

Lectures in Paleomagnetism, 2005  
by Lisa Tauxe

Citation:  
<http://earthref.org/MAGIC/books/Tauxe/2005/>

June 16, 2005



# Chapter 15

## The GPTS and magnetostratigraphy

### Suggested Reading

For background:

Chapter 9: Butler (1992)

Chapters 4 & 5: McElhinny and McFadden (2000)

To learn more:

Opdyke and Channell (1996)

Oreskes (2001)

Glen (1982)

<http://www.stratigraphy.org/>

Gradstein et al., 2004

### 15.1 Introduction

The geological time scale is a list of ordered events placed in a temporal/spatial context. Time (see Figure 15.1) is broken into Eons (e.g., Phanerozoic, Proterozoic), Eras (e.g., Mesozoic, Cenozoic), Periods (e.g., Cretaceous, Paleogene), Series (e.g., Oligocene, Miocene) and Stages (e.g., Messinian, Zanclean). The fundamental unit, the stage is ideally defined by its base at a particular place and many such “Global Standard Section and Points”, or GSSPs have been identified. Numerical ages are attached to these stage boundaries by a variety of methods. Some methods have explicit numerical age control (e.g., from the predictable decay of radioactive isotopes or variations in climate caused by the relationship of the Earth and the sun), while others have only relative age information (e.g., the progressive change of fossil assemblages, or the identification of contemporaneous events in the geological record). Almost always numerical ages are estimated by correlation, interpolation, and/or extrapolation. As such, the geological time scale is a work in constant revision. The most recent is that of Gradstein et al. (2004), which will probably be the standard for about a decade.

One of the important tools in assembling the geological time scale is the geomagnetic polarity time scale (GPTS). Identification of a particular polarity reversal allows direct correlation of isochronous events between continental and marine sequences, between northern and southern hemispheres and between the Pacific and Atlantic realms. Apart from the identification of unique ash layers or the very rare geochemical tracers like an iridium spike, there is no better way to tie together the stratigraphic record. In this lecture we will review how the modern GPTS was constructed and will briefly consider some applications of the GPTS to geological problems.

CHAPTER 15. THE GPTS AND MAGNETOSTRATIGRAPHY

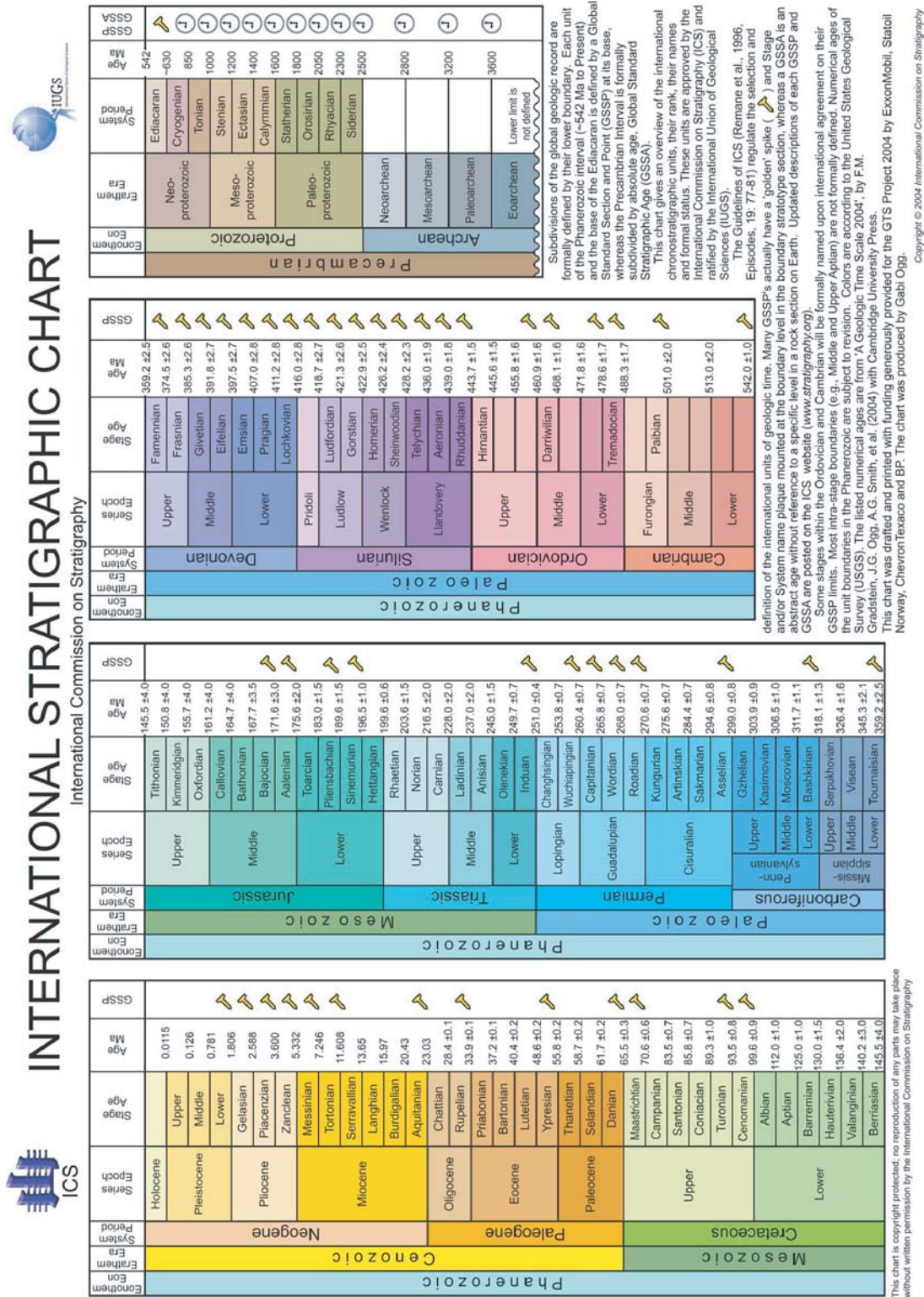


Figure 15.1: The International Stratigraphic Chart. (See interactive version at: [http://www.stratigraphy.org/.](http://www.stratigraphy.org/))

## 15.2. EARLY EFFORTS IN DEFINING THE GPTS

### 15.2 Early efforts in defining the GPTS

We learned in Lecture 14 that early workers discovered reversely magnetized rocks in the early 20<sup>th</sup> century, and some suspected that there was a globally synchronous pattern of polarity reversals (e.g., Matuyama, 1929). However, it was not until combined studies of both age (using the newly developed age dating technique using the decay of radioactive potassium to argon) and polarity (from globally distributed lava flows) that the first Geomagnetic Polarity Time Scales (GPTS) began to take shape (Figure 15.2; see e.g., Cox et al., 1963, 1964).

