktic species Globigerinoides sacculifer and the benthic genus Oridorsalis (Figure 3a). This included 4 analyses of individual Oridorsalis sp specimens that were large enough for analysis. The planktic 14C ages appeared to confirm the stratigraphic ages inferred from the G. ruber δ18O stratigraphy. The G. sacculifer 14C age at 199 cm of 19,030 years is consistent with
Table 1  MD9821-64 $^{14}$C results.

| Depth (cm) | Fossils           | Date analyzed | Weight (mg) | Planktic $^{14}$C age (year) | Benthic $^{14}$C age (year) | Error (yrs) | Accession |
|------------|-------------------|---------------|-------------|------------------------------|----------------------------|-------------|-----------|
| 3          | Oridorsalis       | Dec. 11, 2009 | 3.51        | 2180                         | 15                         | 71595       |
| 3          | G. sacculifer     | Dec. 11, 2009 | 6.313       | 1730                         | 20                         | 71596       |
| 11         | Oridorsalis       | Dec. 11, 2009 | 4.501       | 2660                         | 20                         | 71597       |
| 11         | G. sacculifer     | Dec. 11, 2009 | 6.742       | 2035                         | 20                         | 71598       |
| 61         | Oridorsalis       | Dec. 11, 2009 | 6.637       | 4940                         | 20                         | 71599       |
| 61         | G. sacculifer     | Dec. 11, 2009 | 8.828       | 4670                         | 15                         | 71600       |
| 65         | Oridorsalis       | Dec. 11, 2009 | 6.62        | 5260                         | 25                         | 71601       |
| 65         | G. sacculifer     | Dec. 11, 2009 | 8.776       | 4600                         | 20                         | 71602       |
| 71         | Oridorsalis       | Dec. 11, 2009 | 5.946       | 4905                         | 20                         | 71603       |
| 71         | G. sacculifer     | Dec. 11, 2009 | 7.311       | 4625                         | 15                         | 71604       |
| 101        | Oridorsalis       | May 12, 2010  | 3.17        | 8010                         | 25                         | 77272       |
| 101        | Oridorsalis (A)   | May 12, 2010  | 1.184       | 8150                         | 60                         | 77273       |
| 101        | Oridorsalis (B)   | May 12, 2010  | 1.254       | 7055                         | 45                         | 77274       |
| 101        | G. sacculifer     | May 12, 2010  | 7.352       | 8060                         | 20                         | 77275       |
| 111        | Oridorsalis       | May 12, 2010  | 4.109       | 7450                         | 20                         | 77276       |
| 111        | G. sacculifer     | May 12, 2010  | 6.749       | 7075                         | 20                         | 77277       |
| 121        | Oridorsalis       | May 12, 2010  | 2.701       | 12125                        | 45                         | 77278       |
| 121        | G. sacculifer     | May 12, 2010  | 6.708       | 9905                         | 25                         | 77279       |
| 141        | Oridorsalis       | May 12, 2010  | 2.616       | 13240                        | 50                         | 77280       |
| 141        | G. sacculifer     | May 12, 2010  | 5.454       | 13090                        | 40                         | 77281       |
| 161        | Oridorsalis       | May 12, 2010  | 1.576       | 14250                        | 110                        | 77282       |
| 161        | G. sacculifer     | May 12, 2010  | 5.97        | 14885                        | 45                         | 77283       |
| 199        | Oridorsalis       | May 12, 2010  | 2.083       | 25100                        | 310                        | 77284       |
| 199        | Oridorsalis (A)   | May 12, 2010  | 1.933       | 21290                        | 270                        | 77285       |
| 199        | Oridorsalis (B)   | May 12, 2010  | 1.72        | 22440                        | 320                        | 77286       |
| 199        | G. sacculifer     | May 12, 2010  | 3.832       | 19030                        | 110                        | 77287       |
| 199        | N. dutertrei      | June 1, 2010  | 7.691       | 8595                         | 20                         | 78031       |
| 199        | G. sacculifer     | June 1, 2010  | 8.345       | 7820                         | 20                         | 78032       |
| 199        | Oridorsalis       | June 1, 2010  | 2.197       | 8480                         | 40                         | 78033       |
| 199        | Cibicides         | June 1, 2010  | 2.119       | 7995                         | 45                         | 78034       |
| 141        | N. dutertrei      | June 1, 2010  | 9.503       | 14685                        | 35                         | 78038       |
| 161        | N. dutertrei      | June 1, 2010  | 7.682       | 15730                        | 60                         | 78036       |
| 171        | N. dutertrei      | June 1, 2010  | 9.411       | 18435                        | 50                         | 78037       |
| 171        | G. sacculifer     | June 1, 2010  | 7.835       | 18100                        | 80                         | 78038       |
| 171        | Oridorsalis       | June 1, 2010  | 2.788       | 20000                        | 160                        | 78039       |
| 181        | N. dutertrei      | June 1, 2010  | 6.844       | 19370                        | 70                         | 78043       |
| 181        | G. sacculifer     | June 1, 2010  | 6.919       | 19210                        | 70                         | 78044       |
| 181        | Oridorsalis       | June 1, 2010  | 2.804       | 18890                        | 170                        | 78045       |
| 181        | Oridorsalis (A)   | June 1, 2010  | 5.134       | 19970                        | 80                         | 78046       |
| 191        | N. dutertrei      | June 1, 2010  | 9.08        | 17195                        | 40                         | 78047       |
| 191        | G. sacculifer     | June 1, 2010  | 8.131       | 12320                        | 40                         | 78048       |
| 191        | Oridorsalis       | June 1, 2010  | 5.491       | 16900                        | 60                         | 78049       |
| 191        | Gastropod         | June 1, 2010  | 21.835      | 18375                        | 50                         | 78050       |
| 195        | N. dutertrei      | June 1, 2010  | 7.887       | 17100                        | 50                         | 78051       |
Table 1 (Continued)

