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Correction of non-intrusive drill core physical properties data for variability in recovered sediment volume

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SUMMARY

Non-intrusive track-based physical properties measurements of sediment cores recovered during ocean drilling are often biased by imperfect recovery within sediment core liners, particularly in heterogeneous and/or partially lithified sediments. These biases result in misrepresentation in measurements of true sediment physical properties, and can complicate integration of the composite site records assembled from recovered cores with borehole logs of the stratigraphic section. Here we develop a strategy utilizing gamma ray attenuation (GRA) density to generate mass-specific magnetic susceptibility (MS) and natural gamma radiation (NGR) data. Shipboard GRA density is collected in all cores that comprise a site at equivalent or higher resolution than the corresponding MS and NGR data. All instruments are calibrated assuming a volume of sediment in their detector windows equivalent to that present in a perfectly full core liner; changes in sediment bulk density related to compaction, and/or imperfect sediment recovery resulting in a partially filled core liner thus influence all three measurements proportional to their detector sensitivities. In principle it may be possible to correct MS or NGR data for variable sediment volume by normalizing them to GRA measured at equivalent depth on a sensing track, assuming that the volumetric bias is comparable in all three datasets. Because GRA is measured in much greater detail, it must be smoothed by the known measurement windows of the other parameters for the assumption of comparable analytical sediment volume to be true. Normalizing MS or NGR by the equivalently smoothed GRA in down-hole records should thus remove the bias associated with variable sediment volume in the detector windows, allowing for robust mass-specific determination of these volume-based sediment physical properties.

Key words: Downhole methods; Ocean drilling.

INTRODUCTION

Measurements of sediment physical properties are most efficiently made by non-intrusive sensing of whole round sediment cores, for example, gamma ray attenuation bulk density (GRA), magnetic susceptibility (MS), point-sensing magnetic susceptibility (MSP), natural gamma radiation (NGR) and others (Blum 1997). Such measures are now routinely used on marine geology field programs, including expeditions of the International Ocean Discovery Program (IODP). Measurement accuracy for non-intrusive sensing assumes a constant geometry of the sample, for example that core liners are completely filled (i.e. that the cross-sectional area of sediment in the sensor is constant). This assumption often fails; cores contain cracks and voids, and also the diameter of recovered cores inside core liners varies on a core-to-core basis, driven by changes in lithology and coring methods (Fig. 1). Here we document sensitivity of physical properties sensors to errors in sediment volume within core liners and define corrections to make these measures more robust to coring

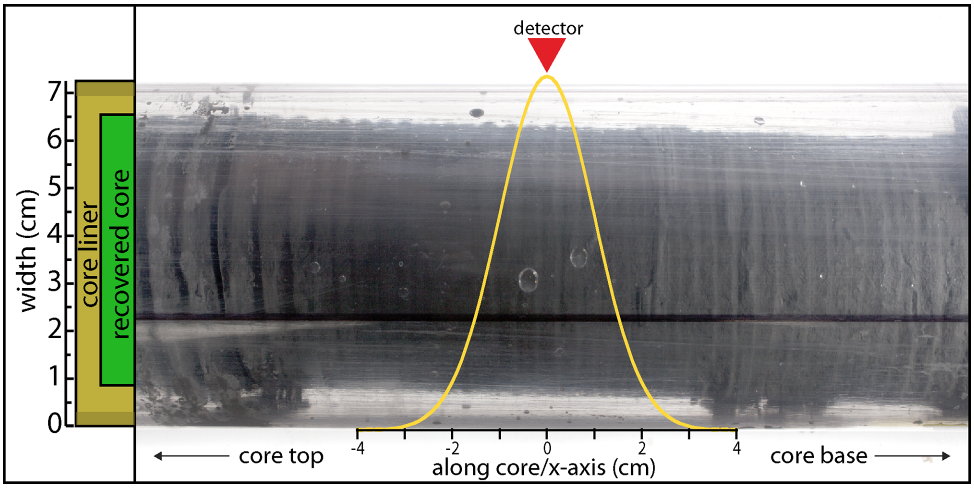

Figure 1. Photograph of a typical drilled (as opposed to piston) core section from Site U1418. The Gaussian instrument sensitivity window of a hypothetical sensor with a σ of ~1 is also shown (yellow line). Note that the core diameter is over a centimetre less than that of the core liner interior. As core cross-sectional area is a function of the square of diameter, this corresponds to a reduction of ~30 per cent in measured volume relative to the volume to which the physical properties sensors are calibrated. The diameter of cores recovered via the extended core barrel (XCB) and rotary core barrel (RCB; this image) drilling techniques are highly variable, but inevitably fail to fill the core liner.

artifacts. We illustrate these issues based on instruments available on the drilling vessel *JOIDES Resolution*, which is operated by IODP, but the data correction strategies are universally applicable to marine geological studies that use non-intrusive sensing data on sediment cores.

