Data Repository item 2004077

Supplementary Appendix and Figure Captions for "PALEOCLIMATIC INFERENCES FROM PALEOPEDOLOGY AND MAGNETISM OF THE PERMIAN MAROON FORMATION LOESSITE, COLORADO, USA"

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(for GSA Data Repository)

APPENDIX DR1. PALEOMAGNETIC AND ROCK MAGNETIC METHODS

The natural remanent magnetizations (NRMs) were measured on a 2G three-axes cryogenic magnetometer located in a magnetically shielded room. A representative set of specimens were selected for stepwise demagnetized by alternating field (AF) demagnetization (n = 33) up to 100 mT in a 2G Automated Degaussing System and by thermal demagnetization (n = 49) up to 700°C in an Schonstedt TSD-1 oven. The decay patterns were displayed in orthogonal projections (Zijderveld, 1967) and line segments were identified. Principal component analysis (Kirschvink, 1980) was performed to identify the components. The mean angular deviation (MAD) angles were less than 15°. The mean direction was calculated using Fisher (1953) statistics. In addition, an impulse magnetizer was used to obtain the acquisition pattern of an isothermal remanent magnetization (IRM). This was followed by thermal decay of three perpendicular IRMs (Lowrie, 1990) with fields of 120 mT, 500 mT and 2500 mT.

Paleomagnetism and Rock magnetic Results

Alternating field demagnetization did not remove a linear component of magnetization. The AF treatment did remove a significant fraction of the magnetization (mean = 15%, standard deviation = 13.5%, n=33) with a range from 0% to 48%. The amount of AF decay in paleosols

(18%, standard deviation = 13.5%) was higher than that in loessite (14%, standard deviation = 13.9%) although the values are similar and the standard deviations overlap.

Thermal demagnetization generally resulted in erratic decay but a characteristic remanent magnetization (ChRM) with southeasterly declinations and shallow inclinations could be identified after removal of a generally poorly defined viscous remanent magnetization (VRM) at temperatures below 300°C (Figure 1). The ChRM was isolated in about two thirds of the specimens (32/49) although many of the mean angular deviation (MAD) values were generally high (>10°). The magnetization in those specimens without the ChRM exhibits erratic decay and linear components could not be isolated although most of the directions had southeasterly declinations. In most specimens with the ChRM, the decay had a thermally discrete pattern although a few had a more gradual, thermally-distributed unblocking temperature pattern. There are no obvious differences in the decay patterns of loessites and paleosols. The mean direction for ChRM is declination 162.2°, inclination –15.5° (n/n$_o$ = 32/49, α_{95} = 6.6°, k = 16.0). The pole position for the ChRM (45°N, and 117°E) falls near the late Paleozoic part of the apparent polar wander path.

Acquisition curves of IRMs for samples from the Maroon Formation show a rapid rise by 100 mT and then a more gradual rise up to 2500 mT (Figure 2a). This suggests that a low-coercivity phase is present but that the remanence is dominated by a high-coercivity phase. Subsequent stepwise thermal demagnetization of a tri-axial IRM (Lowrie, 1990) provides only limited information about the magnetite mineralogy. The high coercivity components decay gradually up to about 650-670 °C where the remaining IRM decays abruptly, suggesting that the remanence is dominated by hematite (Figure 2b) although maghemite could also be present. The intermediate and low-coercivity components decay below 400 °C but then generally show

irregular behavior (Figure 2b) which may indicate creation of new phases during heating.

Because of the irregular behavior we can not definitely conclude that magnetite is present based

on the decay curves. The shape of the acquisition curves for paleosol and loessite samples are

similar.

The ChRM is interpreted to reside in hematite. A component residing in magnetite could

not be isolated. The late Permian pole position for the ChRM is younger than the inferred age for

the Maroon Formation loessite (Early Permian), which suggests that the ChRM is secondary.

Although it is difficult to determine if the ChRM is primary or secondary without field tests (e.g.,

conglomerate test), based on the pole position and the presence of abundant authigenic hematite

in the rocks, the ChRM is interpreted to be an early chemical remanent magnetization (CRM)

residing in hematite similar to that found in some other red beds (e.g., Butler, 1992).

REFERENCES

Butler, R. F., 1992, Paleomagnetism: Magnetic Domains to Geologic Terranes, Blackwell

Scientific Publications, Boston, MA, 319 pp.

