Paleocurrents of the Middle–Upper Jurassic strata in the Paradox Basin, Colorado, inferred from anisotropy of magnetic susceptibility (AMS)

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1. Synopsis

- The anisotropy of magnetic susceptibility (AMS) is a useful and rapid tool in studying syndepositional and post-depositional processes in sedimentary systems
- In general, the principal axes of the AMS ellipsoid correspond to the sedimentary petrofabric axes defined by the bedding plane and transport direction regardless of the tectonic setting
- Our original intention was to use the AMS technique to determine syndepositional paleocurrent directions from sedimentary rocks deposited in the Paradox Basin during the Middle-Late Jurassic. In contrast with many AMS studies in similar materials, our results show that the AMS of these rocks originates from mineral phases that precipitated from iron-rich fluids after deposition
- Our investigations also show that the AMS tracks diagenetic to post-diagenetic fluid migration pathways in highly permeable sedimentary units. This new aspect may have important implications for predicting fluid migration in reservoir rocks at the basinal and regional scale

2. Goals of Study

- Utilize anisotropy of magnetic susceptibility to constrain either syndepositional paleocurrents and early diagenetic fluid pathways in the Middle-Upper Jurassic strata in the Paradox Basin
- Evaluate the influence of mineralogy and lithological change on the origin and development of magnetic fabrics in eolian and lacustrine systems
- Assess the origin and significance of AMS in these sedimentary rocks

3. Tectonic Setting and Sedimentary Framework of Study Area

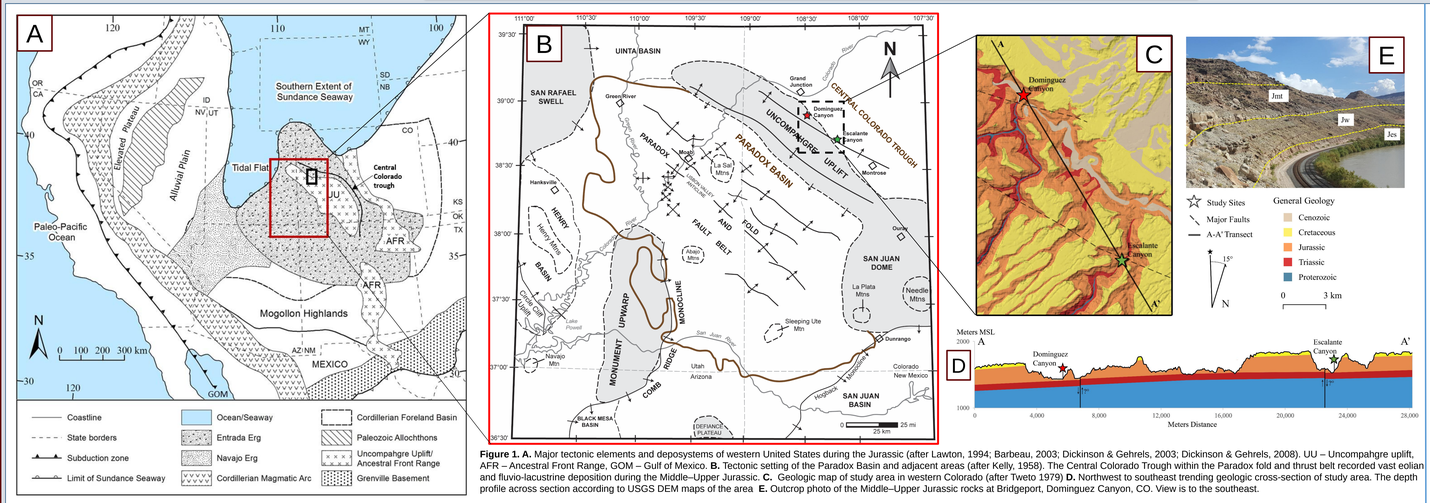

Figure 1. A. Major tectonic elements and deposystems of western United States during the Jurassic (after Lawton, 1994; Barbeau, 2003; Dickinson & Gehrels, 2003; Dickinson & Gehrels, 2008). UU – Uncompahgre uplift, AFR – Ancestral Front Range, GOM – Gulf of Mexico. **B.** Tectonic setting of the Paradox Basin and adjacent areas (after Kelly, 1958). The Central Colorado Trough within the Paradox fold and thrust belt recorded vast eolian and fluvio-lacustrine deposition during the Middle–Upper Jurassic. **C.** Geologic map of study area in western Colorado (after Tweto 1979) **D.** Northwest to southeast trending geologic cross-section of study area. The depth profile across section according to USGS DEM maps of the area **E.** Outcrop photo of the Middle–Upper Jurassic rocks at Bridgeport, Dominguez Canyon, CO. View is to the southeast.

