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REMAGNETIZATION AND TECTONIC ROTATION OF UPPER PRECAMBRIAN AND LOWER PALEOZOIC STRATA FROM THE DESERT RANGE, SOUTHERN NEVADA

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Abstract. In the Desert Range of southern Nevada, miogeoclinal sedimentary rocks, mostly shallow-water limestones of latest Precambrian through Early Ordovician age, yield three components of magnetization having different blocking temperature spectra: (1) a low blocking temperature component near the direction of the present axial-dipole field; (2) an intermediate blocking temperature component with northerly declination and inclination ~+60°; and (3) a characteristic component with southeasterly declination and inclination ~-20°. Combinations of alternating field and thermal demagnetization indicate that the intermediate and characteristic components reside in magnetite. The intermediate magnetization probably reflects a viscous partial thermoremanent magnetization (VPTRM) imposed between the Late Cretaceous and mid-Cenozoic; it was probably acquired when the strata were dipping slightly eastward. The characteristic magnetization is probably a VPTRM imposed during regional uplift in the Late Permian. The degree of heating required to have destroyed any primary magnetization is consistent with the conodont color alteration index observed in the Ordovician rocks; additionally, the characteristic magnetization in those rocks is younger than bedding disruption caused by major, late stylolitization. Red-purple mudstones from the middle member of the Wood Canyon Formation, in which a directionally similar characteristic magnetization resides in fine-grained hematite, also appear to have been remagnetized; in these rocks, the remagnetization probably reflects partial recrystallization, as the blocking temperatures are too high to have been reset by burial heating. The sampled sections have undergone relative tectonic rotation about a vertical axis, consistent with late Tertiary oroflexural bending that had been proposed on independent geologic evidence. The characteristic magnetization probably provides a reliable estimate of the magnitudes of the vertical axis rotations, as the regional geology suggests the Desert Range strata were essentially horizontal throughout the Paleozoic. The total observed relative rotation is 44°±5°, representing absolute counterclockwise rotation (27°±4°) of the northern part of the Desert Range, and absolute clockwise rotation (17°±5°) of the southern part. The only unit in the Desert Range sequence that may retain a primary magnetization is the late Precambrian Rainstorm Member of the Johnnie Formation. The characteristic magnetization of this unit exhibits two polarities and probably resides in specular hematite; after correction for 18° of counterclockwise rotation, the resulting pole (5°N, 151°E) is near other late Hadrynian poles from North America.

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Introduction

This paper reports an extensive follow-up study on the paleomagnetism of some late Precambrian and early Paleozoic strata in the Desert Range, Nevada, where a spectacular miogeoclinal section spanning the Precambrian-Cambrian boundary is exposed. Results from the initial study have been reported in several abstracts and in two previous papers [Gillett and Van Alstine, 1979; Van Alstine and Gillett, 1979a]. We tentatively concluded that primary magnetizations exist in many of the strata and that 36° of clockwise rotation of the Desert Range occurred with respect to the craton. It will be shown in this paper that these conclusions must be modified.

This paper incorporates data from the progressive demagnetization of over 500 new samples, as well as additional magnetic experiments performed on duplicate specimens from the earlier samples. Extensive petrographic study on both old and new samples has also been done, and details of the petrography where textural relations are particularly important in interpreting the magnetizations are presented elsewhere [Gillett, 1983a,b].

The geologic setting of the Desert Range is rather complex (Figures 1 and 2) [Gillett and Van Alstine, 1979; Guth, 1981]. Briefly, pre-Mesozoic strata in the area are miogeoclinal facies of the Cordilleran geosyncline and range in age from late Precambrian to Permian. Little tectonism affected the area until the end of the Paleozoic. Cretaceous thrusting from the Sevier Orogeny is prominent, as is late Tertiary Basin and Range normal faulting. A right-lateral fault zone, the Las Vegas Shear Zone, occurs to the south of the Desert Range, and a left-lateral shear system, the Pahranagat Shear System [Tschanz and Pampeyan, 1970] trends westward toward the northern part of the range (Figure 1). Wright [1976] suggests that the Pahranagat Shear System and the Las Vegas Shear Zone are conjugate faults. Albers [1967] proposed large-scale,

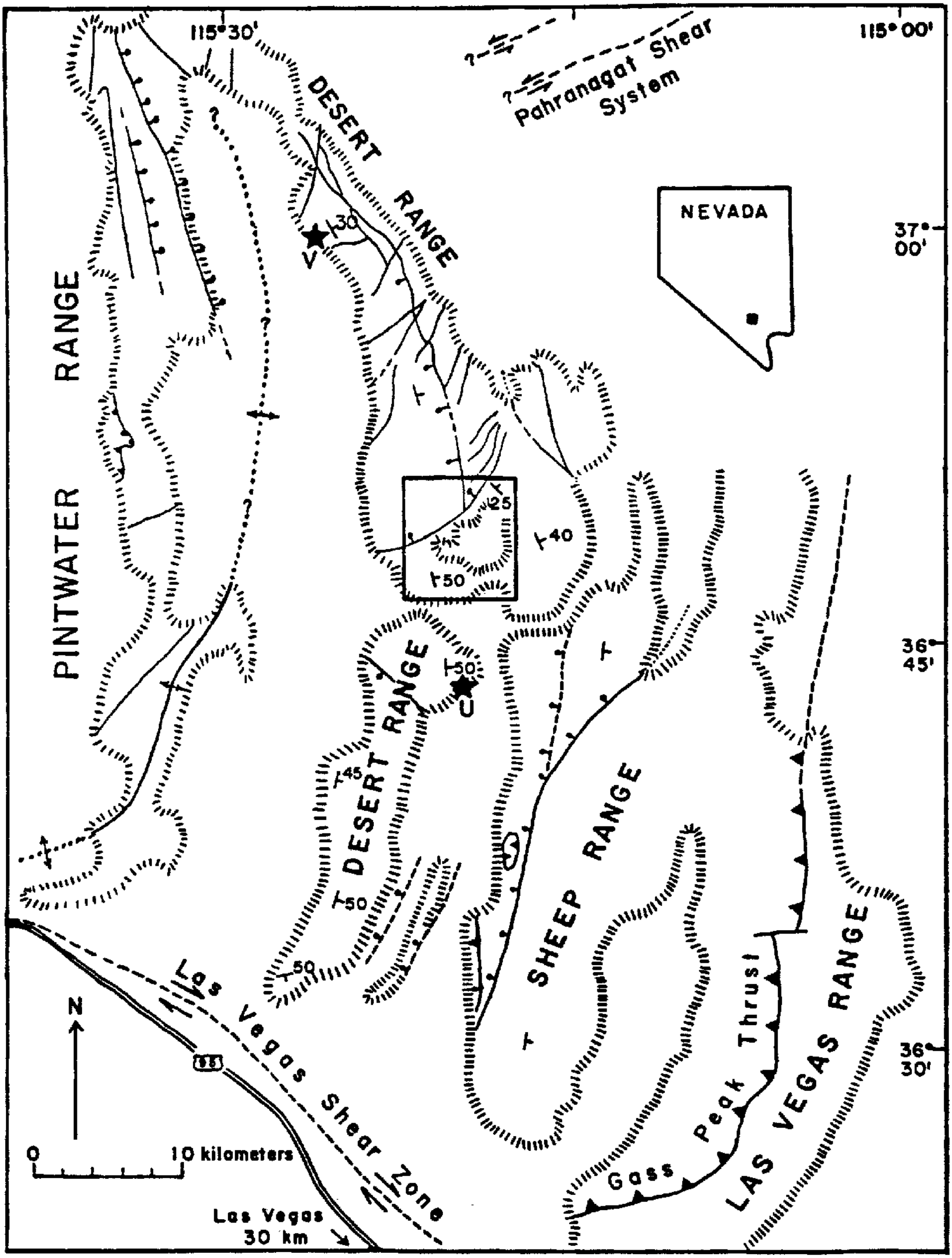


Fig. 1. Geographic and tectonic setting of the Desert Range. The outlined area in the middle part of the range is where most sampling was concentrated and is shown in detail in Figure 2. U and V represent sampling sites south and north of the main sampling area (see text). Mapping of geologic structures adapted from Longwell et al. [1965] and Tshanz and Pampeyan [1970].

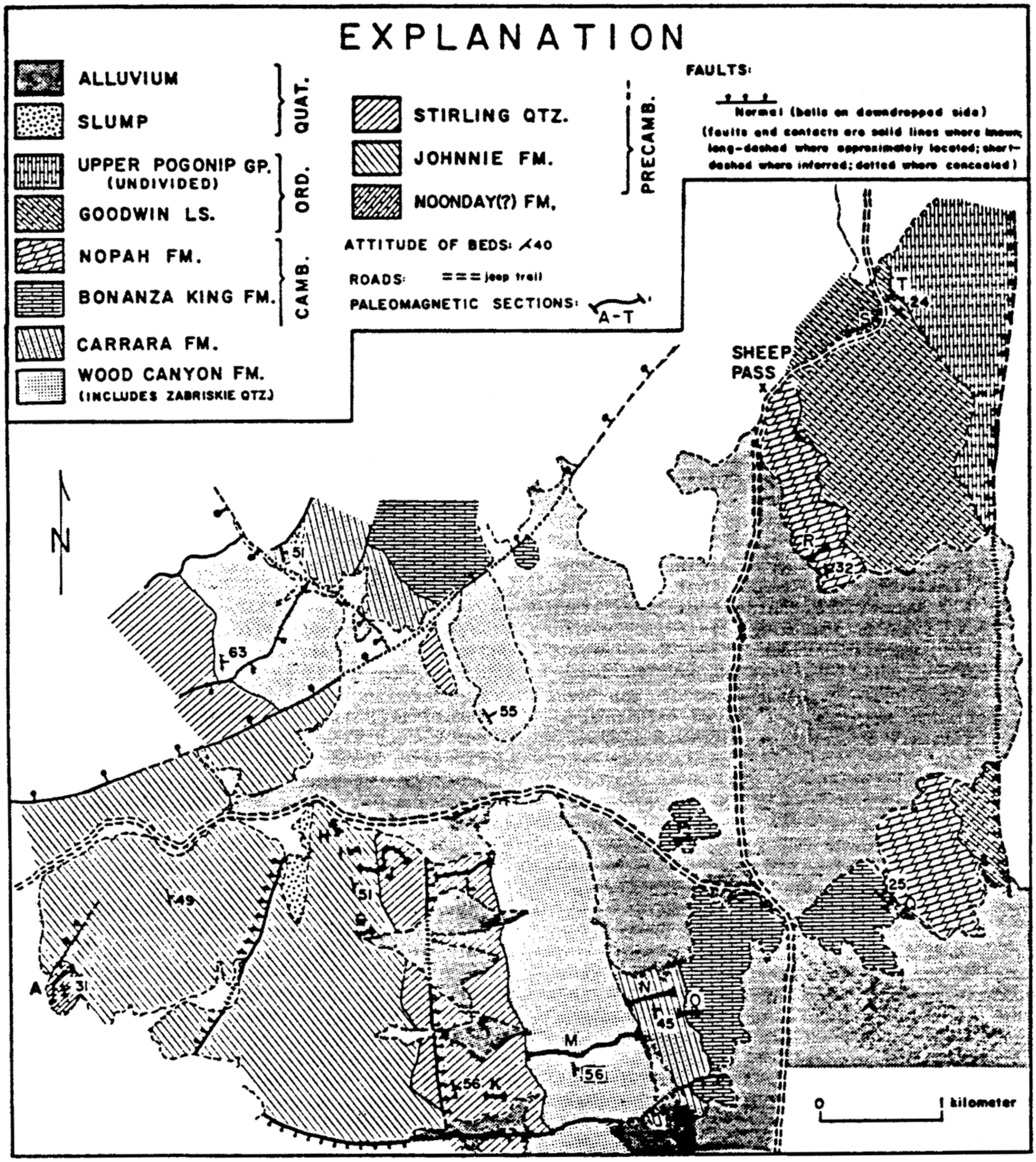


Fig. 2. Generalized geologic map of part of the Desert Range, where most paleomagnetic sampling was conducted. Geology by S. L. Gillett and D. R. Van Alstine, 1975-1979.

clockwise tectonic bending ('oroflexural bending') to account for curves in the trends of isopachs, Mesozoic structural features, and the topographic expression of the ranges themselves as they near the Las Vegas Shear Zone. Accommodation of displacement by such bending could also account for the lack of left-lateral strike slip offset from the Pahranagat Shear System in the northern Desert Range. The faulting and the oroflexural bending were both active in late Tertiary time.

This paper presents paleomagnetic data from the Carrara Formation (Lower and Middle Cambrian), the lowermost Bonanza King Formation (Middle Cambrian), the uppermost Bonanza King Formation (Upper Cambrian), the upper Nopah Formation (Upper Cambrian), and the Goodwin Limestone (Lower Ordovician). In addition, data are presented on a secondary magnetization in an upper Precambrian limestone unit tentatively referred to the Noonday Formation.

Sampling, Laboratory, and Statistical Procedures

Oriented block samples were collected using a technique described by Gillett and Van Alstine

[1979]. Generally, one block sample was collected from each sampled bed, and two cylindrical cores 2.5 cm in diameter were drilled from most blocks. Initially, a single specimen 2.5 cm long was trimmed from each core; duplicate specimens for additional demagnetization experiments were cut as needed. Trimmed carbonate specimens were rinsed briefly with dilute HCl to remove possible magnetic contamination resulting from the drilling and sawing. Magnetic measurements were made on ScT superconducting rock magnetometers interfaced with computers; the systems used have background noise levels of less than 1×10^{-10} A m^2 (1×10^{-7} emu) and allow immediate, on-line data reduction.'

Progressive thermal and/or alternating field (af) demagnetization was performed on all samples. Initially, thermal demagnetization had been done in a noninductively wound electrical oven shielded from the Earth's ambient field only with Helmholz coils. Although spot checks of the field within the sample area showed variations of the order of 10-15 nT (1 nT = 1 γ), it is certain that some spurious components were imparted by this oven; many samples treated in this oven have erratic demagnetization paths. Different electrical ovens, in which the shielding is accomplished by nested sets of μ-metal cylinders, were used for all subsequent thermal demagnetization work. These systems are much more reliable than the previous one, as evidenced by very smooth demagnetization paths observed in samples demagnetized with them. Irrespective of the oven used, specimens were always placed with nonsystematic azimuthal orientations during demagnetization, so that systematic spurious components could not be imparted.

The af demagnetization was done mostly with a Schonstedt GSD-1 nontumbling demagnetizer but in part with a Schonstedt GSD-5 tumbling demagnetizer. The GSD-5 reverses the sense of tumbling about every second, further minimizing the possibility of imposing spurious magnetizations.

