

A GRAPHIC METHOD FOR DEPICTING HORIZONTAL DIRECTION DATA ON VERTICAL OUTCROP PHOTOGRAPHS

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ABSTRACT: Outcrop photographs which show two-dimensional representations of three-dimensionally dipping surfaces (e.g., bedding planes, cross-bed foresets) are commonly utilized in the description of sedimentary strata. In many instances, accurate depiction of the dip direction of such features is paramount for understanding their interpretation, and for visualizing the true form of three-dimensional bodies (e.g., conceptualizing the form of an architectural element in a cliff-face, preserved as a vertical slice that has been cut oblique to paleocurrent direction). However, as an outcrop photograph often presents information on a vertical plane and directional data refers to a horizontal plane, the accurate co-depiction of both sets of information may be challenging. There is presently no universal method for illustrating such measurements on outcrop photographs: techniques in common usage are often imprecise, and the lack of uniformity hinders comparison between different images. Here we present a method for accurately depicting horizontal direction data on vertical outcrop photographs which permits instant visualization of dip relative to the illustrated outcrop geometry. The method is simple to apply, does not compromise primary data, and is unobtrusive to other visual information within images; thus having utility across a broad spectrum of geological investigations.

INTRODUCTION

Sedimentary strata and bedforms are three-dimensional objects, the geometric analysis of which requires the collection of data pertaining to the dip of depositional surfaces. Dip data may be used to recognize facets of sedimentary stratigraphy including paleocurrent direction and the form of partially preserved ancient topography (e.g., channels, scours, or bar-forms). Accurate recognition of the dip direction of sedimentary surfaces is particularly important for visualizing stratal forms expressed in vertical rock outcrop (e.g., a cliff face). Most natural outcrops of strata will present only a two-dimensional slice through their internal geometries, which more often than not will be cut obliquely to the dip and strike of many key surfaces.

While geometric characteristics, and the relationship between depositional forms and their appearance at outcrop, can be readily understood by any geologist who has collected such data, disseminating such observations and interpretations in a visual format is challenging. Photographs render these three-dimensional forms in two-dimensions, so if dip direction data are to be shown in conjunction with the image of an outcrop, they too must be rendered in two dimensions. However, as an image of a cliff face provides information on a vertical plane, the concurrent depiction of data from a horizontal plane (i.e., direction) is problematic and no single method of doing so is universally applied. Further, in part due to this lack of a universal methodology, those methods that are presently utilized may be unclear or compromised in their accuracy, and any links between the vertical and horizontal information may not be immediately recognizable. In this short paper, we: 1) summarize existing methods that are used to display direction data from a horizontal plane on vertical outcrop photographs, and discuss their limitations, and 2) introduce a simple

diagrammatic method for depicting such data on photographs; one which is visually unique, does not compromise data accuracy, and permits the rapid cognition of dip directions and their implications.

EXISTING METHODS FOR DISPLAYING HORIZONTAL DIRECTION DATA ON VERTICAL OUTCROP PHOTOGRAPHS

In one year of articles in the *Journal of Sedimentary Research* (v. 86, no. 12 to v. 87 no. 11), a number of publications showed both outcrop imagery and direction data (e.g., paleoflow) that were intended to be understood concurrently. Of these, three used outcrop images with paleoflow rose diagrams shown in separate figures (Gall et al. 2017, their Figs. 9, 10; Korus and Fielding 2017; Shiers et al. 2017), three noted direction or approximate direction within the figure caption to the outcrop photograph (Jordan et al. 2016; Ainsworth et al. 2017, his Fig. 10; Dasgupta et al. 2017, their Figs. 9, 16), one used a north-oriented rose diagram on the vertical panel (Rossi et al. 2017, their Fig. 3), and one used an approximate directional arrow (Gall et al. 2017, their Fig. 8). This lack of a universal consensus regarding the illustration of directional data on outcrop photographs demonstrates that there is presently limited comparability between images presented in sedimentological publications. Further, those techniques which are commonly employed all have inherent limitations (Fig. 1).

