Deriving palaeomagnetic poles from independently assessed inclination and declination data: implications for South American poles since 120 Ma

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SUMMARY

Palaeomagnetic poles for a stable continental block are typically defined from a combination of declination and inclination information from several temporally constrained studies. Poles from regions that have undergone vertical-axis rotation as a consequence of tectonics are excluded due to the absence of declination data. These poles, however, do contain useful information in their inclinations. We develop a simple but statistically rigorous technique allowing palaeomagnetic poles to be calculated from a mixture of declination and inclination data drawn from localities in the stable continental block and inclination data from the regions disturbed by vertical-axis rotation. Together this provides a larger data set of high-quality palaeomagnetic poles from which to calculate reference poles. The technique was used to define palaeomagnetic poles for South America for the Late Cretaceous–Cenozoic (120–5 Ma) period. Data from stable, cratonic South America, combined with data from Africa, rotated into a South America reference frame, and the Andean margin, yield reference poles, as well as mean poles for the Palaeogene and Neogene. Analysis of the data reveals systematic biases in the data set, and, in particular, the fit of the inclination data is poor for most time periods. In many cases, this situation is improved if the effect of inclination shallowing due to sedimentary depositional processes and subsequent compaction is removed. The best-fit poles define an apparent polar wander path for South America that is consistent with the global plate reconstruction parameters. Use of the new poles in studies of tectonic rotation should allow greater temporal and spatial resolution of vertical-axis rotation and offer the ability to identify smaller rotations in the Andean margin.

Key words: apparent polar wander, palaeomagnetism, tectonics.

1 INTRODUCTION

The interpretation of palaeomagnetic data is usually based on the assumption that, when averaged over tens of thousands of years, the Earth has a geocentric axial dipole magnetic field with poles that coincide with the geographical poles. A suite of measurements of remanent magnetism in rocks at a sampling location (hereafter called a palaeomagnetic locality), when averaged to remove the effects of short-term palaeosecular variation of the magnetic field, is potentially capable of recovering the local direction of this average field when the magnetization was acquired. Conventionally, the orientation of the magnetic field is defined in terms of the azimuth of its horizontal projection, referred to as the declination, and its plunge, referred to as the inclination. For a geocentric axial dipole field, the position of a palaeomagnetic pole can be defined from inclination and declination measurements at a particular palaeomagnetic locality. If there has been motion of the palaeomagnetic locality since the magnetization was acquired, this palaeomagnetic pole, will not, in general, coincide with one of the geographical poles. Thus, palaeomagnetic poles provide important information about tectonic displacements or rotations. Temporally restricted palaeomagnetic poles from a large plate form reference poles that can be used to determine motions of crustal blocks in adjacent deformed zones, relative to the cratonic plate.

In this paper, we develop a simple method to determine palaeomagnetic reference poles, using inclination and declination data separately, taking account of the individual uncertainties in the measurements. The advantage of this method is that in certain circumstances it can greatly increase the available data available.
set by incorporating inclination data from deformed zones where local rotations of crustal blocks about a vertical axis may have occurred. In addition, the method provides a way of assessing the existence of systematic biases or uncertainties in the data set. We use our method to investigate the stable South American palaeomagnetic reference poles for the Late Cretaceous and Cenozoic, exploiting the wealth of palaeomagnetic data in the Andean deformed zone.

2 METHODOLOGY

2.1 Palaeomagnetic poles

We assume that the mean declination and inclination of remanent magnetizations at a given palaeomagnetic locality uniquely define the position of a palaeomagnetic pole on the Earth’s surface (Fig. 1). For a geocentric axial dipole magnetic field, the mean inclination (I) constrains the angle (Fig. 1a and b), subtended from the centre of the Earth, between the magnetic pole and the palaeomagnetic locality, referred to as the palaeomagnetic colatitude (θ),

\[
\tan \theta = \frac{2}{\tan I}.
\]  

(1)

The pole lies along the great circle that passes through the palaeomagnetic locality, with a local azimuth equal to the declination (Fig. 1c).

A palaeomagnetic pole is overconstrained by measurements at several palaeomagnetic localities of the mean direction of remanent magnetization. In this case, a method for calculating a pole that best fits these directions should depend on assumptions about the distribution of errors in the observations. Most palaeomagnetic studies assume a circular cone of confidence to describe the directional uncertainties. The question becomes whether this circular cone of confidence applies to the local mean direction of the magnetic field at the palaeomagnetic locality, or the equivalent mean palaeomagnetic pole. In the former case, the circular cone of confidence for the local field direction will translate into an elliptical cone of confidence for the calculated pole. In the latter case, the circular cone of confidence for the pole translates into an elliptical cone of confidence for the estimate of the local magnetic direction. The colatitude of the palaeomagnetic locality strongly influences

the shape of the confidence region and, when dealing with palaeomagnetic data from equatorial regions, an axially symmetric cone of confidence for the pole implies a highly elliptical confidence cone for the local direction of the magnetic field (Cederquist et al. 1997).

2.2 Merit function

Many studies of palaeomagnetic poles consider poles determined at a range of palaeomagnetic localities. Even for temporally restricted poles from a single craton there will be a scatter in the positions of these poles that reflects the uncertainties in any individual mean pole determination for a particular palaeomagnetic locality (Butler 1992). We need a criterion for deciding upon a palaeomagnetic pole that best fits the data from a range of palaeomagnetic localities, given these uncertainties. The usual criterion in ‘fitting’ problems is some sort of merit function that we seek to minimize in order to determine the most probable solution—this is the basis of least-squares fitting procedures (Press et al. 1992). In order to derive such a criterion for directional data, we begin by assuming that an axially symmetric Fisher probability density function (Fisher distribution) defines the confidence limits we can place on our observed mean direction of a geocentric axial dipole field at a palaeomagnetic locality (see Appendix A). In this case, it is easy to show that, for data with sufficiently tightly specified confidence limits (e.g. 95 per cent confidence angular radius = 95° < 20°) with observed mean inclinations less than ~75° (i.e. palaeomagnetic localities with palaeolatitudes < 60°), the most probable palaeomagnetic pole, given the N means of observations at N palaeomagnetic localities, is the one that minimizes the value of \( \chi^2 \), summed over the N palaeomagnetic localities (see Appendix A),

\[
\chi^2 = \sum_N \left( \frac{I_{\text{obs}} - I_{\text{calc}}}{\sigma_{I_n}} \right)^2 + \sum_N \left( \frac{D_{\text{obs}} - D_{\text{calc}}}{\sigma_{D_n}} \right)^2,
\]  

(2)

where \( I_{\text{obs}} \) and \( D_{\text{obs}} \) are the observed mean inclination and declination of the field at the \( n \)th palaeomagnetic locality, and \( I_{\text{calc}} \) and \( D_{\text{calc}} \) are those calculated from the palaeomagnetic pole, assuming a dipolar magnetic field. The uncertainties at the 68 per cent confidence level in the mean inclination (\( \sigma_{I_n} \)) and declination (\( \sigma_{D_n} \)) measurements at the \( n \)th palaeomagnetic

(c) The declination is defined by the local azimuth of a great circle that passes through the palaeomagnetic pole and the sampling locality. The inclination defines a small circle around the sampling locality, with an angular radius equal to the palaeomagnetic colatitude.
locality are given by (see Appendix A)
\[
\sigma_{D_n} = 0.4 \sin^{-1} \left( \frac{\sin \varphi_n}{\cos I_{obs}} \right) \approx 0.4 \varphi_n \cos I_{obs},
\]
\[
\sigma_{I_n} = 0.4 \sin^{-1} \left( \frac{4 + \tan^2 I}{2} \right)^{1/2},
\]
where \( \varphi_n \) is the angular radius of the 95 per cent confidence cone for the field direction at the \( n \)th palaeomagnetic locality. In eqs (2) and (3), we have a \( \chi^2 \) merit function that we can use to estimate a best-fit pole, given a set of mean inclination and declination measurements and their associated uncertainties at a range of palaeomagnetic localities. We stress, however, that this merit function is only valid strictly speaking for data with moderate to shallow mean inclinations (\( I_{obs} < 75^\circ \)) and relatively tight confidence limits (\( \varphi_n < 20^\circ \)). Given these assumptions, it is easy to show that eqs (2) and (3) can be generalized for the case where the cone of confidence for individual measurements is elliptical, such as a Fisher–Bingham distribution (Kent 1982), rather than axially symmetric. For example, if the mean palaeomagnetic pole corresponding to any particular local magnetic field direction has an axially symmetric cone of confidence (95 per cent confidence angular radius for the palaeomagnetic pole = \( A_{\varphi} \)), then the 68 per cent confidence limits of the mean declination and inclination of the local field direction can be expressed (Butler 1992) as
\[
\sigma_D = 0.4 \sin^{-1} \left( \frac{\sin A_{\varphi}}{\cos I_{obs}} \right) \sqrt{\left(4 + \tan^2 I_{obs}\right)/2}.
\]
\[
\sigma_I = 0.4 A_{\varphi} \left(1 + 3 \cos^2 I_{obs}\right)/2.
\]
Thus, for very shallow inclinations \( \sigma_I \sim 0.8 A_{\varphi} \) and \( \sigma_D \sim 0.4 A_{\varphi} \); for steep inclinations, \( \sigma_I < 0.4 A_{\varphi} \) and \( \sigma_D \sim A_{\varphi} \).

The best-fit palaeomagnetic pole that minimizes \( \chi^2 \) in eq. (2) is most easily found through a grid search of all possible trial palaeomagnetic poles. For each trial pole, we first calculate the corresponding inclinations and declinations of the direction of the magnetic field at all the palaeomagnetic localities and use these values to calculate \( \chi^2 \). The grid search can be carried out at any specified resolution. In this study, we iterate with increments of 1° of latitude and 5° of longitude.

2.3 Using inclination-only or declination-only data

Eqs (2)–(4) suggest a more general method for determining a palaeomagnetic pole using either inclination-only or declination-only data or a variable combination of both these data, assuming a dipolar magnetic field. This is easy to understand geometrically. For example, if we only have declination measurements, we can constrain the pole to lie along great circles that pass through the sample locations, with local azimuths that are the palaeomagnetic declinations (Fig. 2a). These great circles intersect at two antipodal locations, defining the palaeomagnetic poles; two great circles are sufficient. Alternatively, if we only have inclination measurements, we can constrain the pole to lie on small circles about the sample localities, with angular radii equal to the palaeomagnetic colatitudes (eq. 1, Fig. 2b). Inclination measurements from two separated localities will constrain the palaeomagnetic pole to two possible positions defined by the intersection of two small circles (Fig. 2b).

