The Late Cretaceous paleomagnetic field in North America: a South American perspective

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Abstract: Determining the Late Cretaceous paleomagnetic pole for North America has been difficult because of the lack of suitable rocks of that age in cratonic areas to provide the necessary data. As an alternative, different studies have appealed to paleomagnetic data from rocks in western North America. Using paleopoles from stable areas in neighboring continents, it is suggested that the available Late Cretaceous paleomagnetic record in western North America should be analyzed in terms of rigid body deformations rather than be used to represent the cratonic reference field.

Résumé : Il est difficile de déterminer le pôle paléomagnétique de l'Amérique du Nord au Crétacé tardif en raison de manque de roches convenables de cet âge dans des régions cratoniques qui peuvent fournir les données nécessaires. Comme autre option possible, diverses études ont fait appel à des données paléomagnétiques de roches situées dans l'ouest de l'Amérique du Nord. En se basant sur les paléopôles d'endroits stables dans des continents voisins, il est suggéré d'analyser les données paléomagnétiques disponibles du Crétacé tardif de l'ouest de l'Amérique du Nord en termes de déformations d'amas rigides plutôt que de les utiliser pour représenter le champ de référence cratonique.

[Traduit par la Rédaction]

Introduction

Paleomagnetic studies in rocks from cratonic North America have shown that the 125 to 90 Ma poles plot close to each other in the region of the Chukchi Sea, off the coast of northwest Alaska (Mankinen 1978; Globerman and Irving 1988; Van Fossen and Kent 1992), defining thus a ~35 million-year period of negligible continental motion with respect to the Earth's spin axis in the frame of the geocentric axial dipole (GAD) hypothesis. The extend of this period of polar stillstand cannot be unambiguously determined because of the apparent lack of suitable outcrops of Upper Cretaceous rocks in stable North America. As an alternative, most researchers utilize paleomagnetic results from Upper Cretaceous rocks in western Norh America. In particular, the Upper Cretaceous volcanic rocks from Montana have provided pole positions removed from the 125–90 Ma pole (Diehl 1991; Gunderson and Sheriff 1991), leading these researchers to suggest that the mid-Cretaceous polar stillstand ended between 90 and 85 Ma and was followed by a brief period of fast polar motion that has been associated with the beginning of Laramide orogeny (e.g., Diehl 1991; Gunderson and Sheriff 1991; Beck and Housen 2003). Nevertheless, it is well recognized that there are difficulties in establishing the Late Cretaceous reference pole for North America (e.g., Diehl 1991; Gunderson and Sheriff 1991; Enkin et al. 2001). Moreover, the abrupt change of continental motion at ~85 Ma suggested by poles from North American rocks has been considered unrealistic (e.g., Enkin 2006).

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In stable South America, paleomagnetic studies from widely distributed outcrops of mid-Cretaceous rocks have shown that the ca. 125 to ca. 95 Ma poles plot close to each other, yielding a mean pole position indistinguishable from the present-day spin-axis (Somoza and Zaffarana 2008; Font et al. 2009). In contrast with the North American case, the availability of Late Cretaceous igneous rocks in stable areas of South America has allowed the definition of a cratonic pole position that is ~10° away from the South American mid-Cretaceous pole (Ernesto et al. 2002; Somoza 2002; Ernesto 2006; Somoza and Zaffarana 2008).

Since the tectonic evolution of the central and South Atlantic oceans is well known, transferring the Late Cretaceous South American pole to North American coordinates allows testing of the suitability of the Montana poles to represent the Late Cretaceous paleomagnetic field of cratonic North America. The transferred South American poles are not concordant with Late Cretaceous poles from localities in the eastern border of the Rocky Mountains but are roughly coincident with the mid-Cretaceous poles from stable North America, suggesting that the North American polar stillstand lasted at least until latest Cretaceous. As a consequence, it is suggested that some of the localities in Montana are recording Late Cretaceous remanences that do not accurately represent the paleomagnetic field of stable North America. The meaning of the observed magnetizations in these Late Cretaceous localities is discussed.

