3D-Modeling and Magnetic (AMS) Analysis of Mesozoic Diabase Dikes in North Carolina

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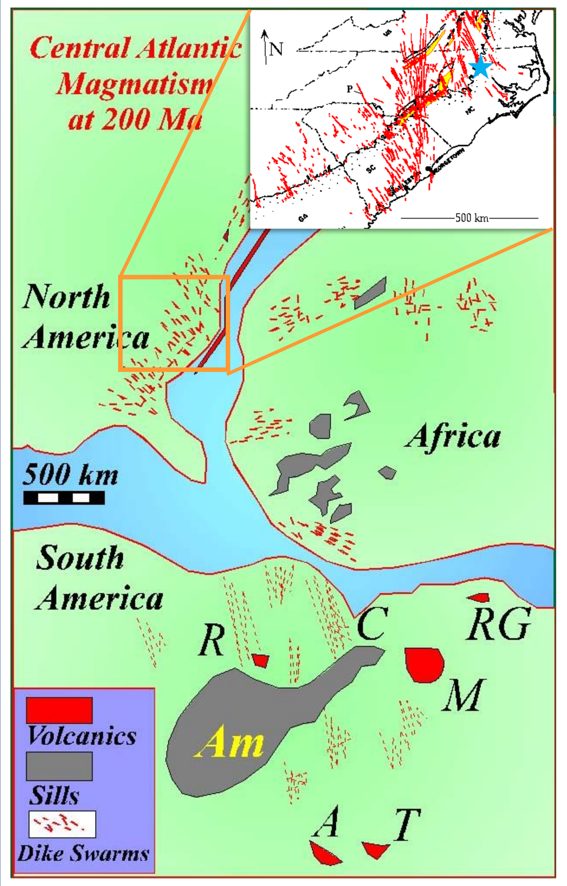
Dikes of the CAMP



At the end of the Triassic period, basaltic lavas flowed over many parts of eastern North America, western Africa, South America, and Europe as Pangea broke up and the Atlantic Ocean formed. This event, which produced the Central Atlantic Magmatic Province (CAMP), ravaged ecosystems and likely contributed to the end-Triassic extinction (Blackburn et al., 2013). Where did these lavas come from, and how did they travel through the crust?

The dikes through which these magmas flowed crop out extensively in eastern North Carolina, and are well-exposed in quarries across the Piedmont. Here we present 3D reconstructions of these excavated dikes and estimates of the magma flow direction from magnetic analysis.

Figure 1: Distribution of CAMP magmatism during the breakup of Pangea (Marzoli et al., 1999). Inset from Ragland et al. (1983) shows dike locations in the southeastern US. Blue star marks the Nash County Quarry in NC.

Dikes at the Quarry

Dikes at the Nash County Quarry are composed of diabase, cutting through granite in the Rocky Mount Intrusive Suite. At most outcrops, we observe that each dike, 3-10 m thick, is composed of multiple smaller dikelets 20-100 cm wide. At the quarry, excavation exposes dikes on each bench level, revealing changes in the structure and interconnectivity of the dikes both laterally and vertically (Figure 3).

Aerial Imaging & 3D Modeling Process

We conducted aerial surveys using a DJI Phantom 4 Pro Plus drone, collecting 200-900 vertical and oblique photos to construct each 3D model:

- Marked and surveyed ground control points within 1-2 cm error using real-time kinematic GPS unit before drone flight
- Used Pix4D Mapper and Cloud software to construct high-resolution, georeferenced orthophotos and 3D models of each set of dike exposures
- Traced 3D polylines along the contacts between the dike and wall rock
- Imported 3D model of the full quarry and all polylines into ESRI ArcScene to visualize, measure, and reconstruct dike planes across the excavated area

