Earth and Planetary Science Letters, 60 (1982) 140–146
Elsevier Scientific Publishing Company, Amsterdam – Printed in The Netherlands

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Paleomagnetic and rock magnetic results from the Twin Creek Formation (Middle Jurassic), Wyoming

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Received October 28, 1981
Revised version received May 24, 1982

A magnetization which passes the fold test has been observed in 73 limestone samples (10 sites) from the Middle Jurassic Twin Creek Formation. The pole calculated from the site mean poles is located at 68.4°N, 145.0°E ($K = 31.8$, $A_{95} = 8.7°$). This pole lies in a segment of the North American apparent polar wander (APW) path for which there are only a few reliable poles in the literature. The results corroborate earlier studies which conclude that the Jurassic segment of the APW path does not include the present north pole. However, the position of the Twin Creek pole suggests that significantly more APW took place prior to the late Jurassic than previous studies indicated.

1. Introduction

Reported Jurassic paleopoles for the North American craton are in poor agreement in contrast to the well defined Triassic and Cretaceous pole positions. Some results [1,2] suggested that the Jurassic apparent polar wander (APW) path included the present north pole. Several later studies [3–6] yielded poles intermediate between the Triassic and Cretaceous poles and concluded that the high-latitude poles were remagnetized in the present field. Other results, notably from the west coast of North America, have yielded highly anomalous poles which have led to speculation that the terranes from which they were derived were not associated with stable North America during the Jurassic [7].

Compilations of North American paleopoles [3,8], from which results suspected of being not reliable have been eliminated, contain a surprisingly small number of Jurassic poles. In addition, those poles judged reliable which were derived from Lower Jurassic rocks are hardly distinguishable from Upper Triassic results. This leaves only a few reliable Middle and Upper Jurassic poles to fill the large gap between the Upper Triassic/Lower Jurassic and the Lower Cretaceous pole positions. An expected Jurassic APW path has been derived from studies of the motion of North America away from Africa [6]. However, the exact position and the timing of this path is not well constrained due to the small number of poles which define it. The present study was undertaken to add to our understanding of APW during this poorly known interval.

2. Geology and sampling

The Twin Creek Formation was deposited in a shallow epicontinental seaway [9]. It is composed largely of calcareous shales with intercalated gray to bluish micrites and oolites. Marine fossils are abundant and indicate that the age of the Twin Creek is Middle Bajocian near the bottom of the section and Lower Callovian at the top [10]. A compressional tectonic regime existed in the area from the latest Jurassic until the early Tertiary resulting in folded strata and thrust and reverse faults [11].

The sampling area in northwest Wyoming lies in the area where the overthrust belt impinges upon basement uplifts on the foreland (Fig. 1). Samles were taken where limestone outcrops were accessible, and where the beds were tilted so that a fold test could be applied [12]. The sites are in the Prospect Thrust (sites 1–5), the Darby Thrust (sites 9–13), and from the Gros Ventre Block (sites 6–8) which is a basement uplift on the foreland. Since rotations have been documented in Triassic strata in the overthrust belt [13], the sites on the foreland are particularly important. They serve as a control to test for bias in the mean direction due to the rotation of thrust sheets.

Six to eight samples were taken from each site either by drilling in the field with a portable rock drill or by taking oriented hand samples for later drilling in the laboratory. Cores were cut into standard 2.2 cm specimens for paleomagnetic and rock magnetic investigations.

