A paleomagnetic solution for the age controversy in the Upper Molasse of the Northern Alpine Foreland Basin

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***Abstract* – During the last two decades, research on the Western Paratethys and especially on the Northern Alpine Foreland Basin (Molasse) concentrated on improving the basin wide correlation because substantial uncertainties have led to considerable controversies, especially with regard to the dynamics of the basin's depositional history. These uncertainties resulted in at least two widely different stratigraphic frameworks for the Bavarian and Swiss Molasse which results in ages that are about 1 Myr apart. This difference is mainly related to the assumption that a major hiatus is present in southern Germany, similar to the Styrian unconformity in Austria. The different opinions have led to different correlations of the Upper Molasse to either the Ottnangian or the Karpatian. The definitions, of these regional stages, are very strongly interconnected to each other, which will result in a review of the exact age of the Ottnangian – Karpatian boundary. To resolve this risen controversy a joint effort was undertaken. With new biostratigraphic, paleomagnetic and radiometric data from several key sections in Switzerland and from boreholes taken throughout Bavaria (Southern Germany) combined with data from the last decades resulted in the conclusion that the Ottnangian-Karpatian boundary has an age of 16.3 Ma (+/- 0.1 Myr). As a result the Karpatian becomes significant shorter in time than assumed before.**

Key words: Paleomagnetism, Molasse, Biostratigraphy, NAFB, middle Miocene, Alps, Ottnangian, Karpatian

Introduction:

The Northern Alpine Foreland Basin (NAFB) is a classical foreland basin located at the northern part of the Alps. In the early Cenozoic it formed as a result of the evolution of the Alps (Schlunegger et al., 1997). The increase in tectonic load caused a buldge in the lithosphere which formed the basin as we know it today. The NAFB is mainly filled with debris from the Alps however a small part also finds it origin in the Bohemian massif to the North. The basin which is also known as the Molasse basin is part of the Western Paratethys and is filled up with thousands of meters sediment at the border with the Alps which diminishes to a few and even zero meters in the northern part. The basin stretches from Haute Savoy in France through Switzerland and Bavaria (Southern Germany) into Austria and the Vienna region (Figure 1). It has an approximated length of about 1000 km and is about 150 km wide on its maximum value in Bavaria. The fill of the NAFB started in the Paleocene according to Lihou and Allen (1996). The deposition of the Molasse sequences first occurred at the Early Oligocene at about 32 Ma (Schlunegger et al., 1996) and kept filling the basin until the Late Miocene 11 Ma. According to Kälin and Kempf (2009) all major litho-stratigraphic units in the Molasse basin are at least partially diachronous.

The complete Molasse sequence can roughly be divided into two large episodes which are both characterized by a transgressive-regressive cycle. This results in the following succession, in which the abbreviations are the German abbreviation because these are commonly used in most publications: Lower Marine- (UMM), Lower Brackish water- (UBM) and Lower Freshwater Molasse (USM) and Upper Marine- (OMM), Upper Brackish water- (OBM) and Upper Freshwater Molasse (OSM). The timing of

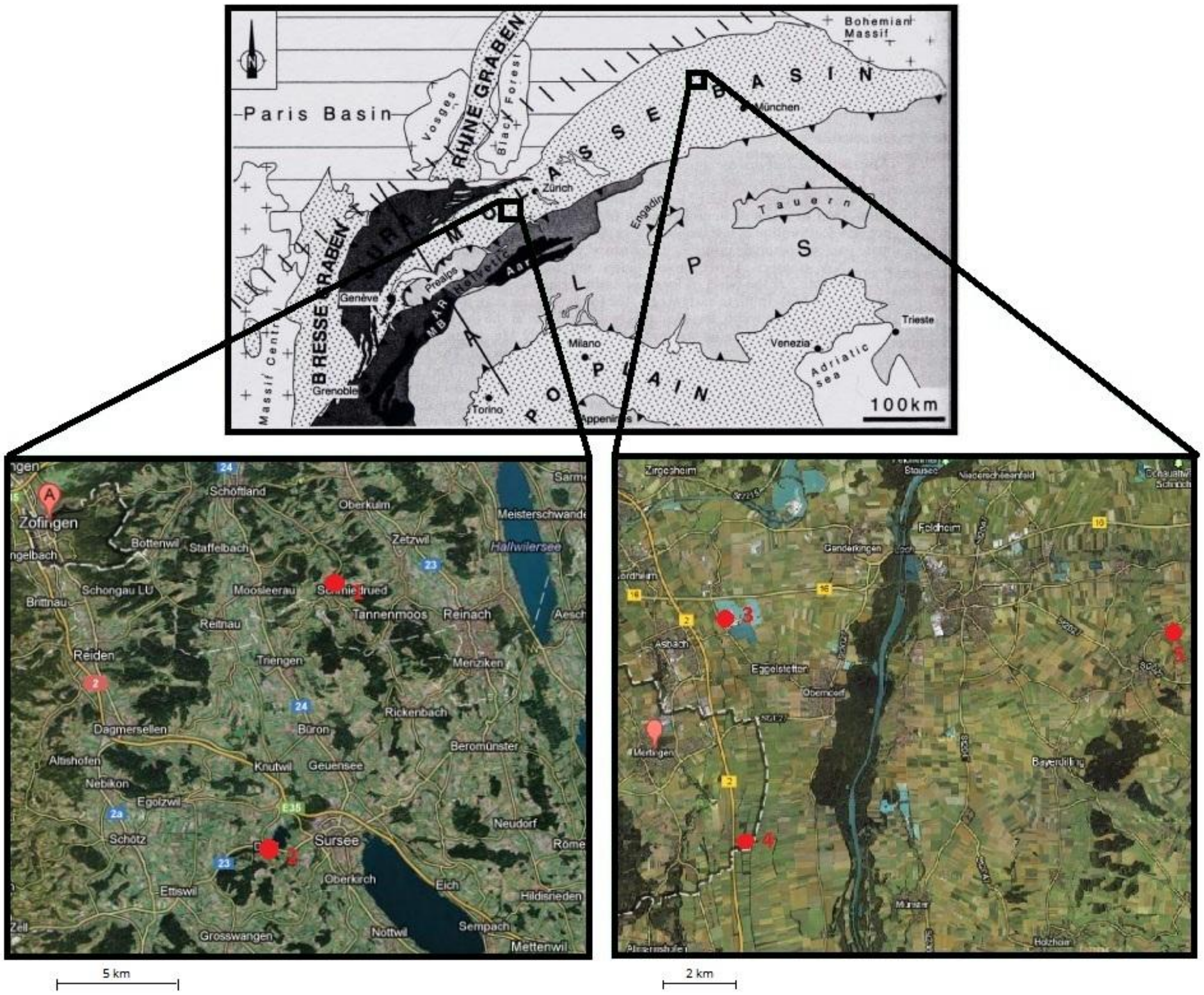

Figure 1: The figure on top shows the Molasse basin within the NAFB (Burkhard & Sommaruga, 1998). The two figures below show the locations of the sections and boreholes within Switzerland and Bavaria. 1) Schmiedrued Pfyfrütti(47°16’N 08°06’O); 2) Mauensee(47°09’N 08°04’O); 3) Hamler1(48°41’N 10°49’O); 4) Druisheim(48°37’N 10°50’O); 5) Gempfing(48°41’N 11°00’O).

these Molasse units is still debated and due to the diachronous nature not easy to solve. What is necessary is a good stratigraphical framework.

A good stratigraphical framework leads also to a better understanding of the depositional en tectonic dynamics that are important in this region during these times. How did sedimentation rates develop/change? When did some thrusts occur? All questions that need a good framework are in most cases also in need of a good time constraint. On these subjects many authors e.g. (Schlunegger et al., 1997) (Reichenbacher et al., 2005; 2010) (Kälin and Kempf, 2009) (Abdul-Aziz et al., 2009) have provided a great understanding in all aspects of this stratigraphical framework. However one important piece, which connects all the different data, is still heavily debated. This is a good and reliable time frame. Although recent studies from Kälin and Kempf (2009) and Abdul-Aziz et al. (2009) have combined and integrated several dating methods like biostratigraphy, radio isotopic dating and magnetostratigraphy, the debate is still not solved and these two papers form a good illustration of the problem at hand. As shown in (Figure 2) the Styrian unconformity and the time span it covers is one of the main causes of the problems and hampers a straightforward correlation between Bavaria and Switzerland.

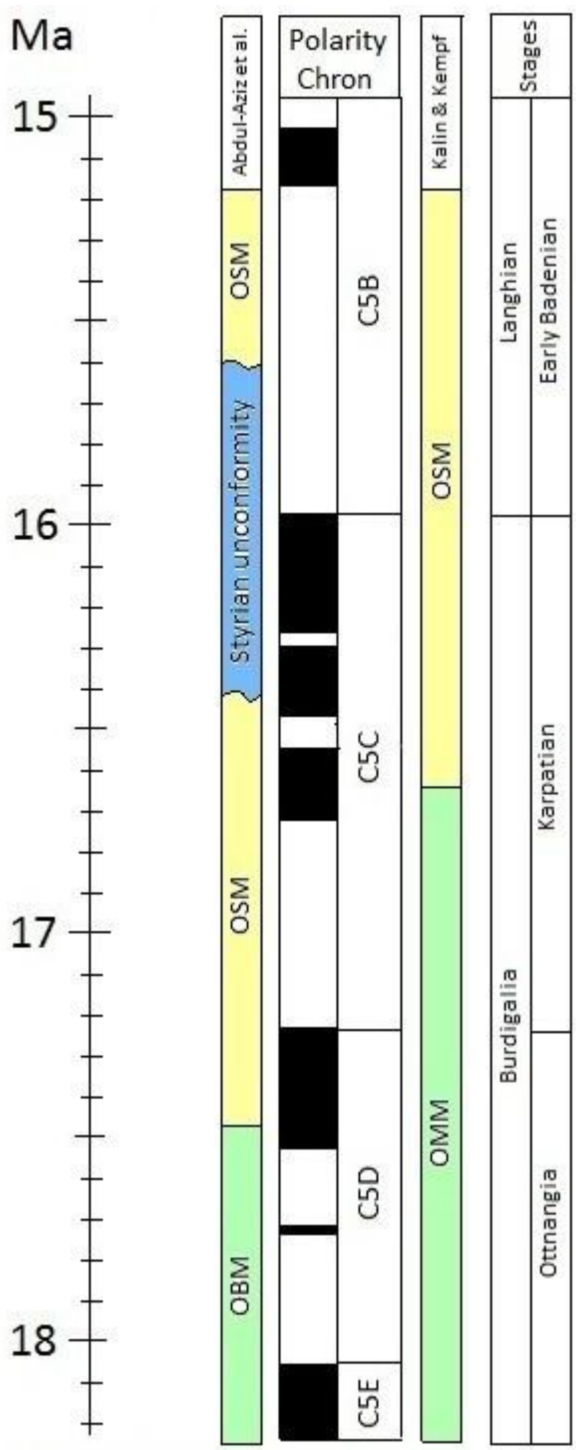

Figure 2: An schematic overview of the two major opinions (Abdul-Aziz et al., 2009) and (Kälin & Kempf, 2009). Also the different regional stages are presented based on (Piller et al., 2007)

In this thesis we will present new magnetostratigraphic data on the latest subdivisions of the Molasse. We will also include new biostratigraphical data (from German colleagues of the University of Munich), from sections and boreholes sampled both in Switzerland and Bavaria. We will discuss this new data in relation to: the definitions of the Ottnangian and Karpatian, the definition of the Molasse and recent research results over the past few years.

