A stratigraphic network across the Subtropical Front in the central South Atlantic: Multi-parameter correlation of magnetic susceptibility, density, X-ray fluorescence and \( \delta^{18}O \) records

Daniela I. Hofmann, Karl Fabian*, Frank Schmieder, Barbara Donner, Ulrich Bleil

University of Bremen, Department of Geoscience, Postbox 330440, 28334 Bremen, Germany

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Abstract

Computer aided multi-parameter signal correlation is used to develop a common high-precision age model for eight gravity cores from the subtropical and subantarctic South Atlantic. Since correlations between all pairs of multi-parameter sequences are used, and correlation errors between core pairs \((A, B)\) and \((B, C)\) are controlled by comparison with \((A, C)\), the resulting age model is called a stratigraphic network. Precise inter-core correlation is achieved using high-resolution records of magnetic susceptibility \(k\), wet bulk density \(\rho\) and X-ray fluorescence scans of elemental composition. Additional \(\delta^{18}O\) records are available for two cores. The data indicate nearly undisturbed sediment series and the absence of significant hiatuses or turbidites. After establishing a high-precision common depth scale by synchronously correlating four densely measured parameters (Fe, Ca, \(k\), \(\rho\)), the final age model is obtained by simultaneously fitting the aligned \(\delta^{18}O\) and \(k\) records of the stratigraphic network to orbitally tuned oxygen isotope [J. Imbrie, J. D. Hays, D. G. Martinson, A. McIntyre, A. C. Mix, J. J. Morley, N. G. Piasias, W. L. Prell, N. J. Shackleton, The orbital theory of Pleistocene climate: support from a revised chronology of the marine \(\delta^{18}O\) record, in: A. Berger, J. Imbrie, J. Hays, G. Kuukla, B. Saltzman (Eds.), Milankovitch and Climate: Understanding the Response to Orbital Forcing, Reidel Publishing, Dordrecht, 1984, pp. 269-305; D. Martinson, N. Piasias, J. Hays, J. Imbrie, T. C. Moore Jr., N. Shackleton, Age dating and the orbital theory of the Ice Ages: development of a high-resolution 0 to 300.000-Year chronostratigraphy, Quat. Res. 27 (1987) 1-29.] or susceptibility stacks [T. von Dobeneck, F. Schmieder, Using rock magnetic proxy records for orbital tuning and extended time series analyses into the super- and sub-Milankovitch Bands, in: G. Fischer, G. Wefer (Eds.), Use of proxies in paleoceanography: Examples from the South Atlantic, Springer-Verlag, Berlin (1999), pp. 601-633.]. Besides the detection and elimination of errors in single records, the stratigraphic network approach allows to check the intrinsic consistency of the final result by comparing it to the outcome of more restricted alignment procedures. The final South Atlantic stratigraphic network covers the last 400 kyr south and the last 1200 kyr north of the Subtropical Front (STF) and provides a highly precise age model across the STF representing extremely different sedimentary regimes. This allows to detect temporal shifts of the STF by mapping \(\delta\)Mn/Fe. It turns out that the apparent STF movements by about 200 km are not directly related to marine oxygen isotope stages.

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Keywords: signal correlation; chronostratigraphy; oxygen isotope records; magnetic susceptibility; XRF; Subtropical Front; South Atlantic

1. Introduction

Ice cores, marine, lacustrine and continental sediments continuously record climatic and environmental
changes as well as geomagnetic variations [1,4–9]. Precise and accurate dating is of paramount importance to combine these records into a global geological archive, [2,10–12]. Temporal calibration of single stratified records is commonly based on either layer counting techniques [13,14] or time-series modelling of variations in $\delta^{13}$O coupled to orbital-forcing climate theory [2,3,15,16]. Reversals of the Earth magnetic field recorded in the natural remanent magnetization (NRM) of marine sediments that at least recorded one geomagnetic reversal, enables dating by comparison to the geomagnetic polarity timescale [17]. For the Brunhes chron it has been proposed to use relative paleointensity records in comparison to a global paleointensity stack as a dating tool [18]. Dating by radiogenic isotopes (U–Th, K–Ar, $^{40}$Ar/$^{39}$Ar) or cosmogenic nuclides ($^{14}$C) is commonly precluded by the lack of adequate material in deep-sea deposits. In addition to the above dating methods, physical properties become more and more accepted parameters for chronostratigraphy, because they can be measured relatively quickly and with high resolution [11,19–21]. Dating problems arise from deficient temporal resolution of the defining parameter or from secondary processes of biological, physical or chemical origin which overprint or alter the original sedimentary stratification. All these approaches compare single sediment records of a single parameter to some calibrated reference curve. Here, two steps are introduced to improve upon this procedure. First, an automatic signal correlation algorithm has been developed which considerably simplifies multi-parameter correlation between pairs of sediment records or calibrated reference curves. Second, instead of dating single records, a stratigraphic network of several sediment cores is constructed by first optimizing the correlation between all pairs of the network cores. Only then the optimal common depth scale is used for comparison with the calibrated reference curve. The new method is demonstrated in a comprehensive case study on eight gravity cores from the subtropical and subantarctic South Atlantic. These cores show considerable variations in lithology and sedimentation rates. They were selected for detailed rock magnetic and relative paleointensity studies [22] requiring a common highly accurate age model.

