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Quantifying Stratigraphic Completeness: A Probabilistic Approach Using Paleomagnetic Data[1]

Thomas J. Algeo

H. N. Fisk Laboratory of Sedimentology, Department of Geology, University of Cincinnati, Cincinnati, OH 45221-0013

ABSTRACT

Although sedimentary hiati of variable magnitude are abundant in most stratigraphic sections, quantification of the degree of completeness for individual sections has proven difficult. A new method of estimating stratigraphic completeness is developed for sections that preserve a detrital remanent magnetic reversal history. Because the timing of geomagnetic reversals is independent of sedimentation events, the distribution of reversals in a stratigraphic section can be used to evaluate completeness. The most direct method, in which sections are sampled at the top and base of each stratigraphic unit, evaluates the frequency of reversals within units versus at unit contacts. The more complete a section, the greater the probability that reversals occurred during depositional events and are recorded as within-unit reversals; the less complete a section, the greater the probability that reversals occurred during depositional hiati and are recorded as unit-contact reversals. Monte Carlo simulations suggest that, under favorable conditions, completeness estimates fall within ±5% of the actual completeness value 68% of the time. The technique works best for intervals where the relative frequency of magnetic reversals to stratigraphic units is between 1:8 and 2:1. Given Cenozoic reversal frequencies of ca. 1–5/m.y., the method has the potential to quantify completeness in sections where the average recurrence interval for stratigraphic units is between 25 ka and 2 m.y., or roughly the range of many parasequences and sequences. For sections that cannot be tied to an established magnetic reversal stratigraphy, the method also permits estimation of *magneto*stratigraphic completeness, i.e., the fraction of the total number of magnetic reversals during a given time interval that are recorded at least in part, offering a means of evaluating potential magnetostratigraphic reference sections for the pre-Late Jurassic.

Introduction

Stratigraphic completeness, i.e., the fraction of total time represented by some increment of sediment in a stratigraphic section, has long interested geologists owing to its bearing on a variety of fundamental geologic problems (e.g., Barrell 1917). In sedimentology, the completeness of a rock sequence is an important consideration in assessing original environments of deposition (e.g., Is the rock record biased toward continuous processes such as tides or rare events such as storms?: Dott 1983). In paleontology, knowledge of stratigraphic completeness is essential to evaluating such important issues as punctuated versus gradualistic models of evolution (e.g., McKinney 1985; MacLeod 1991), normal versus elevated rates of extinction (e.g., Behrensmeyer and Schindel 1983; Dingus 1984), and incompleteness of taxon ranges (e.g., McKinney 1986). In paleomagnetism, reconstruction of the earth's geomagnetic reversal history during the Paleozoic and early Mesozoic (e.g., Hailwood 1989) is dependent on identification of relatively complete reference sections (e.g., Hall and Butler 1983; May et al. 1985).

The stratigraphic record is generally regarded as rather incomplete (e.g., Sadler 1981). A variety of graphical and mathematical models illustrate the episodic nature of sediment accumulation (e.g., Tipper 1983; Crowley 1984; Friend et al. 1989; Sadler and Strauss 1990), and some of these apply to studies of "unsteadiness," or variability in sediment accumulation rates, in various stratigraphic sections (e.g., Beer 1990; McRae 1990). Quantification of the actual degree of completeness of an individual section has proven extraordinarily difficult, however. The most widely applied method of estimating completeness is based on the ratio of long-term accumulation rate for a section of inter-

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est to average short-term sedimentation rate for the same type of depositional environment (e.g., Reineck 1960; Sadler 1981; Schindel 1982; Dingus 1984; McShea and Raup 1986; Allmon 1989; McRae 1990). This method is flawed owing to problems in ascertaining meaningful average short-term sedimentation rates for most depositional environments (Anders et al. 1987). Statistical approaches to examining "polarity completeness" or "magnetostratigraphic completeness" (i.e., the degree of preservation of magnetic chrons or reversals in a stratigraphic section: Beer 1990) were developed by Johnson and McGee (1983) and Denham (1984), but these do not address the question of *litho*stratigraphic completeness. Other proposed methods of quantifying stratigraphic completeness either require extraordinary conditions, e.g., presence of tiered trace-fossil assemblages (Wetzel and Aigner 1986), or have limited application, e.g., measurement of excess activity of ^{234}Th, ^{228}Th, or ^{210}Pb in sediments less than 100 years old (McKee et al. 1983; Crusius and Anderson 1992).

