Data report: revised composite depth scale and splice for IODP Site U1406[1]

Tim E. van Peer,[2] Diederik Liebrand,[2] Chuang Xuan,[2] Peter C. Lippert,[3] Claudia Agnini,[4, 5] Nevin Blum,[6] Peter Blum,[6] Steven M. Bohaty,[2] Paul R. Bown,[7] Rosanna Greenop,[2, 8] Wendy E.C. Kordesch,[2] Dominik Leonhardt,[9] Oliver Friedrich,[10] and Paul A. Wilson [2]

Chapter contents

[1]van Peer, T.E., Liebrand, D., Xuan, C., Lippert, P.C., Agnini, C., Blum, N., Blum, P., Bohaty, S.M., Bown, P.R., Greenop, R., Kordesch, W.E.C., Leonhardt, D., Friedrich, O., and Wilson, P.A., 2017. Data report: revised composite depth scale and splice for IODP Site U1406. *In* Norris, R.D., Wilson, P.A., Blum, P., and the Expedition 342 Scientists, *Proceedings of the Integrated Ocean Drilling Program*, 342: College Station, TX (Integrated Ocean Drilling Program).
doi:10.2204/iodp.proc.342.202.2017

[2]Ocean and Earth Science, University of Southampton, Southampton SO14 3ZH, UK.
Correspondence author:
T.E.vanPeer@soton.ac.uk
[3]Department of Geology & Geophysics, University of Utah, Salt Lake City UT 84112, USA.
[4]Department of Geosciences, University of Padova, 35131 Padova, Italy.
[5]Department of Geological Sciences, Stockholm University, 106 91 Stockholm, Sweden.
[6]International Ocean Discovery Program, Texas A&M University, College Station TX 77845, USA.
[7]Department of Earth Sciences, University College London, London WC1E 6BT, UK.
[8]School of Geography & Geosciences, Earth Sciences, St. Andrews KY16 9AL, UK.
[9]Institute of Geosciences, Goethe-Universität Frankfurt, 60438 Frankfurt, Germany.
[10]Institute of Earth Sciences, Ruprecht-Karls-Universität Heidelberg, 69120 Heidelberg, Germany.

Abstract

Integrated Ocean Drilling Program (IODP) Expedition 342 recovered exceptional Paleogene to early Neogene sedimentary archives from clay-rich sediments in the northwest Atlantic Ocean. These archives present an opportunity to study Cenozoic climate in a highly sensitive region at often unprecedented resolution. Such studies require continuous records in the depth and time domains. Using records from multiple adjacent drilled holes, intervals within consecutive cores are typically spliced into a single composite record on board the R/V *JOIDES Resolution* using high-resolution physical properties data sets acquired before the cores are split. The highly dynamic nature of the sediment drifts drilled during Expedition 342 and the modest amplitude of variance in the physical property records made it possible to construct only highly tentative initial working splices, which require extensive postexpedition follow-up work. Postexpedition, high-resolution X-ray fluorescence (XRF) core scanning data enabled the construction of a preliminary composite depth scale and splice. Here, we present the revised composite depth scale and splice for IODP Site U1406, predominantly constructed using detailed hole-to-hole correlations of newly generated high-resolution XRF data and revisions of the initial XRF data set. The revised composite depth scale and splice serve as a reference framework for future research on Site U1406 sediments.

Introduction

Integrated Ocean Drilling Program (IODP) Expedition 342, "Paleogene Newfoundland Sediment Drifts," was completed during June and July 2012 and recovered a total of ~5.4 km of predominantly Paleogene clay-rich sediments (see the **"Expedition 342 summary"** and **"Methods"** chapters [Norris et al., 2014a, 2014b]). The nine sites drilled on the J-Anomaly and Newfoundland Ridges span a depth transect from ~4.9 km (Site U1403) to ~3.0 km water depth (Site U1408). The sites at the J-Anomaly Ridge (Sites U1403–U1406) recovered expanded records (up to 25 cm/ky at Site U1405) of late Paleogene to early Neogene age.

Site U1406 (40°21′N, 51°39′W; Fig. **F1**) is located in the middle of the Expedition 342 depth transect at 3.8 km present-day water depth. A comprehensive recognition and characterization of climatic events recorded at Site U1406 requires a continuous and undisturbed sequence. A single IODP hole inevitably yields discontinuous geological records because of stratigraphic gaps between successive cores. Recovered cores from a single hole may also contain disturbed intervals. Drilling of multiple closely spaced holes is therefore crucial to ensure complete recovery for the construction of a continuous composite record or "splice" (e.g., Ruddiman et al., 1987; Hagelberg et al., 1992; Westerhold et al., 2012). Correlating stratigraphic information from multiple holes also helps identifying hiatuses and condensed or expanded intervals because such stratigraphically complex intervals may only occur in a subset of holes. Once a composite record has been constructed, additional scaling ("stretching and squeezing") is typically required to correlate off-splice intervals to the composite record in the depth domain (e.g., Hagelberg et al., 1995; Westerhold et al., 2012).

The modest variability of the physical properties data (i.e., magnetic susceptibility, gamma ray attenuation [GRA], and natural gamma radiation [NGR]) from the clay-rich drift sediments at Site U1406 challenged the construction of a reliable shipboard splice (see the **"Site U1406"** chapter [Norris et al., 2014c]). Postexpedition high-resolution X-ray fluorescence (XRF) core scanning, however, has made it possible to construct a decimeter-scale composite depth scale and near-continuous spliced record. This initial depth scale, hereinafter referred to as the "shipboard splice," was generated using a subset of the postexpedition XRF data. In this report, we present an updated composite depth scale and revised splice for Site U1406 developed after reassessing the available XRF data, aided by newly generated XRF core scanning data. We also present detailed (i.e., decimeter-scale) correlations to the revised splice for core intervals that lie outside the revised splice.

Material and methods

The shipboard composite depth scale and splice for Site U1406 were revised using primarily XRF core scanning data. XRF elemental counts were generated using an Avaatech XRF Core Scanner at the Gulf Coast Repository (Texas, USA), equipped with an Oxford Instruments 100W Neptune Rh X-ray tube and a Canberra X-PIPS detector. The X-ray tube was run at 10 kV and 1000 µA, the measurement area was set with a cross-core slit of 10 mm and a downcore slit of 12 mm, and measurements were taken at 2 cm intervals with a live counting time of 20 s. For some intervals where XRF data alone do not yield satisfactory correlations, we correlated intervals using physical properties data (i.e., magnetic susceptibility, GRA, NGR, and color reflectance; see the **"Site U1406"** chapter [Norris et al., 2014c]). We cleaned the XRF and physical properties data by removing all data points in intervals with drilling disturbance (e.g., core tops) and visual outliers.

The primary depth scale representing the position of a sample or measurement is core depth below seafloor, Method A (CSF-A), in IODP nomenclature (Fig. **F2**; also available as IODP Depth Scales Terminology v.2 at **http://www.iodp.org/policies-and-guidelines**). This scale represents the distance from seafloor to a target level within a recovered core. Because cores may expand upon recovery by up to 20%, the IODP database also provides the CSF-B depth scale, where each core with >100% recovery is scaled back into the cored interval but other cores with <100% recovery are not scaled. During Expedition 342, only the CSF-A depth scale was used, equivalent to the mbsf depth scale used during the Deep Sea Drilling Project and Ocean Drilling Program (ODP). The main advantage of the CSF-A scale is that it affords straightforward calculation of sample positions within holes, cores, and sections. The caveat is that it allows for overlaps at core boundaries due to core expansion upon recovery.

The composite depth scale, core composite depth below seafloor (CCSF; equivalent to meters composite depth in ODP nomenclature), is defined by adding offsets to the CSF-A depths of cores to align correlative features in cores from multiple holes, simultaneously eliminating overlaps and filling in core gaps. We named the composite depth scale CCSF-A to emphasize that the CCSF depth scale is the composite version of the CSF-A scale. The core depth shifts that define the CCSF-A scale are based on one correlative feature between any two cores; this depth scale does not involve stretching and squeezing because it is an affine transformation. Here, we revise the shipboard offsets given to cores in the **"Site U1406"** chapter (Norris et al., 2014c) and present a revised CCSF-A depth scale for Site U1406. In cases where no correlation tie points could be established, we shifted the tops of cores 1 m below the bottom of the previous core, instead of the +0.01 m used for the shipboard splice (see the **"Site U1406"** chapter [Norris et al., 2014c]). This 1 m shift is based on offsets of cores where we could establish good correlation tie points. Thus, we made a more generous (yet still speculative) accommodation for unrecovered sediments.

We only revised the shipboard splice for Site U1406 (used to guide postexpedition sampling) where we collected new data (Cores 342-U1406A-1H and 342-U1406B-1H and Sections 342-U1406B-2H-1 and 342-U1406C-1H-1 through 1H-5) or where existing data resulted in reinterpretations of core offsets. The construction of the revised splice follows the same procedures as that of the shipboard splice (see the **"Methods"** chapter [Norris et al., 2014b]). First, we avoid disturbed intervals and do not use the top and bottom ~50 cm intervals of a core where possible. Second, we select intervals from cores that are most characteristic of the stratigraphic interval as represented in the three available holes.

Despite the close proximity between drill holes from a single IODP site, aligned cores from different holes can have different thicknesses for the same stratigraphic interval. This difference may be the result of differential physical compression or expansion of cores during the coring process, or it may represent stratigraphic heterogeneity at the drill location that can be attributed to varying bed form thicknesses. Note that the standard IODP practice for drilling adjacent holes at a given site is to offset the ship by 20 m. Distance between drill sites at the seafloor are likely to be larger, especially where ocean currents are vigorous, as in the case of Expedition 342. In any case, this circumstance requires scaling (i.e., the stretching and squeezing) by mapping multiple stratigraphic features within cores to correlate off-splice intervals to the splice. The scaled off-splice intervals constitute an adjusted CCSF depth scale (CCSF-M). Method M denotes that off-splice intervals have been mapped (hence "M") to the splice using a scaling factor. By definition, any interval on the splice will have the same numerical depth on the revised CCSF-A scale and the CCSF-M scale. Selected tie points ("mapping pairs") with well-defined features (e.g., clear maximum or minimum of a data record) control the mapping of off-splice intervals, with linear interpolation between mapping pair tie points.

Compound and composite core images were created using Code for Ocean Drilling Data (CODD), an updated version of the ODP Macro software (Wilkens et al., 2009, 2017). In this program, all cropped core section images collected by the Section Half Imaging Logger (SHIL) are combined into one compound core image based on the CSF-A depth scales for each hole. These compound core images are converted to the revised CCSF-A depth scale using the revised offset table. Subsequently, using the splice intervals and the mapping pair tie points, the images are presented on the CCSF-M scale.