Fisher. R. A., 1953, Dispersion on a sphere: Proceedings of the Royal Society of London, v.

A217, 295-305.

Kirschvink, J.L., 1990 The least-squares line and plane and the analysis of paleomagnetic data,

Geophysical Journal of the Royal Astronomical Society, v. 62, p. 699-718.

Lowrie, W., 1990, Identification of ferromagnetic minerals in a rock by coercivity and

unblocking temperature properties: Geophysical Research Letters, v. 17, p. 159-162.

Van der Voo, R., 1993, Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans, Cambridge

University Press, Cambridge, 411 p.

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Zijderveld, J.D.A., 1967, A.c. demagnetization of rocks: Analysis of results, *in* Collinson, D.W.,

Creer, K.M., and Runcorn S.K (eds.), Methods in Paleomagnetism: Elsevier, p. 254-286.

Figure Captions

Figure DR1. Orthogonal projection of the typical thermal demagnetization behavior (temperature

steps in °C) of the magnetization in a representative specimen. Note removal of a poorly defined

VRM below 300 °C and a magnetization with southeasterly declinations and shallow inclinations

above 300 °C. Solid squares represent the vertical component, open squares represent the

horizontal component.

Figure DR2. Representative IRM acquisition (a) for a paleosol and loess sample, and thermal

triaxial decay (b) curves for a representative Maroon loessite. The steep slope below 100 mT in

the acquisition curves suggest that a low coercivity phase is present and the rise above 200 mT

indicates the presence of a high coercivity phase. Decay of the high coercivity component to 680
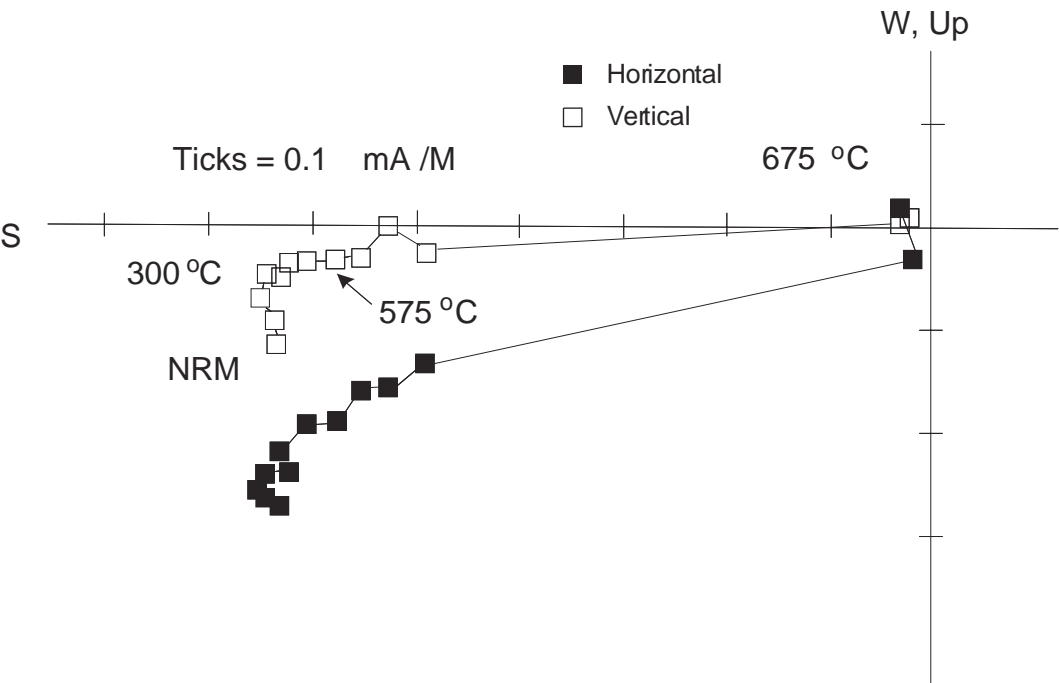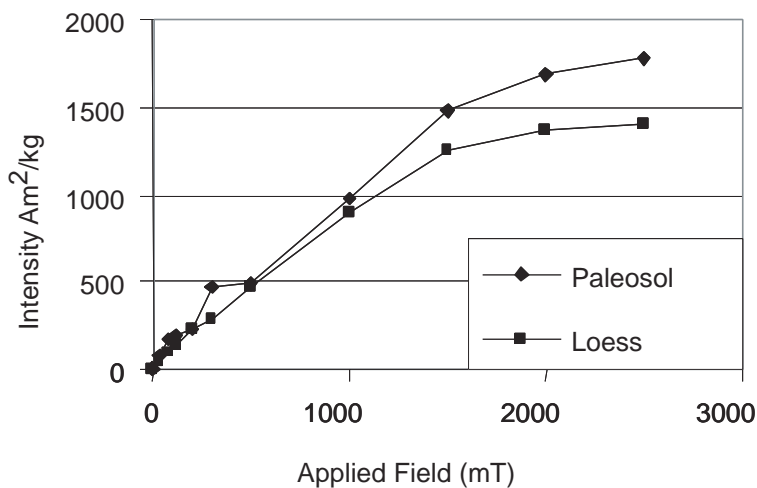
°C indicates that hematite is present.
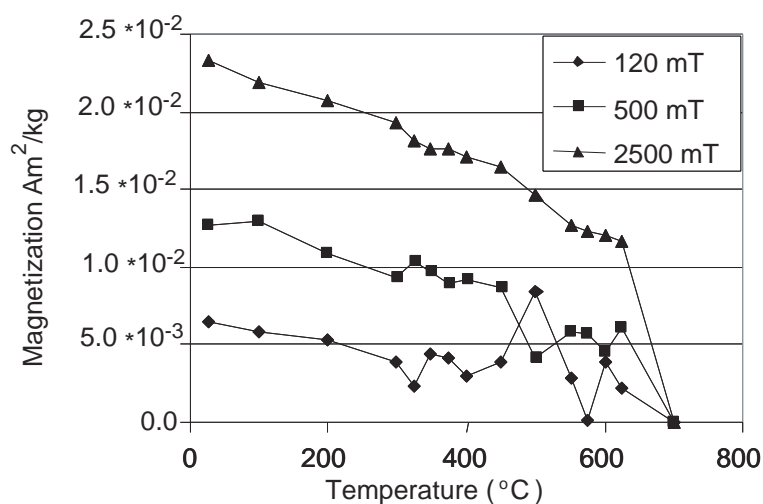
Figure 1. Data repository Tramp et al., 2002

