Influence of the Choice of a Geomagnetic Polarity Time Scale on Results of the Geochronological and Geohistorical Analysis of the Marine Magnetic Anomalies

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Abstract Based on the Vine-Matthews hypothesis, dozens of magnetic reversal time scales have been constructed over the past 50 years, covering the Cenozoic and part of the Mesozoic eras. Using these time scales, marine magnetic anomalies have been identified, the grids of ocean floor ages have been constructed, and plate rotation parameters have been estimated from reconstructions of the edges of magnetic isochrons. Here, we study how the choice of a geomagnetic time scale influences geochronological and geohistorical interpretations of magnetic anomalies using well-mapped marine magnetic anomalies from the Indian Ocean. For the analysis, 15 of the most widely used Cenozoic time scales were chosen. For chrons C1–C5 and C23–C26, we quantify the degree of influence of the reversal time scales on the geohistorical and kinematic analysis.

Keywords Magnetic field · Paleomagnetism · Earth's magnetic field reversals · Geomagnetic time scale · Marine magnetic anomalies

1 Introduction

Study of the history of changes in the geomagnetic field is one of the fundamental problems of geophysics and is a central problem in paleomagnetism. One of the

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main characteristics of the Earth's magnetic field are polarity reversals, which have occurred many times in the past. Development and improvement of geomagnetic polarity time scales (GPTS), which are based on the record of field reversals that are preserved on land and in the ocean basins, is one of the important problems of geophysics. Refinements in GPTS have been nearly continuous as new data have accumulated, and improved methods of analysis have been developed.

Progress in solving a large number of geological and geophysical problems such identifying marine magnetic anomalies, determining ocean floor ages, determining the kinematic parameters of tectonic plate motion, and calculating sea floor spreading rates [1] depends critically on improvements in our knowledge of the history of

Table 1 Reversal scales considered in the present study

Time Scale Author, Date, and References	Abbreviation	Number of reversals/the shortest polarity interval, Ma	Number of calibrating points
Heirtzler et al., 1968 [5]	HDHPL68	170/0.04	2
Tarling and Mitchell, 1976 [6]	TM76	206/0.01	2
LaBrecque et al., 1977 [7]	LKC77	192/0.02	2
Mankinen and Dalrymple, 1979 [8]	MD79	196/0.02	2
Ness et al., 1980 [9]	NLC80	198/0.02	4
Lowrie and Alvarez, 1981 [10]	LA81	176/0.03	11
Harland et al., 1982 [11]	GTS82	196/0.02	6
Berggren et al., 1985 [12]	BKFV85	139/0.02	6
Kent and Gradstein, 1986 [13]	KG86	142/0.02	6
Harland et al., 1989 [14]	GTS89	196/0.02	6
Cande and Kent, 1982 [15]	CK92	186/0.01	9
Cande and Kent, 1995 [16]	CK95	350/0.007	9
Berggren et al., 1995 [17]	IMBTS95	188/0.008	9
Huestis and Acton, 1997 [18]	HA97	130/0.008	9
Gradstein et al., 2012 [19]	GTS2012	278/0.009	9

geomagnetic field. Studies of all these problems require the use of geomagnetic polarity time scales and thus depend on the GPTS that is used for a given study. Qualitative comparisons of geomagnetic polarity time scales have been carried out by many previous authors [2–4], but no previous study has fully treated the question of how the choice of a GPTS affects the estimates of seafloor spreading rates and seafloor ages when solving inverse problems. In this paper, we compare how interpretations of young and ancient sequences of magnetic anomalies in the northwestern Indian Ocean, both formed during periods of steady spreading rates, vary depending on the magnetic reversal time scale that is adopted.

Fifteen of the best known Cenozoic time scales are used for our analysis, ranging from the earliest time scale of Heirtzler et al. [5] to the most recent geologic time scale of Gradstein et al. [19]. For convenience, we have used generally accepted abbreviation of the time scales [4, 19] and literature references according to the following Table 1.

These time scales, which are depicted in Fig. 1, differ in many characteristics, including the spreading model that was used to derive them, the nomenclature of the magnetic anomalies that were included or excluded from each time scale (see, for example [7]), the tie-point dating method used for their calibration curve, the radiometric decay constant used for radiometric ages, and extrapolation method used to find ages for magnetic reversals between the tie points.

2 History

The earliest reversal time scales were based on absolute ages for reversals determined from radiometric dating of rocks using the potassium-argon method, of which the well-known Cox's time scale [20] for the past 5 million years is an example. Based on absolute age estimates for some reversals, magnetic anomaly time scales for the Cenozoic and Cretaceous periods were constructed by identifying reversals in lineated marine magnetic anomalies flanking the mid-ocean ridges. The first such time scale, which was published in 1968 [5], was derived from seafloor spreading magnetic anomalies in the South Atlantic. The authors identified magnetic anomalies C1 near the axis of seafloor spreading, to C32, with an approximate age of 80 million years. In fact, when constructing anomaly timescales, the sequence of reversals is based on a sequence of magnetic anomalies, and their age is determined by biostratigraphic data from the most ancient sediments covering the basalt basement and (or) with estimates of the absolute age of basalts [21].