Bulk susceptibility was measured on a large number of samples, as it is useful in monitoring possible chemical changes occurring during thermal demagnetization [e.g., Turner, 1975]. Susceptibilities were measured using the cryogenic magnetometers, as described by Gillett et al. [1982].

Progressive demagnetization data from all specimens were plotted by computer, using a modification of Zijderveld's [1967] demagnetization diagrams similar to that employed by Roy and Park [1974]. Components of magnetization were identified visually on the demagnetization diagrams and a least squares line fitted to them as described by Gillett et al. [1982]. The computer search technique of Kirschvink [1980] was not employed, as it yielded estimates of components that were somewhat biased by curved parts of the demagnetization path.

In the previous two papers [Gillett and Van Alstine, 1979; Van Alstine and Gillett, 1979a], representative directions for each formation were calculated from a modal analysis technique developed by Van Alstine [1980]. In most cases the distributions of directions were skewed, probably because of the incomplete removal of secondary components; in such cases a mode is a better estimate of central tendency than the mean. In this paper, Bingham statistics [Bingham, 1974; Onstott, 1980] have been used as a guide to where modal analysis may be appropriate [Gillett et al., 1982]. In a few cases, modes were also calculated where the Fisher 95% confidence angles are large (>10°). Finally, obvious outliers were discarded before statistical analysis was begun when the vector diagrams indicated anomalous demagnetization behavior.

To supplement the magnetic work, an unweathered, trimmed end from each core was polished and examined under a binocular microscope. For limestones, such a polished section was also etched with dilute (~5%) HCl. In many cases, large polished sections were made from the blocks remaining after the samples were drilled. About 100 thin sections were also examined under reflected and transmitted light; a number were also examined with cathodoluminescence, using a Nuclide Corporation Luminoscope. The goals of the petrographic work were (1) to define the various lithologic types present, checking for correlations between rock type and magnetic behavior, and (2) to seek textural features that might constrain the timing of magnetization.

Results

Noonday(?) Formation

During this investigation, a thick oolitic limestone was discovered stratigraphically underlying the oldest beds of the Johnnie Formation that were described by Stewart and Barnes [1966]. Tentatively, this limestone is correlated with the Noonday Dolomite that underlies the Johnnie elsewhere in the southern Great Basin [Stewart, 1970]; the occurrence of a unit correlative with the Noonday in this area had been suggested by Longwell (quoted by Tschanz and Pampeyan [1970, p. 12]). Therefore, this limestone will be referred to as the Noonday(?) Formation.

The Noonday(?) was sampled at section A (Figure 2; Table 1). The Noonday(?) samples were subjected to progressive af demagnetization at five steps between 10 and 75 mT, as well as to progressive thermal demagnetization at 250°C and 320°C, continuing in some cases to over 600°C. The directions of natural remanent magnetization (NRM) in the Noonday(?) are generally near that of the present axial dipole field (PADF) at the site, but the distribution is somewhat skewed to the northwest. At 250°C, the drop in magnetic intensity ranges from slight to pronounced, and the directions of most samples move farther to the northwest; in turn, there is a modest to very large drop in intensity at 320°C (Figure 3a). Above 320°C, the Noonday(?) displays a two-polarity, high blocking temperature magnetization aligned essentially parallel and antiparallel to the PADF.

The northwesterly skewing of remanence directions at low thermal demagnetization steps reflects an intermediate blocking temperature magnetization which has northwesterly declination, positive inclination, and a blocking temperature of <320°C. The direction of this component was estimated as the subtracted vector between the 250° and 320°C steps (Figure 3b and Table 1). This magnetization greatly resembles an intermediate blocking temperature magnetization found in the Paleozoic limestones, as discussed below.

The af demagnetization resulted generally in little to no intensity decay, suggesting that the PADF component present in NRM at least partly resides in some species with high coercivity. This species is probably goethite resulting from recent weathering, as the PADF direction is readily destroyed by thermal demagnetization to less than 200°C.

The high blocking temperature magnetization of the Noonday resembles that in the lower two thirds of the overlying Johnnie Formation; it is a two-polarity remanence, residing in hematite, that apparently reflects Tertiary chemical remagnetization [Van Alstine and Gillett, 1979b].

Lower Carrara Formation

Several sedimentary cycles, each tens of meters thick, characterize the Carrara Formation of Early and Middle Cambrian age [Palmer, 1971]. Each cycle includes fine-grained, terrigenous rocks (siltstones and shales, with minor quartzite) in the lower part that grade to limestone in the upper part. On the basis of these cycles, Palmer and Halley [1979] divided the Carrara into nine members; Gillett and Van Alstine [1979] reported paleomagnetic data from the lower seven members (Group I) separately from the upper two (Group II).

Gray limestones, irrespective of their detailed type, gave the most consistent paleomagnetic results from the Carrara, yielding a southeasterly 'characteristic' [Zijderveld, 1967] direction with shallow negative inclination. Reexamination of the vector diagrams for all Carrara specimens shows that the demagnetization paths for thermally demagnetized specimens are quite erratic, probably from imposition of spurious components of magnetization by the old thermal demagnetization oven; hence, the characteristic component of these samples cannot be estimated by fitting a least squares segment to the demagnetization path. For this reason, the mode of directions calculated by Gillett and Van Alstine [1979], which was derived from specimens that had undergone combined thermal and af demagnetization, probably remains the best estimate of the Carrara Group I characteristic direction (Table 1).

An intermediate blocking temperature component of magnetization is also present in the Carrara limestones. This component has been estimated as the mode of subtracted vectors between the 200° and 300°C thermal demagnetization steps (Figure 4a and Table 1). This component is less affected by the imposition of spurious magnetizations, as its intensity is much larger than the characteristic component. Af-following-thermal demagnetization experiments (as discussed below) on five duplicate specimens suggest that this intermediate component resides in a species with moderate coercivity, but these experiments did not cleanly separate this component from a low coercivity component roughly aligned with the PADF.

Upper Carrara and Lowermost Bonanza King Formations

The upper two members of the Carrara Formation, the Jangle Limestone and the argillaceous Desert Limestone, define the limy upper part and shaly lower part of the fourth and fifth sedimentary cycles, respectively. The Carrara is in turn conformably overlain by the Bonanza King Formation, an immense section of carbonate rock that is of Middle and Late Cambrian age. The lowermost part of the Bonanza King, immediately above the Desert Limestone, roughly defines the top of the fifth large-scale sedimentary cycle.

In the original study the upper Carrara and lowermost Bonanza King Formations were sampled at section O (Figure 2; Table 1). Additional samples have now been collected in both the lower Jangle Limestone and lowermost Bonanza King Formation at section V (Figure 1) to test the inferred 36° clockwise rotation of section O [Gillett and Van Alstine, 1979].

Detailed descriptions of the Jangle Limestone and lowermost Bonanza King Formations are given by Gillett [1983a] and are only summarized here. Both the lower part of the Jangle Limestone, where paleomagnetic sampling was concentrated, and the lowermost Bonanza King Formation are mostly dark gray lime mudstone. Gray, oolitic grainstone is locally common in the Jangle, whereas pods, stringers, and laminae of orange, limonite-stained dolomite are common in the Bonanza King.

In both sampled sections, a large breccia zone extends from about the middle of the Jangle Limestone locally up several tens of meters into the lowest Bonanza King Formation. This breccia probably results from collapse of an ancient cave [Gillett, 1983a]. Blocks of the host limestone in the breccia afforded the possibility of a conglomerate test [Graham, 1949] for constraining when the magnetizations were acquired. Hence, at section O about 100 samples were collected in breccia blocks and their matrix, and about 20 samples were also collected in an unbrecciated part of the upper Jangle. The results of the conglomerate tests are presented by Gillett [1983a], and their significance is discussed below.

Data from section V will be presented first, as more extensive demagnetization was done on these rocks and the demagnetization paths are much smoother, probably because the better shielded ovens were used. Experience with carbonate rocks from the Desert Range indicated that they responded very well to thermal demagnetization. Hence, all specimens from the Jangle and Bonanza King were subjected to progressive thermal demagnetization at 10 steps between 150° and 500°C.

Nearly all samples had NRM directions very near that of the PADF. Thermal demagnetization, however, revealed that at least three components of magnetization are present in these limestones (Figure 5a): (1) a component roughly aligned with the PADF that has a very low blocking temperature (<200°C) or chemical stability limit; (2) a component of intermediate thermal stability, isolated between 200° and 350°C, with northwesterly declination and moderate positive inclination; and (3) a characteristic component, isolated between 400° and 500°C, with 10-20% of the NRM intensity, a stratigraphic ('dip-corrected') declination near 120°, and a shallow negative inclination.

Least squares fits were made to the linear segments representing the intermediate and char-

TABLE 1. Summary of Paleomagnetic Results From Late Precambrian

Rock Unit (Abbreviation)	Section	Average Attitude (Strike, Dip)		Intermediate Magnetization: Geographic Coordinates D	I	k	α_{95}	N/N_{tot}	Stratigraphic Coordinates D	I	k	α_{95}	N/N_{tot}
†Noonday(?) Formation (Nd)	A	337°	31°E	293°	47°	---	1°	91/123	336°	59°	---	1°	108/123
				(k_1 = -16.3, k_2 = -7.1)					(k_1 = -18.0, k_2 = -7.1)				
				(b^1 = 26.5*, g^2 = 352)					(b^1 = 34.1*, g^2 = 352)				
Rainstorm Member Johnnie Formation	H,I, J	344°	51°E	----------------------					----------------------				
†Wood Canyon Formation middle member (W)	M	356°	58°E	----------------------					----------------------				
†Lower Carrara Formation, Group I (£C)	N	351°	43°E	296°	44°	---	2°	24/89	1°	64°	---	2°	27/89
				(k_1 = -13.6, k_2 = -7.4)					(k_1 = -11.1, k_2 = -6.3)				
				(b^1 = 10.1*, g^2 = 266)					(b^1 = 9.1*, g^2 = 217)				
Carrara Formation, lower Jangle Member only	O	351°	48°E	304°	43°	89	6°	7/7	7°	59°	66	7°	7/7
				(k_1 = -73, k_2 = -40)					(k_1 = -76, k_2 = -26)				
				(b^1 = 0.8, g^2 = 155)					(b^1 = 2.7, g^2 = 98)				
Carrara Formation, Jangle Member only (JV)	V	329°	46°E	283°	32°	223	2°	32/33	325°	54°	248	2°	32/33
				(k_1 = -154, k_2 = -93)					(k_1 = -140, k_2 = -119)				
				(b^1 = 2.1, g^2 = 1518)					(b^1 = 0.2, g^2 = 1947)				
Group II (Jangle Member + lowermost Bonanza King Formation.) †(II, characteristic only)	O	352°	47°E	305°	42°	49	4°	28/28	4°	58°	46	4°	28/28
				(k_1 = -35, k_2 = -22)					(k_1 = -34, k_2 = -21)				
				(b^1 = 1.8, g^2 = 368)					(b^1 = 2.3, g^2 = 338)				
Lowest Bonanza King Formation, intra-formational conglomerate	O	356°	42°E	303°	42°	---	3°	5/7	1°	58°	---	3°	6/7
				(k_1 = -683, k_2 = -150)					(k_1 = -150, k_2 = -23)				
				(b^1 = 6.5*, g^2 = 430)					(b^1 = 8.2*, g^2 = 78)				
Lowest Bonanza King Formation	O	351°	48°E	----------------------					----------------------				
Group II, all rock types †(II, intermediate only)	O	357°	47°E	305°	42°	57	3°	42/42	4°	57°	49	3°	42/42
				(k_1 = -41, k_2 = -26)					(k_1 = -32, k_2 = -23)				
				(b^1 = 2.4, g^2 = 514)					(b^1 = 1.4, g^2 = 451)				
†Lowest Bonanza King Formation (BKV)	V	333°	31°E	288°	42°	---	2°	33/45	323°	57°	---	3°	41/45
				(k_1 = -115, k_2 = -22)					(k_1 = -85, k_2 = -20)				
				(b^1 = 37*, g^2 = 443)					(b^1 = 27*, g^2 = 390)				
†Uppermost Bonanza King Formation; biomere boundary (see text). (BQ)	Q	327°	25°E	Mode:									
				322°	61°	---	3°	11/22	6°	54°	---	4°	12/22
				(327°	61°	7	13°	22/22)	(6°	53°	7	13°	22/22)
				(k_1 = -8.1, k_2 = -5.5)					(k_1 = -8.3, k_2 = -5.7)				
				(b^1 = 1.1, g^2 = 44)					(b^1 = 1.0, g^2 = 45)				
†Uppermost Bonanza King Formation, biomere boundary. (BU)	U	7°	36°E	326°	57°	50	3°	44/44	33°	63°	55	3°	44/44
				(k_1 = -41, k_2 = -20)					(k_1 = -41, k_2 = -24)				
				(b^1 = 5.8, g^2 = 423)					(b^1 = 3.5, g^2 = 497)				
As above	U	7°	36°E	----------------------					----------------------				