The illustration of paleoflow on an outcrop image can utilize methodology similar to that employed in sedimentary architectural analysis (Miall 1985), where an interpreted architectural panel is shown to represent a vertical slice through an outcrop. In such analyses, an individual paleocurrent measurement for a particular stratum is displayed as an arrow pointing towards flow direction, and commonly shown

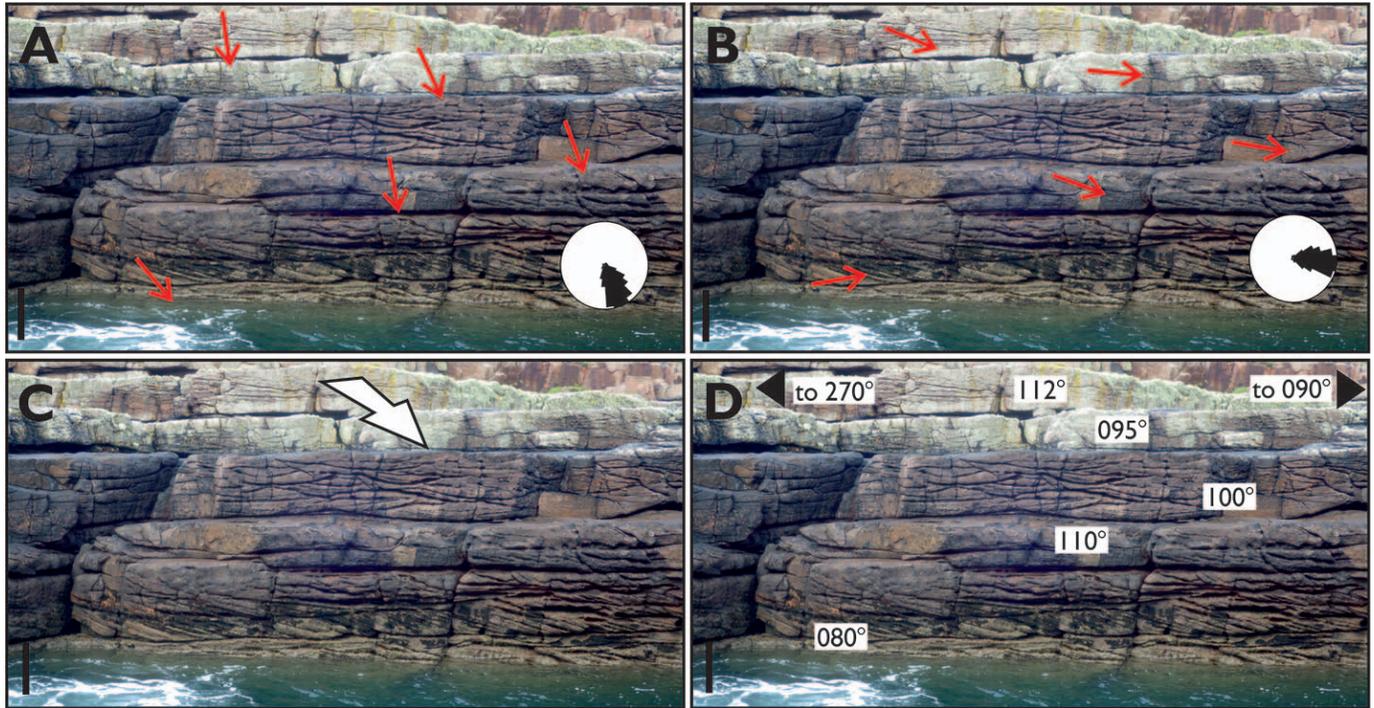


Fig. 1.—Existing and contrasting techniques for representing paleocurrent data on a vertical outcrop image. Image shown illustrates an outcrop of the Neoproterozoic Applecross Formation on Handa Island, Scotland, where foresets of braided-river alluvium exhibit a mean paleoflow towards the ESE (100°). Photograph taken facing 320° NW. Scale bar 1 meter. **A)** Arrows oriented relative to outcrop strike. **B)** Arrows oriented relative to north. **C)** 3D arrow. **D)** Textual information.