Refinements to geomagnetic polarity scales since 1968 and the emergence of new scales were based on several methodological and other advances. First, the resolution of the time scales increased as short-duration (<20 k.y.) geomagnetic events (cryptochrons) were identified [22]. Second, the relative spacing of seafloor spreading magnetic anomalies was revised, leading to improvements in the structure of the time scale. Third, improved methods for calibrating time scales (the number of points and the smoothing method) were adopted. During the past two decades, the

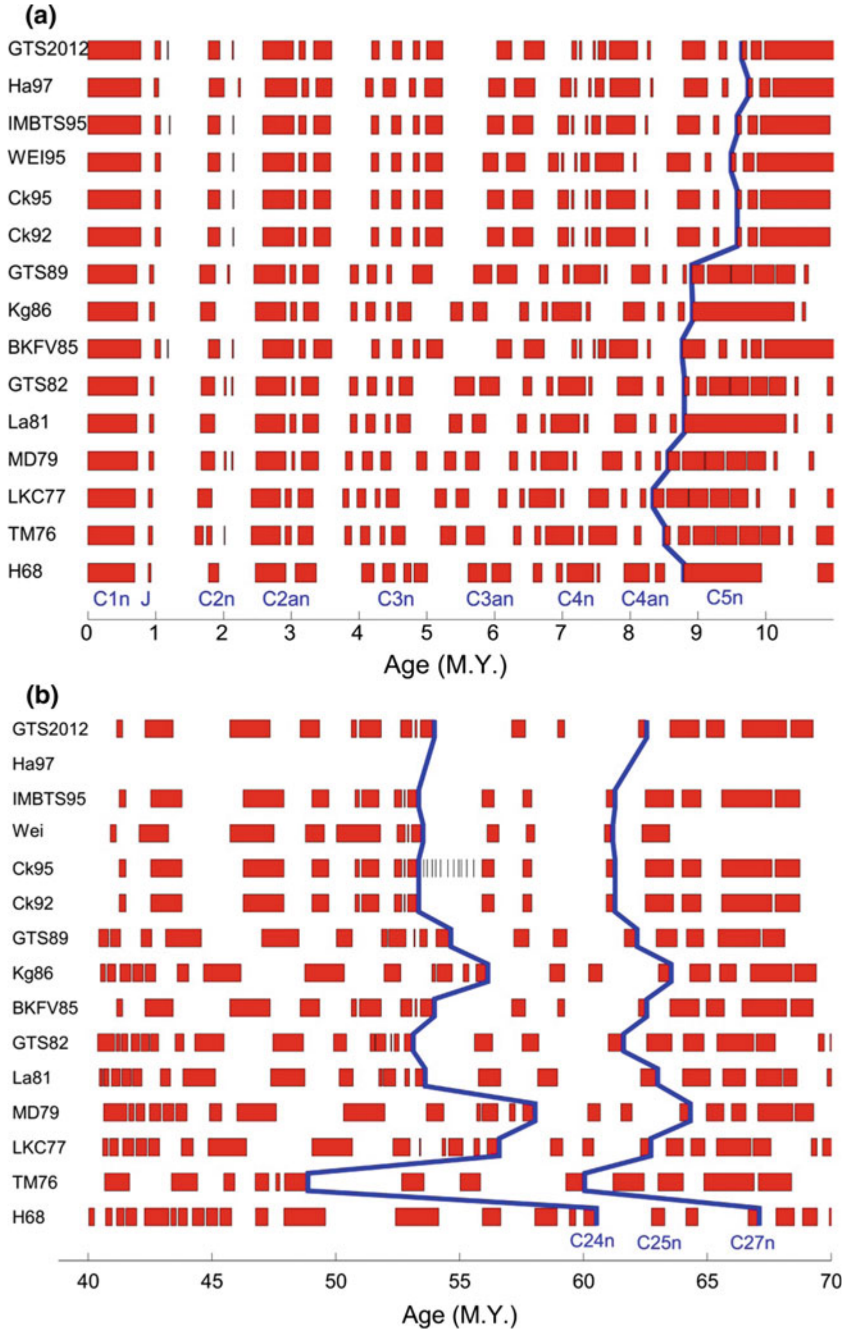


Fig. 1 Correlated paleomagnetic intervals from the studied Cenozoic time scales for 0–10 m.a. (top) and 40–70 m.a. (bottom). Red indicates intervals of normal polarity; white indicates intervals of reversed polarity. Blue tie lines are drawn between some selected anomaly boundaries

combination of radioisotopic dating and astrochronological tuning have improved the accuracy of estimated reversal ages and reduced their uncertainties, and the use of statistical methods for constructing optimal time scales have also significantly reduced uncertainties in the ages of individual chrons and their relationship with each other [23–25].

