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Big data in microstructure analysis: Building a universal orientation system for thin sections

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ABSTRACT

We present an orientation system for thin sections used for microanalysis, applicable to both billets and cores. The orientation system enables spatially referenced observations and consists of three parts. First, we establish a reference corner that is the uppermost corner of the sample on the thin section, in its original geographic orientation in the field or laboratory setting. This corner is tied to a right-hand coordinate system, in which all reference axes point downward. A geographic direction-based, rather than uppermost corner-based, convention for a reference corner can be substituted for projects that utilize sub-horizontally oriented thin sections. The reference corner - combined with orientation metadata - define a unique position of the thin section in geographic space. Second, we propose a system of small saw cuts (notches) that minimizes the number of notches required on the sample, to distinguish both the reference corner and the orientation of the thin section relative to fabric (e.g., foliation/lineation), if present. The utility of a notching standard is that it provides an inherent doublecheck on thin section orientation and facilitates sharing between users. Third, we develop a grid system in order to locate features of interest on the thin section, relative to the reference corner. Any of these systems – referencing, notching, and gridding – can be used independently. These systems are specifically designed to work with digital data systems, which are currently being developed, allowing researchers to share microstructural data with each other and facilitating new types of big data science in the field of structural geology.

1. Introduction

Major advances and innovative research in structural geology and tectonics can result from sharing of geologic data within and beyond our disciplines. These data, however, typically require a spatially referenced context to be useful. For example, tracking the geospatial orientation of a sample allows one to relate microstructural information to its original geographic orientation (geographic space) to interpret its tectonic relevance. One obstacle to sharing data that is spatially referenced is the complete lack of a standard practice across research groups for orienting samples in the field and laboratory and for communicating spatial information related to those samples. The advent of digital databases should greatly facilitate the sharing of data within the structural geology and tectonics community, but requires a common convention for thin section orientation to allow interoperability between individuals and groups. There is at present, to our knowledge, no systematic way to orient samples (e.g., thin sections) relative to a field or laboratory context. Typically, each research group has a unique way to orient thin sections with respect to geographic space, kinematic framework and/or structural features (e.g., fabric, fracture plane).

In addition to the lack of standardization for orientation, we also require a method for tracking spatial data at the microscale. Tracking spatial data at the microscale is becoming a critical issue, as structural geologists are now routinely using a variety of analytical instruments -including light microscopy, Scanning Electron Microscope (SEM), Electron BackScatter Diffraction (EBSD), Energy Dispersive X-rays (EDX), Cathodoluminescence (CL), Transmitted Electron Microscope (TEM), Electron MicroProbe (EMP), Secondary Ion Mass Spectrometer (SIMS), and Atom Probe - in order to image and analyze different attributes of a thin section. In order to coordinate data and images across instruments, even an individual investigator needs a mechanism to communicate location within a thin section (see Linzmeier et al., 2018). A standard procedure for tracking data and images on a thin section will also significantly facilitate communication between different users who utilize digital data, when working collaboratively or when conducting an additional study.

This manuscript presents an orientation system for thin sections and samples. We use the term "thin section" in this manuscript to describe a sample, although the same system may be applied to any rock section (such as billets and oriented cores) utilized for microstructural analyses. We propose a mechanism for standardization that is composed of three parts: 1) A reference system for thin sections that will work with any existing laboratory practice that uniquely defines the orientation of a thin section in geographic space; 2) A notch system for samples that

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provides a straightforward way to communicate both its orientation in geographic space and the relationship between the rock fabric and the thin section (or just orientation if there is no obvious fabric); and 3) A grid system that allows data collected on different instrumentation (e.g., light microscope, SEM-EBSD, EMP, SIMS) to be put into a common spatial framework. This grid system is similar to the Universal Transverse Mercator (UTM) position used for maps, with the first digit indicating centimeters, the second digit indicating millimeters, and so forth. These standardizations will allow researchers to track orientation and location of data collected across analytical instruments, and to productively interact with each other's data. Sharing of microstructural data will increase the quality of science and transform the types of science that can be done.

2. Reference corner and reference axes

2.1. Reference corner

The goal of the reference system is to allow one to easily reorient a thin section back into its original geographic orientation. To do so, we must uniquely orient the axes of the thin section in space. Each of these axes is a unit vector (vector magnitude = 1) and, following common structural geology convention, the axes point downward. To accommodate this orientation convention, we introduce the concept of a reference corner. The reference corner is communicated through metadata including: 1) The orientation of the three axes in space; and 2) Specification of the reference corner through the proposed notching convention (see Section 3) or a digital image of the thin section.

In the most common case, there is one corner of the thin section that is, in its original orientation in the field, higher in space than the other corners (Fig. 1A). *This highest corner is the reference corner.* This reference corner is critical as it serves two main purposes: 1) The reference corner is the connection between the thin section reference frame and the original geographic or laboratory orientation; and 2) The reference corner is the origin of the reference grid to track location of data within the thin section, described below in section 5. Imagine three mutually perpendicular axes oriented relative to the edges of the thin section, but with the axes emanating from the reference corner: One parallel to the long axis of the thin section, one parallel to the short axis of the thin section, and one normal to the plane of the thin section, towards the glass. By choosing the highest corner as the reference corner, all axes point down into the Earth when the thin section is restored to its original field or laboratory orientation (Fig. 1).

Consider the reorientation of that thin section from geographic space (Fig. 1A) onto a flat surface (Fig. 1B) in order to take a micrograph image. There needs to be a convention for designation of which of the four corners of the thin section is the (uppermost) reference corner. We propose that in the reference position, the (uppermost) reference corner is the upper left corner of the thin section (Fig. 1B, bottom row). Note that the thin section will sometimes be oriented in landscape mode (longer in the horizontal than the vertical) and other times in portrait mode (longer in the vertical than horizontal) (Figs. 1 and 2). If one of these orientations is preferred, the user can always cut a billet to accommodate that preference.

