Addressing the problem of inclination shallowing in paleomagnetism: A study of the Cut Face Creek Sandstone

James S Pierce[1]

[1] Department of Earth and Planetary Science, University of California, Berkeley, CA, USA

1 ABSTRACT

Inclination is the angle of a magnetic vector from horizontal generated by Earth's magnetic field, which is recorded by magnetic grains within rocks as they form. Clastic sedimentary rocks often suffer from inclination shallowing due to flattening of magnetic grains during deposition of compaction. This discordance is often referred to as "the inclination shallowing problem," and is problematic when determining paleolatitudes for plate reconstruction models. The Cut Face Creek Sandstone is unique as it is an interflow sediment within lava flows of the North Shore Volcanic Group (NSVG). We found the inclination of the characteristic remanence direction recorded by the Cut Face Creek Sandstone to be 29° compared to the expected inclination of 41.4° recorded by a thermal remanence magnetization of the NSVG volcanics. From this data we determined that a flattening factor of $f = 0.635^{+0.114}_{-0.089}$ should be applied to the Cut Face Creek Sandstone. We then derive a flattening factor of $f = 0.607^{+0.058}_{-0.051}$ by comparing two remanence directions of the Cut Face Creek Sandstone: the characteristic remanent magnetization which is shallowed and the secondary chemical remanent magnetization which was not shallowed. Finally, we applied the elongation/inclination (E/I) method to the directions of the Cut Face Creek Sandstone. The factor of $f = 0.685$ suggested by the E/I method fell within the error bounds of our empirically derived values, suggesting that the E/I method can accurately be applied to Mesoproterozoic rocks. Implementing an accurate method to correct for inclination shallowing will improve paleogeographic reconstructions during this period.

2 INTRODUCTION

Hematite bearing sedimentary rocks at earth's surface are widespread and serve as a vital resource for determining paleolatitudes of past continents. Unfortunately, the accuracy of paleomagnetic directions obtained from the detrital remanent magnetization (DRM) of sedimentary rocks have long been problematic due to the issue of inclination shallowing. The deposition and compaction of elongate particles, such as detrital hematite and magnetite, can result in paleomagnetic directions with inclinations that are biased shallow, relative to the local geomagnetic field in which they were acquired (Tauxe, 2005). The geocentric axial dipole (GAD) hypothesis states that the long-term average of the magnetic field is dipolar and that the geomagnetic and geographic poles overlap. This allows us to use the inclination formula, $\tan I = 2 \tan \phi$, to translate inclinations (I) into latitudes (ϕ) (Fig. 1). Shallower inclinations obtained from sedimentary rocks result in underestimates of paleolatitudes, biasing the interpreted position of past continents and hindering plate reconstructions (Domeier et al., 2012). Despite this challenge, the abundance and long-term magnetic and geochemical stability of hematite, makes hematite-bearing sediments a very important archive of information regarding paleogeography and Earth's ancient magnetic field.

An additional complication in hematite-bearing rocks ("red beds") is the presence of post-depositional hematite that carries a chemical remanent magnetization (CRM). This secondary hematite recorded the magnetic field when it crystallized, which could be soon after deposition or potentially long after lithification (Swanson-Hysell et al., 2019). Thus, it cannot be concluded with certainty that the secondary hematite represents the magnetic field at the time of deposition. While this secondary hematite can complicate the paleomagnetic signal of red beds, it can be isolated using thermal demagnetization, as the finer grained secondary hematite will unblock at lower temperatures than the coarser grained detrital particles (Tauxe et al., 1980; Swanson-Hysell et al., 2019). After removing this secondary component, the DRM will become apparent near the Neél Temperature of hematite (682°C), at temperatures of ∼665-680°C (Butler, 1992; Lu and Meng, 2010).

To elucidate factors that contribute to inclination shallowing of sedimentary rocks, King (1955) conducted laboratory redeposition experiments. King quantified the shallowing effect with the flattening function $\tan(I_o) = f\tan(I_f)$, where I_o represents the observed inclination of the specimen magnetization and I_f represents the inclination of the field in which the magnetization was acquired (Fig. 1). The flattening factor is represented by f, which ranges from 1 for no flattening to 0 for completely flattened. Major contributing processes to inclination shallowing include the initial settling of particles, compaction during lithification, as well as deposition on an inclined bedding plane. Additionally, the degree of flattening can be influenced by differences in sedimentary lithology (Bilardello and Kodama, 2010). King (1955) modeled sedimentation by artificially depositing varved "clay" sediments, consisting of unconsolidated glacial deposits from Sweden containing detrital magnetite, in a tank over a period of twenty-four hours to obtain a flattening factor of 0.4 (Griffiths et al., 1960). The mechanism for shallowing during the experiment was suggested to be the settling of elongate particles during deposition.

Correcting the effects of inclination shallowing is crucial for estimating the true inclination, and two classes of correction methods are used. The first class of methods involves investigating the magnetic fabrics of the sedimentary rocks of interest. Such an approach was pioneered in Jackson et al. (1991), where anhysteretic remanent magnetization (ARM) was used to determine the extent at which elongate particles lie horizontal during deposition. Implementation of this model depends on the amount remanent vectors are rotated towards the horizontal, while the ARM depends on the anisotropy of individual particles (Bilardello, 2016). A difficulty in applying this method to hematite-bearing sedimentary rocks is that both pigmentary hematite and detrital hematite contribute to the overall magnetic fabric. As a result more involved methods, such as a step-wise geothermal remanent magnetization (IRM), are necessary to isolate the anisotropy of the hematite carrying the detrital remanent magnetization (Bilardello, 2015).

The other primary method for correcting inclination shallowing is the elongation/inclination (E/I) method, presented in Tauxe and Kent (2004). The E/I method uses the TK03 model of paleosecular variation to predict the distribution and shape of paleomagnetic directions. For a given latitude, a distribution of paleomagnetic directions, which sample geomagnetic secular variation, will have a predictable shape. The magnitude of deviation of the observed directions from this predicted shape is used to determine a flattening factor. The E/I method requires a data set large enough to account for paleosecular variation (at least 100-150 samples), which at times is not available (Tauxe et al., 2008). Additionally, the E/I method depends on the the geomagnetic field model TK03, which uses data from lava flows throughout the last five million years compiled in Johnson and Constable (1996) to model paleosecular variation. Applying it to a different time period assumes the temporal variations of the past five millions are characteristic of the field through time.

In published literature, a typical flattening factor applied to inclination is between 0.4 and 0.6. In a survey of previously published works, Bilardello (2016) found the mean f factor used to be 0.65. Torsvik et al. (2012) presents a compilation of apparent polar wander paths that justifies applying a flattening factor of 0.6 to sedimentary units, as it is a commonly observed flattening factor in previous literature in published literature (Torsvik et al., 2012). The study lacks an empirical basis for this flattening factor. A study conducted by Kent and Olsen (2008) looks at the paleomagnetic directions measured from the Jurassic East Berlin, Shuttle Meadow, and Portland sedimentary formations and compares their inclinations to that of the coeval Central Atlantic Magmatic Province (CAMP). Kent and Olsen (2008) found the mean inclination of the Jurassic sedimentary units to be $22.2 \pm 3.7°$ from 71 sites while the inclination of the CAMP extrusives was determined to be $33.9 \pm 9°$ in Prévot and McWilliams (1989). The flattening factor recovered using the E/I method was $f = 0.54$.

In this study, we used the ca. 1093 Ma Cut Face Creek Sandstone to empirically constrain the degree of inclination shallowing while evaluating the application of the elongation/inclination method to Mesoproterozoic magnetizations. The Cut Face Creek Sandstone is a ∼95 meter thick interval of interflow sediments within lava flows of the North Shore Volcanic Group on the North Shore of Lake Superior (Fig. 2). Since the sandstone is bracketed by lava flows, the age and expected paleomagnetic direction is constrained by prior studies. Paleomagnetic data from the North Shore Volcanic Group lavas (Fig. 2), which do not suffer from inclination shallowing, were used to calculate an accurate paleomagnetic pole at the time of deposition of the Cut Face Creek Sandstone. The directions acquired from the Cut Face Creek specimens were then compared to that of the North Shore Volcanic Group to determine the amount of inclination shallowing that took place. Next, to determine whether the elongation/inclination method can be applied to ancient rocks, we applied the E/I method to the Cut Face Creek directions to obtain an "unflattened" paleomagnetic direction. This new direction was then compared to the direction of the North Shore Volcanic Group in order to determine the accuracy of the recovered paleomagnetic signal.