An inclination measurement from a third site, which does not lie on the great circle through the other two sites, will define uniquely the palaeomagnetic pole (Fig. 2b). Westphal (1993) used a similar technique to calculate a pole for the Eocene–Oligocene of Eurasia, using only inclinations. Van der Voo (1992) used a combination of North American cratonic declination and inclination data and rotated inclination data from the Atlantic-bordering continents to constrain the Middle–Late Jurassic North American palaeomagnetic pole better.

Usually in palaeomagnetic studies, the declination and inclination measurements are used together to define the position of the pole uniquely. The value of using declination and inclination measurements independently to define palaeomagnetic poles is that it allows one to reject components of the data that may be systematically biased or unreliable, and also to assess the data critically. For instance, if it is suspected that there has been local rotation of crustal blocks about a vertical axis, then the inclination data can be used without the declination measurements. Conversely, if there is the possibility that the inclination measurements have a systematic bias, perhaps because of compaction-related inclination flattening, then the declination data can still be used. We can also significantly increase the size of the available data set for the determination of a reference palaeomagnetic pole for the boundary of a deformed zone by using the abundant inclination data from the deformed zone itself. In this case, it is necessary to constrain the relative

![Figure 2.](https://academic.oup.com/gji/article-abstract/146/2/349/639317)
horizontal motions of the palaeomagnetic localities. Thus, the approach is dependent on an understanding of the deformation in the region where the palaeomagnetic localities lie (see discussion).

2.4 Goodness of fit

For relatively tight confidence limits, a Fisher distribution for the uncertainties in the local estimate of the true field direction at a particular palaeomagnetic locality is essentially the product of normal probability functions for the uncertainties in the estimates of the mean inclination and declination individually (see eq. A4). This suggests that the \( \chi^2 \) probability function will be a guide to the probability that \( \chi^2 \), as defined in eq. (2), is likely to exceed any particular value. In effect, we are testing how well our model fits the data. To do this, we also need to know the number of degrees of freedom in our fit. Any model can be fitted if there are a sufficient number of parameters that can be adjusted. The minimum number of data needed to define a pole, if we use some combination of both declination and inclination measurements, is two. If the number of fitted parameters is \( N \), then the number of degrees of freedom is \( N - 2 \). As a general guide, we would expect a good fit to have a \( \chi^2 \) value that is roughly the number of degrees of freedom—in this case the calculated declinations and inclinations lie, on average, within one standard deviation of the observations. This corresponds to a probability greater than one in 10 of obtaining a \( \chi^2 \) less than or equal to the observed value (10 per cent \( \chi^2 \) significance level). If our minimum \( \chi^2 \) value is much greater than the number of degrees of freedom, such that the probability of obtaining this value is less than one in 1000 (0.1 per cent significance level), then we might reject the model of a geocentric axial dipole field (Press et al. 1992). Alternatively, if we insist on the model, then we would be forced to conclude that we have underestimated the errors in our observations, or there is a systematic bias. Underestimating the errors by a factor of two, on average, would lead to a fourfold reduction in the \( \chi^2 \) value, and the model might become statistically acceptable.

We can contour the \( \chi^2 \) values for the trial poles used in the grid search. These contours are estimates of the confidence limits around the mean (\( \chi^2_{\text{min}} \)). As a rough guide, the 68 per cent confidence limit corresponds to a change in \( \chi^2 \), from its minimum value, equal to the degrees of freedom (DF). Thus the 68 per cent confidence contour corresponds roughly to the \( \chi^2_{\text{min}} + \text{DF contour} \). The goodness of fit parameter \( F \) for the \( \chi^2 \) value is informally defined as \( [\chi^2_{\text{min}}/\text{DF}]^{0.5} \). If \( F = 1 \), the fit is good, with data being fitted on average within its 68 per cent confidence level. If \( F > 2 \), then the data are being fitted on average outside their 95 per cent confidence level.

By treating declination and inclination independently, we are effectively assuming that the errors in these observations are also independent. This is not true, strictly speaking, because the mean values of both the inclination and the declination, based on a set of palaeomagnetic observations at a single locality, are a function of both the declination and the inclination of the individual measurements. This is because we are dealing with directional data in three dimensions. In addition, the uncertainty in the declination measurement is a function of both the cone of confidence and the mean inclination (\( I \)) itself (eq. 3). Thus, we cannot completely uncouple the inclination from the declination of the magnetic field, although we can significantly weaken the link. For example, if we differentiate eq. (3), we can quantify the dependence of errors in declination (\( \sigma_d \)) on inclination (\( I \)),

\[
d\sigma_d \sim -0.4 \frac{\pi a}{180 \cos I} \sin I \, dl.
\]

Eq. (5) shows that for inclinations less than \( \sim 70^\circ \), the change in the declination uncertainty (\( \sigma_d \)) is only a small fraction of any bias in inclination (\( dl \)). In addition, if we are dealing mainly with one type of data, either inclination or declination, and any systematic bias in the inclination measurements is relatively small (\(< 10^\circ \)), the absolute value of the declination or inclination error is not so important. This is because we are really concerned with the relative, rather than absolute, weighting of the observational data in determining the ‘best-fit’ pole. We can verify the uncertainties in our estimate of the ‘best-fit’ pole by using a Monte Carlo technique to produce multiple realizations of the observational data, given the statistics of the data uncertainties.

3 TESTING THE METHOD

3.1 Synthetic data

We can test our \( \chi^2 \) minimization procedure for determining the most probable palaeomagnetic pole from mean inclination and declination measurements at a range of palaeomagnetic localities by analysing sets of synthetic data. We choose a random selection of the palaeomagnetic localities in South America and Africa for which we have actual palaeomagnetic data; we will analyse the actual data in Section 5 to constrain Cenozoic reference poles for South America. We calculate the mean declinations and inclinations of the local magnetic field at all the localities for a single specified palaeomagnetic pole, assuming a geocentric axial dipole field. However, we modify the calculated local directions of the magnetic field for our specified pole by perturbing them randomly (see Appendix A), assuming circular confidence limits, described by a Fisher distribution, for either the estimate of the local field direction or the corresponding pole. We arbitrarily choose a south magnetic pole with longitude and latitude coordinates 330°E and 75°S, respectively. This way, we generate plausible data sets with similar statistics and similar uncertainties to those we might anticipate in our real data set.

3.2 Circular confidence limits for local field direction

We generate a synthetic data set consisting of local field directions for a suite of palaeomagnetic localities (based on a palaeomagnetic pole of 330°E/75°S) using the procedure described in Section 3.1 and assuming circular confidence limits for the estimate of the local direction of the magnetic field at a palaeomagnetic locality, with an \( \alpha_{95} \) of \( \sim 10^\circ \) in all cases. We begin by using the synthetic data set to search for a best-fit pole using both declination and inclination data, minimizing eq. (2). In this case, we retrieve our original pole (330°E/75°S) with a \( \chi^2_{\text{min}} \) of \( \sim 15 \) (Fig. 3c) for 20 degrees of freedom (DF = 20). The contours of equal \( \chi^2 \) value about the minimum value define an elliptical bulls-eye. Each contour defines the region of uncertainty for specific confidence limits; the \( \chi^2 \sim 5 \) (2DF + \( \chi^2_{\text{min}} \)) contour is approximately the 95 per cent uncertainty limit.

We now use the synthetic data set to search for the palaeomagnetic pole using only inclination data. In this case, we are minimizing only the part of eq. (2) that contains inclinations in the numerator. The shape of the confidence limits, defined by
contours of $\chi^2$, is markedly elongate (Fig. 3a), but our original pole ($330^\circ\text{E}/75^\circ\text{S}$) is well within the estimated 68 per cent confidence limit ($DF + x_{\min}^2$). The long axis of the uncertainty ellipse is roughly orthogonal to the great circle that passes through the best-fit pole and the general location of the sample localities; the inclination data provide strong constraints on the direction parallel to the great circle, but less good constraints at right angles to this. If we now use only declination data, minimizing only the term in eq. (2) that contains declinations, the confidence region is highly elongate in a direction at right angles to the long axis of the inclination-only confidence regions (Fig. 3b). Again, our original pole is well within the estimated 68 per cent confidence limit.

We now repeat all of the above analyses with a synthetic data set with the same statistics as above, but a much more restricted distribution of localities. We choose only localities from the central Andes, which have a limited longitudinal distribution of only a few degrees, but $\sim 20^\circ$ spread of latitudes. Using both our synthetic inclination and declination measurements, we retrieve our original pole with a $x_{\min}^2 \approx 35$ for 38 degrees of freedom (Fig. 3d). However, if we use only inclination measurements, we can only constrain the pole at the 68 per cent confidence level to a narrow curved zone that passes through the original pole (Fig. 3f). Likewise, with only declination data, we constrain the pole to a narrow zone, essentially at right angles to the inclination-only zone, and intersecting at the original pole (Fig. 3e). Thus, the success of using only inclination or declination data depends to a large extent on the distribution of the sample localities. These data will always provide important constraints, limiting the pole to a narrow zone, but may not uniquely define the pole if the sample sites are too close together.

### 3.3 Circular confidence limits for the palaeomagnetic pole

We repeat the analysis in Section 3.2 with a synthetic data set generated by perturbing the local direction of the magnetic field at palaeomagnetic localities, assuming circular confidence limits for the estimate of the direction of the corresponding palaeomagnetic pole (for a geocentric axial dipole field), with an $A_{95}$ of $10^\circ$. In this case, the uncertainty limits for the mean inclination and declination of the local field direction at palaeomagnetic localities are defined by eq. (4), with an elliptical cone of confidence for the mean field direction. Our estimates of the
most probable palaeomagnetic pole, using various combinations of inclination and declination data (see Fig. 4), are very similar to those obtained in Section 3.2, validating the method for the more general case where the cone of confidence for the field direction is elliptical rather than circular. However, the best-fit poles, using both inclination and declination data, have circular rather than elliptical confidence limits (Fig. 4c). This is hardly surprising because the synthetic data set was generated in the first place with the assumption of circular confidence limits for the estimate of the palaeomagnetic pole. As before, the uncertainty limits for the best-fit pole, based on either inclination-only or declination-only data for the more restricted localities from the central Andes, form an arcuate zone passing through the original pole (Figs 4d and e).