A

B

Figure 2 Data Repository, Tramp et al., 2003

Table 1. Parent material geochemical proportions and Zr ratios from Maroon Formation samples

Sample section and number	Parent material major oxide proportion (weight percent)*								Parent material Zr weathering ratios						
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MgO	CaO	K_2O	ZrO_2	SiO_2/ZrO_2	TiO_2/ZrO_2	Al_2O_3/ZrO_2	FeO/ZrO_2	MgO/ZrO_2	CaO/ZrO_2	K_2O/ZrO_2
RR 37.1	78.3	0.45	6.08	1.64	1.83	2.41	2.18	0.069	1210.1	6.95	93.97	25.35	28.28	37.25	33.7
M 1.6	75.9	0.37	5.88	1.61	2.01	4.13	2.23	0.053	1543.9	7.53	119.59	32.74	40.88	84.00	45.4
LR 20.3	83.1	0.26	6.01	2.93	0.39	0.99	2.03	0.026	3399.3	10.63	245.81	119.84	15.95	40.49	83.0
UR 166.0	81.8	0.36	6.13	1.61	0.97	1.45	2.44	0.056	1580.5	6.96	118.49	31.12	18.75	28.03	47.2
UR 177.6	86.8	0.29	5.64	1.41	0.18	0.1	2.32	0.042	2208.9	7.38	143.48	35.87	4.58	2.54	59.0
UR 362.4	78.3	0.5	6.71	1.64	1.42	2.03	1.84	0.059	1424.9	9.09	122.05	29.83	25.83	36.92	33.5
UR 174.0	84.5	0.41	6.44	1.59	0.47	0.47	2.44	0.069	1323.0	6.42	100.79	24.89	7.36	7.36	38.2
UR 215.0	82.6	0.27	5.53	1.36	0.22	2.71	2.03	0.041	2161.8	7.06	144.66	35.58	5.75	70.89	53.1
mean	81.4	0.364	6.053	1.724	0.936	1.786	2.189	0.052	1856.6	7.8	136.1	41.9	18.4	38.4	49.1
standard deviation	3.6	0.087	0.390	0.499	0.736	1.316	0.213	0.015	723.1	1.4	47.8	31.8	12.7	28.0	16.4