Using the upper left corner of the thin section as the reference corner works well for a right-handed coordinate system (of axes *l*, *m*, and *n*) (Fig. 1B). Looking down on the thin section in the reference position, the *l*-axis is toward the right side of the thin section across the top, the *m*-axis is down the left side of the thin section, and the *n*-axis is directly away from the observer (e.g., into the glass of the thin section). If the reference corner is the highest corner on the thin section, then the *l*- and *m*-axes are necessarily pointing downward into the Earth, toward the rock from which the sample was collected. The default assumption for the *n*-axis is that it points downward in geographic space.

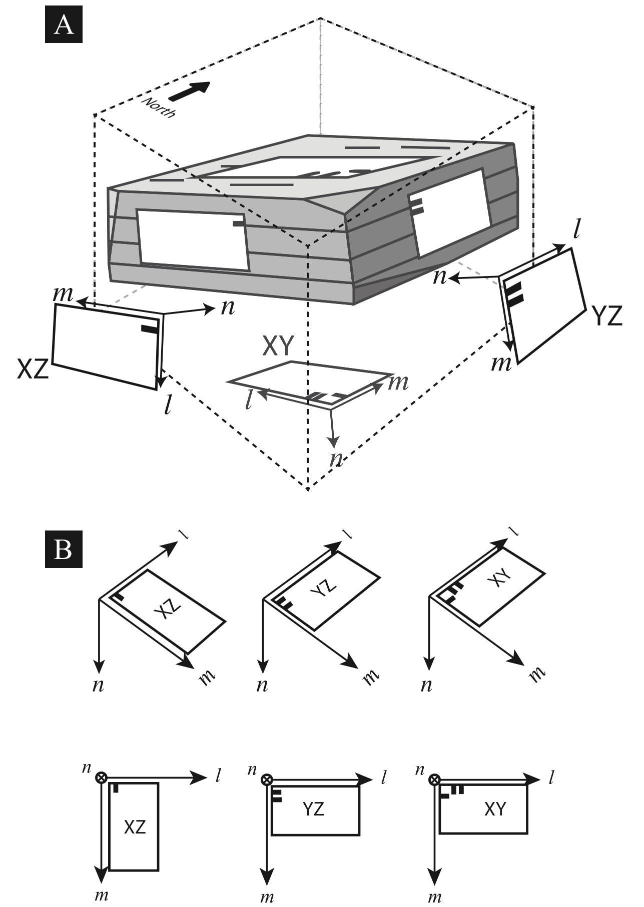

Fig. 1. The orientation of three thin sections, cut relative to field fabrics (foliation, lineation), in the general case of an oriented thin section. The diagram exhibits both the reference and notch system for thin sections. For this figure, the orientation of the thin section is shown; it is assumed that the down-facing side of the billet is placed on the slide so that all microstructural observations on the thin section are made looking down into the Earth (see Fig. 6). A. A fabric is shown with a shallowly NW-dipping foliation and a W-plunging lineation. The highest point on every thin section is the reference corner and, consistent with standard convention, the observer looks down onto the thin section. Consequently, the reference axes (*l*, *m*, and *n*) – given by a right-handed coordinate system centered on the reference corner – all point downward in space. The notch (or notches) on the thin section is cut close to the reference corner. B. Top row: The orientation of a thin section in 3D space relative to *l*, *m*, and *n* reference axes. Bottom row: The same thin sections oriented in a horizontal plane, with the orientation of the reference axes shown. Reference axis *n* goes into the page.

2.2. Upward-facing thin sections in the geospatial system

The reference corner provides unique spatial orientations when looking downward onto the top of a thin section. Occasionally, a thin section is cut that faces upward in space, by design or by accident. In this instance, the shear sense (if present) is reversed relative to looking at the same section facing downward. It is, therefore, necessary to indicate that the thin section is “upward facing.” In this case, the *l*- and *m*-axes are still necessarily pointing downward into the Earth, but the n-axis points upwards (and is a negative value).

2.3. Shallowly dipping planes

The idea of a reference corner as the uppermost corner does not work well for thin sections cut on subhorizontal planes (< 10°). In these cases, azimuthal direction – rather than topmost corner - takes precedence as the criterion for the reference corner. Consider an

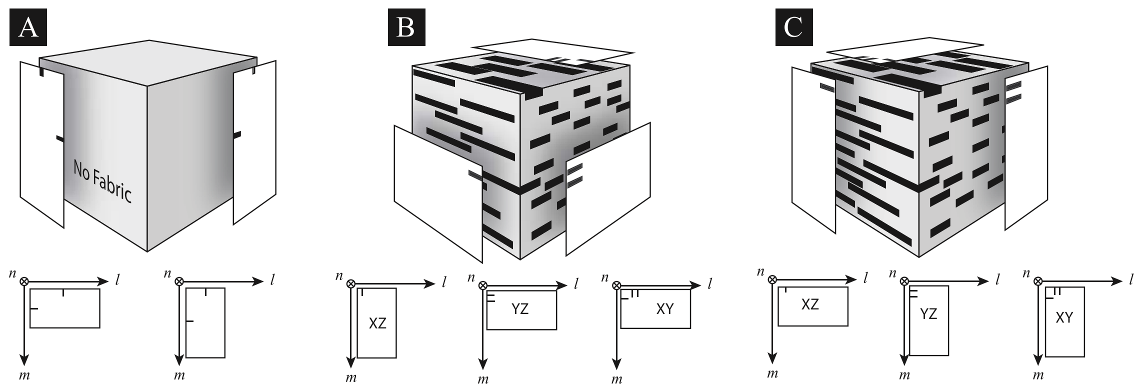

Fig. 2. The proposed notch system. The upper corner of the block - closest to the reader - is assumed to be the uppermost point: Consequently, the upper corner on each thin section – the closest corer to the reader - is the reference corner. The top part of the diagram shows the thin sections relative to the sample and the bottom part shows the thin sections in a horizontal plane. A. If a rock sample is oriented but has no fabric, the notches are put in the middle of the thin section but on the side adjacent to the reference corner. B. For a rock with both foliation and lineation, three typical combinations are possible with respect to fabric. For the XZ (lineation parallel, foliation perpendicular) section, a single notch is put parallel to X direction adjacent to the reference corner. That is, the notch is on the uphill side of the thin section. For the YZ (lineation perpendicular, foliation perpendicular) section, two notches are put parallel to Y direction adjacent to the reference corner. For the XY (foliation plane) section, a single notch is put parallel to X direction adjacent to the reference corner and two notches are put parallel to Y direction adjacent to the reference corner. C. The exact same fabric as in B, but the orientation of all three thin sections has switched 90°. In this case, the orientation of the thin sections is rotated 90° relative to the reference corner. This notch convention allows practitioners to comprehend the orientation of fabrics relative to the thin section immediately and reorient a thin section in geographic space by knowing solely the orientation of fabric.