oriented relative to the strike of the vertical face (which is represented by a horizontal line perpendicular to the tail of the arrow; sometimes illustrated (e.g., Miall 1988; Long 2006) and sometimes only inferred (e.g., Bridge 1993; Willis 1993)) (Fig. 1A). Using this technique, an arrow pointing upwards indicates paleoflow into the outcrop, an arrow pointing downwards indicates paleoflow out of the outcrop, and a horizontal arrow pointing left or right indicates paleoflow parallel to outcrop strike. The same technique can be applied for general paleocurrent data gathered from across an illustrated outcrop, in which instances vectors or a circular rose diagram (with outcrop strike represented as the horizontal equator) are displayed vertically at a point on the panel (e.g., Long 2017). While these techniques provide an accurate representation of paleocurrent data, at either bed or outcrop scale, they do not facilitate instant visual cognition: the arrows or rose diagrams must first be pictured on a plane that must then be mentally tilted down and backwards into the vertical image. Further, in order to preserve accuracy, the arrows must always be shown relative to outcrop strike. This works if a cliff face is a perfectly straight wall (e.g., a road cutting), but in many real-world, irregular-shaped outcrops strike direction changes laterally. Thus, if directional arrows are shown relative to outcrop (rather than image) strike, then they can be compared between one another only through careful study of the three-dimensional outcrop complexity shown in the two-dimensional photograph.

Additional complications with this method arise because the technique has not been adopted universally: there are numerous instances where apparently similar arrows or rose diagrams on panels or photographs are shown which are oriented relative to north rather than outcrop strike (e.g., Mountney and Jagger 2004; Batezelli 2017) (Fig. 1B). This variant of the technique permits instant comparison between directional arrows on a photograph but is less satisfactory for relating them directly to the image, because it requires mental rotation of the presented data, even before it is

visualized as tilted back into the outcrop (there are published instances where this is not even possible, as the orientation of the outcrop photograph is not reported). Regardless of individual merit, both outcrop-oriented and north-oriented arrows are both in common usage, and are insufficiently visually different from one another to be immediately distinguished. The significance of arrows on photographs is further complicated because they may sometimes be used for wholly different reasons (e.g., pointing towards a specific characteristic salient to the text). Thus cross-comparison between outcrop images in different papers, and understanding the intended meaning of arrows shown on photographs, is hindered without careful reading of the small print within figure captions.

Recently a number of papers have attempted to show directional data on photographs using flat arrows rendered as oriented objects (i.e., as if positioned on a subhorizontal plane) and shown obliquely approaching or departing the vertical face (Fig. 1C) (e.g., Ielpi and Ghinassi 2015; McMahon and Davies 2018). The technique works well where outcrops exhibit a horizontal dimension (i.e., both vertical cliffs and horizontal bedding planes) (e.g., Ghinassi and Ielpi 2015). However, for photographs that show a view directly into a vertical cliff face, any flat arrow should technically appear as a straight line (i.e., seen looking onto the side of the flat object). Thus for vertical images, the flow direction illustrated by a flat arrow must first employ an artificial dip to be visible, and so can only ever be an approximation rather than a reflection of accurate measurement (unless its obliquity and tilt relative to the vertical plane of the photograph were to be discussed).

