A period of calm in Scottish seas: A comprehensive study of $\Delta R$ values for the northern British Isles coast and the consequent implications for archaeology and oceanography

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1. Introduction

The Marine Radiocarbon Reservoir Effect (MRE) is a $^{14}C$ age offset between contemporary marine- and terrestrially-derived carbon. In Northern Hemisphere surface waters it is of the order of 400 years but temporal and spatial deviations, known as $\Delta R$, occur. This study provides a comprehensive dataset of 21 $\Delta R$ and MRE values for the east coast of Scotland and 21 recalculated values for the west coast of Scotland and Ireland, for the period c. 3500 BC to 1450 AD. They are presented as mean, site-specific $\Delta R$ and MRE values, together with their associated uncertainties, calculated as standard errors for predicted values. The $\Delta R$ values range from $-320 \pm 35$ to $+150 \pm 28$ $^{14}C$ years and show no spatial or temporal trends. The MRE values range from $59 \pm 40$ to $531 \pm 26$, show an almost identical distribution pattern to the $\Delta R$ values and again show no spatial or temporal trends. Results show that $\Delta R$ values calculated for a single site using statistically indistinguishable groups of terrestrial and marine radiocarbon age measurements can produce variability of up to 225 $^{14}C$ years. $\Delta R$ is an important factor in the accurate calibration of samples containing marine-derived carbon for archaeological interpretation but is often also used as an indicator of changes in $^{14}C$ specific activity of the oceans, and therefore a proxy for changes in ocean circulation and/or climate. Using the methods outlined in this paper, it is apparent that $\Delta R$ values for the northern part of the British Isles have been relatively stable, within our ability to quantify non-random variation in the data. The fact that significant climatic shifts have been recorded during this time, yet these are not visible in the $\Delta R$ data, presents a cautionary tale regarding the use of $\Delta R$ to infer large-scale oceanographic or climatic changes. Upon the exclusion of 5 outliers from the 42 values, the remaining $\Delta R$ values are statistically indistinguishable from one another and range from $-142 \pm 61$ to $+40 \pm 47$ $^{14}C$ years. 34 of these values are from Scottish archaeological sites and can be combined to produce a mean value for Scotland of $-47 \pm 52^{14}C$ years for the period 3500 BC to 1450 AD, to be used only in the absence of site- and period-specific data.
Marine radiocarbon ages are calibrated using a modelled marine curve based on atmospheric data. The current calibration curve (Marine13) (Reimer et al., 2013) uses the ocean-atmosphere box diffusion model (Oeschger et al., 1975; Stuiver and Braziunas, 1993). This modelled marine calibration curve accounts for the global average offset of oceanic \(^{14}\)C with respect to the atmosphere, producing a present-day average surface water reservoir offset of 405 ± 22 \(^{14}\)C yr (Hughen et al., 2004), however, temporal and spatial deviations from this offset, known as \(\Delta R\), are evident (Stuiver and Braziunas, 1993; Ascough et al., 2006). Robust \(\Delta R\) values are calculated using multiple paired samples of terrestrial and marine origin that are of the same calendar age. The \(\Delta R\) value is calculated by converting the terrestrial/atmospheric \(^{14}\)C age ±1 sigma to a modelled marine age via interpolation between the INTCAL 13 atmospheric curve and the MARINE13 curve (Reimer et al., 2013). \(\Delta R\) is the difference between this modelled marine \(^{14}\)C age and the measured \(^{14}\)C age of the corresponding marine carbon sample. The 1\(\sigma\) error on the \(\Delta R\) values is calculated by the propagation of errors on both ages. \(\Delta R\) is factored into the calibration process by subtracting it from the conventional radiocarbon age (CRA) and then recalibrating with the marine curve. A positive \(\Delta R\) will therefore increase the MRE for the area, relative to the global average, whilst a negative \(\Delta R\) will decrease it. Globally, \(\Delta R\) values can show significant variation (Fig. 1) as shown by the data held on the 14 CHRONO Marine Reservoir database at http://intcal.qub.ac.uk/marine/.

1.1. Variations in \(\Delta R\) as oceanographic indicators

The spread of \(\Delta R\) values shown in Fig. 1 demonstrates the global variability. This variability in \(\Delta R\) is often attributed to changes in ocean water \(^{14}\)C activity, related to shifts in circulation patterns. Using this rationale, \(\Delta R\) is often used as a proxy for identifying past oceanographic changes.