2. Investigated area

During R/V Meteor Cruise M46/4 a set of 29 gravity cores were recovered from the western flank of the Mid Atlantic Ridge (MAR) and in the adjacent basins including the Argentine Basin, the Cape Basin and the Brasil Basin [23]. Lithologic description and shipboard measurements of magnetic susceptibility and wet bulk density [23] were used to select eight apparently continuous and undisturbed gravity cores for further study. The coring sites are located between 32°S, 19°W and 42°S, 24°W at water depths ranging from 3380 to 4385 m (Table 1). The core locations form a N–S profile across the Subtropical Front (STF), separating the subtropical South Atlantic in the North from the subantarctic South Atlantic in the South (Fig. 1). The STF is indicated by a sharp surface temperature and salinity discontinuity of at least 4°C and 0.005. At the STF the Subantarctic Surface Water (SASW) subducts beneath the northern South Atlantic Central Water (SACW) and merges with the Antarctic Intermediate Water (AAIW). The prevailing deep water masses are nutrient poor North Atlantic Deep Water (NADW) in the northern part and nutrient rich Antarctic Bottom Water (AABW) in the south [24–27]. The differences between these water masses strongly affect sediment accumulation and composition. This results in noticeable lithologic variations between different cores of the transect. Also within single sediment series which recorded the temporal shifts of the STF during the Quaternary strong lithologic variations are present. Accordingly, the eight cores can be divided into three types of lithology [23,28]. The northernmost cores GeoB 6425-2, GeoB 6426-1 and GeoB 6428-1 lie in the oligotrophic subtropical South Atlantic north of the STF and contain mainly clay bearing nanofossil ooze. The foram bearing nanofossil ooze of cores GeoB 6407-1, GeoB 6421-2, GeoB 6422-1 has a higher carbonate content. While cores GeoB 6421-2 and GeoB 6422-1 lie in the vicinity of the STF, core GeoB 6407-1 is located further south close to cores GeoB 6405-6 and GeoB 6408-4 but at shallower water depth (Table 1). The southernmost

<table>
<thead>
<tr>
<th>GeoB</th>
<th>Latitude (S)</th>
<th>Longitude (W)</th>
<th>Length (m)</th>
<th>Depth (m)</th>
<th>Age (ka)</th>
<th>$\sigma_{est}$ (cm/kyr)</th>
</tr>
</thead>
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<tr>
<td>6428-1</td>
<td>32°30.60’</td>
<td>24°14.91’</td>
<td>7.26</td>
<td>4015</td>
<td>1801</td>
<td>0.4</td>
</tr>
<tr>
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<td>33°30.00’</td>
<td>24°01.50’</td>
<td>13.31</td>
<td>4385</td>
<td>1323</td>
<td>1.0</td>
</tr>
<tr>
<td>6425-2</td>
<td>33°49.51’</td>
<td>23°35.24’</td>
<td>10.89</td>
<td>4352</td>
<td>1028</td>
<td>1.0</td>
</tr>
<tr>
<td>6422-1</td>
<td>35°42.45’</td>
<td>22°44.01’</td>
<td>5.45</td>
<td>3972</td>
<td>297</td>
<td>1.8</td>
</tr>
<tr>
<td>6421-2</td>
<td>36°26.70’</td>
<td>22°26.70’</td>
<td>9.60</td>
<td>4220</td>
<td>442</td>
<td>2.2</td>
</tr>
<tr>
<td>6407-1</td>
<td>42°02.70’</td>
<td>19°30.00’</td>
<td>5.45</td>
<td>3384</td>
<td>388</td>
<td>1.4</td>
</tr>
<tr>
<td>6408-4</td>
<td>43°36.85’</td>
<td>20°26.46’</td>
<td>10.57</td>
<td>3797</td>
<td>302</td>
<td>3.5</td>
</tr>
<tr>
<td>6405-6</td>
<td>42°00.00’</td>
<td>21°51.19’</td>
<td>12.12</td>
<td>3862</td>
<td>302</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Ages and average sedimentation rates are roughly estimated by matching susceptibility records to SUSAS [3].
cores GeoB 6405-6 and GeoB 6408-4 contain diatom bearing nannofossil ooze.