approximately NS-striking, sub-vertical shear zone, with foliation dipping steeply E or W and the lineation plunging gently N or S. The geologist chooses to cut thin sections perpendicular to the foliation and parallel to the lineation. However, because the foliation dips steeply E or W, and the lineation plunges gently N or S, the uppermost corner could occur on the NE, NW, SE, or SW corner, depending on slight variations in the foliation dip and lineation plunge directions. The uppermost corner is not a practical consideration in this example: A practicing geologist would likely rather easily identify the overall N-direction of each thin section in order to compare observations with other thin sections from the same zone. Thus, for subhorizontal thin sections, we propose that *the northernmost corner is the reference corner*. In the cases where there are two northernmost corners (e.g., NS- or EW-oriented, horizontal sections), the easternmost corner is the reference corner. This criterion is consistent with the notching convention proposed, below (see section 3).

It is useful to discuss this issue in terms of reference axes. For subhorizontal thin sections, the *n*-axis is always sub-vertical (and downward/positive). The *l*-axis and *m*-axis are thus allowed to become slightly downward-plunging (positive number) or upward-plunging (negative number). The benefit to the proposed system, however, is that the *l*- and *m*-axes will generally have the same orientations in space for a particular geological structure (provided the long axis of the thin sections are always cut in a uniform way; that is, in the example of the NS-striking, sub-vertical shear zone the long axis of the thin section is always N-S oriented, rather than alternating between N-S and E-W oriented).

The shallowly dipping planes example presented above illustrates the utility of the reference axes concept: It is a case of the exception proving the rule. As long as a reference corner is designated in a consistent way for a given study – and the orientations of the reference axes are provided – the thin section can be re-oriented to its original spatial position.

2.4. Re-orientations to geographic space

Thin section coordinates (*l*, *m*, and *n*-axes) are re-oriented into geographic space utilizing directional cosines (Fig. 3). For geographic space, we utilize the right-hand coordinate system of Northing (x), Easting (y), and down (z). Taking, for example, the *m*-axis, the angle α is the minimum angle between the *m*-axis and Northing, the angle β is the minimum angle between the *m*-axis and Easting, and the angle γ is the minimum angle between the *m*-axis and a downward vertical axis. The cosines of these values for the *m*-axis form the second row of a matrix, with the property of:

$$(\cos\alpha_m)^2 + (\cos\beta_m)^2 + (\cos\gamma_m)^2 = 1$$

The same is done with the *l*- and *n*-axes (Fig. 3B). By arranging these direction cosines into a tensor, one can transform between the thin section space and geographic space. The same transformation can be done with any orientation data that is obtained with reference to a thin section (e.g., data obtained from analytical instrument software such as SEM-EBSD data, or grain boundary orientation data collected via a universal stage), in order to transfer it into geographic-space coordinates.

Thin sections will need to be accompanied by metadata (specification of a reference corner and orientation of the *l*, *m*, and *n*-reference axes) that can reorient them to their correct position in geographic space. For any fabric measurement, structural geologists are adept at using a stereonet to determine a trend and plunge value for any line in space. Allmendinger et al. (2012; Section 2.3.7) explicitly address how any trend and plunge measurements can be converted to direction cosines, and provide the Matlab code for this operation.

3. Much ado about notching (notch convention)

Structural geology requires orientation data to interpret mechanical and kinematic processes in both natural and laboratory settings. Therefore, it is necessary to track the geospatial orientation of a sample from its field or laboratory setting to the thin section in order to relate the microstructural-scale data to geographic space and thus interpret its tectonic relevance (e.g., Webber et al., 2008). In order to retain orientation data from its original setting to the thin section, it is common to make use of specially placed small saw cuts (notches) along the edges of the sample, or the billet, from which the thin section is made. These notches are preserved in the thin section, thus preserving the orientation context of the data. Frequently, thin sections are prepared relative to the rock fabric (e.g., foliation and lineation), and notches are commonly used to note these fabric orientations (e.g., Passchier and Trouw, 2005).

In our discussions regarding the development of a standard notching convention, we noted that first, there is no current standard convention

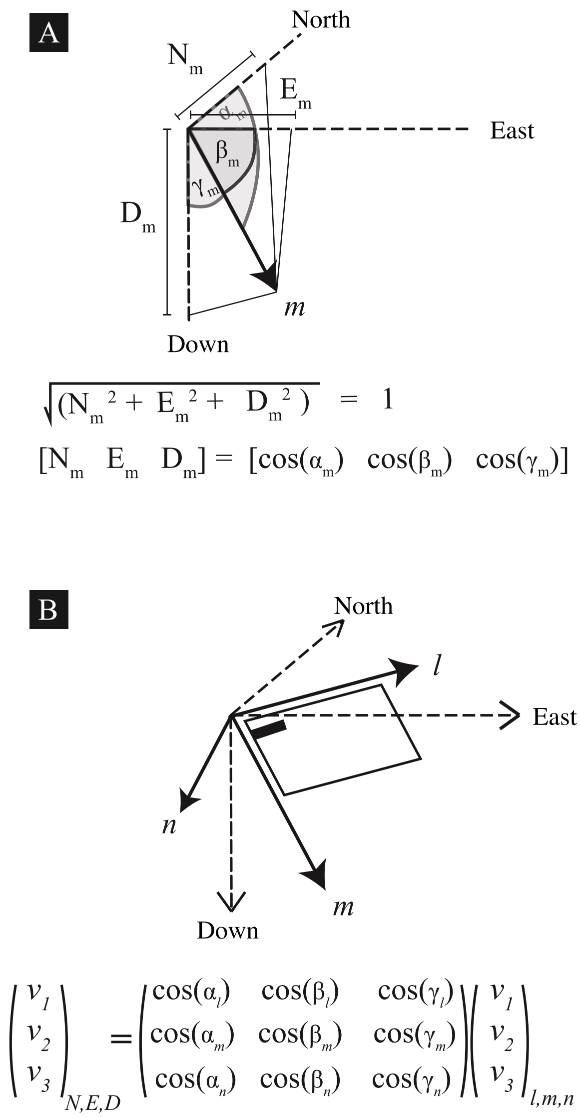

Fig. 3. A. The orientation of a single thin-section reference axis (*m*) in geographic space. The magnitude of any reference axis is 1 (unit vector), and hence the distances along the north (N), east (E), and downward (D) geographic axes are given by direction cosines. B. The orientation of all reference axes in geographic space. Transformation between thin-section space and geographic space is given by a tensor whose elements are the direction cosines of the reference axes.