Palaeoclimatic variations that affect the amount of time that water is in contact with the atmosphere can affect the MRE. Colder conditions such as the extension of the Arctic ice sheet would increase sea ice cover, leading to less area available for ocean/atmosphere CO\(_2\) exchange. Deep waters would become increasingly depleted in \(^{14}\)C as they are further removed from contact with the atmosphere. Conditions which induce a higher rate of upwelling of deep, older waters will increase the MRE and vice versa, any conditions which allow the waters to stay near the surface, in contact with the atmosphere, will reduce the MRE. The MRE therefore has the power to reflect large scale shifts in ocean \(^{14}\)C activity, provided that trends and shifts in the MRE (or \(\Delta R\) values) are accurately identified.

Russell et al. (2011a) suggest a methodological approach to the publication of \(\Delta R\) values and their errors in an attempt to raise awareness of the inherent variability in \(\Delta R\) calculations. If this inherent variability is not accounted for in the published \(\Delta R\) values, using their associated errors, misleading significance of changes in \(\Delta R\) may well be interpreted as an indicator of oceanographic shifts. Various authors have used \(\Delta R\) as a climatic/oceanographic proxy using a variety of methods of calculation (e.g. Etayo-Cadavid et al., 2013; Hideshima et al., 2001; Jones et al., 2007a; Kennett et al., 1997; Matos Martins and Monge Soares 2013). In some instances, application of the methodology employed by Russell et al. (2011a) to the data renders the differences in \(\Delta R\) insignificant and
therefore the associated oceanographic proxies that have been drawn, invalid.

1.2. $\Delta R$ impacts on archaeological calibration

Accurate and precise quantification of the MRE and/or $\Delta R$ is of paramount importance for enabling the accurate calibration of $^{14}$C age measurements made on samples containing marine-derived carbon that are of archaeological importance. Previous studies at SUERC which refined $\Delta R$ values for the west coast of Scotland, northern Iceland and the Faroes (Ascough et al., 2004, 2006; 2007a, 2007b; 2009) have led to significant chronological re-interpretation of Scottish archaeological sites, where conclusions had previously been drawn that were based upon radiocarbon age measurements made on marine derived carbon (e.g. Barber, 2003). The accuracy and precision of $\Delta R$ values and their associated errors therefore have the potential to impact significantly on the interpretation and evaluation of archaeological and oceanographic research alike.

$\Delta R$ values have been calculated for 21 contexts from 11 archaeological sites on the east coast of Scotland and recalculated for 21 contexts from 13 archaeological sites on the west coast of Scotland and Ireland. The west coast values were previously published using the method of Ascough (2005) but have been recalculated using the method recommended by Russell et al. (2011a) to allow comparability of results. This gives a total of 42 $\Delta R$ values for the UK coast which can be used to aid archaeological interpretation and paleo-oceanographic investigation.

1.3. Regional setting

The UK is situated to the North-west of continental Europe, bordered by the North Sea to the east, the English Channel to the south and the Irish Sea/Celtic Sea and Atlantic Ocean to the west (Fig. 2). Warm surface waters from the North Atlantic flow north-west, towards the Norwegian Sea as the North Atlantic Current (NAC), skirting the west coast of the UK as a variety of coastal currents before diverging into the North Sea (Fig. 4). OSPAR (2000), Baxter et al. (2008) and UKMMS (2010), all provide more detailed discussion on UK coastal circulation. Russell et al. (2010, 2011b), Ascough et al. (2004, 2005a,b, 2006, 2007a,b) and Cage et al. (2006) all relate these specific current patterns and the characteristics of local circulation directly to UK MRE values.

The majority of sites from this study were located in the Northern British Isles, particularly Scotland. The sites range from Quoygrew on Orkney in the North, to Doonloughan in Ireland (Fig. 2) and span a temporal range from the 4th millennium BC to the 15th century AD (Table 1). The sites also occupy a variety of open coastal and estuarine locations. Some of the sites have the potential to be subject to coastal estuarine processes, particularly around the sea lochs of western Scotland and the major estuaries (firths) on the east coast of Scotland and any values calculated from such environments may not represent a true MRE per se and instead may demonstrate a local MRE, diluted by freshwater input.