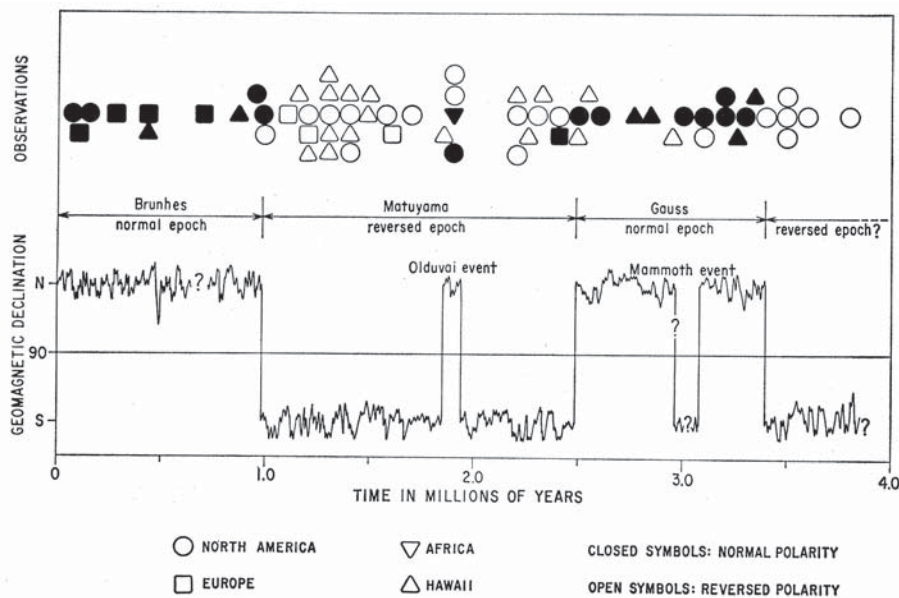


Figure 15.2: Magnetic polarities from volcanic units plotted against age as determined by the potassium-argon method. The first three long intervals were named after famous geomagnetists. [Figure from rom Cox et al., 1964].

Cox et al. (1964) broke the polarity sequence into times of dominantly normal polarity (i.e., the field vector more or less parallel to today's field) and times of dominantly reverse polarity (i.e., the field vector more or less antipodal to today's field). They called these time units "Epochs" (note that they are now known as *Chronos*). The first three were named after some major players in geomagnetism: B. Brunhes (who first discovered reversely magnetized rocks), M. Matuyama (who first saw that the reversely magnetized rocks were older than the normal ones), and F. Gauss (who worked out the first geomagnetic field model). A fourth was later named after W. Gilbert (who first realized that the Earth itself was a magnet). Cox et al. (1964) also recognized the existence of shorter intervals which they called "Events" (e.g., the Olduvai and Mammoth events in Figure 15.2; note that events are now known as *sub-chrons*). These shorter intervals are traditionally named after the place where they were first documented.

Time scales constructed in the manner of Cox and colleagues based on discrete polarity, date pairs are necessarily limited by the uncertainty in the dating of young basalts. In the early 60's this uncertainty exceeded the average duration of polarity intervals for times prior to about five million years (except for the very long intervals of a single polarity like the Permian "Kiaman" interval which lasted over 50 million years).

## CHAPTER 15. THE GPTS AND MAGNETOSTRATIGRAPHY



Figure 15.3: Map of the pattern of magnetic anomalies off northwestern North America. [Modified from Mason and Raff, 1961.]

Shortly after the publication of Cox et al. (1963) and McDougall and Tarling (1963), which essentially laid to rest doubts about the validity of geomagnetic reversals and sketched the rudiments of the first GPTS, Vine and Matthews (1963) put ideas about polarity reversals and the bizarre “magnetic stripes” in marine magnetic anomaly data (Figure 15.3; e.g., Mason and Raff, 1961) together as strong proof of sea floor spreading. The realization that the marine magnetic anomalies were a record of polarity history meant that the template for the pattern of reversals could be extended far beyond the resolution of the K-Ar method (see Figure 15.4, e.g., Pitman and Heirtzler 1966). It was not long before such a template for paleomagnetic reversals based on magnetic anomalies (numbering 1 to 31) was proposed. By assigning an age of 0 Ma to the ridge crest, an age of 3.35 Ma to the of the Gauss/Gilbert boundary (stars in Figure 15.4) and assuming constant spreading for the South Atlantic anomaly sequence, Heirtzler et al. (1968) produced a GPTS that extended to about 80 Ma. The age of anomaly 31 was estimated to be about 71.5 Ma. The truly astounding thing is that the currently accepted age for anomaly 31 is about 68 Ma (e.g., Cande and Kent, 1995) a difference of only a few percent!

In a parallel effort to the marine magnetic anomaly work, several groups were investigating the magnetic stratigraphy of deep sea sediment cores (e.g., Harrison, 1966 and Opdyke et al. 1966). In

## 15.2. EARLY EFFORTS IN DEFINING THE GPTS

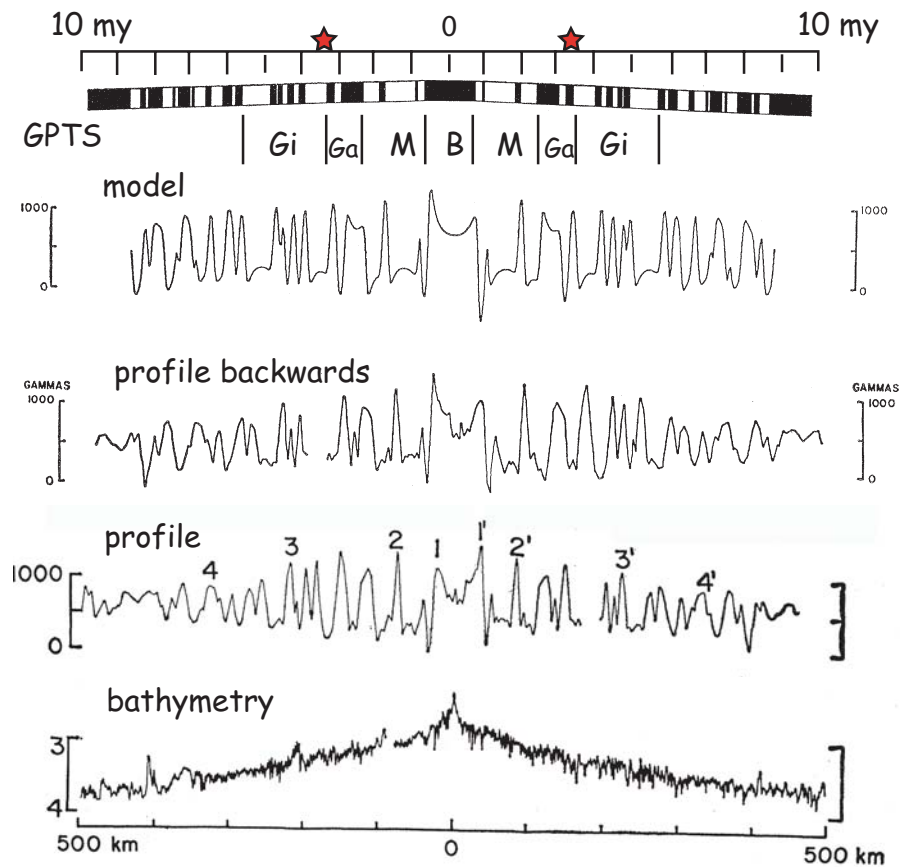


Figure 15.4: A profile of bathymetry (bottom panel) and magnetic anomalies (labelled “profile”) obtained from the East Pacific Rise (Eltanin 19 profile, also known as “the magic profile”). The magnetic anomaly profile, flipped east-to-west is replotted above (labelled “profile backwards”). Assuming a magnetization of a 500 m thick section of oceanic crust (black and white pattern above), a model for the predicted anomalies could be generated (labelled “model”). Above is the inferred time scale. The position of the Gauss/Gilbert boundary is marked by stars. [Adapted from Pitman and Heirtzler, 1966.]