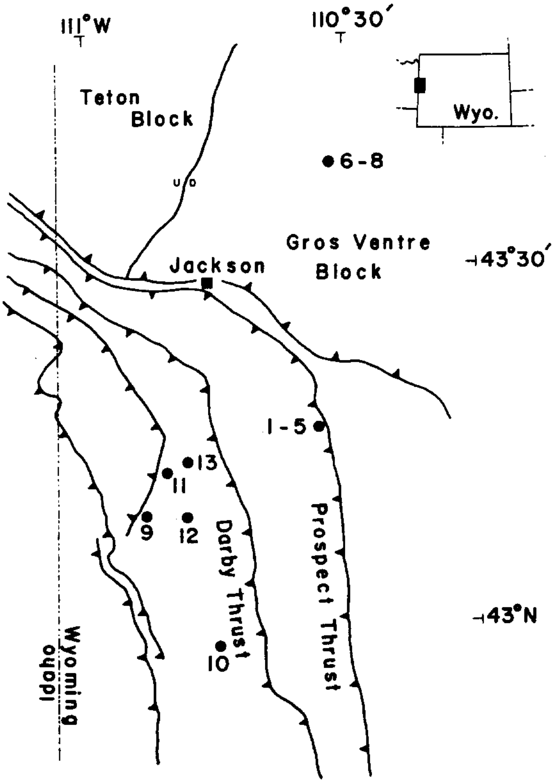

Fig. 1. Sampling area showing location of sites.

3. Paleomagnetic methods and results

Samples were subjected to stepwise thermal demagnetization with a Schonstedt TSD-I furnace or alternating field (AF) demagnetization with a Schonstedt GSD-I. Measurements of remanent magnetization were made with a ScT superconducting magnetometer. All results were plotted on orthogonal demagnetization diagrams [14] for vector analysis. Though thermal and AF treatments yielded similar results, AF was judged superior and the bulk of the collection was treated with stepwise AF demagnetization up to 100 mT.

Demagnetization diagrams for 2 samples showing representative behavior during thermal and AF demagnetization are shown in Fig. 2 in coordinates corrected for tectonic tilt. Two components of magnetization are revealed. A soft magnetization is removed, usually in fields below 15 mT or temperatures below 200°C. The in-situ directions are often steeply down but do not cluster at all well. These magnetizations may be viscous magnetizations acquired in the present field and in the laboratory. Once the soft magnetization is re-

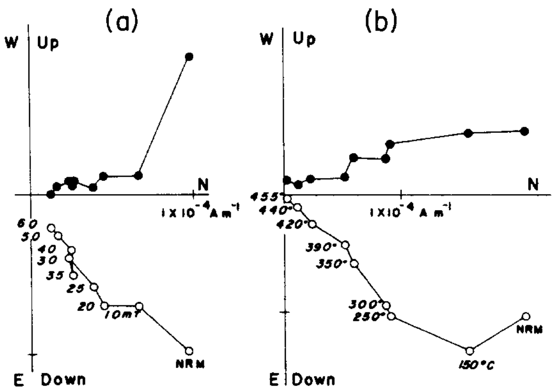

Fig. 2. Orthogonal demagnetization diagrams [14] showing the endpoints of the magnetization vectors during stepwise AF (a) and thermal (b) demagnetization. Coordinates are corrected for structural tilt. Solid circles represent projections on the horizontal plane and open circles those on the north-south vertical plane. Treatments above 60 mT and 455°C did not remove significant magnetization and are not shown for clarity.

moved, a characteristic direction is defined by univectorial decay toward the origin of the diagram. Characteristic directions were calculated by vector subtraction. A summary of site mean directions and their resulting poles is compiled in Table I. About 20% of the samples treated yielded noisy, uninterpretable demagnetization diagrams, and these samples were not used to calculate site mean directions. The column marked N/N_0 in Table I shows the number of directions used in calculation of the mean compared with the number of samples demagnetized. All of the interpretable magnetizations were of normal polarity.

The within-site precision parameter, k [15], varied markedly between sites, ranging from 103.2 (site 1) to 8.3 (site 7) to less than 3 (sites 3, 4, and 9). We have attempted to explain the extremely poor clustering of directions from sites 3, 4, and 9. Site 3 had been interpreted in the field as a tectonic breccia. Thus the highly dispersed directions from this site were not surprising. Site 9 had anomalous rock magnetic properties. The remanence was found to reside in a carrier of high coercivity (greater than 100 mT) which, by comparison with the low coercivities found in the other sites suggests that alteration of the magnetic mineralogy has taken place. The field appearance of this site is also different from the other sites. The samples have a tan color in contrast to the gray and bluish gray samples from the other sites. The high coercivities, poor paleomagnetic reliability, and the tan color of the samples from site 9 suggest that it has been exposed to recent oxidation which has destroyed its paleomagnetic properties. Similar alteration has been reported in some samples of limestones from the Swiss and French Jura [16]. Site 4 was similar both in lithology and rock magnetic characteristics to the other good sites and we are unable to explain its poor paleomagnetic reliability. Sites 3, 4, and 9 were rejected from consideration in the final pole calculations due to the poor clustering of within-site directions.