accepted by the structural geology community (although conventions have been proposed, such as in Passchier and Trouw, 2005). Second, there is great variability from one practitioner to another (including amongst the authors of this article). Third, if a structural geologist prefers a different convention, we want to allow flexibility to accommodate variations. Consequently, though the notch convention described here has been designed to work seamlessly with the reference corner convention, the two are independent. Those who wish to continue with a different notching convention may do so and still use the reference corner and reference axes convention, as well as the grid convention (described below in section 5).

For samples with a fabric, the notching convention indicates the fabric orientation(s). The number of notches on an edge indicates direction relative to the standard XYZ fabric orientation framework (e.g., X is lineation direction; XY is foliation plane). There is a single notch in the X-direction and two notches in the Y-direction. There is no notching in the Z-direction. The orientation of the notch indicates the orientation of the associated axis.

For example, it is probably most common for thin sections to be produced perpendicular to foliation and parallel to lineation (an XZ section; Fig. 1; 2). The fabric is indicated with a single notch in the X direction (lineation parallel), as there is no notch in the Z direction in this convention. We note that the thin section can be oriented in either landscape or portrait mode, relative to the reference corner, depending on how the thin section is cut (Fig. 2B vs. 2C).

3.1. Notches and reference corners

The notches also indicate the geographic orientation of the sample; notches are placed adjacent to the reference corner, i.e. the corner of the thin section that was higher in space in its original context (e.g., the position in the field). In the case of the XZ or YZ plane, there are one or two notches on the thin section, respectively (Figs. 1 and 2). However, the notches are adjacent to the reference corner. In the case of the XY plane (Fig. 1), there are three notches adjacent to the reference corner: One parallel to the X direction and two parallel to the Y direction.

There are cases in which fabric is either not visible before a rock is cut or the rock may not contain any obvious fabric. In these cases, the thin section still has a distinct orientation in space, which does not coincide with any fabric orientation, and a single notch is placed in the center of both of the "uphill" sides of the thin section (Fig. 2A). In this case, the reference corner is still the uppermost corner and the notches flank the reference corner along the *l*- and *m*-axes. Consequently, having a *single* notch on *two* adjoining sides of the thin section immediately denotes that it is not a fabric-based orientation.

The importance for the notching is that it inherently designates the reference corner, which is the basis for the gridding system (See Section 5). Thus, standardization of the notching acts to standardize thin section orientation: It allows interoperability between groups. The above cases simply require that you are looking down onto the thin section.

3.2. Atypical cases

This section addresses how to deal with cases in which "looking down" is ambiguous (or not possible). In some cases, one or two edges of the thin section are horizontal in geographic space, which prevents from being able to define a unique upper corner (Fig. 4). For thin sections oriented with respect to fabric, these atypical cases arise when lineation is horizontal or vertical, foliation is horizontal or vertical, or when both lineation and foliation are either horizontal or vertical. A simple set of rules deals with all atypical cases. First, if there are two upper corners to the thin section, the northernmost corner becomes the reference corner. Second, if there is no upper corner because the thin section is horizontal, the northernmost corner is marked. Third, for sections that are strictly E-W, there will be two equal northernmost corners to mark. In this case, one notches the easternmost of the two northern corners. Fourth, the default for all vertical thin sections is that the user looks in the direction that has a northward component (the *n*-axis points north). In the case of a vertical and exactly NS-oriented and vertical section, the user looks in the direction that has an eastward component. *Hence, the criteria for the reference corner are, in order: 1) Uppermost; 2) Northernmost; and 3) Easternmost.* In all of these cases, the default notch convention can be overridden by specifying the three reference axes (*l*, *m*, *n*) for the actual orientation of the thin section.

3.2.1. One axis of thin section cut in the horizontal plane (Fig. 4A)

Fig. 4A shows the case of a dipping foliation with a horizontal lineation. For the XY and XZ sections, there are two uppermost corners. In this case, we utilize the second criterion and use the northernmost of the two uppermost corners as the reference corner. Note that in this example, we used the default orientation for the YZ section, which is cut to be oriented as if looking northward.

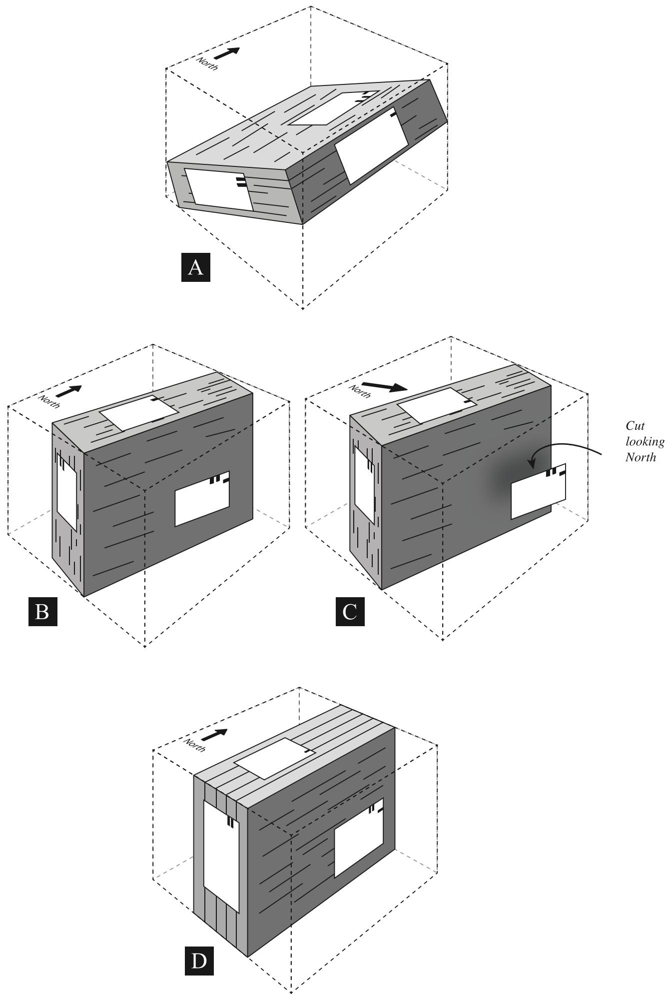

Fig. 4. The four atypical cases for an oriented thin section, which occurs if one or more axes lie in the horizontal plane. See text for details.

