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A graphic method for depicting basin evolution and changes in the dominant hydrodynamic process from paleocurrent data

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ABSTRACT

Paleocurrent data measured on depositional elements and sedimentary structures (e.g., channels, cross-strata) are commonly utilized in the description of sedimentary strata. Paleocurrent data provide information about the depositional setting and in some cases can be useful for immediately detecting specific depositional processes (e.g., herringbone cross-strata for bimodal tidal currents). The typical graphical representation used to report paleocurrent data is the rose diagram. However, rose diagrams are not able to disclose all information contained in paleocurrent data, limiting the potentiality of such a representation method. In particular, there is presently no method to highlight changes in the paleogeographic configuration that can ultimately have an impact on the evolution of depositional processes and paleocurrent direction through time. Here, we present a graphic method that permits instant visualization of anomalies in paleocurrent distributions of the stratigraphic record that can be linked to changes in the paleogeography due to tectonic evolution or in the dominant hydrodynamic process. It is important to highlight that the proposed method does not aspire to replace rose diagrams but to provide an additional tool to be used before and in combination with rose diagrams in order to extrapolate as much information as possible from paleocurrent data.

INTRODUCTION

Numerous publications have focused on looking at different options for best plotting geological data (e.g., Vermeesch, 2012). Paleocurrent data are fundamental to studying geological basins and sedimentary rocks because they can help elucidate regional aspects such as direction of paleoslope and sediment supply (e.g., Dasgupta, 2005; Noda and Toshimitsu, 2009; Korus and Fielding, 2017) and local features such as relations between internal directional structures and sand-body geometry, and they can support interpretation of depositional environments (Chiarella et al., 2012b; Davies et al., 2018). Paleocurrent indicators are usually measured from sedimentary structures (e.g., channels, scours, and cross-strata) in terms of their azimuth, and subsequently analyzed graphically by common methods of representation of directional data such as rose diagrams (Potter and Pettijohn, 2012) or other visual techniques (Davies et al., 2018).

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In the literature, attention has been given mainly to (1) statistical procedures for sampling and testing of preferred paleocurrent direction (Rao and Sengupta, 1972), (2) the correct paleocurrent determination in cross-stratified deposits (DeCelles et al., 1983), (3) rose diagram construction (Nemec, 1988), and (4) the introduction of a new graphic method for depicting paleocurrent data on photographs (Davies et al., 2018). As of today, the rose diagram is still the most commonly used method for graphically summarizing and visualizing the frequency distribution of two-dimensional directional data. One of the main aspects contributing to the widespread use of rose diagrams is their effectiveness for displaying spatial variation of paleoflow in plan view (i.e., on maps). In addition, rose diagrams have gained considerable popularity among sedimentary geologists due to the ease of construction and visual reading of data density variation (Nemec, 1988). For example, rose diagrams continue to be the best solution when we have multiple paleocurrent indicators derived from different structures along the same bed (e.g., ripples, dunes, grooves, flutes, etc.). Rose diagrams are also widely used in different earth science disciplines to investigate the relationships between elongate and/or aligned features such as tectonic or topographic lineaments and other surface or subsurface elements such as fluvial channels (Gioia et al., 2011, 2018), caves (Cafaro et al., 2016), or groundwater flow (Akinluyi et al., 2018). However, although widely used, rose diagrams have several well-known limitations (see Sanderson and Peacock, 2020, for a review): (1) The shape of the diagram is strictly dependent on the arbitrary selection of the bin size (i.e., the petal width), and its inappropriate choice can emphasize a preferential orientation (Nemec, 1988; Gioia and Schiattarella, 2010). (2) Rose diagrams are commonly constructed with the radius in each class proportional to frequency, and this tends to exaggerate statistically insignificant preferred orientations of the data set (Wells, 2000). In order to reduce these limitations, different authors have introduced a rigorous workflow of construction of the rose diagram (Sanderson and Peacock, 2020) or alternative methods of representation of orientation data (Gioia and Schiattarella, 2010). (3) Rose diagram graphic representation can present a limitation on instant visual cognition, producing difficulties in linking vertical and horizontal information (Davies et al., 2018). Finally, (4) rose diagrams do not completely disclose the information contained in paleocurrent data coming from tectonically active basins, hiding important information related to the evolution of the basin (e.g., rotation) contained in the original data.