The paleomagnetic database

Paleomagnetic data from the ~130 Ma Notre Dame Bay dykes in Newfoundland (Lapointe 1979) provide a record of the Early Cretaceous paleomagnetic field for stable North America. In a recent study, Enkin (2006) (see also Kent and Irving 2010) listed a revised pole position for the Notre Dame Bay dykes after including new data. Tarduno and

Smirnov (2001) gathered paleomagnetic data from several mid-Cretaceous plutons cropping out from Quebec to Arkansas, redetermining thereby the mean 125–90 Ma pole position for stable North America.

As pointed out earlier in the text, there are difficulties in determining a Late Cretaceous reference pole derived from studies in North America. In fact, there is no plate from which we could confidently construct a complete apparent polar wander path (APWP) using paleomagnetic data from rocks in the same plate. This is why global compilations (e. g., Besse and Courtillot 2002; Enkin 2006; Torsvik et al. 2008; Kent and Irving 2010) are useful approaches for averaging out unknown residual problems with the selected individual poles, filling gaps in the available data for individual plates, and ultimately facilitating the development of paleogeographic and geodynamics studies, and eventually testing ancient geometries of the Earth's geomagnetic field.

Several Late Cretaceous poles are routinely selected to represent the North American paleomagnetic field for regional and global studies. All four the Late Cretaceous North American poles selected from Besse and Courtillot (2002) come from 80–70 Ma rock units in Montana, namely Maudlow volcanics (Swenson and McWilliams 1989), Elkhorn Mountains volcanics (Diehl 1991), Adel Mountains volcanics (Gunderson and Sheriff 1991), and Boulder Batholith (Hanna 1973). Torsvik et al. (2008) represented the Late Cretaceous paleomagnetic field in North America by the three Montana volcanics paleopoles just noted plus two poles from southeast Arizona from the Tombstone volcanics and intrusives (Hagstrum et al. 1994*a*) and the Roskruge volcanics (Hagstrum et al. 1994*b*). Torsvik et al. (2008) restored the paleomagnetic data from the southeast Arizona localities to cratonic North America by applying the Colorado Plateau rotation proposed by Bryan and Gordon (1990). Recently, Kent and Irving (2010; see also Enkin 2006) represented the Late Cretaceous geomagnetic field for cratonic North America by the Adel Mountains pole from Montana and the Tombstone igneous rocks pole at its in situ (southeast Arizona) coordinates.

The Cretaceous paleomagnetic database for South America has been recently enlarged and discussed (Geuna et al. 2000; Ernesto et al. 2002; Somoza and Zaffarana 2008; Font et al. 2009). The Early Cretaceous is represented by the huge amount of data from lavas in the Parana Magmatic Province of Brazil and Paraguay plus studies in central Argentina (Geuna and Vizán 1998; Ernesto et al. 1999). Likewise, several studies from localities in Brazil and Argentina from 5°S to 48°S define a 125–90 Ma polar stillstand (Somoza and Zaffarana 2008; Font et al. 2009). The Late Cretaceous paleomagnetic field is represented by data from 80–70 Ma alkaline complexes in Brazil and 80–70 Ma basalts in Patagonia (Montes-Lauar et al. 1995; Butler et al. 1991), which yield a pole position about 10° away from the mid-Cretaceous pole (Ernesto et al. 2002; Somoza; 2002; Somoza and Zaffarana 2008; Font et al. 2009). New paleomagnetic data from more than 30 sites in 80–70 Ma intrusives and dykes in the Serra do Mar of coastal Brazil (Ernesto 2006) further reinforce the South American Late Cretaceous pole position.

To enlarge the Late Cretaceous data set with high-quality data from stable areas, both the mean pole from the 90–84 Ma magmatic province in Madagascar (Torsvik et al. 1998) and the ~78 Ma paleolatitude from the Detroit Seamount in the Pacific Ocean (Doubrovine and Tarduno; 2008*a*) are also included in the analysis.