3.2.2. Two axes of thin section cut in the horizontal plane (Fig. 4B and C)

Fig. 4B and C shows two cases of a vertical foliation and a horizontal lineation, where the fabric is oriented in different orientations in the two block diagrams. In both of these cases, the reference corner is both uppermost (first criterion) and northernmost (second criterion), as described below. The difference between the diagrams is the orientation of the N arrow, which will determine which corner is notched. In the horizontal plane, the XZ section is just notched on the northernmost point. In the YZ section (which is vertical), the northernmost point is also notched, but it falls on the left side (Fig. 4B) or the right side (Fig. 4C) depending on the orientation of the fabric with respect to N. For the XY section (which is vertical), it is cut so that the geologist looks N into the thin section and the reference corner is the northernmost of the two uppermost corners (second criterion) (Fig. 4C).

3.2.3. Two axes of thin section cut in the horizontal plane and oriented N-S/E-W (Fig. 4D)

Fig. 4D shows the case of vertical foliation with a horizontal lineation, but with the foliation oriented N-S. The same situation would occur if: 1) The lineation was vertical; 2) The vertical foliation was oriented E-W and the lineation was either horizontal or vertical; or 3) The foliation was horizontal and the lineation was exactly N-S or E-W. In any of these cases, there will be thin sections with all four corners being uppermost for one fabric-based cut (first criterion) and two corners being northernmost for another fabric-based cut (second criterion). Thus, for these orientations, we default to the third criterion of the easternmost of the two northernmost corners. In the example shown in Fig. 4D, the horizontal XZ section has a notch in the northeastern corner of the thin section, the vertical YZ section has two notches in the upper-easternmost corner, and the vertical XY section has notches in the upper-northernmost corner.

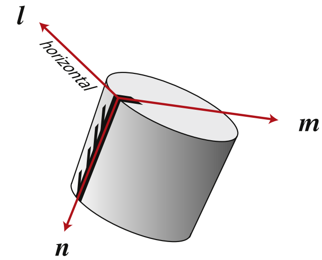

Fig. 5. Reference axes for the case of an oriented core. If the thin section is not cut perpendicular to the length of the core, the reference axes must be calculated.

3.3. Oriented cores

Structural geologists often make thin sections from oriented cores. Since the core is oriented, the *l*-, *m*-, and *n*-axes are defined by the location of the notch that occurs on the top of the core (Fig. 5). The following describes the situation in which a thin section is cut perpendicular to the long axis of the core. In this case, the *n*-axis is down the axis of the core. Hence, the *l*- and *m*-axes lie in the circular cross-section of the core. Because we are using the right-hand rule, the *m*-axis points down the circular cross section of the core parallel to the typical direction of the notch. The plunge of the *m*-axis is a complement (hade) to the plunge of the *n*-axis, and the trend of *m*-axis is 180° different from the *n*-axis. The *l*-axis is orthogonal to the notch and is necessarily horizontal in space. Thus, when the thin section is made perpendicular to the long axis of the core, the orientations of all three axes are immediately determined from the orientation of the core. In the case where a core is cut to make a thin section that is not perpendicular to its long axis, one would have to independently determine the orientation of the *l*-, *m*-, and *n*-axes as described above.

3.4. Comparison to other notching methods

There is no standard convention for notching a thin section used by the structural geology community. Passchier and Trouw (2005), in their Fig. 12.1, provide a robust method that uniquely orients a thin section in space. They use a combination of: 1) A notch on the top edge of a thin section; and 2) An arrow that shows the direction of which of the two corners is higher in geographic space. Their method of combining a notch and a scratched arrow, however, has some disadvantages, including: 1) The notch provides no information about the fabric (e.g., one notch does not define that you are looking at a plane perpendicular to foliation and parallel to lineation); 2) It requires a mark on the glass of the thin section, which requires the person making the thin section – typically a technician - to place the arrow correctly; 3) The convention does not work for other microsamples, such as billets, because there is no glass to scratch; and 4) There is no convention for rocks that do not show an obvious foliation and lineation.

Other practitioners, working with rocks with strong fabrics, tend to notch the "downhill" rather than "uphill" side. Essentially, they are notching opposite from the reference corner. This system works well in the general case, but does not have a clear relation to the reference axes. As mentioned above, any convention may be used, provided that the practitioner provides: 1) The specification of a reference corner; and 2) The orientation of the three reference axes.

There are significant advantages for our community to adopt a standard for thin section notch convention. For instance, one can