3. Measurements and parameters

Setting up a multi-parameter stratigraphic network requires compatible high-resolution measurements of the same parameters for all network cores. Sufficient resolution is achieved by primarily using automated scanning measurements as described below. Care has been taken to ensure that the depth scales for all parameters measured on the same core, but at different instruments, agree to a precision of at least 1 cm.

3.1. Magnetic volume susceptibility

Magnetic volume susceptibility $\kappa$ was measured in 1 cm intervals along the surface of split cores using a Bartington spot sensor type M.S.2.F mounted on a computer controlled positioning system. The instrumental drift was controlled by separate background (zero) readings in air after each measurement. Magnetic susceptibility subsumes ferri-, para- and diamagnetic contributions.

It is the most widely used parameter to quantify concentration changes of the magnetic mineral fraction in marine sediments [30–32]. For magnetite, $\kappa$ is relatively constant for grain sizes between 0.1 and 10,000 $\mu$m, but increases towards smaller superparamagnetic (SP) grains [33]. In the here investigated South Atlantic sediments, variation of $\kappa$ is mainly due to changes of (titano-) magnetite concentration. Thus, $\kappa$ is a proper proxy for terrigenous input in this region [11]. A first approximate chronostratigraphy (Table 1, Fig. 2) was constructed by correlating the susceptibility records with the Subtropical South Atlantic susceptibility stack (SUSAS) [3].

3.2. Elemental records from XRF measurements

High-resolution records of elements from potassium through strontium have been determined using an X-ray fluorescence (XRF) scanner developed and built at the Netherlands Institute for Sea Research [34]. The obtained XRF spectra are processed with the software toolbox KEVEX™ [35] calculating relative element intensities in counts per second (cps).

The XRF Fe-records, similar to magnetic susceptibility, correspond to terrigenous content, while Ca-records indicate variations in biogenic carbonate input. Therefore, Fe should essentially mirror the variations of $\kappa$, while the Ca records are inverse to both (Fig. 3). Nonetheless, there are small differences in signal variation between the $\kappa$, Fe and Ca records. These are consistent over different cores and thus very specifically for obtaining a precise correlation. XRF records of other elements are not used for chronostratigraphy because element concentrations and consequently the signal-to-noise ratios are too low to provide reliable tie-points. However, it will be shown in the discussion that at least the Mn-record contains additional oceanographic information, which together with the final age model, allows to infer the temporal variation of the STF.

Fig. 1. Location of the eight gravity cores used to build the stratigraphic network. The dashed line indicates the approximate current position of the Subtropical Front as derived from satellite data of pigment distribution in surface waters [29].
3.3. Wet bulk density

Wet bulk density $q$ is inferred from electrical resistivity measurements performed directly after core recovery with a resolution of 2 cm [23]. It reflects a combination of compaction and variations in particle size and texture of the sediment matrix. Due to the higher intrinsic density of calcareous nannofossil ooze as compared to silicates, $q$ essentially correlates with Ca for all cores.

3.4. Stable oxygen isotopes

Stable oxygen isotopes are evaluated on hand-picked specimens of the benthonic foraminifer Cibicides wuellerstorfi from sites GeoB 6408-4 and
GeoB 6421-2 using a Finnigan MAT251 mass spectrometer, equipped with an automated Kiel carbonate preparation line. Calibration of the lab internal standard to a PDB standard scale (PeeDee Belemnite) was achieved using the NBS 19 standard (National Bureau of Standards, Vienna, Austria). Analytical precision is better than 0.07\%. $\delta^{18}$O records of the benthonic foraminifer of cores GeoB 6408-4 and GeoB 6421-2 correlate well with SPECMAP and the stack of Martinson et al. [1,2] (Fig. 4).