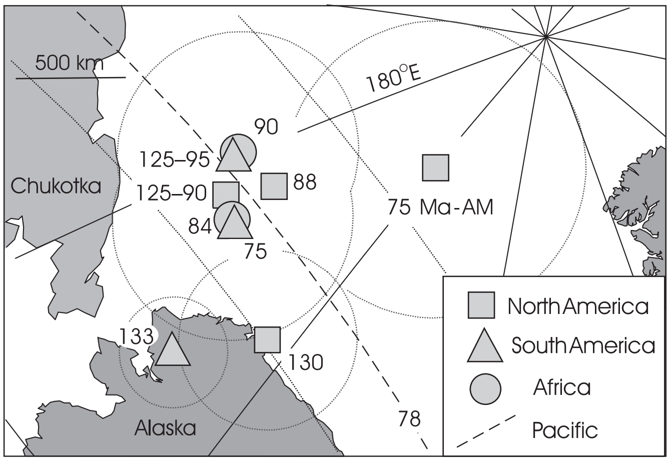


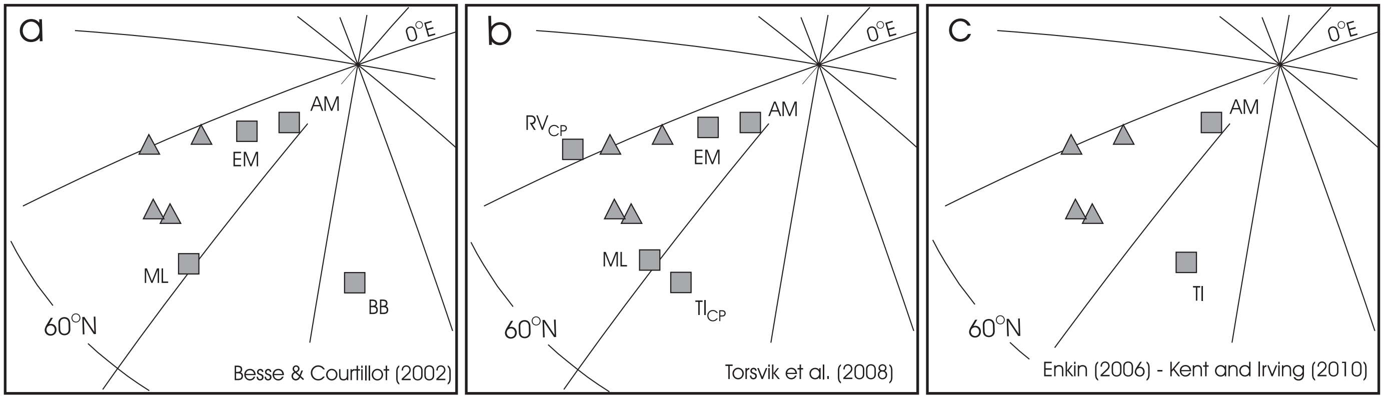
Fig. 1. Comparison of Cretaceous paleomagnetic poles from stable North America, South America, Africa, and Pacific plate (colatitude). Numbers indicate the age (in Ma) of each pole as cited in the text. Dotted circle-lines denote 95% confidence intervals. The A95 from the two reconstructed positions of the African pole enclose all A95 for 125–75 Ma poles of the Americas. Source of rotations to transfer South American and African poles to North American coordinates are mentioned in the text and in the caption for Fig. 2.

The Cretaceous paleomagnetic field of the Americas

Figure 1 shows the mean Cretaceous paleomagnetic poles from stable areas of the Americas in North American coordinates. Enkin's (2006) version of the ~130 Ma Notre Dame Bay dikes' pole plots close to the transferred position of the ~133 Ma pole from South America. Likewise, there is an excellent fit between the mean mid-Cretaceous poles from both continents, as has been shown by Somoza and Zaffarana (2008). Figure 1 also shows (1) the Turonian–Coniacian (~88 Ma) pole from the Fort Hays Limestone Member of the Niobrara Formation (Acton and Gordon 2005); (2) the transferred position of the Late Cretaceous (80–70 Ma) pole for South America after applying an anomaly 33y (~74 Ma) South America to North America rotation (Müller et al. 1999); (3) the transferred position of the 85–90 Ma pole from Madagascar after applying both 90 and 83.5 Ma Africa to North America reconstructions (Torsvik et al. 2008); and, (4) the ~78 Ma paleocolatitude of the Detroit Seamount transferred to North America using the Doubrovine and Tarduno (2008*b*) rotation. Thus, the South American paleomagnetic record suggests that the Cretaceous polar stillstand for North America lasted until latest Cretaceous, which is further supported by high-quality paleomagnetic data from Africa and the Pacific Ocean (Fig. 1).