This paper presents a new method of quantifying stratigraphic completeness using probability theory and paleomagnetic data. The method is feasible owing to the independent occurrence of depositional events (controlled by earth-surface processes) and reversals of the earth's magnetic field (controlled by convection in the outer core and dynamics of the core-mantle boundary; e.g., Loper 1992). Depositional events represent discrete intervals of time during which genetically related sediment packages are deposited more-or-less continuously at a given locale. Paleomagnetic reversals are rapid on a geologic timescale (4–5 ky, Merrill and McElhinny 1983; 8–10 ky, Fuller et al. 1979) and represent, for present purposes, single points in time. Random temporal distribution of reversals (Cox 1968; McFadden 1984) results in an unbiased sampling of depositional versus hiatal time.

The independence of depositional events and geomagnetic reversals permits estimation of stratigraphic completeness because the relative frequency of reversals within stratigraphic units versus at unit contacts reflects the relative proportion of depositional versus hiatal time. Conceptually, the more complete a section, the greater the probability that reversals occurred during depositional events and are recorded as within-unit reversals; the less complete a section, the greater the probability that reversals occurred during depositional hiati and are recorded as unit-contact reversals. The relationship between stratigraphic completeness and reversal frequency can be mathematically defined using probability theory.

Estimation of Stratigraphic Completeness Using Paleomagnetic Data

Definition of Stratigraphic Unit. Stratigraphic sections are generally comprised of units representing individual, more-or-less continuous depositional events (e.g., beds) or genetically related packages of events (e.g., cycles) separated by sharp contacts representing depositional hiati of greater duration than any diastems within the depositional unit (figure 1). The viability of the method developed is thus dependent on careful stratigraphic analysis of the section of interest. The goal of this analysis must be to divide the section into separate units of approximately equal "stratigraphic rank" based on: (1) the degree of development of unit contacts, and (2) genetic relatedness of the enclosed sedimentary packages. In this regard, Schwarzacher and Fischer's (1982) approach to hierarchical categorization of bed contacts, using features such as lateral continuity, topographic expression, and the presence or absence of shaly/cherty interbeds, may be useful. With respect to the genetic relatedness of stratal packages, sections may be analyzed with a sequence stratigraphic framework and subdivided into parasequences or sequences (e.g., Van Wagoner et al. 1990).

Sample Transition Types. For any stratigraphic section with preserved detrital remanent magnetization, a corresponding paleomagnetic reversal

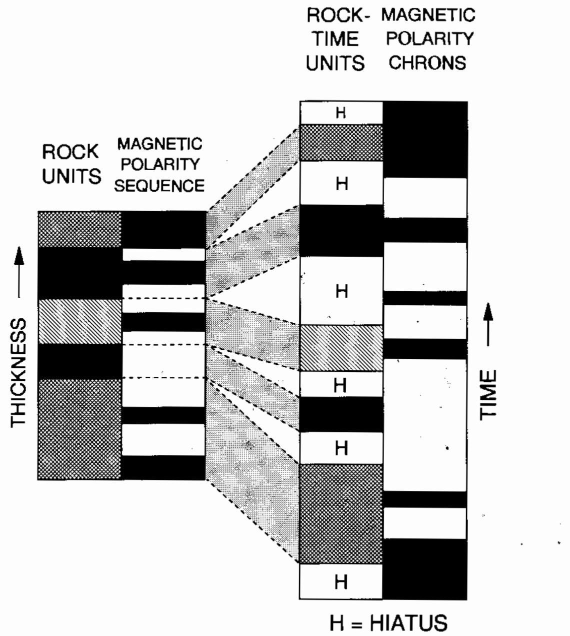

Figure 1. Synthetic stratigraphic section. Rock and magnetostratigraphic columns (left) are scaled in units of thickness; rock-time and magnetic polarity columns (right) are scaled in units of time. H = hiatus.

