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CRETACEOUS PALEOMAGNETISM OF THE METHOW-PASAYTEN BELT, WASHINGTON

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Abstract. Detailed demagnetization experiments isolated a characteristic remanent magnetization in ten stable sites from the upper Cretaceous Winthrop and Midnight Peak Formations in the Methow-Pasayten belt of north-central Washington. This remanence agrees best between opposite limbs of a fold (the Goat Peak syncline) when corrected for 46% of tilt. This is consistent with magnetization acquired during deformation. Synfolding magnetization may have been facilitated by a thermo-chemical event associated with synkinematic intrusions along the axis of folding. The mean direction ($D=12.0^{o}$, $I=61.1^{o}$, Alpha-95=4.8^{o}) is highly discordant with respect to the expected direction for north-central Washington. This discordance points to about 1,400 km of poleward transport and 48^{o} of clockwise rotation between 93 and 45-48 Ma.

Introduction

Most of the terranes surrounding the Methow-Pasayten belt of north central Washington (Figure 1) are "suspect" in that they show paleomagnetic and/or geologic evidence for significant tectonic translation [Irving et al., 1985]. Over the past decade many examples of anomolously shallow magnetic directions probably indicating poleward transport have been reported from most parts of the western edge of North America [Beck, 1980]. Much of this evidence comes from study of Mesozoic intrusive rocks, and these lack paleohorizontal control needed for tectonic reconstruction. We studied the Methow-Pasayten belt, which preserves a sequence of Mesozoic sediments and layered volcanics that appeared to be an excellent target for a paleomagnetic study of Mesozoic rocks to test tectonics in the region. Our results indicate, however, that the rocks have been remagnetized during folding, enormously complicating interpretation.

The Methow-Pasayten belt is flanked by highly deformed plutonic complexes (Figure 1). East of the Chewack-Pasayten fault is the Okanogan gneiss complex [Fox et al., 1976]. To the west, the Black Peak batholith occupies the Ross Lake fault zone and ties the Methow-Pasayten belt to the Cascade terrane since at least the late-Cretaceous. Within the Cascade terrane, the Cretaceous Mount Stuart batholith preserves magnetic directions consistent with large poleward displacement and clockwise rotation [Beck et. al., 1982a].

Rocks in the Methow-Pasayten belt record several episodes of deformation. The most recent major deformation created a synclinorium of broad, gently plunging, en echelon synclines that are separated by high angle faults [Barksdale, 1975]. We sampled the structurally uncomplicated upper Cretaceous Winthrop Formation and the overlying Ventura Member of the Midnight Peak Formation in the Goat Peak syncline (Figure 2). The Winthrop Formation is an arkosic sandstone that was deposited rapidly and then deformed before it had completely lithified [V. Todd, oral communication, 1985]. The Ventura Member of the Midnight Peak Formation is a hematite-cemented quartz arenite. Barksdale [1975], Tennyson [1974], and Trexler and Bourgeois [1985] described the local geology.

Methods and Results

Sites consist of six to twelve independently oriented samples collected over several tens of square meters within a single bed or flow unit. Alternating field (A.F.) demagnetization of specimens from three sites in the Winthrop Formation removed a steeply inclined low coercivity magnetic component below 20 mT. From 20 mT to 100 mT a single shallow magnetization was isolated. Specimens of the Ventura Member red beds were unaffected by A.F. demagnetization. Stepwise thermal demagnetization to 700^{o} C removed a component steeply inclined down to the north, similar to the present Earth's field below 200^{o} C, then a single magnetization. The directions of the highest stability components were derived using a least-squares method [Kirschvink, 1980].

Site mean directions of these high stability components showed some streaking but were in closer agreement within a limb than between limbs

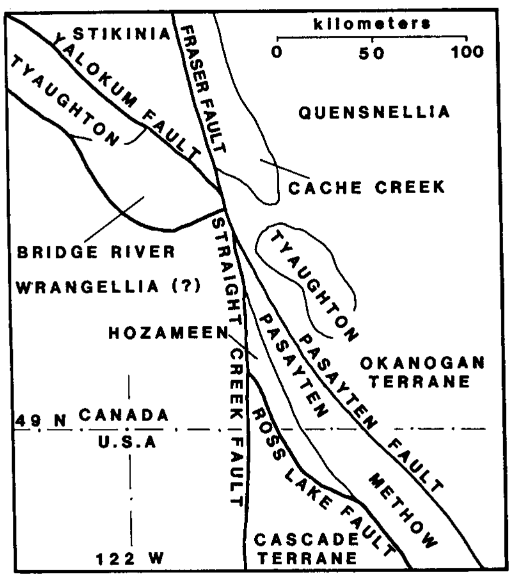

Fig. 1. Location map showing major tectonic terranes and sutures associated with the Methow-Pasayten belt. After Trexler and Bourgeois [1985].