In this paper, we propose a diagrammatic method of paleocurrent data representation that allows rapid recognition of anomalous distributions and

possible implications. Directional data are represented through a time-series diagram—a simple complementary method that facilitates the graphical plotting and interpretation of paleocurrent data sets. Moreover, this method allows display of several paleocurrent populations in the same graph, thus favoring the visualization of tectonic impact on the sedimentation and better emphasizing the related paleogeographic configuration changes. Data from the lower Pleistocene deposits of the Catanzaro Strait (Calabrian arc, southern Italy) are used to illustrate and test the proposed method. The selected study area represents a good example of an intramontane basin with a tectonostratigraphic evolution controlled by syntectonic block rotation due to strike-slip faulting. Stratigraphic features and trends of paleocurrent data record this tectonic evolution and its influence on the variation of the strike of the main axis of the depositional environment.

■ REGIONAL SETTING OF THE CATANZARO STRAIT

The Catanzaro Strait is a depression that separates the Sila and Serre massifs (Fig. 1A). It formed during the Pleistocene in response to a regional strike-slip fault system (northwest-southeast-trending left-lateral shear zones) that dissects the Calabrian arc into several blocks (Del Ben et al., 2008). The basin is bounded on both sides by east-west and WNW-ESE transcurrent left-lateral faults active during the sedimentation of the Pleistocene deposits (Van Dijk et al., 2000; Bonardi et al., 2001; Tansi et al., 2007). The Pliocene–Pleistocene succession of the Catanzaro Strait is composed from the base to the top by the Marcellinara marls (Pliocene) and the Catanzaro mixed siliciclastic-carbonate deposits (early Pleistocene). The latter are overlain unconformably by marine and fluvial terrace deposits (Chiarella et al., 2012a; Longhitano et al., 2014). Mixed siliciclastic-carbonate deposits (*sensu* Chiarella et al., 2017) consist of a series of vertically stacked cross-strata (50–500 cm thick) composed of sediment driven by tidal current and accumulated in a tectonically confined narrow basin elongated in an east-west direction (Chiarella et al., 2012a, 2016; Longhitano et al., 2014) (Fig. 1B). Paleocurrent directions measured on cross-strata are bidirectional toward WNW or ESE (Fig. 1C).

Paleomagnetic studies (Sagnotti, 1992; Scheepers et al., 1994; Speranza et al., 2000, 2011; Mattei et al., 2004, 2007; Cifelli et al., 2008) documented the clockwise rotation of $\sim 20^\circ$ affecting the Calabrian arc. According to the results of these studies, the rotations ceased near the end of the early Pleistocene. Moreover, Mattei et al. (2004, 2007) observed that the very high rate of rotation of the Calabrian arc was associated with the spreading of the Marsili Basin in the Tyrrhenian Sea, which occurred between ca. 2.1 and 1.6 Ma.

■ TRADITIONAL METHODS OF PALEOCURRENT ANALYSIS: THE ROSE DIAGRAM

Classical plots of frequency analysis of directional or angular data consist of a circular histogram or rose diagram formed by segments of circles with radius

proportional to the frequency (Davis, 1986). Different types of rose diagrams are based on a different representation of frequency radius (Fig. 2), as explained below.

It has been widely reported that the construction of rose diagrams is frequently inaccurate (Nemec, 1988; Wells, 2000; Sanderson and Peacock, 2020). Rose diagrams are commonly constructed with the radius in each class proportional to frequency, although it has been demonstrated that this kind of representation emphasizes the preferential orientation of quasi-random circular data (Nemec, 1988; Sanderson and Peacock, 2020). To avoid this issue, several authors have suggested the use of a radial scale, with radius proportional to the square root of frequency (e.g., Nemec, 1988), in a diagram that is generally referred to as an equal-area wedge diagram (*sensu* Sanderson and Peacock, 2020). However, although this type of diagram is strongly recommended (e.g., Nemec, 1988) and is available through dedicated software (Baas, 2000), there is still little use of it (Sanderson and Peacock, 2020). As a matter of fact, research works dealing with the analysis of directional data show that the rose diagrams with radius proportional to the frequency are still the prevalent ones (e.g., Freitas et al., 2021). The accurate selection of the bin size is another cause of potential misinterpretation of preferential orientation of circular data, and several authors have recommended a choice of the petal width as a function of the number of observations (Nemec, 1988; Gioia and Schiattarella, 2010).