Sample and site mean directions from the 10

TABLE 1

Summary of paleomagnetic data by site and mean poles calculated from site mean poles. N/N_0 is the number of sample directions used in the calculation of the site means compared to the number of samples demagnetized. D and I are declination and inclination. Poles are given in degrees north latitude and degrees east longitude. k, K, α_{95} and A_{95} are statistical parameters [15]

Site	N/N_0	k	α_{95}	Before tectonic correction		After tectonic correction	
				direction D/I	pole (lat., long.)	direction D/I	pole (lat., long.)
1	11/11	103.2	4.5	274.0/48.9	22.6, 179.8	337.5/53.5	70.2, 139.2
2	10/10	76.5	5.6	280.6/50.4	28.0, 177.2	341.0/47.9	70.3, 125.6
3	6/6	1.4	90.0				
4	7/7	2.4	49.8				
5	7/12	14.4	16.4	263.3/59.1	22.0, 194.2	348.7/47.9	73.0, 105.5
6	5/7	14.2	21.0	317.9/62.9	59.9, 176.2	316.2/53.0	54.7, 158.5
7	6/6	8.3	24.8	353.9/70.9	77.6, 232.9	339.8/62.7	75.4, 168.2
8	7/8	81.3	6.7	309.9/76.7	55.3, 214.4	335.9/56.3	70.5, 147.5
9	8/10	1.8	60.1				
10	8/11	21.9	12.1	17.2/47.9	70.3, 19.1	335.3/54.4	69.2, 144.5
11	8/11	49.2	8.0	285.1/−23.4	−2.4, 319.9	331.9/54.7	67.0, 148.4
12	5/11	70.0	9.3	292.2/32.3	28.0, 157.5	352.7/39.7	68.6, 88.0
13	6/6	34.3	13.2	9.8/60.0	82.4, 354.0	296.8/57.3	42.9, 175.3
Mean poles					60.7, 194.0 $K=3.2$, $A_{95}=32.4$		68.4, 145.0 $K=31.8$, $A_{95}=8.7$

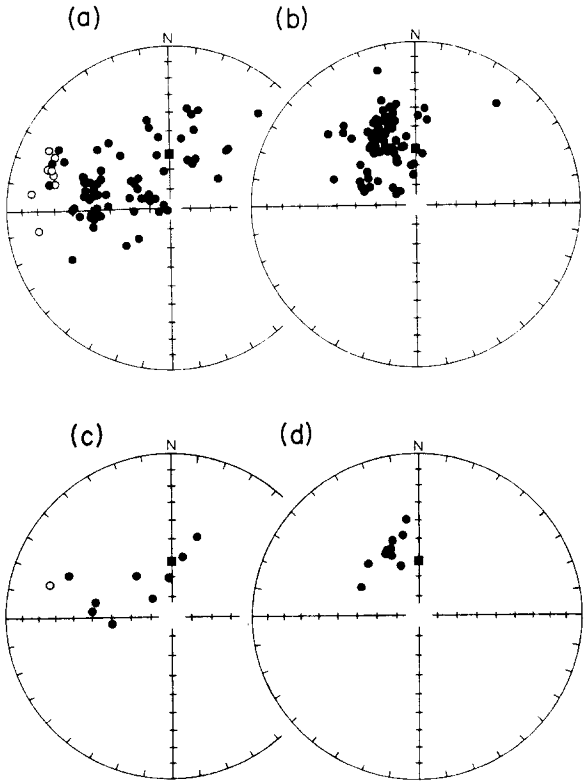

Fig. 3. Equal area plots of characteristic directions (a) from 73 specimens before tilt correction and (b) after tilt correction and (c) 10 site mean directions before correction and (d) after correction. Closed circles represent positive (down) inclinations, open circles negative ones. The present axial dipole direction is marked with a square.

good sites are plotted on equal area projections before and after correction for tectonic tilt (Fig. 3). A marked improvement in clustering of the directions is apparent after the structural correction is applied. The pole after structural correction lies at 68.4°N, 145.0°E ($K = 31.8, A_{95} = 8.7°$). Since directions from strata which lie at different attitudes cluster so much better after structural correction, the fold test [12] is positive. This test, based on the k ratios, is significant at the 99% confidence level.