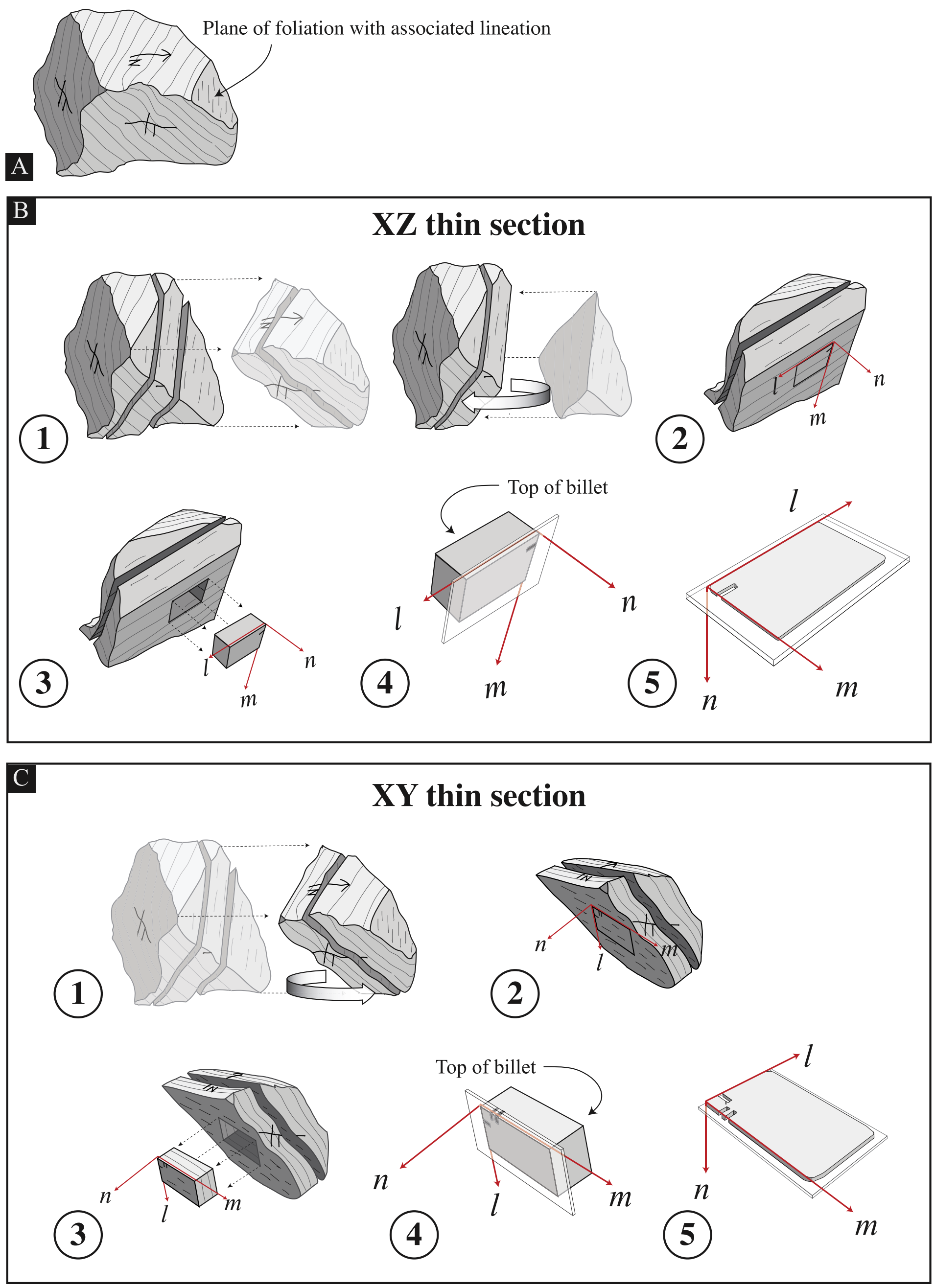

Fig. 6. A cartoon showing how an oriented rock is cut to provide reference axes and notches according to the proposed convention. A. A rock oriented in the field. The convention used for orienting the rock in the field is the use of one North arrow and two horizontal lines on differently oriented faces (with the two lines pointing down and the one line pointing up, to make the shape of a lowercase "h"). B. The procedure for producing an oriented thin section in the XZ (fabric) plane. C. The procedure for producing an oriented thin section in the XZ (fabric) plane. Both C and B follow the same 5 steps: 1) Cut a slab parallel to the desired thin section (e.g. XZ, XY); 2) Mark the underside of the slab following the convention described in the text; 3) Trim the slab into a billet and cut notches on the bottom of the billet; and 4) The bottom of the billet is attached to the glass slide. Following this procedure, the *l-, m-, and n*-axes all point downward.

immediately look at a thin section with a single notch in a corner and know: 1) It is a XZ section; and 2) It is geographically referenced. Similar knowledge is available in the other fabric-based and non-fabric-based sections. Further, if one is given a thin section that is notched with this convention, and provided with the fabric orientation, one can geospatially orient the thin section *and all microstructural data* associated with that thin section. Further, if one uses the metadata associated with the orientation of the *l*-, *m*-, and *n*-axes – such as would be recorded in a digital database – the orientation of the thin section can be double checked. This level of redundancy will result in significantly fewer errors in reorienting thin sections.

The above notching system does break down in the case where there are multiple fabrics. One can easily imagine a rock with a primary and tectonic fabric, or another rock with multiple tectonic fabrics. As a default, we suggest using the best-developed fabric. The use of the reference axes will allow these cases to be distinguished.

4. Practical rock-cutting for oriented thin section

Fig. 6 illustrates the process of making an oriented thin section starting from a field-oriented rock, which incorporates the reference axes and the notching convention discussed above. A field-oriented rock is shown in Fig. 6A; although a specific convention of horizontal and north markings is used, any geographically based markings would work. Fig. 6B shows a rock being cut for an XZ-oriented sample. A slab is cut parallel to the face from which the thin section will ultimately be taken (Fig. 6B; Step 1). The billet is then chosen from that face (Fig. 6B; Step 2). The notches are made at this point, adjacent to the uppermost (reference) corner. The orientation of reference axes are known at this point, and the *l*-, *m*-, and *n*-axes all point downward. It is typically desired that the thin section is produced so that observations are made looking down the Earth; consequently, the bottom of the billet is used (Fig. 6B; Step 3 &4). Note that if the billet was to be analyzed directly without the production of a thin section, the top of the billet would receive the notches (rather than the bottom of the billet). As show in Fig. 6B (Step 5), the notch indicates the reference corner and uniquely denotes the reference axes. Fig. 6C shows the same rock being cut for an XY-oriented section; again the *l-, m-*, and *n*-axes all point downward. Note that Fig. 6B results in a thin section in landscape orientation and Fig. 6C results in a thin section in portrait orientation, although these geometries are a result in how one cuts the rock slabs (Step 3).