3.5. Assessing the influence of reductive diagenesis

Post-depositional chemical alteration is a major error source for stratigraphic correlation. Ferric iron minerals, are dissolved due to sedimentary iron reduction, which transforms Fe$^{3+}$-ions, originating mainly from ferri- or antiferro-magnetic minerals like magnetite or hematite, into Fe$^{2+}$-ions typically related to paramagnetic minerals [36]. Since magnetic susceptibility $\kappa$ primarily reflects the ferrimagnetic mineral concentration it is easily af-

![Fig. 3. Wet bulk density $\rho$, Iron (Fe) and Calcium (Ca) records for eight sediment series. High Fe values are related to low Ca values and vice versa in all cores. Density correlates with Ca for all cores, except for GeoB 6428-1. The ratio Fe/$\kappa$, indicating reductive diagenesis, is presented as a background linear gray scale from Fe/$\kappa$ \leq 10 Mcps (white) to Fe/$\kappa$ \geq 40 Mcps (black).](image-url)
fected by reductive diagenesis. Because alteration may occur at different age levels in different cores, it diminishes the worth of magnetic susceptibility as a chronostratigraphic parameter. While on one hand the sensitivity of $j$ with respect to diagenesis is an unwanted effect, it can be used on the other hand to detect diagenetic processes. This can be done by observing that the strong correlation between $j$ and Fe results from a time independent ratio of ferrimagnetic to paramagnetic Fe compounds of the terrigenous iron source region. Post-depositional reductive diagenesis can reduce ferrimagnetic iron minerals to paramagnetic iron compounds whereby $j$ is noticeably diminished. Since diffusion rates are small, the local Fe concentration remains nearly constant during this process. Consequently, reductive diagenesis increases the ratio $\text{Fe} / \kappa$ above the constant value characteristic for the undisturbed terrigenous phase [36]. To avoid a possible singularity of $\text{Fe} / \kappa$ for $\kappa = 0$ it was suggested to correct $\kappa$ for an estimated average diamagnetic contribution from the sediment matrix [36]. In our case, $\kappa$ is used directly, since it is positive throughout and much larger than the suggested correction of $15 \cdot 10^{-6} \text{SI}$. Fig. 3 shows that in the studied cores low reductive diagenesis is associated with values of $\text{Fe} / \kappa$ below 10 Mcps. Values above 40 Mcps indicate substantial reductive diagenesis. To identify diagenetic influence in the records, a linear gray scale plot of $\text{Fe} / \kappa$ is used as background shading in Fig. 3. Here, black colors indicate values above 40 Mcps and white color values below 10 Mcps. Fig. 3 also documents that on average diagenetic influence increases from North to South.

4. Signal correlation method

4.1. Computer aided multi-parameter correlation

Manual multi-parameter correlation requires the simultaneous overview over several wiggle-matching tasks while keeping track of the list of common tie points on various depth axes. Apparently, this is a time-consuming and visually challenging undertaking that can be considerably simplified and accelerated by using a specially designed computer algorithm. The program ASC (Automatic Signal Correlation) has been developed to either support the above described manual task of multi-parameter signal correlation, or to propose an automatic correlation. Thereby, it finally allows to construct a transfer function between depth or age scales from two sediment series by synchronous wiggle matching based on any number of parameters.

Manual correlation in ASC is iteratively done by stepwise adding new tie-points between the multi-parameter records at any position using any of the available parameters. After each step the change in correlation effected by the new tie-point is immediately shown and each single parameter record is mapped to the new scale. This manual iterative matching already improves on previous single-parameter correlation programs.

In addition, ASC also can calculate an automatic multi-parameter signal correlation. Automatic signal correlation of geological time series is a difficult and not completely solved problem. As already noted by Martinson et al. [37], a major problem in geological signal correlation is the request of finding a globally — as opposed to a mere locally — optimal match between two given records. A more practical problem is computation speed. In geological applications the final result always must be manually confirmed and corrected. Therefore a sufficiently rapid automatic fitting procedure is essential to allow for interactive work. Here a dynamic time warping (DTW) algorithm is used for globally minimizing a prescribed distance function. DTW has been originally developed in the context of speech recognition [38], but it turns out to be especially suited for geological time series. As in the recent approach by Lisiecki and Lisiecki [39], DTW is based on dynamic programming [40] to perform a fast global optimization of the multi-parameter correlation instead of locally improving a prescribed initial guess.
The use of multi-parameter records for pattern matching considerably reduces the chances of misalignment during the automated fitting process. However, the quality of the fit still depends on the measurements signal-to-noise ratios, on preceding smoothing, normalization and detrending procedures and on the function that is used to calculate the distance between two multi-parameter signals. Our experience shows, that least-square distance is the best choice even for multiple parameters, but each parameter should be weighed according to its actual information content. This requires not only insight into data quality (noisy data should have less weight), but also should take into account systematic dependencies between seemingly different parameters like Fe and $\kappa$. The DTW algorithm also includes the possibility to impose slope constraints [38]. They restrict the possible slope of the transfer function to some interval $[1/n, n]$ and thereby prevent unrealistic jumps. This can be used