4. Rock magnetic methods and results

Rock magnetic experiments were conducted to shed light on the nature of the remanence carriers in Twin Creek samples. Typical plots of the acquisition and thermal demagnetization of isothermal remanent magnetization (IRM) are shown for two samples in Fig. 4. Fig. 4a reveals a rapid acquisition of IRM below 300 mT followed by a gradual rise. Saturation is not reached even in fields as high as 5 T. Plots of the thermal demagnetization of this IRM are shown in Fig. 4b. Both samples show an initial decrease in magnetization below 100°C and both have a very small remanence above 580°C, the Curie temperature of pure magnetite.

The IRM experiments suggest that the dominant carrier present is magnetite and that hematite and possibly goethite may also be present. How-

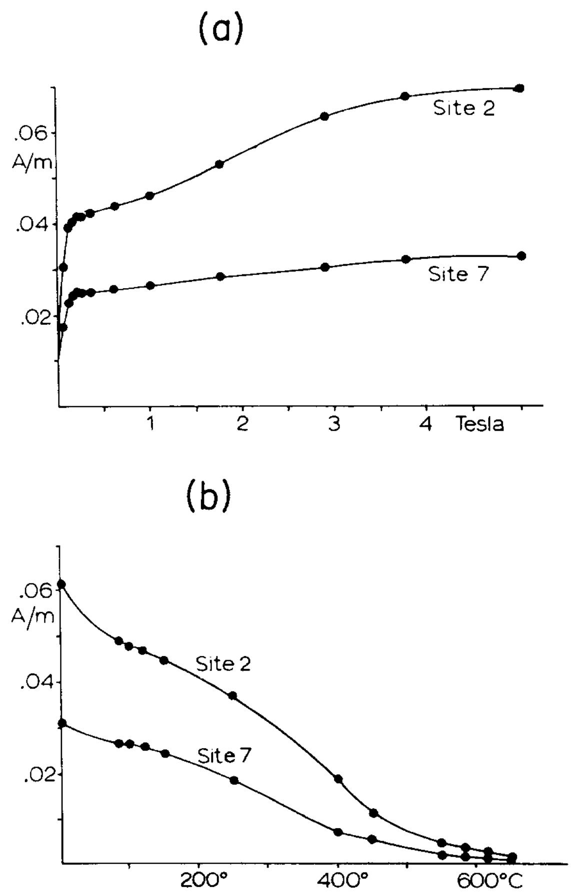

Fig. 4. Acquisition (a) and thermal demagnetization (b) of isothermal remanent magnetization for two samples. See text for interpretation.

ever, results from the AF demagnetization of natural remanent magnetization (NRM) show that most of the NRM is removed in fields below 100 mT from samples from all sites except the anomalous site 9. Thus it seems that hematite or goethite, which are usually characterized by very high coercivities, do not play an important role in the NRM of the bulk of the samples.

Low-temperature experiments were also conducted on a few samples to determine if the low-temperature magnetocrystalline transition of magnetite is present. A small thermocouple was implanted in the sample to be tested which was cooled to liquid nitrogen temperature, then placed in the cryogenic magnetometer and allowed to warm slowly while temperature was measured as a function of time. The thermocouple was then disconnected and under otherwise identical conditions the sample was cooled, given an IRM and placed in the cryogenic magnetometer where magnetization was measured as a function of time. It was then possible to eliminate the common axis (time) and plot magnetization against temperature. We have found that this method gives repeatable results in samples of a number of lithologies, and whether or not the transition is present. Fig. 5 shows a gradual decrease in magnetization during warming. However, no clearly defined low-temperature transition is present. This indicates that if