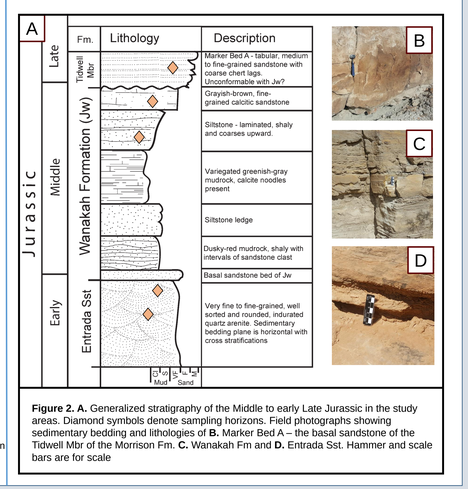

Figure 2. A. Generalized stratigraphy of the Middle to early Late Jurassic in the study areas. Diamond symbols denote sampling horizons. Field photographs showing sedimentary bedding and lithologies of **B.** Marker Bed A – the basal sandstone of the Tidwell Mbr of the Morrison Fm. **C.** Wanakah Fm and **D.** Entrada Sst. Hammer and scale bars are for scale

4. Methods and Principles of AMS

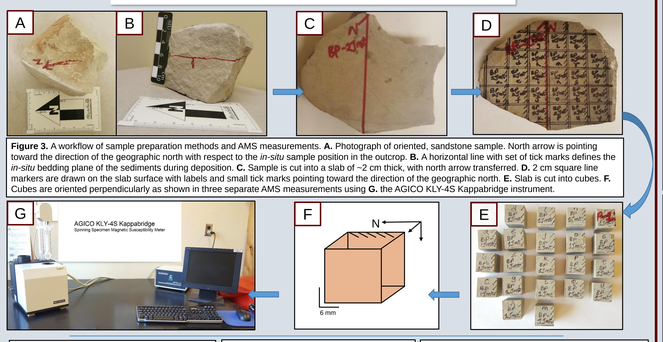

Figure 3. A workflow of sample preparation methods and AMS measurements. **A.** Photograph of oriented, sandstone sample. North arrow is pointing toward the direction of the geographic north with respect to the *in-situ* sample position in the outcrop. **B.** A horizontal line with set of tick marks defines the *in-situ* bedding plane of the sediments during deposition. **C.** Sample is cut into a slab of ~2 cm thick, with north arrow transferred. **D.** 2 cm square line markers are drawn on the slab surface with labels and small tick marks pointing toward the direction of the geographic north. **E.** Slab is cut into cubes. **F.** Cubes are oriented perpendicularly as shown in three separate AMS measurements using **G.** the AGICO KLY-4S Kappabridge instrument.

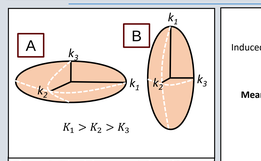

Figure 4. Tri-axial representation of the shapes of the AMS ellipsoid. **A.** Shape is oblate and depicts planar fabric. **B.** Shape is prolate and depicts linear fabric. The Shape factor, T describes the eccentricity of the AMS ellipsoid and are expressed in terms of foliation and lineation, respectively.

AMS Parameters

Induced magnetization, $\boldsymbol{J} \propto$ Mag. field, $\boldsymbol{H}$

$$\boldsymbol{J} = K\boldsymbol{H} \; ; \; \boldsymbol{K} = \frac{J}{H}$$

Mean Magnetic Susceptibility (K_m)

$$\boldsymbol{K_m} = \frac{K_1 + K_2 + K_3}{3}$$

Shape Factor (T)

$$Prolate = \frac{K_1}{K_2} ; Oblate = \frac{K_2}{K_3}$$

Degree of Magnetic Susceptibility (P')

$$\boldsymbol{P'} = \frac{K_1}{K_3}$$

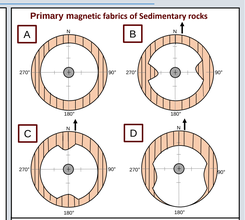

Figure 5. Depositional fabrics with zero flow on **A.** a horizontal plane and **B.** shallowly sloping plane. Horizontal plane deposition by **C.** a Weak current (<1 cm/s) and **D.** a strong current (>1 cm/s). The shaded, gray circle and hatched areas depict the orientations of the K_1 and K_3 axes, respectively. Arrow in **B** points to the slope direction while those in **C** and **D** indicate the flow directions. **Figure 5** is modified after Tarling and Hrouda, 1993.