| Depth (cm) | Fossils       | Date analyzed | Weight (mg) | Planktic $^{14}$C age (year) | Benthic $^{14}$C age (year) | Error (yrs) | Accession |
|------------|---------------|---------------|-------------|------------------------------|----------------------------|-------------|-----------|
| 195        | *G. sacculifer* | June 1, 2010  | 7.322       | 11325                        |                             | 30          | 78055     |
| 195        | *Oridorsalis*  | June 1, 2010  | 3.815       | 15120                        |                             | 70          | 78056     |
| 195        | Bivalve        | June 1, 2010  | 1.441       | 19580                        |                             | 270         | 78057     |
| 199        | *N. dutertrei* | June 1, 2010  | 6.29        | 20450                        |                             | 100         | 78058     |
| 199        | Bivalve        | June 1, 2010  | 2.112       | 20340                        |                             | 190         | 78059     |
| 81         | *Oridorsalis*  | Jul. 04, 2010 | 5.368       | 6380                         |                             | 20          | 79027     |
| 81         | *G. ruber*     | Jul. 04, 2010 | 5.09        | 5255                         |                             | 15          | 79028     |
| 81         | *G. sacculifer*| Jul. 04, 2010 | 9.866       | 5155                         |                             | 15          | 79029     |
| 191        | *G. ruber*     | Jul. 04, 2010 | 6.678       | 17270                        |                             | 60          | 79030     |
| 191        | *G. sacculifer*| Jul. 04, 2010 | 6.288       | 14050                        |                             | 35          | 79031     |
| 191        | *G. sacculifer*| Jul. 18, 2010 | 3.3         | 13790                        |                             | 35          | 79555     |
| 191        | *G. sacculifer*| Jul. 18, 2010 | 3.3         | 13330                        |                             | 60          | 79556     |
| 195        | *G. sacculifer*| Jul. 18, 2010 | 3.5         | 12265                        |                             | 35          | 79557     |
| 195        | *G. sacculifer*| Jul. 18, 2010 | 3.5         | 12280                        |                             | 40          | 79558     |

Note: Fossil names followed by (A) or (B) are individual specimen. Fossil names followed by (1) or (2) were replicate, multi-specimen samples. All results have been corrected for isotopic fractionation according to the conventions of Stuiver and Polach (1977), with $\delta^{13}$C values measured on prepared graphite using the AMS spectrometer at UCI.

Figure 2  Multi-specimen $\delta^{18}$O % values of *G. ruber* (white) from core MD98-2164.
this being the last glacial maximum. At the same time, several observations stood out when comparing the benthic and planktic $^{14}$C ages. At the top of the core the B-P $^{14}$C ages are 450 and 625 years, close to modern sea water age contrast between the surface and 700–800 m. But the B-P $^{14}$C values for the 101 cm and 161 cm samples are reversed (−322 and −635 years, respectively). And even more striking, the B-P $^{14}$C age for the multi-specimen samples increase to 6070 years in the 199-cm sample. By contrast, the single specimen *Oridorsalis* to planktic age difference, is 3410 and 2260 years.

