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Reply

MICKEY C. VAN FOSSEN AND DENNIS V. KENT

Lamont-Doherty Geological Observatory and Department of Geological Sciences, Columbia University, Palisades, New York

Butler et al. [this issue] question the reliability of our 166 Ma Moat volcanics pole (82°N, 090°E, $A95 = 5.6°$) and high-latitude model for Middle Jurassic North American apparent polar wander (APW) [*Van Fossen and Kent,* 1990]. They review arguments in support of the 172 Ma Corral Canyon result (62°N, 116°E, $A95 = 6.2°$ [*May et al.,* 1986]) as a key Middle Jurassic reference pole for their lower-latitude paleomagnetic Euler pole model of Jurassic North American APW [*May and Butler,* 1986]. In this reply we address their concerns and maintain that the Corral Canyon pole and the lower-latitude model of APW it contributes to are suspect in light of global Jurassic paleomagnetic data and especially recent paleomagnetic studies that document tectonic rotations in the Basin and Range province of southern Arizona where the Corral Canyon pole was obtained.

Contrary to Butler et al.'s statement, we did not dismiss the Moat normal polarity (Cn) magnetizations but rather emphasized the importance of the reverse polarity (Cr) component in light of the inherent difficulties faced in interpreting a stable normal polarity magnetization aligned near to the present-day field. The Cr component can not be of recent origin and was featured as a lower limit on the absolute inclination of the Moat volcanics high unblocking temperature and high coercivity magnetization, allowing for the possibility of a small and still unremoved normal polarity contamination. That is, the paleopole for Middle Jurassic Moat volcanics should be no lower in latitude than the Cr pole (79°N, 090°E). To sharpen the debate, however, we accept as the representative Moat volcanics magnetization the dual polarity C component pole (82°N, 090°E, $A95 = 5.6°$) calculated using nine reverse and seven normal site-mean virtual geomagnetic poles. This pole passes a reversal test (B class [*McFadden and McElhinny,* 1990]), is distinct from the dipole axis, and falls 21° arc distance from the lower-latitude Corral Canyon pole of ostensibly similar age.

We had suggested either Cretaceous remagnetization and/or tectonic rotation(s) in the Patagonia Mountains of southern Arizona as possible explanations for the discrepancy between the Corral Canyon pole and Moat volcanics pole. The arguments presented by Butler et al. to discount remagnetization of the Corral Canyon rocks ironically could be applied to the Moat volcanics. While they expressed difficulty in imagining a (thermo)chemical remagnetization which could overprint unblocking temperatures up to 680°C and result in normal and reverse polarities while leaving the Rb/Sr system undisturbed, as in the case of the Corral Canyon rocks, this is precisely what we document in the Moat volcanics. For the Moat volcanics, however, there are thermochronometric data which provide younger age constraints on the demonstrable remagnetization event (i.e., K/Ar and zircon fission track dates of 168 and 163 Ma, respectively, on the Conway granite which intrudes the tilted Moat volcanics with an Rb/Sr date of 169 Ma); these data suggested to us an age of about 166 Ma for the Moat volcanics paleopole. On the other hand, such constraining thermochronometric data are not cited for the Corral Canyon rocks which may be remagnetized on the basis of an indeterminate fold test, and in this regard we pointed out that the reported Corral Canyon magnetizations without tilt correction give a pole position (61°N, 173°E) that is suspiciously near to Cretaceous poles for North America.

There are, however, likely to be more general problems with interpreting Corral Canyon magnetizations as cratonic reference data in view of the growing paleomagnetic evidence for tectonic rotations in southern Arizona. We called attention in our paper to a significant (~40°) rotation of Cretaceous rocks documented in the Silver Bell Mountains [*Hagstrum and Sawyer,* 1989], which has since been found also in Cretaceous rocks from the Tucson Mountains [*Hagstrum and Lipman,* 1991*a*]; both of these localities are about 150 km north of the Corral Canyon area. More pertinent to the present discussion is that *Hagstrum and Lipman* [1991*b*] have recently established a case for nearly 60° of relative rotation in Jurassic rocks among various fault-bounded blocks in the Canelo Hills, Mustang Mountains, and Huachuca Mountains, all within 50 km to the northeast of the Corral Canyon area. In a previous study of Middle Jurassic rocks in the Canelo Hills, *May and Butler* [1987] determined mean locality poles from Parker Canyon, Collins, and Canelo Pass sections and attributed the streaked dispersion to nondipole field effects. Alternatively, the relative distribution of these poles could be due to local tectonic rotations in southern Arizona as suggested by *Hagstrum and Lipman* [1991*b*].