Results

The newly generated XRF data, together with those used for the construction of shipboard splice, enabled several revisions for the Site U1406 composite depth scale (Table **T1**) and splice (Tables **T2** and **T3**). In addition, we present mapping pairs to adjust off-splice intervals to the spliced record in Table **T4**. Notably, we revised the first four tie points in the shipboard splice of Site U1406 (see the **"Site U1406"** chapter [Norris et al., 2014c]). In the shipboard splice, these revisions were solely based on physical properties data (Tables **T5**, **T6**, **T7**, **T8**) and therefore labeled as "tentative." Additional XRF core scanning data guided our splice revisions in this interval, because the ln(Ca/K) ratio (Table **T9**) shows excellent correlation among the three holes. We noticed that core photos and color data plotted on the revised depth scale reveal an apparent mismatch at the top of the record (Figs. **F3** and **F4** at ~23 m CCSF-M). We hypothesize that a redox front reached different depths in the three holes, possibly due to variable paleobathymetry of the drift sediments (see the **"Expedition 342 summary"** chapter [Norris et al., 2014a]) or local variations in organic carbon supply.

Another significant revision to the composite depth scale and splice is required at ~94 m CCSF-M (uppermost Oligocene to lowermost Miocene) (see the **"Site U1406"** chapter [Norris et al., 2014c]). The XRF patterns of Holes U1406A and U1406B were dominant during the construction of the shipboard splice. After a thorough investigation, we present a reinterpretation in which we identify that Core 342-U1406A-9H contains a condensed interval and Core 342-U1406B-10H contains a ~2 m hiatus (Table **T4**; Fig. **F4**). Importantly, Hole U1406C contains the most suitable, and probably complete, sequence and is therefore selected for the revised splice for this interval (Tables **T2**, **T3**).

For the middle Oligocene interval, Cores 342-U1406B-15H and 342-U1406C-15H are misaligned in the shipboard composite depth model; we increased the offset between the two cores by ~1 m and added this to the revised splice. Further downhole, the shipboard lithostratigraphy (see the **"Site U1406"** chapter [Norris et al., 2014c]) discusses microfaults and possible slumping. This hampers the confident construction of a continuous splice for this interval, and Cores 342-U1406A-17H and 342-U1406B-18H are therefore appended (Fig. **F4**; Tables **T2**, **T3**).

Following the shipboard tie points from ~186 m CCSF-M downward, we extensively revised the splice for the lower Oligocene and near the Eocene–Oligocene transition (Tables **T2** and **T3**). A distinct maximum in magnetic susceptibility at ~255 m CCSF-M is used to tie the three holes at Site U1406 together (Fig. **F4**). This reinterpretation results in a much better correlation for the ln(Ca/K) records from the different holes, compared to the shipboard splice. The total length of the revised splice increases by 32.17 m to a total of 340.55 m CCSF-M. This revision results in growth factors of ~1.23 for all three holes (Fig. F5).

Summary

We presented the revised composite depth scale and splice for Site U1406 that is predominantly based on XRF core scanning data. We also mapped off-splice core segments to the revised splice to accommodate for lateral variations in thickness of stratigraphic features, making most off-splice core material available for sampling on a consistent depth scale. The revised composite depth scale and splice for Site U1406, integrated across all three holes, enables placement of the records from Site U1406 into a larger Expedition 342–wide and global framework. This forms a fundamental step toward a continuous magnetostratigraphy and astrochronologic framework for key intervals recovered at Site U1406.

Acknowledgments

We thank the Captain, crew, and shipboard scientists from IODP Expedition 342 for their contributions to the recovery and preliminary analysis of these unique sediments. We gratefully acknowledge the kind assistance of Thomas Gorgas, Walter Hale, Shari Hilding-Kronforst, David Houpt, Melanie Siegburg, and Alex Wülbers; CODD guidance by Anna Joy Drury and Roy Wilkens; and the beneficial review of James Ogg. Samples and data are provided by IODP, which is sponsored by the US National Science Foundation and participating countries. We acknowledge the financial support from the National Environmental Research Council (NERC) and UK IODP in the form of grants NE/K006800/1 (to PAW), NE/K014137/1 (to PAW, CX and DL), a Royal Society Research Merit Award to PAW, and a National Oceanography Centre Southampton (NOCS) studentship to TEvP. Funding from the German Research Foundation (DFG) (grants OF 2544/2-1 and OF 2544/7-1) is acknowledged by OF. Data are archived in the Pangaea database: **https://doi.pangaea.de/10.1594/PANGAEA.872548**.

References

Hagelberg, T., Shackleton, N., Pisias, N., and Shipboard Scientific Party, 1992. Development of composite depth sections for Sites 844 through 854. *In* Mayer, L., Pisias, N., Janecek, T., et al., *Proceedings of the Ocean Drilling Program, Initial Reports,* 138: College Station, TX (Ocean Drilling Program), 67–77. **http://dx.doi.org/10.2973/odp.proc.ir.138.105.1992**

Hagelberg, T.K., Pisias, N.G., Shackleton, N.J., Mix, A.C., and Harris, S., 1995. Refinement of a high-resolution, continuous sedimentary section for studying equatorial Pacific Ocean paleoceanography, Leg 138. *In* Pisias, N.G., Mayer, L.A., Janecek, T.R., Palmer-Julson, A., and van Andel, T.H. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results,* 138: College Station, TX (Ocean Drilling Program), 31–46. **http://dx.doi.org/10.2973/odp.proc.sr.138.103.1995**

Norris, R.D., Wilson, P.A., Blum, P., Fehr, A., Agnini, C., Bornemann, A., Boulila, S., Bown, P.R., Cournede, C., Friedrich, O., Ghosh, A.K., Hollis, C.J., Hull, P.M., Jo, K., Junium, C.K., Kaneko, M., Liebrand, D., Lippert, P.C., Liu, Z., Matsui, H., Moriya, K., Nishi, H., Opdyke, B.N., Penman, D., Romans, B., Scher, H.D., Sexton, P., Takagi, H., Turner, S.K., Whiteside, J.H., Yamaguchi, T., and Yamamoto, Y., 2014a. Expedition 342 summary. *In* Norris, R.D., Wilson, P.A., Blum, P., and the Expedition 342 Scientists, *Proceedings of the Integrated Ocean Drilling Program,* 342: College Station, TX (Integrated Ocean Drilling Program). **http://dx.doi.org/10.2204/iodp.proc.342.101.2014**

Norris, R.D., Wilson, P.A., Blum, P., Fehr, A., Agnini, C., Bornemann, A., Boulila, S., Bown, P.R., Cournede, C., Friedrich, O., Ghosh, A.K., Hollis, C.J., Hull, P.M., Jo, K., Junium, C.K., Kaneko, M., Liebrand, D., Lippert, P.C., Liu, Z., Matsui, H., Moriya, K., Nishi, H., Opdyke, B.N., Penman, D., Romans, B., Scher, H.D., Sexton, P., Takagi, H., Turner, S.K., Whiteside, J.H., Yamaguchi, T., and Yamamoto, Y., 2014b. Methods. *In* Norris, R.D., Wilson, P.A., Blum, P., and the Expedition 342 Scientists, *Proceedings of the Integrated Ocean Drilling Program,* 342: College Station, TX (Integrated Ocean Drilling Program). **http://dx.doi.org/10.2204/iodp.proc.342.102.2014**

Norris, R.D., Wilson, P.A., Blum, P., Fehr, A., Agnini, C., Bornemann, A., Boulila, S., Bown, P.R., Cournede, C., Friedrich, O., Ghosh, A.K., Hollis, C.J., Hull, P.M., Jo, K., Junium, C.K., Kaneko, M., Liebrand, D., Lippert, P.C., Liu, Z., Matsui, H., Moriya, K., Nishi, H., Opdyke, B.N., Penman, D., Romans, B., Scher, H.D., Sexton, P., Takagi, H., Turner, S.K., Whiteside, J.H., Yamaguchi, T., and Yamamoto, Y., 2014c. Site U1406. *In* Norris, R.D., Wilson, P.A., Blum, P., and the Expedition 342 Scientists, *Proceedings of the Integrated Ocean Drilling Program,* 342: College Station, TX (Integrated Ocean Drilling Program). **http://dx.doi.org/10.2204/iodp.proc.342.107.2014**

Ruddiman, W.F., Cameron, D., and Clement, B.M., 1987. Sediment disturbance and correlation of offset holes drilled with the hydraulic piston corer: Leg 94. *In* Ruddiman, W.F., Kidd, R.B., Thomas, E., et al., *Initial Reports of the Deep Sea Drilling Project,* 94: Washington, DC (U.S. Govt. Printing Office), 615–634. **http://dx.doi.org/10.2973/dsdp.proc.94.111.1987**

Westerhold, T., Röhl, U., Wilkens, R., Pälike, H., Lyle, M., Dunkley Jones, T., Bown, P., Moore, T., Kamikuri, S., Acton, G., Ohneiser, C., Yamamoto, Y., Richter, C., Fitch, P., Scher, H., Liebrand, D., and the Expedition 320/321 Scientists, 2012. Revised composite depth scales and integration of IODP Sites U1331–U1334 and ODP Sites 1218–1220. *In* Pälike, H., Lyle, M., Nishi, H., Raffi, I., Gamage, K., Klaus, A., and the Expedition 320/

321 Scientists, *Proceedings of the Integrated Ocean Drilling Program,* 320/321: Tokyo (Integrated Ocean Drilling Program Management International, Inc.). **http://dx.doi.org/10.2204/iodp.proc.320321.201.2012**

Wilkens, R., Westerhold, T., Drury, A.J., Lyle, M., Gorgas, T., and Tian, J., 2017. Revisiting the Ceara Rise, equatorial Atlantic Ocean: isotope stratigraphy of ODP Leg 154. *Climate of the Past.* **https://doi.org/10.5194/cp-2016-140**

Wilkens, R.H., Niklis, N., and Frazer, M., 2009. Data report: digital core images as data: an example from IODP Expedition 303. *In* Channell, J.E.T., Kanamatsu, T., Sato, T., Stein, R., Alvarez Zarikian, C.A., Malone, M.J., and the Expedition 303/306 Scientists, *Proceedings of the Integrated Ocean Drilling Program,* 303/306: College Station, TX (Integrated Ocean Drilling Program Management International, Inc.). **http://dx.doi.org/10.2204/iodp.proc.303306.201.2009**

Initial receipt: 26 February 2016
Acceptance: 9 May 2017
Publication: 31 July 2017
MS 342-202

Figure F1. Location of Expedition 342 sites (yellow circles). IODP Site U1406 is highlighted in red. (Modified from Norris et al., 2014a.)