Table 2. Paleosol rating scale for the Maroon Formation

	Macromorphological rating scale
Color [+]	reddish brown* laterally continuous horizon, faint peds
	reddish brown color change >0.3 m but < 0.5 m [#]
	reddish brown color change > 0.5 m but < 1.0 m
	reddish brown color change >1.0 m
	dark red brown color
Structure	pedogenic structure
	pedogenic structure >0.3 m but < 0.5 m
	pedogenic structure > 0.5 m but < 1.0 m
	pedogenic structure > 1.0 m
Mottles[**]	few
	common
	many
Traces	roots/burrows
Texture	upward increase of clay

* Munsell color value: 10R 4/6

** The concentration of mottles follows definitions provided by Retallack, G.J. 1988. Field recognition of paleosols. In: Paleosols and weathering through geologic time: Principles and applications. J. Reinhardt and W.R. Sigleo (eds.). Geological Society of America Special Papers 216, p. 1-20.

[#] On the basis of color and structure thicknesses observed in the study section, 0.3 m, 0 m, and 1.0 m were chosen.

[+]Although Wright, 1992 (Wright, V.P., 1992, Paleosol recognition: A guide to early diagenesis in terrestrial settings, in Wolf, K.H., and Chilingarian, G.V., eds., Diagenesis III: Amersterdam, Elsevier, p. 591-619.) cautions the use of color as a descriptor of paleosols, the early reddening of upper Paleozoic red beds (Walker, T.R., 1967, Formation of red beds in modern and ancient deserts: Geological Society of America Bulletin, v. 78, p. 353-368.; Dubiel, R.F. and Smoot, J.P., 1994, Criteria for interpreting paleoclimate from red beds- a tool for Pangean reconstructions, in Embry, A.F., Beauchamp, B., and Glass, D.J., eds, Pangea: global environments and resources: Canadian Society of Petroleum Geologists Memoir 17, p. 295-310. aids in differentiation paleosol from loessite.)

Table 3a. Major oxide ratios and percent deviation from parent material with respect to Zirconium and Titanium from Maroon Formation samples **

		sample section and number	TiO_2/ZrO_2	deviation from PM	Al_2O_3/ZrO_2	deviation from PM	SiO_2/ZrO_2	deviation from PM	K_2O/ZrO_2	deviation from PM	MgO/ZrO_2	deviation from PM	CaO/ZrO_2	deviation from PM	Sample designation*
Protosol		UR 174.0	6.42	0.00	100.79	0.00	1323.00	0.00	28.66	0.00	7.36	0.00	7.36	0.00	PM
		UR 175.1	8.94	2.52	162.04	25.94	1742.80	419.81	46.61	17.95	49.96	42.61	63.49	56.13	25.00
		UR 175.25	9.03	2.62	160.62	24.52	1629.10	306.11	46.13	17.47	55.52	48.17	69.62	62.27	10.00
		UR 175.3	8.61	2.19	157.96	21.86	1599.18	276.19	45.70	17.05	51.65	44.29	64.13	56.77	5.00
		UR 175.35	9.20	2.79	162.99	26.89	1493.90	170.90	48.34	19.68	52.56	45.20	62.78	55.43	Top
	calcite***	LR 20.3	10.63	0.00	245.81	0.00	3399.25	0.00	83.03	0.00	15.95	0.00	40.49	0.00	PM
		LR 20.5	9.04	-1.59	151.48	-94.33	1874.21	-1525.04	49.11	-33.92	10.02	-5.93	121.43	80.94	40.00
		LR 20.7	7.67	-2.96	108.94	-136.87	1168.38	-2230.87	35.21	-47.82	9.33	-6.62	47.55	7.06	20.00
		LR 20.9	8.15	-2.48	129.43	-116.38	1303.43	-2095.82	40.92	-42.10	11.81	-4.14	35.77	-4.72	Top
		UR 177.6	7.38	0.00	143.48	0.00	2208.95	0.00	59.02	0.00	4.58	0.00	2.54	0.00	PM
		UR178.2	9.72	2.35	207.66	64.18	2481.27	272.32	82.81	23.79	51.76	47.18	64.62	62.08	35.00
		UR 178.3	10.00	2.62	198.04	54.56	2122.29	-86.66	81.05	22.03	40.26	35.68	44.85	42.31	25.00
		UR 178.35	9.52	2.15	173.82	30.34	1690.57	-518.38	70.13	11.11	30.95	26.37	30.74	28.19	20.00
		UR 178.4	9.43	2.05	162.40	18.91	1516.93	-692.02	65.98	6.96	28.47	23.89	27.49	24.95	15.00
		UR 178.45	8.90	1.52	157.36	13.88	1605.00	-603.95	64.12	5.10	23.67	19.09	22.05	19.50	5.00
		UR 178.55	9.99	2.61	184.75	41.27	1701.39	-507.56	74.25	15.23	26.70	22.12	21.06	18.51	Top