The overall distribution of the Jurassic virtual geomagnetic poles from the Canelo Hills, Mustang Mountains, and Huachuca Mountains [*Hagstrum and Lipman,* 1991*b*; *May and Butler,* 1987] indeed conforms to that expected from rotations about local vertical axes in that the poles tend to be dispersed within a relatively narrow small circle band centered in southern Arizona (Figure 1). Given this evidence for relative rotations in southern Arizona, it follows that the Corral Canyon rocks (as well as the 151 Ma Glance conglomerate from the Canelo Hills [*Kluth et al.,* 1982]), which come from the same general areas, may also have been rotated and consequently may be inappropriate for establishing reference poles for stable North America. Two Corral Canyon site-mean directions were in fact rejected because of local tectonic rotations [*May et al.,* 1986], whereas the "robust" positive reversal test for the Glance conglomerate pole would become negative if one deviating (rotated?) site mean (CH022) was excluded. In this context, the cratonic coherence of the Moat volcanics in New England is not an issue, and we note that a relatively modest clockwise (restorative) rotation of ~20° would bring the Corral Canyon pole to within ~7° of the Moat volcanics reference pole (Figure 1).

With regard to testing the internal consistency of paleomagnetic poles from different continents, we showed that Jurassic paleomagnetic poles from Gondwana predict a high-latitude Middle

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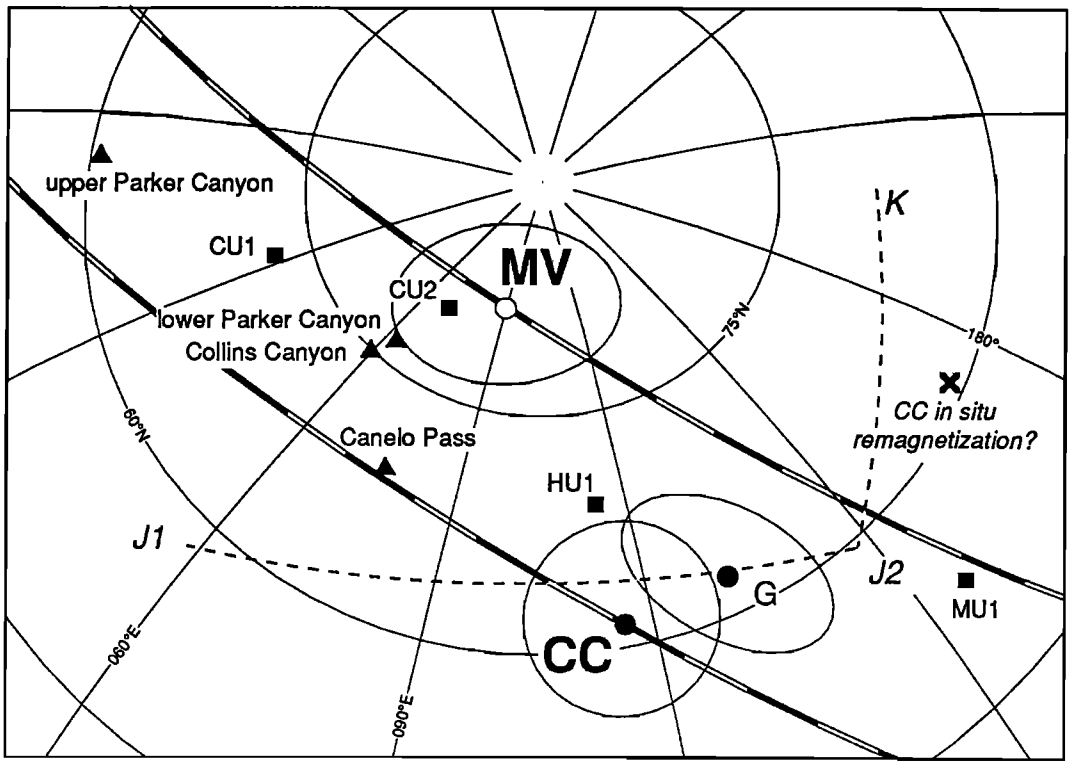