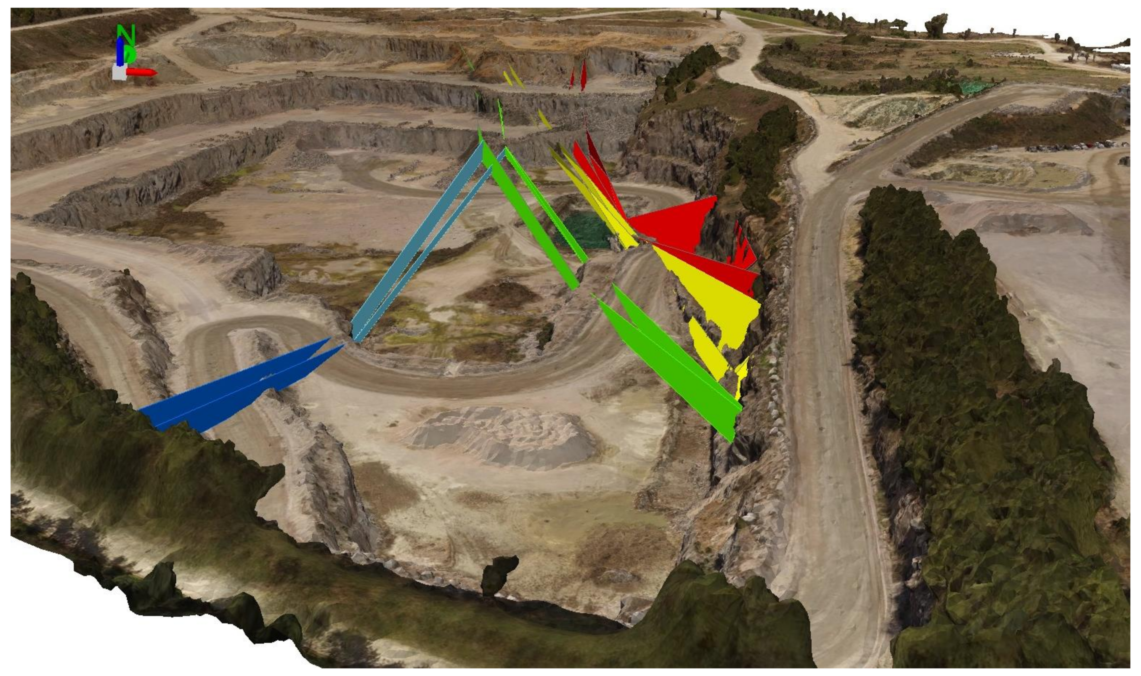


Figure 2: Reconstructed dike planes across the quarry pit. Polylines from 5 drone surveys over 8 months are connected in this model, enabling the comparison of present and past dike exposures, and visualization of the material excavated between surveys. Dikes are only exposed on vertical faces, so connections between outcrops were inferred based on field observations and cross-model measurements. This is just one possible model.

How does magnetism describe magma flow?

- Magma flow tends to foliate or lineate crystals along the direction of flow as they form, resulting in a subtle fabric of mineral alignment in the fully crystallized rock.
- When a magnetic field is applied to a rock, the rock will respond with its own magnetization.
- Based on the shape and alignment of individual minerals, the strength of the induced magnetization may vary based on the rock's orientation within the applied field. This variation is called **magnetic anisotropy.**
- By measuring the anisotropy of an igneous rock, we measure the overall shape and alignment of its constituent minerals and can make inferences about how it flowed as a magma.

Anisotropy of Magnetic Susceptibility in Dikes

The magnetic foliations measured in dike samples are oriented close to the magma flow plane, and friction along the margins of a dike can imbricate these foliations away from the flow plane (Tarling and Hrouda, 1993). By measuring the AMS of samples collected across the width of a dike, we can quantify this imbrication and observe its symmetry around the dike plane.