4 APPLICATION TO SOUTH AMERICA

4.1 Tectonic rotations in the central Andes

Palaeomagnetic studies have played an important role in the development of tectonic models of the Andean margin of South America (e.g. Beck 1988; Hartley et al. 1988; Isacks 1988; Roperch & Carlier 1992; Forsythe & Chisholm 1994; Butler et al. 1995; Randall et al. 1996; Prezzi & Vilas 1998). Measurements of the amount of vertical-axis rotation allow constraints to be placed on the nature and timing of deformational events within the deformation zone. A significant number of studies have now been carried out on Palaeozoic to Pliocene rocks throughout the Andean margin that demonstrate variable amounts of both clockwise and anticlockwise vertical-axis rotation with insignificant latitudinal shift for Mesozoic and older rocks (e.g. Beck 1988; Beck et al. 1994; Somoza et al. 1996; Randall 1998). The amount of vertical-axis rotation is obtained by comparing the palaeomagnetic data from the deformed zone with reference directions, determined for unrotated data from the stable craton. Many of the Central Andean studies have been carried out in rocks of Cenozoic age, a crucial period in the tectonic development of the Andean margin (Dewey & Lamb 1992; Somoza et al. 1996; Lamb et al. 1997). These studies show small but significant tectonic rotations, generally less than 20°; the small magnitude of the rotations highlights the importance of well-determined reference poles. When the Cenozoic Andean poles are compared with the available cratonic reference poles from South America, some have inclination discrepancies that suggest small, but sometimes statistically significant, amounts of southward latitudinal shift (Randall 1998). However, there is no geological evidence for this and it is difficult to reconcile this observation with...
the Mesozoic data that show no latitudinal displacement. The amount of apparent displacement depends strongly on which reference pole is used, suggesting that the Cenozoic reference poles currently available are not well defined.

The foremost problem with the Cenozoic reference poles for South America is simply the lack of available data; only three high-quality studies are available from the stable craton for the Palaeocene to the Pliocene. Additionally, the amount and rate of apparent polar wander of the South American plate during the period has been disputed (Butler et al. 1991). As a result various authors have used several different reference poles for comparison with Andean data. These include South American crustatic poles (e.g. Hartley et al. 1992; Somoza et al. 1996; Beck 1999), a North American reference pole rotated to South America coordinates (Riley et al. 1993; Butler et al. 1995), the African master curve of Besse & Courtillot (1991) rotated to South America coordinates (Roperch & Carlier 1992; Butler et al. 1995; Aubry et al. 1996; Prezzi & Vilas 1998), a combination of South American and African crustatic poles (Randall 1998) and the present rotation axis (e.g. Beck 1988; MacFadden et al. 1990, 1995; Hartley et al. 1992). There is clearly a need to constrain the South American Cenozoic reference poles better.

4.2 Constraining the South American reference poles

We use our method to investigate the South American reference poles for the Late Cretaceous and Cenozoic, exploiting the inclination data from the extensive Andean data set. The Andean data are likely to be affected by tectonic rotations about a vertical axis, so that declination data from different sample sites would not be expected to define a palaeomagnetic reference pole. However, the palaeomagnetic inclination contains useful information because, if the magnetization is primary, the angle between the direction of the remnant magnetization and the palaeohorizontal (e.g. rock bedding) is a measure of the inclination of the Earth’s field at the time the magnetization was acquired.

The principal objection to using palaeomagnetic data from a deformed zone to determine a palaeomagnetic reference pole is that the sample localities have been displaced, as a consequence of the deformation, relative to the stable margin. Indeed, given a reference pole, palaeomagnetic data can be used to constrain this displacement. However, in the case of the central Andes, in Peru, Bolivia and northern Chile, we can confidently constrain the finite motions of material points in the deforming zone relative to stable South America. This is because there is a pronounced bend, up to ~45°, in the topographic and structural trends of the central Andes at the latitudes of Bolivia, defining the Bolivian orocline (Isacks 1988). The obliquity of plate motion during the Cenozoic (Pardo-Casas & Molnar 1987), relative to the trend of the Andes, suggests a component of dextral shear, parallel to the plate margin, at latitudes south of the oroclinal bend at c. 17°S, and sinistral shear further north. However, there is no evidence for a significant change in the style of deformation in the hinge of the bend compared to regions further north or south. The principal deformation is folding and faulting, with fold axes trending subparallel to the trend of the mountain belt, with no evidence for major strike-slip faults with significant displacement (greater than tens of kilometres) parallel to the range or major zones of oblique normal or thrust faulting.

To avoid strain incompatibility in the hinge of the Bolivian orocline, the motion of material points must be nearly parallel everywhere, both north and south of the hinge. All this suggests that displacement is essentially parallel to the relative plate convergence vector, as is observed for deformation since the Late Miocene (Lamb 2000), with displacements up to 350 km for those parts of the high Central Andes furthest away from the stable South American plate. In this case, the latitudinal shift of even the most displaced parts of the deforming zone, relative to stable South America, will be much less than 1° northwards, whilst the longitudinal shift is less than 4° eastwards. These displacements will have a negligible effect on estimates of reference poles using inclination-only data, although they have been taken into account when fitting data to a best-fit pole in this study.

4.3 Palaeomagnetic data selection

Data have been selected from the literature and assessed using the following strict criteria (Tables 1 and 2). All palaeomagnetic selection criteria are necessarily arbitrary, and the strictness that can be applied to a given data set is a function of the general quality and amount of data available. The criteria used here are designed to ensure that, as far as possible, we are confident that the palaeomagnetic data reflects the Earth’s average magnetic field direction, over tens of thousands of years, at a specified time in the past. Some of these data assume circular confidence limits for the estimate of the local mean field direction (angular radius of 95 per cent cone of confidence = a95). However, other data assume circular confidence limits for the estimate of the calculated mean palaeomagnetic pole for a palaeomagnetic locality, given the local mean inclination and declination measurements (angular radius of 95 per cent cone of confidence = A95).

Selection criteria:
(1) the age of sampled units is known to within 15 Myr;
(2) mean palaeomagnetic directions or poles for individual localities are calculated from at least six sites or 36 samples;
(3) palaeomagnetic directions or poles have an a95 or A95 <15° (although most are <10°);
(4) palaeomagnetic analysis involves laboratory demagnetization;
(5) the structural context of the sample locality is well defined;
(6) there is evidence that the recovered magnetization is primary; this will involve a range of tests such as a fold test or evidence for reversed polarity; however, reversals are not expected in rocks between 84 and 120 Myr in age, as any primary magnetization would have been acquired during the Cretaceous normal polarity superchron;
(7) there are no obvious systematic biases in the data, discussed by the authors, such as problems with averaging of palaeosecular variation or geological evidence for latitudinal displacements.

We restrict our analysis to the period 5–120 Ma, which is the most critical for understanding the tectonic evolution of the Andes. The strict nature of our criteria means that many palaeomagnetic studies have been rejected. However, poorly constrained data may obscure the analysis. We use 30 data items from the Andes in the latitude range 13°S–35°S; the longitude range is more restricted between 65°W and 74°W.

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### Table 1. Palaeomagnetic data for 5–120 Ma localities from the Andean margin of South America.

<table>
<thead>
<tr>
<th>Location</th>
<th>Age range (Ma)</th>
<th>N*</th>
<th>Palaeomagnetic locality</th>
<th>Palaeomagnetic pole</th>
<th>Palaeomagnetic direction</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catamarca Sediments, Argentina</td>
<td>3–8</td>
<td>5.5</td>
<td>99</td>
<td>–27</td>
<td>294</td>
<td>30</td>
</tr>
<tr>
<td>Ocos Dyke Swarm, Peru</td>
<td>5–7</td>
<td>6</td>
<td>25</td>
<td>–13</td>
<td>286</td>
<td>75</td>
</tr>
<tr>
<td>Sierra de Huaco, Argentina</td>
<td>3–10</td>
<td>6.5</td>
<td>212</td>
<td>–30</td>
<td>292</td>
<td>81</td>
</tr>
<tr>
<td>Micaña, Bolivia</td>
<td>6–8</td>
<td>7</td>
<td>25</td>
<td>–18</td>
<td>293</td>
<td>84</td>
</tr>
<tr>
<td>Sediments and ignimbrites, Chile</td>
<td>5–12</td>
<td>8.5</td>
<td>11</td>
<td>–21</td>
<td>292</td>
<td>84</td>
</tr>
<tr>
<td>Liptiyoc, Argentina</td>
<td>~9</td>
<td>9</td>
<td>17</td>
<td>–23</td>
<td>293</td>
<td>86</td>
</tr>
<tr>
<td>Sierra de Huaca, Argentina</td>
<td>~10</td>
<td>10</td>
<td>8</td>
<td>–27</td>
<td>294</td>
<td>75</td>
</tr>
<tr>
<td>Quehun, Bolivia</td>
<td>8–13</td>
<td>10.5</td>
<td>25</td>
<td>–20</td>
<td>293</td>
<td>76</td>
</tr>
<tr>
<td>Totorah Fm. mean, Bolivia</td>
<td>9–14</td>
<td>11.5</td>
<td>69</td>
<td>–18</td>
<td>292</td>
<td>76</td>
</tr>
<tr>
<td>Quebrada Honda, Bolivia</td>
<td>11.5–12.5</td>
<td>12</td>
<td>79</td>
<td>–22</td>
<td>295</td>
<td>73</td>
</tr>
<tr>
<td>Lipez, Bolivia</td>
<td>~20</td>
<td>20</td>
<td>15</td>
<td>–22</td>
<td>293</td>
<td>54</td>
</tr>
<tr>
<td>Salla, Bolivia</td>
<td>20–24</td>
<td>22</td>
<td>72</td>
<td>–17</td>
<td>292</td>
<td>85</td>
</tr>
<tr>
<td>Santa Lucia Fm., Tapiapa, Bol.</td>
<td>58–60</td>
<td>59</td>
<td>7</td>
<td>–18</td>
<td>295</td>
<td>77</td>
</tr>
<tr>
<td>Santa Lucia Fm., Sucuma, Bol.</td>
<td>58–60</td>
<td>59</td>
<td>8</td>
<td>–18</td>
<td>294</td>
<td>56</td>
</tr>
<tr>
<td>Cerro Valiente sequence, Chile</td>
<td>55–63</td>
<td>59</td>
<td>9</td>
<td>–27</td>
<td>291</td>
<td>27</td>
</tr>
<tr>
<td>Umayo Fm., Laguna Umayo, Bol.</td>
<td>55–65</td>
<td>60</td>
<td>13</td>
<td>–16</td>
<td>290</td>
<td>50</td>
</tr>
<tr>
<td>Agua Dulce limestones, Bol.</td>
<td>60–70</td>
<td>65</td>
<td>7</td>
<td>–20</td>
<td>293</td>
<td>62</td>
</tr>
<tr>
<td>Cochabamba limestones, Bol.</td>
<td>60–70</td>
<td>65</td>
<td>25(4)</td>
<td>–18</td>
<td>293</td>
<td>65</td>
</tr>
<tr>
<td>Otavi limestones, Bol.</td>
<td>75–85</td>
<td>80</td>
<td>15(3)</td>
<td>–20</td>
<td>295</td>
<td>77</td>
</tr>
<tr>
<td>Camargo limestones, Bol.</td>
<td>60–70</td>
<td>65</td>
<td>21(3)</td>
<td>–21</td>
<td>295</td>
<td>78</td>
</tr>
<tr>
<td>El Homos limestones, Bol.</td>
<td>60–70</td>
<td>65</td>
<td>12</td>
<td>–22</td>
<td>295</td>
<td>59</td>
</tr>
<tr>
<td>Sierra La Dihusa, Chile</td>
<td>62–77</td>
<td>70</td>
<td>7</td>
<td>–27</td>
<td>290</td>
<td>64</td>
</tr>
<tr>
<td>Viñi Fm., Chile</td>
<td>94–104</td>
<td>99</td>
<td>13</td>
<td>–30</td>
<td>289</td>
<td>82</td>
</tr>
<tr>
<td>San Fernando Volcanics, Chile</td>
<td>97–108</td>
<td>103</td>
<td>22</td>
<td>–35</td>
<td>289</td>
<td>75</td>
</tr>
</tbody>
</table>

