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Correlation of Greenland ice-core isotope profiles and the terrestrial record of the Alpine Rhine glacier for the period 32–15 ka

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Abstract

We present a newly extended stratigraphic subdivision of the Greenland NGRIP, GRIP and GISP2 ice cores for the period 32–15 ka. Our classification emphasizes the multiscale nature of the climatic oscillations. Spectral trend analysis of isotopic data supports this interpretation. We compare this time series with the stratigraphy of the last major Pleistocene (Weichselian, Würmian) glaciation in the area of the Rhine glacier (Germany and Austria) as chronicled by a detailed inventory of landforms and deposits, dated in part with ¹⁴C analyses, and their interpretation in terms of climate change. Both time series show a major climatic oscillation, consisting of a colder period (glaciation) followed by a warmer period (deglaciation). The available dates allow the time

- tion) followed by a warmer period (deglaciation). The available dates allow the time of change, at 23.4 ka, to be correlated between the two. Pattern analysis clearly indicates that higher-order oscillations were superimposed on the major oscillation in both areas, emphasizing the multiscale nature of the underlying pattern of climate change. The correlation between the two areas is sufficiently good to propose that the pattern of
- climate change was synchronous (within the available time resolution) between Greenland and the Rhine glacier area. Comparison of our results with other high resolution climate proxies is expected to further improve the understanding of the climate changes during the Late Weichselian.

1 Introduction

Progress in Pleistocene stratigraphy and the understanding of climate change is being achieved through comparisons and correlations among the time-series derived from many different climate change proxies from different areas. In this paper, we seek to draw new conclusions from a comparison between climate change stratigraphies of two quite different kinds for the time interval broadly corresponding to the Upper Würmian in Alpine Europe, 32–15 ka. Our two contrasting datasets are from the Greenland ice





cores and from the area of the former Rhine glacier in southern Germany and adjacent parts of Austria and Switzerland.

- The Greenland ice cores provide data series of unparalleled continuity in a number of important climate proxies. From these, we have selected $\delta^{18}O$ – an indicator of the state of the ocean-atmosphere-glacier system (if not strictly of temperature), and $[Ca^{2+}] - a$ measure of atmospheric dust flux. Of these, we use $\delta^{18}O$ as the primary time-series, with input from the $[Ca^{2+}]$ data where this is able to help to resolve ambiguities. The stratigraphy and correlation/synchronization of successive ice-cored wells in Greenland have become increasingly refined; the standard stratigraphy is by Andersen et al. (2006), Lowe et al. (2008) and Rasmussen et al. (2008). The interval of interest in this paper is currently divided into a series of alternating stadials and interstadials, beginning with the interstadial GI-5, followed by the stadial GS-4, and so on up to GS-2 at the top. In a different approach, we have recently proposed a ninefold subdivision of the second half of this interval (23–15 ka), supported by analysis of spectral trend curves derived from the $\delta^{18}O$ and $[Ca^{2+}]$ time-series (De Jong et al., 2009).
- Contrasting with this is the chronology of glacial advance and retreat based on many years of our own field observation in the area of the Rhine glacier in the Alps and in the Alpine foreland (De Jong et al., 1995; de Graaff et al., 2007). Situated to the NE, E and SE of Lake Constance, this area covers nearly 2500 km² of the Allgäu region of southern Germany, the Austrian state of Vorarlberg, and adjacent parts of Switzerland. Compared with the continuity of the ice core data, the time series in this case is pieced together from a detailed inventory of landforms and deposits throughout the study area. These deposits are tied to the numerical time scale through a number of ¹⁴C analyses. Unlike the ice core data, the field data can be directly interpreted in
- terms of glacial advance and (especially) retreat. Whereas the ice core data can be interpreted in terms of the general state of the ocean-atmosphere-cryosphere system, the Rhine glacier data are more specifically linked to the state of an individual glacier system and its oscillations between advance, stabilization, and retreat. The important feature of the time series that emerges from our field data is that individual episodes





of glacial advance or retreat can be seen to be superimposed on a longer term pattern of advance/retreat, forming a pattern at more than one scale. It is this multiscale pattern that we use as the link between the Greenland ice cores and the Rhine glacier chronology.

 In this paper, we first describe our newly extended analysis of the time interval 32– 15 ka in the Greenland ice core data. In particular, we describe and classify it into *climatic oscillations*, for better comparison with the more conventional glacial stratigraphy of the Rhine glacier area. We then outline the stratigraphic chronology of the Rhine glacier through the Upper Würmian, the interval corresponding to that studied by us in the ice cores.

Finally, we offer a correlation of the two datasets, in which the importance of understanding the multiscale nature of climate change is emphasized. We draw conclusions regarding (1) the synchrony of climate change in the two areas of our study, and (2) the continuing importance of combining the information from many datasets in interpreting climate change during the latest Pleistocene and, by extension, more generally.

The correlations of the ice cores have been carried out in terms of borehole depth, to avoid potential complications due to uncertainties in the synchronization of GRIP and GISP 2 with NGRIP as proposed by Rasmussen et al. (2008). The depth-to-age conversion used throughout this paper is based on the GICC05 time scale as determined from NGRIP data (Rasmussen et al., 2008).

2 The Greenland ice core data

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Ice cores, particularly those from Greenland, have revolutionized our understanding of the patterns of climate change through the later part of the Quaternary. It is the high degree of continuity obtainable in ice core records, together with the high resolution sampling that is possible from them, that makes them such an outstanding repository of information. The order of events in an ice core is generally not in question, which is not the case for conventional chronologies pieced together from many different localities.



The consistent nature of the recording medium also contributes to the quality of the information that can be gained from them. And the possibility of identifying annual increments in the ice opens up the possibility of collecting data that form a true time-series, in the mathematical sense.

- ⁵ Our work has focused on three ice cores: GISP2, GRIP and NGRIP. The data series that we have selected from the many available are the δ^{18} O and [Ca²⁺] series. The oxygen isotope data, originally taken to be a direct proxy for sea temperature (Emiliani, 1966), is now accepted as a more general indicator of the thermal state of the ocean-atmosphere-cryosphere system; lower values represent a cooler climatic state
- and higher values represent a warmer climatic state (Wolff et al., 2010). Calcium concentration is taken to be a proxy for atmospheric dust flux, also a proxy for climate changes. These and other climate proxies have been used for classification of the ice cores into a comprehensive set of alternating stadial and interstadial stratigraphic units, representing a corresponding alternation of (respectively) cool and warm time intervals
 (Andersen et al., 2006; Lowe et al., 2008; Rasmussen et al., 2008).
 - Based on experience in its application to stratigraphic correlation of conventional wireline log data from exploration wells (De Jong et al., 2007), we have pioneered the application of spectral trend time-series analysis to the stratigraphic and climatic interpretation of the three Greenland ice cores (De Jong et al., 2009 and this paper).
- Depending on the complexity of the stratigraphic signal in the data series and the state of existing knowledge, this method, whose procedures are briefly described below, can be used in several ways. It may help to reduce the degree of uncertainty of an existing interpretation, or lead to adjustments due to better insight. It may also reveal patterns that have been overlooked in the unprocessed data series. The patterns,
- ²⁵ when matched between well or ice core profiles, substantiate or allow the identification of correlatable points in different profiles. This in turn can guide the classification of the succession into a set of stratigraphic units. The method, thus, is a correlation tool that helps to better understand the patterns in the input data; it offers guidance and constraints to the interpretation of the unprocessed data.