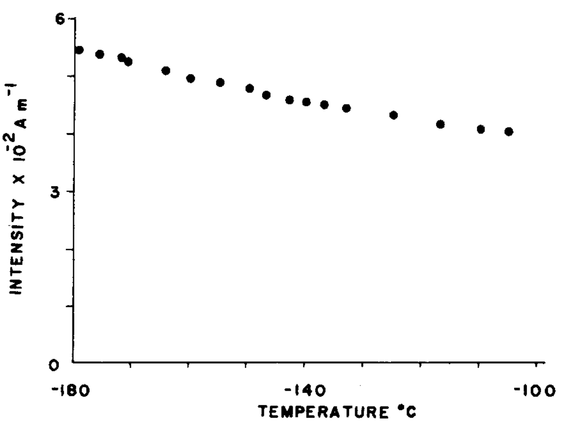

Fig. 5. The intensity of isothermal remanent magnetization acquired at liquid nitrogen temperatures, measured quasi-continuously as the sample is allowed to warm up in the cryogenic magnetometer.

magnetite is present, anisotropies other than the magnetocrystalline anisotropy are dominant. These may be related to grain shape or grain size [17].

The rock magnetic evidence presented here, while not conclusive, is consistent with the dominance of magnetite in the magnetic mineralogy of the Twin Creek samples tested.

5. Discussion and conclusion

Both clockwise and counterclockwise rotations of Triassic strata have been documented in thrust sheets in the study area [13]. Thus we cannot claim to have obtained a pole representative of cratonic North America unless it can be shown that our data are not biased due to rotations. To test for this we have divided all sample directions (after structural correction) into two groups: one group from the Gros Ventre Block on the foreland (sites 6–8) which we assume are not rotated [11,13], and another group that includes the results from the overthrust belt which may be rotated. Mean directions and their statistical parameters were calculated for these two populations, and for all directions combined. It was then possible to test whether the means from the two populations are statistically different. We have used the test of McFadden and Lowes [18]: this test was chosen because it can be used when the k values from the two populations are statistically different (as they are in this case) by using the k ratio as an estimate of the Kappa ratio in the equations. The results, shown in Table 2, indicate that the mean directions from the overthrust belt and from the foreland are not different at the probability $(p) = 0.05$ level of significance. Thus the accuracy of the Twin Creek mean pole has not been significantly affected by rotations; if these strata have been rotated, clockwise and counterclockwise rotations have effectively canceled each other.

The Twin Creek pole is plotted in Fig. 6 along with other Middle and Upper Jurassic poles. Though it falls on the expected Jurassic APW path [6] it is more easterly (i.e. younger) than the pole derived from the Summerville Formation [5]. This result is unexpected: the Twin Creek is Middle Bajocian to Lower Callovian while the Summer-

TABLE 2

In the test of McFadden and Lowes [18] the null hypothesis that 2 populations with different precision parameters share a common true mean may be rejected at the $p=0.05$ level of significance if the quantity labeled * below is greater than that labeled **. The 2 populations, in this case the directions from the foreland and those from the thrust belt, are not significantly different at the specified confidence level. D/I is the mean declination and inclination of a population, N is the number of sample directions in the population, R is the length of the resultant vector, k is the estimate of the precision parameter, and r is the estimate of the ratio of the precision parameters of two populations. In this case $r=k_2/k_1$. All directions used have been corrected for structural tilt

	Population of sample directions		
	all	thrust belt	foreland
D/I	335.9/53.6	337.3/52.3	330.9/57.8
N	$N=73$	$N_1=55$	$N_2=18$
R	$R=69.77$	$R_1=52.93$	$R_2=16.93$
k	$k=22.28$	$k_1=26.06$	$k_2=15.85$
* $\dfrac{r\left[(R_1+R_2)^2-R^2\right]}{2[(N_1-R_1)+r(N_2-R_2)](R_1+rR_2)}$		** $\left(\dfrac{1}{0.05}\right)^{1/(N-2)}-1$	significant
0.022		0.043	no