* Number of sites (localities)
† Angular radius of 95 per cent cone of confidence for local field direction.
Table 2. Palaeomagnetic data for 5–120 Ma cratonic localities in South America and Africa.

<table>
<thead>
<tr>
<th>Location</th>
<th>Age range (Ma)</th>
<th>Age (Ma)</th>
<th>N*</th>
<th>Palaeomagnetic locality†</th>
<th>Palaeomagnetic pole†</th>
<th>Palaeomagnetic direction†</th>
<th>As§ (°)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ngaoundere Plateau, Cameroon</td>
<td>6.5–11</td>
<td>9</td>
<td>8</td>
<td>6 011</td>
<td>83 343</td>
<td>183 0</td>
<td>9</td>
<td>Ubangoh et al. (1998)</td>
</tr>
<tr>
<td>Remédios Fm., Fern. de Noronha, Brazil</td>
<td>8–12</td>
<td>10 17</td>
<td>–4</td>
<td>2 328</td>
<td>86 313</td>
<td>178 –5</td>
<td>8</td>
<td>Schultz et al. (1986)</td>
</tr>
<tr>
<td>Jebel Soda volcanics Comb., Libya</td>
<td>10–13</td>
<td>11.5 24</td>
<td>27</td>
<td>013</td>
<td>75 007</td>
<td>182 –23</td>
<td>6</td>
<td>Ade-Hall et al. (1975)</td>
</tr>
<tr>
<td>Ngorora Formation, Kenya</td>
<td>10–13</td>
<td>11.5 50</td>
<td>–1</td>
<td>032</td>
<td>86 186</td>
<td>178 –5</td>
<td>5</td>
<td>Tauxe et al. (1985)</td>
</tr>
<tr>
<td>East Africa vol., Kenya/Tanzania</td>
<td>11–13</td>
<td>12 22</td>
<td>–2</td>
<td>032</td>
<td>88 318</td>
<td>182 5</td>
<td>9</td>
<td>Reilly et al. (1976)</td>
</tr>
<tr>
<td>Narosura/Magadi volcanics, Kenya</td>
<td>12–15</td>
<td>13.5 14</td>
<td>–4</td>
<td>032</td>
<td>78 214</td>
<td>180 –16</td>
<td>9</td>
<td>Patel &amp; Raja (1979)</td>
</tr>
<tr>
<td>Bamboutou, Cameroon</td>
<td>12–17</td>
<td>15 33</td>
<td>4</td>
<td>006</td>
<td>86 299</td>
<td>184 –5</td>
<td>3</td>
<td>Ubangoh et al. (1998)</td>
</tr>
<tr>
<td>Turkana Lava, Kenya</td>
<td>14–23</td>
<td>18.5 62</td>
<td>–3</td>
<td>030</td>
<td>85 298</td>
<td>185 6</td>
<td>3</td>
<td>Reilly et al. (1976)</td>
</tr>
<tr>
<td>Bamenza-Oku, Cameroon</td>
<td>20–24</td>
<td>22 26</td>
<td>4</td>
<td>003</td>
<td>84 290</td>
<td>186 –5</td>
<td>5</td>
<td>Ubangoh et al. (1998)</td>
</tr>
<tr>
<td>Bamenza-Oku, Cameroon</td>
<td>28–31</td>
<td>29.5 13</td>
<td>3</td>
<td>003</td>
<td>75 326</td>
<td>189 18</td>
<td>10</td>
<td>Ubangoh et al. (1998)</td>
</tr>
<tr>
<td>Ethiopian Traps</td>
<td>29–31</td>
<td>30 53</td>
<td>6</td>
<td>028</td>
<td>82 356</td>
<td>184 2</td>
<td>4</td>
<td>Rochette et al. (1998)</td>
</tr>
<tr>
<td>Passa Quatro/Italiaia intrusives, Brazil</td>
<td>62–74</td>
<td>68 18</td>
<td>–23</td>
<td>030</td>
<td>80 000</td>
<td>352 –49</td>
<td>6</td>
<td>Montes-Laur et al. (1995)</td>
</tr>
<tr>
<td>Patagonian Basalts, Argentina and Chile</td>
<td>64–79</td>
<td>72 18</td>
<td>–46</td>
<td>028</td>
<td>79 358</td>
<td>344 –66</td>
<td>6</td>
<td>Butler et al. (1991)</td>
</tr>
<tr>
<td>Dakhla Shale, Gebel Gilata, Egypt</td>
<td>69–79</td>
<td>74 7</td>
<td>16</td>
<td>007</td>
<td>84 256</td>
<td>186 –33</td>
<td>9</td>
<td>Saradeth et al. (1987)</td>
</tr>
<tr>
<td>Abu Krug Ring Complex, Egypt</td>
<td>87–91</td>
<td>89 6</td>
<td>12</td>
<td>006</td>
<td>73 069</td>
<td>165 –8</td>
<td>13</td>
<td>Resaret et al. (1981)</td>
</tr>
<tr>
<td>Cabo de Santo Agostinho, vol, Brazil</td>
<td>85–99</td>
<td>92 9</td>
<td>–8</td>
<td>035</td>
<td>88 315</td>
<td>000 –21</td>
<td>5</td>
<td>Schult &amp; Guerreiro (1980)</td>
</tr>
<tr>
<td>Wadi Natash Volcanics, Egypt</td>
<td>86–100</td>
<td>93 15</td>
<td>9</td>
<td>038</td>
<td>86 084</td>
<td>176 –17</td>
<td>9</td>
<td>Schult et al. (1981)</td>
</tr>
<tr>
<td>Lupata Volcanics, Mozambique</td>
<td>109–113</td>
<td>111 7</td>
<td>–17</td>
<td>034</td>
<td>82 085</td>
<td>171 53</td>
<td>3</td>
<td>Gough &amp; Opdyke (1963)</td>
</tr>
</tbody>
</table>

* Number of sites
† The palaeomagnetic localities, palaeomagnetic poles and palaeomagnetic directions for the African data have been rotated into a South America reference frame. For times between 120 and 100 Ma, the African blocks have been rotated into South African coordinates prior to rotation into a South America reference frame. Partial rotations were made from the following absolute rotations: northwest Africa to South Africa, 9.34° N, 5.70° E, angle 7.82° clockwise; Morocco to South Africa, 11.06° N, 4.99° E, angle 7.38° clockwise; northeast Africa to South Africa, 16.30° S, 41.71° E, angle 2.53° clockwise; eastern Africa to South Africa, 22.79° S, 40.96° E, angle 3.44° clockwise (all from Lottes & Rowley 1990). For times after 100 Ma Africa is assumed to be a single continental block and no internal rotations have been applied. Euler rotation poles from Africa to South America for times between 120 and 80 Ma are from Klitgord & Schouten (1986) and for times after 80 Ma from Cande et al. (1988).
§ Angular radius of 95 per cent cone of confidence for palaeomagnetic pole.
These data assume circular confidence limits for the estimate of the local mean field direction (angular radius of 95 per cent cone of confidence = $a_{95}$). In addition, we use five data from cratonic South America (Table 2). We can supplement these data by including data from another continent rotated into a South American reference frame. This would not only give a larger data set from which to calculate an average, but would also increase the geographical distribution of the palaeomagnetic localities. When considering South America the most obvious continent is Africa. The reconstruction parameters between the two continents are well constrained for the late Mesozoic and Cenozoic and a significantly larger amount of stable cratonic data are available for Africa. Randall (1998) noted that there were no systematic discrepancies between the cratonic South American and African data sets after rotation, supporting the integrity of the rotation parameters. Although data from other continents could be considered, the cumulative effects of uncertainties in the reconstruction parameters increase the possibilities of systematic discrepancies. The data used in this study are therefore restricted to those available from South America and Africa. We use 20 data items from cratonic Africa (Table 2), which have been recalculated in South American coordinates by removing the effects of relative motion between South America and Africa since the magnetization was acquired, using the relevant plate reconstruction rotation parameters (Klitgord & Schouten 1986; Cande et al. 1988; Lottes & Rowley 1990). The stable South American and African data are referred to hereafter as the cratonic data.