3 The Method and the Data

According to the hypothesis of Vine and Matthews, the reversal-spreading mechanism of formation of the magnetoactive layer of oceanic lithosphere provides a record of the geomagnetic field reversal history. This record can be deciphered by examining marine magnetic anomalies measured in the ocean basins. From systematic studies of marine magnetic anomalies in the northwestern part of the Indian Ocean, we have identified two sequences of marine magnetic anomalies (A1–A6 and A23–A26) that record two distinct stages of spreading. For both sequences the anomalies can be identified with high confidence using geomagnetic time scales. Based on these identifications, the age of the oceanic lithosphere for the two sequences is 0–20 Ma for A1–A6 and 53–63 Ma for A23–A26 [26, 27].

The conjugate magnetic lineations and fracture zones on each side of the ridge are used to calculate poles of rotation of the Indian and Somali plates. For the sequence A1–A6 of young anomalies (0–20 million years), a detailed kinematic model was proposed and seafloor spreading rates were calculated at one million year intervals [26]. This study shows that spreading rates decreased steadily from 20 to 10 million years and have remained steady for the last 10 million years [26]. Analysis of anomalies C24–C26 from the Arabian and Somali basins showed that seafloor spreading rates were rapid and remained steady from 63 to 53 Ma.

For this analysis, we use the same two sequences of anomalies, when spreading rates and the pole of rotation were both stable. A magnetic anomaly grid of the northwestern Indian Ocean is given on Fig. 2.

Geochronological interpretations of marine magnetic anomalies depend on matching observed and synthetic magnetic profiles, the latter calculated using a spreading block model that explores a range of possible spreading rates and different subsets of the magnetic reversal sequence. The choice of the best spreading rate and reversal sequence is based on the goodness of fit of the model to the observed profile, which is usually evaluated by eye. To carry out a quantitative comparison of all fifteen reversal time scales and assess their influence on the geochronological interpretation of a given observed profile, we calculated modeled magnetic profiles for each GPTS while varying the range of possible spreading rates and the assumed sequence of magnetic reversals in each modeled profile. A correlation coefficient between the observed magnetic profile and each possible modeled profile is calculated to quantify the goodness-of-fit between the two.

For each of the 15 reversal time scales listed in the Table, we repeated the above procedure to identify the optimal parameters from the wide range of values that