![Fig. 5. Magnetic susceptibility records of cores GeoB 6408-4 and GeoB 6421-2. As in Fig. 3 the background shading represents the variation of Fe/$\kappa$. In the undisturbed regions the $\kappa$ records correlate well. Dashed lines indicate prominent synchronous signal patterns. No reliable correlation is found in the parts where Fe/$\kappa$ indicates considerable diagenesis.](image)

![Fig. 6. Correlating Fe, Ca, $\rho$ and $\delta^{18}O$ for GeoB 6408-4, GeoB 6421-2. Solid lines indicate the tie points from Fig. 5. Dashed lines represent additional tie points. Again, Fe/$\kappa$ is represented by the background shading as in Fig. 3.](image)
Fig. 7. (a) Magnetic susceptibility versus the different depth scales obtained by matching either only $\kappa$ (triangles), $\kappa$ and Fe (squares) or all available parameters (stars) between GeoB 6408-4 and GeoB 6421-2. The different depth models are compared to the final network multi-parameter correlation (filled background plot). (b) shows the corresponding deviation between the depth-to-depth correlations. The intrinsic error is minimized using all available parameters (stars). In (c) and (d) the transfer functions for the different correlation approaches are presented. (c) shows the nearly undisturbed upper part of the core and (d) the altered part below 5 m core depth (gray).
to avoid noise fitting that may occur in the unconstraint case. On the other hand, a strong slope constraint hinders the global optimization of highly distorted signals. The best trade-off is found by starting with unconstraint fitting and by afterwards stepwise introduction of stronger slope constrains.

In case of the South Atlantic stratigraphic network automatically found correlations were merely used to survey the correlation properties of all core pairs and to rapidly detect similarities and problematic regions between the stratigraphic sequences. All final correlations have been manually checked and refined to optimally include all relevant information.

4.2. Intrinsic error estimates in multi-parameter correlation

The alignment of GeoB 6408-4 and GeoB 6421-2 provides a typical example for improving the correlation by using a multi-parameter data set. These cores are especially important for the network chronology because only for them δ18O records are available.

The κ record of GeoB 6421-2 (Fig. 5) shows a sharp decrease at 3.5 m core depth. Without the clear indication of diagenetic alteration by Fe/κ at this depth, it would be tempting to erroneously align this decrease with the drop in κ of GeoB 6408-4 at 4.3 m. Only in the undisturbed regions some clear pattern similarities of the κ records can be reliably aligned (dashed lines in Fig. 5). By including ρ, δ18O, Fe and Ca records into the correlation process, the alignment becomes much more detailed. The dashed lines in Fig. 6 delineate for each of the four additional parameters some newly found pattern similarities which step-by-step improve upon the initial tie-points from Fig. 5 (solid lines in Fig. 6). Already by adding the less diagenetically influenced Fe-record it is possible to resolve the potential mismatch at 3.5 m core depth of GeoB 6421-2. In the alignment shown in Fig. 6, all parameters are aligned simultaneously using ASC and each additional tie-point restricts the degrees of freedom of the following ones. Thus, most of the shown tie-points effect only a tiny shift with respect to the previously correlated depth-scale. They align peaks or slopes of already close patterns and the consistency of their position with the other parameters is immediately checked.