The cratonic data assume circular confidence limits for the estimate of the calculated mean palaeomagnetic pole for a palaeomagnetic locality, given the local mean inclination and declination measurements (angular radius of 95 per cent cone of confidence = $a_{95}$). Therefore, the cones of confidence for the local mean field directions are elliptical and have been calculated from eq. (4).

5 RESULTS

5.1 Time intervals

The palaeomagnetic data have been used to determine average palaeomagnetic reference poles for stable South America in six time intervals: (1) 5–10 Ma, (2) 10–20 Ma, (3) 20–30 Ma, (4) 30–50 Ma, (5) 50–80 Ma and (6) 80–120 Ma. In addition, average poles for the Neogene (5–25 Ma) and Palaeogene (25–65 Ma) have been calculated. All these periods have been selected to make full use of the general age distribution of the data, as well as coinciding with tectonically significant periods in the evolution of the Andes. Thus, the pole for the 50–80 Ma interval provides a palaeomagnetic reference direction just prior to the onset of Cenozoic deformation in the central Andes, whilst the three intervals spanning 5–30 Ma coincide with major phases of Andean deformation (Lamb et al. 1997).

The 80–120 Ma interval provides a broader perspective of the long-term trend of migration of the reference poles.

The data for individual time intervals are analysed in several ways. First, the cratonic data are analysed using either inclination-only measurements or declination-only measurements. This way, we can assess whether these data are internally self-consistent. Second, the cratonic declination and inclination data are used in combination. Third, the Andean data are analysed on their own, using the inclination-only measurements.

This makes it possible to see if there is a systematic misfit between the Andean and cratonic (stable South America and Africa) data. Finally, the Andean inclination data, together with the combined cratonic declination and inclination data, are used to determine a best-fit palaeomagnetic pole for all the available data.

Poles that yield minimum $\chi^2$ values ($\chi^2_{\text{min}}$) are listed in Table 3, together with the number of degrees of freedom and a goodness of fit parameter, $F$. Results are also shown as contoured stereographic plots of $\chi^2$ values (Figs 5–11). An approximate $A_{95}$ is given for best-fit poles based on a combination of inclination and declination data; this is derived from a multiple Monte Carlo realization of the palaeomagnetic data for individual localities, given their uncertainties (see Table 3).

5.2 Late Miocene (5–10 Ma) reference pole

The cratonic declinations and inclinations, used individually, define most-probable palaeomagnetic poles with moderately elliptical uncertainty regions that overlap at the 95 per cent confidence level (Figs 5a and b). Thus, the cratonic declination and inclination data, used together, define a more ‘bull’s eye’ uncertainty region about the $\chi^2$ minimum (Fig. 5c), whilst that for the Andean inclination data is spread out along an approximate small circle (Fig. 5d). The latter is mainly a consequence of the relatively narrow longitude and latitude spread for Andean sample localities, a feature of the Andean data for all the time intervals. The Andean $\chi^2$ minimum overlaps with that of the cratonic data at the 95 per cent confidence level. In other words, all these data are compatible with a uniquely defined dipolar magnetic field. Thus, the global minimum, using both the Andean and cratonic data, is well defined (Fig. 5e), with a fit $F$ of $\sim 2.1$—the data are being fitted, on average, at their 95 per cent confidence limits.

5.3 Early–Middle Miocene (10–20 Ma) reference pole

The cratonic declination and inclination data, used together, define a circular ‘bull’s eye’ uncertainty region about the $\chi^2$ minimum (Fig. 6c). However, the fit is poor, with a fit $F \sim 3.2$. If the cratonic inclinations (Fig. 6a) or declinations (Fig. 6b) are considered separately, it is clear that whilst the declinations provide a good fit ($F = 1.4$), the inclinations can only be very poorly fitted ($F = 4.6$). In addition, the uncertainty region about the $\chi^2$ minimum for the Andean inclination data is spread out along an approximate small circle and does not overlap with that of the cratonic data at the 95 per cent confidence level, or even the 99 per cent level (Figs 6c–e). Thus, although the global minimum, using both the Andean and cratonic data, is well defined, the fit is very poor, with $F = 3.9$. The data are being fitted, on average, well outside their 95 per cent confidence limits.

5.4 Oligo-Miocene (20–30 Ma) reference pole

The general features of the quality of the poles are similar to those for the 10–20 Ma time interval. The fit for combined inclination and declination measurements of the cratonic data (Fig. 7c) is poor, with a fit $F \sim 2.9$. Neither the cratonic inclinations (Fig. 7a) nor the declinations (Fig. 7b), on their own, provide a good fit (the inclination fit is worse with $F \sim 3.9$), and best-fit poles for each of these do not overlap at the 95 per cent confidence limits.

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In addition, the Andean inclination \( x^2 \) minimum does not overlap the cratonic data at the 95 per cent confidence level (Fig. 7d). Thus, although the global minimum, using both the Andean and the cratonic data, is well defined, the fit is poor, with \( F \sim 2.9 \). The data are being fitted, on average, well outside their 95 per cent confidence limits (Fig. 7e).

5.5 Eocene–Oligocene (30–50 Ma) reference pole

Very little data were available for this time interval (three localities), and all these were cratonic. The combined declinations and inclinations define a good ‘bull’s eye’ uncertainty region around the \( x^2 \) minimum (Fig. 8c), although the fit is poor \( (F \sim 2.9) \). This reflects the fact that the 95 per cent uncertainty regions for the poles defined by inclination (Fig. 8a) or declination data (Fig. 8b), used separately, do not overlap.

5.6 Late Cretaceous–Eocene (50–80 Ma) reference pole

Unlike most of the previous Cenozoic time intervals, the fits for this time interval were moderately good. The best-fit pole for the Andean inclination data overlaps at the 95 per cent confidence level. In addition, the Andean inclination \( x^2 \) minimum does not overlap the cratonic data at the 95 per cent confidence level (Fig. 7d). Thus, although the global minimum, using both the Andean and the cratonic data, is well defined, the fit is poor, with \( F \sim 2.9 \). The data are being fitted, on average, well outside their 95 per cent confidence limits (Fig. 7e).

Table 3. Results of various runs for time intervals analysed in this study.

<table>
<thead>
<tr>
<th>Time period</th>
<th>Data*</th>
<th>Lat S</th>
<th>Long E</th>
<th>( x^2 )</th>
<th>DF#</th>
<th>( F_\beta )</th>
<th>( A_{95}^{**} )</th>
<th>After decompaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>5–10 Ma</td>
<td>Crat. I.</td>
<td>85</td>
<td>030</td>
<td>6</td>
<td>1</td>
<td>2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. D.</td>
<td>80</td>
<td>315</td>
<td>2</td>
<td>1</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. I. + D.</td>
<td>85</td>
<td>320</td>
<td>11</td>
<td>4</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Andes I.</td>
<td>86</td>
<td>050</td>
<td>61</td>
<td>14</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Andes + Crat.</td>
<td>86</td>
<td>050</td>
<td>61</td>
<td>14</td>
<td>2.1</td>
<td>3</td>
<td>0.83 87 350 54 14 2.0 5</td>
</tr>
<tr>
<td>10–20 Ma</td>
<td>Crat. I.</td>
<td>82</td>
<td>330</td>
<td>126</td>
<td>6</td>
<td>4.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. D.</td>
<td>86</td>
<td>260</td>
<td>11</td>
<td>6</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. I. + D.</td>
<td>84</td>
<td>345</td>
<td>143</td>
<td>14</td>
<td>3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Andes I.</td>
<td>85</td>
<td>55</td>
<td>7</td>
<td>2.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Andes + Crat.</td>
<td>85</td>
<td>040</td>
<td>353</td>
<td>23</td>
<td>3.9</td>
<td>2</td>
<td>0.63 86 305 142 23 2.5 3</td>
</tr>
<tr>
<td>20–30 Ma</td>
<td>Crat. I.</td>
<td>86</td>
<td>350</td>
<td>31</td>
<td>2</td>
<td>3.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. D.</td>
<td>83</td>
<td>265</td>
<td>18</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. I. + D.</td>
<td>83</td>
<td>315</td>
<td>52</td>
<td>6</td>
<td>2.9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Andes I.</td>
<td>87</td>
<td>355</td>
<td>108</td>
<td>13</td>
<td>2.9</td>
<td>3</td>
<td>0.71 83 310 75 13 2.4 4</td>
</tr>
<tr>
<td>30–50 Ma</td>
<td>Crat. I.</td>
<td>61</td>
<td>305</td>
<td>17</td>
<td>1</td>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. D.</td>
<td>60</td>
<td>020</td>
<td>2</td>
<td>1</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. I. + D.</td>
<td>84</td>
<td>355</td>
<td>33</td>
<td>4</td>
<td>2.9</td>
<td>4</td>
<td>No improvement</td>
</tr>
<tr>
<td>50–80 Ma</td>
<td>Crat. I.</td>
<td>85</td>
<td>285</td>
<td>3</td>
<td>1</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. D.</td>
<td>78</td>
<td>345</td>
<td>1</td>
<td>1</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. I. + D.</td>
<td>82</td>
<td>350</td>
<td>13</td>
<td>4</td>
<td>1.8</td>
<td>4</td>
<td>No improvement</td>
</tr>
<tr>
<td></td>
<td>Andes I.</td>
<td>78</td>
<td>345</td>
<td>13</td>
<td>4</td>
<td>1.8</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Andes + Crat.</td>
<td>81</td>
<td>345</td>
<td>49</td>
<td>15</td>
<td>1.8</td>
<td>3</td>
<td>No improvement</td>
</tr>
<tr>
<td>80–120 Ma</td>
<td>Crat. I.</td>
<td>74</td>
<td>030</td>
<td>7</td>
<td>3</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. D.</td>
<td>80</td>
<td>145</td>
<td>3</td>
<td>3</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. I. + D.</td>
<td>78</td>
<td>055</td>
<td>131</td>
<td>8</td>
<td>4.0</td>
<td>3</td>
<td>No improvement</td>
</tr>
<tr>
<td></td>
<td>Andes + Crat.</td>
<td>79</td>
<td>040</td>
<td>172</td>
<td>10</td>
<td>4.1</td>
<td>2</td>
<td>No improvement</td>
</tr>
<tr>
<td>5–25 Ma</td>
<td>Crat. I.</td>
<td>85</td>
<td>035</td>
<td>137</td>
<td>8</td>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. D.</td>
<td>86</td>
<td>260</td>
<td>14</td>
<td>8</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. I. + D.</td>
<td>84</td>
<td>340</td>
<td>163</td>
<td>18</td>
<td>3.0</td>
<td>2</td>
<td>0.71 86 315 89 18 2.3 2</td>
</tr>
<tr>
<td></td>
<td>Andes + Crat.</td>
<td>85</td>
<td>035</td>
<td>442</td>
<td>37</td>
<td>3.5</td>
<td>2</td>
<td>0.71 86 320 239 37 2.6 3</td>
</tr>
<tr>
<td>25–65 Ma</td>
<td>Crat. I.</td>
<td>66</td>
<td>300</td>
<td>42</td>
<td>3</td>
<td>3.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. D.</td>
<td>80</td>
<td>355</td>
<td>32</td>
<td>3</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crat. I. + D.</td>
<td>84</td>
<td>330</td>
<td>82</td>
<td>8</td>
<td>3.2</td>
<td>3</td>
<td>No decompaction</td>
</tr>
<tr>
<td></td>
<td>Andes + Crat.</td>
<td>85</td>
<td>345</td>
<td>177</td>
<td>22</td>
<td>2.8</td>
<td>3</td>
<td>0.83 83 320 168 22 2.8 4</td>
</tr>
</tbody>
</table>