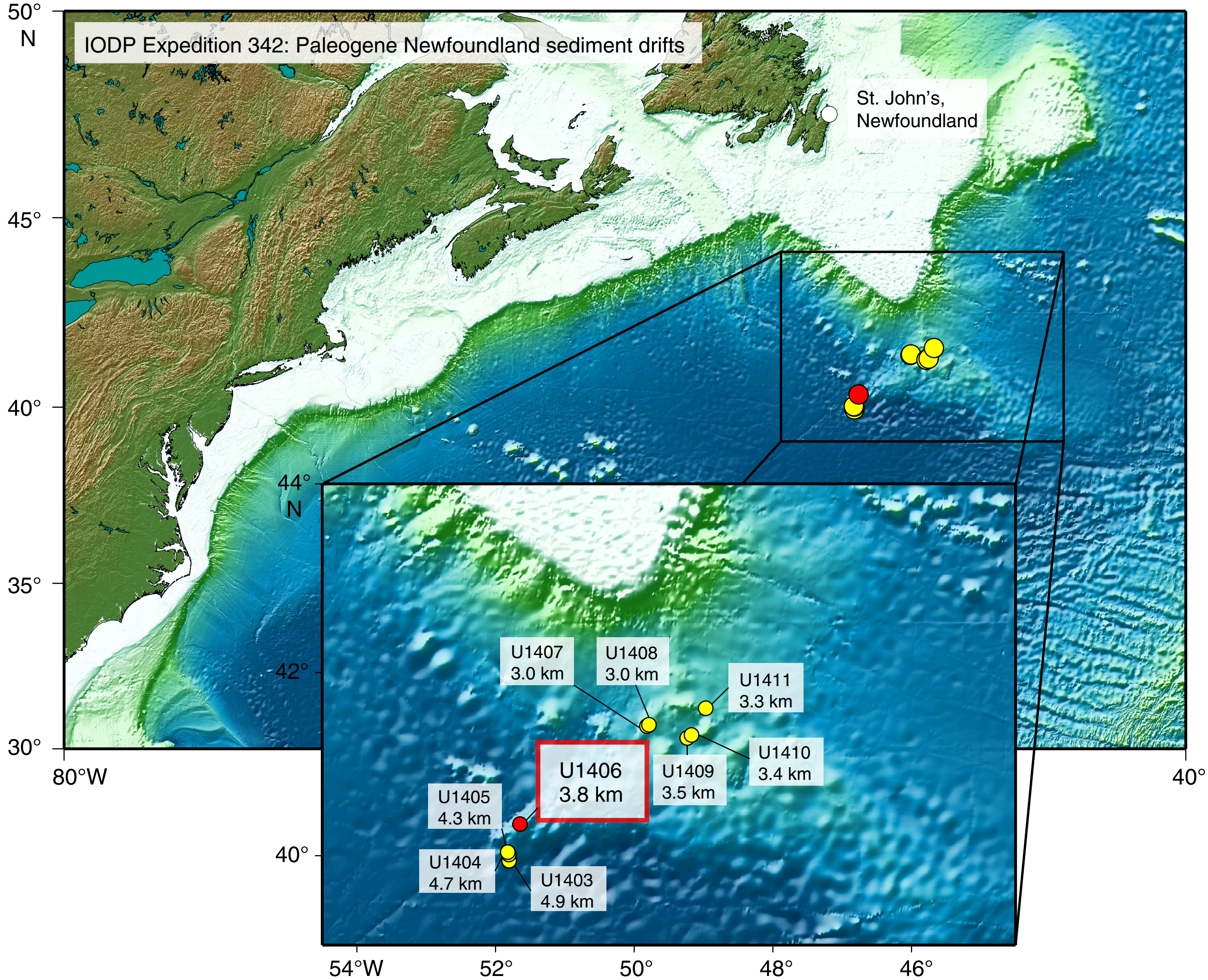

Figure F2. Depth scale nomenclature. See **"Material and methods"** for discussion.

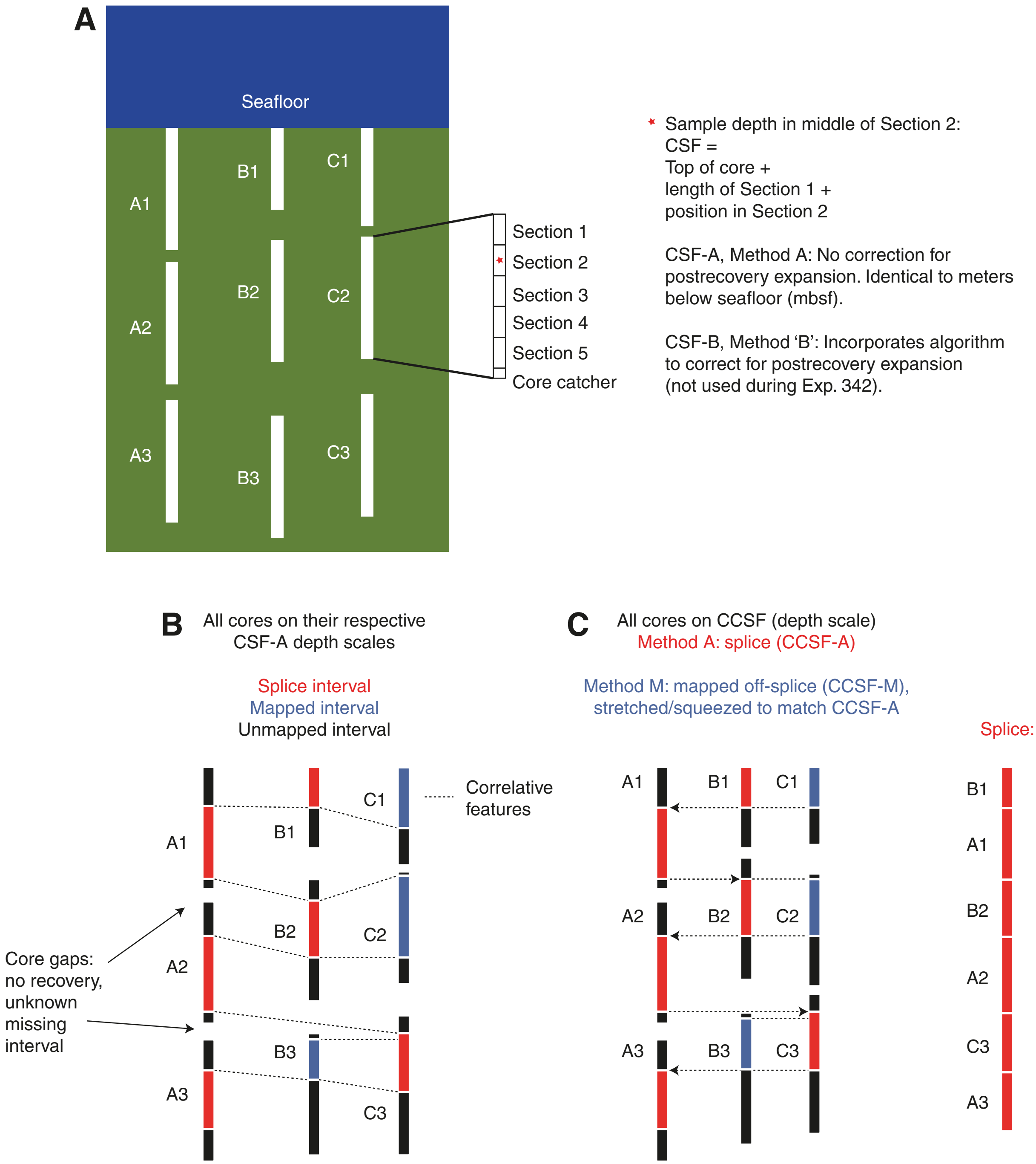

Figure F3. Spliced core images in 50 m intervals, Site U1406. Splice intervals: top = yellow line, bottom = red line. Off-spliced intervals are mapped to the splice using correlative features and corresponding mapping pair tie points. **A.** 0–50 m CCSF-M. (Continued on next six pages.)

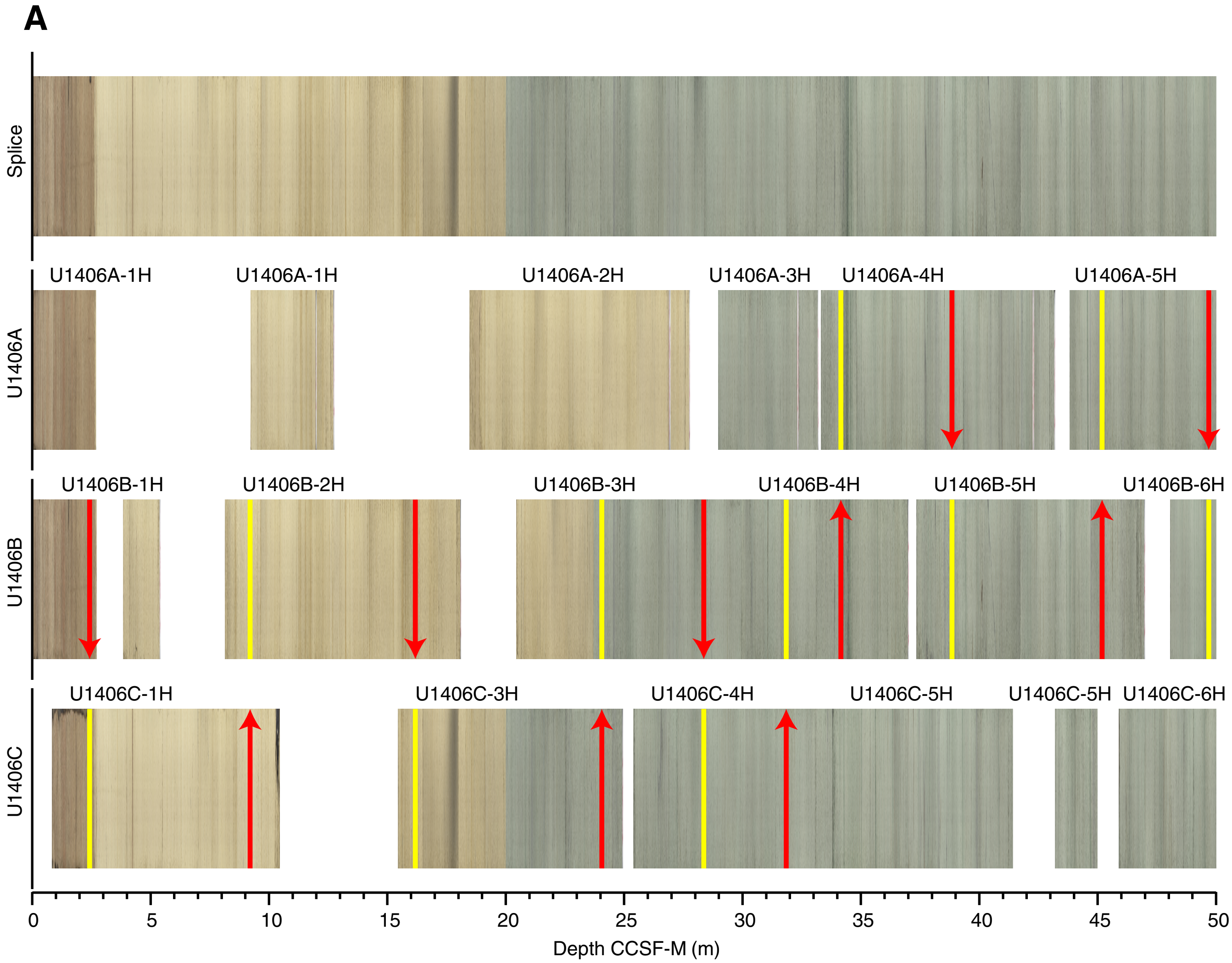

Figure F3 (continued). B. 50–100 m CCSF-M. (Continued on next page.)