stratigraphy can be determined, in which some reversals occur at unit contacts and some within units. This results from the random distribution of reversals with respect to depositional events, as a consequence of which some magnetic chrons are recorded completely or in part, while others coincide entirely with depositional hiati and are not recorded at all (figure 1). As this method of estimating stratigraphic completeness is based on the relative frequency of occurrence of magnetic reversals within units versus at unit contacts, it is necessary to first tabulate reversal frequencies. In all, four types of relationships are possible between successive samples in a stratigraphic section. Samples may be collected either within the same unit or across a unit contact (stratigraphic relationship) and may exhibit either the same polarity or reversed polarity (paleomagnetic relationship), defining a matrix of four possible outcomes: (1) within-unit constant polarity (*W* transitions), (2) within-unit reversed polarity (*X* transitions), (3) unit-contact constant polarity (*Y* transitions), and (4) unit-contact reversed polarity (*Z* transitions; figure 2).

Only *X* and *Z* transitions are useful for completeness analysis. The frequency of within-unit same-polarity (*W*) transitions is mainly a function of sampling density (i.e., an infinite number of samples will produce an infinite number of *W* transitions) and, therefore, provides no meaningful information regarding completeness. The frequency of unit-contact same-polarity (*Y*) transitions, while meaningful, varies inversely with the number of unit-contact reversed-polarity (*Z*) transitions owing to the fixed number of unit contacts in a stratigraphic section, and, consequently, no additional information is gained. Owing to differences between stratigraphic sections in number of contained units, it is necessary to normalize *X* and *Z* transition tallies to a per-unit basis by dividing by the total number of units (N_s) in the section of interest, yielding the normalized reversal frequencies $\overline{X}$ and $\overline{Z}$.

Sampling Strategy. Two general sampling strategies are possible to determine stratigraphic and paleomagnetic relations between successive samples. "Top-base sampling" is a selective strategy based on determination of magnetic orientations at the top and base of each stratigraphic unit (e.g., figure 2), thus attempting to evaluate the full time interval represented by each depositional unit with a minimum number of samples. This method automatically identifies all unit-contact reversals (*Z* transitions) but does not attempt to locate all within-unit reversals (*X* transitions). In contrast, "total sampling" calls for densely distributed samples within stratigraphic units to identify all within-unit reversals (*X* transitions). It is time-consuming and generally adds little information to that from top-base sampling. Therefore, subsequent discussion focuses on the use of a top-base sampling strategy for estimation of stratigraphic completeness.