3 GEOLOGIC SETTING

The Midcontinent Rift is a protracted intracontinental rift punctuated by rapid and voluminous magmatism throughout its history. A result of extension and subsidence from ca. 1109 to 1084 Ma, the Mesoproterozoic Midcontinent Rift extends over 2,000 km Southwest from Lake Superior to central Kansas and southeast to central Michigan (Fig. 2). The ca. 1096 Ma Duluth Complex was a major geologic event that emplaced the intrusive rocks of the Duluth Complex, coeval with the eruption of associated 8 km of lava flows of the NSVG, outcropping today in northeastern Minnesota. Within the NSVG lies an interflow sedimentary unit called the Cut Face Sandstone (Swanson-Hysell et al., 2012). It is bracketed by the underlying Good Harbour Bay andesites and the overlying Terrace Point basalt (Fig. 2).

Most of the Midcontinent Rift System is overlain by Paleozoic sedimentary rocks with nearly all exposure occurring near Lake Superior (Fig. 2). The North Shore Volcanic Group (NSVG) sits stratigraphically atop the Duluth Complex and extends the length of Minnesota's north shore of Lake Superior from the city of Duluth to near the border with Canada. The NSVG is divided into the Southwest and Northeast Sequences with the Cut Face Creek Sandstone sitting within the volcanics of the Upper Northeast Sequence. The 95 meter thick Good Harbor Bay andesites sit beneath the Cut Face Creek Sandstone, while the 50 meter thick Terrace Point Basalt erupted on top of the sandstone (Fig. 3; Fig. 4). Beneath the Good Harbor Bay andesites sits the 122 meter thick Breakwater basalt which is exposed along a roadcut to the northeast of Cut Face Creek (Green, 1989, 1979). The Breakwater basalt contacts the top of the Grand Marais Rhyolite, which has a Uranium-Lead (CA-ID-TIMS) date of 1093.52 $\pm$ 0.43 Ma (Swanson-Hysell et al., 2019) and serves as a maximum age for the deposition of Cut Face Creek Sandstone. An aplite intrusion within the Silver Bay intrusions of the Beaver Bay Complex which cross cuts the North Shore Volcanic Group, has a date of 1091.61 $\pm$ 0.14 Ma (Swanson-Hysell et al., 2019). This date serves as the upper age limit. Using data from Books (1972) and Tauxe and Kodama (2009), a paleomagnetic pole has been developed from twenty-eight sites throughout the upper Northeast sequence of the North Shore Volcanic Group (location of sites shown in Fig. 2)(Swanson-Hysell et al., 2019). The pole for the upper Northeast sequence of the North Shore Volcanic Group has a latitude of 31.1°N and a longitude of 181.7°E. This correlates to an inclination direction of 41.4° and a dip direction of 290.7°, which were used as the expected paleomagnetic directions from the Cut Face Creek sandstone.

4 CUT FACE CREEK SANDSTONE SEDIMENTOLOGY

Driving along Minnesota Highway 61, at Good Harbor Bay, eight kilometers to the southwest of Grand Marais, the Cut Face Creek Sandstone is a prominent roadcut with a striking deep red color and juxtaposition with the overlying Terrace Point Basalt (Fig. 4E and F). The depositional environment of this ~95 meter thick sedimentary unit has been interpreted to be a part of a fluvial-lacustrine system, likely a braided stream (Jirsa, 1984). The finer grained siltstone layers are likely overbank, or flood plain, deposits. Jirsa (1984) suggests the source of sediment to be almost entirely the rocks of the local North Shore Volcanic Group. Desiccation cracks throughout indicate periodic subaerial exposure as stream channels migrated and ponds dried up (Fig. 4A and B). Stream channels occur throughout and consist of fine to medium sands while the presence of laminated sand and mudstone indicates frequent overbank flooding, typical of a braided stream or ponding fluvial system (Mitchell and Sheldon, 2009).

The Cut Face Creek Sandstone is a 95 meter-thick sedimentary unit (Fig. 3) deposited atop the vesiculated flow top of the uppermost lava flow of the Good Harbor Bay andesites (Fig. 3; Fig. 2). The interflow sediments are overlain by the Terrace Point Basalt and underwent soft sediment deformation from the lava flow (Fig. 4). The Cut Face Creek Sandstone has a dip direction of 166.5° and dip of 10.0° to the southeast. The structural orientation stays consistent throughout the unit and the uncertainty on the bedding pole position is 0.74° based on 44 measurements. The section is not disrupted by significant deformation or major faulting. The stratigraphy was measured at a decimeter scale, noting all sedimentary structures throughout as well as thickness of bedding and grain size (Fig. 3).

The Good Harbor Bay andesites are fine-grained, greenish-grey, volcanic rocks that become increasingly vesicular up to the flow top that is overlain by the Cut Face Creek Sandstone. The basal contact of the andesites with the Cut Face Creek Sandstone can be found by walking ∼160 meters northwest upstream from Highway 61. The lowermost meter of the Cut Face Creek Sandstone is a pebble conglomerate with some mud-cracked silty laminations. This conglomerate is followed by ∼10 meters of medium to fine-grained lithic arkose that generally fines upwards. The next ∼32 meters dominantly consists of very fine to fine-grained sandstone, often containing asymmetric current ripples (Fig. 4C). Some horizons of shale to siltstone contain mud cracks, indicating an interval of subaerial deposition. Rip-up clasts of siltstone layers are frequently incorporated into overlying sandstone layers. Thin (∼1.5 cm thick) reworked volcanic ashes are found between 34.0 to 34.7 meters. Starting at 47.2 meters, is a 25 meter interval of predominantly siltstone to very-fine sandstone with minor fine to medium sandstone interbedded with ripple cross-stratification that can be channelized and contain siltstone rip-up clasts. The siltstone is often mudcracked and can be disrupted by fluid escape structures. The remaining 27.1 meters coarsens upwards from ∼30% siltstone to well-lithified medium and fine sandstone layers. Flame structures common throughout the top section (Fig. 4E) with some cross-bedding. The uppermost five meters includes light tan colored horizons (Fig. 4B) that are likely products of reduction from fluid intrusion and effects of the eruption of the massive dark grey and black Terrace Point Basalt. The top 1.1 meters consists of baked siltstone with mudcracks and slaty cleavage. The contact with between the Cut Face Creek Sandstone and the Terrace Point has undergone soft sediment deformation as the basalt erupted onto the sediments, “bulldozing” them significantly (Fig 4F).

5 METHODS AND RESULTS

The Cut Face Creek Sandstone was sampled every ∼40 centimeters of stratigraphic height. A total of 186 standard paleomagnetic core samples were collected and spatially oriented using a Pomeroy device along with a magnetic and sun compass. Sun compass data were preferentially used to determine orientation when available. Fine-grained siltstone layers were preferentially sampled as they have low permeability, thus are less susceptible to reductive dissolution than the coarser grained sandstone. Additionally, deposition in a a non-turbulent environment in which particle flux is low, increases the likelihood that a particle will acquire a DRM (Tauxe and Kent, 1984). Thus sampling in finer-grained lithologies was favored over coarser-grained lithologies interpreted to have been deposited in a high energy environment. Care was also taken to avoid samples containing randomly oriented rip-up clasts from underlying strata. Once transported back to the lab, the samples were cut and sanded to produce oriented cylindrical specimens that are ~2.5 cm in diameter and range in height between 0.9 and 2.6 cm. Many of the samples needed to be glued together using non-magnetic sodium silicate, as the samples tended to break along the very finely laminated bedding planes. Gluing was done inside the magnetically shielded room at the Berkeley Paleomagnetism Lab.

Samples were measured at the Berkeley Paleomagnetism Lab on a 2G DC-SQUID magnetometer. High-resolution thermal demagnetization was used to isolate the characteristic component of hematite. A total of thirty-one temperature steps were measured, ranging from 0°C (i.e. the NRM) to 687°C, with finer steps approaching the Neél Temperature of hematite, with the final measurements being 2°C apart. Implementing precise thermal demagnetization steps allowed us to differentiate detrital hematite from secondary hematite based on unblocking spectra (Swanson-Hysell et al., 2019). After measuring the samples, least squares regression lines were fit to data from each sample. Most samples exhibited three distinct components: a low temperature component ranging from 0°to 200°C, a mid temperature component, typically ranging from 450°C to 600°C, and a high temperature component ranging from 650°to 687°C. Of the 186 samples taken of the Cut Face Creek sandstone, a high temperature component was resolved in 152 specimens, while a mid temperature component was resolved in 160 specimens, and a low temperature component in 113 specimens.