* Type of data: cratonic, Crat.; Andean, Andes; I, Inclination; D, Declination.
† Latitude and longitude of best-fit palaeomagnetic pole.
§ Minimum value of \( x^2 \) for best-fit pole (eq. 2).
¶ Number of degrees of freedom (number of fitted parameters – 2).
\( F_\beta \) Goodness of fit parameter \( F = (x^2_{\min}/DF)^{0.5} \).
** Angular radius in degrees of 95 per cent confidence cone for best-fit pole, calculated from a Monte Carlo realization of data, given their uncertainties.
‡§ Compaction factor (ratio of final to initial thickness of sediment).

5–25 Ma

Crat. I. & 85 & 035 & 137 & 8 & 4.1 & & & &
Crat. D. & 86 & 260 & 14 & 8 & 1.3 & & & &
Crat. I. + D. & 84 & 340 & 163 & 18 & 3.0 & 2 & 0.71 & 86 & 315 & 89 & 18 & 2.3 & 2
Andes + Crat. & 85 & 035 & 442 & 37 & 3.5 & 2 & 0.71 & 86 & 320 & 239 & 37 & 2.6 & 3

25–65 Ma

Crat. I. & 66 & 300 & 42 & 3 & 3.7 & & & &
Crat. D. & 80 & 355 & 32 & 3 & 3.3 & & & &
Crat. I. + D. & 84 & 330 & 82 & 8 & 3.2 & 3 & No decompaction & & & &
Andes + Crat. & 85 & 345 & 177 & 22 & 2.8 & 3 & 0.83 & 83 & 320 & 168 & 22 & 2.8 & 4

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Figures 5. Stereographic polar map projections (South Pole) showing the $\chi^2$ minimum values for data combinations listed in Table 3 for 5–10 Ma. The loops around the $\chi^2$ minimum value are contours of $\chi^2$ values (values labelled), defining the approximate 68 and 95 per cent confidence intervals for the orientation of the best-fit pole. In some cases, only the 95 per cent confidence contour is shown. (a) $\chi^2$ values using only cratonic inclination data; (b) $\chi^2$ values using only cratonic declination data; (c) $\chi^2$ values using combined cratonic inclination and declination data; (d) $\chi^2$ values using only inclination data from the central Andes; (e) $\chi^2$ values using cratonic inclination and declination data combined with Andean inclination data.

Figures 6. As Fig. 5 for the time interval 10–20 Ma.
confidence level those from the cratonic declination and inclination data, used either together or individually (Figs 9a–d). Thus, the global minimum for combined Andean and cratonic data (Fig. 9e) is well defined with a fit $F \sim 1.8$, and all the data are fitted, on average, within their 95 per cent confidence limits.

5.7 Middle–Late Cretaceous (80–120) Ma reference pole
Most of the data available for this time interval are cratonic. The inclinations and declinations for cratonic and combined cratonic and Andean data define a good ‘bull’s eye’ uncertainty.

Figures 7. As Fig. 5 for the time interval 20–30 Ma.

Figures 8. As Fig. 5 for the time interval 30–50 Ma.
region around the $\chi^2$ minimum (Figs 10c–e), although the fit is very poor ($F \approx 4.1$). This reflects the fact that none of the 95 per cent uncertainty regions for the best-fit poles, defined by either inclination (Figs 10a and d) or declination data (Fig. 10b), overlaps.

5.8 Palaeogene and Neogene reference poles

The generally poor fits of poles for the Cenozoic data, described in Sections 5.2–5.5, is reflected in the ‘best-fit’ Neogene and Palaeogene poles (Table 3 and Fig. 11d).

Figures 9. As Fig. 5 for the time interval 50–80 Ma.

Figures 10. As Fig. 5 for the time interval 80–120 Ma.
Figure 11. Stereographic polar map projections (South Pole) of Cretaceous to Late Cenozoic stable South American reference palaeomagnetic poles calculated in this study or previously published. Circles show the associated 95 per cent confidence limits about the mean (black dot) calculated from a Monte Carlo random simulation of the data. The thick line is an apparent polar wander path interpreted through the data. Labels refer to the mean age in millions of years of a particular reference pole. The 130 Ma pole is from Ernesto & Pacca (1988), based on numerous palaeomagnetic measurements of the Parana flood basalts, and is one of the best-determined South American palaeomagnetic poles. (a) Poles from Roperch & Carlier (1992), based on the apparent polar wander path for Africa (Besse & Courtillot 1991) rotated into the South American frame of reference. (b) Poles calculated in this study from combined inclination and declination measurements at cratonic (South American and African) palaeomagnetic localities. (c) Poles calculated in this study from combined inclination and declination measurements at cratonic localities and inclination measurements at central Andean localities. (d) The mean Neogene (5–25 Ma) and Palaeogene (25–65 Ma) palaeomagnetic poles calculated in this study. The shaded regions show the full 95 per cent confidence limits, taking account of the effects of compaction or different combinations of Andean and cratonic data (see Table 3). (e) Poles calculated in this study from combined inclination and declination measurements at cratonic localities after simple decompactions for certain time groupings that give the best improvement in the fit (see Table 3). (f) Poles calculated in this study from combined inclination and declination measurements at cratonic localities and inclination measurements at central Andean localities after simple decompactions for certain time groupings that give the best improvement in the fit (see Table 3).
6 DISCUSSION

6.1 Inclination misfits

The striking feature of this analysis is that, with the exception of the 5–10 Ma and 50–80 Ma time intervals, the calculated 'best-fit' palaeomagnetic poles have very poor fits, with minimum $\chi^2$ values that are not significant at the 0.1 per cent level. In other words, the probability of obtaining a $\chi^2$ value equal to or less than our calculated $\chi^2_{\text{min}}$ is less than one in 1000. Note that even with these poor fits, our small-angle assumption, implicit in eq. (2), is not significantly violated (i.e. $\theta < 20'$). The main cause of the poor fits is the inability to fit the inclination data within the 95 per cent or even 99 per cent confidence limits. Expressed another way, all these poor fits imply that the inclination data do not conform to a geocentric axial dipole magnetic field at these confidence levels. The problem manifests itself both in a marked discrepancy between 'best-fit' poles calculated from the Andean data alone and that calculated from the cratonic data, and also in the misfits in the cratonic data alone. However, an important feature of any discrepancy between the Andean and cratonic data is that it would be removed if the Andean inclinations were, on average, steeper. In some cases, the amount they would need to steepen ($> 10$'), in order to improve the fit, far exceeds that which could be plausibly explained by a systematic latitudinal shift of Andean localities during the Cenozoic as a consequence of margin-parallel tectonic displacements. In addition, the direction of the required displacement is opposite to the general latitudinal transport predicted from the Cenozoic relative plate convergence vector. More importantly, the moderately good inclination fits for the Late Cretaceous–earliest Cenozoic palaeomagnetic pole (50–80 Ma) are incompatible with this displacement.

6.2 Sedimentary effects

If we rule out large-scale southward tectonic displacement of the Andean localities, relative to stable South America, then we need to consider other plausible explanations for the discrepancy between the Andean and cratonic inclinations for many of the Cenozoic time intervals analysed above. Another possibility is the well-known phenomenon of inclination flattening due to either sedimentary deposition of detrital grains (Tauxe & Kent 1984) or post-depositional compaction (Arason & Levi 1990; Deamer & Kodama 1990).

Depositional and post-depositional processes can influence the direction of the observed magnetic inclination in a number of ways. If the magnetic grains have a shape fabric that is more or less coincident with the direction of remanent magnetization, there will be a tendency for the long axes of the magnetic grains to rotate during compaction towards a direction at right angles to the direction of flattening. Most inclination shallow- ing, however, is likely to occur during diagenesis and the extent to which it occurs is dependent on lithology (Deamer & Kodama 1990). During sediment dewatering and subsequent compaction, shallowing of the inclination may be achieved through several mechanisms (Arason & Levi 1990). These include the rotation of elongate grains to more horizontal orientations, rotation towards the horizontal of platy non-magnetic grains to which smaller magnetic grains are adhered, or randomization of inclination by rolling of roughly spherical magnetic grains. If the sediments are essentially flat-lying, compaction will progressively rotate the direction of remanent magnetization towards the horizon-ental. All of these processes can result in a systematic flattening of the inclination, without a significant change in the mean declination (Griffiths et al. 1960; Tauxe & Kent 1984). Thick sequences of rapidly accumulating sediments will experience a protracted history of diagenesis and compaction during burial, after the acquisition of a remanent magnetization, and the amount of shallowing may increase with increased burial depth. Depositional and post-depositional sedimentary processes have been identified as a likely cause of inclination shallowing in several Andean studies of thick sedimentary sequences (e.g. Roperch et al. 1999; Coutand et al. 1999). This type of inclination flattening is easy to quantify if we assume that the magnetic grains behave like passive marker lines in the rock. If we define the compaction factor $\lambda$ as the ratio of the final to initial thickness, then we can calculate the initial inclination ($I_i$), given the observed inclination ($I_{\text{obs}}$),

$$I_i = \tan^{-1} \left( \frac{\tan I_{\text{obs}}}{\lambda} \right).$$

(6)

Compaction will also modify the uncertainty estimate ($\Delta I$) for the inclination,

$$\Delta I = \sigma = 0.5 \tan^{-1} \left( \frac{\tan(I_{\text{obs}} + \sigma_I)}{\lambda} \right)$$

$$- 0.5 \tan^{-1} \left( \frac{\tan(I_{\text{obs}} - \sigma_I)}{\lambda} \right).$$

(7)

We can use eqs (6) and (7) to correct for compaction-induced flattening of the inclinations in our palaeomagnetic data set if we know the compaction factor $\lambda$.