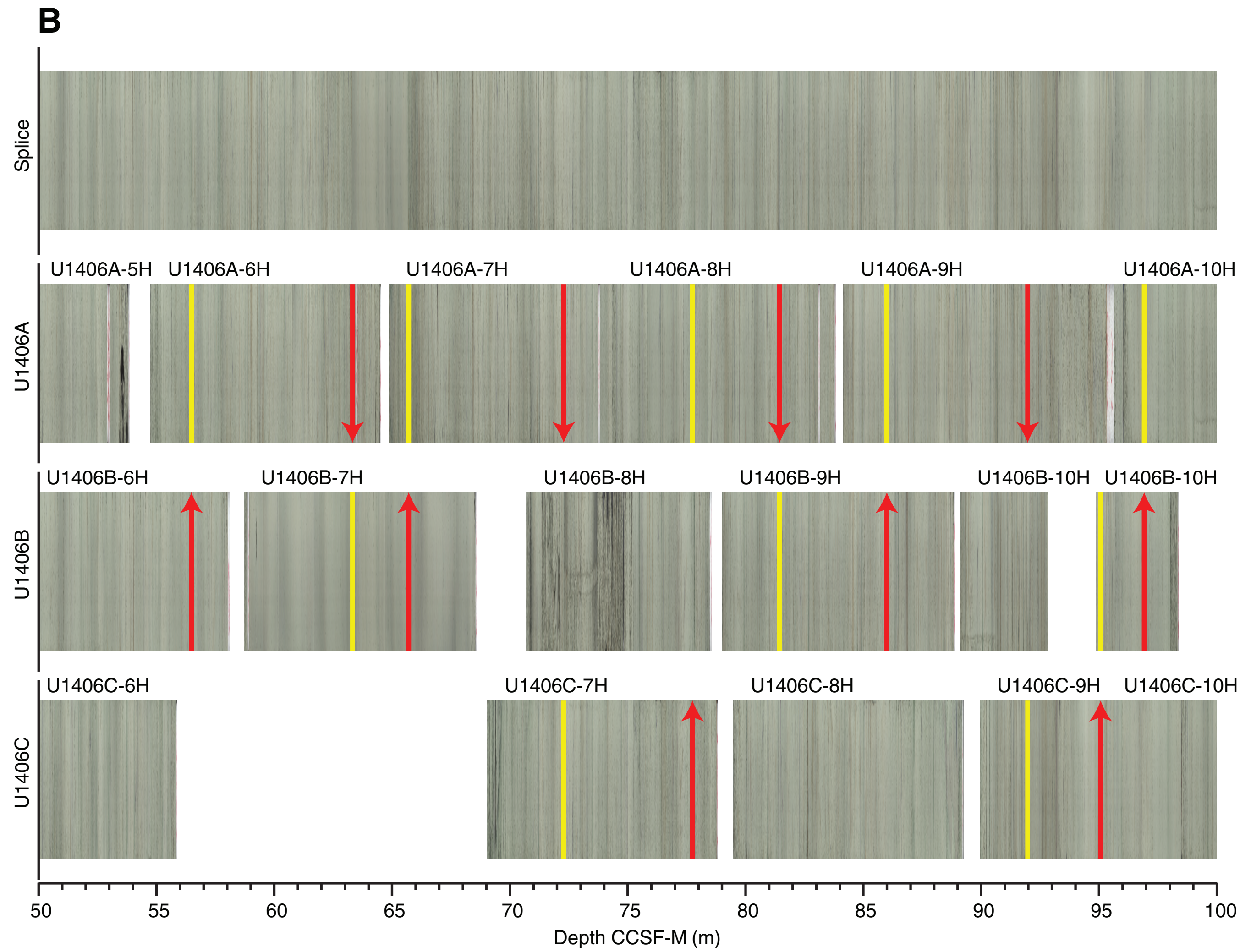

Figure F3 (continued). **C.** 100–150 m CCSF-M. (Continued on next page.)

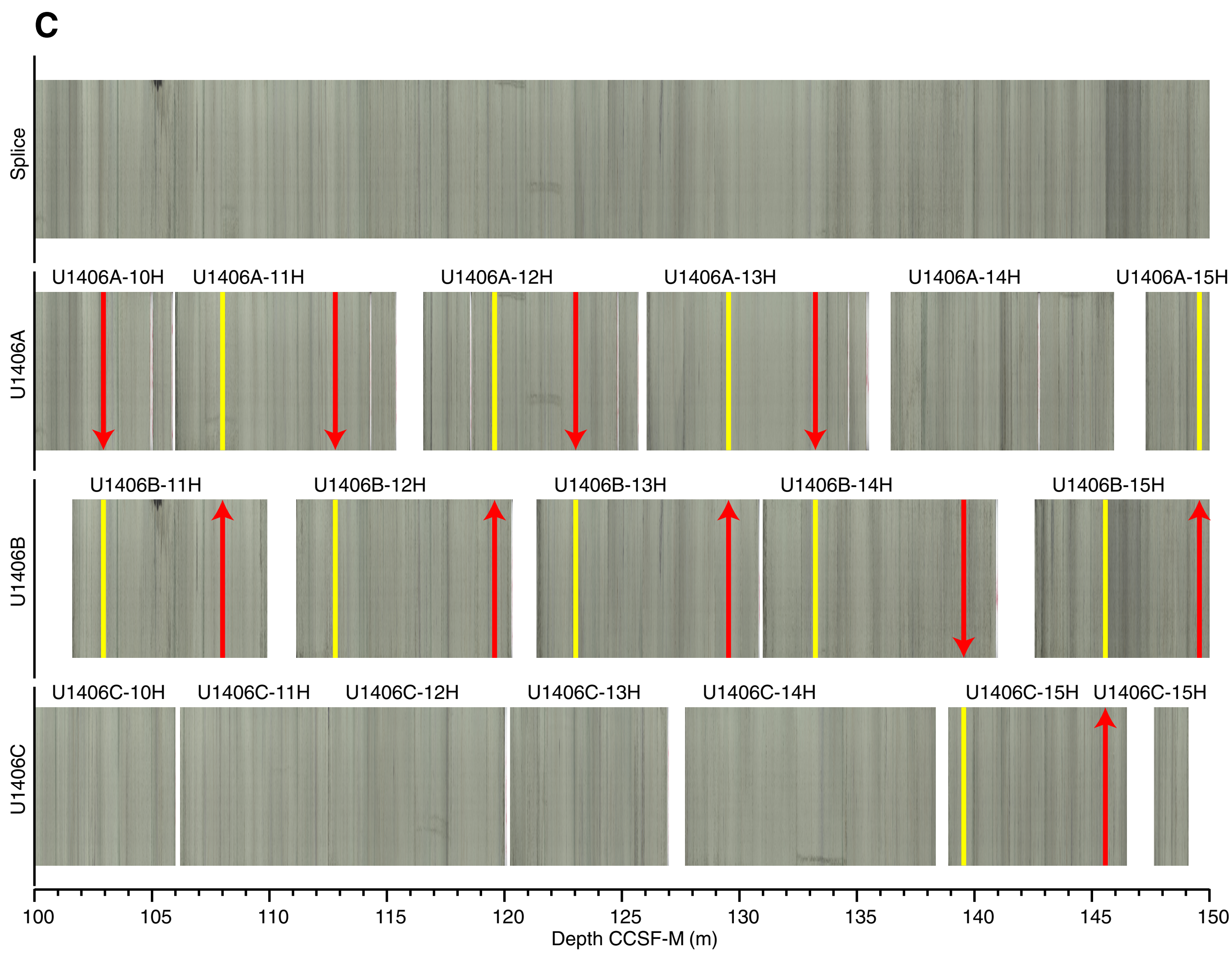

Figure F3 (continued). D. 150–200 m CCSF-M. (Continued on next page.)

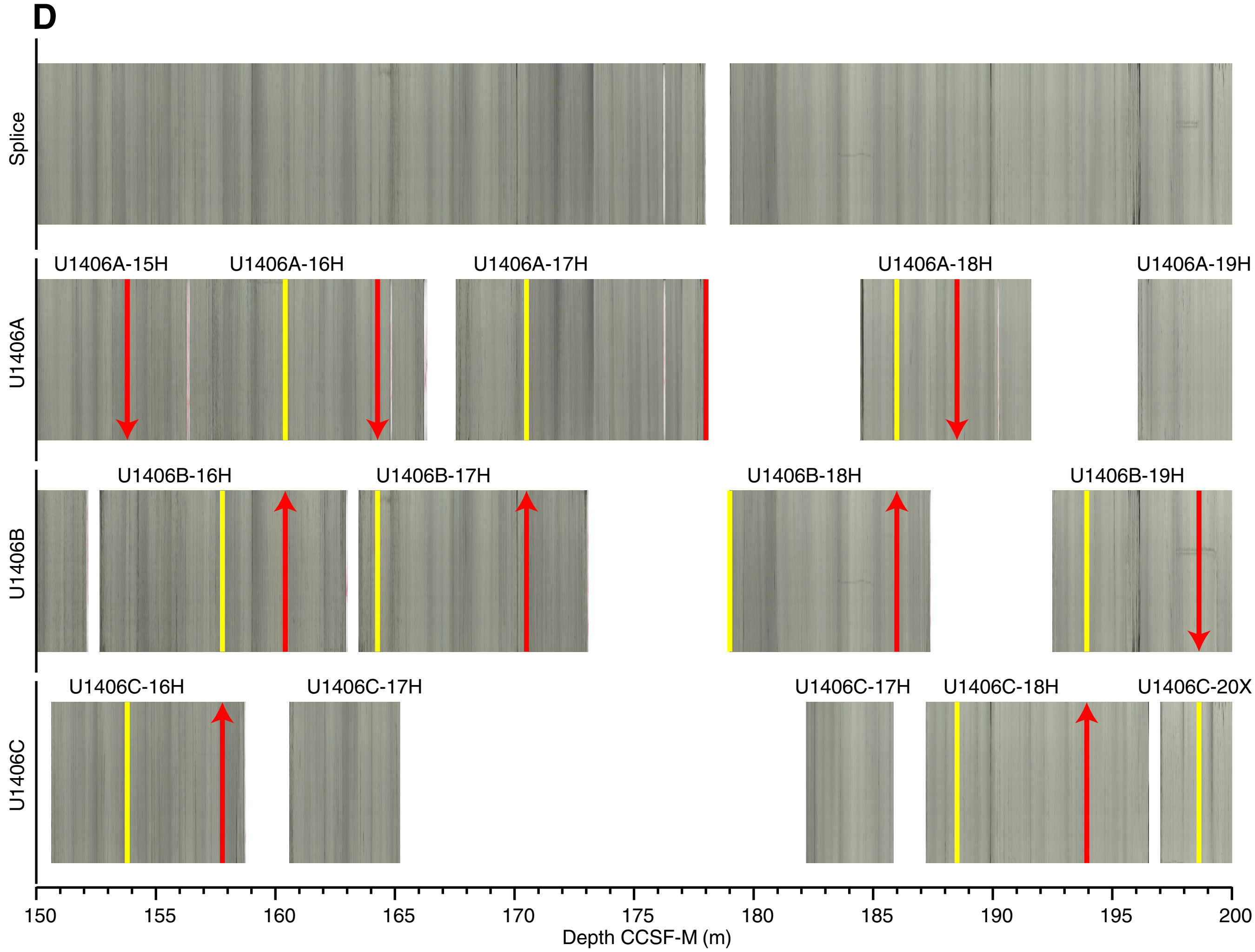

Figure F3 (continued). E. 200–250 m CCSF-M. (Continued on next page.)