2. Methodology

This study recalculated $\Delta R$ values that were previously published by Ascough et al. (2004, 2006, 2007a, 2009) and Ascough (2005), as well as those published by Russell et al. (2010, 2011a, 2011b) and Russell (2011), by employing the statistical methodology recommended by Russell et al. (2011a). Most of the radiocarbon measurements were carried out at the SUERC laboratory in East Kilbride, Scotland. All site-specific $\Delta R$ values from both studies were determined using the multiple paired sample approach as advised by Ascough et al. (2005, 2009). Secure archaeological contexts were established through close consultations with site excavators and by examination of excavation reports. This identified contexts containing suitable marine (generally mollusc shell or fish bone) and terrestrial entities (roundwood charcoal, charred grains, herbivore bones etc.) which had been relatively unaffected by post-depositional disturbance (e.g. Ascough et al., 2007a, 2009) and which were likely to have been deposited at the same time, suggesting a similar calendar age for both sample types. The methodology advocated the collection of at least 4 suitable marine and 4 suitable terrestrial entities per archaeological context to allow the resulting ages to be tested for contemporaneity. Detection of anomalous age measurements (or outliers) is difficult in very small sets of dates, and we have employed a manual approach (Bronk Ramsay, 2009), informed by a simple chi-squared ($\chi^2$) test of the marine and terrestrial data to demonstrate that the ages are indicative of a single deposition time (within statistical limits). Thus, unrounded radiocarbon ages and their associated errors were $\chi^2$ tested for contemporaneity before calculating $\Delta R$ values. The $\chi^2$ test determines whether each sample within a group is statistically indistinguishable at 95% confidence from the remainder and therefore can be considered contemporary. Only samples which pass the $\chi^2$ test are then used to calculate $\Delta R$. The critical value for the $\chi^2$ test differs according to the number of measurements within a group and this value is compared to the T-statistic calculated for each group to determine whether the samples are statistically indistinguishable (Ward and Wilson, 1978). The calculation of the T-statistic is shown in Eq. (1).

\[
T = \frac{\sum (t_i - \bar{t})^2}{\sigma^2_i}
\]

where: $t = \text{the weighted mean of the } ^{14}\text{C age group}$
$t_i = \text{the individual } ^{14}\text{C measurement}$
$\sigma_i = \text{the error on the individual measurement}$

Eq. (1): T-statistic calculation.

$^{14}$C ages that pass the $\chi^2$ test are then used to calculate $\Delta R$. In cases where samples do not pass the $\chi^2$ test, a judgement call has to be made on whether or not the samples from this context are in fact suitable for determining a $\Delta R$ value. By using every possible pairing when all samples pass the $\chi^2$ test, 16 estimates of $\Delta R$ can be calculated for a context from which the 4 terrestrial and 4 marine entities were selected.

Our approach is closely related to bootstrapping which is a statistical procedure to estimate a parameter associated with a population which may be too difficult or expensive to measure directly. In a similar manner, Jones et al. (2007b) approached the same problem of calculating $\Delta R$ in archeological contexts by applying Bayesian analysis, solved using a MCMC approach. Bootstrapping is a nonparametric re-sampling method, not dependent on distributional assumptions, which in this context allows us to estimate the population variance and hence the standard error on delta R, based on a relatively small set of $^{14}$C measurements. Our use of a resampling technique is to ensure that we have an appropriate and realistic estimate of the population variance. We sample independently and with replacement from the terrestrial and marine samples.

The spread of $\Delta R$ values for each site/context can be fully represented using histograms alongside a weighted mean and the standard error for predicted values. The standard error for predicted values gives the best indication of where future values from
a similar time and place may lie, using the root sum of squares of the standard deviation and the error on the mean for each group. The benefits of publishing according to this protocol and the potential impact it could have on interpreting ΔR values is discussed in detail by Russell et al. (2011a). This method provides the most robust way of interpreting ΔR values in relation to one another and of statistically addressing the inherent variability within the calculation of ΔR values, and their subsequent use in oceanographic and archaeological interpretation.