Generally, the compaction factor $\lambda$ is unknown. However, we can test whether compaction is a plausible explanation for the poor fits of our data to a particular palaeomagnetic pole by assuming a single compaction factor for inclination flattening. If we find that a single compaction factor for any particular time interval, implying a plausible amount of compaction, will significantly improve the fit, then this not only suggests that compaction has occurred, but potentially refines our estimate of the palaeomagnetic poles for the relevant time intervals. In effect, we are reducing by one the degrees of freedom in our $\chi^2$ minimization procedure. We would expect a plausible compaction factor for essentially internally undeformed rocks to range between 0.5 and 1.0. We also assume that compaction is only likely to be significant in clastic sedimentary rocks. As the bulk of the cratonic data comes from igneous rocks, compaction is only likely to have a large effect on the Andean data.

We have used the previous analysis to search for a palaeo- magnetic pole that yields a minimum value of $\chi^2$ for the data in our selected time intervals, applying a series of compaction factors, ranging between 0.5 and 1.0, to the data from sedimentary rocks. Plausible amounts of compaction between 0.63 and 0.83 markedly improve the fit for palaeomagnetic poles in the Neogene period, particularly the time intervals 10–20 Ma and 20–30 Ma (Table 3), although in some cases the best-fit poles still fail a $\chi^2$ test at the 0.1 per cent level. Clearly, it is a gross simplification to assume the same amount of compaction for all clastic sedimentary rocks for a particular time period. However, the improvement in fit of the data to the ‘best-fit’ palaeomagnetic pole, taking into account a plausible amount of sedimentary compaction, is highly suggestive that compaction has played a significant role in producing the poor overall fits.

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6.3 Non-geocentric dipole field

Another explanation for the poor fits of the palaeomagnetic poles in this study is that the average magnetic field has not always been a geocentric axial dipole field. On short time scales, less than a few thousand years, there have been significant non-dipolar components to the Earth’s magnetic field (Butler 1992). For instance, the inclinations over South America today are up to 20° flatter than one would predict from the best-fit dipole field. If such fluctuations are, at least partly, responsible for the observed poor fits of declination and inclination data with a geocentric axial dipole field, then we need to postulate longer-term non-dipolar components to the Earth’s magnetic field, on a timescale of millions to tens of millions of years. However, global analyses of palaeomagnetic inclination data (Schneider & Kent 1990) suggest that long-term non-dipolar components of the Earth’s magnetic field are small and cannot account for the poor fits in this study.

In addition to non-dipolar components, the Earth’s magnetic field may be eccentric so that the dipolar component is not centred at the Earth’s centre, but is shifted along the spin axis. Such an eccentric field has been invoked to explain the far-sided effect in Cenozoic rocks, where palaeomagnetic poles calculated from palaeomagnetic localities tend to lie consistently on the far side of the geographical pole, irrespective of the longitude of the palaeomagnetic locality. Wilson (1971) showed from an analysis of Neogene volcanic rocks that the far-sided behaviour could be explained if the magnetic dipole is shifted northwards along the spin axis by about 280 km, resulting in a systematic flattening, up to about 6°, of inclinations for Northern Hemisphere localities compared to that expected for a geocentric axial dipole field. Hailwood (1977) showed that such a northward shift of the dipole may have extended into the Palaeocene. However, a northward shift of the magnetic dipole along the spin axis cannot explain the poor fits of Southern Hemisphere palaeomagnetic data encountered in this study. This is because it would result in steepening of the expected inclinations for Southern Hemisphere palaeomagnetic localities compared to inclinations calculated from a geocentric axial dipole, increasing the discrepancy between the expected and observed inclinations in our data. For example, a northward shift of the dipole of 280 km along the spin axis results in a significantly poorer fit for the cratonic and Andean Neogene (5–25 Ma) palaeomagnetic data in this study ($\chi^2_{\text{min}} = 808$) compared to the fit for a geocentric axial dipole field ($\chi^2_{\text{min}} = 442$) for 37 degrees of freedom. We can improve both of these fits by applying a decompaction factor $\lambda$ to the inclinations. However, this factor would have to be greater for the case where we assume an eccentric dipole field ($\chi^2_{\text{min}} = 323$ for $\lambda \sim 0.63$) compared to the case of a geocentric axial dipole field ($\chi^2_{\text{min}} = 252$ for $\lambda \sim 0.71$); the final best-fit palaeomagnetic poles in either case are not significantly different. Thus, we can rule out the far-sided effect as an explanation for the poor fits in this study.

6.4 Palaeomagnetic errors

Another explanation for the poor fits of the ‘best-fit’ poles is that the confidence limits for the mean direction of the observations at individual palaeomagnetic localities have been significantly underestimated. For instance, if we allow the true confidence limits to be a factor $\beta$ greater than the quoted limits, then the $\chi^2$ minimum values would be reduced by a factor of $\beta^2$.

To make all of the ‘best-fit’ poles statistically significant at least at the 0.1 per cent level, $\beta$ would need to be between 1 and 2. In addition, compaction effects would add a systematic bias to measurements from individual localities. One reason that the confidence limits may be underestimated is that the actual spread of the observations at a palaeomagnetic site, given the number of observations $M$, may not always be a reliable guide to the confidence limits on the mean direction. For example, with small values of $M$, the application of the $M^{-0.5}$ factor to the spread in the actual data to determine the confidence limits for the mean direction may significantly underestimate the true uncertainty. It is noteworthy that allowing the observation errors to increase by a factor $\beta$ has the effect of increasing the $A_05$ on the best-fit pole by a similar factor.

7 SOUTH AMERICAN APPARENT POLAR WANDER PATH

We can examine possible Cretaceous to Cenozoic apparent polar wander paths for South American palaeomagnetic poles by considering our estimates of these palaeomagnetic poles for various time intervals (Fig. 11). We compare these with a previous study of palaeomagnetic poles for North America, Eurasia and Africa (Besse & Courtillot 1991) that have been rotated into the South American frame of reference, using the relevant Euler poles (Fig. 11a; Roperch & Carlier 1992). In addition, for reference, we plot the well-defined Early Cretaceous (~130 Ma) South American pole based on numerous data from the Paraná flood basalts (Ernesto & Paccia 1988).

The good fit obtained in this study for the Eocene to Late Cretaceous (50–80 Ma) palaeomagnetic pole, using the combined cratonic and Andean data without the need for any decompaction, suggests that this pole is the best available ‘anchor’ point in the Cretaceous to Cenozoic South American apparent polar wander path. It is identical within error to the ~60 Ma pole derived by Roperch & Carlier (1992) from Besse & Courtillot’s (1991) synthetic polar wander curve.

It is clear that, overall, the Cretaceous to Cenozoic South American apparent polar wander path for the cratonic data in this study (Fig. 11b) is very similar, at the 95 per cent confidence level, to that determined by Roperch & Carlier (1992). The most notable discrepancy is with the 100 Ma pole, which in our study lies well into the 0–90°E quadrant, although it just overlaps with the Roperch & Carlier (1992) pole at the 95 per cent confidence level. However, we note that the well-determined 130 Ma pole of Ernesto & Paccia (1988) also only just overlaps the Roperch & Carlier (1992) 130 Ma pole at the 95 per cent confidence level. Also, our 100 Ma pole is partly based on a new determination of the ~116 Ma palaeomagnetic pole for cratonic South America (Somoza 1994), published since the analysis of Roperch & Carlier (1992), although the fit to the data is very poor ($\chi^2_{\text{min}} = 172$ for 10 degrees of freedom). The average Palaeocene and Neogene poles (Fig. 11d) overlap at the 95 per cent confidence level with the relevant poles from Roperch & Carlier (1992). However, the average Palaeogene pole in this study (Fig. 11d) is not well determined, mainly because of a paucity of data.

The South American apparent polar wander path for the combined cratonic and Andean data in this study (Fig. 11c) is both erratic and markedly different to both that based solely on our analysis of the cratonic data (Fig. 11b) and the poles determined by Roperch & Carlier (1992) (Fig. 11a). As discussed in...
Section 6, the fits for many of the Cenozoic time intervals in this study, using combined cratonic and Andean data, are very poor and we therefore do not place much confidence in these poles. However, the improved fits for either the cratonic data or combined Andean and cratonic data, after a simple decompaction as described in Section 6.2, show encouragingly smooth and systematic polar wander paths (Figs 11e and f). In particular, the combined Andean and cratonic data, after a simple decompaction (Fig. 11f), suggest a general northward drift of South America since the Late Cretaceous, consistent with global plate reconstructions in the hotspot frame of reference (Morgan 1983), accompanied by a general westward shift of the pole. Thus, the 100 Ma south magnetic pole is at a latitude of 79°S, whilst younger poles have progressively more southerly latitudes, ranging from 81°S for the Latest Cretaceous (50–80 Ma), to 83°S for the Oligo-Miocene (20–30 Ma), 86°S for the Early Miocene (10–20 Ma), and 87° for the Late Miocene (5–10 Ma).

Despite the generally poor quality of the fits described in Section 6, we believe that the poles calculated here are the best available for South America. They include the maximum amount of high-quality palaeomagnetic data available, and the poles are obtained through rigorous statistical analysis. We believe that these poles will help to define the tectonic processes acting in the Andean margin better.