Figure 2 shows the comparison between poles selected to represent stable North America in the Late Cretaceous in the three recent global studies mentioned earlier and the coeval South American poles from Brazil and Patagonia. The South American poles plot systematically westward of the coeval North American poles and show a better clustering in all cases. The latter is also true when only the poles from the

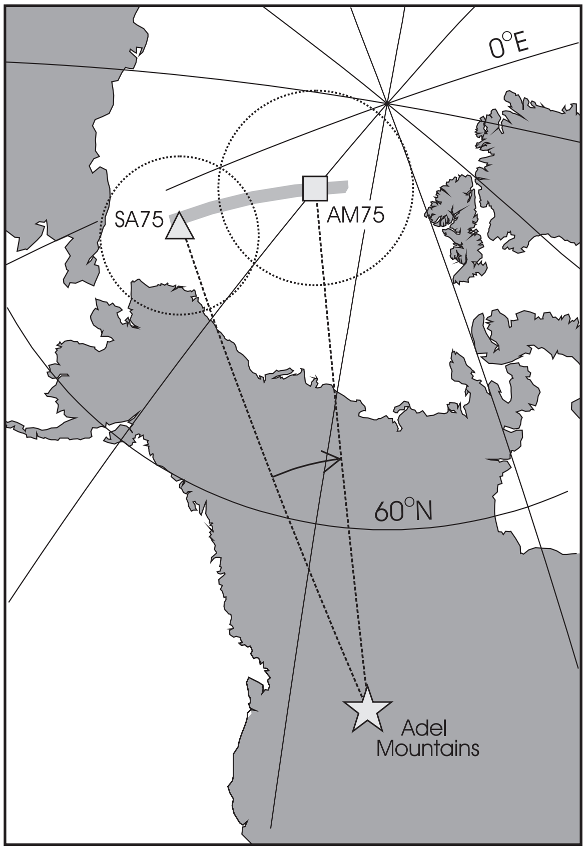
Fig. 2. Triangles are individual Late Cretaceous poles from stable South America transferred to North American coordinates after applying the anomaly 33y (73.6 Ma) reconstruction of Müller et al. (1999) (9.03°N, 56.57°W, angle 9.12° anticlockwise). Squares are North American poles selected to represent the cratonic paleomagnetic field in the studies of (*a*) Besse and Courtillot (2002), (*b*) Torsvik et al. (2008), and (*c*) Enkin (2006) and Kent and Irving (2010). AM, Adel Mountains pole; EM, Elkhorn Mountain pole; ML, Maudlow Formation pole; BB, Boulder Batholith pole; RV_{CP} and TI_{CP}, Roskruge volcanics and Tombstone Igneous poles, respectively, both restored to North America according to the Colorado Plateau rotation model of Bryan and Gordon (1990). In (*c*), TI is Tombstone Igneous pole seen from its southeast Arizona (in-situ) location.



Montana region (Fig. 2*a*) are compared with the continental-scale coverage of poles for South America.

The Adel Mountains volcanics pole was selected in all three data compilations shown in Fig. 2, suggesting that it is regarded as an undisputable record of the Late Cretaceous paleomagnetic field for cratonic North America. However, Fig. 1 shows that the Adel Mountains pole is discordant with respect to the coeval South American pole transferred to North American coordinates. This disagreement is not related to problems with the reconstruction because the finite relative rotations of Atlantic bordering continents back to the Cretaceous are known with very good precision, producing good paleomagnetic fits for well-determined poles from stable areas in North America, South America, and Africa (Fig. 1). On the other hand, Gunderson and Sheriff (1991) discounted the possibility of severe problems in averaging out paleosecular variation from the sampled flows and dikes at the Adel Mountains locality, arguing then that they had computed a true Late Cretaceous paleomagnetic pole for the locality. Likewise, Fig. 1 supports the analysis of Tarduno et al. (2002) who suggested that the paleomagnetic field was strongly dominated by the axial dipole from ~130 to ~85 Ma. Further, the fact that the imported South American pole and the coeval Adel Mountains pole show the same paleolatitude suggests that their discordance could be related to tectonic rotation of the Montana locality (Fig. 3).