and Early Paleozoic Strata in the Desert Range, Southern Nevada

Characteristic Magnetization										Angle	Δ Dec		Remarks
Geographic Coordinates					Stratigraphic Coordinates						Inter-mediate	Charac-teristic	
D	I	k	α_{95}	N/N_{tot}	D	I	k	α_{95}	N/N_{tot}				
----------------------					----------------------					-----	-20±7°	-----	Intermediate magnetization estimated from vector, 250°-320°C.
78°	52°	---	--	-----	78°	1°	---	---	----	-----	-----	-----	Average of N and R polarity, Van Alstine and Gillett [1979a].
					(Pole: 10°S, 162°E)								
					96° 1° (after 18° ccw rotation correction--see text)								
					(Revised pole: 5°N, 151°E)								
139°	40°	---	2°	56/122	124°	-3°	---	2°	56/122	-----	-----	-24±4°	Mode from Gillett and Van Alstine [1979a].
131°	15°	---	4°	26/48	130°	-14°	---	4°	26/48	119±4°	5±8°	-18±5°	Intermediate magnetization from vector, 200°-300°C. Characteristic from Gillett and Van Alstine [1979].
126°	22°	12	20°	6/6	123°	-13°	13	20°	6/6	114±21°	11±15°	-25±21°	Subset of Group II. Mode is not significantly different.
(k_1 = -14, k_2 = -6)					(k_1 = -15, k_2 = -6)								
(b^1 = 1.3, g^2 = 14.3)					(b^1 = 1.4, g^2 = 15.2)								
106°	19°	---	3°	25/34	105°	-14°	---	3°	23/34	129±4°	-31±7°	-43±4°	Least squares, thermal demagnetization, this paper.
(k_1 = -34, k_2 = -4.6)					(k_1 = -32, k_2 = -4.6)								
(b^1 = 56*, g^2 = 55)					(b^1 = 53*, g^2 = 54)								
129°	15°	---	2°	47/76	130°	-18°	---	2°	47/76	124±4°	8±10°	-18±4°	Mode of characteristic direction from Gillett and Van Alstine [1979].
133°	16°	247	3°	7/8	132°	-12°	352	3°	7/8	121±4°	5±9°	-16±4°	Least squares, thermal demagnetization, this paper.
(k_1 = -1644, k_2 = -74)					(k_1 = -240, k_2 = -180)								
(b^1 = 34.6*, g^2 = 257)					(b^1 = 0.1, g^2 = 627)								
128°	15°	226	4°	7/8	130°	-19°	179	5°	7/8	-----	-----	-18±6°	Thermal+af demagnetization experiments (see text).
(k_1 = -206, k_2 = -98)					(k_1 = -208, k_2 = -71)								
(b^1 = 1.0, g^2 = 338)					(b^1 = 2.2, g^2 = 244)								
----------------------					----------------------					-----	41±8°	-----	Average plotted in Figure 13.
116°	0°	198	2°	42/45	121°	-18°	178	2°	42/45	138±4°	-33±9°	-27±4°	Least squares, thermal demagnetization, this paper.
(k_1 = -123, k_2 = -88)					(k_1 = -119, k_2 = -75)								
(b^1 = 1.2, g^2 = 1817)					(b^1 = 2.3, g^2 = 1553)								
Mode:													Modes calculated because of large α_{95}.
142°	-9°	---	7°	24/26	146°	-13°	---	8°	25/26	128±9°	10±10°	-2±9°	
(144°	-17°	11	9°	26/28)	(151°	-17°	11	9°	26/28)	(135±16°)	(10±23°)	(3±10°)	Least squares, thermal demagnetization, this paper.
(k_1 = -10.2, k_2 = -5.9)					(k_1 = -10.0, k_2 = -5.6)								
(b^1 = 2.6, g^2 = 57)					(b^1 = 2.8, g^2 = 54)								
157°	-6°	25	4°	47/47	165°	-22°	24	4°	47/47	128±5°	37±9°	17±5°	Least squares, thermal demagnetization, this paper.
(k_1 = -22, k_2 = -14)					(k_1 = -21, k_2 = -14)								
(b^1 = 2.8, g^2 = 288)					(b^1 = 2.3, g^2 = 298)								
160°	-4°	147	4°	10/10	167°	-19°	212	3°	10/10	-----	-----	19±4°	Thermal+af demagnetization experiments.
(k_1 = -135, k_2 = -60)					(k_1 = -134, k_2 = -107)								
(b^1 = 1.8, g^2 = 292)					(b^1 = 0.1, g^2 = 528)								

TABLE 1.

Rock Unit (Abbreviation)	Section	Average Attitude (Strike, Dip)		Intermediate Magnetization: Geographic Coordinates D	I	k	α_{95}	N/N_{tot}	Stratigraphic Coordinates D	I	k	α_{95}	N/N_{tot}
†Nopah Formation, Smoky Member (Np)	R	348°	32°E	Mode: 316°	59°	---	6°	10/25	14°	61°	---	6°	10/25
				(328°	47°	9	10°	25/25)	(4°	48°	9	10°	25/25)
				(k_1 = -6, k_2 = -6)					(k_1 = -6, k_2 = -6)				
				(b = 0.2, g = 50)					(b = 0.2, g = 50)				
As above	R	348°	32°E	----------------------					----------------------				
†Goodwin Limestone (G)	S,T	315°	25°E	311°	70°	132	2°	75/75	1°	60°	---	1°	71/75
				(k_1 = -86, k_2 = -56)					(k_1 = -123, k_2 = -51)				
				(b = 3.5, g = 2050)					(b = 16.0*, g = 1858)				

Abbreviations of rock units are those used in Figures 7 and 13; daggers denote units employed in inclination averages (Table 2) and in Figure 13. Column heads are as follows: Section is where the samples were collected (Figures 1 and 2). Intermediate magnetization is the intermediate blocking temperature component of magnetization; see text. Geographic (stratigraphic) coordinates are not (are) corrected for the dip of the bedding. D is declination; I, inclination; k, unbiased estimate of concentration parameter [Fisher, 1953], not given where modes were calculated. α_{95}, half angle of 95% confidence cone where Fisher [1953] statistics were calculated, or estimate of half-angle of 95% confidence ('β_{95}') [Van Alstine, 1980] where modes were calculated; N_{tot} is total number of samples. For Fisher statistics, N is the number of samples included in the mean; for modal analysis, N is the number of samples with a Fisherian mean equal to the mode (this mean is used to calculate β_{95} [Van Alstine, 1980]). Angle is the included angle between the intermediate and characteristic directions; the error on this angle was computed from $(\alpha_I^2 + \alpha_C^2)^{1/2}$, where α_I, α_C are the confidence angles of the intermediate and characteristic direction, respectively [cf. Beck, 1980]. Δ Dec is the difference in stratigraphic declination (apparent relative rotation) with respect to directions calculated from poles on the reference apparent polar wander path. Angles >0 (<0) are clockwise (counterclockwise) of the reference position. $\Delta D_{Int(Char)}$ is the declination difference of the intermediate (characteristic) component; the reference direction for ΔD_{Int} (D = 356°±7°, I = +56°±5°) is calculated from the interval 2 (mid-Tertiary) pole of Van Alstine and de Boer [1978]. The reference direction for ΔD_{Char} (D = 148°±3°, I = -22°±5°) is calculated from the reversed interval 12 (Late Permian) pole based on the mode of nine site poles ($\alpha_{95} \leq 15°$) from Guadalupian and Ochoan red beds [Peterson and Nairn, 1971]. Confidence limits on Δ Dec are calculated as $(\Delta D_d^2 + \Delta D_p^2)^{1/2}$, where ΔD_d = arcsin(sin α_{95}/cos I) is the uncertainty in declination given α_{95} and inclination I, and ΔD_p = arcsin(sin A_{95}/sin colat) is the uncertainty in the declination calculated from a pole [Beck, 1980]; k_1, k_2 are Bingham [1974] concentration parameters, using notation of Onstott [1980]; b, g are test statistics for circular symmetry [Mardia, 1972; Gillett et al., 1982]; * indicates a significant departure from a circularly symmetric axial distribution at the 99% confidence level.

acteristic components for specimens from both the Bonanza King and the Jangle (Figure 6). After correction for bedding dip, the average directions of the intermediate component of magnetization in both the Jangle and Bonanza King nearly coincide (Table 1), indicating that this magnetization was imposed before these strata were tilted into their present positions.

The characteristic magnetization directions from the Jangle and Bonanza King at section V differ by 16°, however, in stratigraphic declination. This declination difference probably results from incomplete removal of secondary magnetizations in the Jangle, rather than from relative tectonic rotation between the Jangle and Bonanza King. The distribution of characteristic directions from the Jangle is more scattered than that from the Bonanza King (Figures 6c and 6d), and it is significantly noncircular (Table 1). The demagnetization paths are also generally less smooth. The average bulk susceptibilities and intensities of magnetization in the Jangle are almost an order of magnitude lower than in the Bonanza King (Figure 7, BKV and JV), suggesting that less magnetic material is present. Finally, at section O to the south the lower Jangle and lowermost Bonanza King yielded similar directions of magnetization that were combined as Group II [Gillett and Van Alstine, 1979]. The light-colored rocks generally have weaker, more scattered magnetizations.

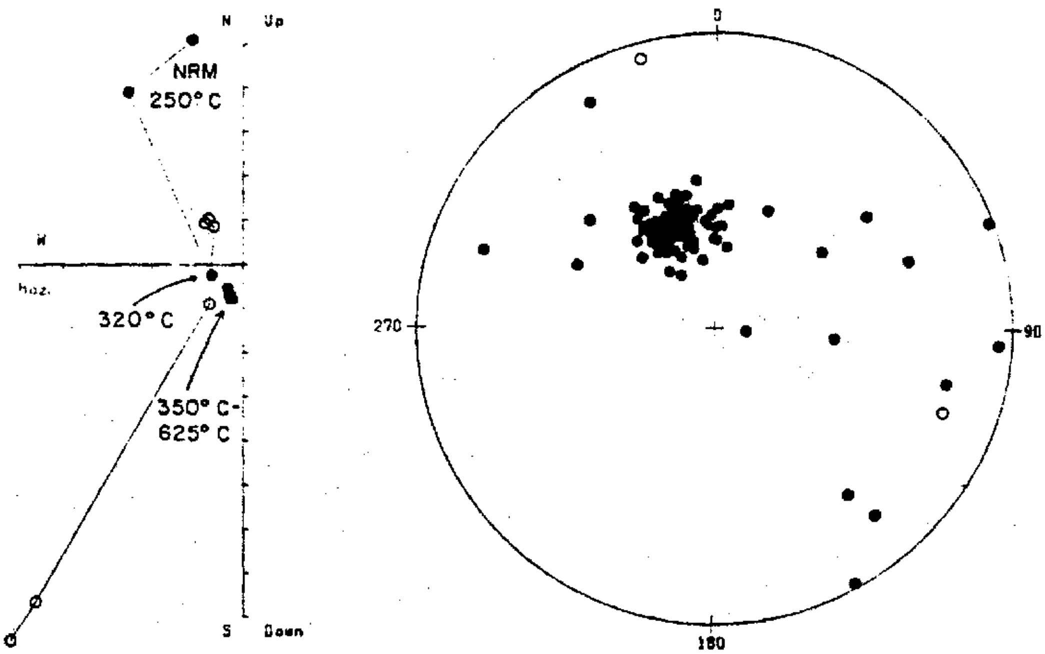
The magnetic behavior of the Jangle Limestone and the lowermost Bonanza King Formation at section O is very similar to that in section V (cf. Figures 6b and 7 of Gillett and Van Alstine [1979]). As with the lower Carrara, however, the estimate of the characteristic direction obtained by modal analysis is still the best available (Table 1). In addition, in these samples, fewer demagnetization steps were done at low tempera-

(Continued.)

Characteristic Magnetization										Angle	Δ Dec		Remarks
Geographic Coordinates					Stratigraphic Coordinates								
D	I	k	α_{95}	N/N_{tot}	D	I	k	α_{95}	N/N_{tot}		Intermediate	Characteristic	
Mode:													
143°	-9°	---	6°	13/35	149°	-20°	---	6°	11/35	127±8°	18±14°	2±7°	Modes calculated because of large α_{95}. Least squares, thermal demagnetization, this paper.
(119°	0°	3	16°	35/35)	(124°	-23°	3	16°	35/35)	(128±18°)	(8±16°)	(-24±18°)	
(k_1 = -4.1, k_2 = -2.2)					(k_1 = -4.1, k_2 = -2.2)								
(b = 3.6, g = 14.1)					(b = 3.6, g = 14.1)								
138°	-7°	---	9°	5/6	145°	-21°	---	9°	5/6	-----	-----	-3±10°	Thermal+af demagnetization experiments (see text).
(k_1 = -181, k_2 = -18.7)					(k_1 = -180, k_2 = -18.6)								
(b = 12.1, g = 53)					(b = 12.0, g = 53)								
134°	-28°	---	1°	57/101	146°	-26°	---	2°	82/101	138±2°	5±7°	-2±4°	'Gray limestones'--see text. Least squares, thermal demagnetization, this paper.
(k_1 = -23, k_2 = -14)					(k_1 = -27, k_2 = -14)								
(b = 6.6, g = 633)					(b = 12.6, g = 623)								

tures; therefore the intermediate component of magnetization has been estimated by using the subtracted vector between either the 200°-300°C or 250°-350°C steps (Figures 4b and 4c and Table 1). These estimates seem reliable because (1) a check using only these steps on the samples from section V, where intermediate steps exist, yielded results similar to those incorporating the intermediate steps, and (2) new samples from some intraformational conglomerate lenses at section O (discussed below), where intermediate steps are also available, yield similar directions to those estimated from only two steps in the original samples.

To interpret the three components of magnetization found in these rocks, it is first neces-



(a) (b)

Fig. 3. (a) Vector demagnetization diagram [Roy and Park, 1974] of samples of gray limestone from the Noonday(?) Formation in the Desert Range. All directions are in stratigraphic (dip-corrected) coordinates. Solid (open) circles represent declination (inclination). Tickmarks on axes are units of 10^{-7} A m^2/kg (1 A m^2/kg = 1 emu/g). (b) Intermediate component of magnetization in the Noonday(?) Formation, estimated by the subtracted vector between the 250° and 320°C demagnetization steps (see text). Equal-area projections in stratigraphic coordinates. Open (solid) symbols are on the upper (lower) hemisphere. The cross marks the direction of the present axial dipole field at the sampling site after rotation for the mean attitude of the bedding.

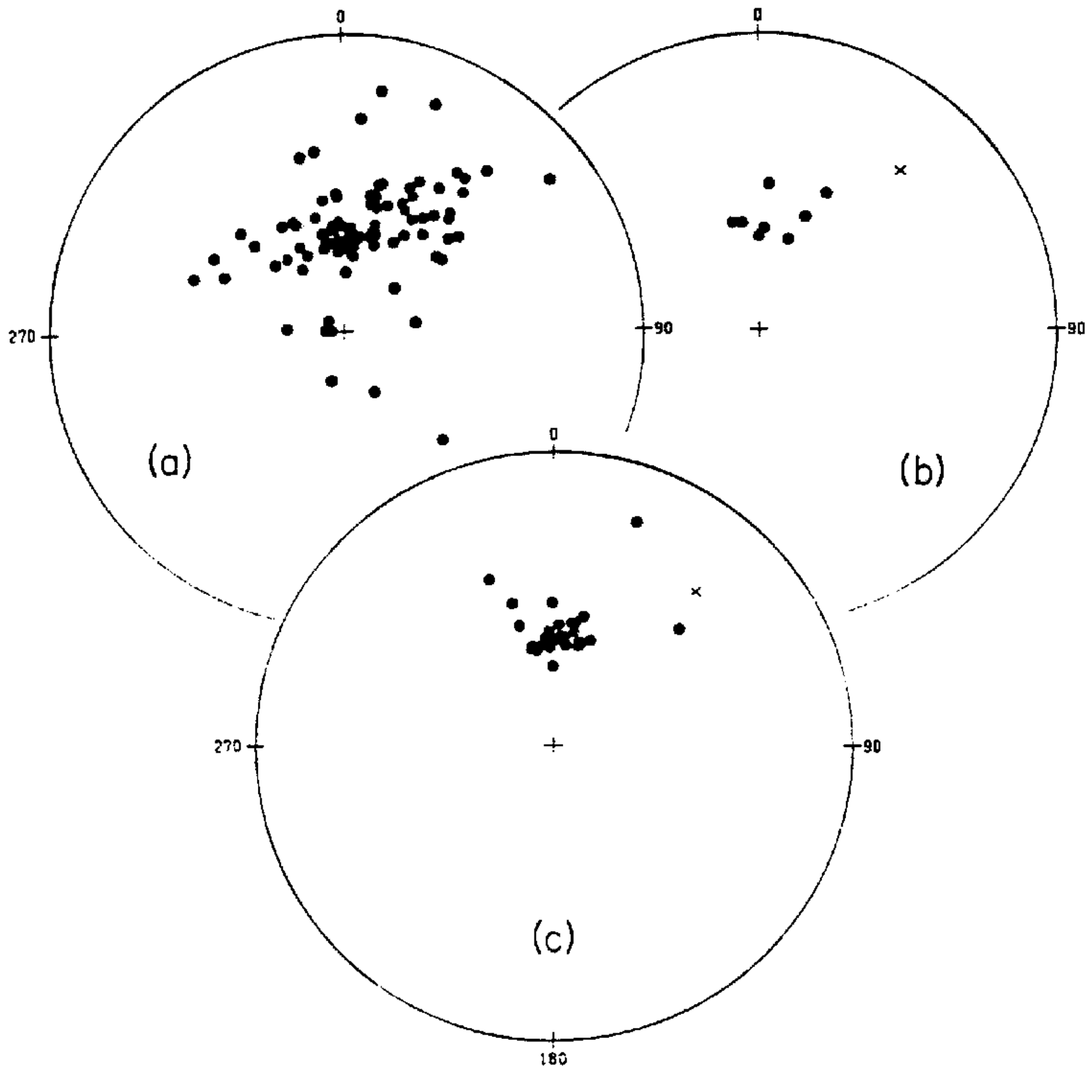


Fig. 4. (a) Intermediate component of magnetization, gray limestones, lower Carrara Formation at section O (Group I of Gillett and Van Alstine [1979]), estimated by subtracted vector between 200 and 300°C steps (see text). (b) Analogous estimate of intermediate component in lower Jangle Limestone. (c) Analogous estimate of intermediate component in lowermost Bonanza King Formation. Conventions of all diagrams are as in Figure 3b.

sary to determine the magnetic species present. Combinations of demagnetization techniques help identify the minerals in which a given direction resides [e.g., Gillett and Van Alstine, 1979; Roy et al., 1979], as one can associate a set of magnetic properties with a particular remanence direction.