3 Spectral trend analysis – principles and practice

3.1 General

Seeking patterns in data series is facilitated by finding the most appropriate way of displaying the data. Maximum entropy methods (MEM), widely used in applications such as image enhancement and voice recognition, have proved to be helpful in confirming the existence of patterns in subsurface geological data, and we here extend the use of such methods to ice core data, as in our earlier study (De Jong et al., 2009). MEM makes no a priori assumptions about the nature of patterns in the data; it makes use of the degree of departure of the data from randomness, which makes it appropriate to our attempts to extract information from data such as wireline logs and ice core profiles. 10 Derived from maximum entropy methods, the spectral trend curve has proved to be useful in the visual, graphical, correlation of wireline logs from conventional (geological) boreholes. This curve is the integral of the prediction errors, i.e. the differences (errors) between a data series and a linear filter optimised to predict data-points ahead of a moving window. Using MEM, a statistical model of the data in the study interval is generated. The model is used as a prediction filter to predict the (moving) window's next data point based on the data points in the window. The prediction filter is converted into a prediction error filter. The latter returns the error in the prediction, i.e. the difference between the predicted data point and the true data point (Nio et al., 2006). The entire study interval is filtered and the results (errors) are presented in the so-called PEFA 20 (Prediction Error Filter Analysis) curve. Integration of the PEFA curve generates the integrated PEFA curve, also called INPEFA (Nio et al., 2005). Linear prediction is a standard technique in signal processing (e.g. Press et al., 2007); we are not aware of

non-geological applications of the integral of the prediction errors. The spectral trend
 ²⁵ curve is so-called because it can also be thought of as expressing changes in the spectral content of the data; the power spectrum of the data can be calculated from the prediction filter. The method is implemented in the software package CycloLog, which was used to generate the INPEFA curves and the charts in Figs. 1 to 4.





Examples of a prediction error curve of δ¹⁸O data are shown in tracks 3 (labeled "PEFA") of the ice core data displays in Fig. 1. The corresponding INPEFA curves are shown in red in tracks 4 of the same displays. Note that all INPEFA curves are standardized and their values always range from 0 to 1; INPEFA therefore shows relative, not absolute, trends. It will be seen that the INPEFA curve, which is deliberately displayed in a wider track, exaggerates features of the original data, allowing better discrimination of features useful for visual comparison (graphical correlation) of curves from different boreholes. Further exaggeration of the detail can be achieved by rerunning INPEFA for shorter intervals of the data – compare the red, blue and purple INPEFA curves in Fig. 1, which were run for the whole dataset, for the top part of the data, and for the lower part of the data, respectively.

3.2 Interpretation of the INPEFA curve

Visual interpretation of INPEFA curves is essentially pattern-identification and - matching coupled with understanding of the nature and significance of the data. In

- the geological context, empirical pattern-matching is balanced against experience of the ways in which the rock strata tend to be packaged. In the ice core context, the significance of the data in terms of climate change needs to be taken into account in order to constrain any conclusions from the spectral trend curves. In a previous study (De Jong et al., 2009), we concluded that spectral trend analysis is useful in the stratigraphic analysis of ice care isotenic data area though the pature of the data is quite
- ²⁰ graphic analysis of ice core isotopic data even though the nature of the data is quite different from the geological data for which the methodology was originally developed.

Figure 1 illustrates the approach used in this paper. Essential is the identification and validation of trends and trend changes in the input data through analysis and interpretation of the INPEFA curves. INPEFA *trends* are described as either positive

(up-to-the-right) or negative (up-to-the-left). Changes of trend may be positive or negative, and are used to locate *turning-points*, which in turn are used to delimit correlatable intervals. Applying graphical correlation, key point is that each time we find more or





less the same succession of trends and trend changes in the profiles, we consider that we are reducing the risk that they are random. Differences of INPEFA pattern between boreholes are commonly apparent (compare the blue INPEFAs for GISP2 and GRIP, for example), but the upward succession of intervals between matched turning-points may still be confidently correlated.

The INPEFA trends, positive and negative, represent the predominant sign of the prediction errors for particular intervals of the data. An interval of positive trend arises from a predominance of positive prediction errors, implying that the prediction tends to under-estimate the δ^{18} 18O values in that interval; the actual values are "warmer", than predicted by the model. Similarly, in an interval of negative trend, the δ^{18} O values are predominantly "cooler" than predicted. In the practice of making correlations, the INPEFA curves assist in the identification of relatively "warm" or "warming" trends and relatively "cool" or "cooling" trends in the input data.

3.3 Identifying climatic oscillations

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- Generally, it is possible to identify climatic oscillations from the δ¹⁸O data alone; referring to the INPEFA curves can, however, help to clarify the interpretation, or to choose between apparently similar alternative interwell correlations. Where the IN-PEFA curves really help is in the recognition of features at more than one scale. For example, the INPEFA motif of a full climatic oscillation, from cool to warm, is a kind of C-shape or semi-circular shape with negative turning-points at top and bottom. It
- comprises a "limb" with negative trend (representing a relatively cool period) and an overlying positive "limb" (corresponding with a relatively warm period). Refer to De Jong et al. (2009); see the INPEFA curve in Fig. 2 (note the bulk shift in the δ^{18} O profile at 23.4 ka). C-shape patterns can be seen repeated at a smaller scale in, for
- example, the blue INPEFA curves in Fig. 1 (intervals NTP4–NTP5 and NTP5–NTP6; note the corresponding subtle but distinct variations in the δ^{18} O profiles). C-shapes are often imperfect or somewhat distorted, due to higher-order effects; what remains is a distinct packaging of units, bounded by negative turning-points. Interpretation of





Late Weichselian climate change as being on more than one scale, and thus effectively hierarchical, is an important conclusion from our work.

3.4 Procedure

Stratigraphic interpretation and correlation with the assistance of INPEFA curves proceeds by a stepwise process: proposing a pattern of subdivision in one ice core and testing it against the information from one or more others. Because we use data known to behave as climate proxies, we are confident that the features we use for correlation correspond to changes in the behaviour of the climate system, in ways that have a strong likelihood of being synchronous among different ice cores in the same region.
While we can expect synchroneity of the events that define the succession of climatic changes, we also expect that the detailed pattern will differ from ice core to ice core *at all scales*, because of differences in local response to the same climatic changes. Such

lateral variation is indeed observed among the three ice cores; Fig. 1 shows examples of clear lateral differences between just two of the cores. In this case, distinguishing one turning-point from another depends as much on position in the vertical succession as on the character of the individual turning point.