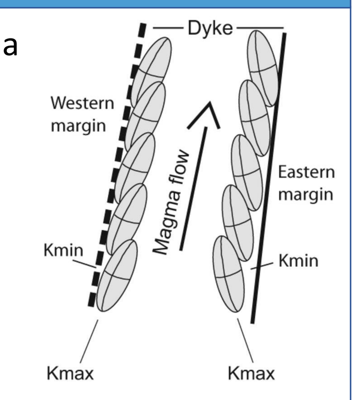


Figure 4: Imbrication of foliation fabrics along the margins of a dike (from Porreca et al., 2015).

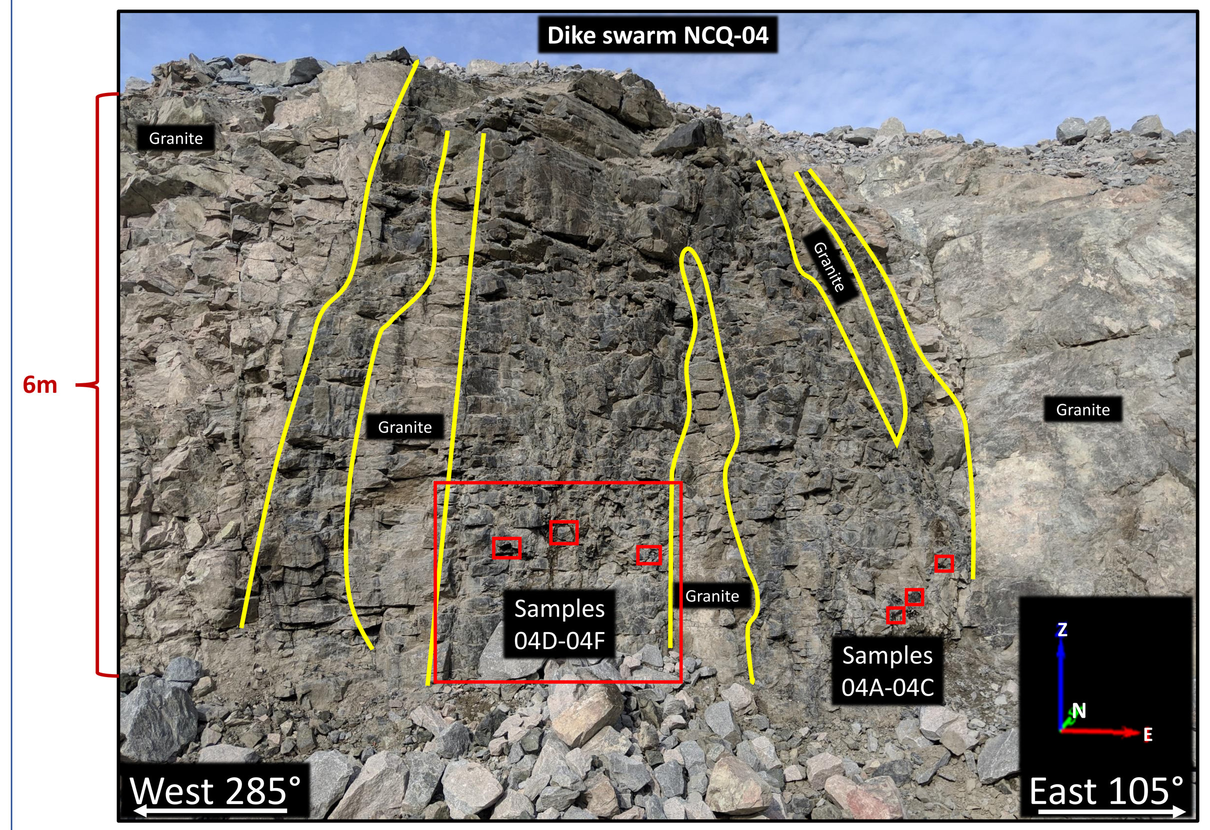


Figure 5: Example AMS sample locations at the Nash County Quarry. Each flow channel must be individually sampled across its width in order to properly characterize imbrication along the margins. This outcrop can be seen on the lowest-level wall of the quarry in each model of Figure 3. AMS results of samples 04D-04F in Figures 6 and 7.