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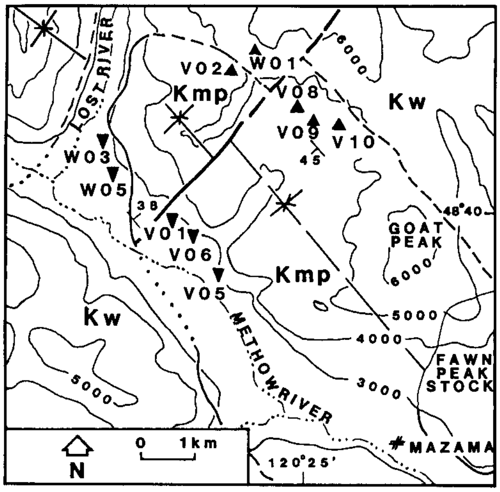

Fig. 2. Simplified geologic map of study area showing contact (bold solid and dashed line) between the Winthrop (Kw) and Midnight Peak (Kmp) Formations, site distribution (▲ in NE limb, ▼ in SW limb) and representative attitudes.

(Table 1, Figure 3a). Restoring beds to paleohorizontal (100% corrected) transposed site mean directions from opposite limbs (Figure 3b) but left the overall mean direction essentially unchanged. Thus the classical fold test is indeterminate.

Analysis

The transposition of directions from opposite limbs suggests that the magnetizations were acquired during folding. Several instances of synfolding magnetization have been reported previously [Schwartz and Van der Voo, 1984; Kent and Opdyke, 1985]. A thermo-chemical event associated with synkinematic intrusions emplaced along the fold axis may have facilitated remagnetization.

The timing of deformation and acquisition of magnetization is constrained to the Late Cretaceous. The youngest rocks affected by this deformation are Late Cretaceous, and synkinematic intrusions have been dated at 80-90 Ma. The consistent normal magnetic polarity found in Winthrop and Midnight Peak Formations suggests acquisition during the Late Cretaceous long normal period. Formations affected by the deformation are unconformably overlain by undisturbed Paleocene Pipestone Canyon Formation.

There are of course other explanations for the peculiar "fold-test" results illustrated in Figure 3. For instance, a similar pattern of magnetic directions might be obtained by mixing prefolding and post-folding magnetizations, but any such components could not be isolated. Explanations invoking remagnetization of only one limb also can be made to work, but they leave intact much of the scatter shown in Figures 3a and b. The best agreement of site means was achieved by correcting all sites for 46% of tilt. This restoration resulted not only in the least dispersion of magnetic directions between opposite limbs but also reduced within-limb dispersion and produced the most circular distribution (1 in Table 2; Figures 3c, 4).

Unfortunately, achievement of high precision of the mean direction does not guarantee its correctness. The rocks have been remagnetized so their layering can no longer be used to determine