Sections and Boreholes:

Switzerland:

<u>Mauensee:</u>
The Mauensee section has a thickness of about 72 m with at the base a 7 m thick conglomerate layer. Overlying this layer a package of sandstones with a thickness of 32 m en poor fossil content follows. Some of the fossils that can be found are fragments of plants and marine fossils like shark teeth and bryozoans. This package is overlain by a 3.7 m thick calcareous mudstone complex containing freshwater and terrestrial mollucs. A small conglomerate layer can be recognized between the mudstone complex and a 25 m thick sequence of siliciclastic material. In this siliciclastic part of the Mauensee section some rare marine fossils can be found. The upper 6-7 m is formed by sandstones, mudstones and black marls with freshwater and terrestrial molluscs.

<u>Pfyfrütti:</u>
The Schmiedrued Pfyfrütti (Pfyfrütti) section is about 100 m thick in total. For this study however we limited ourself by focussing on the upper 35 m of the section which is correlated to the Upper Freshwater Molasse. The section mainly consists of sand- and siltstones with three intercalation of fossil rich layers. These layers are abundant in small mammal fossils which are related to the lower part of MN-5. Some of the more fossil- rich layers also provide

otolith fauna which would give extra support for correlation to biostratigraphic otolith zones.

Bavaria:

Hamler1:

The Hamler1 borehole consists out of three different formation and has a thickness of 38 m. From top to bottom these are the Kirchberg Fm, the Grimmelfingen Fm and a part of the Lower Freshwater Molasse; the latter unit is not relevant for our study. The Grimmelfingen Fm consists mainly of fine sandstones with almost no macro- or microfossils present except for some plant materials which could be recoverd. The Kirchberg Fm can be subdivided into the lower and upper Kirchberg Fm. In Hamler1 the lower Kirchberg Fm has a thickness of 6 m and consists out of sand but mainly marly lithologies with fossil assmblages of bivalve shells, gastropods, ostracods and fish otoliths. This fossil content indicates an brackish depositional environment. The upper Kirchberg Fm is about 12 m thick and has different fossil content were fossils related to brackish circumstances are rare and limnic molluscs occur.

Gempfing:

This borehole is about 48 m thick and has a 7 m thick Grimmelfingen Fm at the base of the OBM which is very similar to the Grimmelfingen Fm found in the Hamler1 borehole consisting out of carbonate poor fine sandstones. The thickness of the lower Kirchberg Fm is about 4 m and its fossil content also indicates brackish water environments during deposition. In the upper Kirchberg Fm some autochtonous well preserved foraminifers appear. The OSM part of this borehole consits mainly out of mudstones with small to none calcerous content.

Druisheim:

The Druisheim borehole has a thickness of about 84 m and consists both out of a OBM and OSM part. In the OBM the Grimmelfingen fm and the Kirchberg Fm can be recognized. The Grimmelfingen Fm shows great similarities with the Grimmelfingen Fm. in the other boreholes. However a few differences occur. In the Druisheim borehole the Grimmelfingen Fm has a thickness of about 32 m. In the lower part bivalve shells and fish teeth occur. In the uppermost 19 m which consists out of silt- and finestones an abundancy in *Rzehakia partschi* and gastropods (*Viviparus)* is found. The following lower Kirchberg Fm has a thickness of 4 m and the upper Kirchberg Fm a thickness of about 20 m. They are very similar to the Kirchberg Fm found in other boreholes. The OSM part of the borehole consist mainly out of brown grey mudstones with in some parts plant remains.

Methods:

The sections in Switzerland were sampled in the field at irregular distances. The sections are in some cases overgrown with vegetation making it impossible to sample the complete stratigraphical succession (Figure 3) which results in several gaps. Another cause for these gaps in the data is the presence of sandstones, which in general give poor or no paleomagnetic signal and are therefore not sampled. In the case of the boreholes from Bavaria, only the presence of these sandstones is responsible for the gaps in the log (Figure 4). Therefore the distances are only dependent on the lithology which resulted in better constrained data points of which most are in between 1 and 2 meters of each other. The boreholes where very dry and breakable which resulted in only small cores from the claystones. The Hof boreholes were already stored for several years and were therefore exposed for a longer time to additional magnetic influences. The samples were drilled with an electric drilling machine providing samples with a diameter of 2.5 cm. In Switzerland the machine was powered by a generator and as coolant water was used. In Hof net power was available at the facility. In the paleomagnetic laboratory of the University of Utrecht the samples (.1 samples) were prepared and cut to specimens with a length of

Figure 3: A photograph illustrating the sections in Switzerland. Which were not always accessible due to vegetation overgrowth.

Figure 4: Illustrating the boreholes stored at the environmental facility of Bavaria in Hof. These picture shows a particular sandy part with poor signals as result.

2.2 cm. This resulted into multiple specimens per sample of which the outer “b-sample part” of the core, was used later on for rockmagnetic analysis. After that the natural remanent magnetization (NRM) was determined by thermal demagnetization. Demagnetization was performed with small temperature increments of 20 – 40°C up to a maximum of 600°C, in a magnetically shielded, laboratory-built, furnace. The NRM was measured on a horizontal 2G Enterprises DC SQUID cryogenic magnetometer (noise level 3 x 10^{-12} Am^2). The measurements took place in an old fortress (location of the paleomagnetic lab in Utrecht) which reduces the magnetic influences and therefore the samples are only exposed at the earth magnetic field. The directions of the NRM components were calculated by principal component analysis and categorized on the base of the quality of the data.

In addition to thermal demagnetization of the NRM, we used all the left “b-samples” to do also some Alternating Field (AF) demagnetization to have some double checks and some valuable extra information for instance on the magnetic carriers in our sections. AF demagnetization is method which uses an oscillating field in a magnetic clean environment. The grains with coercivities below the peak AF will be orientated to that field in between the original and the “new field”. In this way the low stability grains can be filtered out. The AF procedure was done with steps of 5 – 10 mT up to 100 mT. The star symbols in (Figure 6 and 7) are the results of AF demagnetization. Furthermore we conducted Isothermal Remanent Magnetization (IRM) analysis with a DC pulse field to acquire an (IRM) in 61 steps up to 700 mT. After every step the remanence of the samples was measured on a JR5 spinner magnetometer. This analysis gives information on the magnetic carriers and their concentrations within our samples. A distinction can be made in the interpretation of these rock magnetic data based on the coercivity (which can give an idea of magnetic mineralogy) and the dispersion parameter (DP) values (indicating possible origin of the mineral). IRM-fitting curves for typical samples with different origins can be found in Figure 8.

Paleomagnetic results:

The results presented in this paper come from different sections and boreholes in Bavaria and Switzerland. In (Figure 5) we present the Zijderveld diagrams of almost every section (except Dorfbach and Haldenhof). To give a good overview on the general quality of the paleomagnetic signal we present both the TH as well as the AF diagram of the same samples. In most cases the samples from Hof showed a good signal between 100 and 380 degrees Celsius. After that the signal becomes more scattered which could be the result of the formation of new magnetic carriers. Besides a visual inspection of the Zijderveld diagrams also a calculation of the maximum angular deviation (MAD) has been done. All the MAD values higher than 15° or with unconvincing NRM directions are discarded. In the case of Switzerland a clear temperature interval in the Zijderveld diagrams, that is used the calculate the directions, cannot be recognized. In these samples the temperature intervals differ from sample to sample. In the case of the AF diagrams a similar behavior is seen for most of the Hof samples. The best signal is generally present between 10 and 70 mT. The interpretations of these Zijderveld diagrams are translated into the magnetostratigraphic columns (Figure 6 and 7).