DETECTOR RESPONSE FUNCTIONS

Non-intrusive physical property measurements are integrated over an effective sediment volume within the sensitivity window of the instruments, which is characterized by sensor response function. For example, on the *JOIDES Resolution*, the response functions of the sodium iodide detectors of the NGR core analyzer (Vasiliev *et al.* 2011) and the MS loop sensors (Blum 1997), can be approximated as Gaussian distributions with different half-widths.

The effective volume of sediment measured in an instrument response window, which is characterized by relative probability $p(x)$ projected onto a cylinder, can be described as:

$$\mathrm{d}V_{\mathrm{eff}} = p\,(x)\,\mathrm{d}V = p\,(x)\,A\,\mathrm{d}x, \tag{1}$$

where the full cross-sectional area A is defined by $A = \pi\ r^2$, where r represents the interior radius of the core liner.

Assuming that the center of the sensor is located at position $x = 0$ (see Fig. 1) and we normalize the relative probability at $x = 0$–1, the Gaussian distribution $p(x)$ with standard deviation σ is given by:

$$p\,(x) = \exp\left(-\frac{x^2}{2\sigma^2}\right). \tag{2}$$

Thus the effective volume measured by the sensor is:

$$V_{\mathrm{eff}} = \int_{-\infty}^{\infty} \pi r^2\ \exp\left(-\frac{x^2}{2\sigma^2}\right)\ \mathrm{d}x = \sqrt{2}\pi^{1.5} r^2 \sigma. \tag{3}$$

The Gaussian response functions of the instruments are commonly parametrized by the full width at half maximum (FWHM). The relationship between FWHM and σ for a Gaussian distribution is described by:

$$\mathrm{FWHM} = 2\,(2\ln 2)^{0.5}\ \ \sigma \approx 2.355\sigma. \tag{4}$$

Rearranging the above gives the effective volume of a single measurement as:

$$V_{\mathrm{eff}} \approx \sqrt{2}\pi^{1.5} r^2 \left(\frac{\mathrm{FWHM}}{2.355}\right) \approx 3.344 r^2 \times \mathrm{FWHM}. \tag{5}$$

The sensitivity of a given instrument to a reduction in sediment volume relative to that assumed in calibration will depend on the width of its sensor response function, and the cross-sectional area of sediment within the measurement window (r^2). Thus, when normalizing any physical property parameter by any other, care must be taken to first apply a Gaussian smoothing filter to the raw data, nominally of a full width at half maximum (FWHM) equivalent to at least 2σ of the broader of the two detectors' response functions, so that their measurements are compared at a uniform resolution.

Natural gamma radiation measurements have been collected from sediment cores aboard the *JOIDES Resolution* since 1993 (Blum 1997). The current NGR measurement system, installed in 2009, consists of a series of eight large (4 in/~10 cm) sodium iodide detectors that simultaneously measure adjacent sections of the core (Vasiliev *et al.* 2011). NGR, typically recorded in a unit of 'counts per second' (cps), is really a measurement of cps per a unit of effective volume determined by the sensitivity of the individual sodium iodide detectors. The response function of these detectors aboard the *JOIDES Resolution* can be approximated as a Gaussian distribution with an 18 cm FWHM (Vasiliev *et al.* 2011). Based on eq. (5) each cps value for this case study is calculated assuming an idealized volume of 655 cm^3, and will be negatively biased by variability in the cross-sectional area of the core.

Continuous loop magnetic susceptibility (MS) measurements are recorded aboard the *JOIDES Resolution* via Bartington sensors installed on the same multisensor track used for GRA density. Magnetic susceptibility is the ratio of the induced magnetization to a magnetizing field, and is reported in instrument units for the effective volume at the measurement point. On both the 80 and 90 mm diameter Bartington loop sensors, MS is recorded with a response function of 4.5 cm FWHM (Fig. 2; Blum 1997; Bartington Instruments Inc. 2014; Jaeger *et al.* 2014). Based on eq. (5), loop MS is sensitive to an idealized volume of 164 cm^3 and will be negatively biased by variability in the cross-sectional area of the core.