Direction is also sometimes shown as text on photographs, where dip direction is reported as numerical values of compass points (Fig. 1D) (McMahon and Davies 2018). In other instances, dip directions may be reported separately in the text or figure caption, or illustrated as a separate figure (e.g., Went 2017). While accurately preserving primary data,

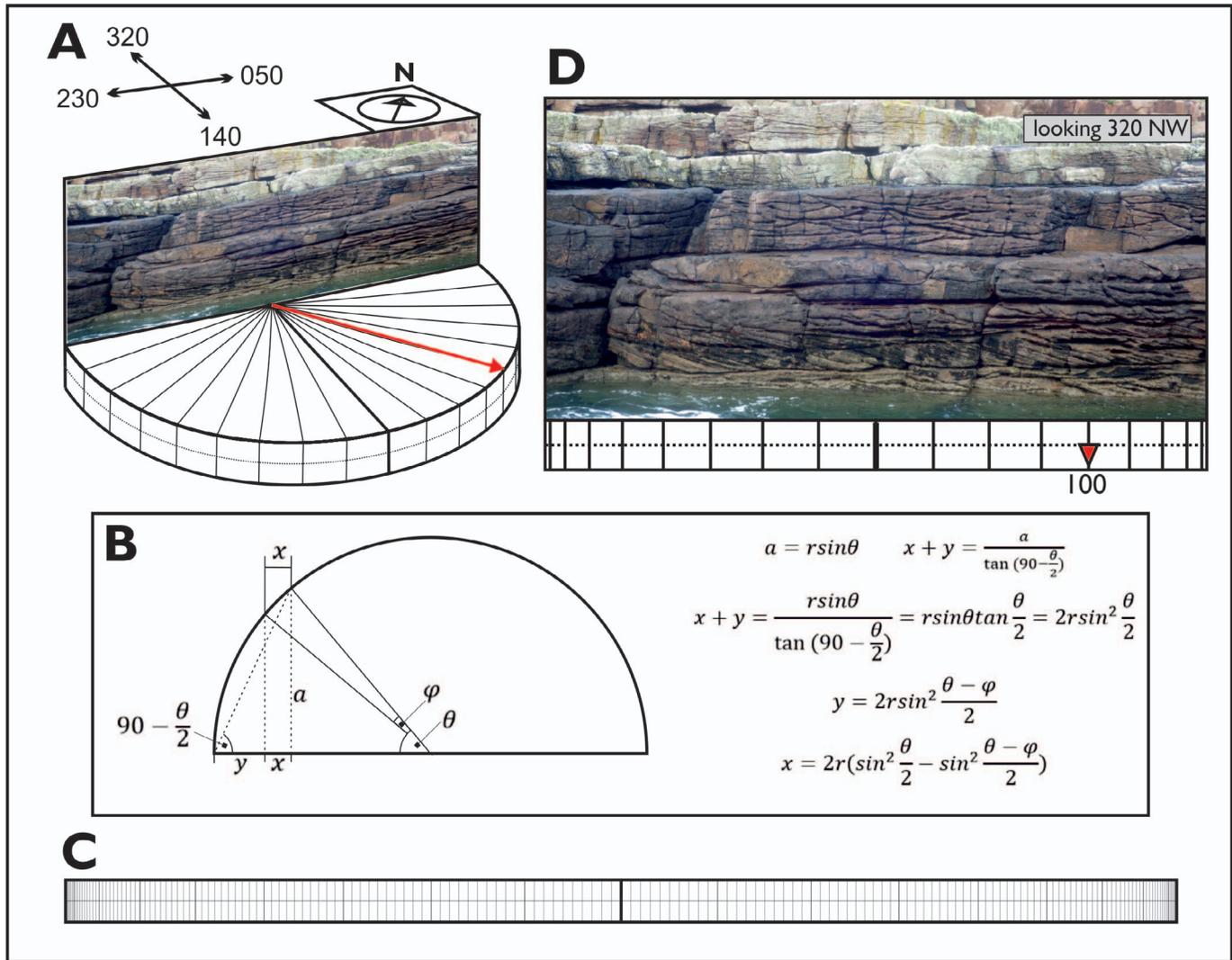


FIG. 2.—Proposed technique. **A**) Visualization of the outcrop face shown in Figure 1, relative to a semicircle (showing paleoflow) and compass points. **B**) Calculations used to determine degree spacing on the 2D bar in Part C: derivation of the length of the projection of an arc onto a line parallel to the diameter of a semicircle (x) for any given θ , φ , and r . Where θ is the central angle of a sector from the diameter encompassing the projected arc, φ is the central angle of a sector encompassing only the projected arc, and r is the radius of the semicircle. **C**) Rectangular bar, subdivided into 180 degree increments, with upper bar indicating flow into outcrop and lower bar indicating flow out of outcrop; to be used as a template for reporting paleoflow relative to outcrop. **D**) Worked example of use of paleocurrent bar using image from Figure 1: note that this image shows only mean paleoflow direction, and that the paleoflow of individual beds could be illustrated (see Fig. 3).