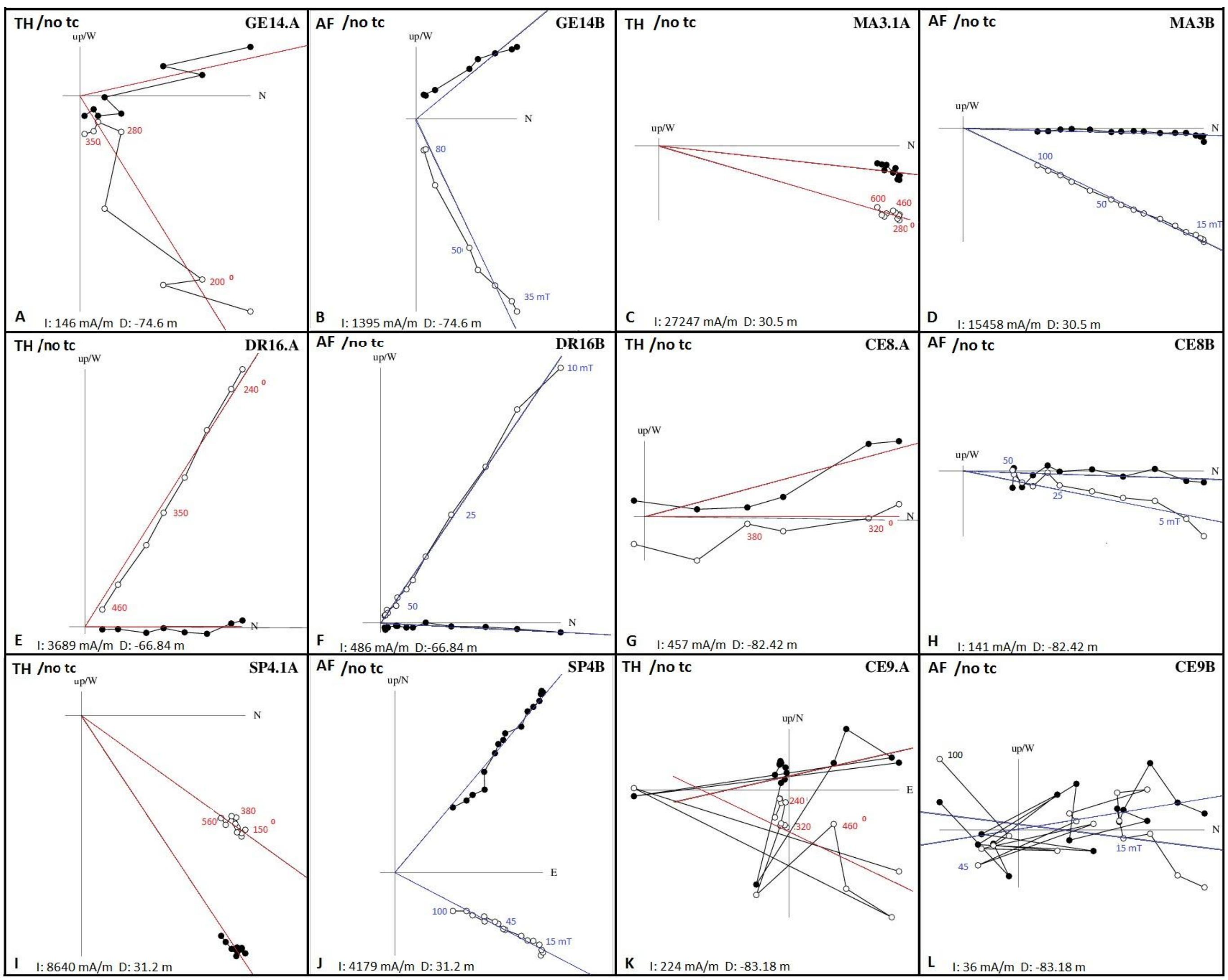

Figure 5: Thermal (th/red) and alternating field (af/blue) demagnetization diagrams of characteristic samples. Per sample: At the lower left side the intensity (I) at 280 degrees or at 35 mT is given. The depth (D) is also provided from the different samples. In the upper left corner is both the method TH/AF provided as well as the interpretation upon tectonic correction (tc). In the upper right part the sample code is provided. In the diagram itself the values along the vectors are given in °C (TH) of mT (AF).

Bavaria:

In Bavaria we sampled three boreholes taken from different location in Southern Germany and stored at the environmental facility of Bavaria. These bore holes all contain the uppermost part of the Molasse. The results of the three boreholes, Hamler1, Gempfing and Druisheim can be found in(Figure 6). This also results in crosses in the column itself. The grey color indicates samples that are not quite clear and give an intermediate signal. The quality of these samples is good. Because the samples are drilled from boreholes which have no directional marking, besides top and bottom, the declination signal cannot be used and only the inclination is presented.

<u>Gempfing:</u>

In total 22 samples from the Gempfing borehole have been analyzed. The quality of the TH and AF demagnetization are in most cases of good quality. The intensity values differ heavily from values of 200 µA/m until 9000 µA/m. The analysis of the Zijderveld diagrams of Gempfing showed in most cases three components of wich the first one is removed at about 100 °C. The second component represents the original signal of the sample and is removed around the 380 °C. After that the signal becomes more scattered which is related to the formation of secondary magnetite. After the calculation of the NRM directions the quality of the signal was determined by visual inspection of the Zijderveld diagrams and the MAD values. The white dots show TH data points of low quality and the crosses show AF data points of low quality. These data points are not taken into account in our further interpretation. The analysis of the inclination shows that in the Upper Freshwater Molasse part of this borehole three polarity reversals are observed. The first interval is of poor quality. Further down we see a large normal section followed by a larger reversed part. The density of samples is well distributed giving a good overall view.

<u>Druisheim:</u>

For the Druisheim borehole 21 samples were analysed which gave an overal good quality. The intensity values are in most cases between 100 and 800 µA/m but a few samples have a much larger value even up to 5000 µA/m. The Zijderveld diagrams show also in this borehole mostly three components of which the component between 100°C and 380°C represent the original signal. The signal at higher temperatures becomes more scattered and is interpretated as the formation of secondary magnetite. The analysis of the inclination values shows that the Upper Freshwater Molasse also, in comparison to Gempfing, contains some polarity reversals although these are less clear. A correlation with Gempfing is also hard to make on the part of the OSM/OBM boundary due to different polarities. However from a paleomagnetic point of view, not taken the different Molasse units into account, Gemphing and Druisheim are much easier to correlate. In that case two correlations are possible. First possibility is that the most upper reversed interval can be correlated with the uppermost reversed interval in Gempfing. A second possibility is the correlation of the upper most reversed interval of Druisheim with the second reversed part in Gempfing. In the lower part of this section a large part is not sampled due to the presence of sandstones.

<u>Hamler 1:</u>

In the case of the Hamler1 borehole 17 samples were analysed of which the overall quality was not as good as in the Gempfing and Druisheim borehole. The intensity values again differ very heavily with values up to 3000 µA/m. Also in this borehole the Zijderveld diagrams show the original signal between 100°C and 380°C. The analysis of the inclination values resulted in a polarity pattern that shows a reversed upper part with a normal lower part. The borehole Hamler1 does not have any Upper Freshwater Molasse deposits in its core. The Upper Brackish

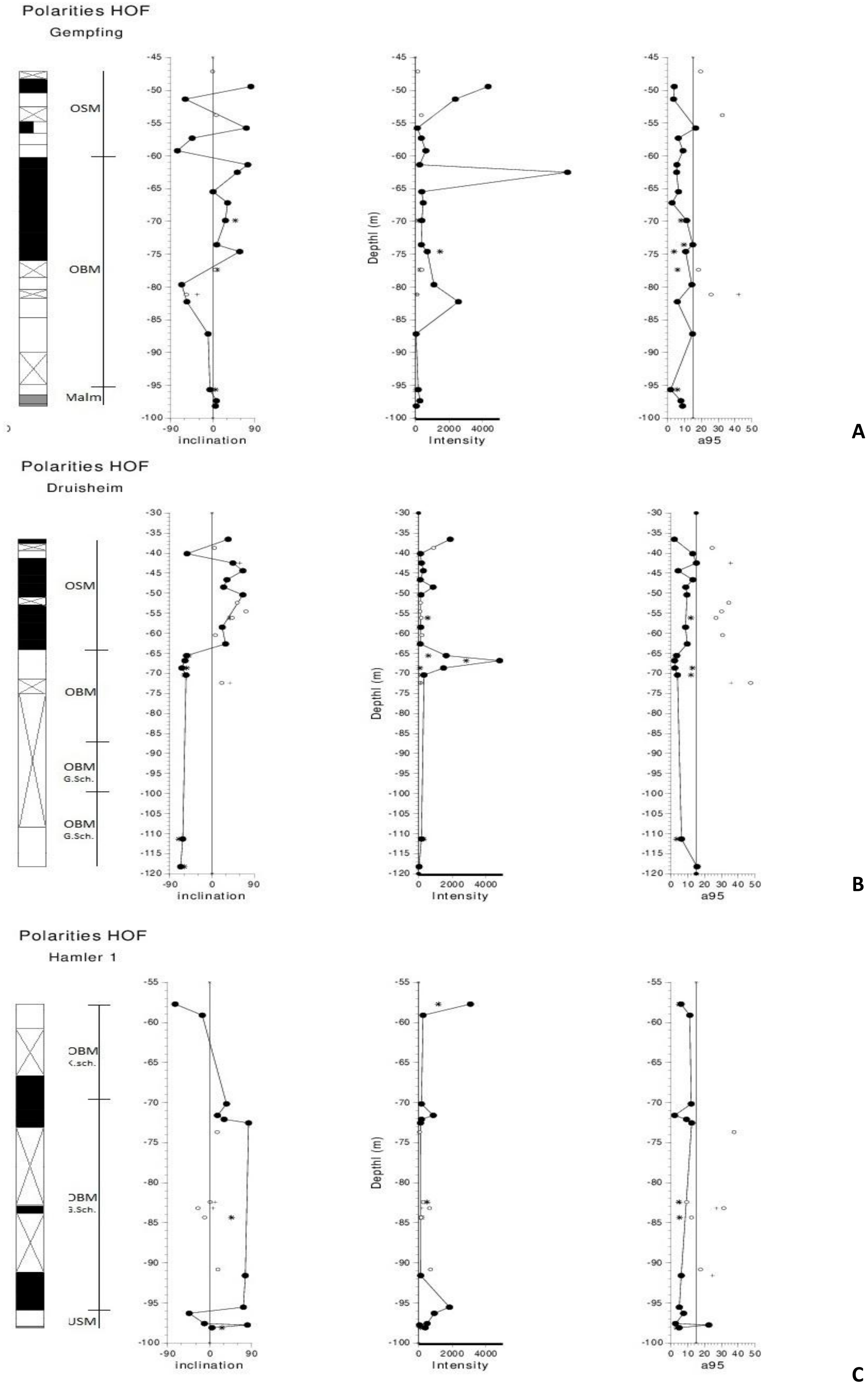

Figure 6: The paleomagnetic results of the boreholes from Hof. A) Gempfing; B) Druisheim; C) Hamler1. In the case of a cross in the column it represents a lack of data for that part of the section/borehole. In the case of a grey color the signal represents an intermediate signal. The black dots are reliable TH results, the white dots are unreliable TH results. The star symbols are reliable AF results and the crosses in the diagrams are unreliable AF results.