Figure 15.5 we show the record of inclination versus depth of Opdyke et al., (1966) obtained from a core taken off the coast of Antarctica. Upwardly pointing (negative) inclinations are normal and positive inclinations are reversely magnetized. This polarity pattern was correlated to the currently available time scale which included the new “event” known as the Jaramillo (Doell and Dalrymple, 1966) and revised age estimates for the “epoch” boundaries.

The polarity sequence from magnetostratigraphic records was extended back into the Miocene by Opdyke et al. (1974, see Figure 15.6). The epochs, defined by the magnetostratigraphy could not easily be correlated to the anomaly data shown in Figure 15.4 and the two numbering schemes (anomaly numbers and epoch numbers) remained separate until the correlation between the two was deemed sufficiently robust.

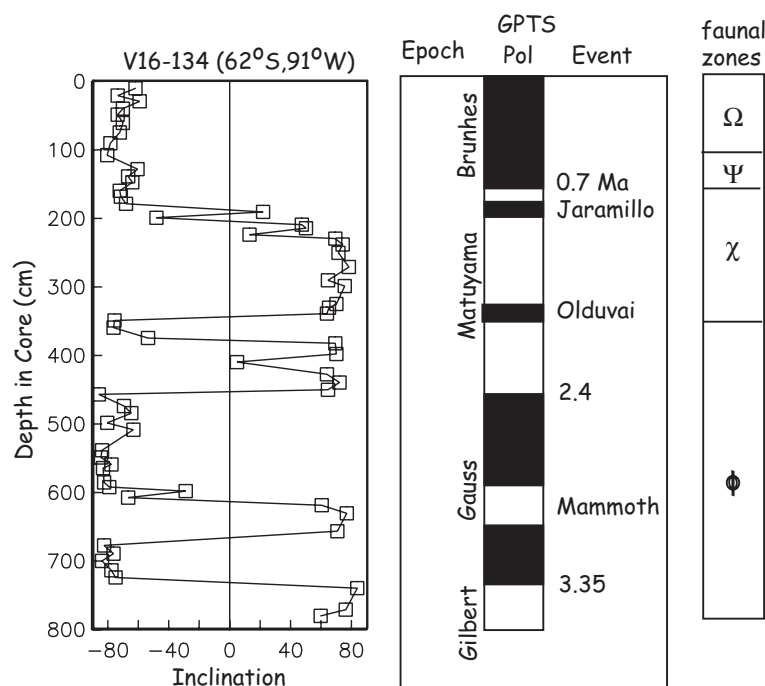


Figure 15.5: left: Inclinations from core V16-134 plotted against depth. middle: The GPTS as it was known in 1966. Faunal zones of the southern ocean identified within the core. [Adapted from Opdyke et al., 1966.]

### 15.2.1 A note about terminology

The Epoch/Event terminology was changed to Chron/sub-chron in 1979 by international agreement (Anonymous, 1979). Along with chrons and sub-chrons, the international subcommission defined “superchrons”. Cande and Kent (1992) later defined “cryptochrons”. Superchrons are extremely long polarity intervals, such as the Kiaman (also known as the Permo-Carboniferous Reverse Superchron or PCRS) which lasted from 298 to 265 Ma (Gradstein et al., 2004) and the Cretaceous Normal Superchron (CNS: 84-125 Ma in Gradstein et al., 2004). Cryptochrons are “tiny wiggles” in the marine magnetic anomaly record that are too short to be unequivocally interpreted as full reversals (i.e., shorter than about 30 kyr). Some of these may be related to geomagnetic “excursions” (see Lecture 14.)

In an attempt to rationalize the Neogene chron (event) terminology (which numbered chrons from 5-22) and the anomaly terminology (running from 1 to about 6C), Cande and Kent (1992) broke the time scale into chrons and sub-chrons based on the anomaly numbering scheme distinguishing chrons from anomalies with the letter “C”. Because the anomaly numbering system only had 34 anomalies from the end of the CNS to the present, many more subdivisions were required, particularly in the very “busy” interval between Anomalies 5 and 6. These anomalies are denoted 5', 5A, 5AA, 5AB and the like, so the present Neogene GPTS is a nightmare of chron and sub-chron names like C4n.1r or C5ADr where the “n”s and “r”s refer to polarity and the .1s refer to sub-chrons within chrons (e.g, C4n). For a complete listing of the GPTS since the CNS, please refer to the Appendix.

## 15.2. EARLY EFFORTS IN DEFINING THE GPTS

### 15.2.2 The addition of biostratigraphy

An interesting aspect to the magnetostratigraphic work typified by Opdyke et al. (1966) was the identification of biostratigraphic zones ( $\Omega$  to  $\phi$  in Figure 15.5) based on faunal assemblages in the core. These zones are therefore tied directly to the magnetostratigraphic record. The addition of biostratigraphy to the GPTS problem brought new possibilities for the calibration of the time scale in that certain boundaries could be dated by radioisotopic means using datable layers (e.g., ash beds) within stratigraphic sections. If a particular well dated biostratigraphic horizon could be tied to the magnetostratigraphic record, then the associated numerical ages could be attached to the GPTS. Exploiting this possibility, LaBrecque et al. (1977) used the magnetostratigraphic record in Italian carbonates (e.g., Alvarez et al., 1977) which tied the Cretaceous/Tertiary (K/T) boundary to a reverse polarity zone between two normal polarity intervals correlated with marine magnetic anomalies 29 and 30. The accepted age for the K/T boundary at the time was 65 Ma (van Hinte, 1976) which is virtually identical to the currently accepted age of  $65.5 \pm 0.3$  Ma (Gradstein et al., 2004), so ages for the anomalies numbered 1-34 could be estimated by interpolation and extrapolation. Note that anomaly 14 is now thought to be a cryptochron (S. Cande, pers. comm.) and has not been included as a numbered anomaly in timescales since LaBrecque et al., 1977.)

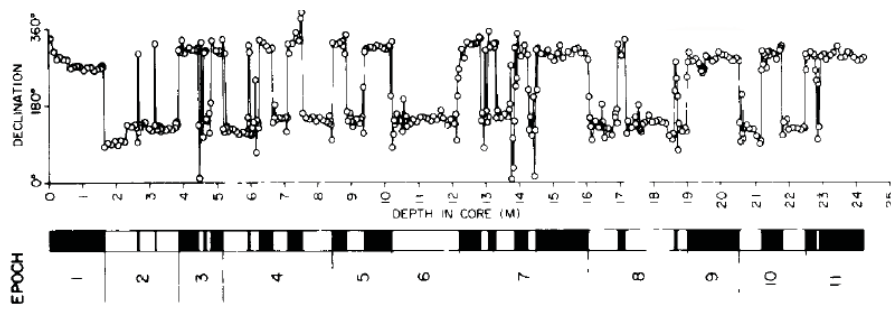


Figure 15.6: Declinations from deep-sea piston core RC12-65 from the equatorial Pacific Ocean (using an arbitrary zero line because the cores were not oriented). The epoch system of magnetostratigraphic nomenclature was extended back to Epoch 11 in this core and to Epoch 19 in companion cores. [Figure from Opdyke et al., 1974].