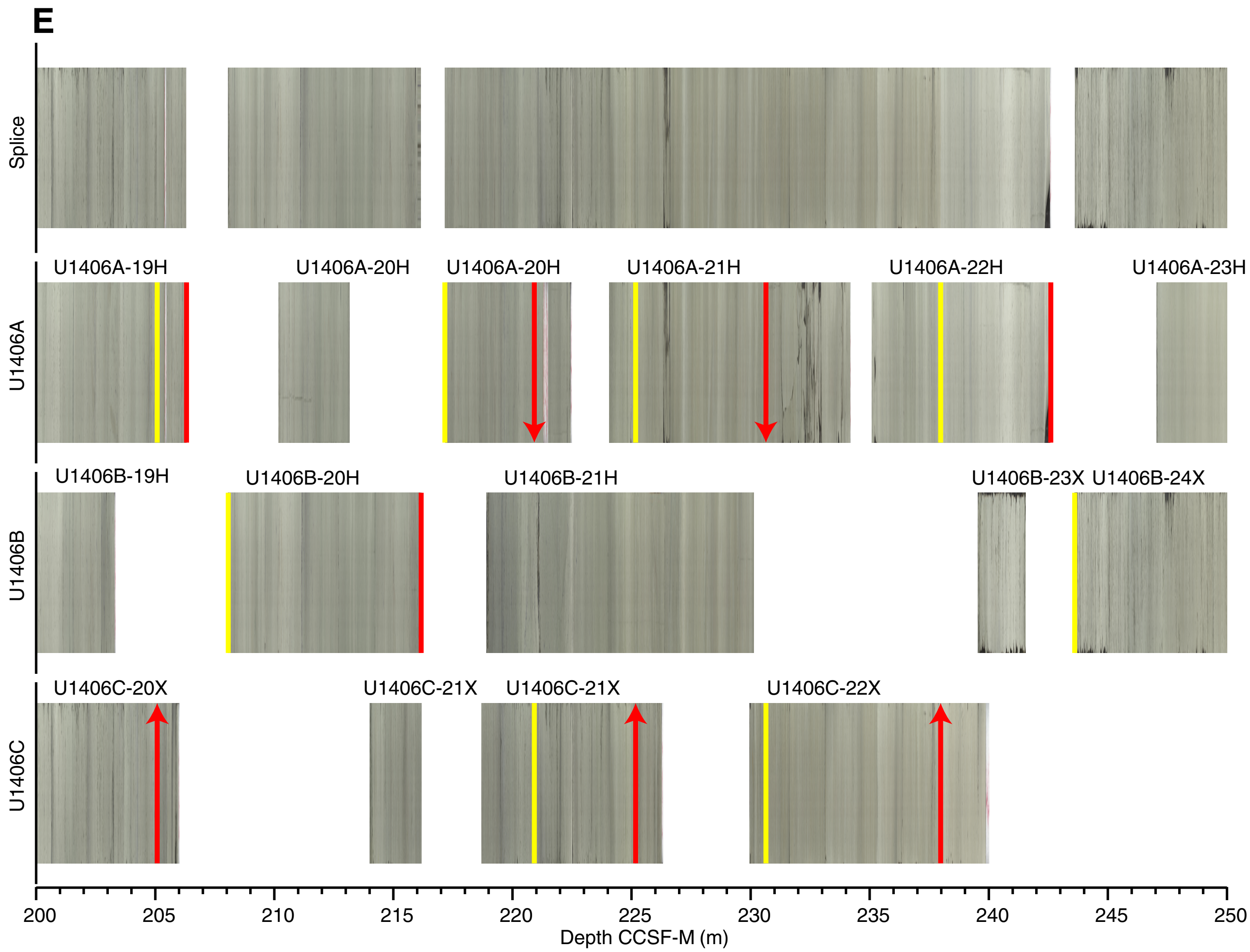

Figure F3 (continued). **F.** 250–300 m CCSF-M. (Continued on next page.)

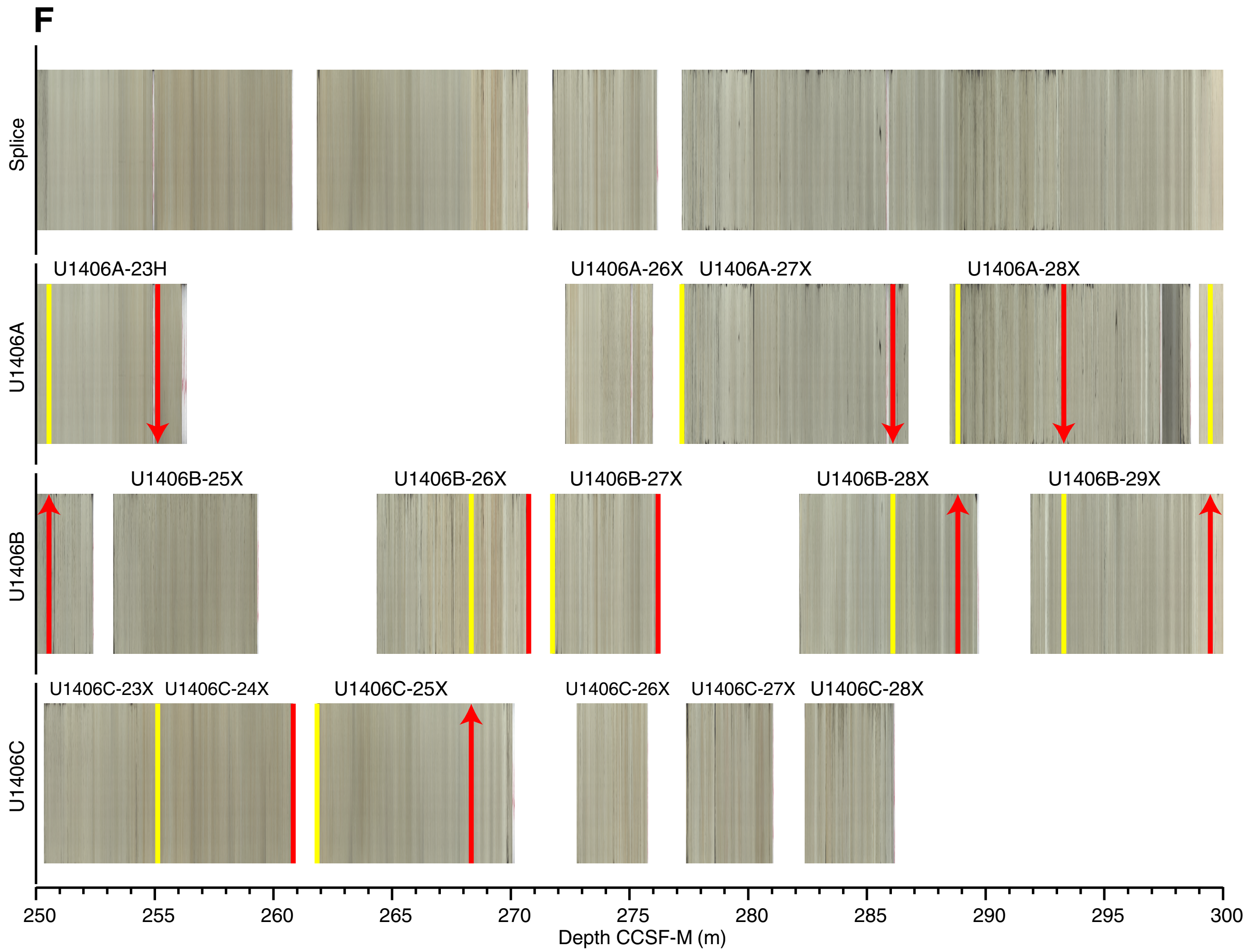

Figure F3 (continued). **G.** 300–350 m CCSF-M.

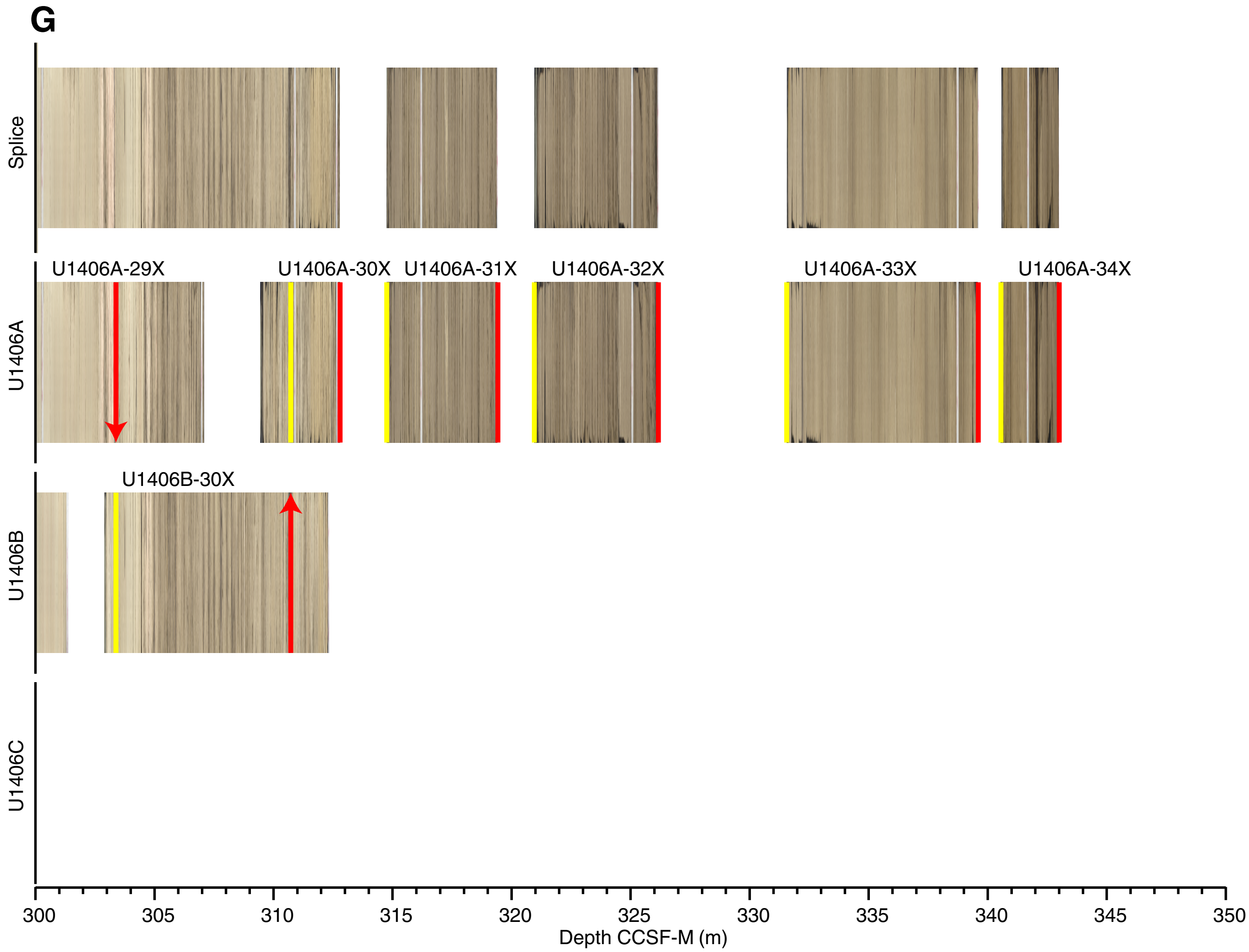

Figure F4. Spliced core image, physical properties, and XRF data in 50 m intervals, Site U1406. XRF data presented as natural logarithm of Ca and K ratios (ln[Ca/K]). Cores: two shades of gray = alternating cores, white = core gaps, red = intervals that overlap between successive cores. Data: dark blue = Hole U1406A, red = Hole U1406B, light blue = Hole U1406C, black = spliced record. Discontinuous intervals of the splice record are due to disturbances and core gaps. **A.** 0–50 m CCSF-M. (Continued on next six pages.)