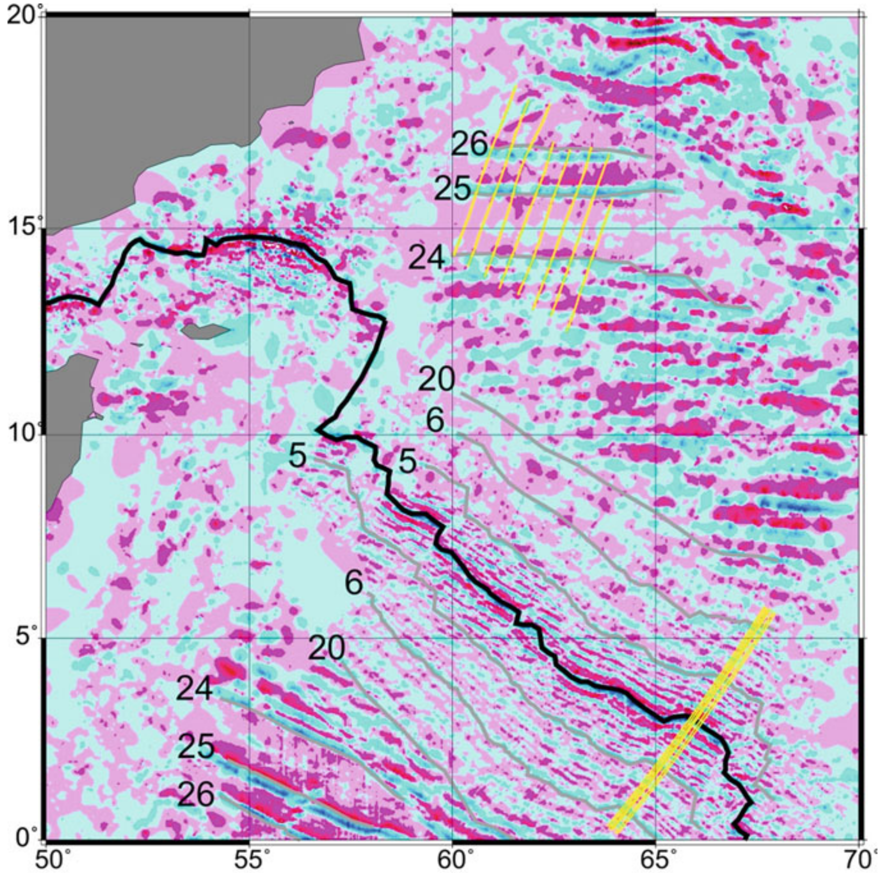


Fig. 2 Magnetic anomaly grid of the northwestern Indian Ocean. Map of linear magnetic anomalies according to [26, 27] and magnetic anomaly profiles, crossing anomalies A1–A6 and A24–A26. Depicted are the plate boundary (black bold line), magnetic lineations (light gray lines) and chron identifiers (5, 6 24–26), and magnetic profiles used for the analysis described below (yellow)

were explored for our synthetic modeling. Spreading rates were varied from 8 to 20 mm/year and possible reversal sequences between ages of 0–80 million year were explored. Readers may also refer to previous studies [27, 29] in which spreading rates and anomaly ages were estimated for these data.

Figure 3 illustrates the process of selecting the spreading rate for A1–A6 anomalies and the subset of magnetic reversals for which the correlation coefficient between the observed profile and the synthetic one is maximized. The same approach was applied to find best-fitting parameters for the A23–A26 anomaly sequence for each of the 15 GPTS included in our earlier table. Figures 4 and 5 compare the best-fitting synthetic magnetic anomaly profiles for all 15 GPTS included in our study to the observed profile for A1–A5 (Fig. 4) and A23–A26 (Fig. 5).

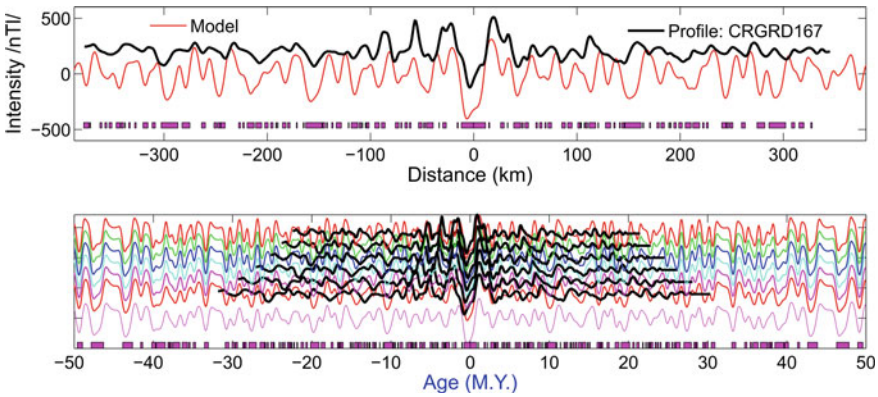


Fig. 3 The fitting procedure for a reduced-to-pole representative profile on the Carlsberg ridge for A1–A6. Theoretical magnetic anomalies calculated in the range of ages (0–50 million years) and half-spreading rate of 8–20 mm/year with a step of 1 mm/year