5. Results

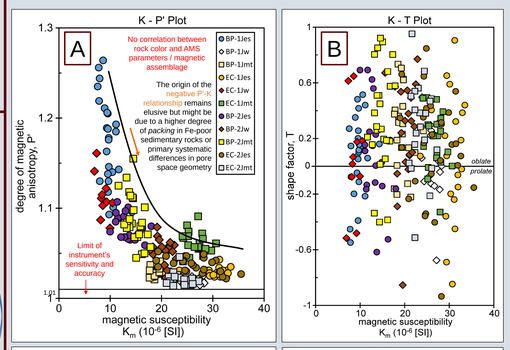

Figure 6. Composite plots of AMS Parameters of all the samples in both localities. **A.** Mean magnetic susceptibility vs. the degree of magnetic anisotropy. **B.** Mean magnetic susceptibility vs. the shape factor and **C.** The degree of magnetic anisotropy vs. the shape factor. **Fig. 6A** shows a negative correlation exist between the magnetic anisotropies and magnetic susceptibilities of all the samples. **Figs. 6B** and **C** show that the predominant AMS petrofabric of all the samples is planar, thus suggesting strong magnetic foliation (also shown in **Fig. 7**) over magnetic lineation.

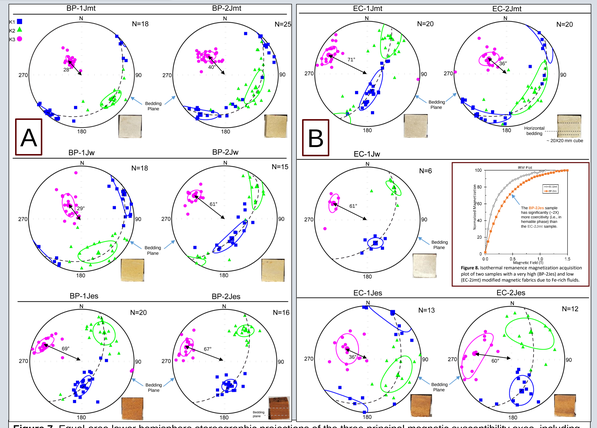

Figure 7. Equal-area lower hemisphere stereographic projections of the three principal magnetic susceptibility axes, including their 95% confidence ellipses around weighted averages derived using Jelinek statistics. Samples in **A** are from Bridgeport in Dominguez Canyon (red star) and **B** Escalante Canyon (green star) **in Fig. 1**. Samples are in stratigraphic order from oldest–youngest: Jes – Entrada sandstone; Jw – Wanakah Fm. and Jmt – Tidwell Mbr of the Morrison Fm. K_{max} in squares, triangles and K_{min} in circles. Dotted arc is the K_{max}–K_{int} plane which defines the magnetic foliation. K_{max} defines the magnetic lineation. The cubes show the *in-situ* horizontal bedding plane of the rocks. Rock samples from both localities do not record any form of strain markers or sediment deformation due to tectonic stresses. The tilt of the magnetic fabric (i.e., the K_{int} axis) from the sedimentary bedding pole is represented on the stereonets for each sample.

6. Discussion

The magnetic fabrics recorded in these sedimentary rocks show some interesting results which have implications on the nature of post-depositional alterations of sedimentary fabrics by diagenetic fluids:

- The rocks have distinct colors (i.e., red, tan and gray. Sample cubes in **Fig. 7A and B**). This suggests various degrees of diagenetic alteration from very high to very low iron solutions
- There is little variation in the mean magnetic susceptibility (ranges from $10 - 30 \times 10^{-6}$ SI) across the sample suites (**Figs. 6A and B**), and thus indicate that ferromagnetic phases (e.g., magnetite and titanomagnetite) are present only in small quantities. The presence of pyrrhotite is ruled out given that it is highly unstable in oxic to semi-oxic environments
- The degree of anisotropy shows an inverse correlation with magnetic susceptibility (**Fig. 6A**). The reason for this anomaly is unclear and is being investigated
- The magnetic fabrics of these rocks are consistent on two scales: on the outcrop scale (i.e., on samples from both localities) and in the measurement scale (i.e., results in **Fig. 7A** and **B**). This implies that the post-depositional alterations and diagenetic fluid pathways through these rocks are regional
- These rocks lack plastic deformation and the fact the fabrics are completely unrelated to the regional/local tectonic setting (**Fig. 1B**) suggests that the magnetic fabric is either syndepositional or diagenetic in origin
- The magnetic fabric is mostly planar (**Fig. 6**) with an average tilt of ~ 50° from the sedimentary pole toward the SE for both localities **(Fig. 7)**

7. Conclusions

- The AMS of sedimentary units in the Paradox Basin is not a depositional fabric
- The red color and magnetic properties of the sediments show that the AMS is controlled by post-depositional ferromagnetic *sensu lato* phases (i.e., magnetite and hematite)
- The AMS of the sedimentary units in the Paradox Basin tracks the migration of Fe-rich, post-depositional fluids that percolated through these formations.

8. Acknowledgements

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