Fisher means were calculated using the interpreted paleomagnetic vectors to establish a mean site direction that incorporates data from all specimens. The mean low temperature vector was found to have a declination of 359.3° and an inclination of 67.42° with an α_{95} of 1.949 and k value of 47.43. This direction is present in most samples and matches the direction of the International

Geomagnetic Reference Field (IGRF) for Cut Face Creek (357.5°/73.0°) (Fig. 7). This suggests that the low temperature direction represents present local field viscous overprint. The direction of the present local field was typically removed after heating to ~ 100°C (Fig. 6). The the mean mid temperature vector ($n = 160$) has a declination of 287.2°and inclination of 41.6°with an α_{95} of 1.516 and a k value of 55.00. This direction is indistinguishable from the NSVG direction of 290.7°/41.4° which suggests that this mid temperature CRM was acquired shortly after deposition and does not suffer from inclination shallowing. The low-temperature component and the mid-temperature component were frequently observed to have overlapping unblocking temperature spectra between 100°C and 200°C (Fig. 6). The mean high temperature vector was determined to have a declination of 287.2° and an inclination of 29.01° with an α_{95} of 1.776 and k value of 42.45. This high temperature component matches the thermal spectrum of coarse grained hematite and is interpreted to be the characteristic remanent magnetism held by detrital hematite (Swanson-Hysell et al., 2019). When elemental analysis was conducted using backscattered electrons (BSE) on a scanning electron microscope (SEM), detrital hematite was observed to be common throughout the sandstone (Fig. 5). This high temperature direction suffers from inclination shallowing relative to the coeval NSVG volcanics and mid temperature component of the Cut Face Creek Sandstone.

Additionally, a relationship was found between grain size and the extent of inclination shallowing (Fig. 8). Using a grain size card and hand lens, all samples were assigned a dominant grain size by percentage, as well as a secondary grain size and examined for the presence of rip up clasts. Samples were then filtered by grain size into three categories consisting of 56 silt and clay size particles, 41 very fine sand, and 55 fine and medium sand. The silt and clay samples had a mean inclination of 25.4°, the very fine sand samples had a mean inclination of 29.6°, and the fine and medium grained samples had a mean inclination of 32.2°. The $\alpha 95$ ellipses of the silt and clay samples and the fine and medium grained sand samples are not overlapping, indicating these differences in inclination are significant. However, when taken by grain size, each sample set was not large enough to determine flattening factors with reasonable error bounds or draw conclusions based on grain size.

6 DISCUSSION

A systematic approach was taken to empirically derive an accurate flattening factor for the Cut Face Creek Sandstone. Flattening factors ranging from 0.5 to 0.8 were applied to the individual specimen directions with a with an interval of 0.001. This resulted in a newly unflattened data set for each flattening factor. A Watson common mean test was then conducted between each of the newly unflattened data sets and the NSVG volcanics directions. The Watson common Mean test uses a Monte Carlo simulation with 5000 simulations assigned to each interval. To pass a Watson common mean test, the angle between the two sets must be below a critical angle determined by the amount of deviation within data sets. Flattening factors that passed the test between the Cut Face Creek sandstone high temperature component and the NSVG volcanics, were between 0.546 and 0.749. The smallest angle between data set means was 3.138° which corresponds to a flattening factor of 0.635.

A Watson common mean test was conducted between the NSVG and mid temperature component of the Cut Face Creek data sets. The data sets were shown to pass the common mean test, with an angle between the data set means of 3.4°. The mid temperature component of the Cut Face Creek Sandstone specimens was typically seen in the range of 400°C to 620°C, consistent with the unblocking temperature of pigmentary hematite (Swanson-Hysell et al., 2019). Pigmentary hematite does not suffer from inclination shallowing as does detrital hematite. Given the similarity between the mean paleomagnetic direction of the mid temperature component of the Cut Face Creek Sandstone and the the direction of the upper northeast NSVG sequence, it is reasonable to conclude that the direction obtained from the mid temperature chemical remanent magnetization of the Cut Face Creek Sandstone represents the magnetic field during, or shortly after deposition. This suggests that the mid temperature component may be used as an analogue for the direction of NSVG volcanics. Using the directions acquired from the mid temperature component has the benefit of being a more robust data set than the NSVG volcanics and will generate less error when determining a flattening factor. The process used to derive an f factor by comparison to the NSVG data was repeated using the mid temperature directions in place of the NSVG volcanics directions. The smallest angle between the data set means was 0.0249°, which correlates to an f factor of 0.607. The range of factors to pass a Watson common mean test was from 0.556 to 0.665, which is a smaller range than that derived from the NSVG directions.

The value of $f = 0.607^{+0.058}_{-0.051}$ derived using the mid temperature Cut Face Creek Sandstone data is similar to the flattening facotr of $f = 0.6$ applied to clastic sedimentary rocks in Torsvik et al. (2012) and justifies its application to similar hematite bearing lithologies. Bilardello (2016) presented a compilation of flattening factors with a mean value of $f = 0.65$ although the data is skewed towards smaller factors and has a mode of $f = 0.49$. Our empirically determined values of $f = 0.607$ and $f = 0.635$ generally supports factors presented in this compilation with the exception of values below $f = 0.546$ or above $f = 0.749$.

A third flattening factor was determined by implementing the elongation/inclination method. The elongation parameter was found to be 1.995 with a suggested flattening factor of 0.685 (Fig. 10). This correlates to a mean inclination correction of 29.0° to 38.5°, with 95% confidence bounds from 32.0° to 44.2°. The data set unflattened empirically using the NSVG volcanics translates to an inclination of 40.4°, while the inclination determined using the mid temperature component translates to an inclination of 41.6°. Both of these inclinations fall well within the bounds calculated using the E/I method and all pass a Watson common mean test against each other. This supports the application of the E/I method to Mesoproterozoic rocks where a sufficient data set is provided.

7 CONCLUSION

The Cut Face Creek Sandstone provided a natural experiment where the expected paleomagnetic direction was provided by the NSVG and a flattening factor of the sedimentary unit could be empirically determined. From the samples taken at Cut Face Creek, a mean high temperature vector held by detrital hematite was determined with a declination of 287.2° and an inclination of 29.01°. These high temperature directions were compared with those from the NSVG volcanics to estimate a flattening factor of $0.637^{+0.126}_{-0.096}$ (Fig. 11). The mid temperature CRM held by the Cut Face Creek Sandstone was acquired shortly after deposition and is analogous to the NSVG direction. This enabled us to use these mid temperature directions to derive a flattening factor of

$f = 0.607^{+0.058}_{-0.051}$ (Fig. 11). The elongation/inclination method was then implemented using the uncorrected directions from the Cut Face Creek Sandstone. The E/I method provided a flattening factor of $f = 0.685$ which falls within the confidence interval of the empirically determined values (Fig. 11). This suggests that the E/I method is valid when applied to Mesoproterozoic rocks, given a sufficient sample size ($n = 100$–150). The empirically derived flattening factor of $f = 0.607$ also supports the use of $f = 0.6$ in previously published literature.

8 Acknowledgements

Support for this research came from the UC Berkeley Summer Undergraduate Research Fellowship as well as by a research grant from the Ramdsen Fund. This work was motivated by and done under the guidance of Professor Nicholas Swanson-Hysell and measurements conducted at the UC Berkeley Paleomagnetism Lab. Maggie Avery and Yiming Zhang provided manuscript edits. Yiming Zhang, Blake Hodgin, Nicholas Swanson-Hysell, Sarah Swanson-Hysell, and Madeline Swanson-Hysell provided field assistance.

References

Bilardello, D., 2015, Isolating the anisotropy of the characteristic remanence-carrying hematite grains: a first multispecimen approach: Geophysical Journal International, vol. 202, pp. 695–712, doi:10.1093/gji/ggv171.

Bilardello, D., 2016, The do's and don'ts of inclination shallowing corrections: The IRM Quarterly, vol. 26, p. 12.

Bilardello, D. and Kodama, K. P., 2010, A new inclination shallowing correction of the Mauch Chunk Formation of Pennsylvania, based on high-field AIR results: Implications for the Carboniferous North American APW path and Pangea reconstructions: Earth and Planetary Science Letters, vol. 299, pp. 218–227, doi:10.1016/j.epsl.2010.09.002.

Books, K., 1972, Paleomagnetism of Some Lake Superior Keweenawan Rocks: Geological Survey Professional Paper 760.

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

Domeier, M., Van der Voo, R., and Torsvik, T. H., 2012, Paleomagnetism and Pangea: The road to reconciliation: Tectonophysics, vol. 514-517, pp. 14–43, doi:10.1016/j.tecto.2011.10.021.

Green, J. C., 1979, Field Trip Guidebook for the Keweenawan (Upper Cambrian) North Shore Volcanic Group, Minnesota.pdf: Minnesota Geological Survey, University of Minnesota, St. Paul, Minnesota 55108, Guidebook Series No. 11.

Green, J. C., 1989, Physical volcanology of mid-Proterozoic plateau lavas: The Keweenawan North Shore volcanic group, Minnesota: Geological Society of America Bulletin, vol. 101, pp. 486–500, publisher: Geological Society of America.

Griffiths, D. H., King, R. F., Rees, A. I., Wright, A. E., and Shotton, F. W., 1960, The remanent magnetism of some recent varved sediments: Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, vol. 256, pp. 359–383, doi:10.1098/rspa.1960.0113, publisher: Royal Society.