5. Grid convention

The construction of an *l, m, n* orientation reference for any oriented or unoriented thin section, billet, or core allows for any microstructural data associated with the sample to be reoriented into geographic space or any other reference frame chosen by the user. This section describes the coordinate system that defines this association. The key criterion that motivates the design of this coordinate system is that it must be able to seamlessly handle microstructural data from the cm to the nanometer (nm) scale. Meeting this criterion allows for a single data structure that stores all microstructural data. Further, these data can be easily extracted without losing either their spatial referencing within the sample or their geographic orientation.

The use of multiple instruments for microanalysis is becoming increasingly common in structural geology. For example, EBSD-SEM analyses were first applied in a systematic way in the 1990s (e.g., Prior et al., 1999), and it is now a common tool for microstructural analysis. Structural data sets may also include compositional or isotopic data obtained from different microanalytical instruments (e.g., SEM, EMP, SIMS, etc.), and it is necessary to coordinate the spatial locations of the data obtained from different sources. Linzmeier et al. (2018) propose using a Geographic Information Systems (GIS) approach for thin section analysis. We propose utilizing a similar system that will easily allow coordination between microstructural data and images obtained from different instruments.

We propose to utilize a grid for each thin section, as a way of preserving spatial orientation (Fig. 7). The origin of the grid is the reference corner. This point sets the zero for the x- (*l*-) and the y- (*m*-) positions of the section grid. The zero for the z- (*n*-) position is at the top of the rock chip. We chose the top of the rock chip rather than the top of the glass slide to allow for recording data when using a system that abrades the thin section (e.g., Focused Ion Beam - FIB). All points are referenced to the reference (upper-left) corner. Using a right-hand convention, the *l*-position is positive to the right (downward in geographic space), the *m*-position is positive downward (downward in geographic space), and the *n*-position is positive toward the glass (downward in geographic space).

The grid works in a similar way to the Universal Tranverse Mercator (UTM) grid system used for topographic maps (Fig. 7). The grid number has eight (8) digits. The first position denotes cm, the second position denotes mm, and each subsequent position denotes another decrease in order of magnitude down to nm (Fig. 7). Hence, if the position (*l, m*) is (20000000, 10000000), it means that the point of interest is 2 cm right and 1 cm down when looking at a thin section (with the reference corner in the upper left). The eight (8) places thus indicate that there is a nm grid. If additional precision is needed, then it is suggested to move into decimal places (e.g., 20000000.1 indicates an angstrom grid). The same grid is available in the *m* direction, with positive in the direction of the sample's interior (e.g., toward the glass) (Fig. 7). As an example, because the top of the rock chip is at 30 microns (thin section is typically 30 µm thick), the glass at the reference corner is at (x, y, z) of (0, 0, 00030000).

A major question is what is the origin (zero point) for the reference system. For the *n*-axis, as noted above, we propose that the top of thin section (or billet) is the zero. There are three alternatives for the plane of the thin section (*l-* and *m-axes*): 1) The corner of the glass of the thin section; 2) The first appearance of rock material in the reference (upper, left) corner of the thin section; or 3) A reference micrograph (indicating any image taken with a microscope) of the thin section. The glass has the option of being the most objective and standardized, although the size of a standard thin section differs in North America and Europe. The second option (uppermost, left corner of rock material) is more practical because workers do not necessarily scan the entire image out to the edges of the glass. This situation is particularly true if the imaging requires beam time (e.g., EBSD-SEM). This alternative has the option of working on a thin section or a billet. In this case, if the edges of the billet are perfectly orthogonal, parallelism of the top of the image with the *l*-axis is the default criterion. The third alternative - a reference image – is appropriate if the reference image for the current study is not an entire thin section. Note, the reference image may be produced using any technique chosen by the practitioner (e.g., optical microscopy, EBSD, BSE). However, a micrograph reference is necessary if an image becomes the basis for the reference system.

Once an origin is set, a location can be given on a thin section using a (*l, m, n*) position. For data that are not point data, but rather encompass areas, a different convention is needed. Here we follow the GIS standard of employing points, lines, and polygons. Most imaging systems work either in circles or parallelograms. A circular marker, such as a laser ablation pit, could be given by a point and a radius. Parallelograms – a type of polygon - also occur during imaging, such as for an EBSD map. Here, the spot is given by denoting corners (vertices) of the polygon.

A critical aspect will be how to compare images from different analytical instruments (e.g., SEM, TEM, etc.). Certainly, the section grid

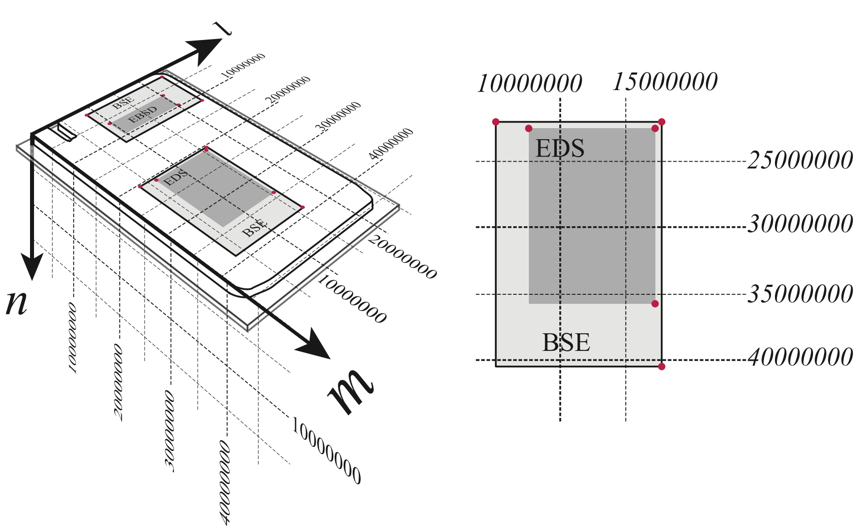

Fig. 7. The grid system applied to thin sections, shown relative to the reference axes (A) or in a horizontal plane (B). The zero point for the grid system along the *l*- and *m*-axes is the reference corner. The zero for the n-position is at the top of the rock chip. The grid works in a similar way to the Universal Tranverse Mercator (UTM) grid system, with the first position denoting the cm position and decreasing by an order of magnitude in spatial scale with the last position denoting the nanometer position. Different images – from different analytical instruments - can be overlaid on the grid. The position of these images are recorded as (*l, m, n*) coordinates for the corners of parallelograms (shown) or as a center point (*l, m, n*) with radius for circles (not shown).

allows the common reference system in which to place all data. While beyond the scope of this contribution, one method will be to choose three (3) reference points in common on the image and on the thin section image (with section grid), and use a Helmert transformation (e.g., B. Linzmeier, pers. comm., 2017). The Helmert transformation is a scaling and rotating transformation that is similar to the deformation matrix (or position gradient tensor) used in structural geology. Locating reference points from some analytical instruments (e.g., SEM, EMP) on a thin section will likely depend on the quality of the micrograph reference (thin section) image. One could, for example, complement the use of the section grid with highly detailed optical scans of thin sections (e.g., J. Urai, pers. comm., 2017).