Fig. 1. Jurassic poles from southern Arizona. Squares, site-mean VGPs from the Canelo Hills, Mustang Mountains, and Huachuca Mountains [*Hagstrum and Lipman*, 1991*b*] (acronyms as in Hagstrum and Lipman's Table 1); triangles, section mean poles from Canelo Hills [*May and Butler*, 1987]; CC, 172 Ma Corral Canyon pole (62°N, 116°E, $A95 = 6.2°$ [*May et al.*, 1986]); and G, 151 Ma Glance pole (63°N, 132°E, $A95 = 6.3°$ [*Kluth et al.*, 1982]). These are all compared to 166 Ma Moat volcanics pole from New England (MV, 82°N, 090°E, $A95 = 5.6°$ [*Van Fossen and Kent*, 1990]) and J1-J2-K model of Jurassic North American APW [*May and Butler*, 1986]. Heavy lines with open/closed pattern at 5° increments are small circles centered at 31.5°N, 249°E to illustrate expected pattern of paleopoles affected by local vertical axis rotations in southern Arizona.

Jurassic pole position for North America. Butler et al. are nevertheless of the opinion that averaging the Gondwana data initially on a per-continent basis, as we did in our analysis, would filter "important" (but unspecified) details of Jurassic APW that when transferred might somehow be more consistent with their lower-latitude model of North American APW. The low scatter ($K = 1242$) of the Africa, Australia, and East Antarctica continental-mean Gondwana poles in reconstructed coordinates already suggests that little apparent polar wander has been averaged. This issue can be further addressed by transferring the 20 Jurassic Gondwana poles (three from Africa, two from Australia, and 15 from the Ferrar dolerite of East Antarctica) to North American coordinates individually (Figure 2). The mean is at 76°N, 106°E ($N = 20$, $K = 109$, $A95 = 3.1°$), indistinguishable from the mean pole we originally obtained by averaging the same data first by continent ($N = 3$). The only transferred Gondwana pole that falls even within 10° of the Corral Canyon pole is from a study of the Ferrar dolerite (pole at 66°N, 131°E in North American coordinates; Figure 2), but these data are from only one site which by itself is unlikely to have averaged paleosecular variation. The large scatter in the Ferrar data set as a whole is most probably a result of paleosecular variation and thus was our motivation for originally calculating a mean of the Ferrar studies to better represent a time-averaged paleopole for East Antarctica. But regardless of how the Gondwana poles are averaged, the mean pole position supports the high-latitude Moat volcanics pole. The distribution of the individual transferred Gondwana poles does not suggest that important details of Jurassic apparent polar wander have been filtered (Figure 2), particularly not those details that would be consistent with the Corral Canyon data as a reliable cratonic reference pole for North America.

Finally, after reviewing *Halvorsen's* [1989] analysis of European Jurassic poles, we suggest that the Swiss Jura pole with positive fold test [*Johnson et al.*, 1984] and the Krakow Upland pole with positive reversal test [*Kadzialko-Hofmokl and Kruczyk*, 1987] are the most reliable Middle-Late Jurassic data available from Europe. These poles also support a high-latitude position for the North American APW path in the middle to late Jurassic. The 144 Ma Svalbard dolerite pole [*Halvorsen*, 1989] is an important result, but the dolerites are at least 20 m.y. younger than either the Moat or Corral Canyon rocks; a discussion of its significance to the correspondingly younger portion of the North American APW path is beyond the confines of this reply but is included in a forthcoming contribution.

In summary, the reliability of the Moat volcanics pole is supported by North American data (Newark B component pole; Witte and Kent, 1989) as well as transferred Gondwana and European Jurassic poles. In their comment, Butler, May and Bazard offer no compelling alternatives to these consistent and independent lines of evidence for high latitude middle Jurassic North American apparent polar wander. On the contrary, we have shown that vertical-axis rotations and/or remagnetization in southern Arizona are viable alternative explanations for the 172 Ma Corral Canyon pole position and perhaps also the 151 Ma Glance conglomerate pole, thereby compromising the reliability of these poles as key reference data in delineating Jurassic North American apparent polar wander.