These initial results constituted a perplexing problem. The reversal of B-P $^{14}$C ages in two intervals might be indicative of a core disturbance and reworking of older material. At the same time, the large increase in B-P $^{14}$C ages at 199 cm was an intriguing indication that the core might also record a large benthic $^{14}$C excursion at the glacial termination like those seen at other sites (Figure 1). And the fact that the two individual benthic specimens at 199 cm have very different ages compared to the bulk specimen sample was also intriguing. It could mean that there was reworking of older materials into this horizon or, it could mean that there was variable input of local geologic “dead” carbon from nearby sources. For this reason, the next logical step was to evaluate whether the planktic foraminifera also contained mixed ages because planktic $^{14}$C ages should not be influenced by localized input of geologic carbon. However, planktic specimens are too small for individual $^{14}$C dating. Instead, a suite of planktic *G. sacculifer* and *G. ruber* were analyzed individually for $\delta^{18}$O in June of 2010 (Figure 4). The results from these analyses were even more perplexing. Among the individual *G. sacculifer* $\delta^{18}$O results at 191 cm and 195 cm there are values that are clearly indicative of early and late Holocene $\delta^{18}$O values. This is at odds with the benthic $^{14}$C ages at 199 cm that appeared to document much older glacial benthic ages, not younger ages. The stable isotopes and the radiocarbon results seemed to be giving very different results. And further perplexing was the fact that there are no *G. ruber* $\delta^{18}$O outliers, only the individual *G. sacculifer* exhibit “younger” outliers (Figure 4).

By the end of June 2010, a decision had to be made whether to proceed with the investigation. On one hand, the large increase in benthic $^{14}$C ages at 199 cm was an intriguing possibility that the core might document “old” carbon at the glacial termination. On the other hand, the fact that the *G. sacculifer* $\delta^{18}$O results contained what appeared to be “younger” ages in the 195 cm sample suggested that this portion of the core may be compromised in some way. The decision was made to submit a second batch of samples for $^{14}$C dating. This time the focus was only on the intervals between 101 and 199 cm. The samples included different species, including some bivalve specimens and a gastropod specimen (Table 1). This second batch also included two separate samples of *G. sacculifer* from the 191-cm and the 195-cm intervals. In this case

| Site           | Latitude | Longitude | Water depth (m) | Author                  |
|----------------|----------|-----------|-----------------|-------------------------|
| VM21-29        | 1.0      | −89.4     | 712             | Stott et al. (2019a)    |
| VM21-30        | −1.2     | −89.7     | 617             | Stott et al. (2019a)    |
| MC19-GC31      | 25.5     | −111      | 705             | Marchitto et al. (2007) |
| RC27-24        | 18.3     | 57.7      | 596             | Bryan et al. (2010)     |
| PC75           | −44.2    | −182      | 967             | Stott et al. (2019)     |
| Brazil corals  | −22.5, −24.5 | −40, −43 | 621–781         | Mangini et al. (2010)   |
Figure 3  Panel A, the initial batch of \(^{14}\)C ages obtained for \(G.\) sacculifer and \(Oridorsalis\) sp. Note the large age offset between the \(Oridorsalis\) and \(G.\) sacculifer ages at the 199-cm horizon. Panel B is the second batch of benthic and planktic \(^{14}\)C ages. Note that in the second batch the ages from the 191 cm and 195 cm samples are much younger than the surrounding intervals, including the 199-cm horizon, just 4 cm deeper in the core. Panel C is the all the data plotted together highlighting the anomalously “young” ages of specimens between 191 cm and 195 cm.
G. sacculifer specimens were split into two categories. Category (1) contained only pristine, unbroken tests. Category (2) specimens were less well-preserved, either because the specimens were slightly broken, abraded or dirtier. The reasoning was that perhaps there were two age groups that might be distinguishable based on their degree of preservation. The findings from the second batch are shown in Figure 3B.