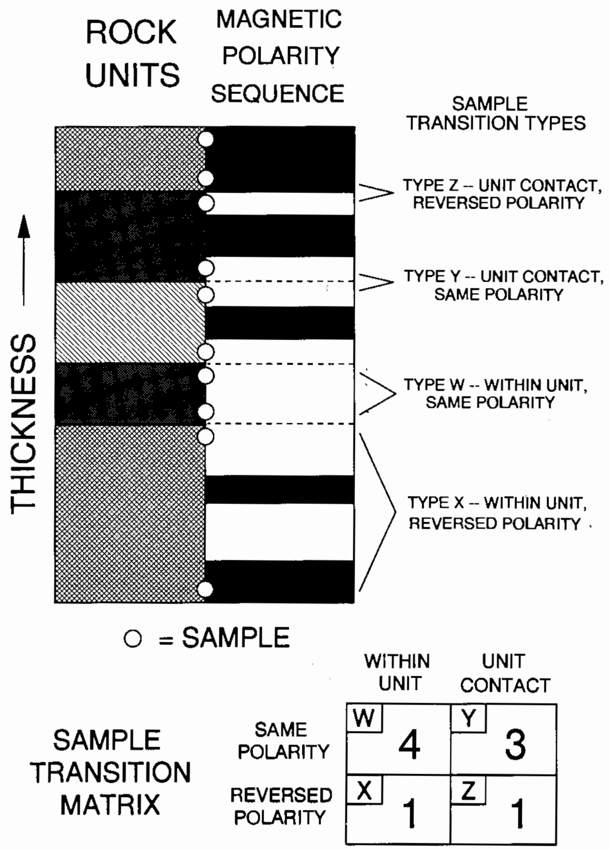

Figure 2. Sample transition types. Successive samples are located either within the same unit or across a unit contact (stratigraphic relationship) and exhibit either the same or reversed polarity (paleomagnetic relationship), defining a matrix of four possible outcomes (lower right). For the five lithostratigraphic units shown, a total of nine transitions occur between the ten successive samples taken at the top and base of each unit.

Probability Model. The relative frequency of *X* and *Z* transitions can be determined for different levels of completeness using a probability model. The conceptual basis of the model is a time interval of arbitrary duration composed of: (1) a series of alternating periods of deposition and nondeposition (with any desired distribution) that, cumulatively, represent fixed proportions of the total time interval (C and $1 - C$, respectively), and (2) a series of randomly distributed magnetic reversals (i.e., exhibiting an exponential distribution for chron durations). The temporal distribution of stratigraphic units is not important as the random distribution of magnetic reversals assures that no relationship exists between these parameters. The number of stratigraphic units (N_s) and magnetic reversals (N_r) within the entire time interval (i.e., including hiati) defines the relative frequency of magnetic reversals to stratigraphic units (N_r:N_s). The total reversals within stratigraphic units (X) and within hiati (Z) are directly proportional to the total number of reversals (N_r) and are linear functions of stratigraphic completeness (C; ranging from 0 to 1):

$$X = N_r * C \tag{1}$$

$$Z = N_r * (1 - C) \tag{2}$$

Similarly, the normalized frequencies of within-unit ($\overline{X}$) and unit-contact reversals ($\overline{Z}$) are directly proportional to the ratio of magnetic reversals to stratigraphic units (N_r:N_s) and are linear functions of completeness:

$$\overline{X} = (N_r : N_s) * C \tag{3}$$

$$\overline{Z} = (N_r : N_s) * (1 - C) \tag{4}$$

A "total" sampling strategy, in which all within-unit reversals (X) are identified through dense sampling, would yield a normalized reversal frequency ($\overline{X}$) based on equation 3 (figure 3*a*, dashed lines). Equation 4 (figure 3*b*, dashed lines) has no utility in practice because the total number of between-unit reversals (Z) cannot be determined owing to the impossibility of recognizing multiple reversals within a hiatus.