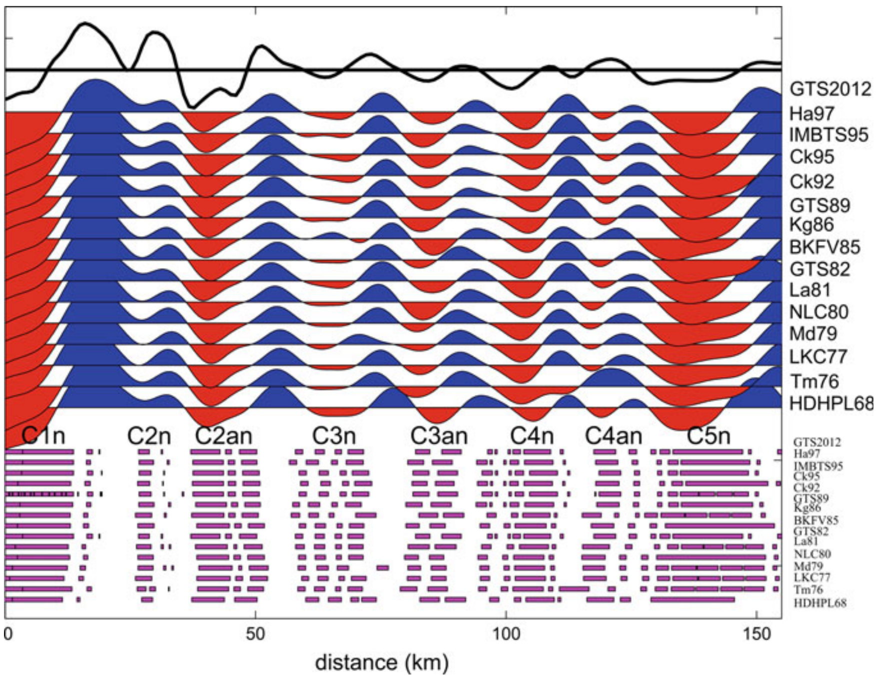


Fig. 4 Comparison of the observed representative magnetic profile (black line) and theoretical magnetic profiles, calculated using the time scales (below) for chrons C1–C5. For each reversal time scale the best spreading rate was found by fitting of the observed profile to the synthetic profiles. Blocks of normal magnetic polarity are shown in purple, reverse polarity—in white. The assigned thickness of the magnetic source layer is 0.5 km. Magnetization of the blocks is ±4 A/m with the centermost block at the ridge crest being ± 8 A/m. The names of the corresponding time scales are on the right-hand side of the figure. The chron names are found above the reversal time scales

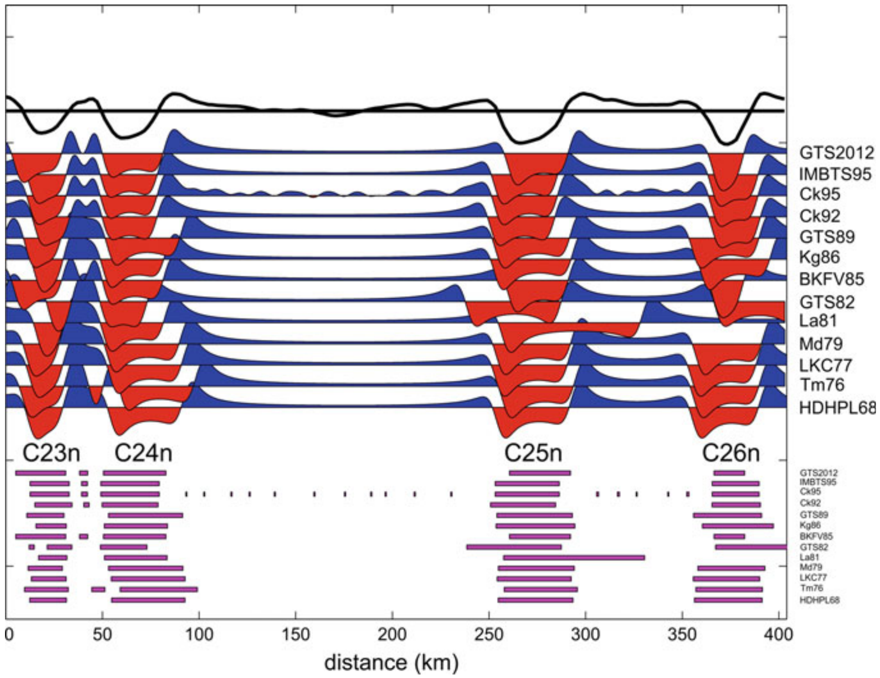


Fig. 5 Comparison of the observed magnetic profile (black line) and theoretical magnetic profiles, calculated using the time scales for chrons C23–C26. Plot conventions are the same as in Fig. 4

4 The Results

Based on our analysis of the representative magnetic profiles from the Carlsberg ridge (A1–A6) and Arabian basin (A24–A26) (yellow lines in Fig. 2), we estimated average half-spreading rates for each of the 15 GPTS that we evaluated using the ages assigned to the reversals for each GPTS. Figures 6 and 7 compare the parameters we estimated for each GPTS. The bottom panel in each figure shows the maximum correlation coefficient between the observed and model profiles for each GPTS. The middle panel shows the best estimated half spreading rate. The upper panel shows the assigned age of chrons C5n1 (Fig. 6) or chrons C23n1, C24n1, and, C26n1 (Fig. 7) for each GPTS.

Finally, we analyzed the influence of two particular reversal time scales on the history of the derived interval spreading rates (Fig. 8). For one time scale, the reversal ages were estimated using astronomical age calibrations [19] (upper). For the other, reversal ages were derived from the width of magnetic anomalies (bottom) [14]. To find the India-Somalia interval spreading rates, we used kinematic parameters from [26]. The variation in interval spreading rates over the last 10 million years is smaller for the astronomically calibrated time scale. Since the simpler spreading-rate history