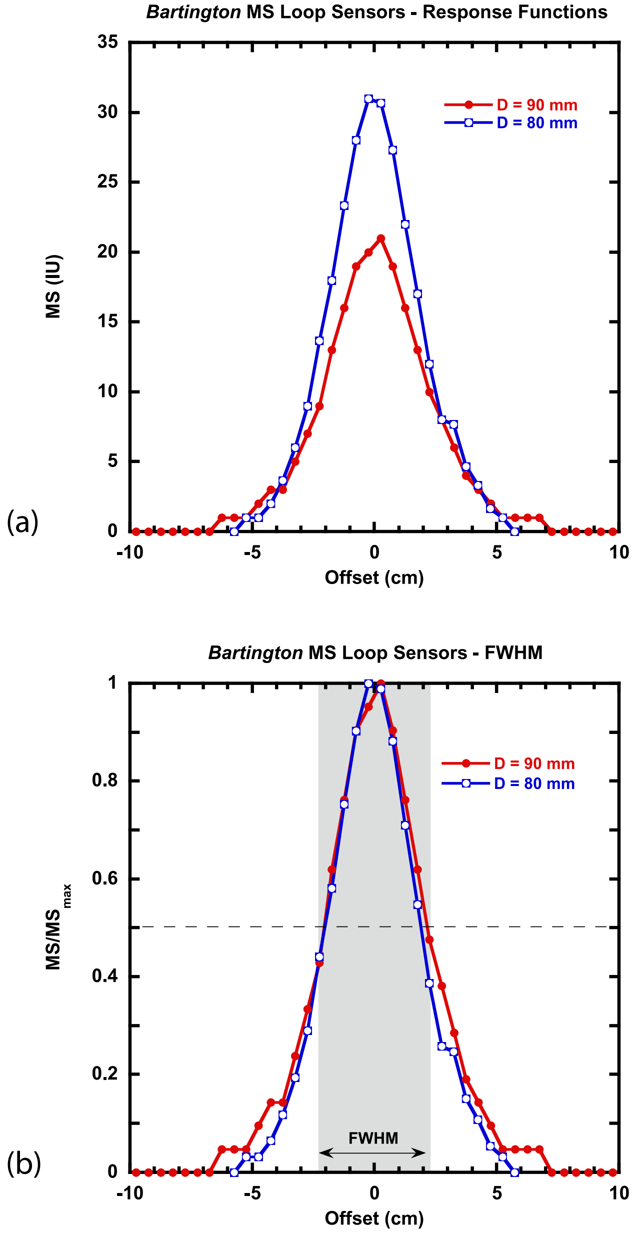

Figure 2. Plots showing the response function of the 80 and 90 mm diameter *Bartington* magnetic susceptibility loop sensors, derived empirically aboard IODP Expedition 341 via a point source of arbitrary strength. An offset of 0 cm corresponds to the center of the detector. (a) The response of the 80 mm sensor to the point source is greater in magnitude to than that of the 90 mm sensor. (b) However, when normalized to the maximum response, the full-width at half-maximum (FWHM) of both the 80 and 90 mm sensors is ~4.5 cm.

In addition to loop MS, the *JOIDES Resolution* is also equipped with a Bartington MS2E magnetic susceptibility point-sensor on a section-half multisensor logging (SHMSL) track. Point-sensor magnetic susceptibility (MSP) measurements respond to an idealized volume of <1 cm^3 (Bartington Instruments Inc. 2014). Because MSP is measured on the cleaned surface of split half-cores it is insensitive to variability in the width of the recovered core in any dimension (provided the core diameter is >1 cm), although it is sensitive to cracks or voids that may fall within its measurement window as well as imperfect contact between the sensor and the split-core surface.

GRA measurements aboard the *JOIDES Resolution* are collected via a multi-sensor track equipped with a gamma ray source and detector. The gamma ray source collimator has two positions, of 2.5 and 5 mm in diameter (Geotek Inc. 2014). If the collimator were infinitely long, producing a perfect photon beam, the resolution for gamma ray measurements in the core would be equivalent to the diameter of the collimator aperture. In practice, because of the size of the source capsule and the length of the collimator (approximately 50 mm), there is primary beam spreading through the core. Thus, when using the standard operating collimator position of 5 mm, the 'real' spatial resolution of a GRA measurement is closer to 10 mm (P. Shultheiss, personal communication, 2014). This measurement is sensitive to changes in core diameter along only its linear beam path, i.e., is more sensitive to small cracks and voids than instrument measurements that integrate larger volumes of the core; in the absence of these problems, the measurement is proportional to core diameter ($2r$) rather than the effective cross-sectional area r^2.

In summary, GRA density is ideally collected through every core depth for which volumetric MS and NGR data exist, although each GRA measurement integrates over 10 mm in the core, versus the 4.5 cm FWHM and 18 cm FWHM response functions that respectively describe the depth integration of MS and NGR measurements. If GRA density is smoothed to reflect the resolution of either MS or NGR, in principle the volumetric bias in the integrated GRA measurements will be equivalent to the volumetric bias in the lower resolution data sets. Thus, normalizing MS or NGR by the equivalently smoothed GRA in a core should cancel calibration errors associated with variable sediment volume in the detector windows, allowing for correct mass-specific determination of these volume-based sediment physical properties.