Apart from the above-mentioned issues related to the construction of rose diagrams, there is an additional limitation on using similar plots to reconstruct the paleoflow in tectonically active basins or depositional systems characterized by changes in the dominant hydrodynamic process—the rose diagram represents just a “one-shot” summary of a long depositional history. This is a limitation when we want to examine the possible variation in the paleocurrent direction related to changes in the main depositional processes or the basin setting over time (geometry and/or configuration). A statistical population characterized by different subgroups is portrayed in a rose diagram with different preferential orientations, which commonly overlap or are not clearly delineated (see, e.g., Fig. 2). A rigorous statistical analysis should include the construction of a single rose diagram for each subpopulation, but the preliminary recognition of multiple subgroups in a complex directional data set is commonly not straightforward. The proposed graphical method overcomes this issue and can furnish a simple and fast approach for the assessment and interpretation of paleocurrent data.

■ PROPOSED ALTERNATIVE GRAPHICAL REPRESENTATION: THE TIME-SERIES DIAGRAM

Rose diagrams are typically used to represent the overall data set measured in a geological formation, specific area, or section in both outcrop and subsurface (Rogala et al., 2007; Chiarella and Longhitano, 2012; Longhitano et al., 2012; Li et al., 2015; Korus and Fielding, 2017; Rossi et al., 2017; Shiers et al., 2017), hiding potentially useful information.

Paleocurrent data from the lower Pleistocene mixed siliciclastic-carbonate successions of the Catanzaro Strait are here used as an example. In particular,