The 14C results from the second batch clearly indicate that the interval centered between 190 and 200 cm of the core contains a mixture of specimens with widely varying ages. And importantly, the second batch of G. sacculifer returned ages that were very different from those from the first batch. The G. sacculifer 14C ages from the 191 cm and 195 cm are between 12,000 and 14,000 years and thus, are not glacial values whereas the first batch of
G. sacculifer from the 199-cm interval has a $^{14}$C age of 19,030 years and is glacial age. And there is no significant age difference between the Category (1) and Category (2) G. sacculifer. Both are anomalously “young”. The Neoglobquadrina dutertrei and G. ruber ages at 191 cm and 195 cm by contrast are much older than G. sacculifer. It is particularly striking that within 4 centimeters, the G. sacculifer $^{14}$C ages differ by as much as 7000 years. Furthermore, the bivalve shell and the Gastropod specimen both have late glacial/early deglacial ages and are not as anomalously young as are the G. sacculifer specimens. However, the Oridorsalis samples at 191 cm and 195 cm are much younger (16,900 and 15,120 years respectively) than the glacial age sample at 199 cm.

When all the $^{14}$C ages are plotted together (Figure 4C) it becomes evident that the entire core between approximately 60 cm and 200 cm contains a menagerie of mixed $^{14}$C ages. And most striking are the anomalously young ages in the 191–199-cm samples, particularly the G. sacculifer and Oridorsalis ages. These results imply that many specimens of G. sacculifer and Oridorsalis have been displaced downward from intervals higher in the sediment column and the displacement is more than 50 cm.

Having invested so much time and financial resources in this core it seemed appropriate to try to determine what process could possibly explain the strange array of radiocarbon ages, particularly the anomalously “young” ages at 191–195 cm. Bioturbation comes in many forms and has varying influences on the sediment mixing. Studies of excess $^{234}$Th and $^{10}$Be have even documented downward transport in modern sediments of as much as 26 cm
But the radiocarbon results from the MD98-2164 core seem to imply that downward sediment transport exceeds more than half a meter. To evaluate whether downward burrowing might account for the anomalously “young” ages in the glacial section of the core, a CT-scan was performed on the core. The CT scans does indeed illustrate extensive burrows below 60 cm (Figure 5). In closeup view of the interval between 60 cm and 110 cm the burrows are very large. Some burrows are more than 2 cm in diameter and are lengthy (Figure 6). Single burrows can be traced in multilayer images (not shown) over 30–40 cm. It is therefore evident that at this location, benthic organisms have effectively corrupted the stratigraphic integrity of the core.
**FINAL THOUGHTS AND CONCLUSIONS**

The results from this study highlight several lessons. The first is that if this study had ended after the first batch of $^{14}$C ages were obtained, the conclusions might have been completely different. The initial planktic $^{14}$C ages did not reveal anything unusual in the stratigraphy. And, the large B-P $^{14}$C age increase at 199 cm might have been mistaken for evidence of local input of "old" carbon. But after conducting the stable isotope measurements of single *G. sacculifer* specimens, it became clear that additional radiocarbon measurements were necessary to better characterize the $^{14}$C record of this core. Secondly, had *G. ruber* been chosen for $^{14}$C age dating instead of *G. sacculifer*, the results may also have been different. For reasons that are not immediately obvious the single specimen $\delta^{18}$O analyses and the $^{14}$C ages for *G. ruber* do not exhibit the same anomalously "young" values at 191–195 cm as do the $G. sacculifer$ values. This is an issue that will require additional investigation. The lesson is that obtaining $^{14}$C ages for multiple species of foraminifera is important. This is not always possible where individual benthic foraminifer species are not abundant enough for single species analyses. In the western equatorial Pacific multispecies analyses and replicating observations from multiple closely associated cores proved valuable in validating the extremely $^{14}$C-depleted benthic foraminiferal records in the shallow-intermediate water depth cores at that location (Stott et al. 2019b). But it is clear that individual data points and even individual core records must be considered with some caution until more comprehensive records become available.

In the MD98-2164 core both benthic and planktic specimens have been displaced downward by as much as 50–60 cm. Presumably, burrowing could also move older sediments upward as well, which would produce what appears to be a $\Delta^{14}$C excursion like those seen in other cores. But burrowing moves both benthic and planktic specimens together, although not necessarily in the same proportion (e.g. *G. ruber* vs. *G. sacculifer*). Therefore, measuring multiple species or genera of both planktic and benthic fossils is an important way to distinguish between vertical displacement and what may be inputs of anomalously old carbon. And finally, CT-scans are a valuable and relatively inexpensive method for evaluating the integrity of a core. Had the CT-scans been conducted on the MD98-2164 core before sampling commenced the core would never have been sampled and a great deal of effort and expense would have been avoided. Unfortunately, CT scans may not be practical when sampling old cores that have dried and been heavily sampled.

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