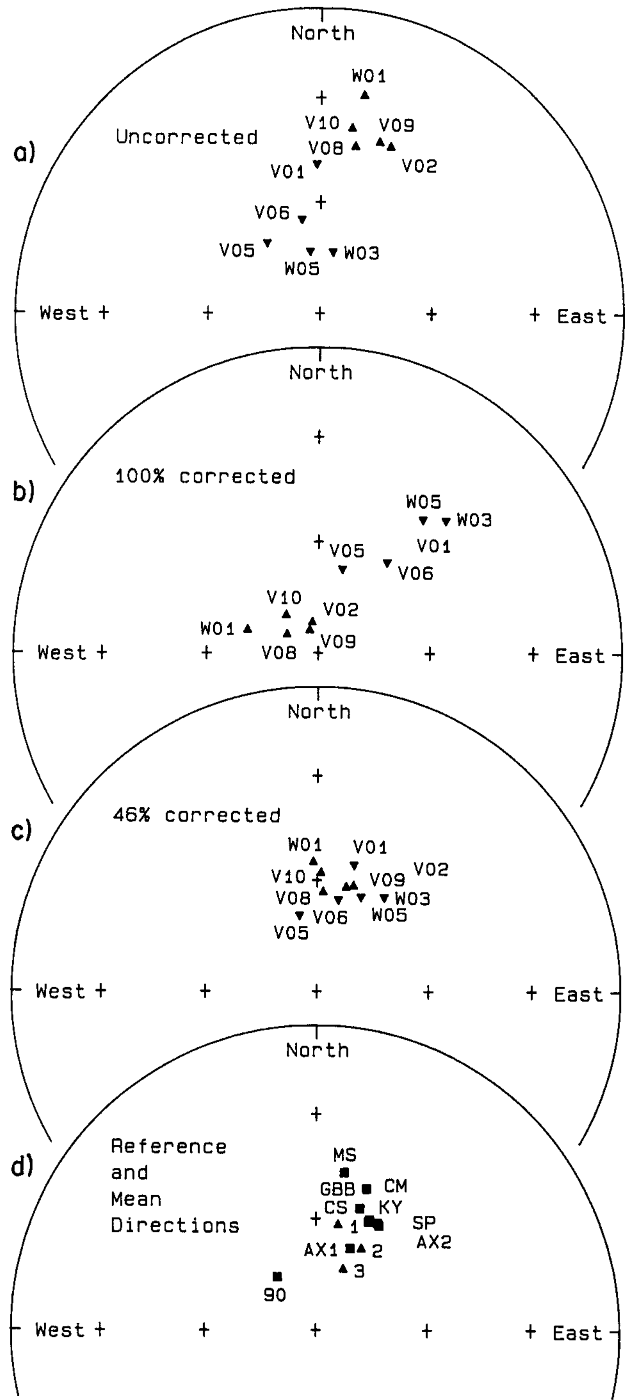

Fig. 3. Stereographic projection of site mean directions from the Goat Peak syncline of the Methow-Pasayten belt in (a) uncorrected, (b) 100% corrected and (c) 46% corrected coordinates. Sites from the NE limb shown by ▲, those from the SW limb shown by ▼. (d) compares directions 1, 2 and 3 of Table 2 with 90 Ma expected direction, and directions predicted from terranes north and west, calculated from tabulation in Irving et al., [1985].

TABLE 1. Mean Directions of Sites From the Goat Peak Syncline

Site	Bed Attitude	Dec.	Inc.	N	Result.	k	A-95	Levels	Ty
Winthrop Formation									
W01	213,65	11.3	+28.1	6	5.866	37	11.1	200 1700	a
W03	060,38	11.6	+73.1	3	2.953	43	19.1	50 1400	a
W05	060,38	350.8	+73.0	5	4.799	20	17.6	25 1000	at
Ventura Member of Midnight Peak Formation									
V01	117,32	358.5	+49.2	4	3.978	136	7.9	300 670	tc
V02	210,43	22.8	+40.5	7	6.963	162	4.7	400 675	tc
V05	080,22	323.2	+66.2	7	6.905	63	7.7	200 675	tc
V06	093,25	348.9	+64.1	6	5.972	178	5.1	200 670	ta
V08	205,45	11.8	+43.4	4	3.978	136	7.9	400 665	t
V09	205,45	19.0	+40.4	5	4.958	95	7.9	435 670	t
V10	205,45	9.6	+38.4	5	4.926	52	10.5	300 680	t

Bed Attitude is azimuth and plunge of dip vector. Abbreviations: Dec. and Inc., declination and inclination of remanent magnetization in geographic coordinates; N, number of samples; Result.; sum of unit vectors used in analysis; k, precision parameter; A-95, semiangle of cone of 95 percent confidence. Levels and Ty show inclusive range and type of demagnetization; a, alternating field in Oersteds; t, thermal in degrees Celcius; c, chemical (HCl). Second type demagnetization refers to treatment of only one speciman.

an unambiguous paleolatitude. Still, the structure sampled provides some evidence for evaluating post-magnetization tilt. If tilt in an arbitrary direction is small, little error is introduced by considering it as due to successive rotations about two orthogonal horizontal axes, one of which is perpendicular to the fold hinge. Rotation about this axis would change the plunge of the fold, whereas rotation about the second horizontal axis would tilt the fold's axial surface.