### 15.2.3 Astrochronology

Until 1990, the GPTS was dated using numerical ages based on the decay of radioactive elements (largely the K/Ar method). An alternative approach to dating of stratigraphic sequences long in use is based on the climatically induced changes in lithology or stable isotopic records in sediments that are caused by variations in the Earth's orbit around the sun. The relationship of the Earth's orbit to the sun results in changes in the amount and latitudinal distribution of solar radiation (so-called "insolation") reaching the Earth as a function of time. According to the *Milankovitch hypothesis* (e.g., Hays et al. 1976), changes in insolation at high northern latitudes vary with periodicities reflecting precession (with a beat of around 21 kyr), obliquity ( $\sim 40$  kyr) and eccentricity ( $\sim 100$  kyr). These changes in insolation resulted in measurable changes in the chemistry of the oceans and atmospheres and left an indelible mark on the lithostratigraphy (e.g., variations in carbonate) and the isotopic ratios of oxygen (the light isotope  $^{16}\text{O}$  gets preferentially incorporated into glacial ice at

## CHAPTER 15. THE GPTS AND MAGNETOSTRATIGRAPHY

high latitudes, leaving the oceans richer in  $^{18}\text{O}$ .) Because the precession, obliquity and eccentricity of Earth's orbit can be robustly predicted as a function of age at least for several million years (and perhaps even 10s of millions of years), identification of these patterns in the stratigraphic record allow numerical ages to be attached to the sedimentary sequence. This is a method known as “astrochronology”. Starting with Shackleton (1990) and Hilgen et al. (1991), astrochronology has been applied to the GPTS (see e.g., Figure 15.7).

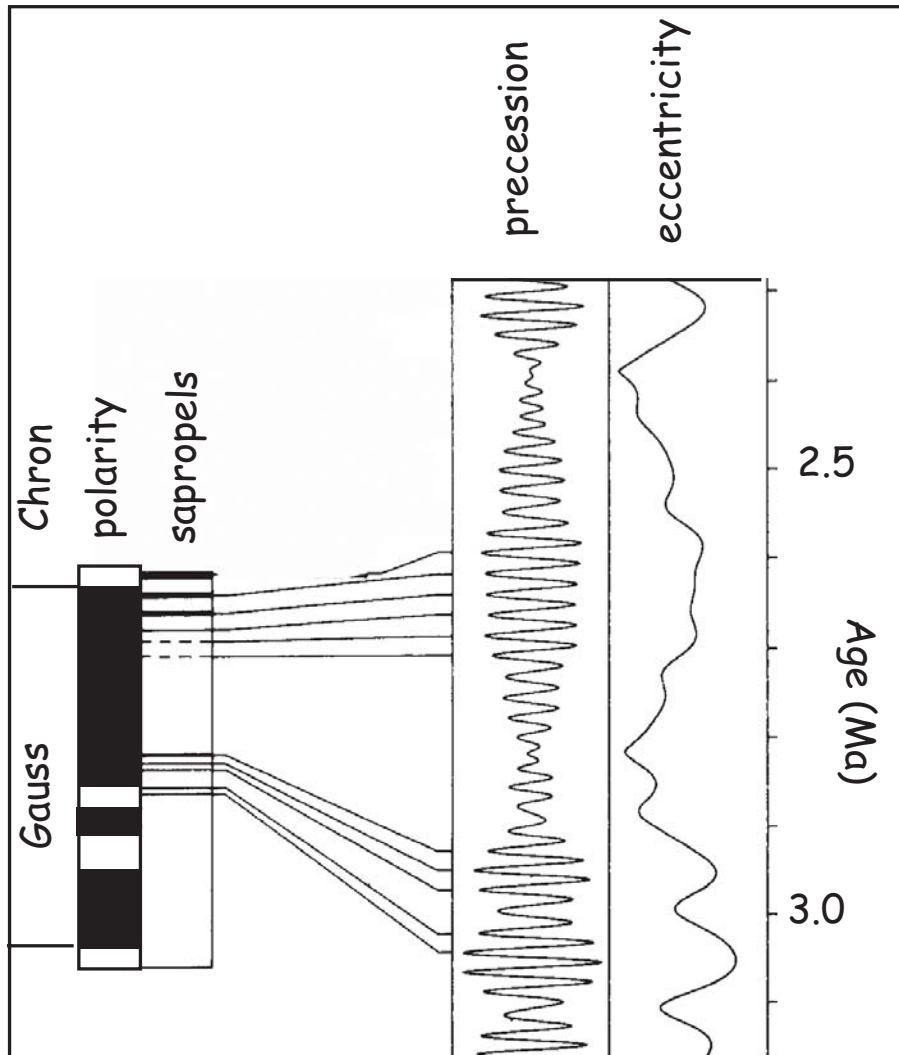


Figure 15.7: Illustration of the “astrochronology” dating method. The sequence of polarity intervals and climatically induced sapropel layers is correlated to the GPTS (left) and the orbital cycles (right). The numerical ages from the orbital cycles can then be transferred to the GPTS. [Adapted from Hilgen et al., 1991.]