How did we measure the AMS?

- We measured the AMS of our samples with a KLY 5a Kappabridge, which uses an automated sample holder to rotate a sample within an applied magnetic field.
- Magnetic susceptibility (K) is measured as the sample rotates, and Safyr7 software finds magnitude and orientation of maximum (K_1), intermediate (K_2) and minimum (K_3) susceptibility in the sample.
- We plot these principal susceptibilities on a stereonet (Figure 7) or as the axes of an ellipsoid to visualize the overall orientation and shape of the magnetic fabric within the core.
- Bulk K can indicate the magnetic mineralogy of the rock.

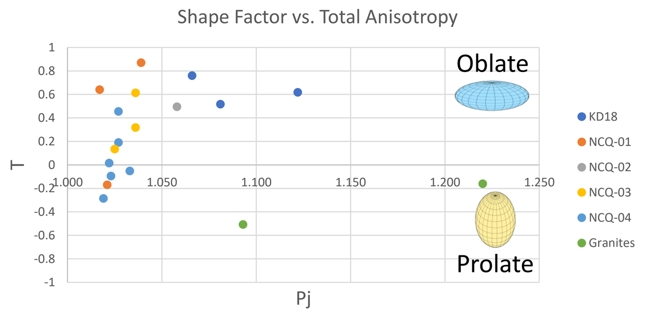


Figure 6: The shape factor (T) is positive for most samples, indicating an oblate-shaped magnetic fabric. The total anisotropy (P_j), which describes the strength of the fabric, is low, but that is typical of mafic dikes (Tarling and Hrouda, 1993).

What does all of this magnetic data mean?!