VOLUMETRIC CORRECTIONS

Natural gamma radiation

To correct the NGR data, in its original units of cps, for changes in volume, we normalize by the GRA bulk density data. First, we divide the raw NGR data by 655 cm^3 (the effective volume in the NGR detection window on a full IODP piston-core liner, based on current practice aboard the *JOIDES Resolution* with nominal interior core liner diameter of 6.6 cm) to convert to cps cm^{-3}, assuming an ideal core recovery ($\mathrm{NGR_{idealvol}}$).

$$\mathrm{NGR_{idealvol}(cps\,cm^{-3})} = \mathrm{NGR_{raw}(cps)/655(cm^3)}. \qquad (6)$$

If we assume a constant cross-sectional area of recovered core along the length of the measurement window, then the bias in volume of the GRA bulk density will be proportional to the bias in volume-normalized NGR data. Assuming NGR and GRA have equivalent measurement windows or homogeneous sediment within their measurement windows, the ratio $\mathrm{NGR_{idealvol}}$ in cps cm^{-3} divided by uncorrected GRA in g cm^{-3} gives NGR activity in units of cps g^{-1} (or 10^{-3} Bq kg^{-1}): a unit ($\mathrm{NGR_{mass}}$) which better represents the radioisotopic composition of recovered sediment.

$$\mathrm{NGR_{mass}(cps\,g^{-1})} = \mathrm{NGR_{idealvol}(cps\,cm^{-3})/GRA_{raw}(g\,cm^{-3})}. \qquad (7)$$

Because the measurement windows for NGR and GRA in practice have slightly different half-widths, on IODP Expedition 341 we applied a Gaussian smoothing of 20 cm FWHM to both variables before calculating the ratio.