Fig. 3. The Late Cretaceous pole from the Adel Mountains volcanics (AM75) is discordant with respect to the 75 Ma South American pole in North American coordinates (SA75; position is 73.2°N, 189.7°E, A95 = 4.3°), suggesting 16° ± 10° of clockwise rotation of Adel Mountains locality.



Discussion and conclusions

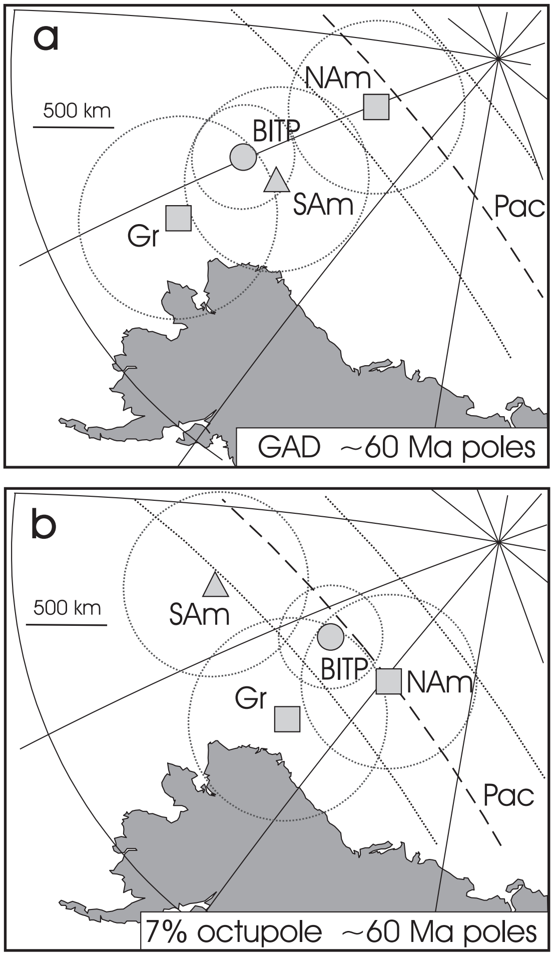
The Adel Mountains locality is not part of stable North America, but rather it is in the broken Laramide foreland that crops out along the eastern margin of the Cordilleran fold and thrust belt (e.g., Harlan et al. 2005). Comparing the Adel Mountains paleopole with a reference direction dictated by the coeval pole from stable South America suggests that this Montana locality underwent a post-75 Ma clockwise rotation of 16° ± 10° without a significant paleolatitudinal discrepancy ($P = 0.5° \pm 6°$). The rotation may be the product of overall dextral transpression related to the obliquity of Late Cretaceous to Eocene convergence in North America (Engebretson et al. 1984; Price 1994; Doubrovine and Tarduno 2008*b*). Alternatively, the rotation may be associated with the development of the fold and thrust belt in Montana. Balanced cross-sections in the Rocky Mountains indicate a southward-decreasing amount of shortening from Alberta to Montana, likely accommodating rotation of the Purcell–Lewis–Eldorado–Hoadley thrust system (e.g., Price and Sears 2000; Sears 2001). At a regional scale, this shortening gradient was described as a clockwise rotation about a pole located close to the Helena salient, which then was south of the Adel Mountains locality (Price and Sears 2000; Sears 2001, 2006). Thus, the rotation in the locality could be associated with the overall evolution of the Cordilleran thrust system. Jolly and Sheriff (1992) recognized that the Adel Mountains locality may have been carried on a blind thrust.