In contrast a "top base" sampling strategy can-

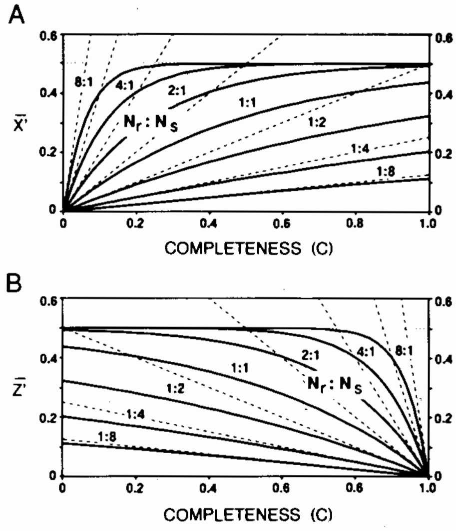

Figure 3. Relationships between stratigraphic completeness (C), ratio of magnetic reversals to stratigraphic units (N_r:N_s), and the normalized reversal frequencies $\overline{X}'$ (top) and $\overline{Z}'$ (bottom). The dashed lines represent normalized within-unit ($\overline{X}$) and unit-contact ($\overline{Z}$) reversal frequencies assuming a "total" sampling scheme, in which the number of reversals per unit would be directly proportional to N_r:N_s ratio (equations 3 and 4). Although possible to estimate $\overline{X}$ through dense sampling of a stratigraphic section, $\overline{Z}$ cannot be determined owing to the impossibility of identifying multiple reversals at a single hiatus. In contrast, the solid lines represent normalized within-unit ($\overline{X}'$) and unit-contact ($\overline{Z}'$) reversal frequencies for a "top-base" sampling scheme (equation 8), which yields reversal frequencies smaller than $\overline{X}$ and $\overline{Z}$, respectively, owing to multiple (and thus uncounted) reversals within some units and at some unit contacts (see figure 4). The number of uncounted reversals increases for large values of N_r:N_s. Note that: (1) normalized within-unit reversal frequency ($\overline{X}'$) is greater at higher levels of completeness, (2) normalized unit-contact reversal frequency ($\overline{Z}'$) is greater at lower levels [illegible]