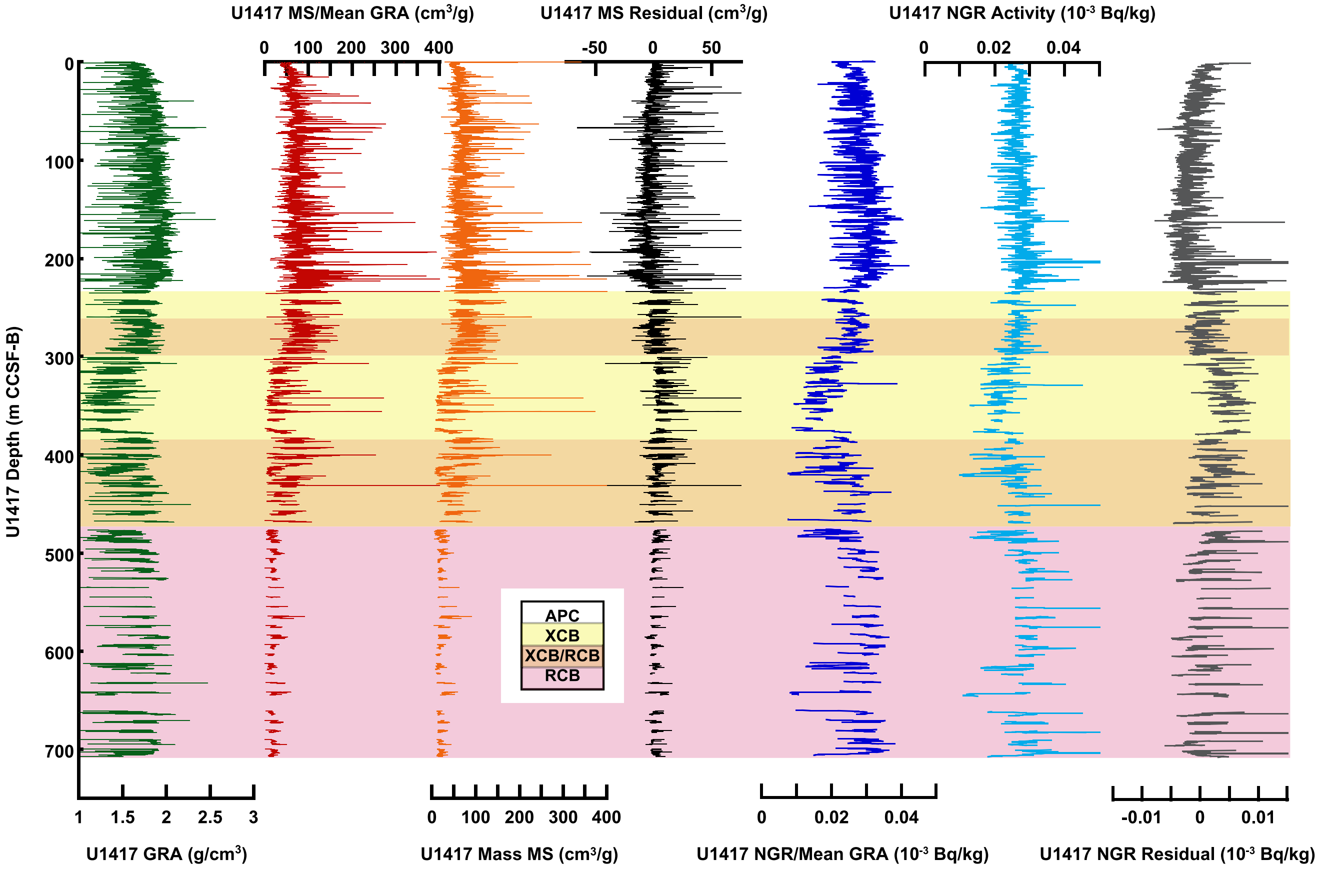

Figure 3. Physical properties data from Site U1417. The GRA bulk density (green) is shown smoothed with a 4.5-cm FWHM Gaussian filter and interpolated to 2.5 cm. Magnetic susceptibility is plotted normalized to the mean Site GRA density (red), to allow direct comparison to the down-core mass magnetic susceptibility (orange). The residuals of the density-corrected MS data are shown in black (see text). All NGR data are shown smoothed with a 20 cm FWHM Gaussian filter and interpolated to 2.5 cm. The raw NGR data were converted into units of cps cm^{-3}, and are also plotted normalized to the mean Site GRA density (dark blue) to allow direct comparison to the down-core NGR activity in the same units (light blue). The residual of the density-corrected NGR data is shown in grey. The uppermost portion of the core (no shading) was recovered by advanced piston coring (APC) coring. Yellow bars denote depths of extended core barrel (XCB) core recovery, pink bars denote depths of rotary core barrel (RCB) core recovery, and orange bars denote depths for which both those coring techniques were employed. See Application section for more information on the generation of the site physical properties stack and GRA normalization of raw MS and NGR data.

Magnetic susceptibility

For known changes in core diameter, true volumetric susceptibility can be recovered using the relationship between effective magnetic susceptibility and the ratio of core to coil diameter (Bartington Instruments Inc. 2014). However, when logging hundreds of metres to kilometres of core, it is impractical to attempt empirical correction for variability in the diameter of every section.

Mass-specific magnetic susceptibility (χ) can be constructed by dividing the shipboard MS data (κ_{raw}; measured in instrument units) by apparent density collected for the same material as measured by GRA.

$$\chi(\text{cm}^3\ \text{g}^{-1}) = \kappa_{\text{raw}}/\text{GRA}_{\text{raw}}(\text{g cm}^{-3}). \tag{8}$$

The units of this mass magnetic susceptibility are cm^3 g^{-1}. As for the NGR data, it is necessary to standardize the volumetric bias between the loop MS data and the GRA bulk-density before this normalization to account for the different smoothing functions of the loop MS and GRA sensors. Here we used a nominal Gaussian smoothing window of 4.5 cm FWHM, reflecting the measurement sensitivity of the loop MS sensors aboard the *JOIDES Resolution* (Fig. 2).

Gamma-ray attenuation bulk density

In principle, GRA bulk density data could be corrected for variable recovery using the ratio of loop to point-sensor MS data (because one type of MS data is sensitive to the width of the core while the other is not). In practice, highly heterogeneous ice-rafted debris sediments, problems with the quality of MSP data associated with variable contact with the sediment surface and instrument drift often preclude use of the MSP/MS ratio for normalization. Judicious use of calibration standards and drift-control procedures could open an avenue to recover volumetrically corrected core density in relatively homogenous lithologies.