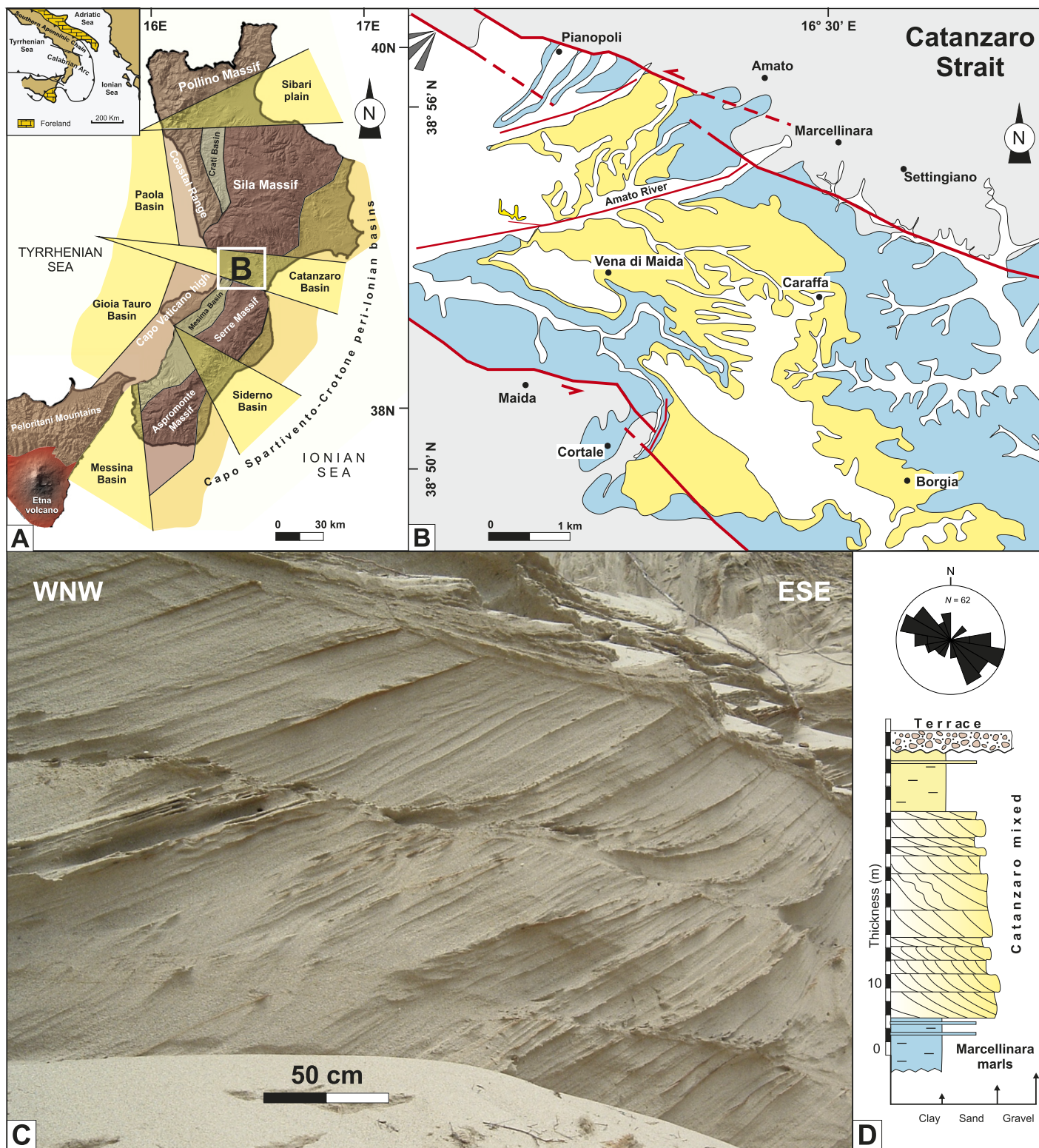


Figure 1. (A) Plio-Pleistocene block segmentation of the Calabrian arc (southern Italy) with the resulting sedimentary basins in yellow (Chiarella, 2016; after Ghisetti, 1979). (B) Geological map of the Catanzaro Basin bounded by sinistral strike-slip faults. Current-dominated deposits (in yellow) pertaining to the Catanzaro Strait accumulated above open-marine marls (in blue). (C) Unidirectional cross-strata of the Catanzaro mixed interval. Cross-strata consist of a compositional siliciclastic-carbonate mixing (*sensu* Chiarella et al., 2017) and were modulated by a tidal current. (D) Stratigraphic column of the Plio-Quaternary infill of the Catanzaro Strait, with a rose diagram reporting the paleocurrent data for the Catanzaro mixed interval. Colors identify the different stratigraphic units.