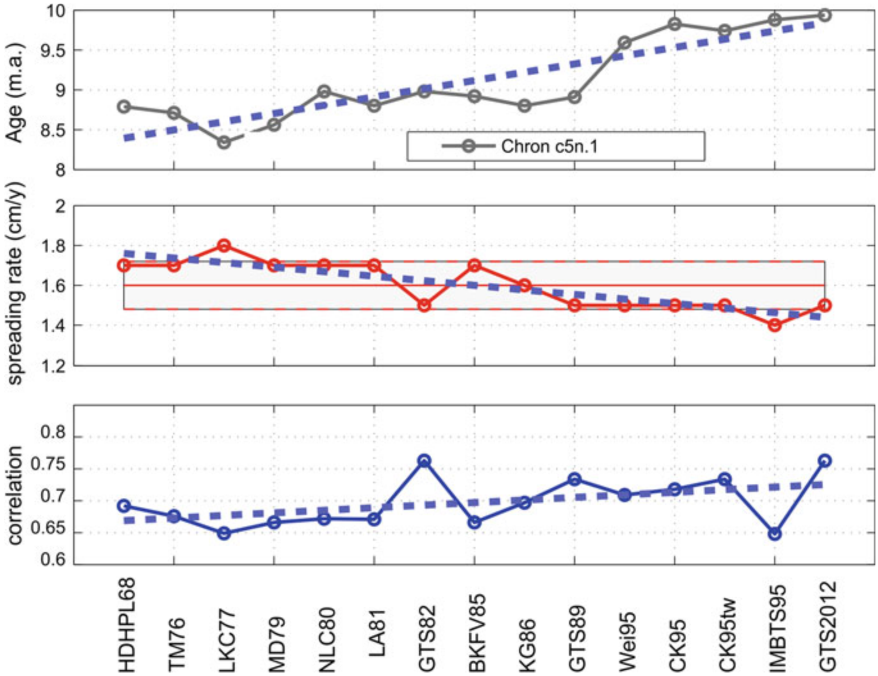


Fig. 6 The age of chron C5n.1 (top), average half-spreading rate for A1–A5 (middle) and correlation coefficient (bottom) between the observed and model profiles for each GPTS

is preferable, this suggests that reversal ages that rely on astronomical tuning are more accurate.

A similar, earlier analysis [28] used magnetic data from Pacific basin spreading centers, where interval spreading rates were estimated from high-resolution plate kinematic models using a reversal time scale based mostly on radiometric age dating and an alternative time scale with astronomical age calibration, in which the estimated reversal age uncertainties are likely to be smaller than 0.02 million years. It has been shown that the spreading rate can remain constant for several million years even for fast moving plates and the magnetic anomaly interpolation method used in [15] can cause variations in spreading rates.

In the region considered in this study, the spreading rate for anomalies A23–A27 was steady, but fast, whereas the spreading rate for A1–A5 is steady, but slow. The transition from fast to slow spreading rates explains the decrease in the spreading rate from A6 (20 m.y.) to A5 (10 m.y.), as seen in Fig. 8.

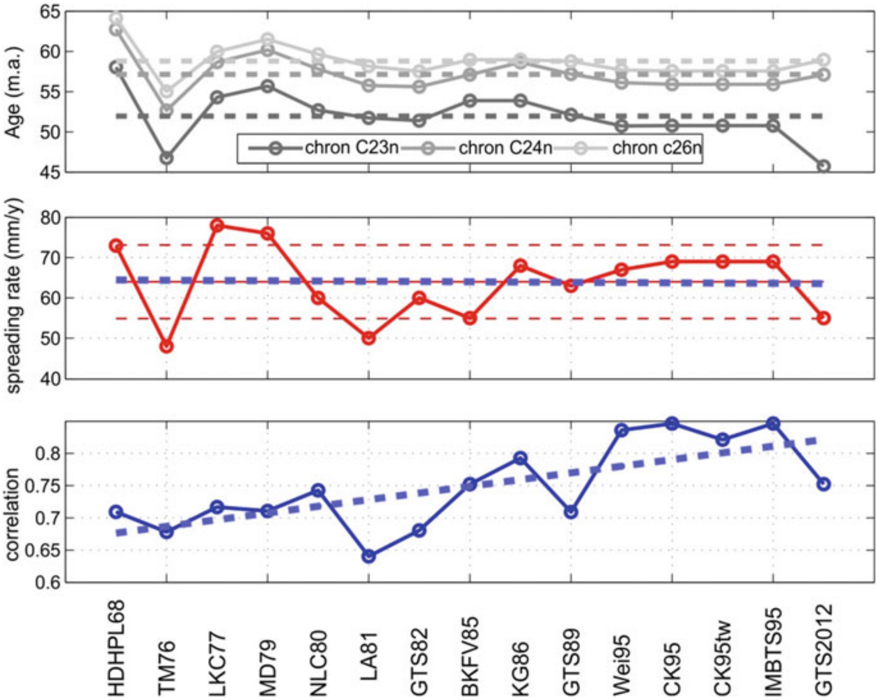
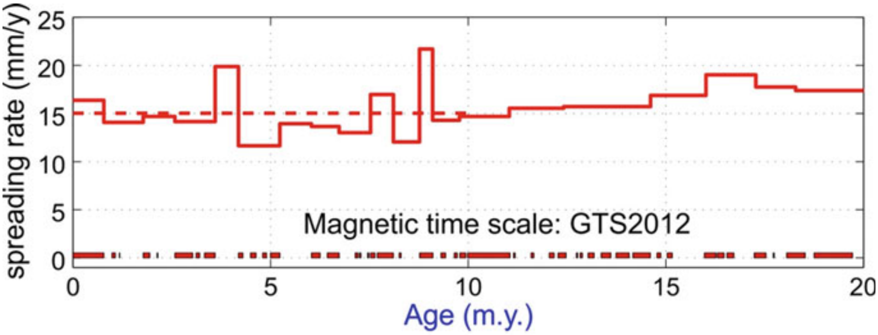