4 Stratigraphic scheme and nomenclature for the Greenland ice cores

4.1 General

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Figure 2 and Table 1 introduce the stratigraphic classification developed here for the interval 32–15 ka, comparing it with the stadial/interstadial classification of Andersen et al. (2006), Lowe et al. (2008) and Rasmussen et al. (2008). First, note that the entire interval forms one complete climatic oscillation in terms of the long-term INPEFA curve (track 4 of Fig. 2); note the "bulk" shift in δ^{18} O values at 23.4 ka (track 3). That is, the overall C-shape of the INPEFA curve follows a cool(ing)-up (negative, or up-to-the-left)



trend from 32 to 23.4 ka, succeeded upwards by a warm(ing)-up (positive, or up-to-the-right) trend from 23.4 to 15 ka. This is the first level in our hierarchical classification. The period of time covered by the study interval is within the Weichselian (Gradstein et al., 2004). We therefore make (informal) use of the term Weichselian to characterize our newly proposed stratigraphic units: we refer to the level-1 oscillation as Last Major Weichselian Oscillation (LMWO).

The iterative interpretation process described above allows us to subdivide the 32– 15 ka interval into six climatic oscillations, which form the second level in our classification. Following geological practice in numbering successive units upwards from the base, we have labeled the level-2 oscillations 1 through 6.

Whereas in De Jong et al. (2009) we subdivided the younger (23–15 ka) part of the present study interval no further than this, we now propose a four-level classification of the entire 32–15 ka interval. Note that also at levels three and four of the classification scheme, each individual climatic oscillation starts and ends at a negative turning point.

¹⁵ We use a combination of numbers and letters for the higher-order subdivisions: see Table 1.

Although we set out the description of our units in a somewhat formal way, this is for clarity and is not intended to convey the impression that we mean them to be formal stratigraphic units. They are erected here for the purpose of this study. The descriptions are mainly based on the δ^{18} O data. Where we have also used the [Ca²⁺] data, this is made clear in the text.

4.2 Last Major Weichselian Oscillation – level 1

- Lower boundary:

The lower boundary of the Last Major Weichselian Oscillation has provisionally been put at the marked cooling event at 32.04 ka (1939.7 m) in NGRIP; the IN-PEFA curve shows a major change of trend at this point. Although not formally defined, the end of GI-5 (Andersen et al., 2006; Fig. 2) essentially corresponds with the start of LMWO. A formal lower boundary of LMWO can only be defined





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after analysis of the complete post-Eemian interval – which is beyond the scope of this paper.

- Upper boundary:

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The upper boundary of LMWO is above the study interval, at the Weichselian-Holocene boundary.

An important event within LMWO occurs at 23.4 ka (1794.5 m), which is very close to the Start of GI-2 of Lowe et al. (2008) at 23.34 ka (1794.08 m). This is confirmed by the very distinct positive turning-point in the NGRIP INPEFA; see Fig. 2. It marks the start of the period of overall warming of the Last Major Weichselian Oscillation. Note that it is also the start of the relatively warm upper subunit of Oscillation 3 at the second level

¹⁰ is also the start of the relatively warm upper subunit of Oscillation 3 at the second level of the hierarchy (see below). The equivalent positive turning-points in the GRIP and GISP2 INPEFA curves are well developed; concurrent changes in the [Ca²⁺] curves and their INPEFA curves are also distinct (see Fig. 1 of De Jong et al., 2009). The depths to the bounding surfaces and the ages are listed in Table 1.

15 4.3 Last Major Weichselian Oscillation – levels 2, 3 and 4

- Oscillation 1:

Oscillation 1 is well-developed in the three ice cores. It is readily identified in the unprocessed and processed curves displayed in Figs. 2 and 3. It shows a relatively long lower cool interval and a relatively short upper warm interval. Oscillation 1 essentially covers the period from the end of GI-5 up to and including GI-4 (Andersen et al., 2006; Lowe et al., 2008). The start and end of Oscillation 1 in NGRIP are at depths of 1939.7 m (32.04 ka) and 1882.6 m (28.6 ka), respectively (Figs. 2 and 3). Through detailed comparison of all curves, the start of Oscillation 1 in GRIP and GISP2 is determined to be at depths of 2088.5 m and 2117.7 m, respectively (Fig. 3). The end of Oscillation 1 in GRIP and GISP2 is distinct in the curves, at depths of 2037.7 m and 2068.8 m, respectively.

Subdivision:

We have differentiated two level-3 subunits in Oscillation 1, labeled 1a and 1b. Guided by distinct changes in the $[Ca^{2+}]$ curves, correlatable negative turning-points in the INPEFA curves of NGRIP, GRIP and GISP2 have been identified with a good degree of confidence at depths of 1916.8 m (30.64 ka), 2068.3 m and 2098.5 m, respectively (Figs. 2 and 3). These are the boundaries between the subunits.

- Oscillation 2.

Oscillation 2 is distinct in all ice cores, and correlation is straightforward using the processed and unprocessed curves displayed in Figs. 2 and 3. Oscillation 2 essentially covers GS-4 and GI-3 (Lowe et al., 2008; Rasmussen et al., 2008). The depths to the bounding surfaces and the ages are listed in Table 1.

Subdivision:

- Oscillation 2 is not subdivided.
 - Oscillation 3:

With its relatively long lower cool interval and a relatively short upper warmer interval, Oscillation 3 resembles Oscillation 1 (Fig. 2). We have put the upper boundary of Oscillation 3 at a depth of 1789.9 m (23.2 ka), which is marked by a distinct negative turning-point in the NGRIP INPEFA curve. Equivalent changes are also well-developed in GRIP and GISP2, at depths of 1947.7 m and 1983.1 m, respectively. Corresponding changes occur in the [Ca²⁺] profiles. Note that this upper boundary does not coincide with the start of GS-2 (end of GI-2) of Lowe et al. (2008), who put it at 1783.62 m (22.9 ka) and 1940.28 m in NGRIP and GRIP, respectively. Our boundary is slightly older, relying on the more pronounced turning-points in the INPEFA curves.

Discussion Paper 7, 4335-4373, 2011 **Greenland ice-core** isotope profiles and terrestrial record of **Discussion** Paper **Alpine Rhine glacier** M. G. G. De Jong et al. **Title Page** Introduction Abstract Discussion Conclusions References Figures Tables Paper Back Close **Discussion** Paper Full Screen / Esc Printer-friendly Version Interactive Discussion

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Subdivision:

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Two level-3 units (3a and 3b) have been differentiated in Oscillation 3. See Fig. 3 for the relevant INPEFA curves. Oscillation 3b has been further subdivided into three level-4 oscillations, labeled 3b1, 3b2 and 3b3 (Table 1). Differentiation of these higher-order units is based on the occurrence of subtle trend changes in the INPEFA curves of NGRIP, guided by the boundaries of the upper and lower dust events of Rasmussen et al. (2008). The corresponding negative turning-points in the GRIP INPEFA curves are fairly distinct. The equivalent boundaries in GISP2 are less easily identified, the overall pattern of the spectral trend curves being modified by higher-order oscillations (Fig. 3). The depths to the boundaries surfaces and their ages are listed in Table 1.