Jackson, M. J., Banerjee, S. K., Marvin, J. A., Lu, R., and Gruber, W., 1991, Detrital Remanence, Inclination Errors, and Anhysteretic Remanence Anisotropy: Quantitative Model and Experimental Results: Geophysical Journal International, vol. 104, pp. 95–103, doi:https://doi.org/10.1111/j.1365-246X.1991.tb02496.x.

Jirsa, M. A., 1984, Interflow Sedimentary Rocks in the Keweenawan North Shore Volcanic Group, Northeastern Minnesota: Minnesota Geological Survey, p. 28.

Johnson, C. L. and Constable, C. G., 1996, Palaeosecular variation recorded by lava flows over the past five million years: Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, vol. 354, pp. 89–141, doi:10.1098/rsta.1996.0004, publisher: Royal Society.

Kent, D. V. and Olsen, P. E., 2008, Early Jurassic magnetostratigraphy and paleolatitudes from the Hartford continental rift basin (eastern North America): Testing for polarity bias and abrupt polar wander in association with the central Atlantic magmatic province: Journal of Geophysical Research: Solid Earth, vol. 113, doi:doi.org/10.1029/2007JB005407.

King, R. F., 1955, The Remanent Magnetism of Artificially Deposited Sediments: Geophysical Supplements to the Monthly Notices of the Royal Astronomical Society, vol. 7, pp. 115–134, doi:10.1111/j.1365-246X.1955.tb06558.x.

Lu, H. M. and Meng, X. K., 2010, Morin Temperature and Néel Temperature of Hematite Nanocrystals: The Journal of Physical Chemistry C, vol. 114, pp. 21,291–21,295, doi:10.1021/jp108703b, publisher: American Chemical Society.

Mitchell, R. and Sheldon, N., 2009, Weathering and paleosol formation in the 1.1Ga Keweenawan Rift: Precambrian Research, vol. 168, pp. 271–283, doi:10.1016/j.precamres.2008.09.013.

Prévot, M. and McWilliams, M., 1989, Paleomagnetic correlation of Newark Supergroup volcanics: Geology, vol. 17, pp. 1007–1010, doi:10.1130/0091-7613(1989)017¡1007:PCONSV¿2.3.CO;2.

Swanson-Hysell, N. L., Maloof, A. C., Kirschvink, J. L., Evans, D. A., Halverson, G. P., and Hurtgen, M. T., 2012, Constraints on Neoproterozoic paleogeography and Paleozoic orogenesis from paleomagnetic records of the Bitter Springs Formation, Amadeus Basin, central Australia: American Journal of Science, vol. 312, pp. 817–884, publisher: American Journal of Science.

Swanson-Hysell, N. L., Ramezani, J., Fairchild, L. M., and Rose, I. R., 2019, Failed rifting and fast drifting: Midcontinent Rift development, Laurentia's rapid motion and the driver of Grenvillian orogenesis: GSA Bulletin, vol. 131, pp. 913–940, doi:10.1130/B31944.1.

Swanson-Hysell, N. L., Fairchild, L. M., and Slotznick, S. P., 2019, Primary and Secondary Red Bed Magnetization Constrained by Fluvial Intraclasts: Journal of Geophysical Research: Solid Earth, vol. 124, pp. 4276–4289, doi:10.1029/2018JB017067.

Tauxe, L., 2005, Inclination flattening and the geocentric axial dipole hypothesis: Earth and Planetary Science Letters, vol. 233, pp. 247–261, doi:10.1016/j.epsl.2005.01.027.

Tauxe, L. and Kent, D. V., 1984, Properties of a detrital remanence carried by haematite from study of modern river deposits and laboratory redeposition experiments: Geophysical Journal International, vol. 76, pp. 543–561, doi:10.1111/j.1365-246X.1984.tb01909.x.

Tauxe, L. and Kent, D. V., 2004, A Simplified Statistical Model for the Geomagnetic Field and the Detection of Shallow Bias in Paleomagnetic Inclinations: was the Ancient Magnetic Field Dipolar?: *In* Channell, J., Kent, D., Lowrie, W., and Meert, J., eds., Geophysical Monograph Series, American Geophysical Union, Washington, D. C., pp. 101–115, doi:10.1029/145GM08.

Tauxe, L., Kent, D. V., and Opdyke, N. D., 1980, Magnetic components contributing to the NRM of Middle Siwalik red beds: Earth and Planetary Science Letters, vol. 47, pp. 279–284, doi:10.1016/0012-821X(80)90044-8.

Tauxe, L. and Kodama, K. P., 2009, Paleosecular variation models for ancient times: Clues from Keweenawan lava flows: Physics of the Earth and Planetary Interiors, vol. 177, pp. 31–45, doi:10.1016/j.pepi.2009.07.006.

Tauxe, L., Kodama, K. P., and Kent, D. V., 2008, Testing corrections for paleomagnetic inclination error in sedimentary rocks: A comparative approach: Physics of the Earth and Planetary Interiors, vol. 169, pp. 152–165, doi:10.1016/j.pepi.2008.05.006.

Torsvik, T. H., Van der Voo, R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P. V., van Hinsbergen, D. J. J., Domeier, M., Gaina, C., Tohver, E., Meert, J. G., McCausland, P. J. A., and Cocks, L. R. M., 2012, Phanerozoic polar wander, palaeogeography and dynamics: Earth-Science Reviews, vol. 114, pp. 325–368, doi:10.1016/j.earscirev.2012.06.007.

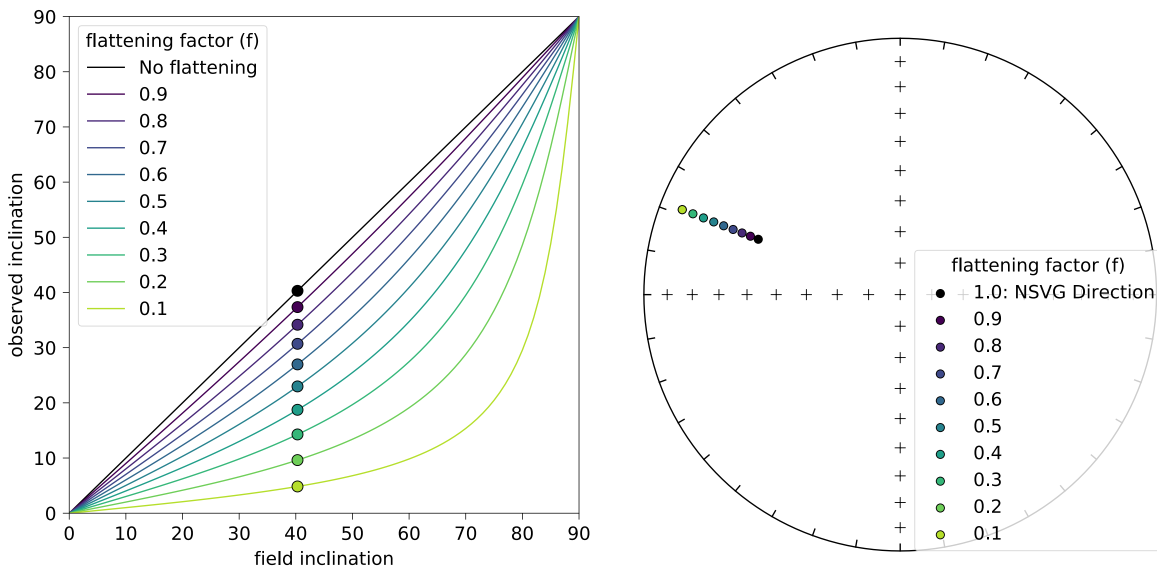

Figure 1. Left panel: the relationship between the inclination of local magnetic field is plotted on the horizontal axis against the observed inclination on the vertical axis. The curved lines show the inclination of sedimentary rocks plotted as lines for different flattening factors (f). The dots show the expected inclination for the Cut Face Creek Sandstone that would result from the first f values. Right panel: a stereonet with the paleomagnetic direction of the North Shore Volcanic Group lavas (declination of 291° and inclination of 40°) and the direction that would result from different flattening factors.