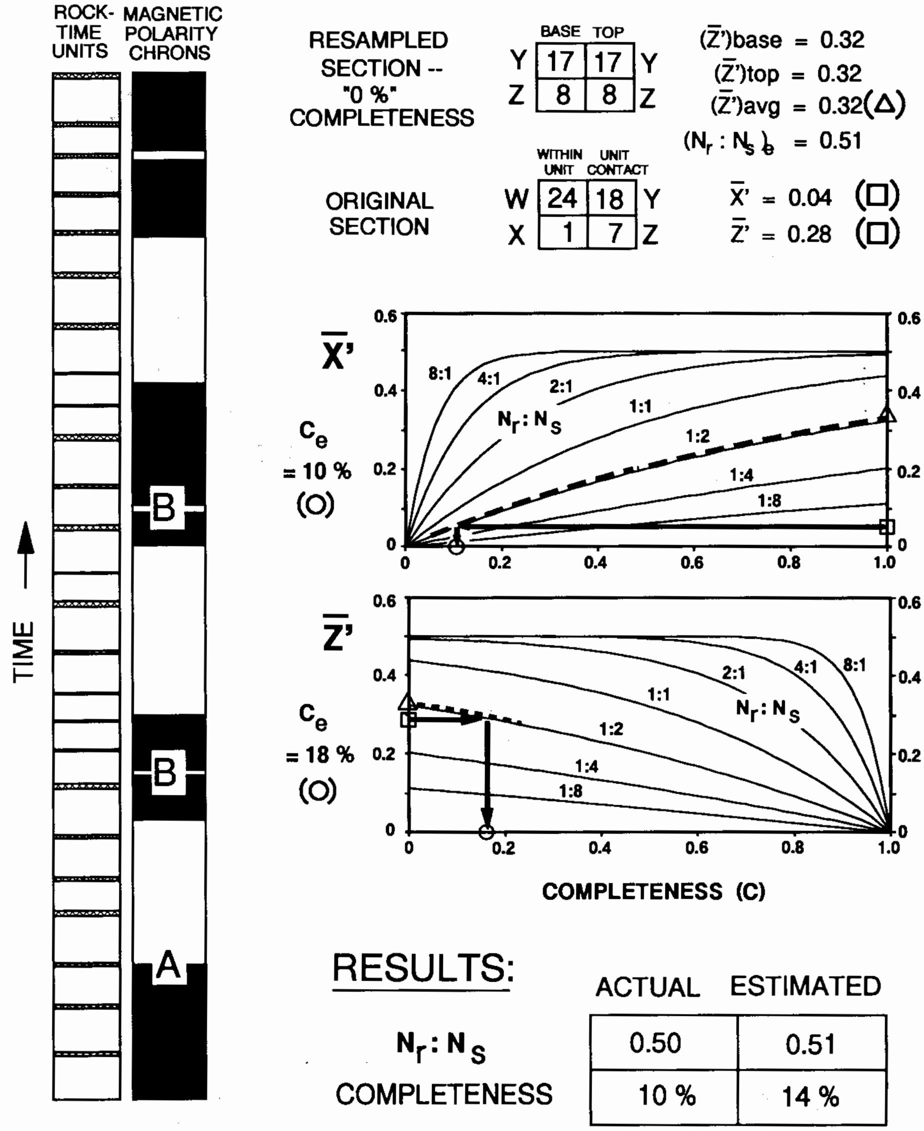

Figure 6. Example of estimation of completeness (C_e) for a synthetic stratigraphic section comprised of 25 rock units exhibiting an actual completeness (C) of 0.10 and a N_r:N_s ratio of 0.50 (model input parameters). The first step is to estimate $(N_r$:$N_s)_e$ through resampling: both unit-top and unit-base samples exhibit 8 reversals in 25 transitions for an average normalized unit-contact reversal frequency at "0%" completeness, i.e., $\bar{Z}'(0)$, of 0.32, which corresponds to a $(N_r$:$N_s)_e$ ratio of 0.51 (triangles). The second step is to calculate normalized within-unit ($\bar{X}'$) and unit-contact ($\bar{Z}'$) reversal frequency values (0.04 and 0.28, respectively; squares) based on X and Z transition tallies for the entire section (1 of 25 within-unit transitions, and 7 of 25 unit-contact transitions, respectively). The third step is to locate the intersection of the $(N_r$:$N_s)_e$ curve (0.51) with the values of $\bar{X}'$ (0.04) and $\bar{Z}'$ (0.28), yielding two estimates of completeness (C_e) read directly from the abscissa (0.10 and 0.18, respectively; circles). These estimates are averaged to yield a final best estimate of completeness (0.14). Note that, in this example, both $(N_r$:$N_s)_e$ (0.51) and C_e (0.14) are in good agreement with the model input parameters N_r:N_s (0.50) and C (0.10). Both the low number of within-unit reversals (1, i.e., A in magnetic polarity column) and the low degree of undercounting of reversals (4, i.e., B in magnetic polarity column) are due to the low actual degree of completeness of the section (0.10).

attached to completeness estimates is smaller than that shown in figures 7 and 8.

Temporal Scales and Stratigraphic Resolution. Completeness is commonly considered to be dependent on the time scale of observation (Sadler 1981; Sadler and Strauss 1990). Thus, a section that is complete at a specified time scale (τ), e.g., 1 m.y., is one in which some sediment was deposited during every 1 m.y. interval throughout the period of interest. Although such a section might be complete at $\tau = 1$ m.y., it is certain to be less complete at smaller values of τ, e.g., many 1 ka intervals probably lack any measurable accumulation of sediment. A definition of completeness with respect to such a temporal "yardstick" is rigorous but unworkable in the real world, except for very large values of τ.

The method developed in this paper is not dependent on specification of a temporal yardstick (τ) in order to estimate stratigraphic completeness. The probability model and Monte Carlo simulation are scale invariant, i.e., resultant completeness estimates are identifical regardless of the time units selected for the lithostratigraphic and magnetostratigraphic columns (e.g., figure 1). The only parameters which control completeness estimates are the actual degree of completeness (C) and the *relative* frequency of magnetic reversals and stratigraphic units (N_r:N_s), which is a non-dimensional parameter. However, when applied to real stratigraphic sections, the resulting completeness estimates are valid only with respect to the time scale of magnetic reversals and depositional events within that section, and, therefore, with respect to some value of τ. The approximate value of τ can be determined as outlined below.