neither of these techniques readily promote three-dimensional visualization of stratal geometry from an outcrop image.

A NEW METHOD FOR ILLUSTRATING PALEOFLOW ON ARCHITECTURAL PANELS AND PHOTOGRAPHS

The adoption of a common and easily applied technique for illustrating horizontal direction is clearly overdue, and will permit greater opportunities for immediate cross-comparison of different outcrop photographs. In Figure 2 we propose a method whereby direction is recorded on a horizontal bar (provided as a template in Fig. 2C), which represents a side-on view of a semicircle extending out from the base of the panel. The bar is composed of 180 increments, each of which represent a degree on the compass: their uneven spacing has been trigonometrically calculated as a two-dimensional representation of the view directly towards the center line of a flat semicircle extending out from the page (Fig. 2B) (i.e., such as

would be seen looking towards the center of a horizontally oriented protractor, with the curved edge facing the viewer).

The bold vertical center line is calibrated to the compass direction towards which the photograph was taken (noted on image): the numerical value in degrees of the leftmost tick is offset by 90° in an anticlockwise direction from this, and the value of the rightmost tick is offset by 90° in a clockwise direction. Thus it requires field measurements to be made of 1) directionality of the sedimentary feature of interest; and 2) the direction of the photograph (sometimes automatically recorded by digital cameras with GPS capacity). The value of the technique is that the reference frame for the directional measurements is orientation of the photograph, rather than outcrop strike or north: meaning that the technique can be employed regardless of the angle (relative to outcrop strike) at which the photograph was taken. The bar is divided bilaterally so that a direction into the photograph can be shown in the upper level, as an upwards arrowhead, and a direction out of the photograph can be shown in the lower level, as a



FIG. 4.—Example of presentation technique applied to an individual bed. Bidirectional dip of superimposed foresets within tidal herringbone cross-stratification. Dip direction of upper set shown at top of image and dip direction of lower set at bottom of image. Silurian Tumblogooda Sandstone, Kalbarri National Park, Western Australia.

downwards arrowhead (a direction parallel to photograph strike can be shown as a sideways-pointing arrowhead at the appropriate end of the bar). The numerical value of the direction, in degrees, is recorded above or below the bar. The technique thus permits accurate directional data to be presented relative to both north and the expression of the outcrop presented in the image, regardless of whether the photograph was taken directly opposite the vertical plane of the outcrop. The technique is intended to enable dip direction to be depicted in instances where it is pertinent to (but not immediately apparent on) a specific photographic illustration. As it is only a technique for presenting information, it should not preclude field measurements such as outcrop strike, which will permit immediate visualization of direction and geometry during data collection. Equally we emphasize that it is not intended as a substitute for more refined analyses of directional measurements, where appropriate.

The illustrative method can be employed to show directional sedimentary data for a variety of purposes and at different scales: for example, it can be used to show mean paleoflow direction for an outcrop (Fig. 2C), or for individual beds within an outcrop (Fig. 3); for dip direction of internal sedimentary laminae of a single bed (Fig. 4); or for key dipping surfaces that form boundaries to a three-dimensional bedform, which may not be immediately apparent within a photograph (Fig. 5).