8 CONCLUSIONS

A statistically rigorous technique has been developed to allow palaeomagnetic poles to be calculated using data from the stable continental block in combination with tectonically disturbed data that have undergone vertical-axis rotation. The combined information provides a much larger data set from which to calculate reference poles. The technique was applied to Late Cretaceous–Cenozoic data from stable South America and Africa, along with data from the Andean margin for the period 5–120 Ma. The analysis has shown that, in general, it is not possible to find palaeomagnetic reference poles for the Cenozoic of South America that have an acceptable fit to all of the data. The main reason for this is the inability to fit the inclinations of palaeomagnetic measurements; it is sometimes possible to obtain acceptable fits using only the declination data. In many cases, especially for the Neogene, there seems to be an incompatibility between the inclination and declination data. This manifests itself both within the cratonic data and with the combined cratonic and Andean data. The situation is improved if allowance is made for possible sedimentary compaction. Even after the effects of compaction have been removed, the χ² minimum values on many of the best-fit poles are still not statistically significant. This may be a consequence of palaeomagnetic studies consistently underestimating the errors on palaeomagnetic inclinations. Significant long-term non-dipole components to the Earth’s magnetic field are probably too small to explain the poor fits.

The results have yielded a range of Late Cretaceous to Late Cenozoic South American palaeomagnetic reference poles, as well as mean palaeomagnetic poles for the Palaeogene and Neogene. We believe that the apparent polar wander path defined by these poles, taking into account the possibility of sedimentary compaction, is currently the best defined for South America, given the available data and their uncertainties. The use of these poles in studies of tectonic rotation should help to define rotations about vertical axes in the Andes better.

REFERENCES


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We begin by assuming that our uncertainty in specifying the true direction of the Earth’s magnetic field at a particular locality lies within an angular area of size \( \pm 1/\Sigma \) of the true direction. We can place confidence limits on this angular deviation. The probability that the true direction of the Earth’s magnetic field at a particular locality lies within an angular area of size \( \pm 1/\Sigma \) of the true direction is given by the probability function (Fisher distribution).

We can greatly simplify eq. (A1) because we are interested only in relatively small departures (\( \theta < 20° \)) of the true direction from our observed mean direction, using a Fisher probability function (Fisher distribution) for the orientation of unit vectors radiating from the centre of a unit sphere, where \( \cos \theta \) is the dot product of the unit vector (\( \mathbf{a}_{\text{calc}} \)) parallel to the true direction of the magnetic field at a particular locality and the observed direction (\( \mathbf{a}_{\text{obs}} \)).

\[
P_{\text{obs}} dA = \frac{k}{4\pi \sinh k} e^{k \cos \theta} dA, \quad (A1)
\]

where \( \cos \theta \) is the dot product of the unit vector (\( \mathbf{a}_{\text{calc}} \)) parallel to the true direction of the magnetic field at a particular locality and the observed direction (\( \mathbf{a}_{\text{obs}} \)). \( \theta = \cos^{-1}(\mathbf{a}_{\text{calc}} \cdot \mathbf{a}_{\text{obs}}) \). \( k \) is a parameter that describes the precision of the Fisher distribution. In this context, note that \( k \) refers to the precision in our estimate of the true field direction and not the precision of the actual spread of observations at a paleomagnetic locality. Therefore, \( k \) is an overestimate of the precision of the Fisher distribution.

We can greatly simplify eq. (A1) because we are interested only in relatively small departures (\( \theta < 20° \)) of the true direction from our observed mean direction (\( \theta_{\text{obs}} < 20° \)). Larger deviations of \( \theta \) imply unacceptably bad fits between the ‘true’ and observed measurements. In addition, with the small-angle approximation, we can specify the elemental angular area in terms of angles from the centre of the sphere in two orthogonal directions.
Thus, we assume to first-order approximation (Fig. A1)  
\[
\cos \theta \approx 1 - \frac{\theta^2}{2}, \\
\sinh k \approx \frac{e^k}{2}, \\
\theta^2 \approx x^2 + y^2, \quad dA \sim dx dy
\]  

In this case, we can write the probability that the true local direction of the magnetic field lies in the elemental area $dxdy$ at angular distances $xy$ from the observed direction (Fig. A1),  
\[
P_{x,y+dx,y+dy} = \frac{k}{2\pi} \exp \left[ -\frac{k(x^2 + y^2)}{2} \right] dx dy. \tag{A4}
\]

Eq. (A4) can be thought of as the product of two normal probability density functions, for $x$ and $y$, where we identify $k$ with the reciprocal of the variance of the two distributions ($k = 1/\sigma^2$). The probability ($P_{\text{total}}$) of the true directions of the local magnetic field deviating from the observed directions, for a set of independent measurements, will be the product of the probabilities for the individual measurements. Thus, for $N$ measurements, this probability will be  
\[
P_{\text{Total}} = P_1P_2P_3 \ldots P_N
\]  
or  
\[
P_{\text{Total}} = \frac{k_1k_2 \ldots k_N}{(2\pi)^N} \exp \left\{ -0.5[k_1(x_1^2 + y_1^2) + k_2(x_2^2 + y_2^2) + \ldots + k_N(x_N^2 + y_N^2)] \right\} (dx dy)^N. \tag{A5}
\]  

Figure A1. Plot showing the angular radius of the cone of confidence for the mean of a sample of $M$ observations ($M = 10$) as an estimate of the mean of a parent Fisher distribution with precision $k$ ($k = 20$) from which the observations were taken. The confidence limits have been calculated using two methods. First, $\alpha$ ($x =$ percentage confidence limit) has been calculated directly using the appropriate formula of Fisher et al. (1987) for determining confidence limits on the mean of $M$ observations drawn from a parent Fisher distribution. Second, an approximate method has been used that assumes that the means of sets of $M$ observations from a parent Fisher distribution also form a Fisher distribution with an effective precision that is $M$ times the precision ($k$) of the parent population. In this case, the angular radius of the cone ($\theta$) in which $x$ per cent of the sample means lie is a factor $1/M^{0.5}$ of the equivalent cone for the parent population. It is clear from the plot that the methods give very similar results for typical quality palaeomagnetic data ($M = 10, k = 20$). The difference between the two methods becomes even less for $M > 10, k > 20$.

Figure A2. Diagram illustrating the geometry of the angular parameters used in this study (see text) to describe the orientation of a direction relative to the mean direction. The mean direction is taken as the origin. In this case, another direction can be described in terms of the intersection of two small circles at angular distances $x$ and $y$ in orthogonal directions, from the centre of a sphere; $\theta$ is the angle between the two directions. For small $\theta$, $\theta^2 \approx x^2 + y^2$. 

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The pole position that maximizes the probability described by eq. (A5) will also maximize the natural logarithm of this probability. In this case, our best-fit pole will be the one that maximizes, with constant terms C,

\[ \log_e (P_{\text{Total}}) + C = -k_1(x_1^2 + y_1^2) - k_2(x_2^2 + y_2^2) - \ldots \]

\[ - k_N(x_N^2 + y_N^2) \quad (A6) \]

or minimizes the negative of the right-hand side of this equation. We can identify \( x \) and \( y \) with the calculated and observed mean inclination \((I_{\text{calc}} \text{ and } I_{\text{obs}})\) and declination \((D_{\text{calc}} \text{ and } D_{\text{obs}})\) of the magnetic field at a palaeomagnetic locality for a given palaeomagnetic pole and again using a small-angle approximation \((x < 20°)\) and assuming moderate to shallow inclinations \((I_{\text{obs}} < 75°)\),

\[ x = \sin^{-1} \left( \frac{\sin(D_{\text{calc}} - D_{\text{obs}})}{\cos I_{\text{obs}}} \right) \approx \frac{(D_{\text{calc}} - D_{\text{obs}})}{\cos I_{\text{obs}}} \quad (A7) \]

where we minimize individually the discrepancy between the observed and calculated inclination and declination measurements, summed over \( N \) palaeomagnetic localities \((\text{subscript } n \text{ refers to the } n\text{th palaeomagnetic locality})\). The uncertainties at the 68 per cent confidence level in the mean inclination and declination measurements \(\) using eq. (A4), we identify \( \sigma \) with \(1/\sqrt{N} \) and assume \( z_{0.95} < 20° \) with \( I_{\text{obs}} < 75° \) are given by \( (\text{cf. Demarest } 1983)\)

\[ \sigma_{D_n} = 0.4 \sin^{-1} \left( \frac{\sin z_{0.95}}{\cos I_{\text{obs}}} \right) \approx \frac{0.4z_{0.95}}{\cos I_{\text{obs}}} \quad (A9) \]

\[ \sigma_{I_n} = 0.4z_{0.95} \quad (A9) \]

We can test our approximation of a Fisher probability function \( (\text{Fisher distribution}) \) for the confidence limits on our data for \( z_{0.95} < 20° \) and \( I < 75° \) and given by eq. (A4) as the product of two independent normal probability functions for the uncertainties in the inclination and declination. If our approximation is good, we can create a Fisher distribution by generating values of inclination and declination independently, using a random probability generator for each with normal variates about specified means defined in eq. (A9). This way, we have created two synthetic data sets containing 500 data each, with an \( \theta_{95} \) of \( \sim 10° \) and \( \sim 20° \), respectively, for a mean inclination of 45°.

Note that \( \theta_{95} \) describes the angular radius of the cone in which 95 per cent of the directions lie. In the context of our analysis to determine the best-fit palaeomagnetic pole, if the directions are a set of mean field directions at a range of palaeomagnetic localities, then \( \theta_{95} \) is the same as \( z_{95} \). Fig. A2 shows both the angular distribution of the synthetic palaeomagnetic directions and those expected for an axially symmetric Fisher distribution. These are shown in terms of the value of the probability function \( P_{\theta_9} (\theta) \) for a direction lying at an angular distance \( \theta \) from the mean direction. It is clear that the synthetic data conform closely to the expected Fisher distribution, even for an \( \theta_{95}(z_{95}) \) of \( \sim 20° \), validating our small-angle approximation. Similarly, a very good fit to the expected Fisher distribution is obtained for synthetic data with a much steeper mean inclination of 70° and an \( \theta_{95}(z_{95}) \) of \( \sim 15° \) (Fig. A3). Smaller values of \( \theta_{95}(z_{95}) \) and inclination \( I \) than those analysed above would result in even better fits between the synthetic data and Fisher distribution.