A difference exists between the formal definition of completeness (e.g., Sadler and Strauss 1990) and the practical application developed herein. Specifically, in utilizing a "top-base" sampling strategy, it is implicitly assumed here that sedimentation was "continuous" during the time interval between deposition of the basal layer and the top layer of a unit. In theory, every stratigraphic unit includes a spectrum of "intraformational" hiati of short duration, causing values of τ shorter than the duration of that unit to yield reduced estimates of completeness for the section as a whole (e.g., Sadler and Strauss 1990). Conversely, values of τ larger than the duration of that unit will yield progressively larger estimates of completeness owing to incorporation of hiatal time. Thus, Sadler and Strauss' τ yields a completeness value equal to the completenesses estimated herein only when τ is equal to the duration of stratigraphic units. If all units in a stratigraphic section have the same duration, τ is exactly equal to that duration. For the (more likely) case in which units are of unequal duration, an exact value of τ cannot be determined. However, the best estimate of τ, i.e., τ_e, is the *average* duration of stratigraphic units in a section of interest. This can be calculated for sections using the method developed herein as a function of the total time interval covered by the section (T), the number of stratigraphic units within the section (N_s), and estimated stratigraphic completeness (C_e):

$$\tau_e = T * C_e / N_s \tag{10}$$

Although estimation of C_e is not dependent on specification of τ (but only on the dimensionless variables N_r:N_s, $\overline{X}'$, and $\overline{Z}'$), C_e can be related to τ through the average duration of the stratigraphic units under study. As mentioned above, when applied to real stratigraphic sections, completeness estimates (C_e) are only valid with respect to some value of τ. Although the investigator cannot define the temporal "yardstick" (τ) at which completeness is estimated, it is nonetheless possible to determine an approximate value for τ for individual stratigraphic sections within the framework of this model.

Many geologic intervals exhibit a characteristic mean reversal frequency, and the temporal scale of depositional processes that may be examined using the proposed method is constrained by this frequency and the range of useful N_r:N_s ratios. For example, for a time interval with an average reversal frequency of 1/m.y., the method could usefully be applied to sections in which the average recurrence interval of stratigraphic units (i.e., average time from the base of one unit to the next, including both depositional and hiatal time) is from about 125 ka (1:8) to 2 m.y. (2:1; table 1).

Geomagnetic reversals are commonly modeled

Table 1. Average Recurrence Interval of Stratigraphic Units

	Reversal frequency per m.y.		
N_r:N_s[a]	1	3	5
1:8	.125[b]	.042	.025
1:2	.50	.17	.10
2:1	2.0	.67	.40

[a] N_r:N_s = relative frequency of magnetic reversals to stratigraphic units within a given time interval.
[b] Recurrence intervals of stratigraphic units given in m.y.

as a time-dependent Poisson process (Marzocchi and Mulargia 1992). Although the length of any given chron is independent of that of preceding chrons, mean reversal frequency exhibits long-term (>10 m.y.) secular variation. Based on the geomagnetic reversal chronology of Harland et al. (1990), the frequency of reversals declines from about 5/m.y. at present to 0/m.y. at 85 Ma, the start of the Cretaceous normal superchron (figure 9). For the Late Jurassic-Early Cretaceous, an M-series of geomagnetic reversals has been established (Hailwood 1989; Harland et al. 1990) which exhibits an increase in reversal frequency from 0/m.y. at 124 Ma to 4–5/m.y. at 158 Ma (figure 9).