- Oscillation 4:

The start of Oscillation 4 in NGRIP is put at a depth of 1789.9 m (23.2 ka); see Fig. 2. Its end in NGRIP is at a depth of 1738.5 m (20.58 ka), corresponding with a marked decrease in δ^{18} O values, which appears as a distinct negative turning-point on the INPEFA curve. Oscillation 4 is characterized by a relatively long overall negative INPEFA trend followed by a short but distinct positive INPEFA trend (Figs. 2 and 4). The pattern is well-developed in all three ice cores. The positive INPEFA turning-points at 1744.05 m (20.84 ka) in NGRIP and at 1899.1 m in GRIP are very close to the Start of GS-2b. Lowe et al. (2008) put it at 1745.31 m and 1899.7 m, respectively.

Subdivision:

We have differentiated two level-3 subunits in Oscillation 4, labeled 4a and 4b (Figs. 2 and 4; Table 1). An interval of overall decreasing δ^{18} O values from bottom to top of Oscillation 4 is reflected in a long overall sub-vertical to negative (up-to-the-left) INPEFA trend. See also the toning applied to the δ^{18} O profiles in Fig. 4. Higher-order oscillations are superimposed on the trend, giving it a somewhat irregular shape. Guided by a marked pattern change in [Ca²⁺] curves

- note the "kink" in the INPEFA curves - we have put the boundary between subunits 4a and 4b at the negative turning-point at 1764.3 m (21.9 ka) in the INPEFA curves of NGRIP. The equivalent boundary in GRIP, at 1918.7 m, is quite distinct in the INPEFA curves. The boundary in GISP2, at 1955.4 m, is slightly less distinct.

Oscillation 4a has been subdivided into three level-4 subunits. Note that the presence of three subunits becomes evident only by comparing the INPEFA curves in the three ice cores. The depths to the bounding surfaces and the ages are listed in Table 1.

¹⁰ – Oscillation 5:

Oscillation 5 has relatively low δ^{18} O values in its lowermost part and relatively high values in the middle and upper parts of the interval (Fig. 4). Notably in GRIP and GISP2, the short-term INPEFA curves form an inverted Fig. "7". The end of Oscillation 5 is well-developed in GRIP (1821.88 m) and GISP2 (1863.79 m) where it is represented by a negative INPEFA turning-point. Although less distinct, the equivalent position can be unequivocally identified in NGRIP at a depth of 1669.02 m (17.84 ka) by using the pattern changes in the INPEFA_[Ca²⁺] curves as guidance.

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Subdivision:

Oscillation 5 has been divided into two level-3 units (Figs. 2 and 4; Table 1). The lower one, 5a, has an overall C-shape in the INPEFA curves of GRIP and GISP2, the tops being negative turning-points at depths of 1865.33 m and 1905.14 m respectively. The corresponding turning-point in NGRIP (at a depth of 1710.41 m or 19.32 ka) is less distinct, due to higher-order oscillations being pronounced. Three level-4 subunits have been differentiated in Oscillation 5a. Oscillation 5b comprises the upper part of Oscillation 5. The overall trends on the INPEFA curves are sub-vertical to positive (up-to-the-right). The four superimposed level-4 units show differences in shape in the INPEFA curves between the

ice-cores (Fig. 4). Turning-points – notably the negative ones – can be correlated, showing the equivalent high-order oscillations. The δ^{18} O values of Oscillation 5b are predominantly relatively high, in line with the overall positive trend of the corresponding INPEFA curves. Note that the similarities in patterns of the [Ca²⁺] INPEFA curves support the identification of the equivalent high-order units in the δ^{18} O INPEFA curves. The depths to the bounding surfaces and the ages are listed in Table 1.

Walker et al. (1999) defined the Start of GS-2a in GRIP at a depth of 1823.7 m, slightly deeper than the pronounced negative turning-point which forms the boundary between Oscillations 5 and 6. Lowe et al. (2008) state that the GS-2a feature is not clear in NGRIP.

- Oscillation 6:

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Oscillation 6 is the youngest unit at the second level of our stratigraphic scheme (Figs. 2 and 4; Table 1); only the lower part is represented in the study interval, which stops at the very pronounced base of a major warming trend. This point is marked by a positive turning-point in the INPEFA curves at 1605.29 m in NGRIP (14.72 ka), 1754.65 m in GRIP and 1799.02 m in GISP2. Lowe et al. (2008) put the Start of GI-1e at 1604.64 m (14.69 ka) and 1753.39 m in NGRIP and GRIP, respectively.

Subdivision:

The proposed three-fold subdivision of Oscillation 6, at level 3 of the hierarchy, is best seen in the GRIP and GISP2 ice cores (Fig. 4). The level-4 units are fairly distinct in the three ice cores. Again, the presence of correlatable patterns in the [Ca²⁺] INPEFA curves helps to reduce very much the uncertainty of the correlations of the δ^{18} O INPEFA curves. The depths to the bounding surfaces and the ages are listed in Table 1.

Discussion Paper 7, 4335-4373, 2011 **Greenland ice-core** isotope profiles and terrestrial record of **Discussion** Paper **Alpine Rhine glacier** M. G. G. De Jong et al. **Title Page** Introduction Abstract **Discussion** Paper Conclusions References Tables Figures Back Close **Discussion** Paper Full Screen / Esc Printer-friendly Version Interactive Discussion

5 Pleistocene Rhine glacier area

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Having established a breakdown of the three ice cores in terms of a climate-based stratigraphic framework, we now introduce the climatic stratigraphy of the area of the Rhine glacier in southern Germany/northwestern Austria and adjacent Switzerland, in which the climatic time series is based on terrestrial proxy data. The study period comprises the Late Weichselian – the Upper Würmian in Alpine terms – and is thus broadly the same as for the Greenland ice core data. The present objective is to compare the two time series, and to use each to better understand the other.

The methodology for the Rhine glacier area is the conventional one of interpretation of the patterns of landforms and deposits in terms of a succession of time intervals with different climatic conditions. Stratigraphic relationships in the field are combined with ¹⁴C dates from sample materials from a limited number of localities, to build up a composite stratigraphy representing the changing climatic environment through time. The ¹⁴C dates used in this account are summarized in Table 2; the field investigations have been presented in a series of papers by ourselves and co-authors: De Jong (1983); Seijmonsbergen (1992); De Jong et al. (1995); de Graaff and De Jong (1995); de

Graaff (1996); de Graaff et al. (2007). Regional overviews have been presented by Keller and Krayss (1980, 1987), Preusser (2004), Monegato et al. (2007) among others. See Fig. 5.