Molasse however seems to be for large part present although an unconformity between the OBM and the Lower Freshwater Molasse (Aquitanian) indicates at least a partly missing section.

Switzerland:

The samples from Switzerland are taken from the sections Pfyfrütti, Schmiedrued Dorfbach, Mauensee and Haldenhof. The section Dorfbach and Haldenhof only represent single layers and are therefore not seperately discussed. Dorfbach, which correlates with the Limnick horizon in the Mauensee section, gives a normal polarity signal. Haldenhof gives a reversed signal and is located at the base of the Upper Freshwater Molasse. For the interpretation of the samples from Switzerland we also used the declination (Figure 7).

<u>Mauensee:</u>

In the case of the Mauensee section 18 samples were analysed over a total thickness of 72 m. The overall quality was good. The intensity ranged from low to medium values up to values of 25000 µA/m. Compared to the samples for

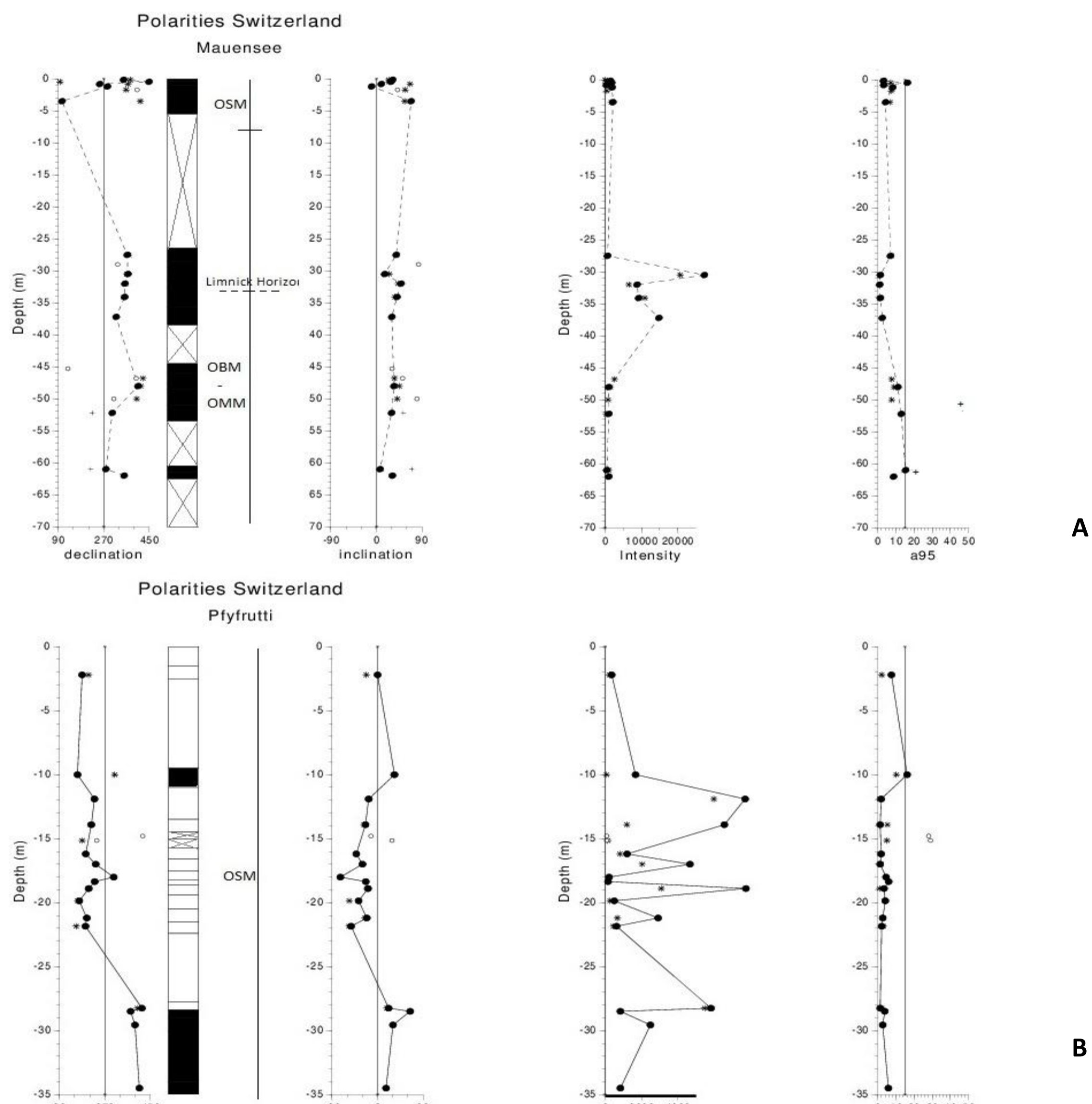

Figure 7: The paleomagnetic results of the sections in Switzerland. A) Mauensee; B) Schmiedrued Pfyfrutti. In this case also the declination results are presented. In the case of a cross in the column it represents a lack of data for that part of the section/borehole. In the case of a grey color the signal represents an intermediate signal. The black dots are reliable TH results, the white dots are unreliable TH results. The star symbols are reliable AF results and the crosses in the diagrams are unreliable AF results.

Bavaria the samples from Mauensee had a large second magnetic component ranging between 100°C and 500°C (Sometimes even as high as 600°C). The quality inspections showed almost no samples with a poor or unreliable signal. Except for two AF signals. The samples in this section are covering the entire section with an overal good density except between 5 and 25 m. The UBM is not present here because it is only found in the Southern parts of Germany. In this case the Upper Freshwater Molasse shares a boundary with the Upper Marine Molasse. Analyzing both the inclination and declination results reveal a OSM consisting of mostly normal signals. At level 44 (33m) the Limnick horizon can be found which correlates with Dorfbach and also in this section a normal polarity signal is found.

<u>Pfyfrütti:</u>

18 samples are analyzed for the Pfufrutti section which has a total length of about 35 m. The general quality of the samples was good. The intensity differs very heavily troughout the section between 100 and 6000 µA/m. Two TH samples had a much to high MAD value to be taken into account. Again in this section a single temperature interval that reveales the original signal in all the samples could not be defined properly. Pfyfrütti shows in this case more similarities with the Mauensee section. This section completely falls within the Upper Freshwater Molasse and after analyzing the declination and inclination results it can be observed that this section has at its base a normal polarity interval. The rest of the section consists of a relatively long reversed interval.

Rock magnetism

In order to investigate the magnetic mineralogy of the samples we conducted some IRM aciqusition experiments on the same samples as those that were AF demagnitized. The results of these experiments were then analysed using an IRM-fitting program from Kruiver et al. (2001) to determine the magnetic carriers, their concentrations and the origin of the carrier. However in this case the results give a good idea on the rock magnetics but are not conclusive. Therefore extra experiments like X-ray diffraction or electronic microscope observations are needed. The results of both the experiment and the interpretation can be found in (Table 1). Most samples were fitted with a small component categorized as "thermal activation". Because of their small contribute to the total magnetization it is likely to assume that these components do not represent actual minerals but they are necessary for the mathematical fitting. The different kind of fitting diagrams (Figure 8) illustrate the differences in 1 or 2 components and between detrital and a biogenic orogin.

<u>Rock magnetic results</u>

In the case of Hamler1 we find that the composition of the samples is consistent through the entire section with a dominant lower coercivity component and a higher coercivity component, which corresponds to presence of magnetite and hematite, respectively (Kruiver et al., 2001) (Egli, 2004). The DP values are between 0.3 and 0.4, which indicates for a detrital origin for both components and is consistent with the environment of these Molasse sediments. The Druisheim section also shows a coercivity distribution similar as the Hamler1 section. However one sample (DR20) seems to have a rather small DP (0.2) which probably indicates a biogenic origin (Kruiver and Passier, 2001). For the Gempfing section we find mostly only magnetite as carrier. Only the sample Ge14 seems to have a small percentage of hematite. Furthermore the samples Ge14 and Ge20 have low DP values (0.17 and 0.2 respectively) indicating a biogenic origin. The main difference between these two however is the important role this magnetite plays in Ge14 (79.41%) whereas the unknown mineral in Ge20 only accounts for (12.3%).