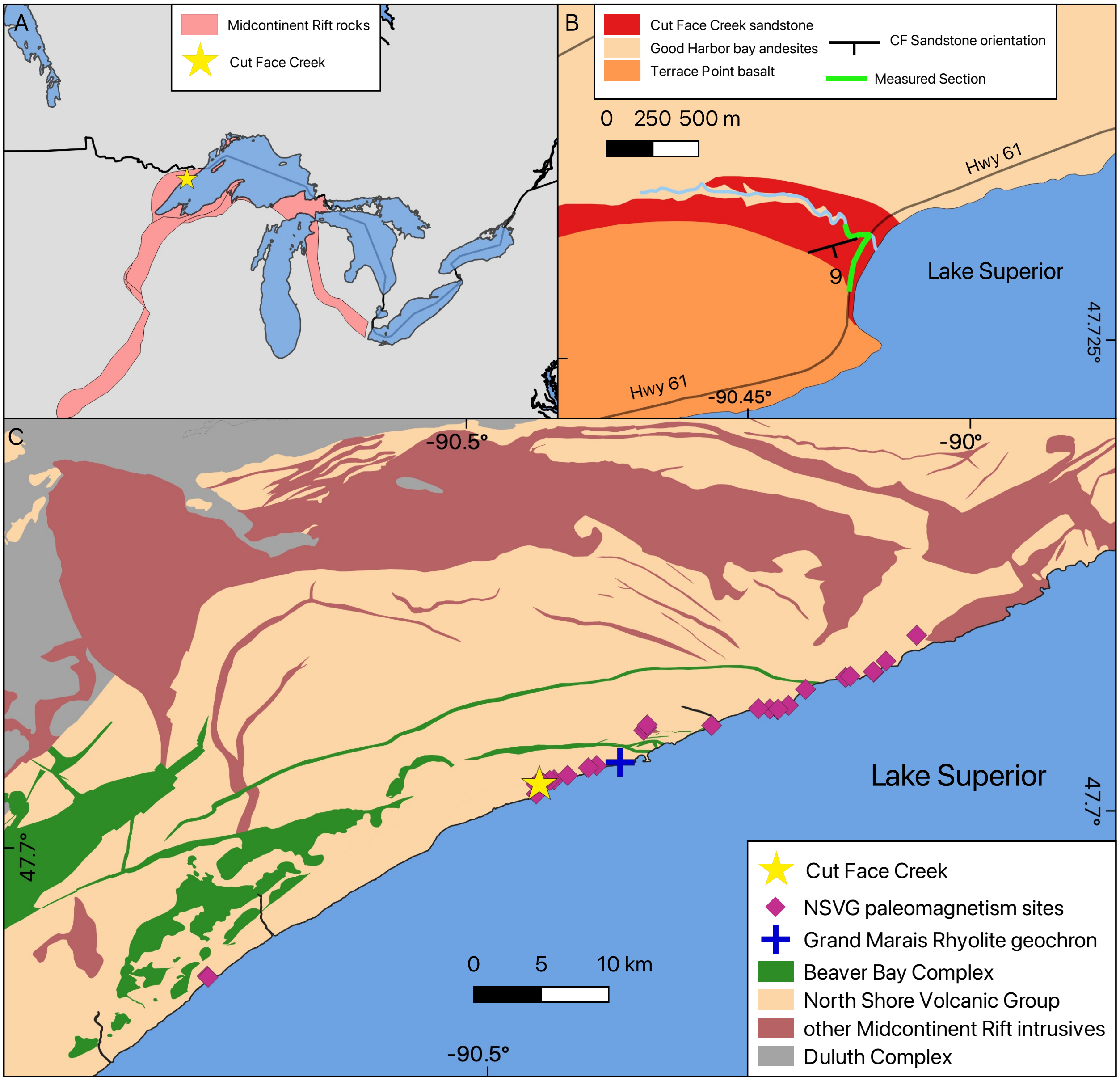

Figure 2. C) A) A map showing the location of the Cut Face Creek Sandstone (yellow star) within the rocks of the Midcontinent Rift (pink). Cut Face Creek Sits on the north shore of Lake Superior. B) A map showing the relative location of the geologic units adjacent to the Cut Face Creek Sandstone used to calculate the expected paleomagnetic direction. The younger Good Harbor Bay andesite sits beneath the sandstone while the Terrace Point basalt overlays the sandstone. The green line indicates the route taken during sampling.C) A map of Minnesota geology on the north shore of Lake Superior showing the location of the Cut Face Creek Sandstone (yellow star) within the North Shore Volcanic Group (green). CA-ID-TIMS $^{206}Pb/^{238}U$ ages obtained from Swanson-Hysell (2019) constrain the Cut Face Creek Sandstone to be younger than the the 1093.52 $\pm$ 0.43 Ma Grand Marais Rhyolite (NSVG-Upper NE Sequence), and older than the 1091.61 Ma $\pm$ 0.14 Ma cross-cutting Beaver Bay Complex.

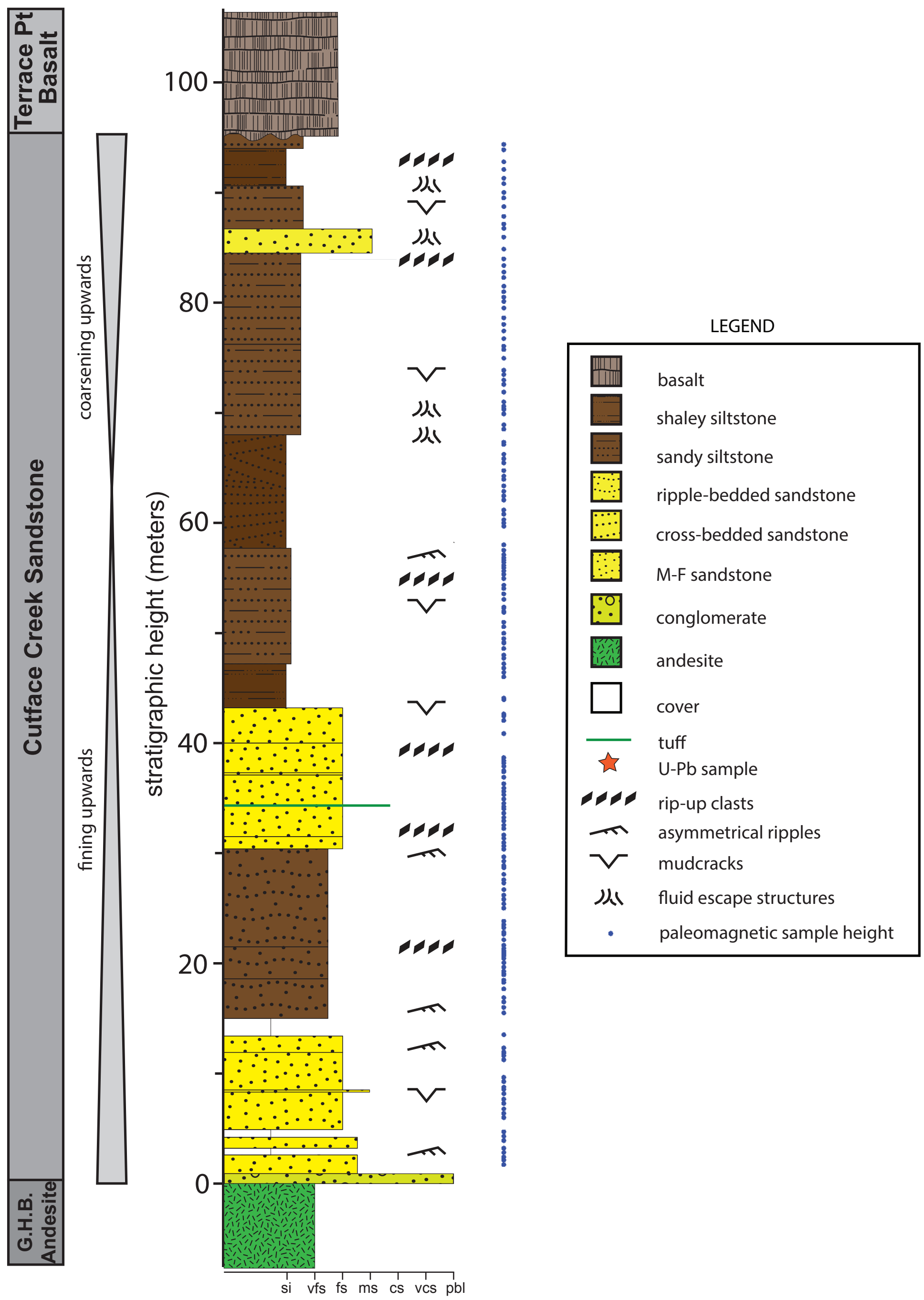

Figure 3. Stratigraphic column of the 95.1 meter thick Cut Face Creek Sandstone as exposed along Cut Face Creek and Hwy 61 (Fig. 2). The Cut Face Creek Sandstone is bracketed by the Good Harbor Andesite in green and the Terrace Creek Basalt in grey, both of which are part of the North Shore Volcanic Group. The Cut Face Creek Sandstone has a one meter thick basal layer of pebble conglomerate, then generally fines upwards to about 68 meters. The top of the unit consists primarily of sandy siltstone, which is characterized by siltstone with thin sandstone interbeds. The contact with the Terrace Point Basalt is marked by soft sediment deformation.