Application

In June–July of 2013, the *JOIDES Resolution* sailed to the Gulf of Alaska on IODP Expedition 341: Southern Alaska Margin

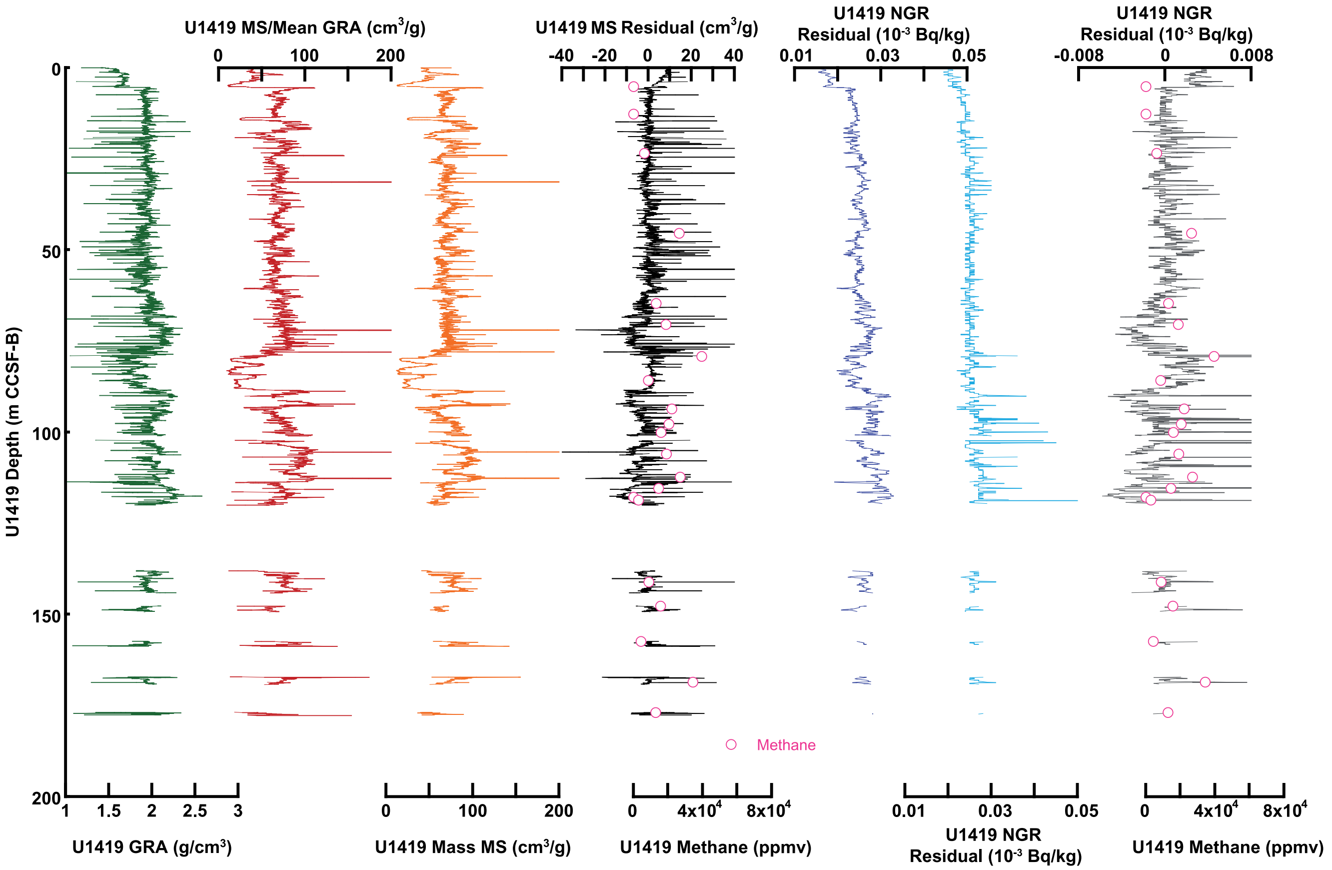

Figure 4. Physical properties data from Site U1419. The GRA bulk density (green) is smoothed with a 4.5 cm FWHM Gaussian filter and interpolated to 2.5 cm. Magnetic susceptibility is plotted normalized to the mean Site GRA density (red), to allow direct comparison to the down-core corrected mass magnetic susceptibility (orange). The residuals of the density-corrected MS data are shown in black (see text). All NGR data were smoothed with a 20 cm FWHM Gaussian filter and interpolated to 2.5 cm. The raw NGR data were converted into units of cps cm^{-3}, and are also plotted normalized to the mean Site GRA density (dark blue) to allow direct comparison to the down-core NGR activity (light blue). The residuals of the density-corrected NGR data are in grey. Headspace methane data are superimposed on the MS and NGR residuals (hollow pink circles). See Application section for more information on the generation of the site physical properties stack and GRA normalization of raw MS and NGR data.

Tectonics, Climate and Sedimentation (Expedition 341 Scientists 2014; Jaeger *et al.* 2014). As is common on drilling expeditions, the non-destructive physical properties data collected during this cruise were occasionally biased by variability in the diameter of recovered core (Fig. 1). However, as discussed above, we can correct for measurement error in the MS and NGR data by converting these properties to mass-normalized units using the shipboard GRA data.