As illustrated in Fig. 7a the multi-parameter approach also allows for an intrinsic error estimate of the alignment process itself. The idea is to assess the alignment error of a correlation process restricted to a smaller parameter set, by comparing it to the final multi-parameter correlation, which is considered to be the optimal estimate. Fig. 7a depicts the results of the alignments by transferring the magnetic susceptibility signal of GeoB 6408-4 to the depth scale of GeoB 6421-2 using the various correlation results (triangles, squares, stars) compared to the final multi-parameter correlation (gray plot). The most simple case is the correlation obtained by using only κ (triangles). While at low depths both approaches coincide very well, there are discrepancies up to 40 cm below 5 m core depth in GeoB 6421-2. The deviation between both correlations is plotted in the top row of Fig. 7b (triangles). It increases at depths where correlation is most heavily deteriorated by diagenesis. Including also Fe in the correlation process (central rows of Fig. 7a and Fig. 7b, squares) the alignment is improved but the transfer function still deviates up to 30 cm from the final solution between 5 and 6 m core depth in GeoB 6421-2. The remaining intrinsic uncertainty within the final transfer function itself is estimated by comparing two separately performed alignments of the same multi-parameter data set (stars in bottom rows of Fig. 7a and b). The result demonstrates that the intrinsic error is everywhere below 10 cm. Fig. 7c shows the transfer functions for the nearly undisturbed upper parts of the cores where all different correlation approaches lead to nearly identical results. In contrast, the transfer functions for the bottom parts of the cores (Fig. 7d) distinctly deviate between the different correlation approaches. The largest deviation occurs when only susceptibility (triangles) is matched, while deviation is continuously reduced by using an increasing number of parameters (squares and stars). This provides strong evidence that the parallel use of several parameters is highly efficient for obtaining a reliable high-resolution pattern alignment.

5. Constructing the SASNET

Before the methods of the previous section are applied to extend the preliminary common depth scale of GeoB 6408-4 and GeoB 6421-2 to the final stratigraphic network, the core set is divided into two groups which are treated differently as sketched in Fig. 8.

The first group contains the northern cores with low sedimentation rate and negligible diagenetic overprint. An optimal age model for these cores has already been developed in a previous study by correlating characteristics of their magnetic susceptibility records to SUSAS [11]. Since all northern cores recorded at least the Brunhes–Matuyama geomagnetic boundary at their base, the age model is additionally constraint by magnetostratigraphic tie-points [11]. Only the remaining five southern cores require detailed multi-parameter
correlation. Here, \( \kappa \) alone is not sufficient for reliable dating since diagenetic alteration substantially distorts the records and considerably deteriorates their correlation with SUSAS. Moreover, the higher sedimentation rates allow to discern more small scale features that can be used for detailed pattern matching.

The lower part of Fig. 8 indicates that all pairwise correlations of the five southern cores are evaluated to construct the age model. Starting from the preliminary common depth scale of GeoB 6408-4 and GeoB 6421-2 from the previous section (Fig. 7), records of other cores are iteratively included into the existing depth scale by synchronous comparison of all available parameters. This approach aims to obtain optimal correlation among each set of three cores \( A, B, C \), by ensuring that after pairwise multi-parameter correlation of \( (A, B) \) and \( (B, C) \) also the correlation between \( (A, C) \) is of the same quality. All tie-points of the correlations are displayed in Fig. 9. Between two tie-points the sedimentation rate is assumed to be constant, which allows to compare the signal patterns of all used parameters and cores on the common depth scale of GeoB 6421-2 in Fig. 9.

Based on the precise depth correlation between the southern cores, it is possible to construct a common age model by assigning ages to each depth level of GeoB 6421-2. This again is done by a multi-parameter correlation between the \( \delta^{18}O \) and \( \kappa \) records of GeoB 6408-4 and GeoB 6421-2 on one hand and with SPECMAP and Martinson [1,2] as well as SUSAS [3,11] on the other hand. The SUSAS age model takes into account a phase lag between \( \delta^{18}O \) and susceptibility, which has been determined using a \( \delta^{18}O \) time scale of the SUSAS-core GeoB 1211-3. In this core susceptibility leads \( \delta^{18}O \) by 3.4 kyr in the obliquity band and there-
fore lags the corresponding insolation forcing by $7.9 - 3.4 \ \text{kyr} = 4.5 \ \text{kyr} \ [3]$.

To document the improvement in precision of the common age model, which arises from the use of multiple parameters, the depth–depth correlation has been performed several times, while each time one or two new parameters were included into the correlation process. Fig. 10 shows the resulting decrease of median deviation from the final model. The first data points have been obtained by solely using the $\kappa$-records. In the next steps were added Fe, then Ca and $\rho$, and finally $\delta^{18}O$. All deviations are transformed to ages by the same final age model. Even though lithology varies considerably between the five cores, it is possible to obtain high internal consistency that ensures a relative median age error of less than 5 ka.