3. Results

This paper does not discuss in detail the production of the 14C ages and δ13C values for each sample used in the study, the references in Table 1 provide all of this supplementary information. In summary, the measured δ13C values of the terrestrial mammal bones used within this study (−19.4% to −23.2%) fall within the typical range for animals existing on purely terrestrial dietary resources in C3-plant dominated environments (e.g. DeNiro and Epstein, 1978; Chisholm et al. 1982, Post, 2002; Peterson and Fry, 1987, Schoeninger and DeNiro, 1984). A significant marine signal within the mammal’s diet would be reflected in a higher δ13C value, which would have resulted in the sample being rejected on the basis of it being unrepresentative of wholly terrestrial material. The measured δ13C values of the carbonized cereal grains ranged from −20.2‰ to −27.0‰, representative of a C3 photosynthetic pathway (Craig, 1953; O’Leary, 1981). The δ13C values for the shells ranged from −2.1 to +2.9, within the accepted range for marine carbonate (Rounick and Winterbourn 1986).

Preliminary studies were undertaken by Ascough et al. (2005b) and Russell et al. (2010) to investigate whether any significant freshwater signals were present at the sites close to estuaries/sea lochs using δ18O measurements on the mollusc shell samples. This would resolve whether the values for these sites represented a true MRE, or a mixed marine/freshwater offset. The authors concluded that none of the shells were formed in an environment with a significant freshwater input, and therefore the published ΔR values are representative of a true MRE. Also, no correlation could be observed between the variability in the ΔR values and the geographical distribution of the sites.

The radiocarbon ages within each terrestrial/marine group at each site/context were tested for contemporaneity using the χ² test. In a few contexts, samples had to be excluded from the χ²-test as a result of their large contributions to the T value. Where exclusions
were made, the data were carefully scrutinized to ensure that they were not subject to excessive rejection to allow the remaining samples to pass. If a context contained a large proportion of samples that were not considered contemporary (by failing the χ²-test), the likelihood of post-depositional disturbance increased, thereby reducing confidence in the security of the context and therefore the validity of any MRE/ΔR that was calculated. It was deemed acceptable to exclude 1 sample from each group of 4 in order for the remainder to pass the χ²-test and still avoid the risk of calculating an MRE/ΔR based on non-contemporary samples. Sites that did not produce suitable results were excluded from the study, owing to archaeological misidentification of the samples as contemporary marine and terrestrial entities. The sites which did pass the χ²-test were then used to calculate ΔR. 

ΔR and MRE values for each context were calculated and the ΔR values displayed as histograms (Supplementary data) showing the spread of values produced by the multiple pairings of marine and terrestrial 14C ages, together with the mean ΔR and standard error for predicted values. This gives a realistic indication of where ΔR values from a similar site and time may lie. The weighted mean ΔR and MRE values for each site/context and their associated errors are provided in Table 1 and illustrated in Fig. 3. These MRE and ΔR values are calculated from sites that range from 492 to 4551 14C years BP and demonstrate no temporal relationship within the data.

The mean ΔR values for each context range from −320 ± 35 to 150 ± 28 14C years and when χ² tested as a complete group, fail the test for comparability as T = 193.4245 (X²=0.05 = 56.942). When 5 sites are excluded, (Scatness 543, Carding Mill Bay, Robert’s Haven 3004 Fish, Freswick Links and St Leonard’s School), the remaining 37 ΔR values pass (T = 47.271 (X²=0.05 = 50.998)). The values which pass the χ² test range from −142 ± 61 to 40 ± 47 14C years and are considered statistically indistinguishable from one another at this level of confidence.

From the results, ΔR values for the northern UK appear to have been relatively stable with little or no temporal or spatial variation over the period represented in the study. On the basis of ΔR measurements, no freshwater effect is evident and any variation in the MRE or ΔR values can be attributed to estuarine locations. The MRE and ΔR values therefore display no temporal or spatial trends.