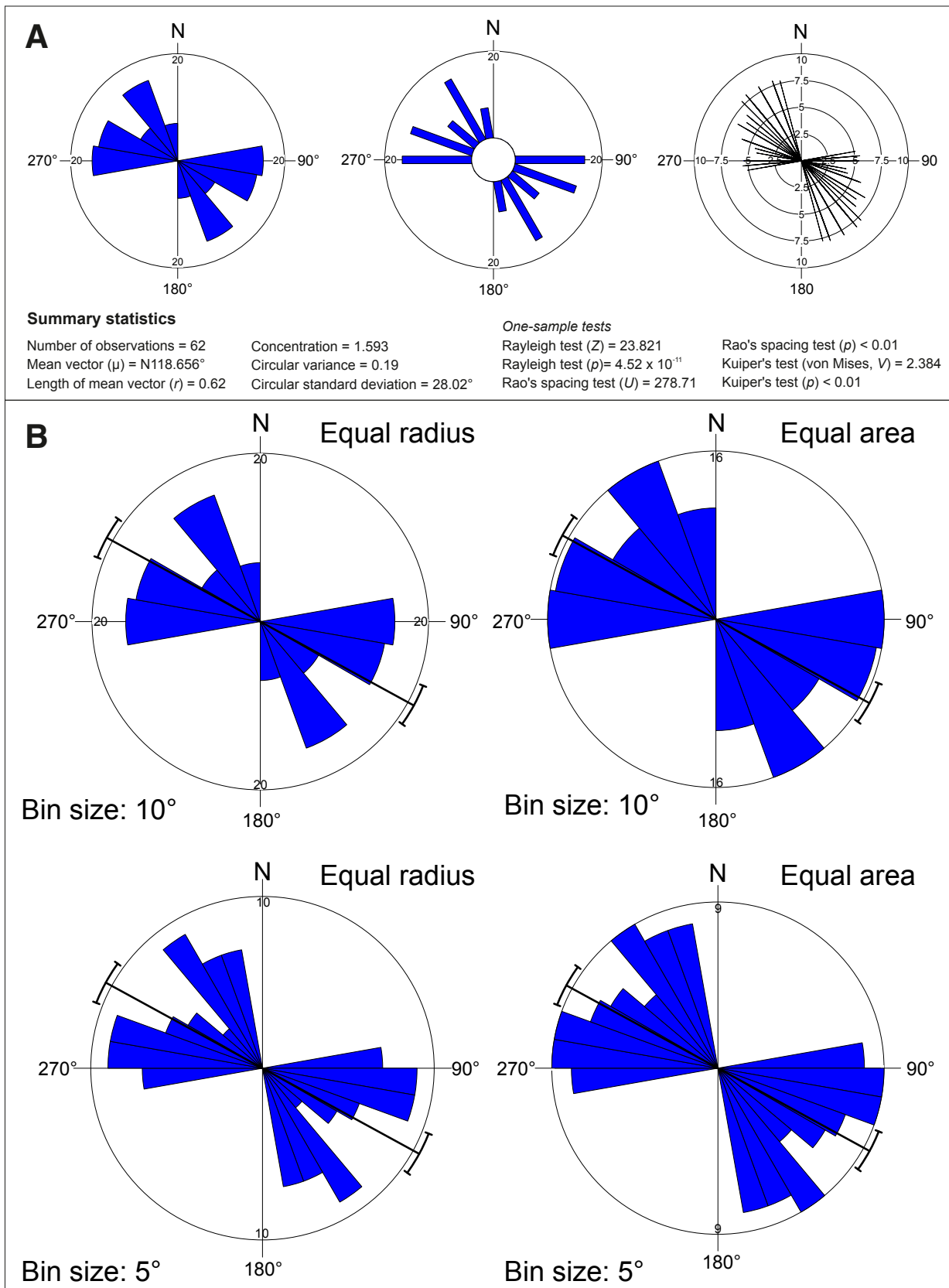


Figure 2. (A) Different rose diagram representations of the Catanzaro Strait paleocurrent data and relative statistical parameters. Concentric circular lines indicate the number of observations. The three representations are quite similar except for the type of bars depicting the number of data. (B) Influence of bin size and radius on the visual aspect of the rose diagram (black lines are the mean vector of the statistical population, whereas the arc circles indicate the 95% confidence interval of the azimuthal data). Note that diagrams with equal radius and smaller bin size tend to overemphasize the local maxima of the statistical population.

the rose diagram presented in Figure 1D show the main paleocurrent trends for this specific stratigraphic interval, characteristic of a particular depositional setting (i.e., strait), but it does not give information about the distribution of the data through time. A possible way to overcome this limitation could be to perform a detailed sedimentological interpretation of the studied interval, try to identify facies associations or units, and generate different rose diagrams for each recognized interval. This would generate several rose diagrams showing snapshots of the succession based on the degree of resolution of geological understanding of the system, although a change in facies association does not necessarily correspond to a change in the paleocurrent trend. However, this process can be affected by bias or error related to the aim of the study or the scientific background of the researcher running the study. Moreover, cutting a statistical population into different subsets can limit the statistical significance of each group.

In Figure 3, we propose a method whereby paleocurrent data are represented in chronological and stratigraphic order in a time-series diagram. Paleocurrent data need to be standardized to represent only the orientation and not the sense (the direction of flow paleocurrent was pointing). For tide influenced and dominated systems where it is possible to have bimodal currents, one of the components needs to be converted to its reflection in order to have all data within the 0° – 180° spectrum. This homogenizes the data that have the same orientation without considering the sense, given that paleocurrents are the record of two different phases related to the same tidal current and paleogeographic setting data are not altered. Accordingly, the x-axis of the diagram is composed of 180 increments, each of which represents the measured or calculated azimuth. The numerical value of the paleocurrent direction, in degrees, is recorded following the stratigraphic order. The y-axis indicates bed number, from older to younger. Missing values represent covered intervals where it was not possible to acquire the paleocurrent measurements or intervals not recording paleocurrent indicators. A similar approach has been used by Muzzi Magalhaes and Tinterri (2010, see their fig. 20) to identify change in basin topography after the emplacement of mass-transport deposits. Like for rose diagrams, multiple sets of paleocurrent data measured on different structures can be plotted on the same time-series diagram using different colors or symbols.