SUMMARY

The benefits of our proposed illustrative technique relative to existing methods are: 1) it permits accurate representation of direction and can be applied at both bed and outcrop scale; 2) it preserves information on direction relative to both outcrop and north; 3) it permits the viewer instant cognition of direction relative to the image seen in the photograph, even when the outcrop is irregular in shape, or when a photograph is taken at an oblique angle to a cliff face; 4) it is visually unique and unobtrusive, such that it is unlikely to be mistaken for any other information in a figure (e.g., a paleoflow arrow versus an arrow highlighting a key feature); and 5) it is readily replicable, using the scale bar in Figure 2C as a template.

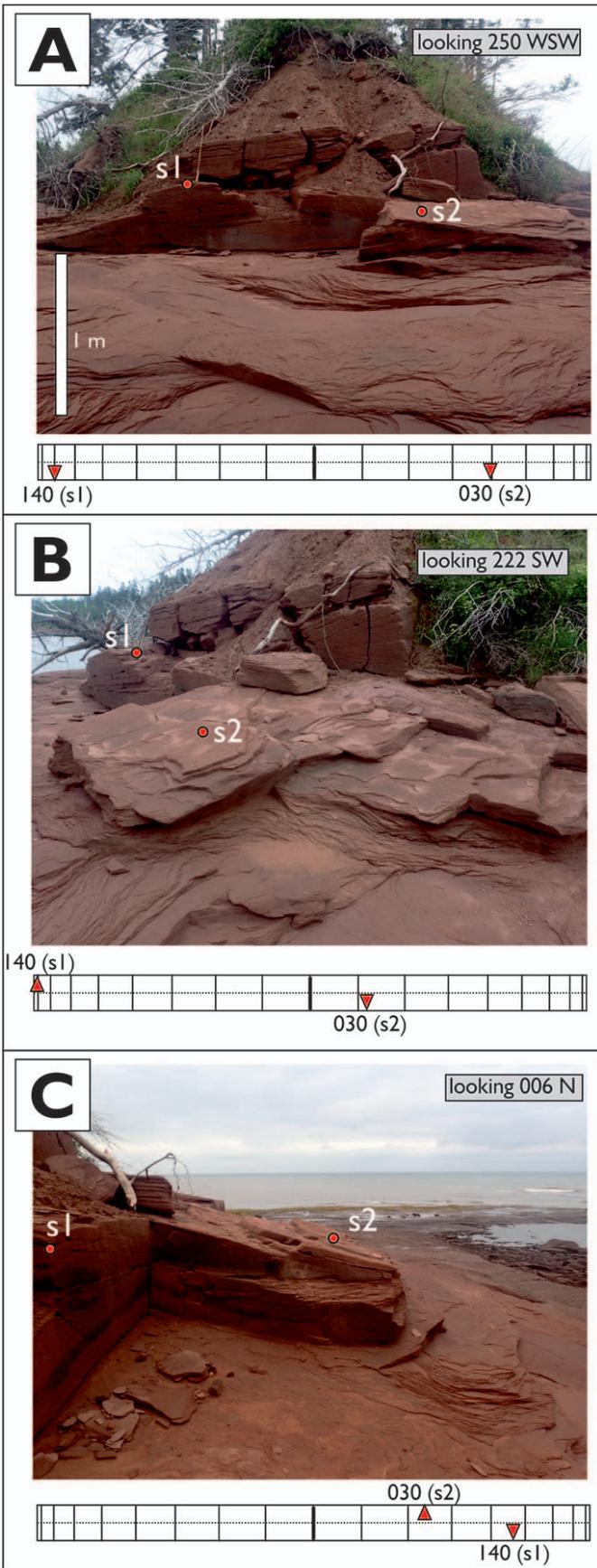
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FIG. 5.—Example of presentation technique applied to dipping surfaces bounding a convex-up three-dimensional fluvial bedform. A–C Images show same bedform photographed from different angles and locations, while directions shown on bar refer to dipping surfaces flanking the bedform (s1 and s2). Note how the three images show illustration of dip direction varying depending on angle of photograph but preserving primary data on direction relative to north. Carboniferous Cape John Formation, Amherst Shore, Nova Scotia, Canada.