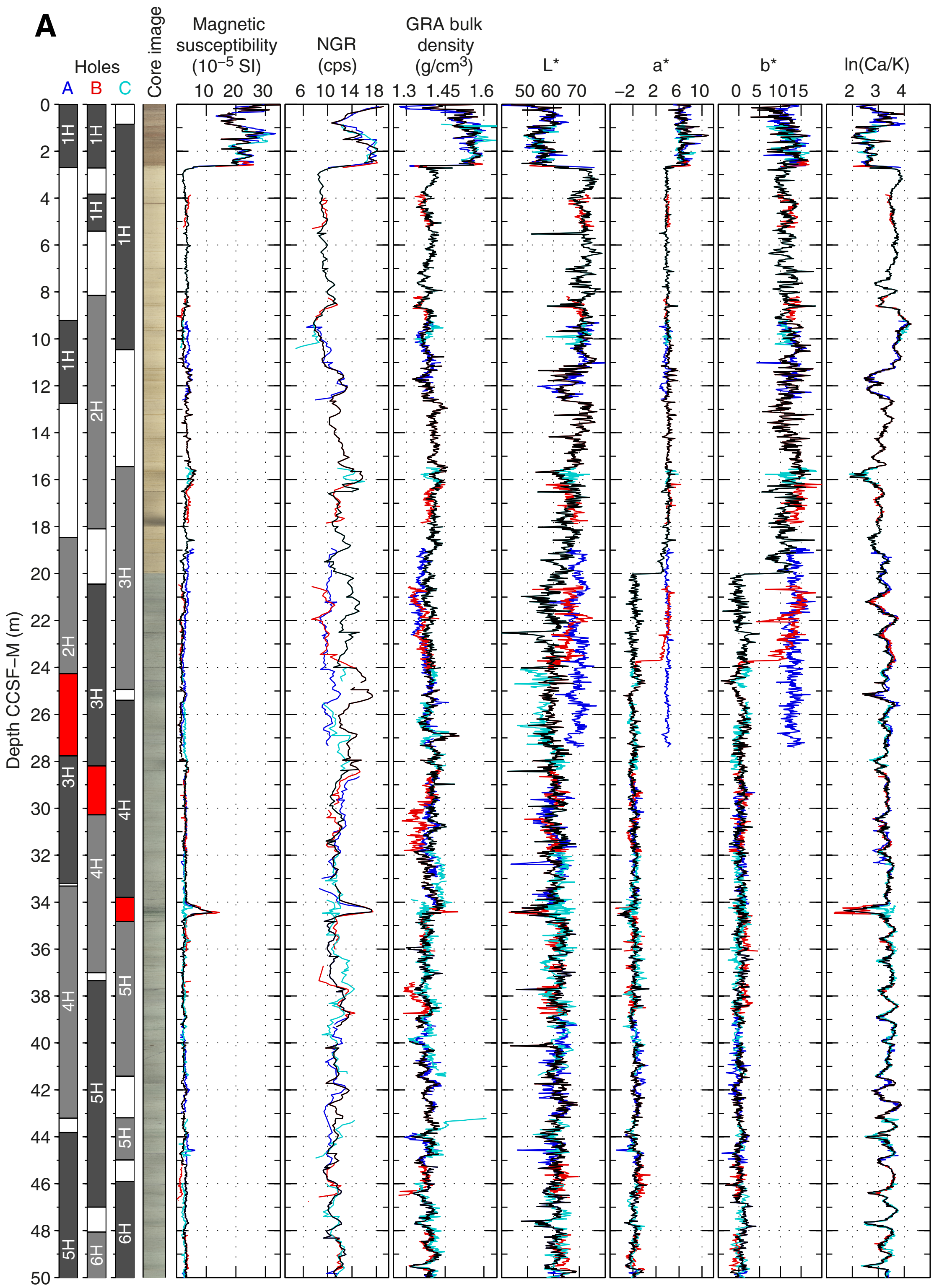

Figure F4 (continued). B. 50–100 m CCSF-M. (Continued on next page.)

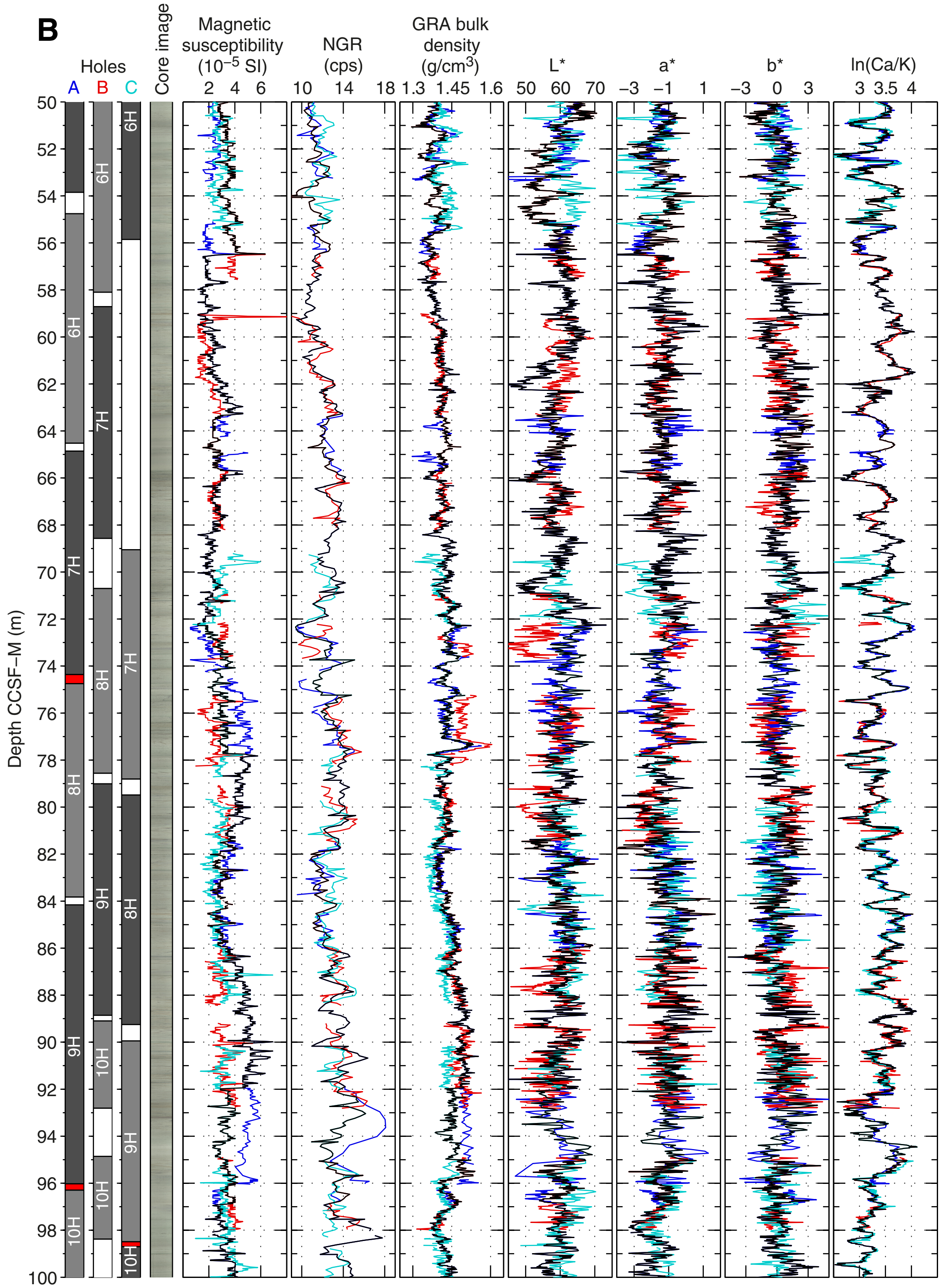

Figure F4 (continued). **C.** 100–150 m CCSF-M. (Continued on next page.)