Accordingly, to investigate the characteristic remanence, eight duplicate specimens from original samples of the Bonanza King Formation were demagnetized at 400°C and then subjected to stepwise, progressive af demagnetization up to 70 mT. The remanence shows a progressive decay upon af demagnetization above 35 mT (Figure 5b), indicating that it probably resides in magnetite with moderate to high coercivity. Hematite is ruled out because grains with blocking temperatures less than ~500°C would have extremely high coercivities [e.g., Dunlop and Stirling, 1977]. This behavior is similar to that seen in the limestone units of the Carrara Formation [Gillett and Van Alstine, 1979, Figure 8]. The mean of the characteristic directions derived from the af-after-thermally demagnetized samples is near the mode of the original, thermally demagnetized samples (Table 1).

Similarly, the intermediate component of remanence was tested in 18 duplicate specimens, which were first demagnetized at 200°C and then subjected to af demagnetization as above. In all cases, the magnetization showed a progressive decay upon af demagnetization, indicating that this component also probably resides in magnetite, but magnetite with a lower coercivity, as the intensity begins to decay by 5 mT. The behavior at high demagnetization steps was not consistent from sample to sample; demagnetization paths did not trend directly toward the origin, and a few trended toward positions similar to that of the characteristic direction (Figure 5c). Indeed, it might be expected that demagnetization of these specimens to high af steps would allow the characteristic remanence to be isolated; that af demagnetization does not 'clean' the samples completely, however, suggests that there is some high-coercivity component still present that obscures the characteristic remanence. This high-coercivity component evidently cannot survive

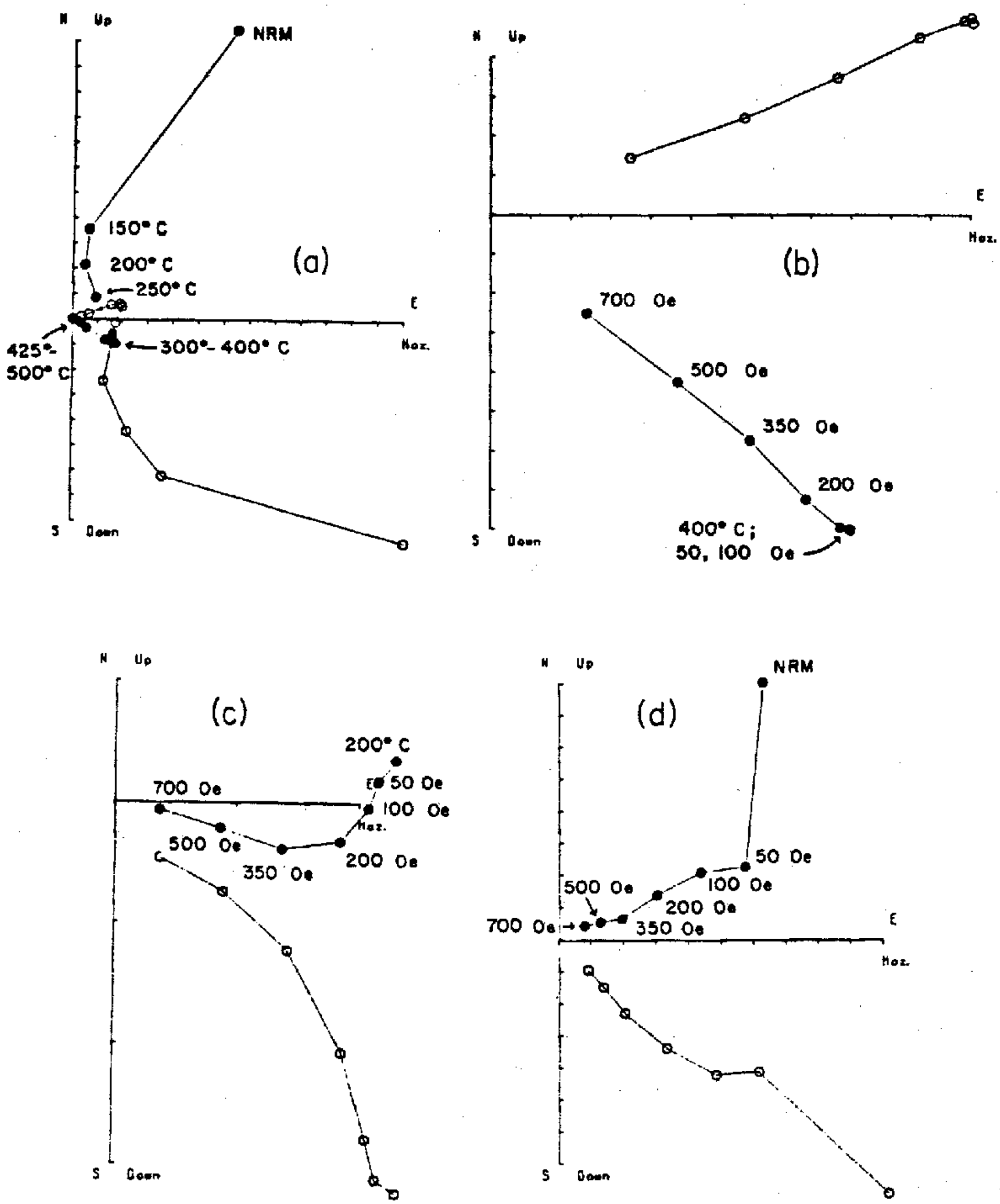


Fig. 5. Lowermost Bonanza King Formation; conventions of diagrams are as in Figure 3a except as noted. (a) Thermal demagnetization, section V; (b) Af-following-thermal demagnetization at 400°C, section O; note that NRM is not plotted. (c) Af-following-thermal demagnetization at 200°C, section O (10 Oe = 1 mT). Note that NRM is not plotted; also, tickmarks are units of 10^{-8} A m^2/kg. (d) Af demagnetization only; section O.

thermal demagnetization to 400°C, since no trace of it was seen in the rocks that were af demagnetized after thermal demagnetization to 400°C. Hence, it seems likely that such a high-coercivity component resides in very fine-grained hematite, which would show the requisite combination of high coercivity and low blocking temperature [e.g., Dunlop and Stirling, 1977].

Eight duplicate specimens from both the Jangle Limestone and the Bonanza King Formation were af demagnetized only. In all cases there was a large drop in intensity to 5 mT, followed by successively smaller decrements (Figure 5d); in fact, in one sample the intensity did not change significantly upon further demagnetization. Furthermore, in most cases the magnetization directions remained near that of the PADF. Hence, it appears that the PADF magnetization seen at NRM results both from weathering oxidation, yielding low blocking temperature goethite and/or hematite, and from viscous acquisition by a magnetically soft species, probably low-coercivity magnetite.

Magnetic susceptibility indicates that some mineral species with significant susceptibility, perhaps magnetite, was in part destroyed during

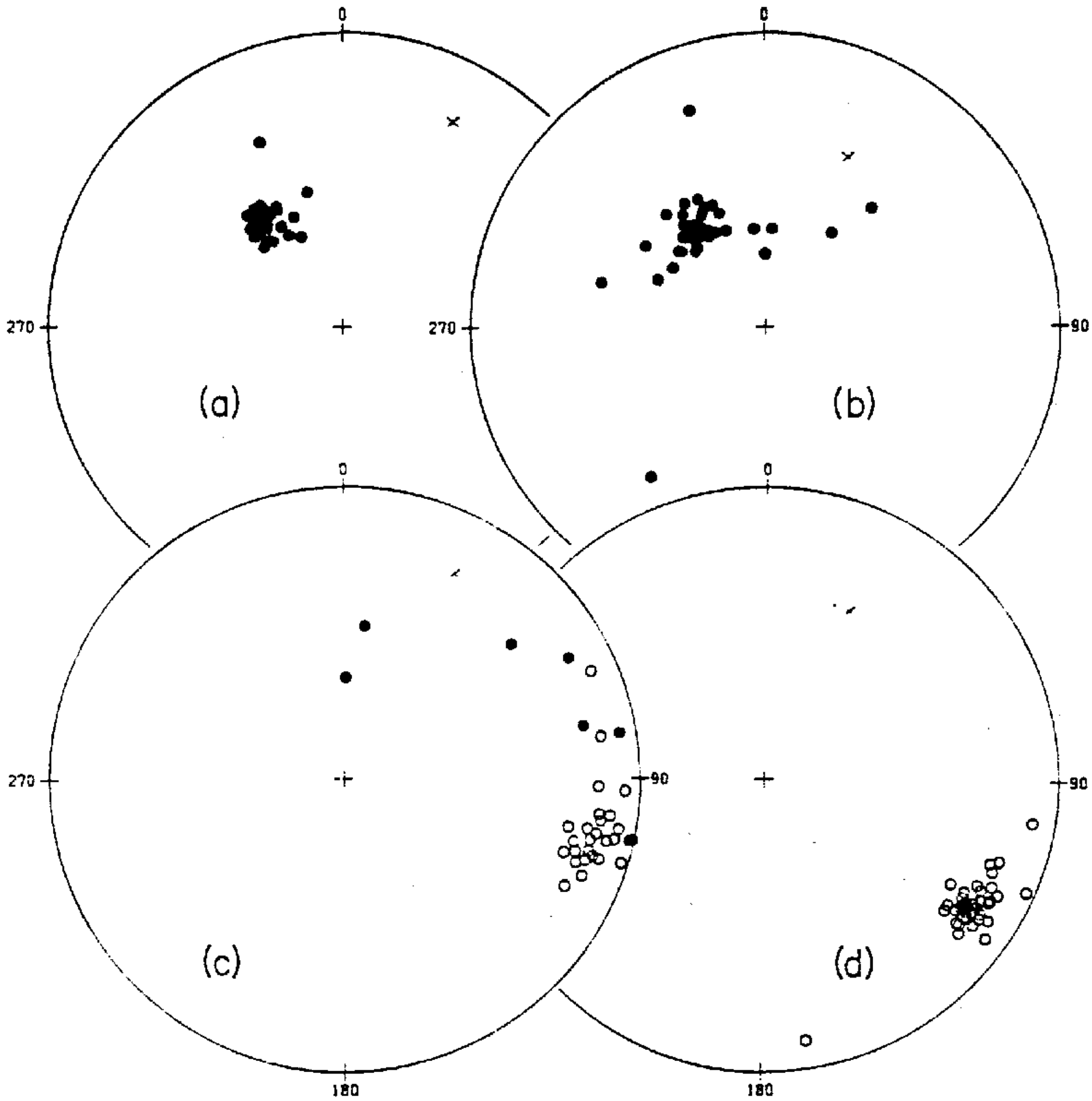


Fig. 6. Least squares fitted directions (see text) from section V in the northern Desert Range; plot conventions are as in Figure 3b. (a) Jangle Limestone, intermediate component of magnetization. (b) Lowermost Bonanza King Formation, intermediate component. (c) Jangle Limestone, characteristic component. (d) Lowermost Bonanza King Formation, characteristic component.

thermal demagnetization, probably by oxidation resulting from heating in air. In both the Bonanza King and the Jangle Limestone, susceptibility generally had decreased significantly by the 500°C step (Figure 7, BKO and BKV, UJ and JV). Moreover, these data indicate that magnetite, inferred to be present from the thermal plus af demagnetization experiments, was not produced by the thermal demagnetization (for example, resulting from in situ reduction of ferric iron [Shive and Diehl, 1977a, b]). If this were the case, susceptibility would have increased as a result of heating.

Field relations yield evidence on the time of acquisition of the intermediate and characteristic magnetizations. In limestone blocks from the lowermost Bonanza King that occur in the major breccia mentioned earlier, both the intermediate and the characteristic components of magnetization pass the conglomerate test, indicating that both magnetizations antedate the formation of the breccia [Gillett, 1983a]. In addition, some beds of intraformational pebble conglomerate in the basal Bonanza King yield directions of magnetization that are statistically identical with those derived from the mudstones (Table 1). Hence, the characteristic magnetization could not have been acquired contemporaneously with deposition; as these conglomerates are a synsedimentary feature, however, their magnetization might have been imposed soon after deposition.