** weathering ratios taken from Maynard,J.B., 1992, Chemistry of Modern Soils as a Guide to Interpreting Precambrian Paleosols: The Journal of Geology, v. 100, p. 279-289. and Mason, J.A., and Jacobs, P.M., 1998, Chemical and particle-size evidence for addition of fine dust to soils of the midwestern United States: Geology, v. 26, p. 1135-1138.   *** pedogenic carbonate is calcite rather than dolomite
* PM = average parent material; Top = top of paleosol; #'s refer to centimeters from top of paleosol

Table 3b. Major oxide ratios and percent deviation from parent material with respect to Zirconium and Titanium from Maroon Formation samples **

	sample section and number	TiO_2/ZrO_2	deviation from PM	Al_2O_3/ZrO_2	deviation from PM	SiO_2/ZrO_2	deviation from PM	K_2O/ZrO_2	deviation from PM	MgO/ZrO_2	deviation from PM	CaO/ZrO_2	deviation from PM	Sample desigation*
moderately developed Argillisol	UR 362.4	9.09	0.00	122.05	0.00	1424.94	0.00	25.12	0.00	25.83	0.00	36.92	0.00	PM
	UR 363.2	9.69	0.60	131.67	9.62	1348.76	-76.19	28.84	3.72	29.08	3.25	37.19	0.27	60.00
	UR 363.4	9.80	0.71	144.00	21.95	1266.12	-158.83	32.47	7.35	31.94	6.12	37.86	0.94	40.00
	UR 363.7	12.39	3.30	180.94	58.89	1174.57	-250.38	46.75	21.63	31.89	6.06	24.95	-11.97	10.00
	UR 363.8	12.26	3.16	181.93	59.88	1148.19	-276.75	46.84	21.72	30.32	4.49	21.93	-14.99	Top
	UR 166.0	6.96	0.00	118.49	0.00	1580.53	0.00	47.16	0.00	18.75	0.00	28.03	0.00	PM
	UR 167.3	8.69	1.73	155.63	37.14	2345.41	764.88	60.29	13.13	22.99	4.25	31.97	3.94	70.00
	UR 167.6	9.00	2.04	175.35	56.86	2133.23	552.70	72.29	25.13	81.87	63.12	126.87	98.84	40.00
	UR 167.8	10.25	3.29	172.99	54.51	1091.49	-489.05	70.51	23.35	25.24	6.49	15.60	-12.43	20.00
	UR 167.9	10.77	3.82	184.08	65.59	1110.45	-470.08	76.34	29.18	21.86	3.11	8.46	-19.56	10.00
	UR 168.0	10.74	3.79	190.53	72.04	1239.38	-341.16	80.74	33.58	19.98	1.23	8.06	-19.97	Top
Accretionary	UR 215.0	7.06	0.00	144.66	0.00	2161.79	0.00	53.10	0.00	5.75	0.00	70.89	0.00	PM
	UR 215.4	10.98	3.92	266.83	122.17	2972.60	810.81	103.72	50.62	126.50	120.75	163.92	93.03	35.00
	UR 215.55	10.04	2.98	173.51	28.85	1373.23	-788.55	66.14	13.04	25.45	19.70	17.75	-53.15	20.00
	UR 215.6	10.04	2.97	162.70	18.04	1232.36	-929.43	60.21	7.11	24.51	18.76	18.75	-52.14	15.00
	UR 215.7	8.57	1.51	128.62	-16.04	1082.87	-1078.92	44.16	-8.94	22.44	16.68	22.29	-48.60	5.00
	UR 215.75	10.94	3.88	165.54	20.88	1106.50	-1055.29	58.22	5.12	23.56	17.81	16.11	-54.78	Top
Truncated	RR 37.1	6.95	0.00	93.97	0.00	1210.14	0.00	33.69	0.00	28.28	0.00	37.25	0.00	PM
	RR 37.7	9.38	2.42	159.66	65.69	1861.86	651.72	57.00	23.31	60.21	31.93	76.50	39.25	10.00
	RR 37.75	8.16	1.21	136.37	42.40	1429.58	219.44	49.91	16.22	30.99	2.70	37.66	0.42	5.00
	RR 37.8	6.77	-0.18	67.59	-26.38	220.76	-989.38	25.98	-7.71	5.29	-22.99	1.41	-35.84	Top