Fig. 7 The ages of chrons C23n1, C24n1, and, C26n1 (top), half-spreading rate (middle) and correlation coefficient (bottom) between the observed and model profiles for each GPTS

5 Conclusion

Ages estimated for marine magnetic reversals in different, published geomagnetic reversal time scales may differ by 15%. For younger anomalies (chrons C1n–C5n), more recently published reversal time scales suggest ages for C5 n.l that are close to 10 m.y. whereas older time scales suggest ages as young as 8.5 m.y. These imply significantly different seafloor spreading rates depending on which is more accurate. Differences in the ages estimated for magnetic reversals older than ~50 m.y. are even greater than for younger reversals.

Based on goodness-of-fit comparisons between observed magnetic profiles and synthetic magnetic profiles for 15 different reversal time scales, we show that the goodness-of-fit as measured by a correlation coefficient varies significantly depending on which reversal time scale is used to create the synthetic magnetic profile. In general, synthetic magnetic profiles that are created using more recently published reversal time scales give higher correlation coefficients between the observed and modeled profiles than for older reversal time scales, particularly for reversals younger than 20 m.y. For reversals older than 50 m.y., the highest correlation coefficients are not always determined from synthetic magnetic profiles based on the more recently



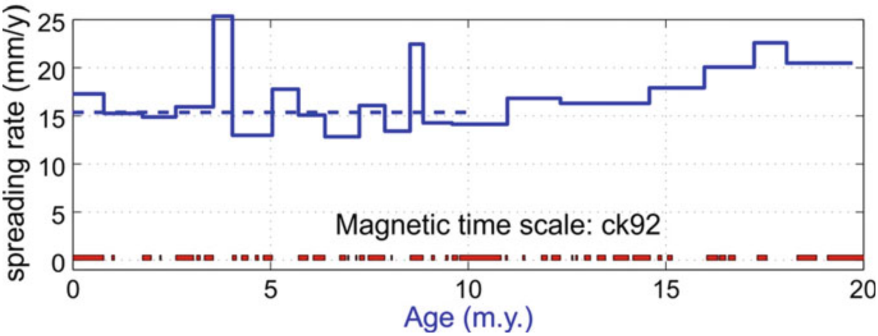


Fig. 8 India-Somalia interval spreading rates calculated by the kinematic parameters [26] for reversal time scales with astronomical age calibrations (upper) and based on the width of magnetic anomalies (lower) [30]. Red blocks indicate the interval of normal polarity, white ones indicate the interval of reverse polarity

published reversal time scales, suggesting that much work remains to improve the accuracy of ages estimated for reversals older than 50 m.y. Finally, the spreading rate history between the India and Somalia plates for the past 10 m.y. is simpler when it is derived using astronomically-tuned reversal ages. Astronomical tuning of reversal ages thus appears to improve the accuracy of reversal age estimates [19].

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References

1. Karasik, A.M.: Magnetic anomalies of the ocean and the ocean floor spreading hypothesis. Geotectonika 2, 3–18 (1971) (in Russian)
2. Heirtzler, J.R.: The paleomagnetic field as inferred from marine magnetic studies. J. Geomag. Geoelectr. **22**(1–2), 197–211 (1970)
3. Shreyder, A.A.: Chronology of linear marine magnetic anomalies. Izvestiya Phys. Solid Earth **29**(4), 305–319 (1993)