Marjumiid-Pterocephalid Biomere Boundary (Upper Cambrian; Bonanza King Formation)

Biomere boundaries yield precise time control for continent-wide comparisons of paleomagnetic data from coeval strata [Gillett, 1982a]. Palmer [1965, 1979] has defined a biomere as a regional biostratigraphic unit that is 'bounded by abrupt non-evolutionary changes in the dominant elements

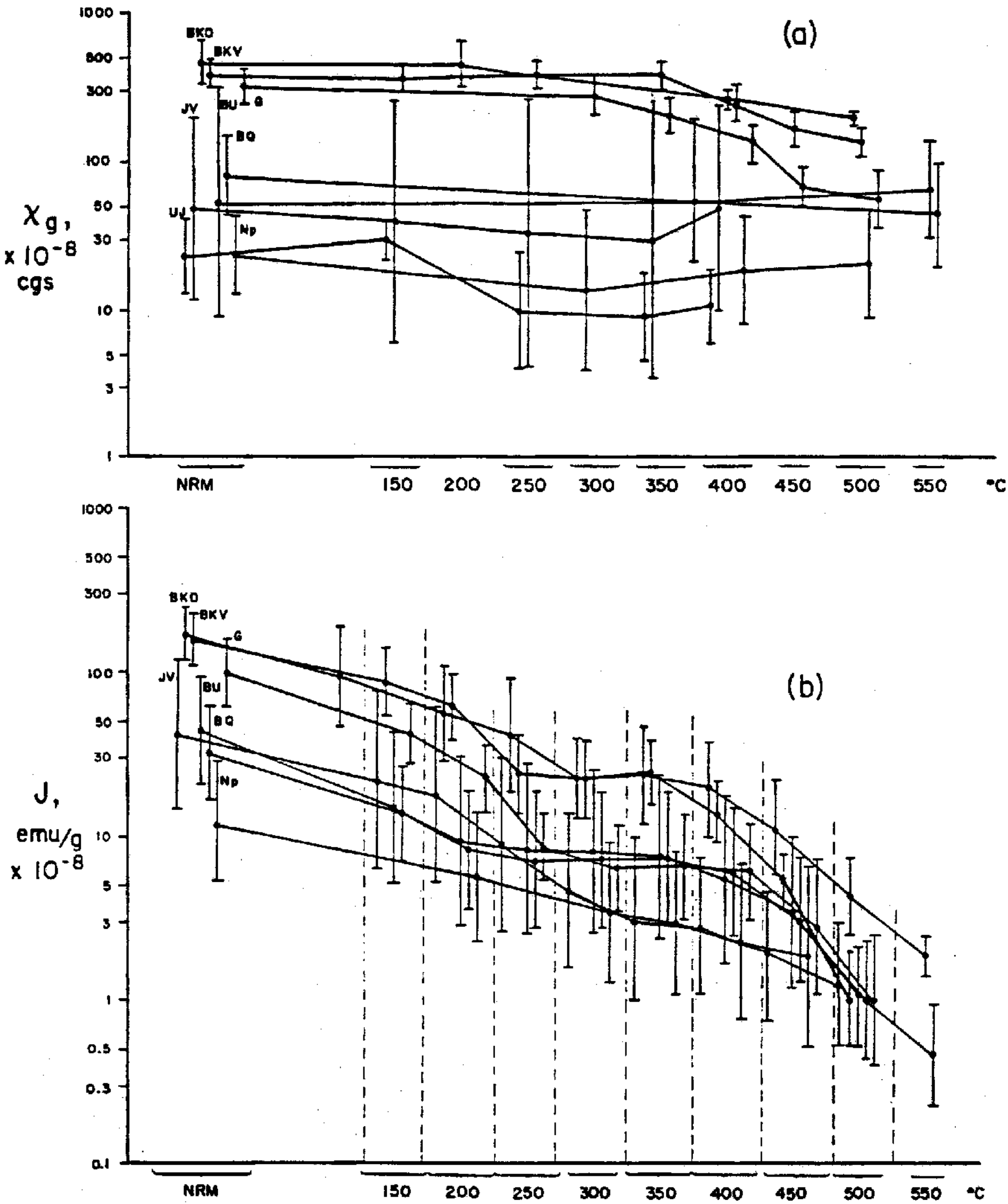


Fig. 7. (a) Gram susceptibility and (b) intensity as functions of thermal demagnetization for some early Paleozoic carbonate units in the Desert Range. Points represent geometric means of intensities; error bars are one standard deviation around the mean. Values for each unit have been offset at each demagnetization step for clarity; where the plot becomes more crowded to the left, points corresponding to the same demagnetization step have been separated by the vertical dashed lines. Abscissa is temperature (°C) of thermal demagnetization step; NRM is natural remanent magnetization. Note that ordinates are logarithmic. Abbreviations are as in Table 1; also UJ is upper Jangle Limestone at section O. The initial decrease to the 'plateau' in intensities from ~300° to ~400°C reflects removal of the intermediate blocking temperature component of magnetization (see text); the decrease above 400°C reflects removal of the characteristic component. This underscores the difference in blocking temperature spectra of these two components, which allows them to be separated by thermal demagnetization. For clarity, some intermediate demagnetization steps that exist for some samples have been omitted.

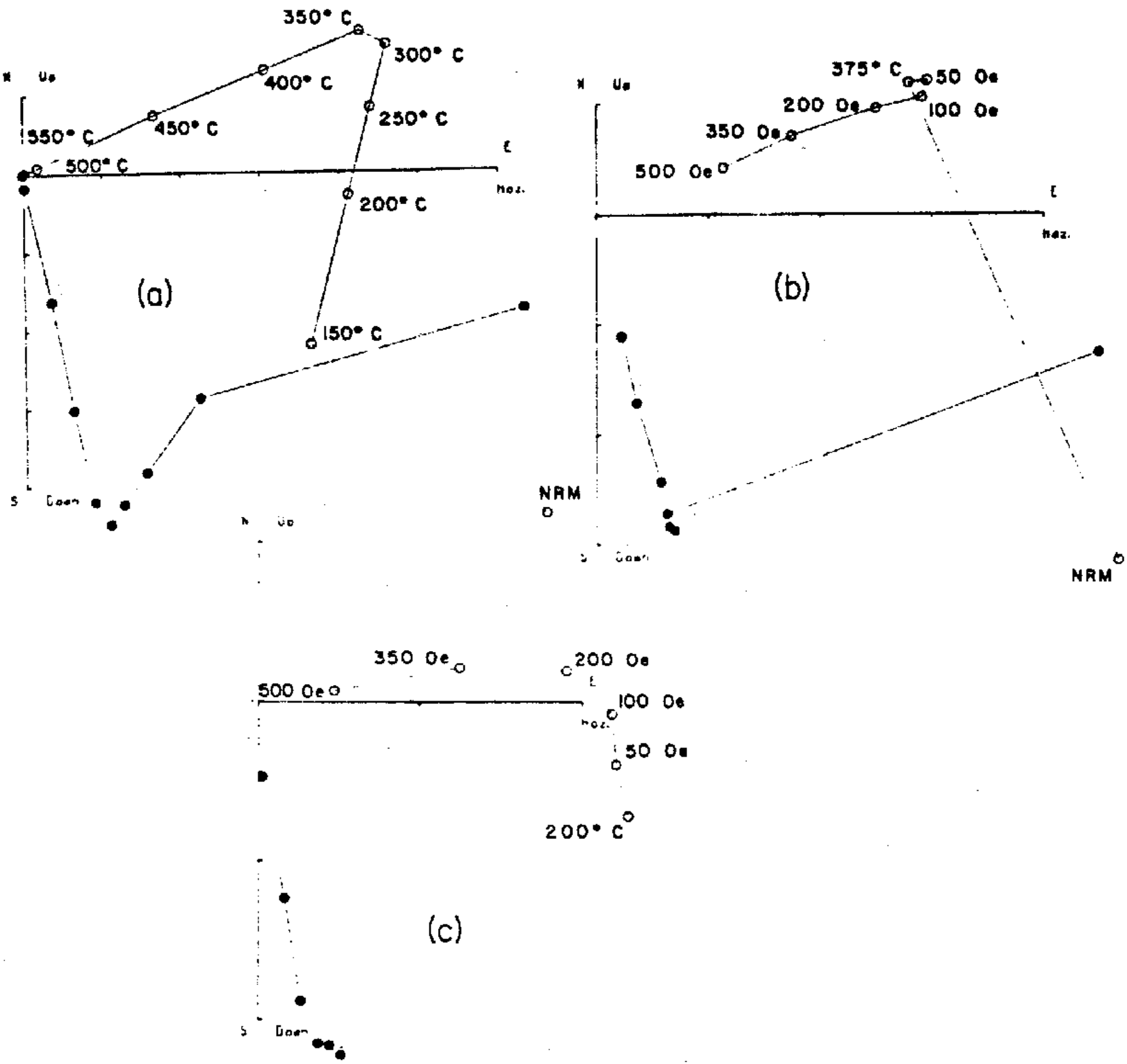


Fig. 8. Uppermost Bonanza King Formation (Marjumiid-Pterocephalid biomere boundary; see text); conventions of diagrams are as in Figure 3a. (a) Thermal demagnetization, section U; (b) af-following-thermal demagnetization at 375°C; (c) af-following-thermal demagnetization at 200°C; note that NRM is not plotted.

of a single phylum.' Although the nature and paleontological significance of biomeres is controversial, biomere boundaries are abrupt, probably spanning less than 10^4 years [Palmer, 1979].

The boundary between the Upper Cambrian Marjumiid and Pterocephalid biomeres, which is also the boundary between the Crepicephalus and Aphelaspis faunal zones, was sampled at two locations in the Desert Range, at section Q (Figure 2), and at section U (Figure 1). Section U corresponds to Palmer's [1979] section 1. In the Desert Range, this biomere boundary occurs in the uppermost part of the Bonanza King Formation, about 13 m below the top.

The strata in the uppermost Bonanza King Formation are a heterogeneous sequence of gray limestones of probably shallow-water origin. Oxidation, almost certainly resulting from recent weathering, is pervasive in these rocks. Limonite, probably mostly goethite, is abundant and imparts an orange cast. Occasional dark red blebs or cubes of hematite are probably pseudomorphs after pyrite, as they greatly resemble such pseudomorphs seen elsewhere in less oxidized rocks where a pyrite core remains [Gillett, 1982a].

Specimens of all samples from sections Q and U were subjected to progressive thermal demagnetization at 10 steps between 150 and 550°C. Upon thermal demagnetization, these samples exhibit three components of magnetization similar to those in the lowermost Bonanza King (Figure 8a); the average intensities of magnetization are weaker, however (Figure 7, BQ and BU). Both the characteristic and intermediate directions are far more scattered at section Q than at U (Figure 9). Section Q is on a ridge crest, whereas section U is on the side of a ravine; hence, it is likely that the additional scatter in section Q results from deeper weathering and probable lightning strikes. Finally, magnetic behavior does not correlate with rock type, despite the heterogeneity of these limestones.

As was inferred for the lower Bonanza King Formation samples, combinations of thermal and af demagnetization indicate that both the intermediate and characteristic magnetizations reside in magnetite, and that the coercivity of the

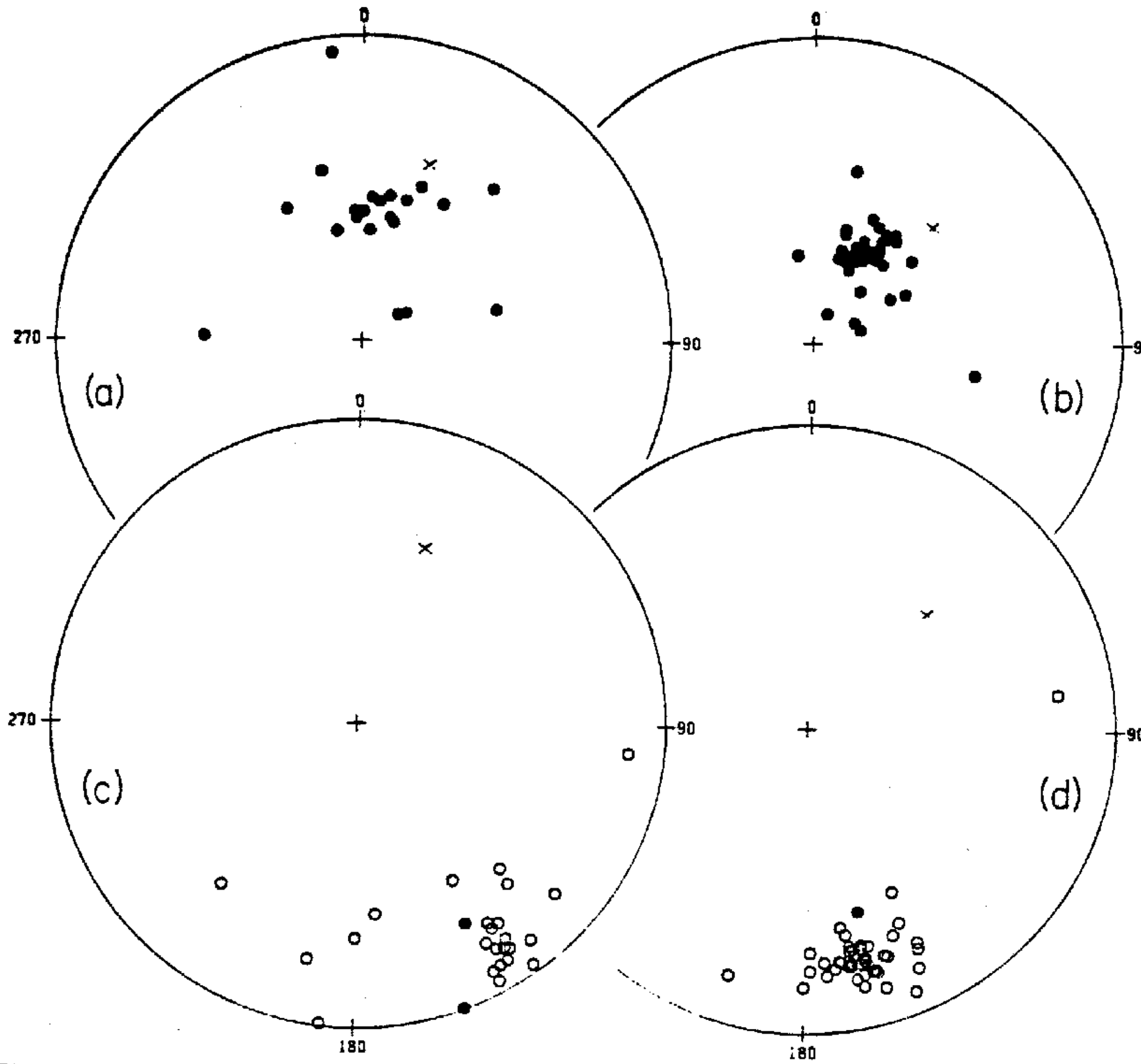


Fig. 9. Least squares fitted directions (see text) from sections in the upper Bonanza King Formation at the Marjumiid-Pterocephalid biomere boundary; plot conventions are as in Figure 3b. (a) Intermediate component of magnetization, section Q. (b) Intermediate component, section U. (c) Characteristic component, section Q. (d) Characteristic component, section U.

intermediate magnetization is lower (Figures 8b and 8c). For the characteristic magnetization, the mean of least squares fits to the linear part of the af demagnetization path is statistically identical to that found from the thermal demagnetization directions (Table 1).