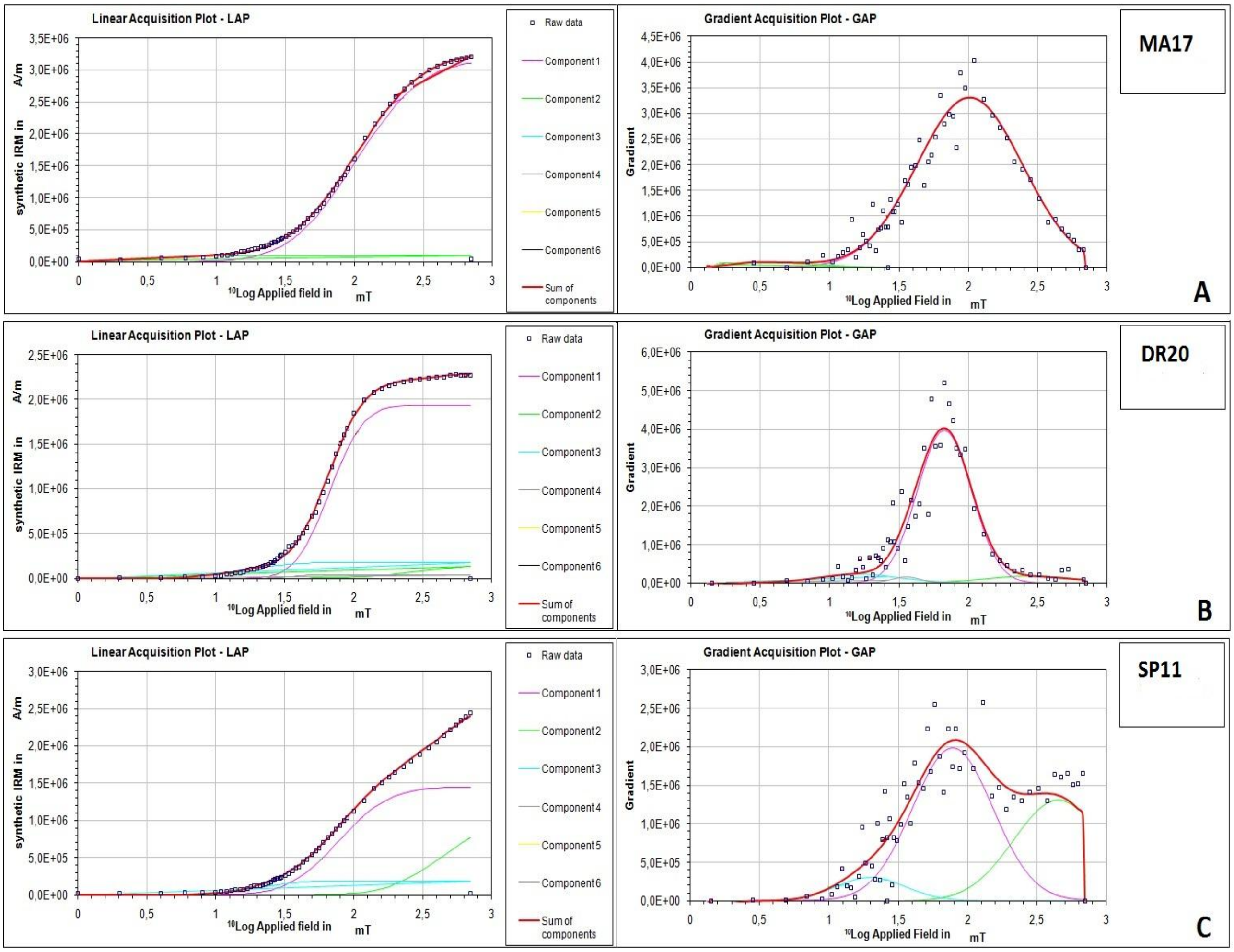

Figure 8: A selection of 3 IRM fitting curves showing different results. A) Is a curve that represents a major component of detrital magnetite. B) Is a curve with a steeper maximum and thus a lower DP. This is often the result of biogenic magnetite. C) Is a curve that consists of two component which in this case probably are magnetite and hematite.

In the Mauensee section most samples are presumably magnetite with a detrital origin and in some cases also with contribution from hematite. Sample Ma1 seems to have a biogenic origin with a small DP value (0.21). Again a large difference in contribution between magnetite and hematite can be observed. The Pfyfrütti section seems to have a similar origin as the rest of the sections described above with mostly detrital magnetite and, in smaller amount, detrital hematite. However in this case two samples stand out. Sp6 which has a DP of 0.24 and it is out of the scope of this thesis what its origin is. It could be biogenic but also detrital. The second sample is Sp16 which has a high DP value of 0.51. But this sample can also be fitted with 2 components (magnetite and hematite). To summerize the results of the rock magnetic experiments we can say that in all sections detrital magnetite and, less abundant, detrital hematite are the carriers of our magnetic signal. These carriers are reliable and give in general good signals.There are also no differences in compositions found between normal and reversed polarity samples which indicates that the normal components are likely to be of the same (primary) origin as the reversed components.

Sample	Contribution (%)	SIRM	$B_{1/2}$	DP	Thermal activation	Detrital	Biogenic	Other	Mineral
CE1	96,77	3,E+06	25,7	0,36		x			Magnetite
	3,23	1,E+05	50,12	0,4	x				-
CE8	89,29	2,E+06	64,57	0,34		x			Magnetite
	8,93	2,E+05	501,2	0,4		x			Hematite
	1,79	4,E+04	12,59	0,4	x				-
CE9	95,28	1,E+06	72,44	0,35		x			Magnetite
	4,72	6,E+04	12,59	0,37	x				-
CE10	94,53	2,E+06	66,07	0,39		x			Magnetite
	2,99	6,E+04	12,59	0,37	x				-
	2,49	5,E+04	562,3	0,1	x				-
CE16	84,64	8,E+05	53,7	0,29		x			Magnetite
	11,49	1,E+05	316,2	0,4		x			Hematite
	3,87	4,E+04	2,512	0,4	x				-
CE17	36,25	6,E+05	46,77	0,3		x			Magnetite
	60,63	1,E+06	371,5	0,3		x			Hematite
	3,13	5,E+04	5,012	0,4	x				-
DR4	74,24	3,E+06	60,26	0,36		x			Magnetite
	25,11	1,E+06	501,2	0,4		x			Hematite
	0,66	3,E+04	6,31	0,4	x				-
DR11	71,06	3,E+06	53,7	0,31		x			Magnetite
	23,26	9,E+05	316,2	0,37		x			Hematite
	5,68	2,E+05	15,85	0,4	x				-
DR15	86,78	1,E+06	26,3	0,31		x			Magnetite
	6,54	1,E+05	199,5	0,37	x				-
	6,68	1,E+05	10	0,3	x				-
DR16	85,88	6,E+06	33,11	0,3		x			Magnetite
	3,20	2,E+05	10,47	0,35	x				-
	10,92	8,E+05	63,1	0,4		x			Magnetite
DR17	92,05	4,E+05	48,98	0,34		x			Magnetite
	5,68	3,E+04	631	0,7	x				Hematite
	2,27	1,E+04	12,59	0,4	x				-
DR18	77,24	2,E+06	60,26	0,24		x			Magnetite
	14,41	3,E+05	199,5	0,35		x			Hematite
	8,35	2,E+05	15,85	0,4	x				-
DR19	97,85	7,E+05	74,13	0,44		x			Magnetite
	2,15	2,E+04	11,22	0,37	x				-
DR20	85,65	2,E+06	66,07	0,2			x		Magnetite
	6,52	2,E+05	281,8	0,33	x				Hematite
	7,83	2,E+05	15,85	0,3	x				-
DR21	86,58	6,E+05	63,1	0,3		x			Magnetite
	6,71	5,E+04	12,59	0,4	x				-
	6,71	5,E+04	316,2	0,5	x				-
GE12	91,11	1,E+06	67,61	0,39		x			Magnetite
	5,19	7,E+04	501,2	0,3	x				-
	3,70	5,E+04	10	0,4	x				-
GE13	94,41	2,E+06	56,23	0,35		x			Magnetite
	5,59	9,E+04	12,59	0,4	x				-
GE14	79,41	3,E+07	81,28	0,17			x		Magnetite
	5,88	2,E+06	31,62	0,4	x				-
	14,71	5,E+06	631	0,45		x			Hematite
GE15	97,11	2,E+06	67,61	0,39		x			Magnetite
	2,89	5,E+04	5,623	0,37	x				-
GE17	90,35	1,E+06	58,88	0,33		x			Magnetite
	7,89	9,E+04	10	0,4	x				-
	1,75	2,E+04	100	0,1	x				-
GE20	87,70	1,E+05	60,26	0,35		x			Magnetite
	12,30	2,E+04	11,22	0,2	x				-
MA1	47,10	1,E+06	61,66	0,21			x		Magnetite
	34,42	1,E+06	398,1	0,28		x			Hematite
	18,48	5,E+05	15,85	0,3	x				-
MA3	85,33	3,E+06	67,61	0,4		x			Magnetite
	14,67	6,E+05	631	0,22				x	Hematite
MA4	100,00	4,E+06	70,79	0,45		x			Magnetite
	0,00	2,E+00	467,7	0,37	x				-
MA5	100,00	4,E+06	72,44	0,44		x			Magnetite
	0,00	2,E+00	467,7	0,37	x				-
MA8	87,27	5,E+06	53,7	0,4		x			Magnetite
	12,73	7,E+05	125,9	0,4	x				-
MA9	90,76	1,E+07	36,31	0,36		x			Magnetite
	9,24	1,E+06	707,9	0,35	x				-
MA10	89,01	4,E+06	41,69	0,37		x			Magnetite
	10,99	5,E+05	707,9	0,23				x	Hematite
MA11	85,37	4,E+06	39,81	0,38		x			Magnetite
	14,63	6,E+05	660,7	0,25		x			Hematite
MA12	86,72	5,E+06	48,98	0,38		x			Magnetite
	0,00	2,E+00	467,7	0,37	x				-
	13,28	7,E+05	676,1	0,25		x			Hematite
MA14	89,86	1,E+06	79,43	0,36		x			Magnetite
	10,14	1,E+05	3,981	0,35		x			-
MA16	90,76	1,E+06	70,79	0,35		x			Magnetite
	3,36	4,E+04	15,85	0,4	x				-
	5,88	7,E+04	660,7	0,2	x				-
MA17	96,92	3,E+06	100	0,38		x			Magnetite
	3,08	1,E+05	3,162	0,37	x				-
MA18	98,84	3,E+06	100	0,45		x			Magnetite
	1,16	3,E+04	3,162	0,37	x				-
MA19	98,59	4,E+06	83,18	0,47		x			Magnetite
	1,41	5,E+04	3,162	0,37	x				-
SP5	95,63	2,E+06	166	0,5		x			Magnetite
	4,37	8,E+04	12,59	0,4	x				-
SP6	42,71	9,E+05	64,57	0,24			x		Magnetite
	51,26	1,E+06	398,1	0,35		x			Hematite
	6,03	1,E+05	15,85	0,3	x				-
SP7	45,49	5,E+05	79,43	0,28		x			Magnetite
	45,49	5,E+05	501,2	0,26		x			Hematite
	9,01	1,E+05	25,12	0,4	x				-
SP8	44,30	1,E+06	74,13	0,27		x			Magnetite
	46,41	1,E+06	380,2	0,29		x			Hematite
	9,28	2,E+05	22,39	0,2	x				-
SP11	53,53	1,E+06	77,62	0,29		x			Magnetite
	39,03	1,E+06	446,7	0,32		x			Hematite
	7,43	2,E+05	19,95	0,25	x				-
SP12	31,80	4,E+05	66,07	0,29		x			Magnetite
	61,92	7,E+05	363,1	0,33		x			Hematite
	6,28	8,E+04	19,95	0,4	x				-
SP13	24,24	4,E+05	81,28	0,37		x			Magnetite
	1,82	3,E+04	4,467	0,37	x				-
	73,94	1,E+06	1000	0,44		x			Goethite
SP15	32,18	1,E+06	67,61	0,39		x			Magnetite
	66,49	3,E+06	436,5	0,42		x			Hematite
	1,33	5,E+04	10	0,1	x				-
SP16	100,00	6,E+06	173,8	0,51		x			Magnetite
	0,00	2,E+00	467,7	0,37		x			Hematite
SP17	97,70	4,E+05	85,11	0,44		x			Magnetite
	2,30	1,E+04	12,59	0,5	x				-
SP18	42,66	6,E+05	69,18	0,38		x			Magnetite
	49,65	7,E+05	384,6	0,33		x			Hematite
	7,69	1,E+05	19,95	0,4	x				-

Table 1: This table lists all the samples that have been used for IRM fitting and its results. The origin can be found in the dark purple columns. The blue column presents an possible mineral interpretation.