## 15.2. EARLY EFFORTS IN DEFINING THE GPTS

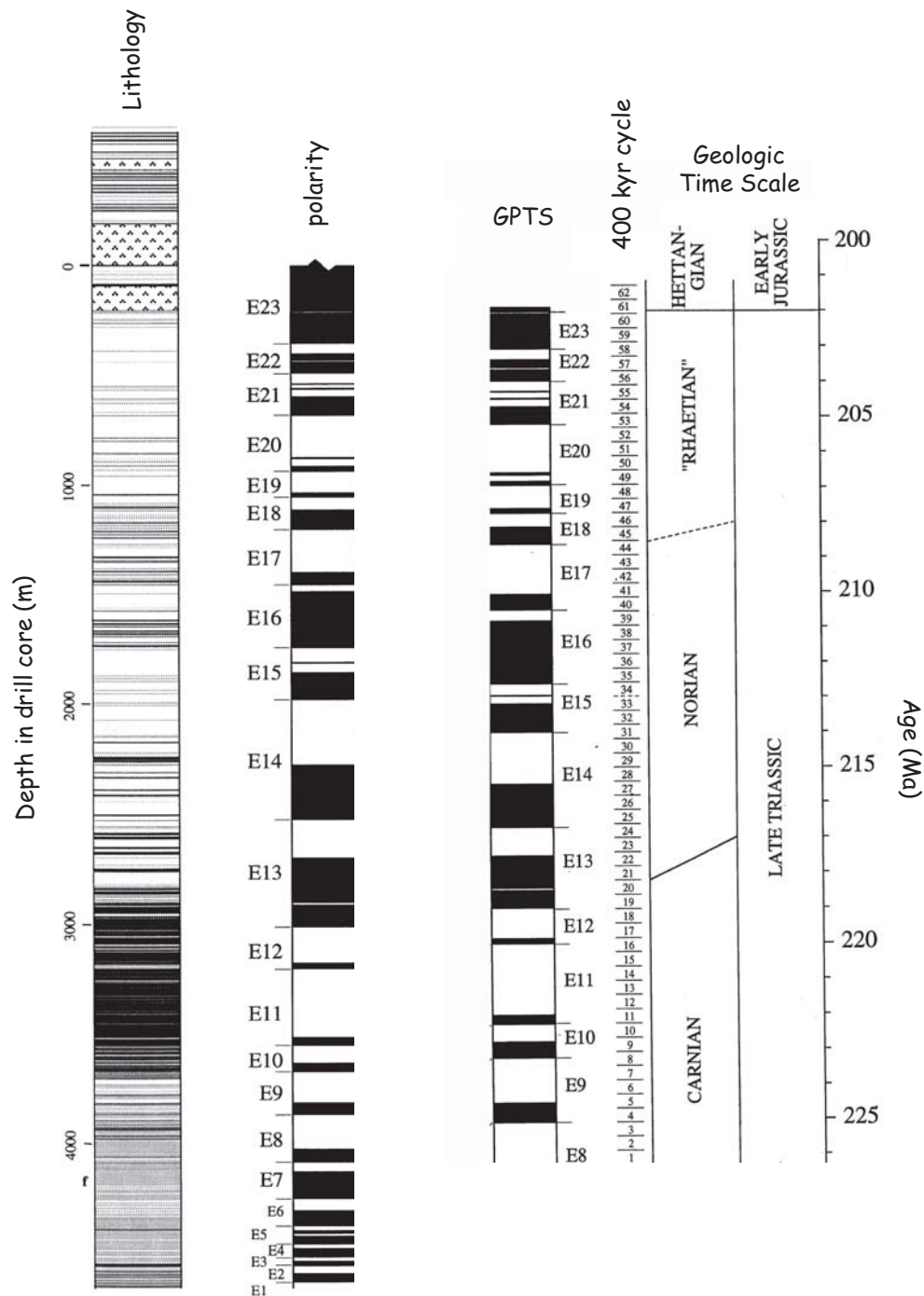


Figure 15.8: Left: Lithostratigraphic and magnetostratigraphic pattern derived from overlapping drill cores into the Newark Basin. Right: Interpretation for the GPTS based on astrochronology and correlation to the Geological Time Scale. [Adapted from Kent et al., 1995 and Kent and Olson, 1999.]

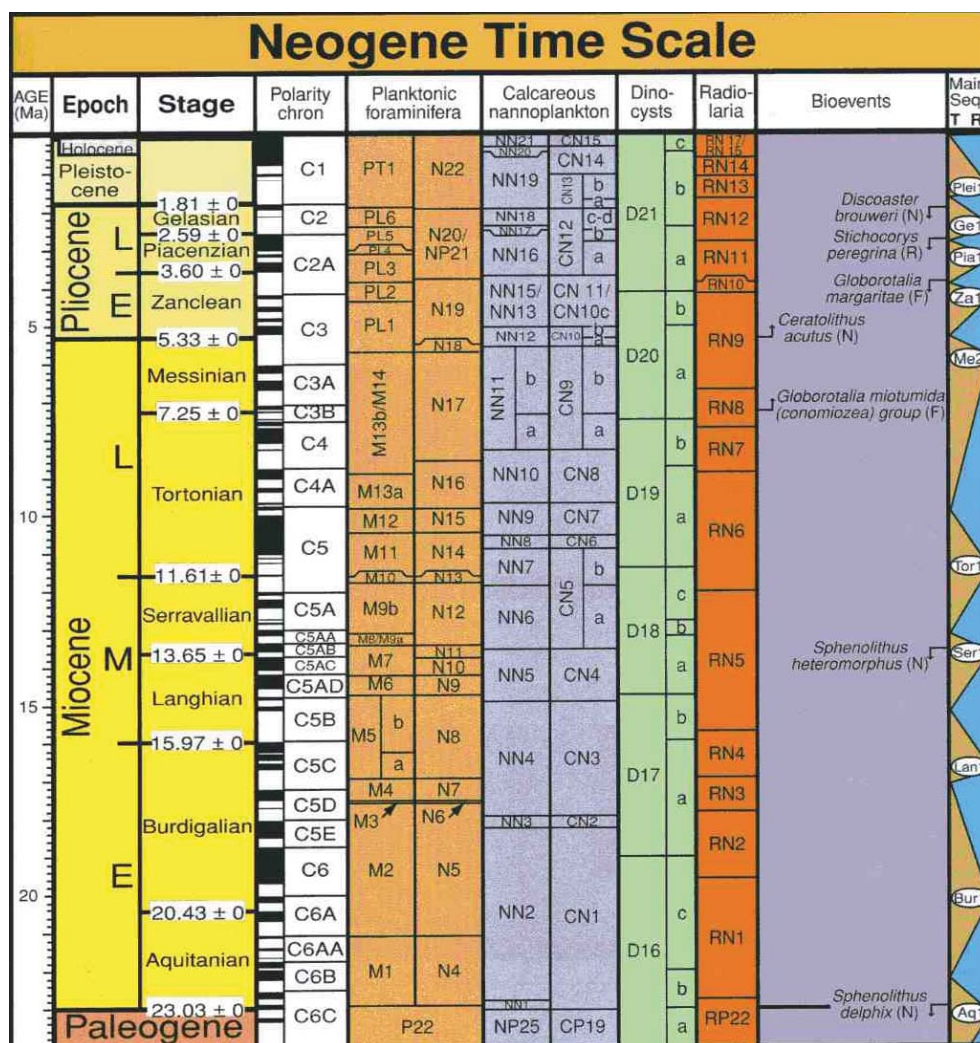


Figure 15.9: The Neogene of the Geological Time Scale. [Figure from Gradstein et al., 2004.]

### 15.2.4 The Mesozoic and beyond

By the early 70s the large scale structure of the marine magnetic anomalies had been sketched out. There was a young set numbered 1-34 which terminated in a vast expanse of oceanic crust with no correlatable anomalies known as the “Cretaceous Quiet Zone” or CQZ. The Cretaceous Quiet Zone is well established as being a period of time with very few (or no!) reversals. The CQZ is synonymous with the Cretaceous Normal Superchron, or CNS and extends from the middle of the Santonian (~ 84 Ma) to the middle of the Aptian stage (~ 125 Ma). On the old end of the CQZ was another set of anomalies, known as the “M-sequence” (e.g., Larson and Heirtzler, 1972). These extend from M0 (which bounds the old end of the CQZ) to M25 based on marine magnetic anomalies.

Because the oldest sea floor is about 180 Ma and the oldest marine magnetic anomaly sequence is very poorly expressed (it is known as the “Jurassic Quiet Zone”), polarity intervals older than

### 15.3. CURRENT STATUS OF THE GEOLOGICAL TIME SCALE.

---

about M25 are defined using various magnetostratigraphic sections obtained from land exposures. The M-sequence of polarity intervals was extended to about M39 using sections from Spain and Poland. The M-sequence has now been fairly firmly tied to geological stages and thereby calibrated in terms of numerical ages (see e.g., Gradstein et al., 2004).

As we go back farther in time, the GPTS necessarily becomes more sketchy. What is required is long sequences of stratigraphic sections with few gaps and reasonably constant sediment accumulation rates. Such sequences are difficult to identify and piece together so the GPTS will only slowly be completed.

One very long part of the GPTS in the middle to late Triassic is, however, quite well known. Using a series of drill cores with overlapping sections, Kent et al. (1995) defined a set of polarity intervals labelled E1 to E23 (see Figure 15.8). Kent and Olson (1999) interpreted lithologic cycles within sections as 400 kyr climatic cycles and calibrated their composite depth scale to time. Their resulting time scale is shown to the right in Figure 15.8.

Painstakingly acquired overlapping stratigraphic sections will be the basis for future extensions of the GPTS. Stay tuned - this is very much a work in progress and is advancing rapidly.

### 15.3 Current Status of the Geological Time Scale.

For reference, we include the dates of the most recent GPTS in the Appendix. As an example of the detailed correlations between the polarity time scale and various biological time scales, we show the Neogene portion from Gradstein et al. (2004) in Figure 15.9. For details, the reader is referred to the original reference. Please note that the time scale is a consensus document that balances a tremendous amount of information from a variety of sources. As such, it is subject to change, although not change should not be frequent or drastic.