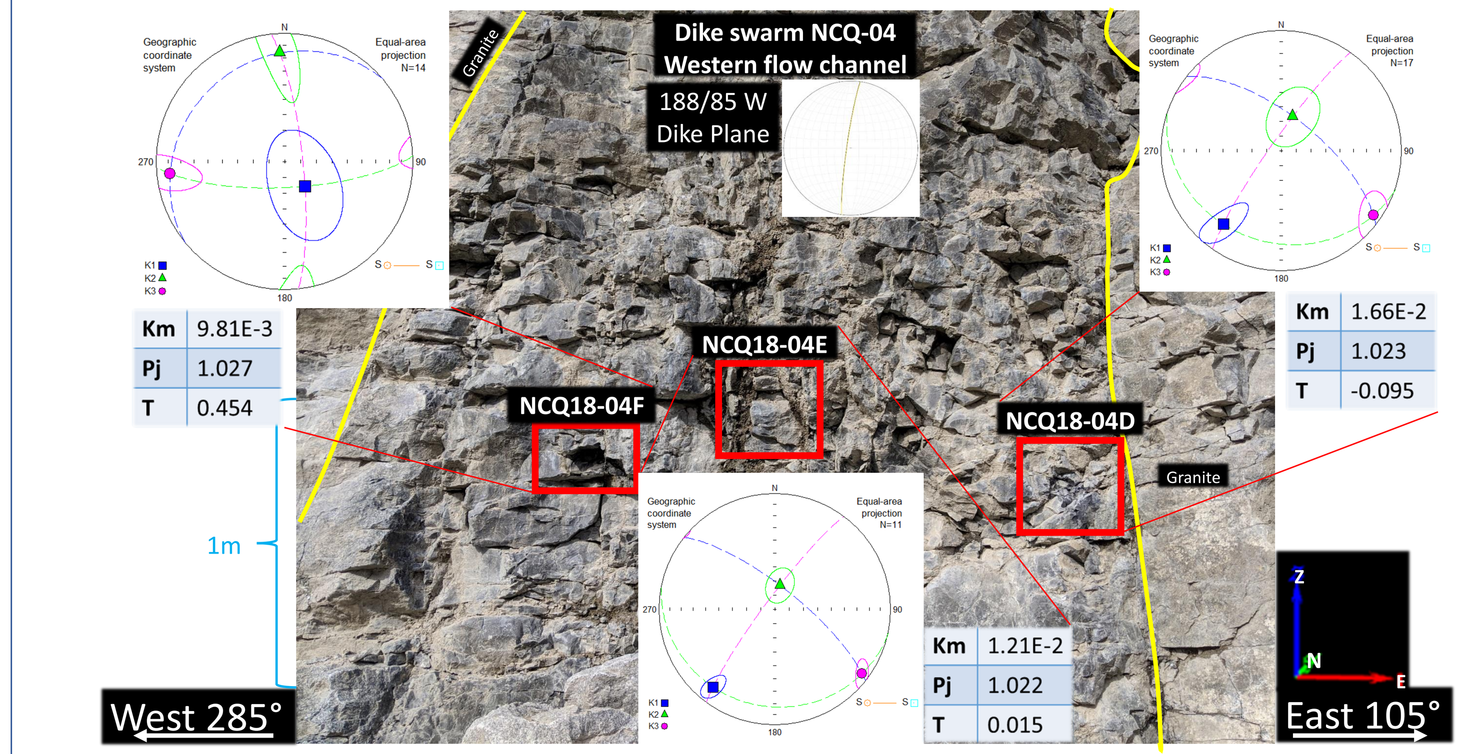


Figure 7: AMS results from one flow channel. High bulk susceptibilities (K_m) suggest that the magnetic fabrics are primarily controlled by magnetite. We compare the strength (P_j) and shape (T) of magnetic fabrics for consistency across the width of a dike and observe the changes in orientation of the K_1, K_2, and K_3 axes. The K_3 axis (pink circle) is the pole to the foliation plane (dashed pink great circle).

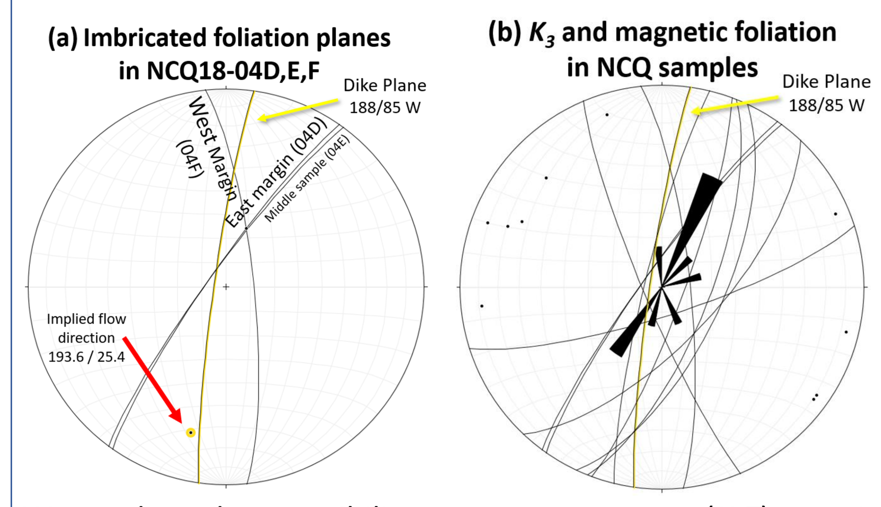
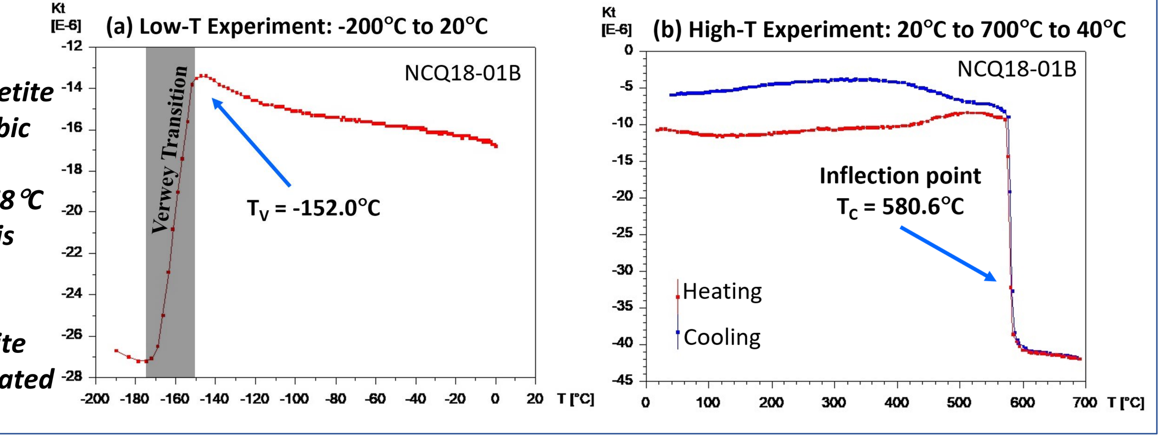