To test alternative tilt corrections we used bed attitudes in Table 1 to determine the best fit fold axis and axial plane dip. On the assumption that the fold was originally horizontal, we corrected for the fold plunge to get direction 2 in Table 2. On the assumption that the fold also was upright when magnetized, we next corrected for tilt of the axial surface to get direction 3.

The first direction in Table 2 is preferred for several reasons: 1) The plunge obtained in the analysis above may be unrepresentative. The closure of the fold shown in Figure 2 is due mainly to topography. Analysis of 21 bed attitudes measured in the Goat Peak syncline showed plunge to the southeast is less than five degrees. 2) Poles to bedding are scattered. Therefore, it seems unwise to treat the data as belonging to a single ideal cylindrical plunging fold. We interpret the marginally higher precision of 1 in Table 2 as confirmation of this. 3) There is no particular reason to suspect that the fold was originally upright. If the fold had evolved its apparent vergence continuously, most of the vergence would have already existed when the rocks were magnetized, and any correction to remove this would be wrong. 4) There is no evidence for major block tilting after development of the Goat Peak Syncline.

Interpretation

The inclination of the third direction in Table 2 is consistent with in situ magnetization, but the declination requires that fold axes trended east to east-northeast at the time of remagnetization. This and the implied presence of a major boundary active in the latest Cretaceous and earliest Tertiary between the Methow-Pasayten belt and the Cascade terrane are difficult to reconcile with the geology. The second direction in Table 2 suggests significant poleward transport of the Methow. However, the large rotation makes generation of the folds difficult to attribute to plate interaction.

The first direction in Table 2, is consistent with plate models and apparent histories of neighboring terranes [Irving et al., 1985] (Figure 3d). The simplest interpretation is that the Methow region experienced about 1400 km of poleward transport and 48^{o} of clockwise rotation.

TABLE 2. Mean Direction for Various Tectonic Corrections

Note	Dec.	Inc.	N	Result.	k	A-95	R	+/- ΔR	F	+/- ΔF
1	12.0	+61.1	10	9.914	105	4.8	47.9	10.1	11.3	4.4
2	29.4	+65.1	10	9.894	85	5.3	65.3	11.8	7.3	4.7
3	24.2	+72.2	10	9.894	85	5.3	60.1	15.4	0.2	4.7
X	324.1	+72.4	5	4.989	348	4.1				

Dec., Inc., N, Result., k, A-95 as in Table 1. R, rotation, and F, flattening of inclination calculated according to Beck [1980]. ΔR and ΔF, 95% confidence intervals from method of Beck [1980] reduced by Demarest [1983] factor of 0.8.

1 Untilt 46% about strike of beds at sites in Table 1.

2 Untilt 44% after restoring fold (132.8^{o} azimuth, 17.8^{o}) plunge to horizontal.

3 Untilt 2 above 7.5^{o} about fold axis to make syncline upright when magnetized.

X Direction expected at mean location (48^{o}, 48'N, 120^{o}, 27'W) for 90 Ma pole of Irving and Irving [1982].

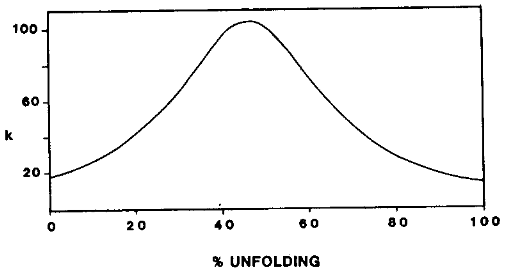

Fig. 4. Graph of between-site Fisher [1953] precision parameter (k) versus percentage unfolding of beds. Between-site dispersion is near minimum when all sites are corrected for 46% of their bed tilt. Nonproportional restoration of limbs produces greater dispersion.

Restoring the Methow-Pasayten belt to its inferred Late Cretaceous location and orientation aligns the axes of last Cretaceous folds roughly east-west. This is nearly normal to the direction of Kula-North America plate convergence [Engebretson et al., 1985]. This convergence can account for docking of the Cascade terrane and the last deformation in the Methow-Pasayten belt better than can Farallon-North American convergence, which suggests that the Kula-Farallon ridge was south of the Methow at about 85 Ma. The subsequent poleward transport of these crustal blocks on or along side of the Kula plate must have ceased by 45-48 Ma, the age of Tertiary plutons which have in situ magnetic directions in the Cascade terrane [Beck et al., 1982b].

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