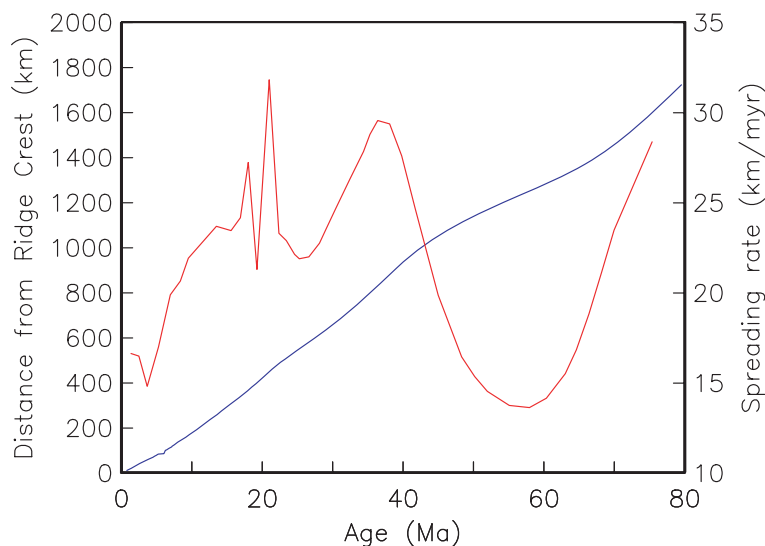


Figure 15.10: Plot of distance from the ridge crest in the South Atlantic versus age using the GPTS of Gradstein et al., (2004). The differential of this curve gives instantaneous spreading rate.

## 15.4 Applications

### 15.4.1 Dating geological sequences

An important application of the fact that the geomagnetic field undergoes frequent reversals, whose ages are fairly well known, at least for the last hundred million years or so, is to use the GPTS as a dating tool for stratigraphic sequences. The pattern of polarity zones is determined by measuring the magnetization of samples taken from the stratigraphic section. If the polarity zones in the so-called *magnetostratigraphy* can be unambiguously correlated to the GPTS, they constitute a precise temporal framework for sedimentary or volcanic sequences. Such records have proved invaluable for correlating stratigraphic information on a global basis and are the primary means for calibrating the Cenozoic fossil record with respect to time. Furthermore, knowing the ages of polarity reversals allows the calculation of rates of processes such as sea-floor spreading, sediment accumulation, extinctions and speciation and provide independent verification of orbital calculations.

Sedimentation is not always a continuous process in many environments and a stratigraphic section may have gaps of significant duration. Also, the magnetic recording process of the rock may be unreliable over all or part of the section. Furthermore, incomplete sampling may give a polarity log that is undersamples. For these reasons, there must be ways of establishing the reliability of a given polarity sequence and the robustness of a given correlation. For a more complete discussion of the subject of magnetostratigraphy, the reader is referred to the comprehensive book by Opdyke and Channell (1996) entitled *Magnetic Stratigraphy*. Briefly, the elements of a good magnetostratigraphic study include the following points.

- It must be established that a single component of magnetization can be (and has been) isolated by stepwise demagnetization. To demonstrate this, examples of demagnetization data should be shown (see Lecture 9). There must also be a clear discussion of how directions were determined for each sample.
- Geological materials are not always perfect recorders of the geomagnetic field. It often happens that a given stratigraphic horizon has no consistent magnetization. Multiple samples per horizon (say three to five separately oriented samples) with coherent directions (i.e., non-random by tests such as those discussed in Lecture 11) indicate that the magnetization at a given level is reproducible. While it is not always possible to take multiple samples (for example from limited drill core material), it is always desirable and certainly should be done whenever possible.
- The directional data must fall into two clearly separated groups that are identifiable as either normal or reverse polarity. If fully oriented samples have been taken, the data can be plotted on an equal area projection (see Appendix to Lecture 2) and/or subjected to the reversals test (Lectures 11 and 12). Often drill cores are not azimuthally oriented, and the paleomagnetic inclination is the only indicator of polarity. In this case, one can plot histograms of the inclination and establish that the two polarities (positive and negative) have discrete “humps” at the values expected for the site (paleo)latitude.
- The average direction should be compared with the reference field (the GAD field; see Lecture 2), and the expected direction based on the age of the formation for the sampling location. This can be done on an equal area projection, or in cartesian coordinates (e.g., using Fisher statistics or a bootstrap as described in Lectures 11 and 12).

## 15.4. APPLICATIONS

---

- Field tests (such as the fold test or conglomerate test as described in Lecture 9) that compare the age of magnetization relative to the rock formation are desirable.
- An independent estimate of the approximate age of the sequence is necessary. The better the age constraints, the more confident we can be in a given interpretation.
- The magnetostratigraphic pattern should match the polarity time scale. Few polarity zones should be ignored either in the section or in the time scale. Ideally, each polarity zone should be based on multiple sites in the section.

### 15.4.2 Measuring rates

One very useful application of the GPTS is to infer rates of for example spreading, sediment accumulation, etc. We illustrate this approach in Figure 15.10. Distance from the ridge crest of each identified anomaly is plotted against age. The previous standard GPTS based on the work of Cande and Kent (1992) built smooth changes in spreading rate into the GPTS itself. The Gradstein et al. (2004) time scale does not have this constraint for the Neogene, because much of it was calibrated using astrochronological methods. As a result there are sharp changes in spreading rate implied, which may be artifacts of the method of calibration. It may therefore be preferable to calibrate the time scale using some balance between astrochronology, smooth variations in spreading rate and radioisotopic methods.

### 15.4.3 Tracing of magnetic isochrons

Most magnetostratigraphic applications involve determination of a magnetostratigraphy through a stratigraphic sequence of sediments. Because polarity transitions occur relatively rapidly, the horizon bounding two polarity zones may represent an almost isochronous level. It is therefore possible to use magnetostratigraphy in a lateral sense, in order to delineate isochronous horizons within a given package of sediments (Behrensmeyer and Tauxe. 1982). In Figure 15.11, we show the application of magnetostratigraphy for tracing isochrons in a series of stratigraphic sections. The small sand body (darker gray) labeled “A” appears to have removed the normal polarity zone seen in sequences on the right of the figure either by erosion or because of unsuitable paleomagnetic properties of sand. Sand bodies B and C appear to represent quasi-isochronous horizons.

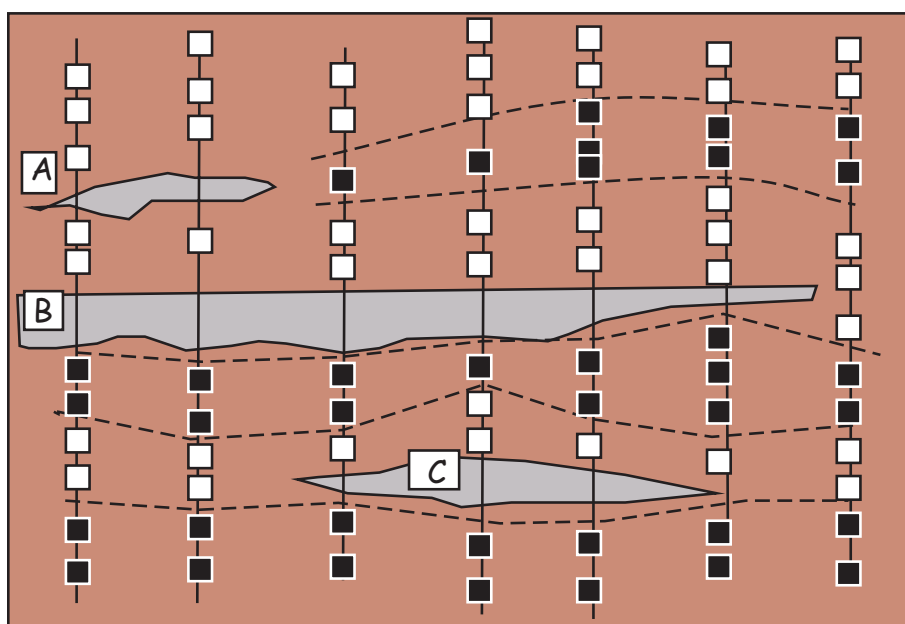


Figure 15.11: Application of magnetostratigraphic techniques for delineating isochronous horizons in a series of stratigraphic sections. The polarities of sampling sites are shown by open (reverse) and solid (normal) symbols. The light shading indicates silts, while the darker shaded units (labelled A-C) represent sand bodies, which were not suitable for paleomagnetic analysis in this example. The inferred isochrons (horizons that separate polarity zones) are shown as heavy dashed lines.