It should be noted, however, that the common reference system described above is independent of the resolution of the images (i.e., pixels), so that users can easily work on areas smaller than the resolution of the reference photomicrograph. For example, a TEM image may be accurately located using an EBSD map that is of higher resolution than light-microscope image of the original thin section. The light microscope image, EBSD map, and TEM map all use the same reference system, despite the fact that each one is accurate to the mm, μm, and nm-scale, respectively.

6. Discussion

6.1. Common convention facilitates data sharing

Currently, no common convention exists for uniquely recording the orientation of a thin section in geographic space or for tracking spatially referenced data within a thin section. The lack of a standard practice is problematic, because the interpretation of any microstructural data, whether qualitative or quantitative, requires knowledge of the original geographic and/or fabric orientation of the thin section. The fact that each practitioner has an individualized way of recording the orientation of thin sections makes it cumbersome to share data directly with collaborators, let alone with others in the microstructural science community.

We propose a standardized system for orienting samples and preserving spatially referenced microstructural data. This system addresses two key hurdles for the incorporation of such data: 1) How to keep microstructural data oriented in geographic space; and 2) How to spatially reference microstructural data within thin sections, billets, or cores. A standardized system will allow scientists to assemble data sets to address specific research questions, making it easier to share data and thereby facilitating new research avenues.

6.2. Sharing data and digital data systems

The advent of open-source digital datasystems has transformed the way that people do research in a variety of disciplines, including within the geologic community; e.g., EarthChem for geochemists, GeoChron for geochronologists, and MacroStrat for stratigraphers. We are motivated to develop a standard orientation system because we are developing the StraboSpot digital data system for structural geology data (StraboSpot.org); a standard system will facilitate maximum sharing of digital data between users. In developing the StraboSpot digital data system, it became clear that there is currently no convention that could be adapted to the data system for uniquely recording the orientation of a thin section in geographic space. The orientation and spatial reference system described here will enable microstructural data—including easily extractable sample, fabric, and geographic reference frames—to be efficiently and effectively shared through open-source databases like StraboSpot.

We understand that legacy samples exist, and that some practitioners will use different orientation or notching systems for a variety of reasons. With the goal of making the StraboSpot or other data systems as accessible as possible, the orientation method, the notching convention, and the grid system are all independent. Consequently, structural geologists who use a different notching system will still be able to record the orientation of the thin section and fabric within the StraboSpot user interface, and thin sections that were notched before this convention could similarly be uploaded into the data system. In these cases, it is only necessary to specify the *l, m,* and *n* reference axes as unit vectors in geographic space, as long as a reference corner (origin) is specified.

There is, however, a major advantage of using the notching convention described above: The thin section orientation is immediately known if the fabric orientation is known. That is, because the orientation of the thin section is known from the notches, the thin section can be oriented in space with a foliation and lineation measurement. This measurement can always be double-checked against the orientation of the *l, m,* and *n* reference axes stored in the database.

There are at least two compelling reasons to adopt a standard convention and participate in a digital database: 1) We can, as a community, do better science; and 2) We can open new avenues for research directions by combining data from different data sets. For example, imagine having the ability to download a decade's worth of published EBSD data for quartzites from all shear zones globally that have been interpreted as wrench-dominated transpression. The data would be easily rotated into the fabric reference frame, allowing one to compare crystallographic preferred orientation and microstructural data within a global data set. Digital databases (such as StraboSpot) will have this capability, but they will necessarily rely on a standardized system for orienting thin sections and tracking spatially referenced microstructural data.

7. Conclusions

We present a system for orienting thin sections and spatially referencing the data within them. The three parts of the system – orienting within a geographic reference frame, notching to indicate fabric reference frame, and gridding to track spatially referenced data – can be used independently. The system may be applied similarly to billets or any other two-dimensional or three-dimensional sample types.

Orienting system: We propose using a reference corner to denote the uppermost corner - in geographic space - of the thin section. The reference corner will become the upper left corner of the thin section. Because it is the uppermost corner, the axes that are oriented parallel to the axes of the thin section and perpendicular to the face of the thin section, all point downward. In the cases where there is at least one axis that is horizontal, we choose the uppermost and/or northernmost point, or the easternmost point in cases where the horizontal feature is oriented perfectly East-West. For vertical thin sections, the default is that the user looks through the thin section toward the North (or East).

Notching system: We propose a notching system that is based on the concept of the reference corner. The notching system geospatially orients the sample, minimizes the number of notches, and inherently communicates the fabric type recorded in the thin section (e.g., XZ face). Thin sections without obvious fabrics also are uniquely oriented in space and the notching denotes the lack of fabric. We emphasize that the reference corner (orienting system) will typically work with any notching convention, although it works particularly well with the proposed orienting system.

Gridding system: We propose a gridding system in order to exactly specify the position on the thin section relative to the reference (upper left) corner. The system works similarly to the UTM system for a map, with the digits of position inherently communicating the precision of the location.

There are several useful outcomes from this three-part approach. First, it allows practitioners to geospatially orient thin sections. Second, it proposes a notching convention that, if adopted, will allow others to quickly and efficiently extract data from published datasets. Third, it allows users to spatially correlate data obtained from different instruments. The greatest utility, however, is to facilitate sharing our data with other practitioners quickly in a comprehensible form. This approach will allow the structural geology/microstructural community to enter the era of big data science.

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