Discussion:

New paleomagnetic data

To improve the time constraint for the Upper Molasse a new research component was conducted by the paleomagnetic laboratory of the University of Utrecht in collaboration with the Ludwig Maximillian University of Munich and the Swiss geological survey. This research was done on several sections in Switzerland (e.g. Schmiedrued and Mauensee) and on several boreholes from Bavaria (Southern Germany) which are stored in a storage facility of the environmental department of Bavaria in the city Hof. In this discussion we will propose a correlation between the different section and in relation to the ATNTS04 (Lourens et al., 2004). Furthermore we will investigate the consequences of our proposed correlation to the definitions of the Molasse and the regional stratigraphic periods.

<u>Hof:</u>

The results of the boreholes from Hof are presented in (Figure 6) and show a subdivision within the different units of the Molasse. These boundaries are established by sedimentary and biostratigraphical research done by Bettina Reichenbacher et al. An interpretation based on the used boundaries between the different parts of the Molasse is difficult. De boundary between OSM and OBM in the Gempfing and Druisheim sections does not correlate good and shows different polarity switches at its boundaries. Another problem with a correlation only based on biostratigraphy is that a good correlation between the different parts that can be recognized within the OBM, is also not possible. Because a lack of samples and a hiatus at the boundary between OBM and OMM in the lower parts of the sections. Furthermore the lack of samples in the lower part of the Druisheim column and the occurrence of bad samples in the Hamler1 column also do not improve the correlation. However the upper part of the OBM Kirchberg Fm. could be in agreement with the OBM part in the Druisheim section although a part of the column is not known and the OBM Kirchberg Fm. is not specified in the Druisheim column.

If we would assume that the different boundaries of the Molasse units are a little bit more flexible, which is a reliable assumption because the boundaries are only based on biostratigraphy and have changed multiple times and even recently, we could use only the magnetostratigraphic pattern for the correlation of the different columns. In this case a correlation between Gempfing and Druisheim could be well established by correlating the upper reversed signal of Druisheim with the uppermost reversed signal of Gempfing. The following pattern can then be correlated in a same manner although the last normal polarity in Druisheim is not well known due to a lack of data. A second possibility to correlate both columns is to correlate the uppermost reversed signal in the Druisheim section with the second reversed signal in the Gemphing section. This would also be in good agreement with the biostratigraphical data of Reichenbacher et al. (recent correspondence). We are of the opinion that the second correlation is more likely because it would mean that the new paleomagnetic data is better in agreement with other data then if we would apply the first correlation. The Hamler1 section is a little bit harder to correlate with the other boreholes due to a huge gap in reliable signals. However using the OSM/OBM boundary the upper reversed part would then be correlated to the second reversed part Druisheim and the lower reversed part in Gempfing.

<u>Switzerland:</u>

For the correlation between the different sections of Switzerland only Mauensee and Pfyfrütti are available. As already mentioned the Dorfbach and the Haldenhof section are too small. However from a biostratigraphic point of view they present some interesting information. The Dorfbach section is also containing the Limnick horizon which can be found also in the Mauensee at stratigraphic level 44. The Haldenhof section is according to Reichenbacher et al. (recent correspondence) situated at the base of the OSM and gives a clear reversed signal. Other biostratigraphic correlations based on the Molasse unit's boundaries are not possible because the position of Pfyfrütti in relation to Mauensee is not clear.

If we now would combine the sections of Hof and Switzerland we can provide, from a paleomagnetic perspective and partly based on the subdivision of the Molasse within our sections, a combined correlation where the lower part of Mauensee and Dorfbach are place at the lower normal part of Gempfing and the middle part of Druisheim. The Haldenhof section would be correlated to the second reversed part in Gempfing and the upper reversed part in Druisheim. Only the exact location of the Pfyfrütti section is hard to define, which makes a correlation with the other sections impossible.

Correlation to ATNTS04.

After establishing a correlation between the different sections we can now try to find a correlation with the ATNTS04 (Lourens et al., 2004). Based on the found pattern we made two different correlations. The first one (A, Figure 9) represents the correlation based on the new paleomagnetic data presented above. This correlation shows a lot of similarity with the Kälin & Kempf (2009) correlation. The second correlation (B, Figure 10) is based on the opinions of the group surrounding Abdul-Aziz, (2009) opinion. In this way a comparison is possible.

Correlation A places the distinct pattern of the Gempfing section in the Chron C5C. The two small reversed part in the time scale correlate nicely to the reversed parts in Gempfing and Druisheim. Also the thicknesses in both boreholes of the different parts are a same proportion as in the time scale itself. The upper normal part of the Hamler1 section would then be correlated to the uppermost normal part of the chron C5D. As a result of this correlation the OSM – OBM/OMM boundary would be placed at around 16.3 Ma (+/- 0.1 Ma) which is in good agreement with the established boundary by Kälin & Kempf (2009). This would also mean that the diachronous nature of the Molasse is much smaller than expected in previous studies. The Pfyfrütti section, which was placed within the OSM but could not be correlated to any other section, is in correlation A placed at the boundary between chron C5C and C5B. Because of its large reversed part it could not be correlated to any other reversed parts within the C5C chron. The other section comes from Abdul-Aziz et al. (2009) where it was placed as can be seen in (Figure 10). We have put these in our correlation to illustrate that our correlation could also be in agreement with the data found by Abdul-Aziz (2009).

Correlation B is based on the correlation of Abdul-Aziz (2009) and recent discussions with Reichenbacher et al. It correlates the second reversed part of Gempfing and Druisheim to the lower reversed part of chron C5C. The lower normal part in the Hamler1 borehole would then be correlated to the second normal part in chron C5C. The Mauensee would be correlated to the upper normal part in chron C5D and Pfyfrütti would be placed in the upper reversed part of chron C5C. This correlation has some effects that are difficult to explain making it unlikely from a magnetostratigraphic point of view. First of all the correlation of the second reversed part in Gempfing would mean a very large difference in sedimentation rate for the reversed section in relation to the normal parts that are present below and above in the Gempfing column. Assuming that only small differences in sedimentation rate could occur, the presented thickness ratios do not match the ratios in the time scale. This is also applicable for the Hamler1 and Druisheim column. The Mauensee section would be, based on fossil

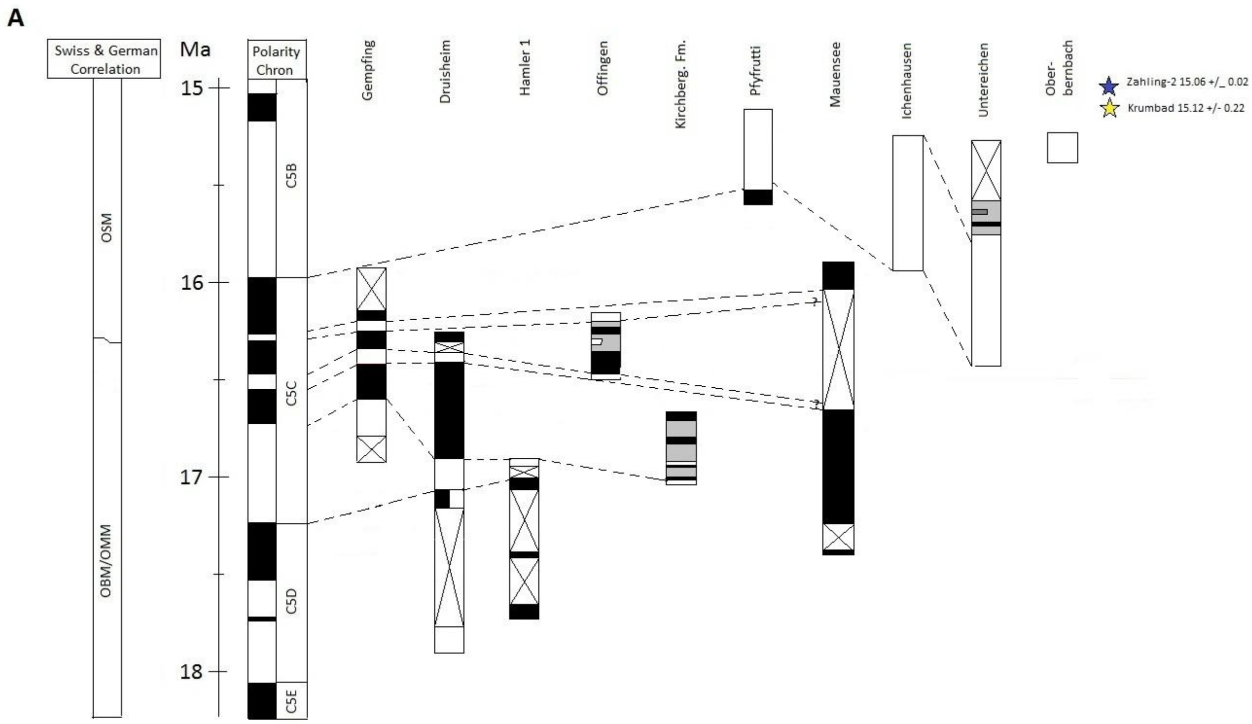

Figure 9: Correlation A is based on new paleomagnetic data and paleomagnetic data from Abdul-Aziz et al. (2009). This correlation is also in agreement with (Kälin & Kempf, 2009). It places the OSM-OBM/OMM boundary at 16.3 Ma (+/- 0.1 Myr)