We calculated volumetric corrections for MS on IODP Expedition 341 Sites U1417, U1418, U1419 and U1420. For each of these records, the shipboard splice (an optimized composite record from multiple holes) was used for the depths over which it was available. Reflecting the instrument response function, MS data from whole-round core analyses were interpolated to 2.5 cm resolution and smoothed with a 4.5 cm FWHM Gaussian filter. Similarly, NGR data were interpolated to 10 cm resolution and smoothed with a 20 cm FWHM Gaussian filter. The NGR data were then corrected to cps cm^{-3} by dividing by 655 cm^3, the nominal measurement volume of the NGR detectors. The GRA data used for the volumetric corrections were interpolated to 2.5 cm with a 4.5 cm FWHM Gaussian smoothing (for correction of MS) and to 10 cm with a 20 cm FWHM Gaussian smoothing (for correction of NGR). Prior to this smoothing and interpolation, we culled spurious GRA values with densities of less than 1 g cm^{-3}, as they reflect intervals with very little or no sediment associated with gaps in core recovery and/or core breaks due to gas expansion.

For depth intervals not covered by the spliced composite, raw data from the cores in each hole were interpolated and smoothed on composite depth scale (CCSF-A; Jaeger *et al.* 2014) following the same parameters described for the spliced interval. Data from multiple holes at Sites U1417, U1418 and U1419 were then stacked on this composite depth scale, with an average value taken across interpolated depth horizons for which multiple records were collected, and appended to the bottom of the spliced interval. As only one hole was drilled at Site U1420, no spliced or stacked composite exists and raw data from the single hole were interpolated and smoothed.

Following interpolation, smoothing, and stacking, the composite MS and NGR records for each hole were divided by a smoothed GRA record (appropriate to their resolution), generating values of mass (specific) MS (cm^3 g^{-1}) and NGR activity (cps g^{-1} or 10^{-3} Bq kg^{-1}).

To compare the continuously normalized data values with original data in the same units and scaling, we divided the uncorrected but equivalently smoothed MS and NGR down-core data by the mean GRA value at each site. This effectively moves the MS and NGR into ‘per mass’ units without imposing a variable volume or porosity correction.

RESULTS AND DISCUSSION

The volume normalization reduces the variance in each data set. The greatest reductions in variance were in NGR, ranging from ∼20 per cent (Site U1418) to ∼50 (Site U1417). Variance in MS was also reduced in every case, from ∼10 per cent (U1417) to ∼25 per cent (U1418). This variance reduction is associated with removal of artifacts associated with incomplete recovery within the core liner.

To evaluate down-core patterns in the corrected versus uncorrected data, we calculate a residual record by subtracting the scaled but non-normalized data from the continuously normalized data. The sign and magnitude of the residual reflect the nature and extent to which down-core variability in sediment volume impact both MS and NGR. To interpret these data, we evaluate them on compression-corrected core composite depth scale CCSF-B, thought to be the closest depth-scale approximation of the actual drilled interval (Jaeger *et al.* 2014). At Site U1417, the trend of both the MS and NGR residuals in the stratigraphic splice (above ∼220 m CCSF-B) generally appear to reflect increasing sediment density related to compaction (Fig. 3). However, at depths greater than the interval covered by the splice, the predominant changes in the residual of both the MS and NGR data coincide with a shift in coring technique, from advanced piston coring (APC) to extended core barrel (XCB) drilling; higher mean residuals that correspond to the XCB drilling are caused by the reduced core diameter within the liner (Figs 1 and 3).

In addition to correcting for the effects of sediment compaction and variable recovered core diameter, normalization corrects for changes in the gas content of the sediment column. At Site U1419, only APC cores were collected and liners appeared to be consistently full, reflecting the ideal volumetric conditions to which the physical properties instrumentation are calibrated. Nonetheless, the residuals of the normalized relative to non-normalized data in both the MS and NGR indicate variable but generally positive excursions between ∼70–120 m CCSF B (Fig. 4). Headspace measurements from cores recovered in this interval indicate high methane gas contents, of up to 60 000 ppmv, which apparently correspond to intervals of negatively biased bulk density (Jaeger *et al.* 2014). When normalized by the GRA data, lows observed in the other whole-round physical properties measurements associated with the dilation of the sediment by gas expansion are reduced, leaving a better signature of true variability in lithology.