²⁰ Critical to our proposed correlation between Greenland and the Rhine glacier area is the very clear indication that both the advance and the retreat of the glacier during the last major glaciation proceeded in a discontinuous, or spasmodic way. Superimposed on the overall advance of the glacier system were intervals of relative warming, during which the advance slowed, stopped, or even reversed before resuming; superimposed

on its overall retreat towards the end of the Würmian were intervals of relative cooling, during which the retreat of the glaciers slowed, stopped, or (rarely) even reversed. The stratigraphic and chronological succession of events shows this very clearly for the period of deglaciation; less clearly for the period of glacial advance.

We consider first the better evidence for discontinuous warming during the retreat of the Rhine glacier from the Alpine foreland to the inner Alps. This spasmodic process is represented by a series of ice-marginal complexes, labeled Recessional Complex I through IV (RC I–IV). These are interpreted to represent stationary ice margins, and hence a pause in the overall warming process. These ice-marginal sediments are predominantly glaciofluvial and/or fluvial, and were deposited by aggradation in front of or along stationary ice margins. Dead-ice structures are abundant in the ice-marginal deposits, indicating deposition on top of or next to decaying ice masses which were disconnected from the moving ice body. Glacier re-advance is of local importance only; thus, the climatic interpretation is of overall warming interrupted by intervals of

¹⁰ only; thus, the climatic interpretation is of overall warming interrupted by intervals of time in which warming slowed or stopped (but only rarely reversed), before resuming again.

Volumetrically, RC I and RC II are more significant and have generally been considered to have formed over a period of several thousands of years (e.g. Penck and
Brückner, 1901/1909; Ivy-Ochs et al., 2004). RC III is volumetrically less important; it is thought to have formed during a period of hundreds of years. Compared with the other complexes, RC IV is volumetrically insignificant; it is interpreted to have formed during a short period of time.

Characteristically, the landforms of RC I, II and III have a relatively well-defined in-²⁰ ner (younger) boundary, whereas the outer (older) boundary is less well-defined. The retreat of the glacier front apparently started to slow down, followed by a still-stand at what we now identify as the inner boundary of a recessional complex, after which the glacier again receded relatively fast into the direction of the Alps. In tandem with the retreat of the glacier front, the drainage pattern in the ice-free area also developed in

²⁵ a spasmodic way. ¹⁴C dates that constrain the ages of these landforms and deposits are listed in Table 2: see item numbers 5, 6 and 7 (RC I, see also below); 8, 9 and 10 (RC II); 11 (RC III); 13 and 14 (RC IV). Note that only age dating number 12, which is linked to RC IV, is inconsistent (i.e. too old) in this series (Fig. 4; Table 1).

By contrast with its retreat, the Würmian advance of the Rhine glacier is much less well documented by stratigraphic deposits. There is nevertheless evidence that this, too, proceeded in a discontinuous way, as follows.

- Large relicts of different generations of "early glacial" sediment fills occur in several ⁵ tributary valleys and niches in the northwestern Alps. Location and vertical succession of lithofacies indicate that they formed in interaction with waxing trunk glaciers, when associated base-levels were abruptly rising (Seijmonsbergen, 1992; de Graaff, 1996; de Graaff et al., 2007). Partly lithified and strongly compacted, these fills often survived glacial and post-glacial erosion. Th/U age datings show some of these deposits to be of ¹⁰ Riss age (Ostermann et al., 2006). Younger fills mainly correspond with the last major
- glacier advance. It is estimated that the formation of the youngest fills in the Southern Walgau region of Vorarlberg took some 2000 years, starting before 30 ka and ending at around 28 ka (de Graaff et al., 2007; see also Preusser, 2004).

The Hochwacht Interstadial is defined by glacially overridden deltaic deposits exposed southeast of Bregenz near Lake Constance in the northwestern Alps. It is interpreted as a glacier-front oscillation during the overall glacier advance toward its maximum position (de Graaff, 1992). A relevant ¹⁴C age dating is item 3 (Table 2).

The landform and deposits of the *Äußere Würmendmoräne* (*Äußere Jungend-moräne*) – here called Maximum Glaciation – have traditionally been interpreted to

- ²⁰ mark the outermost position of the last major advance (see e.g. Penck and Brückner, 1901/1909; De Jong, 1983). There is, however, evidence of a Supermaximum Glaciation (*Supermaximalstand*), showing that the Rhine glacier had moved about 1–3 km further out into relatively low lying areas before *receding* to the position of "Maximum Glaciation" (see e.g. Schreiner, 1992). De Jong (1983) argues that the landforms and
- deposits of the "Maximum Glaciation" should at least in part be interpreted as a *recessional* complex, i.e. they belong to RC I. Erosion and reworking at the glacier front have made it impossible to differentiate precisely between deposits formed during Maximum Glaciation and those formed during the first phases of retreat.

The above stratigraphic succession of landforms and deposits thus reflects a period of overall cold conditions, corresponding with glacier advance, followed by a period of overall warm conditions corresponding with overall glacier retreat. Superimposed on these large-scale climatic trends were higher-order fluctuations. The interstadial deposits and recessional complexes were formed during the resulting slightly warmer and slightly cooler conditions, respectively. This pattern of intermittent cooling and glacial development, to a time of maximum glaciation, followed by intermittent warming and discontinuous deglaciation, is the pattern that guides the following correlation between the very different climate proxy time-series of Greenland and the Rhine glacier area.

6 The ice core records – a comparison with a terrestrial record

6.1 General

Generally speaking, correlatable boundaries or units in the Quaternary are identified on the basis of represented climate changes in combination with age datings (e.g. ^{14}C

age datings). Correlating climate proxies from widely different geographical and, thus, environmental settings is not an easy task given the complexity of climate change and the variable effects of the changes on the natural systems.

Accepting a dominant role for orbital forcing in climate change in the geological past on a time scale of 10s to 100s ka (i.e. Milankovitch cycles), Perlmutter and Plot-

- nick (2002, 2003) argue that regional variations in climate have occurred and that different parts of the Northern Hemisphere have undergone different successions of climate through time. Changes in temperature and humidity may, however, not have been in phase in different climate zones. Perlmutter and Plotnick (2002; 2003: p.55) also point to the possible existence of (1) lag times between the onset of changes in, among
 other things, insolation and regional climates, and of (2) nonlinear responses of these
- systems. In addition, there are the well-known problems of lag times between climate

change and its environmental effects. Given their wide separation and different nature, correlation of the terrestrial proxy and Greenland proxy, notably at high resolution, thus needs to be done with prudence.

The time span of our study interval is more than 15 ka, i.e. more than half of a precession cycle (Kukla and Gavin, 1992; Perlmutter and Plotnick, 2002, 2003). We may expect a general parallelism of climate change in the areas of our proxies, assuming that, at least, the major climate changes are orbitally controlled. It is generally accepted that the relatively long periods of cooler and warmer conditions in the late Pleistocene in the Northern Hemisphere are more or less coeval. We cannot, however, a priori assume that the changes in temperature and humidity, notably the higher-order ones, were in phase and coeval. With regard to the terrestrial proxy, ¹⁴C age datings offer time constraints for the correlation with the Greenland proxy and for the analysis of possible lag times. See also discussion below.