The absolute error of the age model depends not only on the internal resolution of the parameters used for the correlation, but also on precision and accuracy of the alignment with the reference signals (SUSAS, SPECMAP, Martinson). Since these are stacks of several cores, small scale local features are averaged out and cannot be precisely correlated to higher resolving signals. While this effect reduces the accuracy of the age model, it does not influence the internal precision of the network core alignment. Fig. 11 presents time dependent sedimentation rates of core GeoB 6408-4, reconstructed using the different correlation approaches. Obviously only small differences between these approaches are observed. This is confirmed for all cores by comparing the average sedimentation rates inferred from the different correlation approaches that are collected in Table 2. The bottom plot of Fig. 11 additionally shows the summer insolation at $65^\circ \text{N}$, which indicates that sedimentation rates are higher during glacial and lower during interglacial times. This pattern was confirmed for all studied cores.

**Table 2**

Average sedimentation rates obtained using correlation approaches with different numbers of parameters

<table>
<thead>
<tr>
<th>GeoB</th>
<th>$\sigma$</th>
<th>$\sigma$</th>
<th>$\sigma$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(\kappa)$</td>
<td>$(\kappa, \text{Fe})$</td>
<td>$(\kappa, \text{Fe, Ca, } \rho, \delta^{18}O)$</td>
<td>(final)</td>
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<tr>
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<td>4.3</td>
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<td>1.4</td>
<td>1.4</td>
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</table>

The parameters used for correlation are given in parentheses. $\sigma$ (final) refers to the final network age model.

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Fig. 11. Differences in sedimentation rates using the different correlation approaches are presented for core GeoB 6408-4. Only small variations between the different correlation approaches are found. Comparison with the summer insolation record at $65^\circ \text{N}$ documents higher sedimentation rates during glacial than during interglacial times.
Fig. 12 collects the final age-to-depth relations for the stratigraphic network, which now consistently documents the sedimentation chronology of the last 400 kyr south of the STF, and of the last 1200 kyr north of the STF. The average parameter values based on this age model are given in Table 3.

6. Discussion

After setting up the age model for the stratigraphic network, it is now possible to discuss the paleoclimatic and oceanographic conditions that are reflected by the temporal variation of all available records. Apart from the $\kappa$, $\rho$, Ca and Fe records which are shown in Fig. 13, this includes the complete XRF data set.

The gray shaded areas in Fig. 13 mark the glacial periods of the marine oxygen isotope stages (MIS) according to [1]. In all cores $\kappa$ and Fe values are higher during cold than during warm oxygen isotope stages, while Ca and $\rho$ values show an opposite pattern. This correlation reflects climatic variation in biogenic and lithogenic sediment components, which indicate shifts in carbonate production and concurrent changes in terrigenous input. Similar variations are found in sediments from the Ceará Rise [41]. In general, these climatic variations are linked to a northward movement of the polar front during glacial periods and the corresponding sea level low. Both effects intensify erosion on land and lead to higher terrigenous input into the central South Atlantic. However, large scale climatic changes alone cannot explain the significant differences between the climatic responses of the network cores along the South–North profile. The large deviations, as observed in Fig. 13 and Table 3, even between neighboring cores, are also a consequence of dissimilar water masses that dominate sedimentation at different water depths in this region.

A most pronounced example is the southern group with its very similar records of GeoB 6405-4 and GeoB 6408-4, which differ clearly from the nearby core GeoB 6407-1 (Fig. 13). Especially their $\kappa$-records deviate substantially, and in the upper part, GeoB 6407-1 has a much lower sedimentation rate than the other two cores. The reason for these differences is that GeoB 6405-6 and GeoB 6408-4 are deposited under influence of nutrient rich AABW at a water depth around 3800 m below the carbonate compensation depth (CCD), whilst the slightly shallower position of GeoB 6407-1 already provides a completely different sedimentary environment. This is most clearly demonstrated by the high diatom content along with reduced carbonate content in GeoB 6405-6 and GeoB 6408-4, which fits to the known facts that the AABW transports large amounts of diatoms [42], and that in this region the boundary between the AABW and the NADW coincides with the CCD [43]. On the other hand, the low sedimentation rate, and the high content of calcareous nanofossil ooze [23] indicates that
Fig. 13. Magnetic susceptibility, Fe/o (gray plot), Fe, Ca and wet bulk density records for all cores versus the common network age scale. All cores show similar signal patterns. Gray shading indicates cold oxygen isotope stages.
GeoB 6407-1 lies above the CCD within the realm of the nutrient poor NADW.