A key message from this study reinforces the findings of Russell
et al. (2011a); combining multiple pairs of statistically indistinguishable radiocarbon dates in a matrix-style approach can produce variability in the subsequent ΔR values in excess of 200 14C years. From the sites discussed in this paper, Doonloughan DL3 F319 displays a maximum spread of 225 14C years, (Fig. 4) and it is this variability which is critical to the justification of whether ΔR can be used as a climatic proxy or not. Russell et al. (2011a) have already discussed the variability in ΔR values calculated using this method, and concluded that this variability represents uncertainties inherent within the production and calculation of ΔR values and not as a result of oceanographic/ 14C activity of the local surface waters. They further concluded that variability in ΔR values of less than 200 14C years cannot be reliably used as a climatic proxy. This conclusion was reached due to simple reasoning. The samples from which the ΔR values have been calculated were formed at the same time and place and therefore represent concurrent atmospheric and marine signals. If the signals for an individual sample within an atmospheric or marine group were sufficiently enhanced or depleted enough to suggest variability in the source of 14C, the ages would be offset and would consequently fail the X2 test for compatibility. If 14C ages that are statistically indistinguishable from one another are producing ΔR values with variability of over 200 14C years, then this variability cannot be as a result of the ages themselves (and therefore source 14C) but must be introduced during the production of the ΔR values in the next step of the calculation. This next step involves a box model which is used to model equivalent marine ages from ages based on terrestrial material (Reimer et al., 2013) and it is uncertainties inherent within this model which have to be attributed as the source of the variable outputs in the ΔR values produced. Investigation of the uncertainties in the model was outside the scope of this study but is highlighted for further research. The source of variation is not necessarily the focus of this research, instead, we wish to raise awareness about how to interpret ΔR data and distinguish whether values are significantly different from one another before making climatic and oceanic inferences.

4. Discussion

This study advocates the publication of ΔR values as histograms so that the full range of data for each site is visible and can be interpreted accordingly. This is a large volume of data to make available and in most cases, a mean value is required for the purposes of calibration/ease of publication. Where a mean value is used, we stress that an appropriate error such as the standard error for predicted values should be used. Using a larger error such as the standard error for predicted values alongside the mean ΔR value, may not be desirable (it will increase the calibrated calendar age ranges of marine based samples), but it will offer a more realistic estimate of the range of values in which future calculations of ΔR values for these sites may lie. This is important when considering that ΔR values are often used as proxy indicators for ocean 14C activity and shifts in oceanic regimes that may force such a change (e.g. Kennett et al., 1997; Kvenan and Easterbrook, 2002). For example, Jones et al. (2007a) document intra-shell variability in ΔR of up to 216 14C years, which they interpret in relation to El Nino events. This study has shown that the spread of ΔR values from statistically indistinguishable 14C dates can range up to 225 14C years (Doonloughan DL3 F319). It is therefore entirely possible that variations of 216 14C years could represent similar variability within the calculation of ΔR values, and not true variability in 14C activity related to oceanographic or climatic changes. Caution should therefore be placed on interpretations drawn from single pairs of 14C ages used to calculate a ΔR value, as any variability in the region of 200 14C years may be inherent within the calculation method (which is only visible using the multiple paired sample approach) and not representative of oceanographic/climatic changes influencing local 14C activity in surface waters. It could appear, rather unfortunately, that the variability in ΔR may therefore even have the ability to mask known climatic changes. The Medieval Warm Period (900–1300 AD) followed by the Little Ice Age (1350–1850 AD) are two examples of well documented climatic shifts in UK temperatures. No significant differences in the ΔR record appear in the data presented here from these two periods in time (Table 1). A cautionary approach to using ΔR as a climatic tool should therefore
be employed with a caveat of suggesting that, on the basis of the present study, $\Delta R$ cannot be used as a proxy for oceanographic and or climatic reconstruction unless the shifts are significantly larger than 200 $^{14}$C years.

The principle of the proposed approach of resampling is to ensure that we have a realistic estimate of the population variance, which is the key to determining the uncertainty in delta R. The steps taken are:

1. Resample from the individual marine and terrestrial ages, and then compute the differences, a specified number of times.
2. Calculate the mean $\Delta R$ and the standard deviation from each re-sample.
3. Find the standard error of the mean of the group of $\Delta R$ values.
4. Calculate the prediction uncertainty by propagating both the standard error of the mean and the population variance.

Despite the inherent variability, this study provides a suite of $\Delta R$ values from across the northern UK that will facilitate accurate calibration of radiocarbon ages for samples containing marine derived carbon. A $\Delta R$ value chosen for calibration should be as close as possible in time and space to the site which is to be dated in order to achieve a representative estimate of the local MRE at that time. 42 new $\Delta R$ values are presented in this paper, which cover a large proportion of coastal Northern British Isles and a vast period of human occupation therein. The data in Table 1 should provide sufficient temporal and spatial information for an appropriate $\Delta R$ value to be selected for the majority of calibrations on archaeological, marine derived carbon. This is a critical factor for Scottish archaeology because, owing to our island location, many past communities have typically exploited a large coastal resource base. Consequently, marine-derived material makes a considerable contribution to the national archaeological assemblages and if $^{14}$C dating has to rely on marine-derived material from any of these sites, it is of paramount importance to ensure good chronological control.