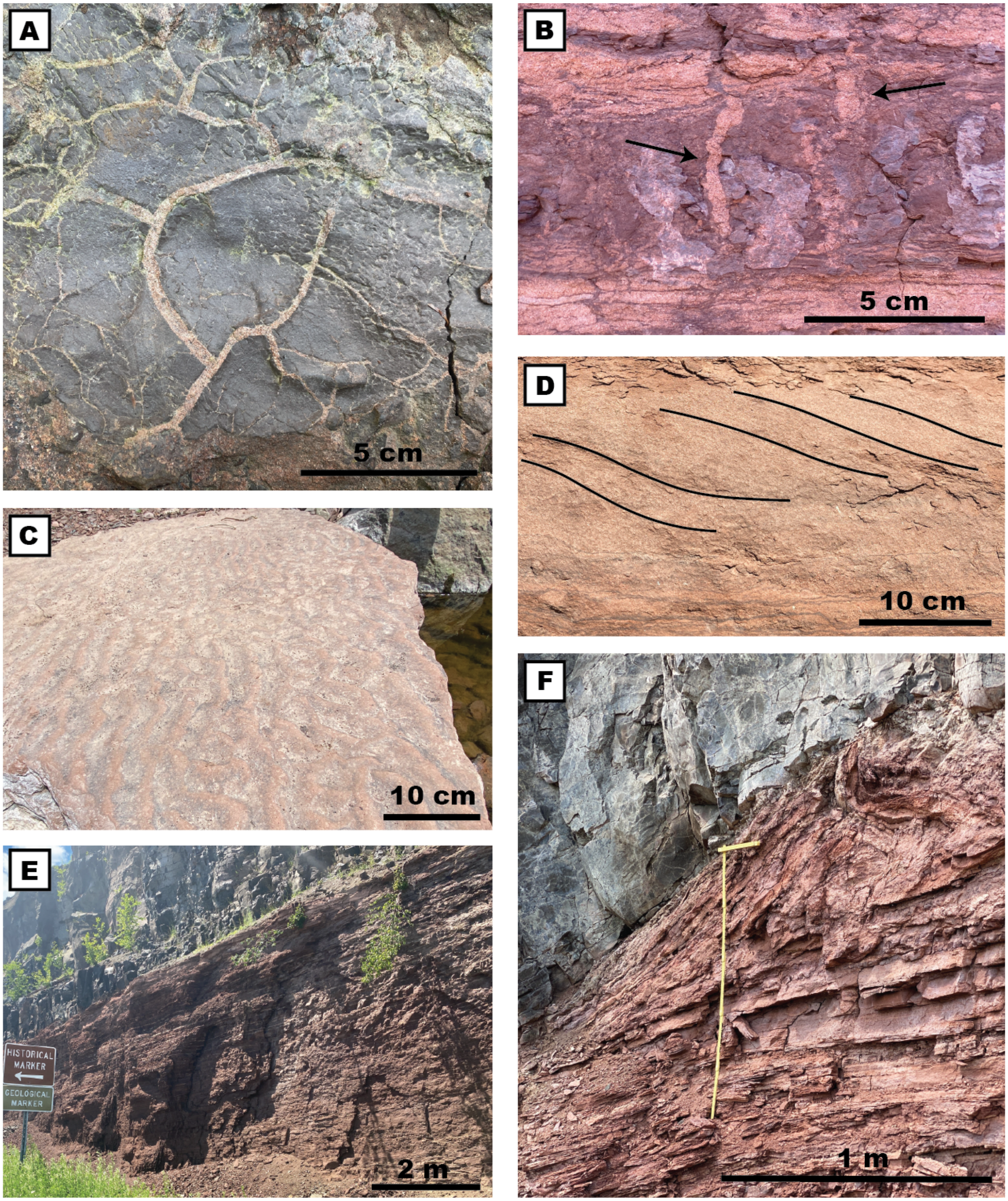

Figure 4. A) Meter level 0 to 1 of the section in Fig. 3 which is exposed along Cut Face Creek. The picture shows well defined mudcracks that overlay pebble conglomerate. B) The picture shows a cross section view of mudcracks in the darker colored siltstone layer. Arrows point to where the mudcracks were filled in by the coarser grained sandstone that was deposited atop. C) The picture shows a large out of place block with well-developed asymmetric ripples. D) A relatively thick sandstone layer with dune-scale ripples. Lines are drawn to accent the progression of ripples. E) The picture shows the top 8 meters of the Cut Face Creek Sandstone and the contact with the Terrace Point Basalt. F) The upper contact of the Cut Face Creek sandstone showing significant soft sediment deformation.

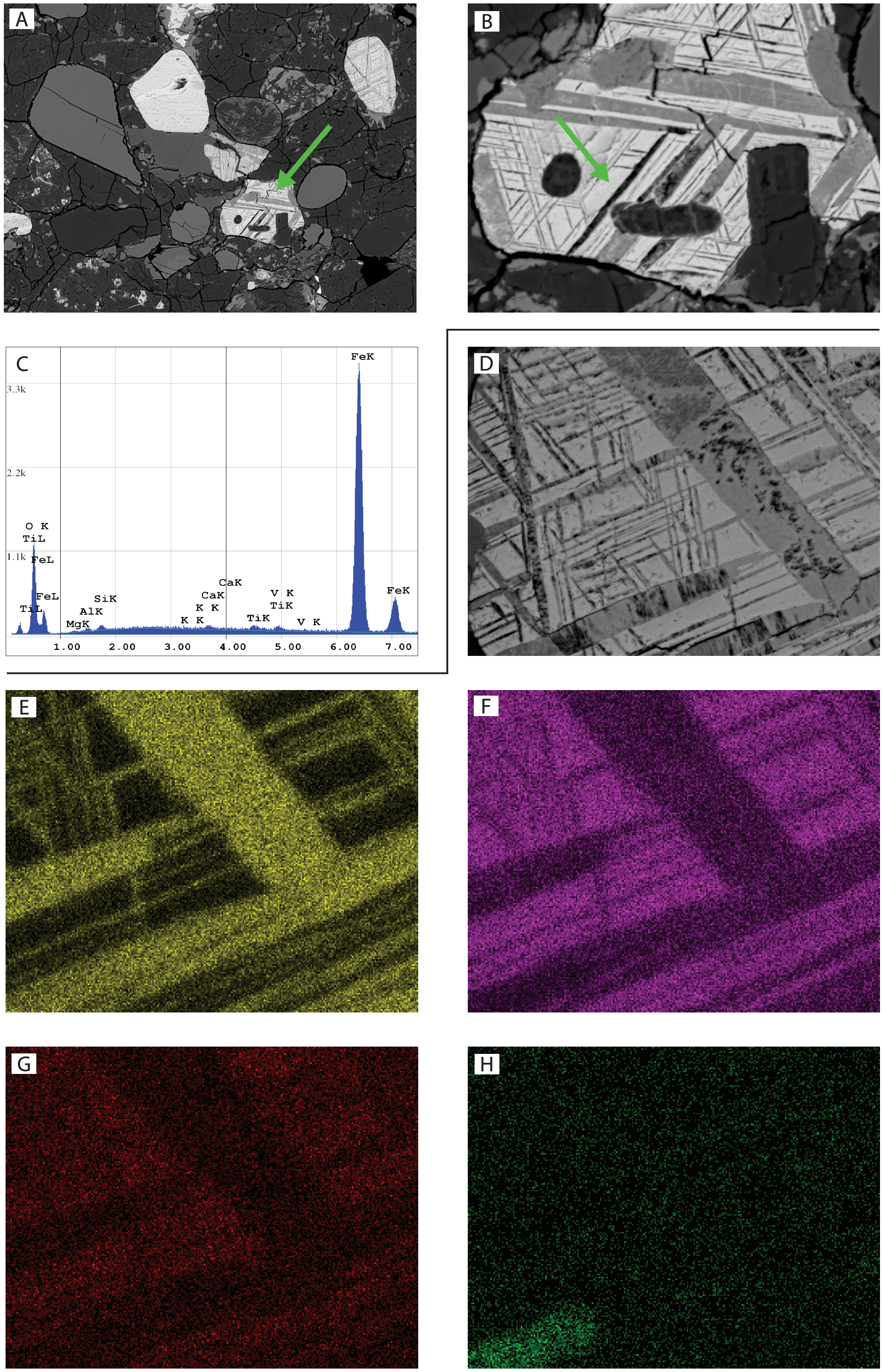

Figure 5. A and B are backscatter scanning electron microscope images of a detrital hematite (lighter color) clast at 521x and 2,5300x respectively. C is the corresponding elemental analysis dominated by iron (40.6%) and oxygen(55.6%). Another hematite clast image is shown in D and corresponding element map in E through H. Yellow is titanium, pink is iron, red is oxygen, and green is silicon