** weathering ratios taken from Maynard,J.B., 1992, Chemistry of Modern Soils as a Guide to Interpreting Precambrian Paleosols: The Journal Geology, v. 100, p. 279-289. and Mason, J.A., and Jacobs, P.M., 1998, Chemical and particle-size evidence for addition of fine dust to soils of the midwestern United States: Geology, v. 26, p. 1135-1138.

* PM = average parent material; Top = top of paleosol; #'s refer to centimeters from top of paleosol

Table 3c. Major oxide ratios and percent deviation from parent material with respect to Zirconium and Titanium from Maroon Formation samples ***

		sample section and number	TiO$_2$/ZrO$_2$	deviation from PM	Al$_2$O$_3$/ZrO$_2$	deviation from PM	SiO$_2$/ZrO$_2$	deviation from PM	K$_2$O/ZrO$_2$	deviation from PM	MgO/ZrO$_2$	deviation from PM	CaO/ZrO$_2$	deviation from PM	Sample desigation**
well developed Argillisol	Superimposed	avg PM	7.75	0.00	136.10	0.00	1856.56	0.00	49.13	0.00	18.42	0.00	38.43	0.00	PM
		RR 133.1*	16.13	8.38	301.91	165.81	1976.48	119.92	125.31	76.19	354.44	336.01	443.77	405.33	95.00
		RR 133.5*	14.30	6.55	290.79	154.69	1914.13	57.57	117.78	68.65	86.93	68.51	70.95	32.51	55.00
		RR 133.7*	14.39	6.63	319.80	183.69	2144.18	287.62	124.38	75.26	66.84	48.41	48.55	10.12	35.00
		RR 133.9*	24.94	17.19	480.39	344.29	2362.53	505.97	179.85	130.72	195.13	176.71	185.08	146.64	15.00
		RR 134.05*	17.03	9.28	292.19	156.09	1765.91	-90.64	110.06	60.94	217.83	199.41	264.35	225.91	Top
		RR 134.2*	12.91	5.16	229.26	93.16	1624.93	-231.62	87.52	38.39	178.48	160.05	226.68	188.25	above top
		M 1.6	7.53	0.00	119.59	0.00	1543.85	0.00	45.35	0.00	40.88	0.00	84.00	0.00	PM
		M 2.5	9.50	1.98	167.07	47.48	1952.80	408.94	62.53	17.17	45.27	4.39	56.77	-27.22	80.00
		M 2.9	11.37	3.84	204.90	85.32	1773.02	229.17	83.02	37.67	107.61	66.73	127.70	43.71	40.00
		M 3.1	13.71	6.18	240.79	121.20	1541.92	-1.93	92.72	47.37	111.92	71.04	119.89	35.90	20.00
		M 3.3	46.76	39.23	897.60	778.01	2516.00	972.15	315.10	269.75	223.60	182.72	104.70	20.70	Top

* parent material was not measured for this profile   *** weathering ratios taken from Maynard,J.B., 1992, Chemistry of Modern Soils as a Guide to Interpreting Precambrian Paleosols: The Journal of Geology, v. 100, p. 279-289. and Mason, J.A., and Jacobs, P.M., 1998, Chemical and particle-size evidence for addition of fine dust to soils of the midwestern United States: Geology, v. 26, p. 1135-1138.

** PM = average parent material; Top = top of paleosol; #'s refer to centimeters from top of paleosol