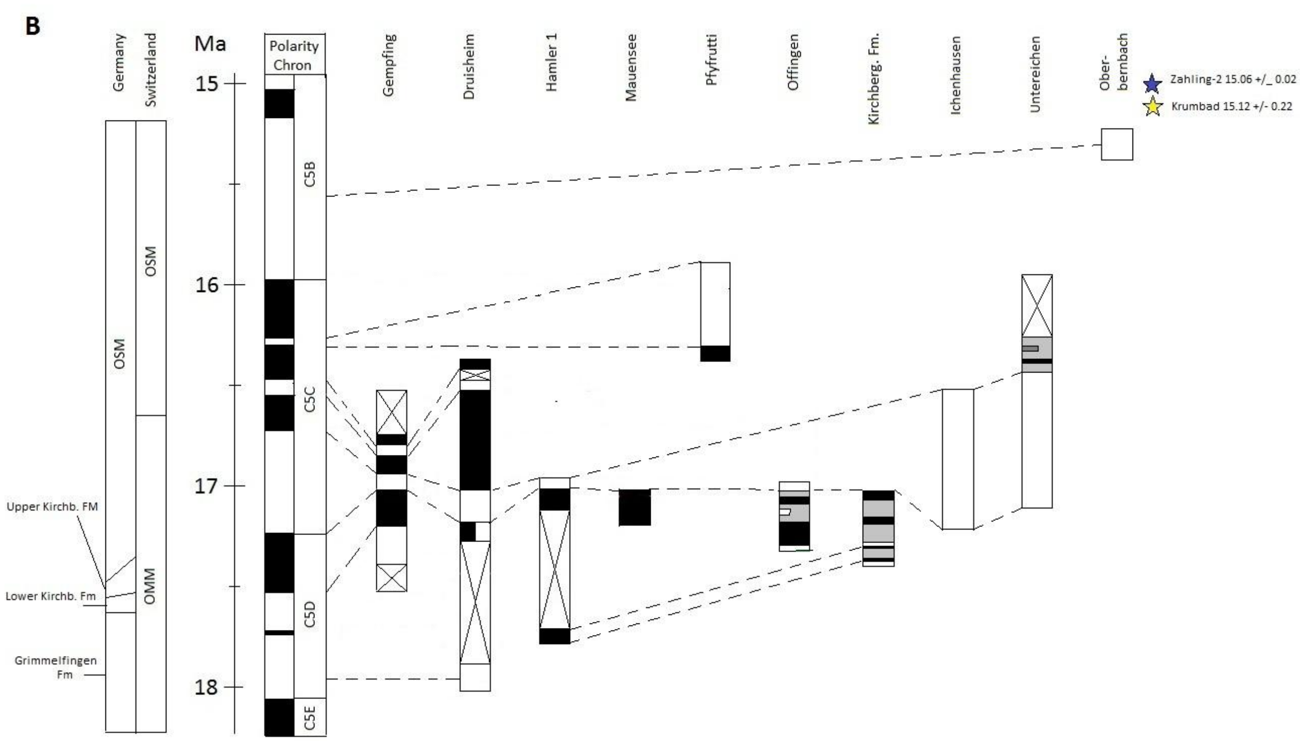

Figure 10: Correlation B is based on Abdul-Aziz et al., (2009). It places the OSM-OBM/OMM boundary in Germany and Switzerland at different ages. This correlation is presented to get a good comparison between the different opinions.

content, placed at the same age as the Offingen section from Abdul-Aziz et al. (2009). However the Mauensee section is a section from Switzerland which according to Kälin & Kempf (2009) has its boundary between OSM and OMM somewhere around 16.6 Ma. According to Reichenbacher et al. (recent correspondence) the boundary between OSM and OBM/OMM is present in the upper part of the Mauensee section. So its position in relation to the ATNTS04 (Lourens et al., 2004) could not combine the fact that it is similar to Offingen but also placed in the C5C chron. The Pfyfrütti section is in this correlation placed at the highest reversed part in the C5C chron. Although the section is incomplete the suggestion that such a large reversed part should fit into that small reversed part of the time scale would also imply strange sedimentation rate differences.

Furthermore Abdul-Aziz (2009) relates the age correlation by assuming an unconformity of about 0.8 Myr. This Styrian unconformity (Figure 2) is poorly described and constrained in time. It is placed from 15.6 Ma to 16.4 Ma and would prohibit a correlation to the upper part of chron C5C. The main question is how reliable is the assumption of an unconformity this large? It would indicate a sedimentation stop for 800 kyr in an area that is under constant tectonic stresses and which has an open connection with other oceans. This combined with a poorly described and constrained description of this unconformity led us to the conclusion that although an unconformity might be present it cannot be as large as presented in (Figure 2). Not taking into account this unconformity would have as result that the correlation by Abdul-Aziz et al. (2009) would be younger and would be in agreement with our new correlation and that of Kälin & Kempf (2009).

Besides the problems with the thickness ratio's in the different columns, the strange correlation of Mauensee and Pfyfrütti and the large age difference between Bavaria and Switzerland on the OSM – OBM/OMM boundary, new radiometric data (Kuiper et al., 2008) shows a shift in the absolute age in the order of 0.5 Myr (Krumbad) and 1.2 Myr (Zahling-2) younger. These data supported at first the claim from Abdul-Aziz et al. (2009) for their correlation but would now be in agreement with correlation A. The next question would be what the implications are for the Molasse assuming correlation A. To provide an answer on these questions a more detailed survey is needed of the definition of the different units of the Molasse.

What is the exact definition and constraints of the Molasse?

According to Reichenbacher et al. (2005) the Molasse basin is the main part of the Northern Alpine Foreland Basin (NAFB) and exists of marine and non marine deposits which are mostly derived from either the Alps in the south or the Bohemian massif in the north. The succession of the Molasse can be divided into two transgressive-regressive megacycles subdividing the Lower Molasse and the Upper Molasse. The entire Molasse sequences would have an age from Kiscellian to Pannonian (32 – 6 Ma). However the dating of the different parts of the Molasse and the basin wide correlation on a chronostratigraphic level are difficult and not yet well constrained. Berger et al. (1996) and Piller et al. (2007) place the Upper Freswater Molasse represented by fluvial-lacustrine environments in the upper part of the Ottnangian. They relate the Molasse sequence to the "two fold stage with normal marine development in its lower part and a predominance of restricted marine to freshwater environments in its upper part" (Piller et al., 2007). Pipperr (2011) says about the Molasse basin that it ranges from Eocene/ early Oligocene to the late Miocene and places the Upper Marine Molasse within the Eggenburgian and the Ottnangian. The main focus of that paper is the observation that on regional scale the facies of the OMM can differ very extremely. It tries to give an explanation that gives a better basin wide facies correlation.

However on the topic of time constraining the OMM it presents only the arguments that already have been discussed above and uses Doppler et al. (2005) to support the statements on the age of the different parts of the Molasse. Another argument that is used by Heckeberg et al. (2010) are the benthic foraminifera within the OMM which would indicate that the OMM is situated in the Eggenburgian and Ottnangian (Hagn, 1961) (Wenger, 1987) (Pipperr et al., 2009) (Pipperr et al., 2010).
The last article found as a support of the time constraints used by other authors on the Molasse sequence in Doppler et al. (2005). In that article, the same time intervals were used for the Lower and Upper Molasse as in Pipperr (2011). The support of these statements was a relation with the sea level movements but not with exact cycles or events.

The interesting aspect of the above mentioned statements is that the Molasse and its different sub domains are not well constrained in time. All authors acknowledge the different parts of the Molasse from Lower Marine, Lower Brackish water, Lower Freshwater to Upper Marine, Upper Brackish and Upper Freshwater Molasse but the time constraint is an interplay between Molasse and the time stages.
Because of the dependence of the Molasse definition on the definitions of the different time stages, a close look to those definitions is needed to get a better grip on consequences of correlation A.

What are the Karpatian and the Ottnangian?

<u>The Ottnangian</u>

The Ottnangian, a stage of the Central Paratethys, is defined near the village of Ottnang in Austria (Figure 11). The base and top cannot be defined very precisely in this section due to problems with unconformities at the base and erosion of the top (Piller et al., 2007). In the more central regions of the basin a continuous sediment package is reported including the lower part of the Ottnangian whereas the upper part is found in the more eastern parts, in north Hungary and Slovakia. The key arguments of the definition of the Ottnangian come from biostratigraphic data and relative sea level change data. The base of the Ottnangian is correlated with the TB 2.1 cycle (Haq et al., 1988) (Figure 12) of sea level changes. This is also confirmed by Kovac et al. (2004) who correlate it to the third order sea level change known as Bur 3 (Hardenbol et al., 1998). The other argument is a result of biostratigraphic research which makes a link between the last occurrence (LO) of the *Catapsydrax* and the LAD event of the *C.unicavus/C. dissimilis* which defines the boundary between M3 and M4 (Berggren et al., 1995). Steininger et al. (1976) and Rögl et al. (2003) stated that the NN3 and NN4 nannoplankton zones are also represented in the Ottnangian.

Considering these arguments, in relation to the definitions of the Ottnangian, results in several unresolved questions. On the side of the relative sea level changes the first question is: 'How reliable is the presented data from the Paratethys?' During this time in the Miocene the Molasse basin has a connection with the open sea but still has the characteristics of a basin. This means that the relation between global sea level changes and the effect on the relative sea level changes in the basin is complicated and is hard to find a good correlation. One could wonder if this argument is as solid as it has been presented. Also because it is a 3rd order sea level change in a region which is under continuous tectonic stress. The effects of tectonic activity during that time in this region are not completely clear and is neglected in the definition of the Ottnangian although it probably plays a major role and can be of great influence on the sea level movements. On the side of the biostratigraphic data also some presented arguments are not completely solid. A first possible weakness is the link between *Catapsydrax* and the LAD event of the *C.unicavus/C. dissimilis.* How strong is this link?