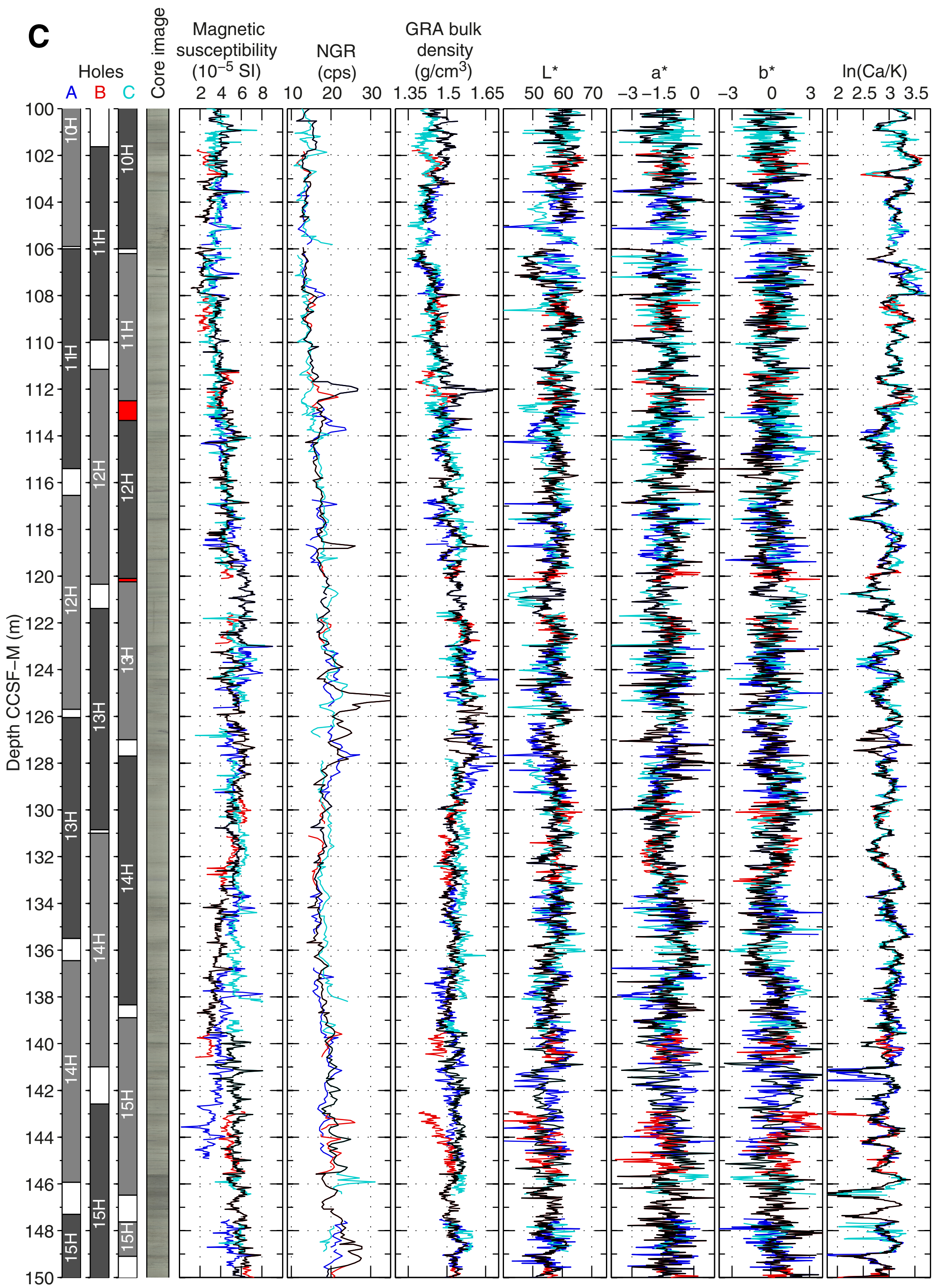

Figure F4 (continued). **D.** 150–200 m CCSF-M. (Continued on next page.)

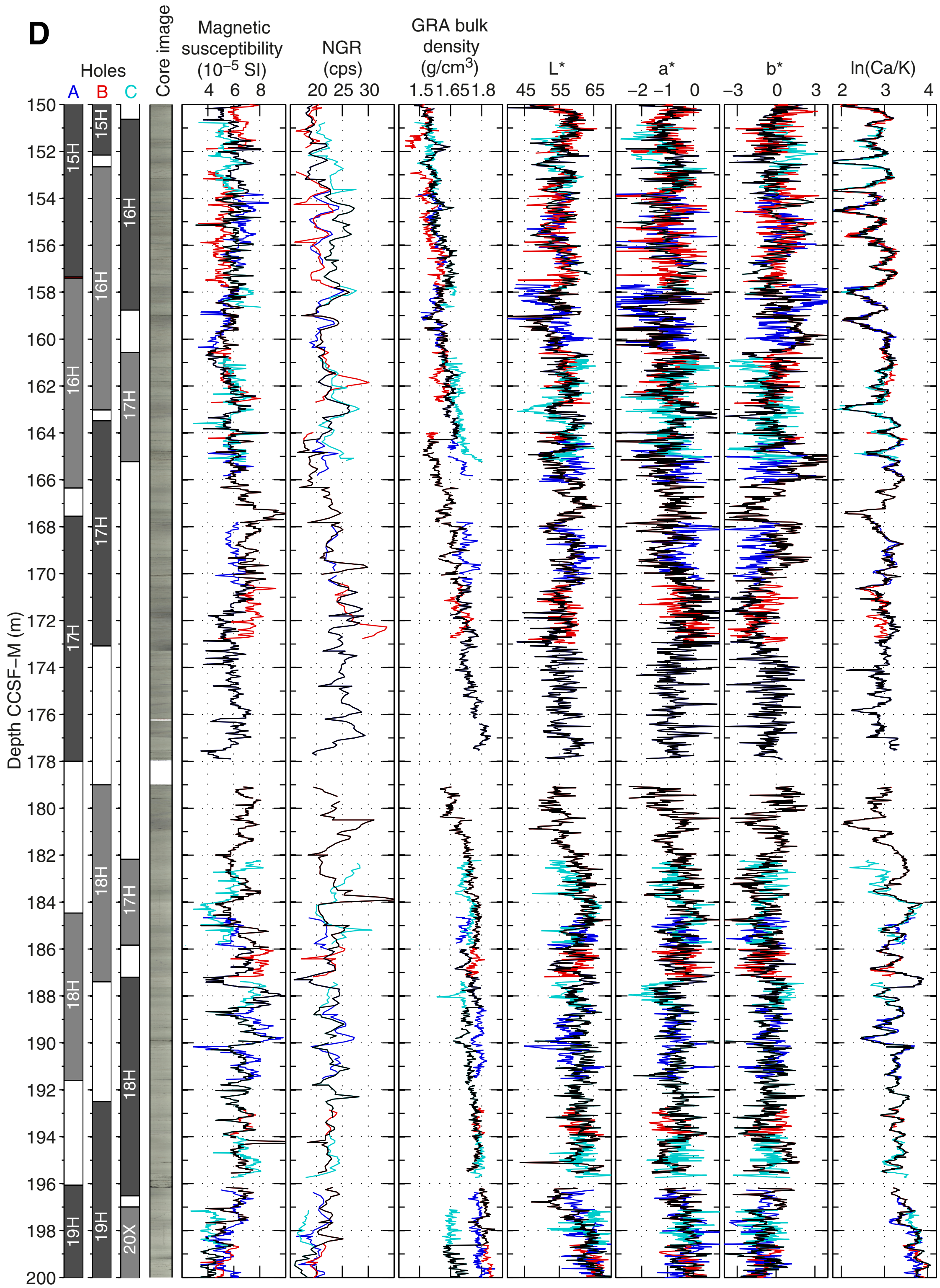

Figure F4 (continued). **E.** 200–250 m CCSF-M. (Continued on next page.)

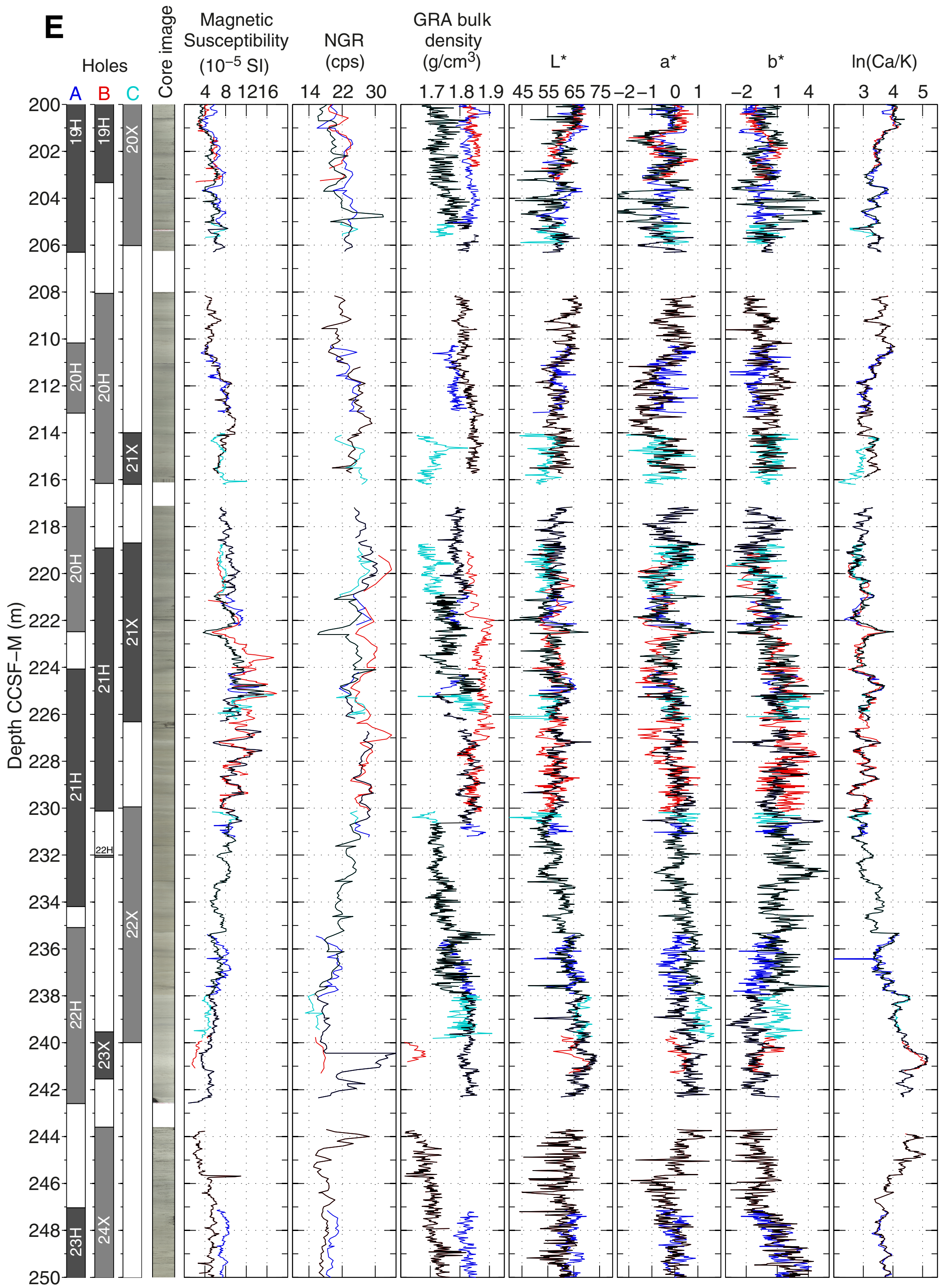

Figure F4 (continued). **F.** 250–300 m CCSF-M. (Continued on next page.)