Correlation of climate proxies of different nature over large distances may be better understood, and accepted, if the primary processes or factors that were responsible for their formation are subject to the same controls. The δ^{18} O variable is still considered to be dependent on temperature, although less closely than thought before (Emiliani, 1966; NGRIP members, 2004; Wolff et al., 2010). As for the terrestrial proxy, it can be argued that the link with temperature is also strong, although less direct. The

- ²⁰ relation between climate and glaciers is often expressed in terms of mass balance or the ratio between accumulation and ablation (AAR = accumulation-ablation ratio). These are both primarily a function of temperature and precipitation (Kerschner et al., 2008). Changes in mass balance result in changes in glacier-margin position. Simply put, the glacier front retreats when ablation is larger than accumulation, and vice
- versa. The movement (dynamics) of glaciers in formerly glaciated areas is inferred from, among many other things, landforms and deposits. Glacier advance and retreat are reconstructed from the temporal and spatial distribution of the various landforms and deposits. The pattern of past glacier advance and retreat reflects changes in mass balance, and thus in temperature and precipitation. It is generally accepted that the lag

time between climate (temperature) change and mass balance change – and, therefore, changes in glacier-margin position – is a short one.

6.2 Linking the proxies

For the period of the last major Pleistocene glaciation, we have time series data for different climate proxies from two areas, which we now wish to compare. From Greenland, we have the virtually continuous record of δ^{18} O (supplemented by the [Ca²⁺] data) from three ice cores, for which the GICC05 synchronization is accepted by us as the standard numerical time scale. From the Rhine glacier area, we have the record of terrestrial deposits and associated landforms, which is notably very discontinuous in the older part. It was pieced together using conventional field methods, and is supported by a limited number of ¹⁴C analyses. For the conversion of the latter to numerical (calendar) ages we have used the IntCal09 calibration protocol (Reimer et al., 2009; calib611 software package from http://www.calib.org). In spite of the occasionally rather large age ranges (Table 2), we consider the datings sufficiently accurate to

Key results from comparing the two are as follows:

- The numerical ages confirm that the Greenland and Rhine glacier time series span more or less the same overall interval of time: 32 to 15 ka.
- Both time series show a twofold division into a colder period followed by a warmer period, which together form one major climatic oscillation.
- Both time series indicate clearly that higher-order climatic oscillations were superimposed on the major one.

The detailed link we propose between the two proxies is shown in Table 1. We equate the end of the last major Weichselian (Würmian) glacier advance of the terrestrial record, i.e. the End of Maximum Glaciation, with the very distinct positive turning-point in the INPEFA curves of the ice cores at 23.4 ka. The onset of Maximum Glaciation is

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proposed to be time-equivalent to the onset of Oscillation 3b3 (23.98 ka). This interpretation is in line with that of Preusser (2004) for the age of the maximum extension of the last glaciation of the Alps. The onset of the Supermaximum Glaciation may be time-equivalent to the onset of Oscillation 3b/3b1 (25.92 ka). We tentatively propose

- the Supermaximum Glaciation and Maximum Glaciation to correlate with the lower dust event and upper dust event, respectively, of Rasmussen et al. (2008). Note that Monegato et al. (2007) report a two-fold glacial advance in the southeastern Alpine foreland of Italy in the period 26.5–21 cal ka BP. The Hochwacht Interstadial is considered time-equivalent with the upper sub-unit of Oscillation 1b, i.e. the interval between the distinct positive turning-point of Oscillation 1 (1b) and the base of Oscillation 2 (28.9 ka
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and 28.6 ka, respectively). We equate the End of RC I with the positive turning-point in the INPEFA curves of the ice cores at 20.84 ka. Both boundaries are distinct in their records. The onset

of RC I is not defined in the terrestrial record. Correlation suggests the formative period for RC I to correspond with the interval between onset of Oscillation 4 and the aforementioned positive turning-point, i.e. between 23.2 ka and 20.84 ka. Using surface exposure datings of erratic blocks, Ivy-Ochs et al. (2004) report that break down of the Rhône piedmont glacier system occurred between 21.1 and 19.1 ka, which we consider in general agreement with our interpretation.

The End of RC II is equated with a positive turning-point in the INPEFA curves of NGRIP at 17.84 ka, within Oscillation 5b4. The equivalent turning-points in GRIP and GISP2 are less distinct. As for RC I, the onset of RC II is not defined in the terrestrial record. Correlation of the proxies suggests the formative period for RC II to correspond with the interval between the onset of Oscillation 5a1 and the intra-Oscillation 5b4 event, i.e. between 20.58 ka and 17.84 ka.

The End of RC III is equated with fairly distinct positive turning-points in NGRIP and GISP2 within Oscillation 6a3 (at 16.68 ka); it is less distinct in NGRIP. The onset of RC III, which is not defined in the field, may correspond with the onset of Oscillation 6a1 of the ice-core records (at 17.48 ka). The End of RC IV is equated with subtle positive

4357

turning-points within Oscillation 6a4 (at 16.32 ka). The onset of RC IV may correspond with the onset of Oscillation 6a4 (at 16.52 ka).

The onset of the last major Pleistocene glaciation is not defined in our terrestrial record. The correlation with the ice cores suggests that the last major advance of the Rhine glacier probably started at about 32 ka, some 3000 yr before the formation of the

5 Rhine glacier probably started at about 32 ka, some 3000 yr before the formation deposits of the Hochwacht Interstadial.

6.3 Discussion

Our analysis and interpretation are based on (1) the *patterns* in the isotopic profiles of the Greenland ice cores and in the terrestrial record in the former Rhine glacier

- area, (2) the interpretation of these patterns in terms of climate changes, and (3) the correlation of the patterns. Climatic oscillations at more than one scale can be identified in both proxies, and these are correlatable. We regard this as a significant contribution to understanding the nature of climate change in this period: the alternative subdivision of the period 32–15 ka into alternating stadials and interstadials (Andersen et al., 2006;
- Lowe et al., 2008; Rasmussen et al., 2008) does not reflect the multiscale, hierarchical pattern of climatic change.

Wolff et al. (2010) describe the variability in the ice-core records as a series of Dansgaard-Oeschger (D-O) cycles, each cycle typically beginning with a warming event. These warming events, generally, are sharp and represent significant climate changes, and are conspicuous in the data. Our approach being more stratigraphic than climatological, we consider a scheme of units with lower boundaries corresponding with a cool(ing) event rather than with a warm(ing) event justified, in line with common sequence stratigraphic approaches (Catuneanu et al., 2009).

It is important to note that we have arrived at the above correlation between the data from Greenland and the Rhine glacier area without having to assume either equivalence or synchroneity of climatic events in the two areas; the correlation emerges from the data. The good correlation between the records from our two study areas can therefore be taken to suggest that climate changes in Greenland and central Europe

were indeed synchronous within the level of resolution available to us. Evidence for synchroneity of climate shifts in the Alpine region and central Greenland for the latest Pleistocene and early Holocene has also been presented by von Grafenstein et al. (1999) and Schwander et al. (2000).