As mentioned in the introduction, a major problem for establishing the Late Cretaceous reference paleomagnetic field for North America is the apparent lack of suitable outcrops in stable North America of that age for paleomagnetic studies. This led the Adel Mountains pole to be the preferred option (Fig. 2) to substitute for this absence of true cratonic paleomagnetic records. However, comparison with a transferred mean pole position derived from studies in widely distributed areas of stable South America, further supported by African and Pacific plate data, supports strongly that the Adel Mountains locality underwent a clockwise rotation, which in turn is compatible with the tectonic evolution of the Canadian – northwestern USA Cordillera. In conclusion, it is suggested that care must be taken when incorporating paleopoles from studies in the North American Cordillera for analyzing the cratonic paleomagnetic field. Instead, Late Cretaceous poles from the Cordillera may provide excellent records of deformation if imported reference poles from stable areas in surrounding continents are used as a reference. A similar scenario is observed in the Central Andes, often considered as a modern analogue of the Laramide orogeny, where paleomagnetic data from Miocene–Pliocene rocks in the broken foreland were severely affected by tectonic rotations (e.g., Aubry et al. 1996) and so cannot be used to determine the cratonic paleomagnetic field.

Nevertheless, it is worth mentioning that the 70–80 Ma North American poles, as predicted by the global compilations discussed earlier in the text, are concordant with the transferred South American pole in Fig. 3, with the angular separation between them varying between 1.6° ± 3.7° (75 Ma South American vs. 80 Ma of Torsvik et al. 2008) and 4.3° ± 5.4° (75 Ma South American vs. 80 Ma of Besse and Courtillot 2002). This highlights the role of global compilation to smooth the problems derived from selected individual poles.

The North American polar stillstand lasted at least until very late in the Cretaceous (Fig. 1). However, resolving the end time of that polar stillstand is not straightforward. In an attempt to explore this, Fig. 4*a* shows the Paleocene (ca. 63 Ma) pole of North America computed by Diehl et al. (1983) in comparison to coeval poles from the British Tertiary Igneous Province (Ganerød et al. 2008), from Greenland (Ganerød et al. 2008), from South America (Somoza 2007), and the paleolatitude from the 58 Ma Suiko Seamount in the Pacific Ocean (e.g., Doubrovine and Tarduno 2008*a*), all of them in North American coordinates. There is a good agreement between the European and South American poles by one side and between the North American and Pacific data by the other side, with the Greenland paleopole plotting closer to the Europe – South America pair. In any case, the distribution in Fig. 4*a* strongly contrasts with the excellent clustering shown by 125–75 Ma poles in Fig. 1.

Fig. 4. (*a*) ~60 Ma poles for North America (NAm, Diehl et al. 1983), British Igneous Tertiary Province (BITP, Ganerød et al. 2008), Greenland (Gr, Ganerød et al. 2008), the inferred pole position for South America (SAm, Somoza 2007), and the paleocolatitude from the Suiko Seamount in the Pacific Ocean (Pac, Doubrovine and Tarduno 2008a). Transference to North American coordinates was made after applying rotations of Torsvik et al. (2008) for BITP and Gr, of Müller et al. (1999) for SAm, and of Doubrovine and Tarduno (2008*b*) for Pac. (*b*) The same paleomagnetic data as in (*a*) after adjusting each time-averaged paleomagnetic field with a 7% octupole component.



To improve clusters of worldwide paleomagnetic poles, some workers have modeled the paleomagnetic field with small, long-term nondipole field components (e.g., Si and Van der Voo 2001; Van der Voo and Torsvik 2001; Torsvik et al. 2001; Besse and Courtillot 2002; Doubrovine and Tarduno 2008*a*). Figure 4*b* shows that recalculating the poles from Fig. 4*a* by applying the 7% zonal octupole component proposed for the Early Cenozoic by Doubrovine and Tarduno (2008*a*) improves the clustering between most of them. The exception in Fig. 4*b* is the South American Paleogene pole, which interestingly is the only one from the southern hemisphere, allowing then the speculation of more complex, nonzonal paleofield geometry. Nevertheless, the incorporation of nondipole fields in paleomagnetic analyzes is controversial. It is concluded that available Paleocene paleomagnetic information does not allow an unambiguous evaluation of the evolution of the polar motion of North America from Late Cretaceous to Early Cenozoic.

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