Given that the frequency of magnetic reversals is well known for much of the Mesozoic and Cenozoic, it is possible to calculate the corresponding range of recurrence intervals for stratigraphic units within which completeness analysis may be successful. In view of the useful range of $N_r : N_s$ ratios (i.e., 1:8 to 2:1), a reversal frequency of 5/m.y. requires that stratigraphic units have an average recurrence interval between 25 and 400 ka, whereas a lower reversal frequency, e.g., 1/m.y., requires average stratigraphic recurrence intervals in the range of 125 ka to 2 m.y. (table 1). The temporal range associated with a reversal frequency of 5/m.y. almost exactly matches that of the Milankovitch orbital periodicities (21–400 ka; Hays et al. 1976), suggesting that this method may be suitable for completeness analysis of many Pleistocene sections subject to orbital modulation (e.g., Moore et al. 1982). In addition, these temporal ranges broadly coincide with those commonly associated with parasequences (10^2–3×10^4 yr), parasequence sets (10^4–3×10^5 yr), and sequences (10^5–3×10^6 yr; Van Wagoner et al. 1990). In this regard, Late Jurassic-Early Cretaceous and Cenozoic reversal frequencies (figure 9) are almost ideally suited for studying completeness within a sequence stratigraphic context. Thus, the method developed herein has the potential to estimate stratigraphic completeness at a resolution more than an order-of-magnitude better than that previously attained through biostratigraphic and magnetostratigraphic methods, which generally are unable to quantify gaps of less than ca. 1 m.y. (e.g., Ledbetter and Ciesielski 1986; Keller and Barron 1987; Allmon 1989).

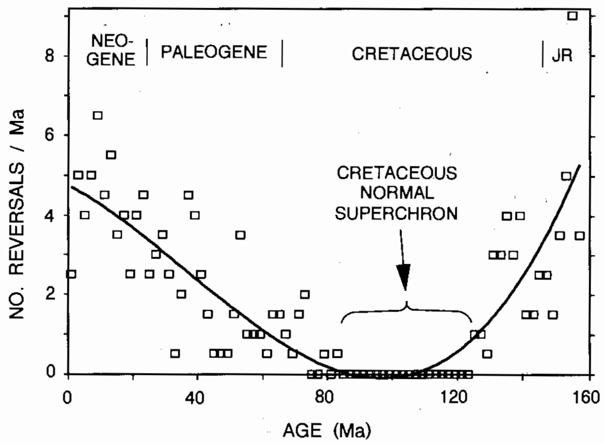

Figure 9. Geomagnetic reversal frequency for the interval from 158 Ma to the present. The frequency of reversals (tallied for successive 2 m.y. intervals; squares) declines from about 4–5/m.y. at 158 Ma to 0/m.y. at 124 Ma, the start of the Cretaceous normal superchron, and increases from 0/m.y. at 84 Ma, the end of the superchron, to about 5/m.y. at present (cf. Marzocchi and Mulargia 1992). Geomagnetic reversal chronology from Harland et al. (1990).

Conclusions

Monte Carlo simulation indicates that uncertainties in completeness estimates in the method developed here are a function of: (1) number of stratigraphic units in the section of interest (large values are best), (2) the ratio of magnetic reversals to stratigraphic units (values between 1:8 and 2:1 are best), and (3) actual completeness (values <0.15 and >0.85 yield the most reliable estimates of completeness). The best estimate of τ, i.e., the temporal "yardstick" for which a completeness estimate is valid, is the *average* duration of stratigraphic units in a section of interest. This can be calculated using the method developed herein as a function of the total time interval covered by the section, the number of stratigraphic units within the section, and its estimated stratigraphic completeness. Completeness estimates can be made independently of τ but are only meaningful when an approximate value of τ has been specified. The applicability of the method is constrained by the average reversal frequency for a given time interval and the useful range of ratios of magnetic reversals to stratigraphic units (1:8 to 2:1). For the Late Jurassic-Early Cretaceous and the Late Cretaceous-present, reversal frequencies of 1–5/m.y. allow the method to be applied to sections with average stratigraphic recurrence intervals in the range of 25 ka to 2 m.y. This range broadly overlaps with that of parasequences and sequences, suggesting potential applications in studying completeness within a sequence stratigraphic context. Estimation of the *magneto*stratigraphic completeness of a section of interest, i.e., the fraction of the total number of magnetic reversals during a given time interval that are recorded at least in part, is possible even for sections that cannot be tied to an established magnetic reversal stratigraphy. This has considerable potential for evaluating potential magnetostratigraphic reference sections for the pre-Late Jurassic.

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