Using apparent density normalization to correct the whole-round physical properties data for changes in core diameter and processes such as post-recovery gas-expansion of the sediments has the potential to improve the integration of core data with downhole logs. Physical properties data, including natural gamma radiation, are routinely collected through downhole logging of boreholes. Downhole logs are continuous, *in situ* measurements that allow sediment characterization in environments where core recovery is poor and core quality is variable and complement core data where both data types are available. During Expedition 341, downhole logging data were collected in one hole at each of Sites U1417, U1418, U1420 and U1421. For core-downhole log integration, data are compared in two different depth scales: wireline log matched depth below seafloor (WMSF) and the most comparable core compressed composite (CCSF-B) depth scale. In a comparison of stratigraphic variability with depth for Sites U1417 and U1418, both of which had 100s of metres of overlap in core recovery and downhole logged depth, evaluation of the physical properties data in mass-normalized units produces significant improvements in core-downhole log integration (Jaeger *et al.* 2014). At Site U1417, for example, the reduction in variance in mass-normalized core NGR activity leads to a higher degree of correspondence between core and downhole log data (Fig. 5). The primary improvement in the normalized data is removal of the erroneous step-like changes associated with changes in the coring device from APC to XCB to RCB; each of these drilling and coring methods recovers systematically different volumes of material within core liners. At submetre scales, improvement of coherence between the track-measured data and the borehole logs were not significant. This may reflect small-scale biases in the borehole logs related to borehole rugosity (Flaum *et al.* 1991), or imperfect removal of coring distortion effects on the depth scale in intervals where lithologic variations were of low amplitude or not diagnostic for purposes of correlation of fine-structure. The increasing trend in NGR with depth deeper than ∼300 m CCSF-B/WMSF in both data sets supports the interpretation of higher natural radioactivity inputs associated with a relative increase in muddier lithologies at Site U1417 (Jaeger *et al.* 2014).

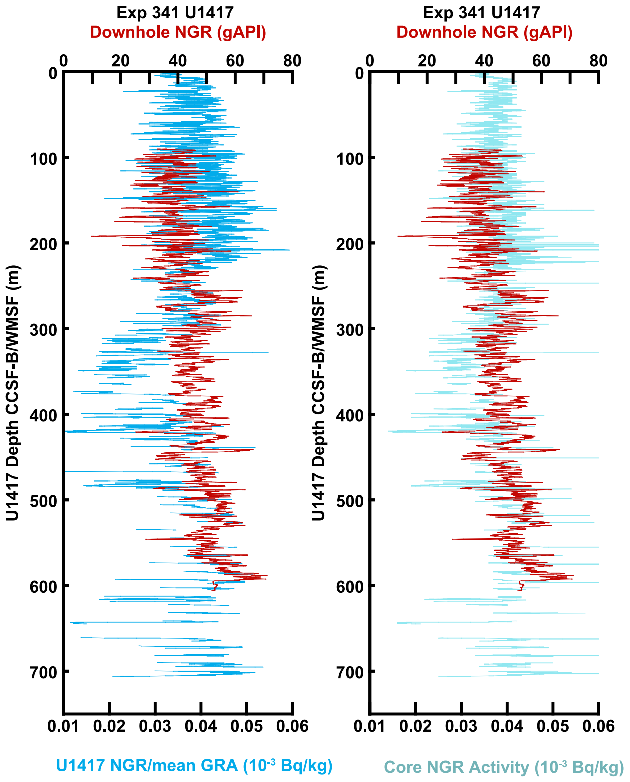

Figure 5. Comparison of core and downhole logging NGR data from Site U1417. The downhole NGR data (red) recorded in Hole U1417E are plotted with core NGR activity normalized by the mean Site GRA density (dark blue) at left, and NGR activity normalized on a sample-by sample basis using GRA density averaged in equivalent measurement windows (light blue) at right. In both examples the NGR data were smoothed with a 20 cm FWHM Gaussian filter and interpolated to 2.5 cm. Downhole logging data are shown in the WMSF (wireline matched depth below seafloor) depth scale, most directly comparable to the core CCSF-B (compressed composite) depth scale. See Expedition 341 Scientists (2014) for more detail on downhole logging, and Application section in this text for more information on the generation of the site physical properties stack and GRA normalization of raw NGR data.

CONCLUSIONS

Non-intrusive shipboard whole-round physical properties measurements reflect variability in sediment compaction, porosity, gas expansion, and recovered core diameter in addition to true sediment lithology. Normalization of the core logging data by apparent density, after smoothing to correct for the varying response functions of the instrumentation converts volumetric MS and NGR whole-round data to mass-specific values that better reflect the sediment composition. This normalization reduced the variance in the physical properties records collected on IODP Expedition 341, by an average of ∼15 per cent for the MS and ∼35 per cent for the NGR data. Evaluating the physical properties data in mass-specific units also supports efforts to correlate core logs to downhole logs, by removing the effects of coring and post-coring deformation.

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