The causes of climate change are subject of an ongoing debate. Orbital forcing, solar forcing and variation in the thermohaline circulation in the North Atlantic are the most often mentioned driving mechanisms (von Grafenstein et al., 1999; Alley and Ágústdóttir, 2005; Rohling and Pälike, 2005; Solé et al., 2007; Thomas et al., 2007; Ditlevsen and Ditlevsen, 2009; and many more). Rohling and Pälike (2005) present
 evidence for the compounded nature of climate signals, more sudden climate changes being superimposed on longer-term trends in the early Holocene. Generally speaking,

however, the compound – multiscale – nature of climate change is somewhat underexposed in the discussions.

Periodicity and recurrence time of climate changes are also subjects of ongoing
discussion. Ditlevsen et al. (2005, 2007) argue on the basis of statistical analysis of Greenland ice-core data that there is no unequivocal evidence for a 1470 years cycle which had been proposed among others by Schulz (2002). Ditlevsen and Ditlevsen (2009) conclude that the rapid climate shifts in the last ice age are best described by a model of random distribution of waiting times. Underlying these analyses
is the assumption that there are two quasi-stationary climate states, i.e. an interstadial state and a stadial state.

The occurrence of climatic oscillations at different scales of time as seen in our proxies suggests a combination of causes which potentially may be independent. The level 1 oscillation may be orbitally controlled (see also Sect. 6.1); the higher-order oscillations may be controlled by processes linked to the thermohaline circulation. A statistical analysis of periodicities or cyclicities should take this nature into account.

On a regional level, the dating of the events in the Rhine glacier area of the Western Alps will contribute to establishing the link with the stadials of the Eastern Alps

Further evaluation of these topics are beyond the scope of this paper.

Analysis of climate proxy data from the Greenland ice cores is facilitated by the use of spectral trend (INPEFA) curves. The relevance of these curves is twofold: (1) the

framework for the entire Alps.

Conclusions

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5 presence of major "low-order" trends and trend changes in the data is easily and convincingly confirmed; (2) stratigraphic patterns are revealed that may otherwise be overlooked, notably the "higher-order" ones. Where climate proxies are the subject of the spectral trend transform, the resulting INPEFA curves can be interpreted in terms of cool/cooling and warm/warming trends. 10

events (Kerschner et al., 2008), and thus to the construction of a chronostratigraphic

A classification of the Late Weichselian succession in the Greenland ice cores is made, in which climatic oscillations, from warm to cool and back again, are seen to exist at several scales. Overall, the study interval of 32-15 ka is one major oscillation which is very clearly subdivided, at 23.4 ka (GICC05 timescale) into an earlier cool/cooling period followed by a later warm/warming period. Recognition of similar oscillations, but at smaller scale, is the basis for proposing higher-order subdivisions within this overall climatic cycle.

A similar pattern of spasmodic cooling and warming is interpreted from the stratigraphic succession of depositional complexes of the last major Pleistocene glaciation

in the Rhine glacier area of southern Germany and adjacent Austria and Switzerland. 20 The period of deglaciation is particularly well represented by a series of Recessional Complexes, tied to the numerical time scale by radiocarbon dating. With the exception of the "early-glacial" valley fills, the period of glacial advance is less well represented by deposits towards the Alpine foreland. The lithostratigraphy of the fills, as well as the evidence for at least one interstadial within the advance, supports the conclusion that 25 the advance was also intermittent.

Discussion Paper

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The Greenland and Rhine glacier successions are therefore similar in overall character, and the available numerical dates allow the Last Major Weichselian Oscillation in Greenland to be equated with the last major Pleistocene advance and retreat of the Rhine glacier. From this, a number of more detailed ties are proposed between the two data series.

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While the ice core data provide a quasi-continuous record of the state of the atmosphere-ocean-cryosphere system, they do not directly predict the way in which the implied climatic changes are expressed elsewhere. Our proposed correlation with the terrestrial succession provides a kind of calibration of the ice core record in terms of the effect of those changes on the succession of glacial advance and retreat in a typical Alpine region, and possibly beyond.

Without the recognition of a multiscale structure to climate change as represented in both proxy data series, a correlation of the two would be significantly more difficult. We therefore commend our approach as an improvement over the previous division of the ice cores into a simple alternation of stadials and interstadials.

Further application of spectral trend analysis to ice core time series data from older and younger intervals than that studied here is considered promising, and will lead to fuller exploitation of these data. Linking the information from these with climate proxies contained in other datasets is predicted to lead to further insights into past climate change, with the potential for better understanding of present and future climate changes.

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Discussion Paper

Discussion Paper

Discussion Paper

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30

7, 4335-4373, 2011 Greenland ice-core isotope profiles and terrestrial record of **Alpine Rhine glacier** M. G. G. De Jong et al. **Title Page** Introduction Abstract Conclusions References Figures Tables Back Close Full Screen / Esc Printer-friendly Version Interactive Discussion

Discussion Paper

Discussion Paper

Discussion Paper

Discussion Paper

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Table 1. Stratigraphic subdivision of the ice cores, displayed in columns under header Stratigraphic Scheme. The stratigraphic subdivision of the terrestrial record of the Pleistocene Rhine glacier area is shown in the right-hand part of the figure. Depths to the proposed boundaries in the three ice cores and GICC05 ages are tabulated under header Greenland Ice Cores. The dashed horizontal lines across the Level 2–4 columns of the Stratigraphic Scheme correspond with distinct positive INPEFA turning-points. See text for explanation.

*note: ages rounded to nearest 20yr value (Rasmussen et al., 2008)

#note: depths and ages refer to lower boundaries of units and subunits

4367

Table 2. ¹⁴C age datings. Key to columns: 1 - sample number used in text and figures; 2, 3 - stratigraphic position of samples; 4 through 8 – location of sampling, type of material, type of deposit, laboratory code, reference; 9, 10 – original, uncalibrated ¹⁴C age and standard deviation; 11, 12, 13 – calibrated ¹⁴C ages and ranges using INTCal09. See text for further explanation.