ville has been assigned younger ages, Callovian [19] or Oxfordian [10]. It seems unlikely, in a time of rapid APW from west to east, that the paleomagnetic pole was in a more easterly position at an earlier time. The possibility of remagnetization of the Twin Creek must therefore be addressed. Though the age of the Twin Creek is well constrained, the age of the magnetization is not. The results of the fold test show that the magnetization was set before tectonism, but a late Jurassic remagnetization cannot be ruled out. A thermal remagnetization is unlikely however. There is less than 2 km of Jurassic and marine Cretaceous above the Twin Creek. Lower Tertiary and Upper Cretaceous synorogenic basin fill can reach considerable thicknesses however, and in some cases (e.g. the Prospect Thrust) basin fill sediments are cut by thrust faults. Determination of the maximum total overburden at any particular locality is thus difficult. However, the position of the Twin Creek pole is significantly to the west of (i.e. older than) the Lower Cretaceous poles. The total Jurassic overburden is less than a kilometer, and thus a late Jurassic thermal remagnetization is highly unlikely. On the other hand, an early chemical remagnetization is possible. Paleomagnetic and rock magnetic studies along with analyses of magnetic extracts from the Siluro-Devonian carbonates in the Appalachians show the carriers to be pure magnetite, but occurring as framboids of diagenetic origin [20]. Work is in progress char-

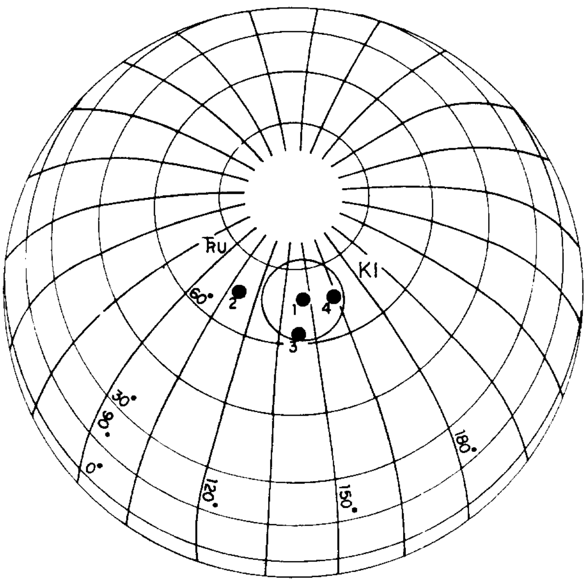

Fig. 6. Orthographic projection showing the approximate position of mean Upper Triassic/Lower Jurassic, and Lower Cretaceous poles. Individual Jurassic poles are: *1* = Twin Creek (this study), *2* = Summerville [5], *3* = Lower Morrison [4] and *4* = Upper Morrison [4]. The Twin Creek pole is shown with its 95% confidence limits.

acterizing magnetic extracts from a number of limestone units, including those from the Twin Creek. We have no reason, on present evidence, to suspect that the Twin Creek has been remagnetized in the same fashion as the Appalachian carbonates. Those limestones were remagnetized during the Alleghenian orogenic event while deeply buried [20]. However, work characterizing magnetic extracts from limestones is at a very early stage and firm conclusions cannot be made. If results of this work eventually yield no reason to suspect early chemical remagnetization of the Twin Creek, then the Summerville results will need to be examined, in particular the age of the Summerville and the nature of its magnetization.

In conclusion, the Twin Creek pole we have obtained passes the fold test, has not been significantly affected by rotations of thrust sheets, and falls on the expected Jurassic APW path. However, a very detailed time calibration of the Jurassic APW path is in question because of the more easterly (i.e. younger) position of the Twin Creek pole compared with the Summerville pole which has been cited as a younger unit. Early chemical remagnetization of the Twin Creek is being studied as a possible reason for this discrepancy. If the Twin Creek pole is the result of a primary magnetization, then our results suggest that significantly more APW occurred prior to the late Jurassic than has been indicated by the Summerville results.

Acknowledgements

Most of the paleomagnetic measurements were performed by Ronna Simon and Marc Frank. Helpful discussions with Jack Dorr and Henry Pollack are acknowledged. A number of people have critically reviewed the manuscript, including two anonymous reviewers; their comments are gratefully acknowledged. This work was supported by the Division of Earth Sciences, The National Science Foundation, grant EAR79-02690.

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