4. Mead, G.A.: Correlation of Cenozoic-late cretaceous geomagnetic polarity time scales: an internet archive. J. Geophys. Res. **101**(B4), 8107–8110 (1996)
5. Heirtzler, J.R., Dickson, G.O., Herron, E.M., Pitman III, W.C., Le Pichon, X.: Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents. J. Geophys. Res. **73**(6), 2119–2136 (1968)
6. Tarling, D.H., Mitchell, J.G.: Revised Cenozoic polarity time scale. Geology **4**(3), 133–136 (1976)
7. LaBrecque, J.L., Kent, D.V., Cande, S.C.: Revised magnetic polarity time scale for Late cretaceous and cenozoic time. Geology **5**(6), 330–335 (1977)
8. Mankinen, E.A., Dalrymple, G.B.: Revised geomagnetic polarity time scale for the interval 0–5 m.y. B.P. J. Geophys. Res. **84**(B2), 615–626 (1979)
9. Ness, G., Levi, S., Couch, R.: Marine magnetic anomaly time scales for the Cenozoic and Late Cretaceous: a Precis, critique, and synthesis. Rev. Geophys. Space Phys. **18**(4), 753–770 (1980)
10. Lowrie, W., Alvarez, W.: One hundred million years of geomagnetic polarity history. Geology **9**(9), 392–397 (1981)
11. Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G., Walters, R.: A Geologic Time Scale, 131 pp. Cambridge University Press (1982)
12. Berggren, W.A., Kent, D.V., Flynn, J.J., Van Couvering, J.A.: Cenozoic geochronology. Geol. Soc. Am. Bull. **96**(11), 1499–1510 (1985)
13. Kent, D.V., Gradstein, F.M.: A Jurassic to recent chronology. In: Vogt, P., Tucholke, B.E. (eds.) The Western North Atlantic Region, vol. M, pp. 45–50, Boulder, CO, Geological Society of America, The Geology of North America (1986)
14. Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., Smith, D.G.: A Geologic Time Scale 1989, 263 pp. Cambridge University Press (1990)
15. Cande, S.C., Kent, D.V.: A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. J. Geophys. Res. **97**(B10), 13917–13951 (1992)
16. Cande, S.C., Kent, D.V.: Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. J. Geophys. Res. **100**(B4), 6093–6095 (1995)
17. Berggren, W.A., Kent, D.V., Swisher III, C.C., Aubry, M.-P.: A revised cenozoic gochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.-P., Hardenbol, J. (eds.) Geochronology time scales and global stratigraphic correlation, pp. 129–212. SEPM, Tulsa, Oklahoma (1995)
18. Huestis, S.P., Acton, G.D.: On the construction of geomagnetic timescales from non-prejudicial treatment of magnetic anomaly data from multiple ridges. Geophys. J. Int. **129**, 176–182 (1997)
19. Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G.: The Geologic Time Scale 2012, 1144 pp. Boston, Elsevier (2012)
20. Cox, A.: Geomagnetic reversals. Science **163**, 237–245 (1969)
21. Gordin, V.M.: Selected Works and Memories, 138 pp. IFZ RAN (2007) (in Russian)
22. Cande, S.C., LaBrecque, J.L.: Behavior of the Earth's paleomagnetic field from small scale marine magnetic anomalies. Nature **247**, 26–28 (1974)
23. Agrinier, P., Gallet, Y., Lewin, E.: On the age calibration of the geomagnetic polarity time scale. Geophys. J. Int. **137**, 81–90 (1999)
24. Malinverno, A., Hildebrandt, J., Tominaga, M., Channell, J.E.T.: M-sequence geomagnetic polarity time scale (MHTC12) that steadies global spreading rates and incorporates astrochronology constraints. J. Geophys. Res. **117**(B6), B06104 (2012). https://doi.org/10.1029/2012jb009260
25. De Vleeschouwer, D., Parnell, A.C.: Reducing time-scale uncertainty for the Devonian by integrating astrochronology and Bayesian statistics. Geology **42**, 491–494 (2014)
26. Merkouriev, S., DeMets, C.: Constraints on Indian plate motion since 20 Ma from dense Russian magnetic data: implications for Indian plate dynamics. Geochem. Geophys. Geosyst. **7**, Q02002 (2006). https://doi.org/10.1029/2005gc001079
27. Seton, M., et al.: Community infrastructure and repository for marine magnetic identifications. Geochem. Geophys. Geosyst. **15**, 1629–1641 (2014)

28. Wilson, D.S.: Confirmation of the astronomical calibration of the magnetic polarity timescale from sea-floor spreading rates. Nature **364**, 788–790 (1993)
29. Ivanov, S.A., Merkuriev, S.A.: Preliminary results of the geohistorical and paleomagnetic analysis of marine magnetic anomalies in the Northwestern Indian Ocean. In: Nurgaliev, D., Shcherbakov, V., Kosterov A., Spassov, S., (eds.) Recent Advances in Rock Magnetism, Environmental Magnetism and Paleomagnetism, pp. 479–490. Springer, Cham (2019)
30. Lourens, L., Hilgen, F.J., Laskar, J., Shackleton, N.J., Wilson, D.: The neogene period. In: Gradstein, F., Ogg, J., Smith, A. (eds.) A Geologic Time Scale 2004, pp. 409–440. Cambridge University Press, New York (2004)
31. Wessel, P., Smith, W.H.F.: Free software helps map and display data. Eos Trans. AGU **72**, 441–446 (1991)