			Sample Information						¹⁴ C Original		IntCal09 (b2k)	
Sample #		Stratigraphy	Location	Material	Deposit	Lab code	Reference	¹⁴ C Age	¹⁴ C Age SD	median	lower cal	upper cal
								(yr BP)	(yr)	probability	range BP (1 sigma)	range BP (1 sigma)
14	General	approx. RC IV eq.	Lake Constance (Upper Lake)	twig	lacustrine	KIA-2516	Wessels (1998)	13090	±60	15 896	15581	16 323
13	Retreat of	post-RC IV	Schleinsee ENE of Kressbronn	Dryas leaves	lacustrine	NA	Schreiner (1978)	13 335	±185	16 307	15973	16 805
12	Rhine Glacier	approx. RC IV eq.	Lake Constance (Upper Lake)	wood fragment	lacustrine	KIA-3121	Wessels (1998)	13930	±250	17 102	16829	17 442
11		RC III eq.	Hinterhausen (Konstanz)	bone	gravels	HV 10653	Geyh and Schreiner (1984)	14 100	±115	17213	17006	17 447
10		post-RC II eq.	Lake Zuerich	twig	lacustrine	GL 2	Lister et al. (1984)	14600	±250	17811	17314	18 472
9		RC II eq.	Steisslingen NE of Singen	bone	gravels	HV 10654	Geyh and Schreiner (1984)	14800	±120	18 075	17864	18 518
8		(post-)RC II	Schweinberg/Leupolz N of Wangen	bone	gravels	GRN 11836	De Jong (1983)	15090	±80	18 301	18 129	18 595
7	General	Maximum Glaciation	Hardtwald near Geisslingen/Klettgau	tusk	gravels	HV 14486	Schreiner (1992)	19895	+1500/-1320	23 851	22 0 39	25 802
6	Advance	Maximum Glaciation	Binningen near Engen	tusk	gravels	HV 13323	Schreiner (1992)	19920	±140	23 842	23583	24 026
5	of Rhine	Maximum Glaciation	Binningen near Engen	tusk	gravels	HV 14390	Schreiner (1992)	20 195	±140	24 165	23973	24 361
4	Glacier	pre-Maximum Glaciation	Knollengraben SE of Ravensburg	humic material	sands between tills	NA	Weinhold (1973)	22 130	±225	26 6 4 6	26219	26 958
3		Hochwacht Interstadial	Hochwacht E of Bregenz	tusk	gravels under till	UTC 1292	de Graaff (1992)	23900	±400	28 800	28410	29 300
2		pre-Maximum Glaciation	Ingoldingen SE of Biberach	tusk	gravels under till	HV 15882	Schreiner (1992)	24910	±215	29 866	29568	30 208
1		pre-Maximum Glaciation	Saulgau	humic material	sands under till	NA	Geyh after Werner (1978)	26 195	±970	30 780	29818	31 484

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Fig. 1. Depth plot, showing δ^{18} O profiles, PEFA and INPEFA curves for a short interval of the GISP2 and GRIP ice cores. Examples of equivalent, correlatable trend changes (turningpoints) in the INPEFA curves are also shown. See text for further explanation.

Key to vertical tracks with reference to GISP2: 1 – depth (m); 2 – δ^{18} O profile (scale from –47 to -36 ‰); 3 – PEFA curve of δ^{18} O data (scale from -1.27 to 1.38 ‰ in GISP2 and from -1.57 to 1.49% in GRIP); 4 – INPEFA curves of δ^{18} O (scale dimensionless from 0 to 1; the red curves are derived from the PEFA curves of track 3, the blue and violet curves have been generated over equivalent, shorter, intervals; examples of C-shape patterns are indicated by the dashed lines); 5 - negative (up-to-the-left; NTP, ntp) and positive (up-to-the-right; PTP) turning-points in INPEFA curves.

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Discussion Paper

Fig. 2. Time plot, showing δ^{18} O profile and INPEFA curve for the NGRIP ice core for the interval 41.5–14 ka. Major stratigraphic events are also shown.

Key to vertical tracks: 1 – GICC05 time-scale (Andersen et al., 2006; Rasmussen et al., 2006, 2007, 2008; Svensson et al., 2006; Vinther et al., 2006); 2 – events after Andersen et al. (2006), Lowe et al. (2008) and Rasmussen et al. (2008); $3 - \delta^{18}$ O profile (scale from –47 to –36 ‰); 4 – INPEFA curve of δ^{18} O data (scale dimensionless from 0 to 1); 5, 6, 7 – stratigraphic subdivision of ice cores (this paper, refer to Table 1 for codes and colors); 8 – equivalent events in Rhine glacier area (RC – Recessional Complex; EMG – End of Maximum Glaciation; OMG – Onset of Maximum Glaciation; OSG – Onset of Supermaximum Glaciation; EHI – End of Hochwacht Interstadial; OHI – Onset of Hochwacht Interstadial). The "Last Major Weichselian Oscillation" interval is examined in detail in Figs. 3 and 4.

Fig. 3. Depth plot, showing isotopic profiles and INPEFA curves for the NGRIP, GRIP and GISP2 ice cores for the lower part of the Last Major Weichselian Oscillation. Stratigraphic interpretations are also shown. See text for explanation.

Key to vertical tracks with reference to NGRIP: 1 – depth (m); $2 - \delta^{18}$ O profile (scale from -47 to -36‰) with black toning to highlight intervals with relatively high δ^{18} O values; $3 - [Ca^{2+}]$ profile (scale from 0 to 1000 ppbw); 4 – INPEFA curves of δ^{18} O (scale dimensionless from 0 to 1; the red, indigo and aqua curves have been generated over equivalent intervals of the ice cores); 5 – events after Lowe et al. (2008) and Rasmussen et al. (2008); 6, 7, 8 – stratigraphic subdivisions of ice cores (this paper, refer to Table 1 for codes and colors); 9 – equivalents of major events in Rhine Glacier Area; 10 – equivalent depth in ice core of calibrated ¹⁴C age datings from Rhine Glacier Area (see Table 2). Abbreviations: Onset of SM. Glaciation? – Onset of "Supermaximum" Glaciation?; End of HI – End of Hochwacht Interstadial; Onset of HI – Onset of Hochwacht Interstadial; EUDE – End of upper dust event; OUDE – Onset of upper dust event; ELDE – End of lower dust event; OLDE – Onset of lower dust event.

Fig. 4. Depth plot, showing isotopic profiles and INPEFA curves for the NGRIP, GRIP and GISP2 ice cores for the upper part of the Last Major Weichselian Oscillation. Stratigraphic interpretations are also shown. See text for explanation.

Key to vertical tracks with reference to NGRIP: 1 – depth (m); $2 - \delta^{18}$ O profile (scale from -47 to -36‰) with toning to highlight intervals with relatively high δ^{18} O values; $3 - [Ca^{2+}]$ profile (scale from 0 to 1000 ppbw); 4, 5 – INPEFA curves of δ^{18} O and $[Ca^{2+}]$ data, respectively (scale dimensionless from 0 to 1; curves have been generated over equivalent intervals of the ice cores, indicated by colors); 6 – events after Lowe et al. (2008) and Rasmussen et al. (2008); 7, 8, 9 – stratigraphic subdivisions of ice cores (this paper, refer to Table 1 for codes and colors); 10 – equivalents of major events in Rhine Glacier Area; 11 – equivalent depth in ice core of calibrated ¹⁴C age datings from Rhine Glacier Area (see Table 2).

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Fig. 5. Generalized position of major Recessional Complexes (RC) of the former Rhine glacier in the Lake Constance area. Modified after Keller and Krayss (1980, 1987).