## 15.4. APPLICATIONS

---

### Appendix

Table A1: Geomagnetic polarity time scale of Gradstein et al. (2004).

Chron	sub-Chron	Dist. of old end from SA ridge (km)	Age of base (Ma)	alternate names
C1	C1n	12.14	0.781	Brunhes
	C1r.1	15.37	0.988	Matuyama
	C1r.1n	16.39	1.072	Jaramillo
	C1r.3r	27.8	1.778	
C2	C2n	31.51	1.945	Olduvai
	C2r.1r	35.04	2.128	
	C2r.1n	35.57	2.1482	Reunion
	C2r.2r	41.75	2.581	
C2A	C2An.1n	49.44	3.032	Gauss
	C2An.1r	50.7	3.116	Kaena
	C2An.2n	52.31	3.207	
	C2An.2r	54.1	3.33	Mammoth
	C2An.3n	58.03	3.596	
C3	C2Ar	66.44	4.187	Gilbert
	C3n.1n	68.23	4.3	
	C3n.1r	70.56	4.493	
	Cn.2n	73.56	4.631	
	C3n.2r	76.76	4.799	
	C3n.3n	78.26	4.896	
	C3n.3r	80.4	4.997	
	C3n.4n	84.68	5.235	
C3A	C3r	86.87	6.033	
	C3An.1n	101.42	6.252	
	C3An.1r	103.92	6.436	
	C3An.2n	109.6	6.733	
C3B	C3Ar	116.7	7.14	
	C3Bn	119.74	7.212	
	C3Br.1r	120.62	7.251	
	C3Br.1n	121.3	7.285	
	C3Br.2r	124.68	7.454	
	C3Br.2n	125.35	7.489	
	C3Br.3r	126.48	7.528	
C4	C4n.1n	129.08	7.642	
	C4n.1r	130.83	7.695	
	C4n.2n	139.37	8.108	
	C4r.1r	142.49	8.254	
	C4r.1n	143.15	8.3	
	C4r.2r	152.32	8.769	

---

**CHAPTER 15. THE GPTS AND MAGNETOSTRATIGRAPHY**

---

Chron	sub-Chron	Dist. of old end	Age of base (Ma)
C4A	C4An	159.16	9.098
	C4Ar.1r	163.49	9.312
	C4Ar.1n	165.16	9.409
	C4Ar.2r	171	9.656
	C4Ar.2n	172.34	9.717
	C4A.3r	174.47	9.779
C5	C5n.1n	177.49	9.934
	C5n.1r	178.38	9.987
	C5n.2n	201.13	11.04
	C5r.1r	203.44	11.118
	C5r.1n	204.51	11.154
	C5r.2r	213.04	11.554
	C5r.2n	214.28	12
C5A	C5r.3r	223.52	12.014
	C5An.1n	226.81	12.116
	C5An.1r	229.23	12.207
	C5An.2n	234.25	12.415
	C5Ar.1r	240.65	12.73
	C5Ar.1n	241.35	12.765
	C5Ar.2r	242.9	12.82
	C5Ar.2n	243.94	12.878
	C5Ar.3r	247.92	13.015
C5AA	C5AAn	251.38	13.183
	C5AAr	255.19	13.369
C5AB	C5ABn	260.03	13.605
	C5ABr	264.53	13.734
C5AC	C5ACn	273.28	14.095
	C5ACr	275.66	14.194
C5AD	C5ADn	285.8	14.581
	C5ADr	290.17	14.784
C5B	C5Bn.1n	292.24	14.877
	C5Bn.1r	295.63	15.032
	C5Bn.2n	298.45	15.16
	C5Br	318.39	15.974
C5C	C5Cn.1n	324.87	16.268
	C5Cn.1r	325.65	16.303
	C5Cn.2n	329.38	16.472
	C5Cn.2r	330.95	16.543
	C5Cn.3n	334.88	16.721
	C5Cr	347.64	17.235

---

## 15.4. APPLICATIONS

---

Chron	sub-Chron	Dist. of old end	Age of base (Ma)
C5D	C5Dn	355.45	17.533
	C5Dr	360.88	17.717
	C5Dr.1n	361.55	17.74
	C5Dr.2r	370.87	18.056
C5E	C5En	382.45	18.524
	C5Er	388.64	18.748
C6	C6n	413.88	20
	C6r	422.93	20.04
C6A	C6An.1n	427.81	20.213
	C6An.1r	434.18	20.439
	C6An.2n	441.85	20.709
	C6Ar	452.46	21.083
C6AA	C6AAAn	454.63	21.159
	C6AAAr.1r	461.59	21.403
	C6AAAr.1n	463.92	21.483
	C6AAAr.1n	468.97	21.659
	C6AAAr.2r	469.79	21.688
	C6AAAr.2n	472.08	21.767
	C6AAAr.3r	475.99	21.936
C6B	C6Bn.1n	477.29	21.992
	C6Bn.2n	483.7	22.268
	C6Br	490.61	22.564
C6C	C6Cn.1n	495.05	22.754
	C6Cn.1r	498.54	22.902
	C6Cn.2n	501.55	23.03
	C6Cn.2r	506.47	23.249
	C6Cn.3n	509.41	23.375
	C6Cr	524.64	24.044
C7	C7n.1n	525.92	24.102
	C7n.1r	527.29	24.163
	C7n.2n	536.04	24.556
	C7r	543.97	24.915
C7A	C7An	547.82	25.091
	C7Ar	552.3	25.295
C8	C8n.1n	555.55	25.444
	C8n.1r	556.6	25.492
	C8n.2n	571.04	26.154
	C8r	583.3	26.714

---

**CHAPTER 15. THE GPTS AND MAGNETOSTRATIGRAPHY**

---

Chron	sub-Chron	Dist. of old end	Age of base (Ma)
C9	C9n	607.96	27.826
	C9 r	616.12	28.186
C10	C10n.1n	622.16	28.45
	C10n.1r	623.9	28.525
	C10n.2n	628.29	28.715
	C10r	645.65	29.451
C11	C11n.1n	652.56	29.74
	C11n.1r	655.31	29.853
	C11n.2n	664.15	30.217
C12	C11r	674.26	30.627
	C12n	686.5	31.116
C13	C12r	742.63	33.266
	C13n	755.44	33.738
C15	C13r	784.4	34.782
	C15n	791.78	35.043
C16	C15r	802.15	35.404
	C16n.1n	806.87	35.567
	C16n.1r	810.93	35.707
	C16n.2n	827.67	36.276
C17	C16r	834.68	36.512
	C17n.1n	856.19	37.235
	C17n.1r	859.46	37.345
	C17n.2n	865.54	37.549
	C17n.2r	867.33	37.61
C18	C17n.3n	872.1	37.771
	C17r	879.83	38.032
	C18n.1n	907.31	38.975
	C18n.1r	909.21	39.041
C19	C18n.2n	921.21	39.464
	C18r	947.96	40.439
C20	C19n	954.12	40.671
	C19r	977.65	41.59
C20	C20n	1006.06	42.774
	C20r	1060.24	45.346