The variations within the central group of the network cores are, at least partly, connected to yet another different phenomenon. Berger and Wefer [29] proposed, that the STF is likely to move northward during glacial periods, but no clear record of such a shift is available. Using the age model of the stratigraphic network, a search for an indication of a STF shift has been performed by systematically plotting the available parameters from the XRF measurements, and their ratios, versus the same highly precise time scale. It turned out that the ratio

\[ \delta \text{Mn/Fe} = \left( \frac{\text{Mn} - \text{Mn}_0}{\text{Fe}} \right) \]

with \( \text{Mn}_0 = 40 \text{ cps} \), shows distinct differences between the cores in terms of their position relative to the STF. The value of \( \text{Mn}_0 \) describes a constant manganese background that is independent of Fe concentration and has been found not to differ significantly between the network cores. As displayed in Fig. 14, \( \delta \text{Mn/Fe} \) is approximately constant for all cores which are either definitely north of the STF (first group in Table 3), or definitely south of the STF (third group in Table 3). The average \( \delta \text{Mn/Fe} \) values lie above 7% in the northern cores, and below 2% in the southern cores. This difference in \( \delta \text{Mn/Fe} \) apparently is due to a lithogenic manganese source which contributes to the sedimentation north of the STF, but delivers no input to the cores south of the STF. Therefore, \( \delta \text{Mn/Fe} \) allows to decide whether the central cores (second group in Table 3) are rather influenced by the regime south or north of the STF. GeoB 6407-1 has \( \delta \text{Mn/Fe} \) ratios below 2% throughout its whole record and accordingly lies definitely in the southern realm with respect to this parameter. This is in contrast to most of its other physical properties, which closely resemble the central core GeoB 6422-1 in the second group in Table 3. This demonstrates that \( \delta \text{Mn/Fe} \) is indeed a geographic signal that is not influenced by water depth relative to the CCD.

As demonstrated in Fig. 14, the \( \delta \text{Mn/Fe} \) records of GeoB 6421-2 and GeoB 6422-1 are strongly modulated. By interpreting the change of their \( \delta \text{Mn/Fe} \) values as switching in time between typical values for northern or southern regime, respectively, these cores provide clear evidence for a movement of the STF. Both have high \( \delta \text{Mn/Fe} \) values at their tops, which agrees with the current position of the STF lying south of them. While the existence of STF shifts confirms the prediction of Berger and Wefer [29], the timing of the STF movements apparently is not directly linked to the marine isotope stages (Fig. 14).

![Fig. 14. \( \delta \text{Mn/Fe} \) ratios of cores GeoB 6421-2 and GeoB 6422-1 (gray background) as compared to the nearly constant ratios of about 7% for the northern cores (light gray) and 2% for the southern cores (black). The temporal changes in \( \delta \text{Mn/Fe} \) probably reflect shifts of the STF which apparently are not directly linked to the marine isotope stages.](image)
A third reason for variation of the physical properties within the SASNET is a general increase of diagenetic influence from North to South. Average values of Fe/κ are highest in core GeoB 6407-1 and lowest in the northernmost core GeoB 6428-1 (Table 3). Strong diagenetic overprint is focused at redox horizons. In core GeoB 6421-2 (Fig. 13), a sharp decrease of magnetic susceptibility related to an increase in Fe/κ provides a typical example for this effect which also produces a Mn peak slightly above the diagenetic front [36]. This event coincides with the boundary between stages 5 and 6 (Termination II). Increasing Fe/κ values at the boundaries of stages 7–8 (Termination III) and 11–12 (Termination V) are remnants of earlier locations of diagenetic redox events.

7. Conclusion

This study presents a precise common age model for eight contiguous sediment cores which cover widely different lithologies. They are located on a N–S profile across the Subtropical Front, separating the subtropical from the subantarctic South Atlantic. Based on high resolution data sets of magnetic susceptibility, Fe, Ca, wet bulk density and δ¹⁸O, a stratigraphic network (SASNET) is constructed which provides equally good correlation between all possible core pairs from the network. To obtain a precise network age model in spite of the considerable lithologic variety, a newly developed program for multi-parameter correlation is applied. This makes it possible to optimize all pairwise correlations between the network cores. Moreover, intrinsic error estimates for inter-core correlation have been obtained, which for the final age model limit the average inconsistency to 2 ka, and indicate that the maximum intrinsic error is about 5 ka. The XRF data set of the SASNET together with the new age model is used to trace temporal shifts of the STF, which are shown to manifest themselves in changes of the δMn/Fe-ratios of the central SASNET cores GeoB 6421-2 and GeoB 6422-1. While a more detailed description of the multi-parameter correlation program ASC will be published elsewhere, a beta version of ASC is available from the second author (KF) upon request.

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