The susceptibility data from the upper Bonanza King are somewhat more varied than in the lower Bonanza King (Figure 7, BQ and BU), but they indicate that the magnetite inferred to be present from the af experiments is not an artifact of thermal demagnetization. The average susceptibilities are also about an order of magnitude lower than those from the lowermost Bonanza King (Figure 7, BQ, BU versus BKO, BKV); together with the overall lower intensities, this suggests that less magnetic material is present in the uppermost Bonanza King strata.

Nopah Formation

The Nopah Formation of Late Cambrian age conformably overlies the Bonanza King Formation. Paleomagnetic sampling was restricted to the Smoky Member, the uppermost member of the Nopah Formation, which consists mostly of massive, gray, nonferroan dolomite.

Petrographic study shows that the dolomite is replacive. Originally, the rocks were probably shallow-water limestones similar to those in the underlying strata. The dolomitization was probably early for two reasons. First, the lack of Fe^{2+} in the dolomite suggests that formation occurred under relatively oxidizing conditions, which in turn suggests that the strata were not yet deeply buried. Second, the Smoky Member is overlain abruptly by the Goodwin Limestone; the sharpness of the contact suggests that the dolomitization occurred in pre-Goodwin time, because it is difficult to imagine a subsequent dolomitization that would exhibit perfect stratigraphic control. Latest Cambrian trilobites (*Saukia*, identified by A.R. Palmer, 1979) occur in the lowest meter of the Goodwin, suggesting that the dolomitization was complete before the end of the Cambrian.

The Smoky Member displays the most heterogeneous magnetic behavior of any single rock unit in

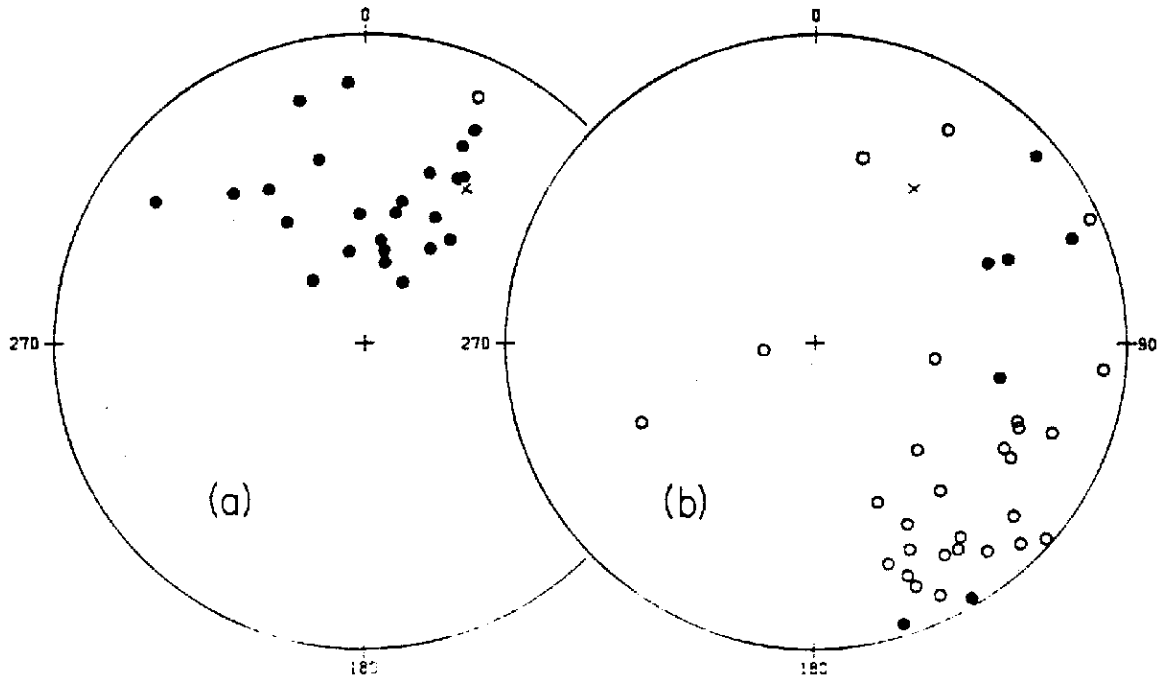


Fig. 10. Least squares fitted directions (see text) for all well-behaved samples from the Smoky Member of the Nopah Formation (section R); plot conventions are as in Figure 3b. (a) Intermediate component of magnetization. (b) Characteristic component.

the Desert Range. Upon thermal demagnetization, generally at seven steps between 200° and 475°C, two extreme types of behavior were observed. Some specimens had large intensity losses, almost immediately becoming unmeasurable, whereas others showed more modest decrements in intensity up to the last demagnetization step. In general, the weak samples are light colored. In some of the stronger samples the thermal demagnetization behavior resembled that seen in the limestones, and three components of magnetization could be recognized. Other strong samples, however, appeared to reflect lightning strikes; they had mutually inconsistent directions that changed little with demagnetization, and they lost only a modest amount of intensity with each demagnetization step. Some lightning strikes are to be expected in this section, as it is on the nose of a ridge. Rough fits to the intermediate and characteristic components of magnetization were made where these two components could be recognized (Figure 10). Despite large scatter, the two components have modes near the directions seen in the limestones below (Table 1).

As in the Desert Range limestones, additional demagnetization experiments indicate that the PADF component is attributable partly to viscous remanent remagnetization and partly to weathering, and that the characteristic component resides in magnetite. In addition, specimens subjected to af demagnetization after a thermal step at 300° or 400°C yield characteristic directions with a mode not significantly different from the mode determined from thermal demagnetization only (Table 1). Finally, most samples showed little change in susceptibility with thermal demagnetization (Figure 7, Np).

Deep weathering may well account for much of the scatter of the paleomagnetic directions in the Smoky Member. The average intensities and bulk susceptibilities of the samples from the Nopah Formation are the smallest of all the carbonate units from the Desert Range (Figure 7, Np), suggesting that these dolomites contain relatively little magnetite, perhaps as a result of deeper weathering. It is unlikely that the dolomitization scattered the directions because the dolomitization probably occurred before the end of the Cambrian, and the intermediate magnetization is also scattered. This magnetization must be much younger than Cambrian, as will be discussed below.

Goodwin Limestone

The Goodwin Limestone, the lowest of three formations in the Pogonip Group, overlies the dolomite of the Nopah Formation with a sharp contact. Although latest Cambrian fossils, as noted, have been found in the basal meter of the Goodwin, most of the formation is of Early Ordovician age. The sections sampled (S and T, Figure 2) begin about 300 m above the base of the Goodwin. Conodonts from these sections range from upper fauna D into fauna E (J. Repetski, written communication, 1980), corresponding to latest middle Early Ordovician (mid-Canadian).

Detailed descriptions of the lithologic types are given by Gillett [1983b] and are briefly summarized. The limestones sampled are gray and probably of shallow-water origin; the dominant lithology is calcarenite composed mainly of fragments of Nuia (a probable alga), with some beds and lenses of intraformational conglomerate. The upper part of the sampled section is finer grained, with common lime mudstone. The rocks contain ~10% insolubles, including terrigenous silt as evidenced by blue-luminescing feldspar [Kastner, 1971]. Brown-weathering chert, occurring as nodules, lenses, and irregular masses, is common particularly in the calcarenites; the chert is replacive [Gillett, 1983b].

About half the samples are in concordant bedding, mostly calcarenite. The other half were collected where an early formed remanence should be disrupted, so that constraints could be placed on the timing of the magnetization. These samples included chert (a few samples contained the host limestone as well); intraformational conglomerate; and grainstones in several places where large, throughgoing stylolites had caused major disruption of the primary bedding.

Upon progressive thermal demagnetization to 500°C, all limestone samples exhibited three components of magnetization that are very similar to those found in the Cambrian limestone units. In turn, combinations of af and thermal demagnetization suggest that, as in the Cambrian carbonates, both the intermediate and characteristic components of the Goodwin reside in magnetite, with the coercivity of the characteristic component being higher. The component reflecting the PADF apparently represents a combination of a soft component in magnetite and a much harder component probably residing in recently formed limonite. Finally, bulk susceptibility indicates that the magnetite is not an artifact of the demagnetization (Figure 7, G). In contrast to the coherent demagnetization behavior observed in the limestones, the magnetization in the cherts was generally erratic.

No significant differences in paleomagnetic direction (Figure 11) or intensity (Figure 12) were found among the varieties of 'gray limestone' present. Most spectacularly, the characteristic direction of the stylolite-distorted beds is the same as that in the concordant limestones; thus, the characteristic magnetization of the Goodwin was imposed after the bedding disruption due to these stylolites. Because of their directional similarity, a grand average was calculated for all limestone samples (Table 1).

Discussion

In all the Paleozoic carbonates in the Desert Range, three components of magnetization are recognized: (1) a low blocking temperature (<200°C) component that is roughly aligned with the PADF; (2) an intermediate blocking temperature component (~350°C) that has a steep, positive inclination with northerly declination; and (3) a characteristic component that has a blocking temperature of ~500°C, a shallow, negative inclination, and a southeasterly declination. Combinations of thermal and af demagnetization demonstrate that (1) the PADF component probably resides partly in low-coercivity magnetite and partly in goethite and/or very fine-grained hematite, the latter minerals resulting from recent weathering, and (2) both the characteristic and intermediate components reside in higher coercivity magnetite. The coercivity of the intermediate component is less than that of the characteristic component, but the contrast is not as marked as in the blocking temperature spectra. Furthermore, bulk susceptibility, measured as a function of thermal demagnetization, shows that the magnetite inferred to be present from the af experiments cannot be an artifact of the heating. Finally, the presence of detrital magnetite is supported by petrographic examination of insoluble residues.

Components with low and intermediate blocking temperature are also present in the late Precambrian Noonday(?) Formation, which lies stratigraphically far below the Paleozoic carbonates. Although the characteristic magnetization of the Noonday(?) has a very different direction and apparently resides in hematite, the other two components resemble the corresponding components in the Paleozoic rocks.

The sections with the highest average intensities and susceptibilities (lowermost Bonanza King Formation and Goodwin Limestone; Figure 7, BKO, BKV, and G) yield the best grouped characteristic magnetizations and generally show the smoothest demagnetization paths. This correlation may be the result of the presence of more magnetite in these rock units, perhaps reflecting a higher detrital content.

Origin and Timing of Intermediate Component

Although the intermediate and characteristic components have somewhat different directions at the different sample localities (Figure 13), it seems probable that at least the intermediate blocking temperature component represents the same ancient magnetization in all sections.

First, the intermediate component must be post-Paleozoic because it is too easily destroyed by heating and it could not survive deep burial. A magnetite-borne magnetization with a blocking temperature of 350°C cannot survive 10^8 years at ~120°C [Pullaiah et al., 1975]. At least 5 km of younger Paleozoic strata once buried the Goodwin Limestone, the uppermost unit sampled, and assuming a conservative geothermal gradient of 25°C/km, this temperature is exceeded.

Second, the directions of the intermediate components in all the sampled sections differ primarily in declination (Table 1 and Figure 13), and the difference is in the same sense as Neogene oroflexural bending of the entire Desert Range proposed on independent geologic evidence. Although it is probable that the intermediate magnetization was imposed on dipping strata, as will be discussed below, the dip of bedding in all sections must have been more concordant when this magnetization was imposed than is presently observed. If Fisher statistics are calculated using only the inclinations [McFadden and Reid, 1982] of the intermediate magnetizations, the grouping of inclinations after correction for bedding is much improved (Table 2), suggesting there is a consistent angle between bedding and inclination. Hence, the major part of the declination dispersion must result from differences in strike; this is consistent with tectonic rotations about a vertical axis.

The intermediate component probably was imposed between the Late Cretaceous and late Tertiary. This component is probably no older than the Late Cretaceous Sevier Orogeny, because a magnetization with a blocking temperature this low would probably have been reset by the orogeny. At the other extreme, this component must be older than late Tertiary, as it antedates the cave breccia that antedates late Tertiary Basin and Range faulting [Gillett, 1983a]. The general consistency of the intermediate direction with the oroflexural bending also supports a pre-late Tertiary time of acquisition.

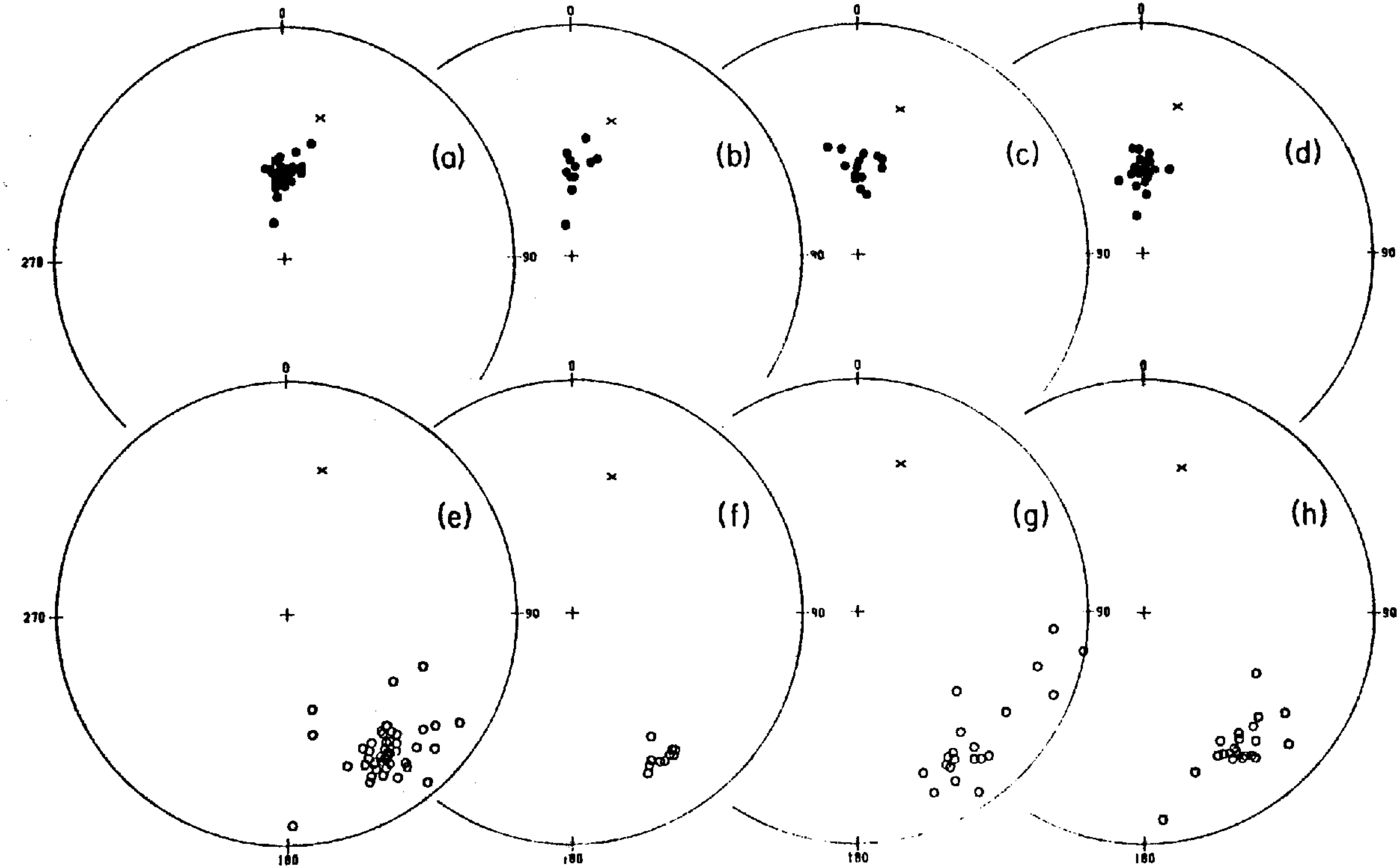


Fig. 11. Least squares fitted directions from various lithologies of gray limestone in the Goodwin Limestone; plot conventions are as in Figure 3b. Detailed descriptions of lithologies are given by Gillett [1983b]. Figures 11a-11d are for the intermediate component: (a) Concordantly bedded Nuia calcarenites. (b) Calcarenites distorted by stylolitic compaction around chert. (c) Micritic limestones, including mudstones, wackestones, and those containing hardground surfaces. (d) Intraformational pebble conglomerates. Figures 11e-11h are for the characteristic component; rock types for each plot correspond to the plot directly above.