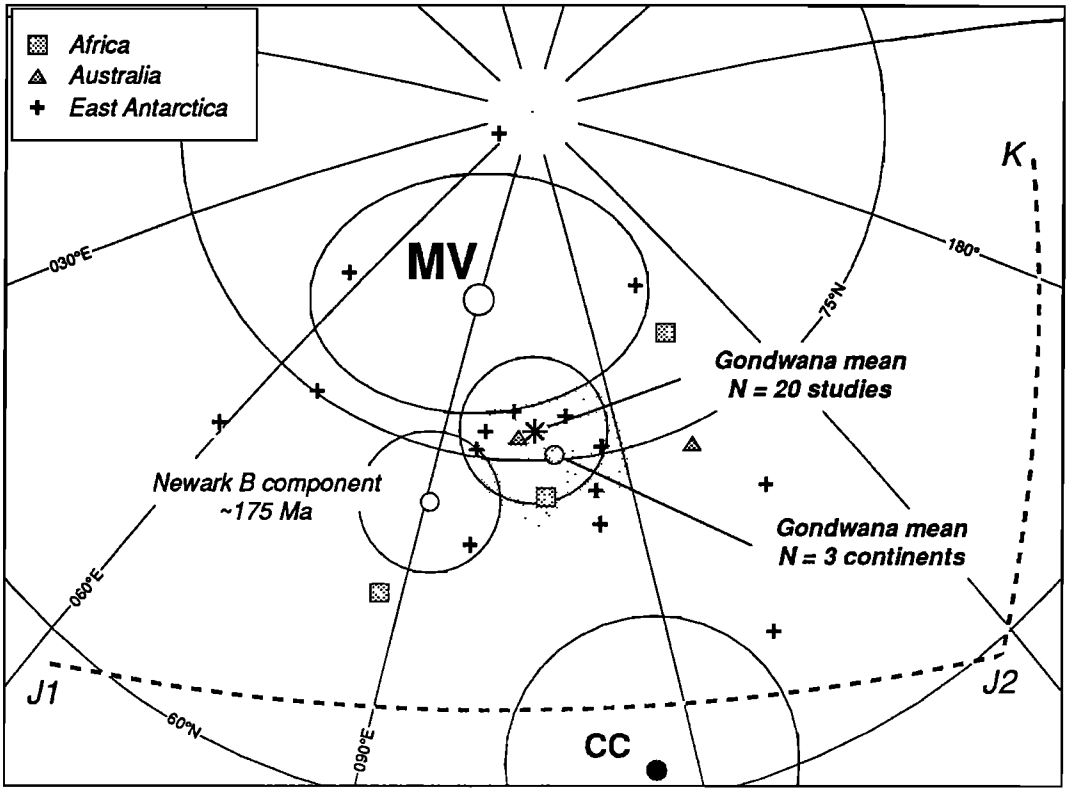

Fig. 2. Middle Jurassic poles from studies cited by *Van Fossen and Kent* [1990] from Africa ($N = 3$), Australia ($N = 2$), and East Antarctica ($N = 15$) transferred to North American coordinates with mean (76°N, 106°E, $A_{95} = 3.1°$ for $N = 20$ studies) indicated by asterisk compared to mean (gray circle) calculated by averaging first by continent (76°N, 109°E, $A_{95} = 3.5°$ for $N = 3$ continents). Transferred poles are compared to 172 Ma Corral Canyon (CC [*May et al.*, 1986]), 166 Ma Moat volcanics (MV [*Van Fossen and Kent*, 1990]), and 175 Ma Newark B component (72°N, 090°E, $A_{95} = 3.4°$, [*Witte and Kent*, 1989]) paleopoles and associated circles of confidence, as well as J1-J2-K model of Jurassic North American APW [*May and Butler*, 1986].

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D. V. Kent and M. C. Van Fossen, Lamont-Doherty Geological Observatory and Department of Geological Sciences, Columbia University, Palisades, NY 10964.

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