The range of data, from $-142 \pm 61$ to $40 \pm 47$ $^{14}$C years, presented in this study shows good agreement relative to previously published $\Delta R$ values for this region. Reimer et al. (2002) quote a value of $-33 \pm 93$ $^{14}$C years for the area encompassing western Ireland, Scotland and the Orkney Islands during the mid to late Holocene (4185–368 BP) whilst Cage et al. (2006) published a value of $-26 \pm 14$ $^{14}$C years on samples dating back to 1850 AD from fjordic and coastal waters in north-west Scotland. If mean values were to be presented in this study alongside the site specific values given in Table 1, enough justification would be present to produce values for the east coast, west coast and an overall mean value for Scotland. By removing outliers which do not pass the $X^2$ tests and removing the sites from Ireland, we propose a weighted mean $\Delta R$ value for the west coast of Scotland of $-68 \pm 90^{14}$C years and a weighted mean of $-29 \pm 53^{14}$C years for the east coast. An overall weighted mean value for Scotland from the Neolithic to the Medieval would be $-47 \pm 52^{14}$C years. Calculating a mean value and comparing it with that derived by Reimer et al. (2002), Cage et al. (2006) or Ascough et al. (2004) can only be justified if the presence of definitive temporal or spatial variations in $\Delta R$ values are considered to be absent or statistically indistinguishable at the level of confidence at which the $\Delta R$ values are reported. This is the case for Reimer et al. (2002) where confidence in a time dependency for $\Delta R$ was lacking and thus justified the publication of a mean $\Delta R$ value $\pm$ the standard deviation on the dataset. A similar case is presented for this study whereby neither spatial nor temporal patterning in the data appears to be present and therefore justifies the publication of a mean value for the dataset $\pm$ one standard error for predicted values.

The five sites for which the $\Delta R$ values were excluded will be investigated further to determine whether they are genuinely outliers and due to excursions in $^{14}$C activity that can be related to climatic/oceanic current changes or whether, again, the values are a product of uncertainties within the modelling that have yet to be understood.

5. Conclusions

Between the Neolithic and Medieval periods, $\Delta R$ (and MRE) values for the UK appear to be relatively stable with little or no temporal or spatial variation. However, variability is noted in the spread of $\Delta R$ values that can be produced from statistically indistinguishable groups of terrestrial and marine radiocarbon ages. This variability is partly derived from the process of calculating $\Delta R$ that uses the box model to produce modelled equivalent marine ages from ages based on terrestrial material. An investigation of the uncertainties in the model was outside the scope of this study but is highlighted for further research. Similar variability is evident in the spread of mean values for the whole region, even for those that pass a $\chi^2$ test for comparability. 42 $\Delta R$ values are presented here, which will allow more accurate calibration of $^{14}$C age measurements made on archaeological samples from the Northern British Isles containing marine derived carbon.

$37 \Delta R$ values from the 42 are statistically indistinguishable from one another. 34 of these values are from Scottish archaeological sites and can be combined to produce a mean value for Scotland of $-47 \pm 52^{14}$C years, applicable from 3500 BC to 1450 AD. This mean value should only be used where site specific data are unavailable for the calibration of marine derived carbon. Many publications on MRE draw interpretations from single pairs of radiocarbon ages used to calculate a $\Delta R$ value, and then infer that large apparent shifts in $\Delta R$ are as a result of large-scale oceanographic or climatic changes. This study has shown that combining multiple pairs of radiocarbon ages that are statistically indistinguishable in a matrix-style approach can produce variability in the subsequent $\Delta R$ values of up to 225 $^{14}$C years. This variability represents uncertainties inherent within the production and calculation of $\Delta R$ values, not as a result of oceanographic/climatic changes influencing the $^{14}$C activity of the local surface waters. A cautionary tale therefore exists regarding the use of $\Delta R$ values as a climate proxy.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quageo.2015.08.001.

References