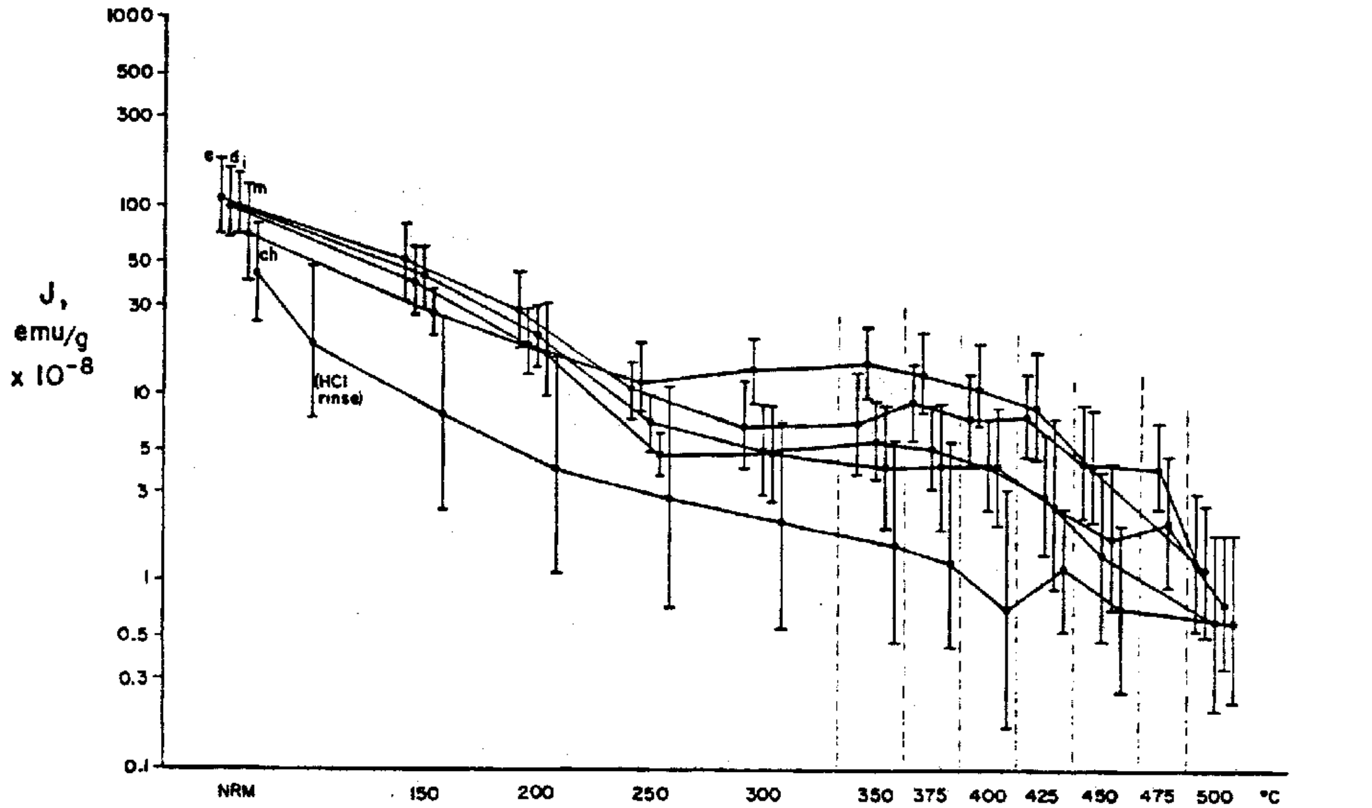


Fig. 12. Intensity of magnetization as a function of thermal demagnetization for various lithologies in the Goodwin Limestone. Conventions of the diagram are as in Figure 7b. The symbols for each lithologic type are as follows: c, Nuia calcarenites; d, compaction-distorted Nuia calcarenites; i, intraformational conglomerate; m, micritic rocks; ch, cherts [Gillett, 1983b]. 'HCl rinse' indicates NRM of cherts remeasured after they were rinsed briefly in concentrated HCl, to remove possible steel contamination from drilling and sawing.

A Late Cretaceous time of acquisition would imply that the magnetization was imposed late in the Sevier Orogeny. Imposition of the magnetization early in the orogeny seems unlikely, because the magnetization only becomes 'frozen in' when the section cools. Because the orogeny probably ended about 85 to 95 m.y. ago [Burchfiel et al., 1974], the single, normal-polarity intermediate magnetization might have recorded the end of the Cretaceous long normal interval, which extended from ~108 m.y. to ~85 m.y. B.P. [Lowrie et al., 1980].

A mid-Cenozoic magnetization may have been imposed during the early stages of Basin and Range formation. Cambrian limestones ~100 km to the east, in an area unaffected by Mesozoic thrust faulting, exhibit a normal-polarity secondary magnetization imposed during the early stages of Basin and Range uplift, largely before tilting and oroflexural bending [Gillett, 1982b]. Both regional uplift [e.g., Eaton, 1979] and higher-than-average heat flow [e.g., Eaton, 1980] accompanied Basin and Range development.

Hence, the present data do not definitely constrain the time of imposition of the intermediate magnetization.

Origin and Timing of the Characteristic Component

Two lines of evidence indicate that the characteristic magnetizations of the Paleozoic limestones are almost certainly older than the intermediate magnetization. First, these magnetizations have higher blocking temperatures and coercivities than the intermediate magnetization, although they also reside in magnetite; therefore, the characteristic magnetization would have survived the thermal event that imposed the intermediate magnetization. Second, as the paleoinclination in the Desert Range is 31° by early Jurassic time (calculated from the interval 9 pole [Van Alstine, 1979]), the low inclinations of the characteristic magnetizations (Table 2) suggest that they are older than this if they were imposed on horizontal strata. Near-horizontality of the Desert Range section through at least the early Triassic is likely; the first major tectonism in the area is evidenced as a regional paraconformity between Early Permian (locally Late Pennsylvanian) and Early Triassic strata [Longwell et al., 1965, pp. 38 and 60]. In addition, assuming a maximum original burial depth of ~10 km and a position ~100 km west of the geosynclinal hinge line, the maximum tilt introduced by subsidence is about 6° to the west. Moreover, the maximum inclination bias that would be introduced by such tilt would occur if the hinge line were perpendicular to the paleomeridian; in fact, the geosyncline trends ~45° to the paleomeridian, so that the maximum bias is reduced to ~4°.

Tectonic vertical axis rotation of the intermediate magnetization indicates that the older, characteristic magnetizations must have undergone

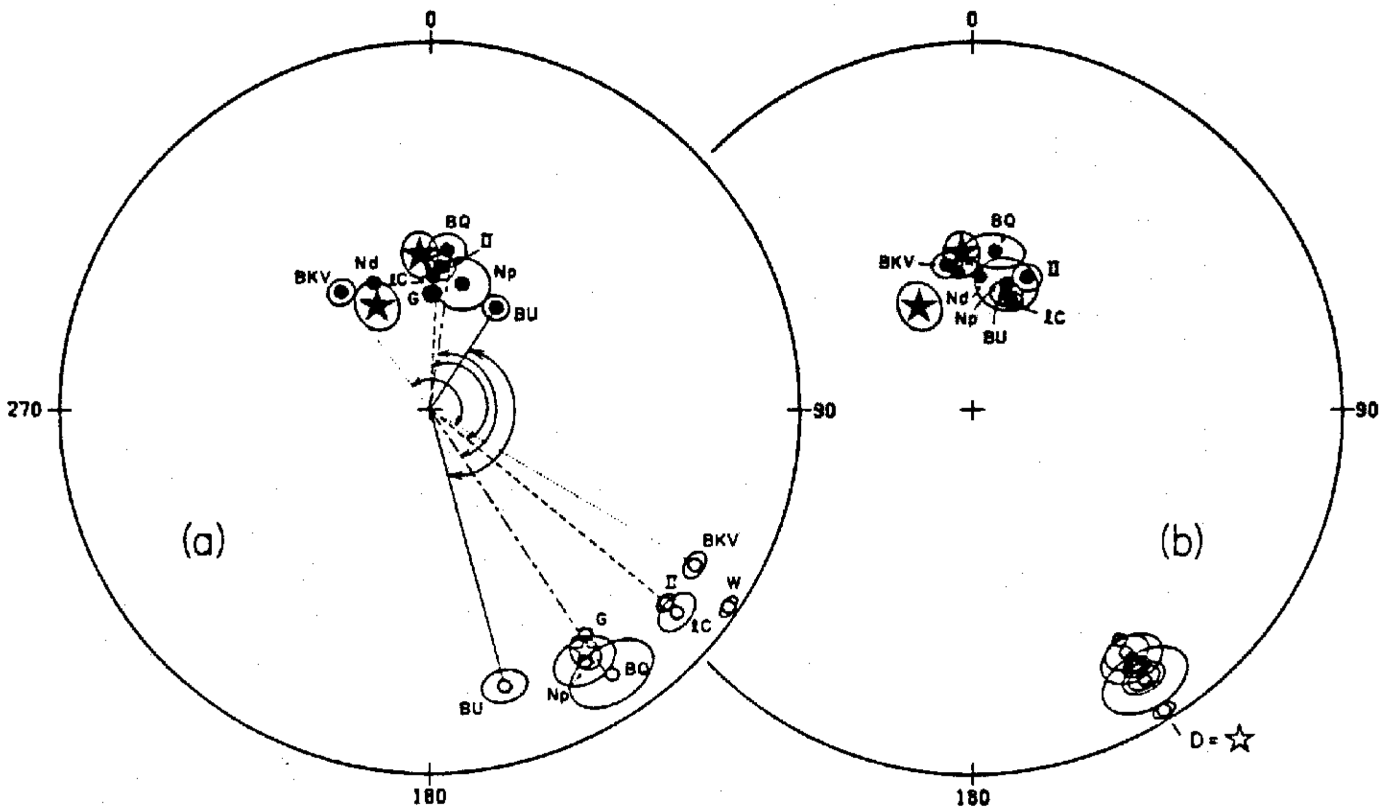


Fig. 13. Equal-area plots of mean or modal intermediate and characteristic directions from rock units in the Desert Range, with formal error cones. All directions are in stratigraphic (dip-corrected) coordinates. Solid circles are the intermediate directions, open circles the characteristic directions; abbreviations as in Table 1 (units with daggers). The northwesterly solid star is the mean position of a late Cretaceous geomagnetic field (D = 333°, I = +62°; interval 4 [Van Alstine and de Boer, 1978]); the northerly solid star is the mean position of a mid-Tertiary geomagnetic field (see Table 1 footnotes); open star is a mean reversed late Permian field (see Table 1 footnotes). Error ovals are calculated as described by Beck [1980]. (a) Stratigraphic coordinates with no vertical axis rotations; patterned lines connect the intermediate and characteristic directions derived from the same unit. (b) Positions of intermediate magnetizations after characteristic magnetizations have been rotated to match the declination of the reference Late Permian directions (D = 148°). Error ovals around rotated directions are elongate because the effect of error in characteristic declination is included.

rotation as well. Indeed, the characteristic magnetizations are dispersed in declination in the same sense as the intermediate magnetization (Table 1 and Figure 13). Furthermore, because the characteristic magnetizations have similar inclinations, it is possible that they also represent a single, ancient component that has undergone rotation around a vertical axis. In particular, declination differences between coeval sections (O, V and Q, U) suggest that vertical axis rotation has occurred. Finally, application of Watson's [1956] F-test to inclination-only averages yields improvement in grouping that is highly significant (Table 2). As with the intermediate magnetization, this result is consistent with dispersion of the declinations by vertical axis rotations.

Although the characteristic magnetizations are ancient, they probably were not acquired penecontemporaneously with deposition. First, the characteristic magnetization in the Goodwin Limestone is younger than major, throughgoing stylolites that locally cause disruption of primary bedding fabric; such major stylolites are late diagenetic features that probably developed over tens of millions of years. Second, the characteristic magnetization was imposed after the limestone was essentially fully cemented [Gillett, 1983b]. Therefore, either this magnetization was imposed on detrital magnetite grains that were not free to rotate, or else it reflects a chemical remanent magnetization in secondary magnetite. Authigenic magnetite, however, is probably precluded by evidence of authigenic iron sulfides in these rocks [Gillett, 1983b]. Thus, the characteristic magnetization of the Goodwin is probably a viscous partial thermoremanent magnetization (VPTRM) acquired at least tens of millions of years after deposition.