---

## 15.4. APPLICATIONS

---

Chron	sub-Chron	Dist. of old end	Age of base (Ma)
C21	C21n	1094.71	47.235
	C21r	1117.55	48.599
C22	C22n	1130.78	49.427
	C22r	1150.83	50.73
C23	C23n.1n	1153.9	50.932
	C23n.1r	1155.75	51.057
	C23n.2n	1168.2	51.901
	C23r	1178.96	52.648
C24	C24n.1n	1184.03	53.004
	C24n.1r	1185.61	53.116
	C24n.2n	1186.34	53.167
	C24n.2r	1188.05	53.286
	C24n.3n	1195.35	53.808
	C24r	1234.51	56.665
C25	C25n	1241.5	57.18
	C25r	1257.81	58.379
C26	C26n	1262.74	58.737
	C26r	1303.81	61.65
C27	C27n	1308.7	61.983
	C27r	1325.71	63.104
C28	C28n	1341.99	64.128
	C28r	1347.03	64.432
C29	C29n	1358.66	65.118
	C29r	1371.84	65.861
C30	C30n	1407.22	67.696
	C30r	1409.56	67.809
C31	C31n	1429.14	68.732
	C31r	1481.12	70.961
C32	C32n.1n	1487.68	71.225
	C32n.1r	1493.94	71.474
	C32n.2n	1531.81	72.929
	C32r.1r	1539.94	73.231
	C32r.1n	1542.32	73.318
	C32r.2r	1549.41	73.577
C33	C33n	1723.76	79.543
	C33r	1862.32	84
CNS	C34n	125.0	

## CHAPTER 15. THE GPTS AND MAGNETOSTRATIGRAPHY

---

# Bibliography

- Alvarez, W., Arthur, M. A., Fischer, A. G., Lowrie, W., Napoleone, G., Premoli-Silva, I. & Roggen-then, W. M. (1977), 'Type section for the Late Cretaceous-Paleocene reversal time scale', *Geol. Soc. Amer. Bull.* **88**, 383–389.
- Anonymous (1979), 'Magnetostratigraphic polarity units- a supplementary chapter of the ISSC International stratigraphic guide', *Geology* **7**, 578–583.
- Behrensmeier, A. K. & Tauxe, L. (1982), 'Isochronous fluvial systems in Miocene deposits of Northern Pakistan', *Sedimentology* **29**, 331–352.
- Butler, R. F. (1992), *Paleomagnetism: Magnetic Domains to Geologic Terranes*, Blackwell Scientific Publications.
- Cande, S. C. & Kent, D. V. (1992), 'A new geomagnetic polarity time scale for the late Cretaceous and Cenozoic', *Jour. Geophys. Res.* **97**, 13917–13951.
- Cande, S. C. & Kent, D. V. (1995), 'Revised calibration of the geomagnetic polarity timescale for the late Cretaceous and Cenozoic', *J. Geophys. Res.* **100**, 6093–6095.
- Cox, A., Doell, R. R. & Dalrymple, G. B. (1964), 'Reversals of the Earth's magnetic field', *Science* **144**, 1537–1543.
- Cox, A. V., Doell, R. R. & Dalrymple, G. B. (1963), 'Geomagnetic polarity epochs and Pleistocene geochronometry', *Nature* **198**, 1049–1051.
- Doell, R. & Dalrymple, G. (1966), 'Geomagnetic polarity epochs: A new polarity event and the age of the Brunhes-Matuyama boundary', *Science* **152**, 1060–1061.
- Glen, W. (1982), 'The Road to Jaramillo'.
- Gradstein, F., Ogg, J. & Smith, A.G., e. (2004), *Geologic Time Scale 2004*, Cambridge University Press, Cambridge.
- Harrison, C. G. A. (1966), 'The paleomagnetism of deep sea sediments', *Jour. Geophys. Res.* **71**, 3033–3043.
- Hays, J. D., Imbrie, J. & Shackleton, N. J. (1976), 'Variations in the Earth's orbit: pacemaker of the ice ages', *Science* **194**, 1121–1132.

- Heirtzler, J. R., Dickson, G. O., Herron, E. M., Pitman, W. C. I. & LePichon, X. (1968), 'Marine magnetic anomalies geomagnetic field reversals, and motions of the ocean floor and continents', *Jour. Geophys. Res.* **73**, 2119–2136.
- Hilgen, F. J. (1991), 'Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the Geomagnetic Polarity Time Scale', *Earth Planet. Sci. Lett.* **104**, 226–244.
- Kent, D. V. & Olsen, P. (1999), 'Astronomically tuned geomagnetic polarity time scale for the Late Triassic', *Jour. Geophys. Res.* **104**, 12831–12841.
- Kent, D. V., Olsen, P. E. & Witte, W. K. (1995), 'Late Triassic-earliest Jurassic geomagnetic polarity sequence and paleolatitudes from drill cores in the Newark rift basin, eastern North America', *Jour. Geophys. Res.* **100**, 14965–14998.
- LaBrecque, J. L., Kent, D. V. & Cande, S. C. (1977), 'Revised magnetic polarity time scale for Late Cretaceous and Cenozoic time', *Geology* **5**, 330–335.
- Larson, R. L. & Pitman, W. C. I. (1972), 'World-wide correlation of Mesozoic magnetic anomalies, and its implications', *Geol. Soc. Amer. Bull.* **83**, 3645–3662.
- Mason, R. & Raff, A. (1961), 'Magnetic survey off the west coast of North America, 32 degrees N. latitude to 42 degrees N. latitude', *Geol. Soc. Amer. bull.* **72**, 1259–1265.
- Matuyama, M. (1929), 'On the direction of magnetisation of basalt in Japan, Tyosen and Manchuria', *Proc. Imp. Acad. Jap.* **5**, 203–205.
- McDougall, I. & D.H., T. (1963), 'Dating reversals of the Earth's magnetic fields', *Nature* **198**, 1012–1013.
- McElhinny, M. & McFadden, P. (2000), *Paleomagnetism: Continents and Oceans*, Academic Press.
- Opdyke, N. D. & Channell, J. E. T. (1996), *Magnetic Stratigraphy*, Academic Press.
- Opdyke, N. D., Glass, B., Hays, J. D. & Foster, J. (1966), 'Paleomagnetic study of Antarctic deep-sea cores', *Science* **154**, 345–357.
- Oreskes, N. (2001), *Plate Tectonics: An insider's history of the modern theory of the Earth*, Westview Press, Boulder, CO.
- Shackleton, N. J., Berger, A. & Peltier, W. R. (1990), 'An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677', *Trans. Roy. Soc. Edinburgh: Earth Sciences* **81**, 251–261.
- van Hinte, J. (1976), 'A Cretaceous time scale', *Am. Assoc. Petroleum Geologists Bull.* **60**, 498–516.
- Vine, F. J. & Matthews, D. H. (1963), 'Magnetic anomalies over oceanic ridges', *Nature* **199**, 947–949.