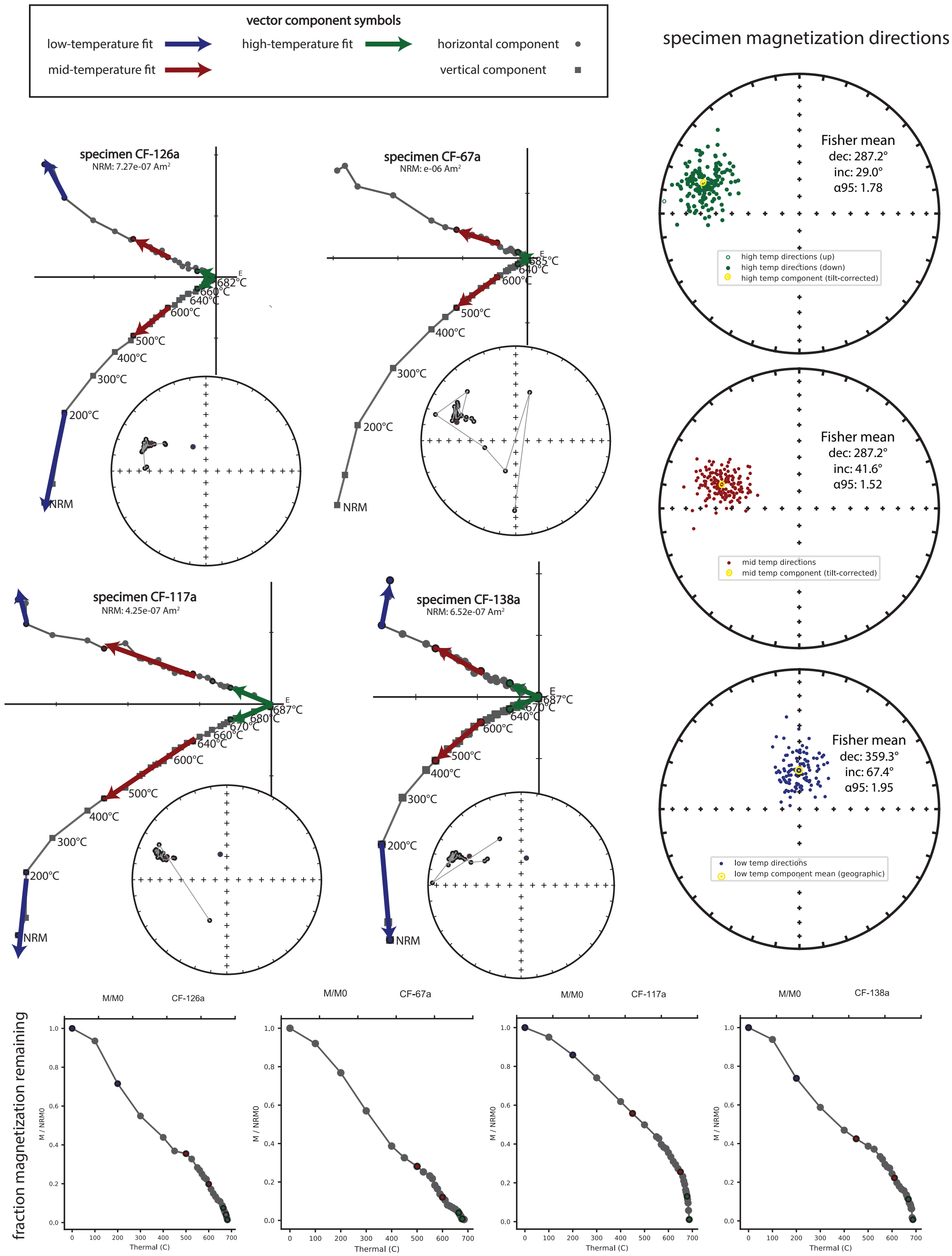

Figure 6. The figure shows the results of thermally demagnetizing 186 specimens from the Cut Face Creek sandstone. The stereonets on the top right show the directions that were able to be recovered from all specimens. Specimens consistently showed influence of the present local field (blue), a mid temperature component (red) interpreted to be a chemical remanent magnetization, and a high temperature componenet (green) which represents the detrital remanent magnetization. The Zijderveld plots on the top left show four specimens showing typical bahavior of the measured specimens. The plots at the bottom show the amount of magnetization remaining after each heating.

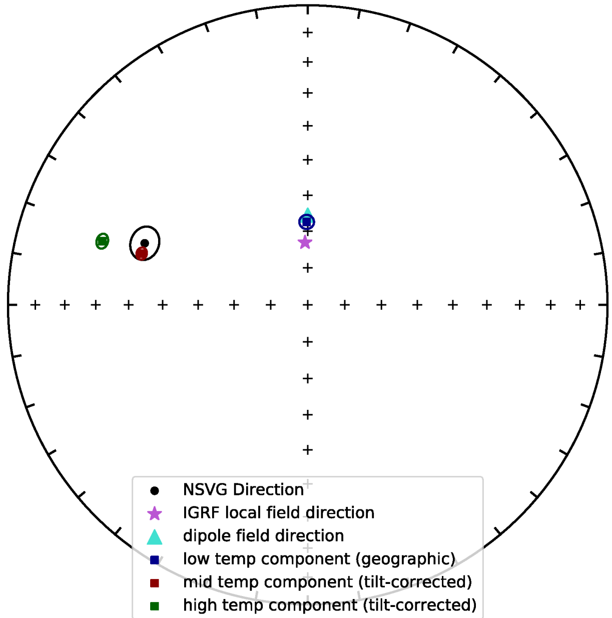

Figure 7. The stereonet above plots the high temperature directions calculated from the Cut Face Sandstone relative to the NSVG paleomagnetic direction. The low temperature component of Cut Face Creek sandstone is then plotted along with the International Geomagnetic Reference Field (IGRF) direction and the dipole field direction for Cut Face Creek Sandstone.

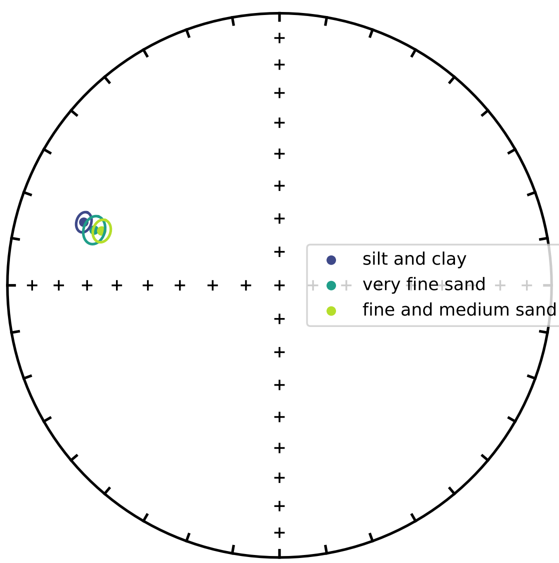

Figure 8. The Cut Face Creek sandstone was filtered by grain size and plotted in this figure to show the relationship between grain size and inclination shallowing. Specimens that were primarily silt and clay suffered from the most shallowing followed specimens that were primarily very fine sand. The fine and medium grained sandstone specimens suffered the least from inclination shallowing.

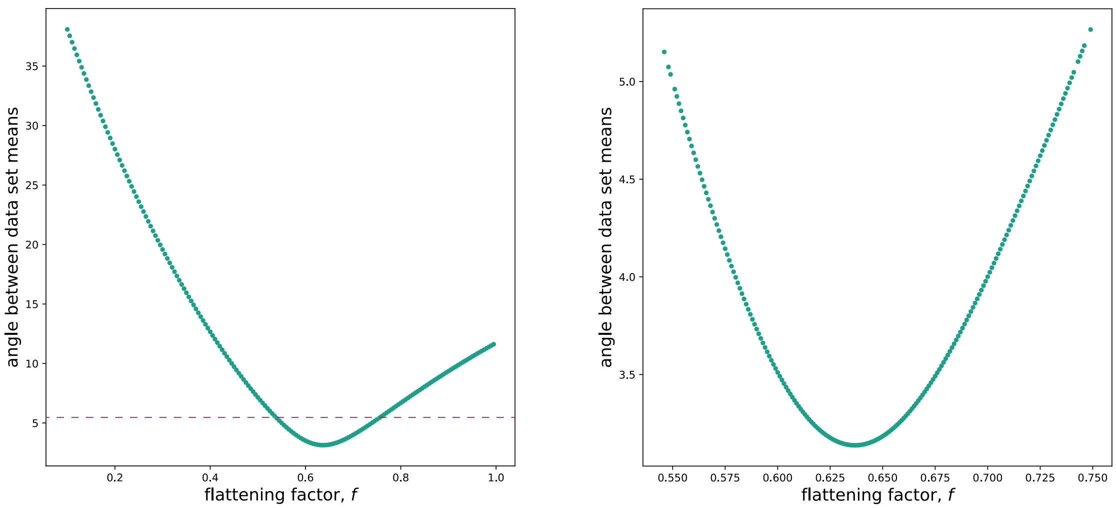

Figure 9. The left panel shows the result of conducting a Watson mean test with North Shore Volcanic group directions and the Cut Face Creek directions. The test determines the angle between the data set means. The smallest angle between data sets implies the optimum flattening factor. The red dotted line indicates the critical angle of 5.3° between the NSVG volcanics and the Cut Face Creek Sandstone. Below the line are factors that passed the test. The panel on the right shows the factors that passed the test, with the lowest angle corresponding to a flattening factor of $f = 0.637$.