A VPTRM origin for this magnetization is supported by consideration of probable burial temperatures and durations. Conodonts from the Goodwin Limestone have a color alteration index (CAI) [Epstein et al., 1977] of 4.5, indicating that these rocks have been subjected to at least 250°C for 10^8 years. A magnetite-borne magnetization with a blocking temperature of 450°C would just barely be destroyed by such heating, whereas a magnetization with a blocking temperature of 500°C would survive [Pullaiah et al., 1975]. The

TABLE 2. 'Fold Test' From Inclinations Only

	N	<I>	k	α_{95}	k_{strat}/k_{geog}	d.f.	c.p
Intermediate magnetization							
Geographic	8	53°	30	11°	9.89**	7	6.99
Stratigraphic	8	59°	295	3°			
Characteristic magnetization							
Geographic	7	3°	15	17°	11.11**	6	8.47
Stratigraphic	7	-19°	162	5°			

The 'fold test' uses inclinations only [McFadden and Reid, 1982] to derive Fisher statistics. Parameters are as follows: N, number of sites (those with a dagger in Table 1 except Wood Canyon); <I>, mean inclination; k, unbiased estimate of Fisher's concentration parameter; k_{strat}/k_{geog}, ratio used in F-test for improvement in grouping [Watson, 1956] (** indicates significant at >99% confidence); d.f., degrees of freedom (same for both k_{strat} and k_{geog}); and c.p., critical point at >99% confidence level.

experimental work done by Pullaiah et al. [1975], however, suggested that their model is rather optimistic at high blocking temperatures, in that magnetizations are reset more easily than the model predicts. Furthermore, the curves for conodont CAI and magnetic blocking temperature as functions of time and temperature are not parallel, and the difference is in the sense that higher temperatures affect magnetization more than CAI. For example, a CAI of 4.5 corresponds also to 350°C for 10^4 years, values that would easily destroy a remanence having a blocking temperature of 450°C.

A burial depth of 5 km for the Goodwin at the end of the Paleozoic coupled with a geothermal gradient of 25°C/km yields estimates of burial temperature less than the 250°C minimum suggested by the conodonts. Several sources of error, however, could raise the temperature estimates: (1) the geothermal gradient may have been somewhat higher; (2) the thickness of overburden may be underestimated; and (3) the original overburden thickness has probably been much reduced by late chemical compaction (stylolitization), as the section above is dominantly carbonate. Mossop [1972], for example, found up to 25% reduction in thickness resulting from stylolitization in Devonian carbonates in Alberta. An original thickness of 8 km (which would yield a present-day thickness of 6 km after 20% stylolitic compaction), in conjunction with a geothermal gradient of 30°C/km, for example, yields burial temperatures on the order of 265°C.

The Goodwin Limestone is the uppermost unit sampled and thus was subjected to the shallowest burial. If its original magnetization has been destroyed by burial heating, the underlying magnetite-bearing carbonates probably are also remagnetized. Neomorphic textures [e.g., Bathurst, 1976, Chapter 12] are common in the Bonanza King and Carrara Formations [Palmer and Halley, 1979; S. L. Gillett, unpublished data, 1978], indicating extensive, late diagenetic recrystallization, which is consistent with significant burial metamorphism.

It seems likely, therefore, that the characteristic magnetizations of the Paleozoic limestones represent a relatively late, thermally imposed secondary magnetization resulting from uplift after deep burial. The first major uplift in the region is evidenced by the regional paraconformity discussed earlier; the Late Permian, therefore, seems to be the most reasonable time to impose the characteristic magnetization.

Tectonic Rotations in the Desert Range: Further Considerations

Declination differences between expected and observed directions have been calculated for both the characteristic magnetization (ΔD_{Char}) and intermediate magnetization (ΔD_{Int}) in all sections (Table 1), assuming a Late Permian age (interval 12 of Van Alstine [1979]) for the characteristic magnetization and a middle Tertiary age (interval 2: late Eocene to early Miocene) for the intermediate magnetization. These differences are related to the sense and magnitude of rotation about a vertical axis; in most sections, however, the ΔD_{Char} and ΔD_{Int} values are significantly different in both sense and magnitude. In part, these differences probably reflect imposition of the intermediate magnetization on tilted strata; in this case, rotation inferred from the intermediate magnetization would be proportional to, not the same as, rotation inferred from the characteristic magnetization. In most cases, the intermediate magnetizations differ by a larger angle than do the characteristic magnetizations. For example, the characteristic magnetization at section V is 9° counterclockwise of that from coeval section O; the intermediate magnetizations from these two sections differ in the same sense, but by 41°. Similarly, the characteristic magnetizations from section Q are 19° counterclockwise of those from coeval section U, but the intermediate magnetizations are 27° counterclockwise.

Imposition of the intermediate magnetization on dipping beds is also suggested by comparing the total angle between the intermediate and characteristic magnetizations at each section (Table 1). For seven sections where both magnetizations were independently recognized, this angle averages 129°, which is somewhat smaller than the angle (141°±6°) between the interval 2 (normal polarity) and interval 12 (reversed polarity) directions. Thus, the intermediate magnetization was imposed on dipping beds, because the characteristic magnetization was imposed on essentially horizontal strata.

In turn, imposition of the characteristic magnetization on horizontal strata indicates that absolute rotations in the Desert Range are more accurately inferred from this magnetization. Upon rotation of the characteristic directions to the interval 12 declination, however, most of the intermediate magnetizations rotate to a northeasterly position (Figure 13b), which does not correspond to any point on the North American apparent polar wander path. Geometrically, the intermediate directions have been rotated too far clockwise. This discrepancy becomes worse if the characteristic magnetization dates from interval 11 (Early Triassic) or interval 13 (Early Permian), as these reference declinations are more southerly than that from interval 12.

This northeasterly bias of the 'corrected' intermediate magnetization may be yet another indication that the intermediate magnetization was imposed on tilted beds. For example, a magnetization direction (D = 356°, I = +56°) acquired during interval 2 (middle Tertiary) would be rotated to the observed northeasterly average position (D = 8°, I = +60°, α_{95} = 5°) upon structural correction for ~10° of dip toward the southeast about a strike of ~40°. Alternatively, a magnetization direction (D = 330°, I = +64°) acquired during interval 5 (Late Cretaceous) would be rotated to the same northeasterly position upon correction for ~18° of dip to the east and a strike of ~350°. An easterly dip of the beds on which the intermediate magnetization was imposed is reasonable considering that the Desert Range approximately forms the eastern limb of a north plunging anticline (Figure 1). The bending of this anticline axis between the Las Vegas-Pahranagat conjugate shear systems suggests that the anticline is older than the vertical axis deformation and may have existed when the intermediate magnetization was acquired.

Other structural explanations could account for at least part of the northeasterly bias. The 8° bias could reflect systematic rotation of the characteristic magnetizations during Mesozoic thrusting [cf. Grubbs and Van der Voo, 1976; Gillett, 1982a]. Alternatively, 'apparent vertical axis rotations' [MacDonald, 1980] are possible; these are second-order declination discrepancies that result when blocks rotated about inclined axes are rotated back to horizontal about horizontal axes (the strikes).

A northeasterly bias of the 'corrected' intermediate magnetization directions might also result in principle from incomplete separation of the intermediate component and the low blocking temperature component representing the post-tilting PADF. If the northeasterly bias were caused by the presence of an unremoved PADF component, however, the directions with more northeasterly declination should also have shallower inclinations, the opposite of what is observed.

The different amounts of rotation suggested by the intermediate and characteristic components underscore the care that must be taken in using paleomagnetic declinations to estimate the magnitudes of tectonic rotations. On the basis of the characteristic direction, the total amount of observed relative rotation (between sections U and V) in the Desert Range is 44°±5°. In an absolute sense, assuming that the characteristic magnetization dates from the Late Permian, section V has probably been rotated counterclockwise by 27°±4°, whereas section U has been rotated clockwise by 17°±5°. Absolute counterclockwise rotation in the Desert Range is probably related to the left-lateral Pahranagat Shear System, whereas absolute clockwise rotation is probably related to the right-lateral Las Vegas Shear Zone.

Implications for Other Desert Range Strata

Middle Member, Wood Canyon Formation. Hematitic strata in the middle member of the Lower Cambrian Wood Canyon Formation yield a characteristic direction, upon thermal demagnetization to ~640°C, that is near the characteristic direction found in the overlying limestones [Gillett and Van Alstine, 1979]. In general, even the 'cleanest' samples do not have paths linear to the origin through the highest demagnetization steps. Thus, the characteristic direction in the Wood Canyon may lie even closer to the direction in the limestones. Gillett and Van Alstine [1979] proposed that the very high blocking temperature of this remanence precludes its being a thermal overprint, and we also presented evidence that the oxidation of the Wood Canyon was probably penecontemporaneous with deposition, not the result of late, prolonged intrastratal alteration. Our evidence for early oxidation still seems strong, but in view of the above discussion it appears likely that the characteristic magnetization in the Wood Canyon is secondary.

Van der Voo and Channell [1980] discussed the problem of magnetizations in hematite that have very high blocking temperatures but that nonetheless are secondary, suggesting that such magnetizations arise chemically. In the Wood Canyon Formation, it appears that such a chemical process must be unrelated to the early oxidation, and we suggest that the remagnetization has arisen from recrystallization. The characteristic remanence resides primarily in a microcrystalline red cement, and fine-grained hematite commonly forms with high internal stresses [e.g., Stacey and Banerjee, 1974, p. 86]; perhaps such crystals anneal over time and thereby acquire a new magnetization.

Qualitative support for recrystallization in the Wood Canyon comes from Folk [1976], who proposed that the color of red beds 'ages' over geologic time and that this aging reflects an increase in grain size during recrystallization. Most of the Wood Canyon fine-grained rocks are red-purple (5 RP 4/2) rather than red; McBride [1974] has presented evidence that red versus purple coloration in hematite-pigmented rocks reflects grain size differences in the hematite, the purple rocks probably being the coarser grained.

The above discussion is qualitative but suggests avenues for further research. Perhaps ancient remanences in hematite may be reset more easily than has generally been thought; in particular, the time of oxidation and hematite formation, when it can be established, may still not reflect the time of characteristic magnetization.

Rainstorm Member, Johnnie Formation. Of all the Desert Range strata, the Rainstorm Member of the Johnnie Formation (late Precambrian) is probably the best candidate for retaining a primary magnetization. The characteristic magnetization of these rocks is a two-polarity remanence (Table 1) that has a blocking temperature of ~650°C and that may be associated with possibly detrital specular hematite [Van Alstine and Gillett, 1979a].

The magnetization of the Rainstorm is probably older than the characteristic magnetization of the Paleozoic limestones. First, the dip-corrected inclination of the Rainstorm's magnetization (~0°) is considerably shallower than the late Paleozoic reference direction (~-19°). Second, the Rainstorm is ~4 km stratigraphically below the Goodwin Limestone; using the 250°C temperature estimated for the Goodwin, and even assuming a high value of the geothermal gradient (30°C/km) below the Goodwin, the depth of the Rainstorm corresponds to a temperature of ~400°C, which is far too cool to affect a hematite remanence with a blocking temperature of 650°C [Pullaiah et al., 1975]. Furthermore, as the remanence resides in relatively coarse-grained hematite, it is probably not vulnerable to a recrystallization remagnetization.

Because the magnetization of the Rainstorm is older than that of the Paleozoic limestones, the Rainstorm direction must be corrected for the vertical axis rotation inferred in the limestones. The characteristic magnetization of section O, about 2 km stratigraphically above the Rainstorm, shows 18° of counterclockwise rotation with respect to the late Permian reference direction. Correcting the Rainstorm magnetization for 18° of counterclockwise rotation moves the corresponding paleomagnetic pole to 5°N, 151°E. This revised Rainstorm pole is concordant with reported late Hadrynian poles for North America [Van Alstine and Gillett, 1979a, Figures 4 and 8]. The Rainstorm pole, therefore, does not imply a large amount of late Precambrian apparent polar wandering, as had been proposed by Van Alstine and Gillett [1979a] on the assumption of primary magnetizations for the Paleozoic strata in the Desert Range.

Conclusions

Three components of magnetization are present in the early Paleozoic limestones of the Desert Range. The first, of recent origin, reflects the PADF and resides partly in low-coercivity magnetite and partly in goethite and/or hematite from recent weathering. The two other components both reside in magnetite; the characteristic component probably dates from the Late Permian, whereas the intermediate blocking temperature component may range in age from mid-Cenozoic to late Cretaceous. The intermediate component is also present in gray limestones of the late Precambrian Noonday(?) Formation. Both the characteristic and intermediate magnetizations apparently record times of uplift after prolonged heating during deep burial; no primary magnetization remains.

The characteristic magnetization in the middle member of the Early Cambrian Wood Canyon Formation resides in microcrystalline hematite and also apparently reflects late Paleozoic remagnetization, showing nearly the same direction as the limestones. The Wood Canyon strata evidently were remagnetized by recrystallization, as field evidence indicates that the iron oxidation occurred early.

Both the intermediate and characteristic directions in the Desert Range strata reflect relative clockwise rotation, north to south, which is consistent with clockwise oroflexural bending of the entire Desert Range that had been proposed earlier on independent geologic evidence. The amount of rotation inferred from the intermediate magnetization differs from the rotation implied by the characteristic magnetization; this probably results from imposition of the intermediate magnetization on dipping strata. Whether the intermediate magnetization is late Cretaceous or Cenozoic, it was probably imposed when bedding in all sections dipped ~10°-20° to the east, consistent with the position of the Desert Range on the eastern limb of a very large, broad, north plunging anticline that antedates the oroflexural bending.

The characteristic magnetization is preferred as the estimator of vertical axis rotations, as geologic evidence suggests that the strata were essentially horizontal throughout the Paleozoic. The total relative rotation observed is 44°±5°; a Late Permian age for the characteristic magnetization implies absolute counterclockwise rotation of 27°±4° for the northernmost section and 17°±5° of absolute clockwise rotation for the southernmost. Clockwise rotation is probably related to the right-lateral Las Vegas Shear Zone to the south, whereas counterclockwise rotation probably results from the possibly conjugate, left-lateral Pahranagat Shear System to the north. On the present evidence, some net rotations resulting from Mesozoic thrusting cannot be ruled out.

The only rock unit in the Desert Range that may retain a primary remanence is the late Precambrian Rainstorm Member of the Johnnie Formation. After correction for a probable counterclockwise rotation of 18°, it yields a pole near other reported late Hadrynian poles from North America. Almost certainly, the Rainstorm has not undergone the 36° clockwise rotation proposed by Van Alstine and Gillett [1979a].

More philosophical but equally important conclusions are also to be drawn from this study. An intricate story has emerged from paleomagnetic investigations in the Desert Range; however, this story ultimately has very little to do with the history of the late Precambrian through early Paleozoic geomagnetic field. Rather, both complex tectonic rotations and three episodes of remagnetization have demonstrably affected the Desert Range strata. Upon progressive demagnetization, the rocks generally yielded well-grouped characteristic magnetization directions far from the PADF. Such magnetizations would have been accepted as primary by the criteria used in many studies, and indeed that was our initial interpretation. To show that these magnetizations are secondary required not just detailed paleomagnetic and rock magnetic work, but also detailed field and petrographic studies. Pervasive remagnetization may be easier to accomplish than has been thought in both magnetite- and hematite-bearing strata; well-grouped directions that yet reflect remagnetization may be the rule in rocks as old as early Paleozoic. Much painstaking work must be done before we can have confidence in apparent polar wander paths derived from ancient rocks.

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