Figure 11: “Geographic distribution of all Miocene strattype localities of Central Paratethys stages” (Piller et al., 2007)

And can it be correlated everywhere in a similar way? Is there accounted for the possibility of reworking of the fossils and what kind of effect would that have on the time constrains? The fact that the NN3 and NN4 zones can be found within the Ottnangian does not constrain the Ottnangian itself either, also because the NN4 zone can also be found in the Karpatian and Badenian. On the side of biostratigraphic data the definition of the base is a linkage between two different foraminifer’s species and an event of one of those species. The upper boundary is somewhere within the NN4 zone which itself covers 3 Myr. What makes it even harder to constrain the Ottnangian is that according to Piller et al. (2007): “Biostratigraphic correlation outside the Paratethys is very limited”.

<u>The Karpatian:</u>

The history of the Karpatian (which is a Central Paratethys stage) stage goes back to 1959 when it was erected by Cicha and Tejkal. The Karpatian was defined in 1967 by Cicha et al. It has rich molluscan fauna which is an important proxy in establishing a good biostratigraphic frame. The base of the Karpatian is formed by an unconformity which resulted in a “Provisional definition of the Karpatian” (Cicha and Rögl, 2003). A good continuous sediment package from the Ottnangian to the Karpatian is not found although it “is expected only in the deeper parts of the Central Paratethys basin particularly in the Pannoniam realm” (Piller et al., 2007) (Cicha and Rögl, 2003). The original reason for establishing the Karpatian stage was due to the presence of new fauna from the Mediterranean. Some new mollucs species occur for the first time at the base of the Karpatian. The species continue also into the Badenian, making it hard to differentiate between the two stages and to constrain the top of the Karpatian (Harzhauser et al., 2002) (Harzhauser et al., 2003).

The biostratigraphic definition of the Karpatian comes from the FAD of *Uvigerina graciliformis* (Papp et al., 1971) and other related co-occurrences of the *Uvigerinids*. The most important event on the side of planktonic

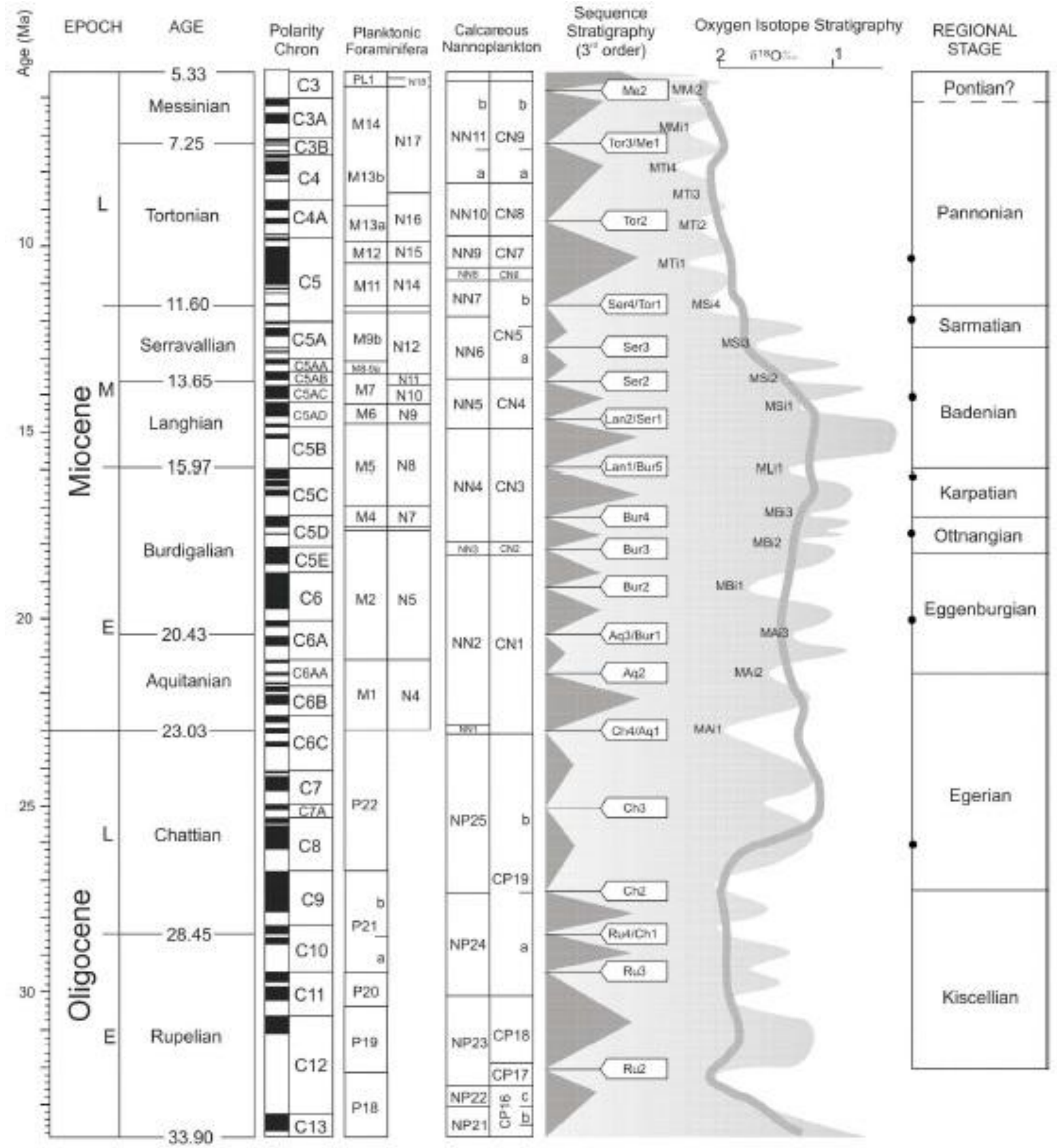

Figure 9: A Oligocene – Miocene Geochronology according to (Lourens et al., 2004). With paleomagnetic chrons, biozonation of foraminifers and nannoplankton, sea level curve (Hardenbol et al., 1998), oxygen isotope stratigraphy (Abreu Haddad, 1998), correlated with the regional chronstratigraphy of the Central Paratethys. (Piller et al., 2007)

foraminifer's data is the FOD of the *Globigerinoides bisphericus* which is correlated to the upper Karpatian. The top of the Karpatian and therefore the boundary between Karpatian and Badenian is defined as the boundary between the Burdigalian and Langhian due to the first appearance of the planktonic foraminifera genus *Preaorbulina* (Brobohaty et al., 2003). This in spite of the fact that the Langhian still is not officially defined. According to Rögl et al. (2003) the lower Karpatian and the Ottnangian show some similarities in the water masses like for instance cool temperatures. Regarding the sequences found in the Karpatian we see at the base terrestrial environments like fluvial, alluvial and deltaic deposits which rapidly develop into more marine conditions (Piller et al., 2007). A similar development as in the Ottnangian it seems. “The Karpatian stage is nowadays consistently considered to be the time-equivalent of the latest Burdigalian“(Piller et al., 2007). This is after a long history known for its misinterpretations and correlations. However the base of the Karpatian can still not be determined exactly with the biostratigraphic data that is available. One thing that can biostratigraphically be said is that the entire Karpatian lies within the nannoplankton zone NN4 which covers 3 Myr and is also found in the lower Badenian. Another biostratigraphic argument for the correlation of the Karpatian is the occurrence of *Globigerinoides bisphericus* in the upper part which also related to the Burdigalian and the foraminifera zone M4b (Berggren et al., 1995). Some of the same questions which are raised for the Ottnangian also apply on this support of the constraints of the Karpatian. Considering for instance the effects of reworking would place the Karpatian in a younger segment of the Miocene within the NN4 zone.

Another correlation, based on biostratigraphic data, is applied on the Karpatian in a similar way as it was used for the Ottnangian namely the sea level curves. Again a 3rd order sea level event. The base of the Karpatian, which is an unconformity, is related to the sea level cycle TB 2.2 of (Haq et al., 1988) and the Bur 4 of (Hardenbol et al., 1998). The top of the Karpatian is correlated with the Burdigalian/Langhian boundary which is also characterized by a drop in sea level which is traceable throughout the entire Central Paratethys. This argument is supported by the fact that nowhere in the Central Paratethys a continuous sedimentation is found from the Karpatian into the Badenian. “The top of the Lower Miocene in the Paratethys basins is marked by erosional surfaces or by an angular discordance between the Lower and Middle Miocene strata, frequently called the “Styrian unconformity”(Stille et al., 1924)(Latal and Piller et al., 2003)”(Piller et al., 2007). As a result the base of the Karpatian can be correlated to sea level changes but the top is still hard to define. Again for this ‘sea level change arguments’ still some questions on the reliability are unresolved just like for the Ottnangian.

Conclusion:

According to the new paleomagnetic data, retrieved from sections and boreholes in Switzerland and Bavaria, a correlation pattern has been found that correlates the OSM-OBM/OMM boundary to an age of 16.3 Ma (+/-0.1 Myr). The quality of the signal and the magnetic carriers has proven to be consistent and of a good quality. This correlation is almost exactly the same as that presented in Kälin & Kempf (2009). The data presented by Abdul-Aziz (2009) can also be correlated to the same magnetostratigraphic pattern leading to the conclusion that from a paleomagnetic point of view all data is in agreement. This correlation is also supported by new radiometric data which shows a shift in the younger direction of magnitude of 0.5 and 1.2 Myr. The described Styrian unconformity is according to us not well enough constrained and would also be quite impossible in the geological setting of that time and place. The definitions of the Molasse and of the Karpatian and Ottnangian where then carefully examined to get a better understanding of the consequences of this correlation. This showed that the definition of some parts of the Molasse are combined with the definitions of the several Central Paratethys regional stages. As a result of these close relations between one another a correlation in a younger direction would mean a shift in the boundaries of those regional stages. In this case it would mean that the boundary between Ottnangian and Karpatian would shift several hundred-thousand years in a younger direction. According to the definitions of both the upper part of the Ottnangian and the lower part of the Karpatian, the exact boundary has never been observed. Establishing a new boundary would therefore not be very controversial.

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