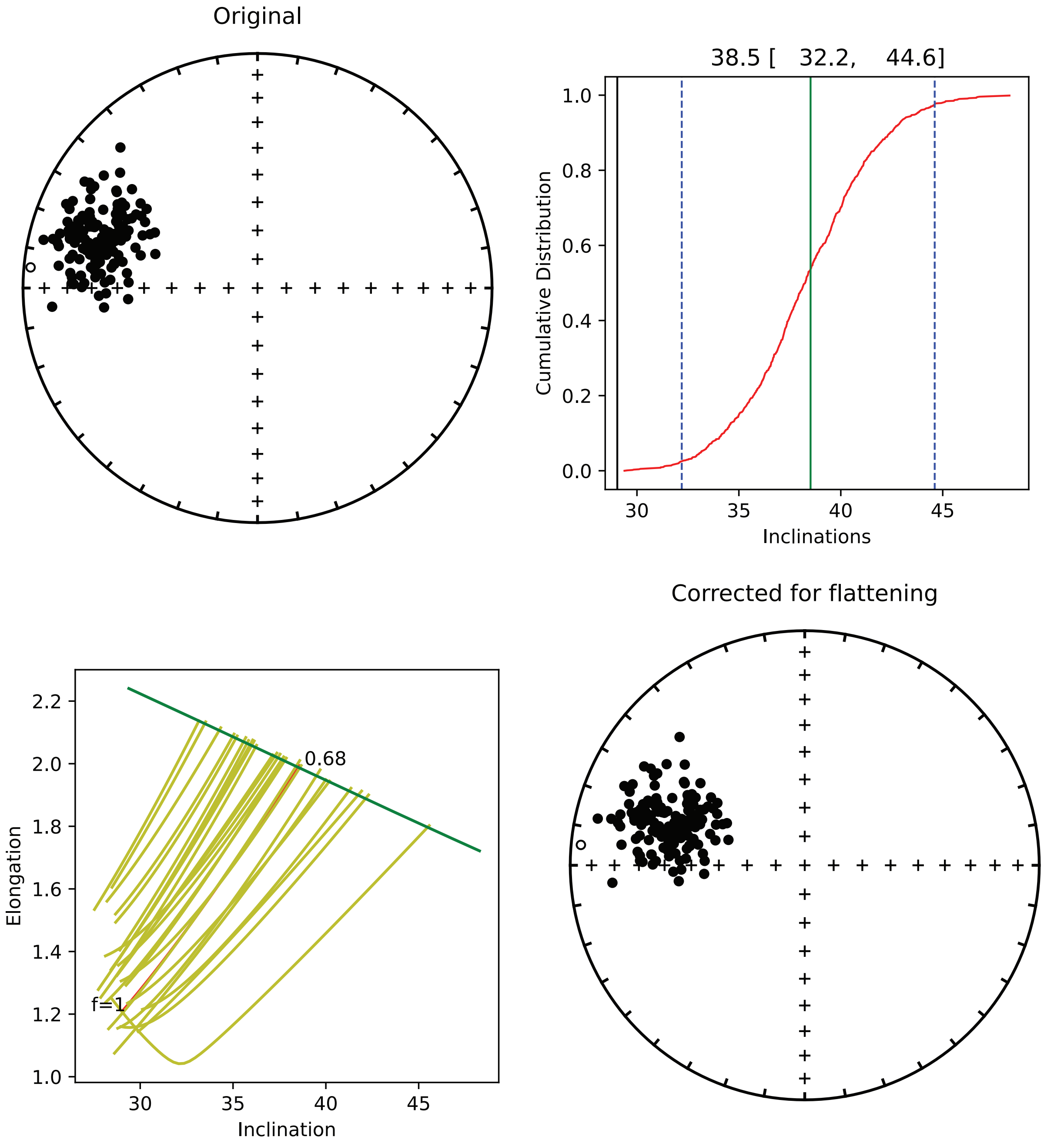

Figure 10. Top left: The stereonet shows the original directions of the Cut Face Creek Sandstone. Top right: The plot shows the distribution of of inclinations after resampling. Bottom left: The plot shows inclination against elongation of data sets after resampling of the Cut Face Creek directions. Bottom left: The stereonet shows the Cut Face Creek Sandstone directions plotted after applying the flattening factor of $f = 0.68$ suggested by the E/I method.

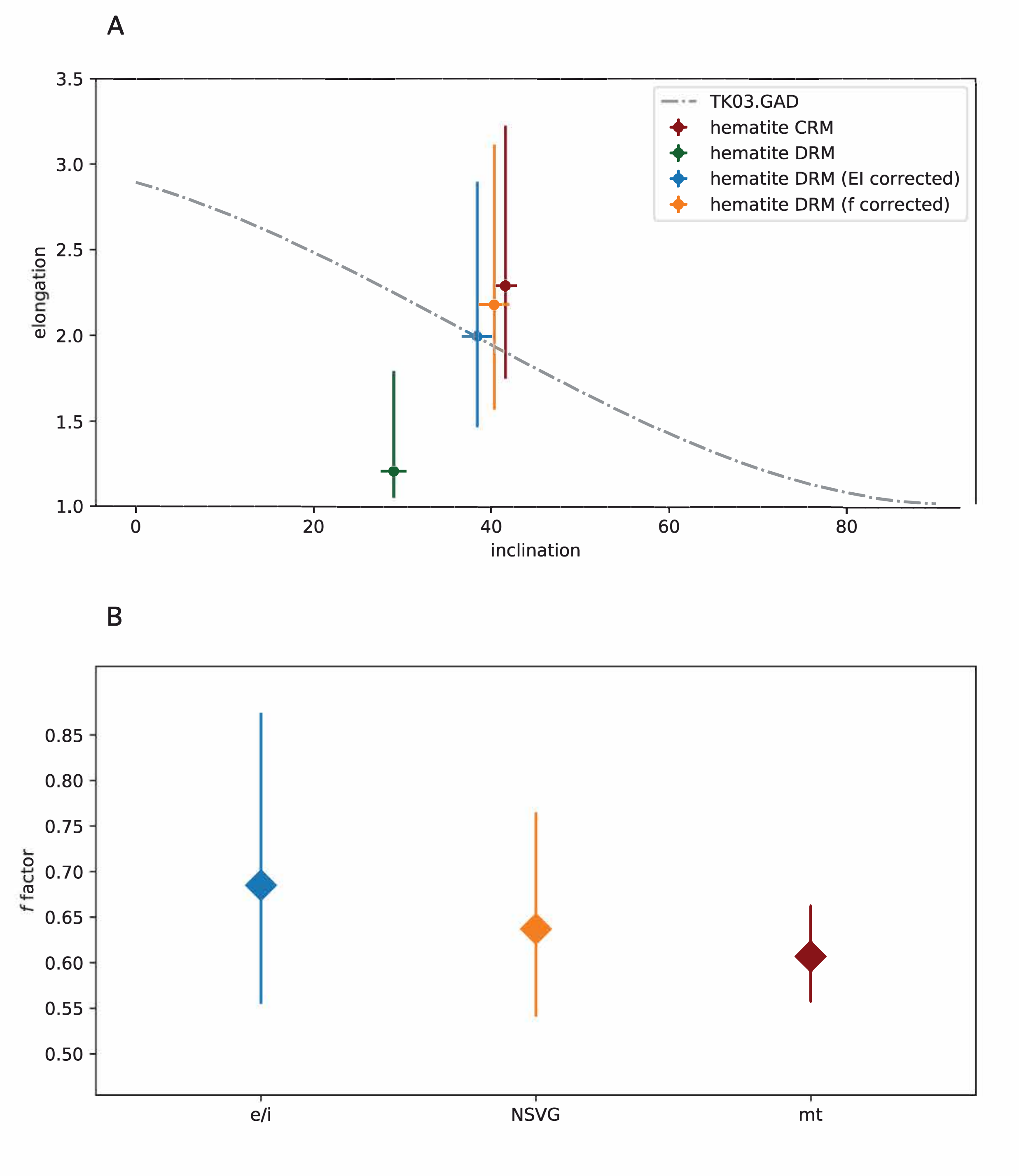

Figure 11. A) The top graph shows the relationship between the elongation of the Cut Face creek directions before and after correcting for inclination shallowing. The E/I method corrects for inclination by moving adjusting the elongation to that predicted by the TK03.GAD model. B) The figure on the bottom shows the three flattening factors determined in this study from the rocks of the Cut Face Creek Sandstone along with their error. The flattening factor suggested by the E/I method is $f = 0.685^{+0.189}_{-0.130}$. The factor determined from the NSVG rocks is $f = 0.637^{+0.114}_{-0.089}$. The flattening factor determined from the mid temperature data of the Cut Face Creek Sandstone in $f = 0.607^{+0.058}_{-0.051}$.