Figure 8: (a) Magnetic foliations and inferred flow direction from Figure 7. The intersection of each dike margin's foliation plane is perpendicular to the hypothetical magma flow direction, oriented sub-horizontally and to the southeast in this dikelet. (b) Foliation planes collected across multiple dike outcrops at NCQ strike most often to the northeast, or imbricate to either side of the dike plane. This geometric relationship indicates horizontal magma flow, but more extensive sampling and AMS analysis is needed to constrain an azimuth of magma flow.

We conducted susceptibility versus temperature (*K-T*) experiments to identify the magnetic mineralogy and correlate the magnetic fabrics with the real petrofabrics. When a mineral is heated to its Curie temperature (T_C), thermal vibration overcomes the alignment of electron spins and causes its susceptibility to sharply drop (Tarling and Hrouda, 1993). The shape of the *K-T* curve identifies the dominant magnetic minerals, their relative grain sizes, and changes to their crystal structures during heating.

Figure 9: Example of K-T experiment results. (a) Verwey transition is observed as magnetite changes from monoclinic to cubic around -160 ℃ (Özdemir et al., 1993). (b) In magnetite, $T_C \approx 578$ ℃ (Tarling and Hrouda, 1993). This sample's magnetic fabric is controlled by multidomain to pseudo-single domain magnetite and is, therefore, closely correlated with its petrofabric.



Summary

- 3D models show that dikes in the quarry strike north to northwest and have a composite structure in which individual dikelets split and cut across each other
- $K_{mean} \approx 10^{-2}$ to 10^{-3} and $T_C \approx 580$°C indicate that the magnetic fabric is carried primarily by magnetite and is closely correlated with the actual petrofabric.
- The imbricated magnetic foliations indicate that magma flowed sub-horizontally in these dikes.
- More sampling and AMS analysis is needed to approximate an overall azimuth of magma flow.

Acknowledgements

This project was made entirely possible by the Daniel Craig Pignatiello Fund for Undergraduate Research and the UNC Department of Geological Sciences. Special thanks to Daniel Pignatiello for creating geoscience research opportunities for UNC undergraduates.

Thank you to Cole Atkins and Wake Stone Corporation for letting us visit your quarries, helping us with drone surveys, and giving so much of your time.

Many thanks to Dr. William McCarthy, Skye McCarthy, and Yuqian Peng at the University of St Andrews for helping run and interpret magnetic analyses, and thanks to Vince Twomey for hosting me in St Andrews.

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Figure 3: 3D models of dike outcrops at the Nash County Quarry, Battleboro, NC reveal vertical and lateral changes in dike structure.