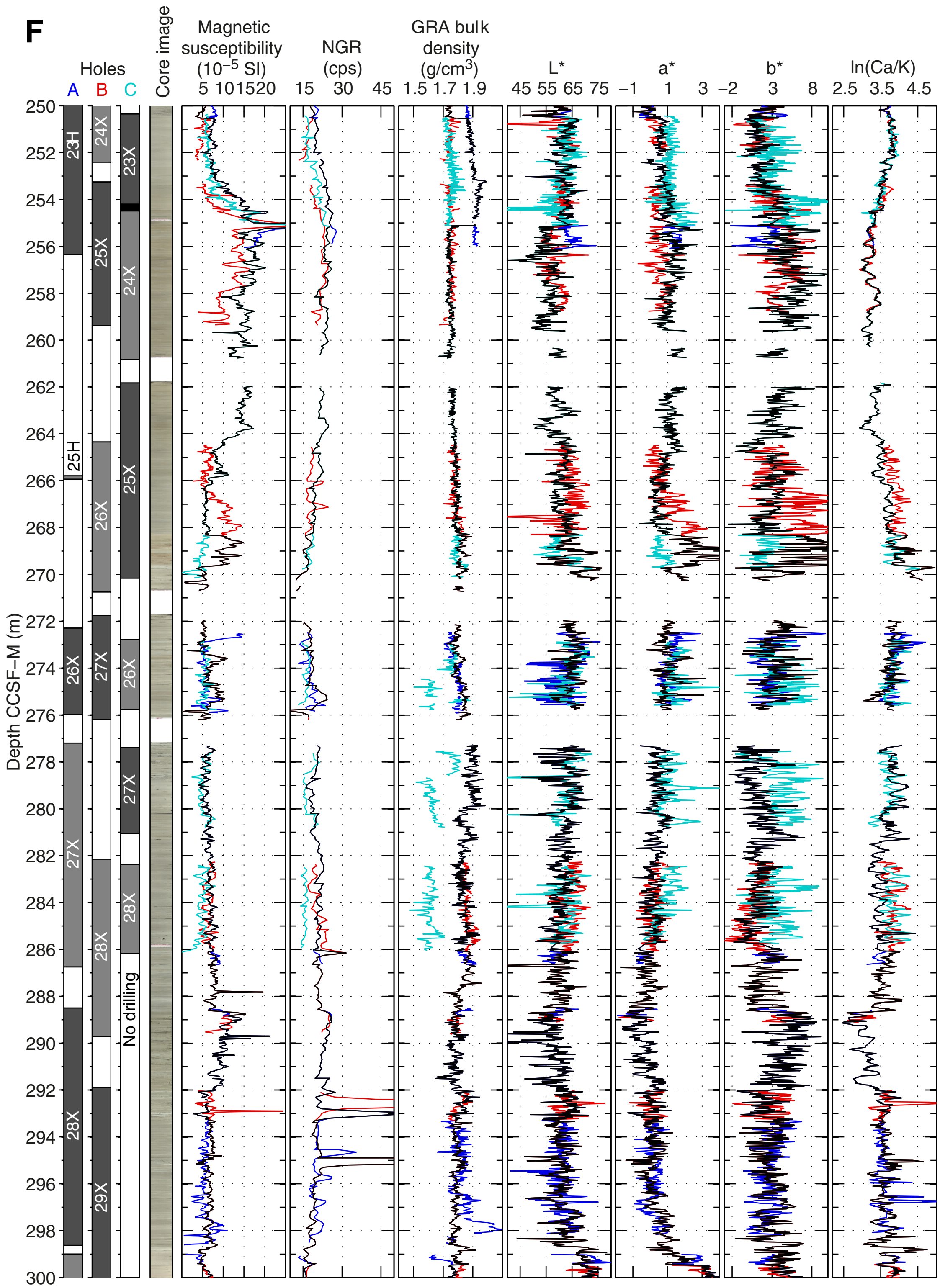

Figure F4 (continued). G. 300–350 m CCSF-M.

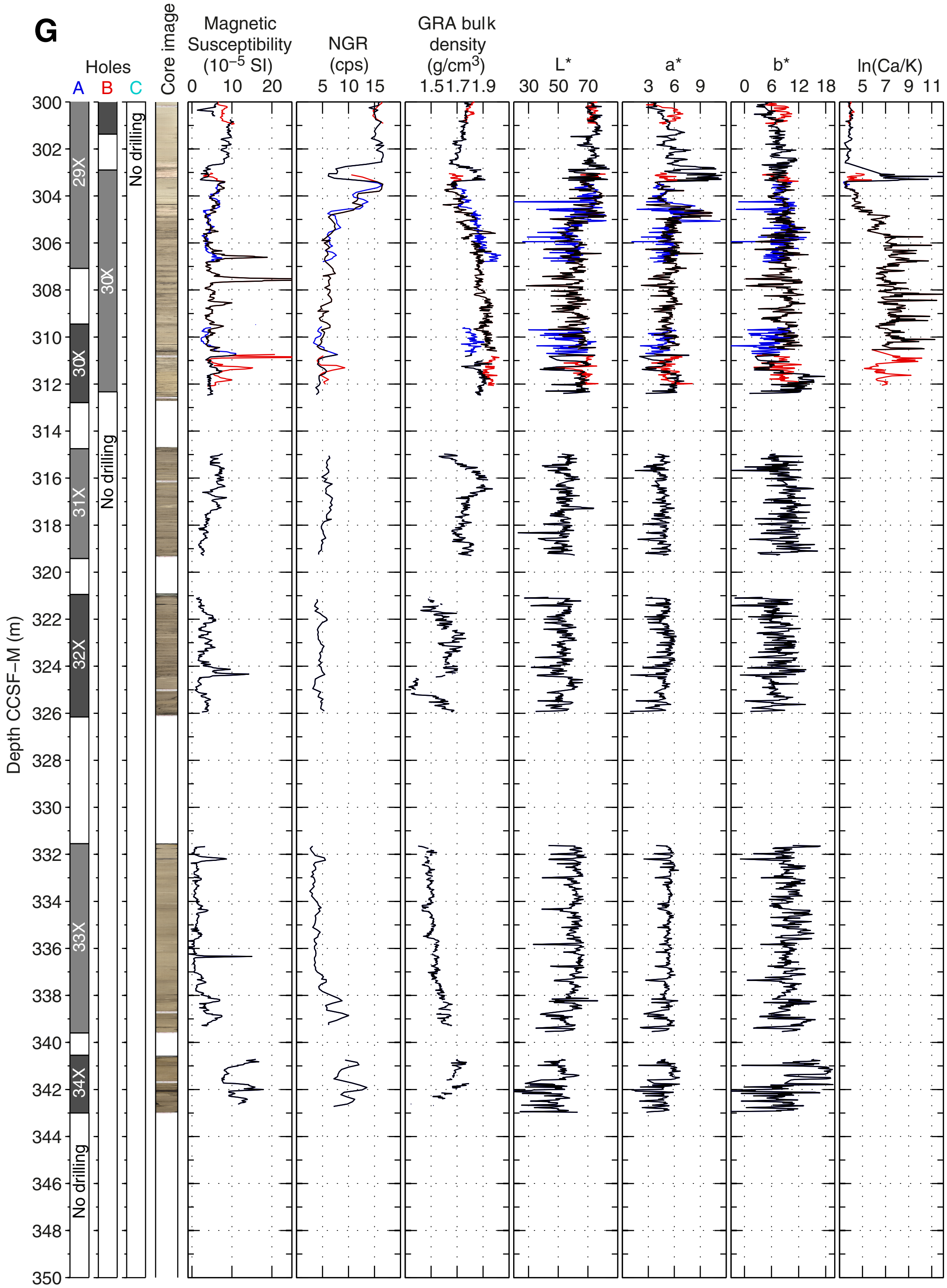

Figure F5. The growth factor of Site U1406, which is defined as the regression slope between the CSF-A and CCSF-M depth scales.

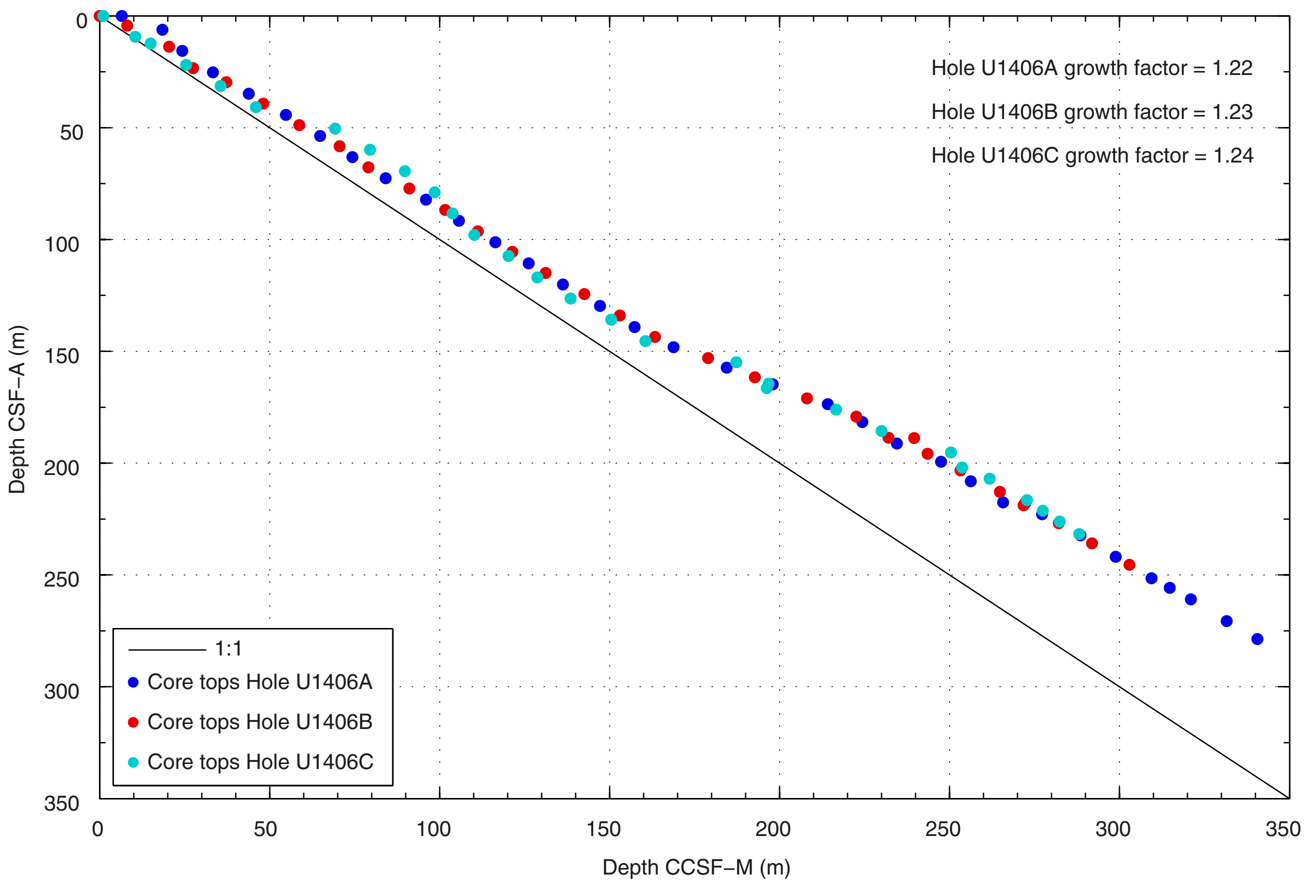

Table T1. Original (shipboard) and revised core offsets and composite depths, Site U1406. This table is available in .csv format.

Table T2. Revised splice tie point table, Site U1406. This table is available in .csv format.

Table T3. Revised splice interval table, Site U1406. This table is available in .csv format.

Table T4. Mapping pairs, Site U1406. This table is available in .csv format.

Table T5. Magnetic susceptibility data, Site U1406. This table is available in .csv format.

Table T6. Gamma ray attenuation data, Site U1406. This table is available in .csv format.

Table T7. Natural gamma radiation data, Site U1406. This table is available in .csv format.

Table T8. Reflectance spectrophotometer data, Site U1406. This table is available in **.csv format.**

Table T9. X-ray fluorescence core scanning ln(Ca/K) data, Site U1406. This table is available in **.csv format.**