It is important to highlight that the proposed time-series representation does not aim to replace the rose diagram, which will continue to be an easy and immediate, although not exhaustive, way to represent paleocurrent data. Moreover, rose diagrams will still represent the best methodology for particular depositional settings (e.g., meandering fluvial settings) characterized by high statistical dispersion of directional data not prone to be converted to the 0° – 180° range used in the time-series diagram.

Figure 4 shows examples of four directional data end members that are possible to record in sedimentary depositional settings. Figure 4A presents a random distribution of directional data, which provides a sawtooth distribution in the time-series diagram. In this case, the rose diagram (e.g., Gomis-Cartesio et al., 2017, see their fig. 4) provides limited information about any possible hidden trend, whereas the proposed graphic method can be useful to discriminate limited portions of the stratigraphic sequence with a relative constant direction

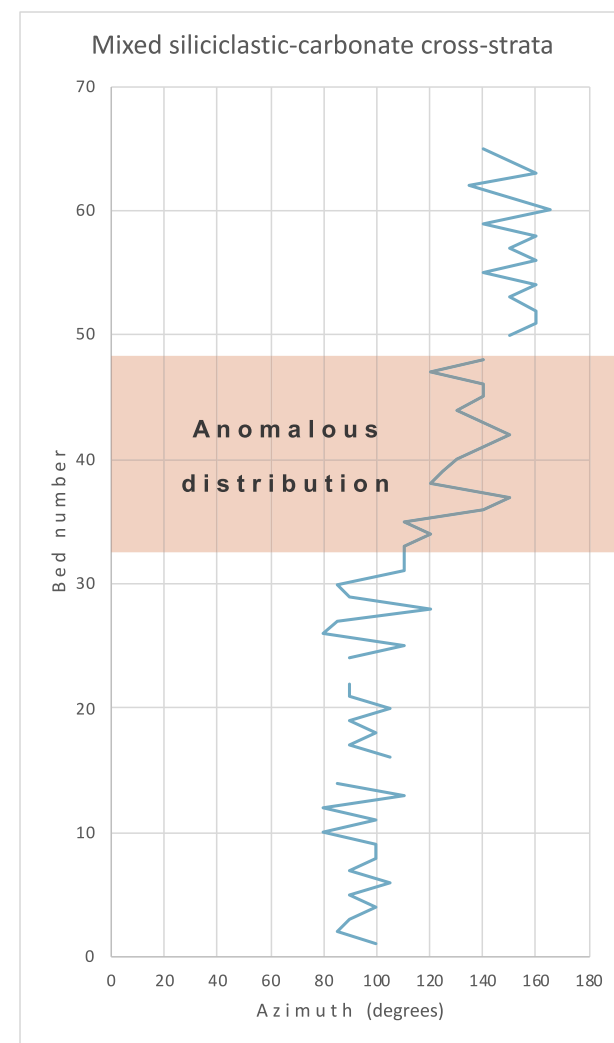


Figure 3. Proposed time-series graphic representation. This example of the presentation technique is applied to paleocurrent data from the Pleistocene Catanzaro mixed siliciclastic-carbonate interval (Catanzaro Strait, southern Italy). Raw data are the same as those used to create the rose diagram presented in Figure 1D. Missing values represent covered intervals where it was not possible to acquire the paleocurrent measurements or intervals not recording paleocurrent indicators. The benefit of the proposed technique is that data are plotted using a time-series diagram following the stratigraphic order. This allows easy visualization of intervals characterized by anomalous distributions (red area) potentially linked to change in the paleogeographic setting of the basin.

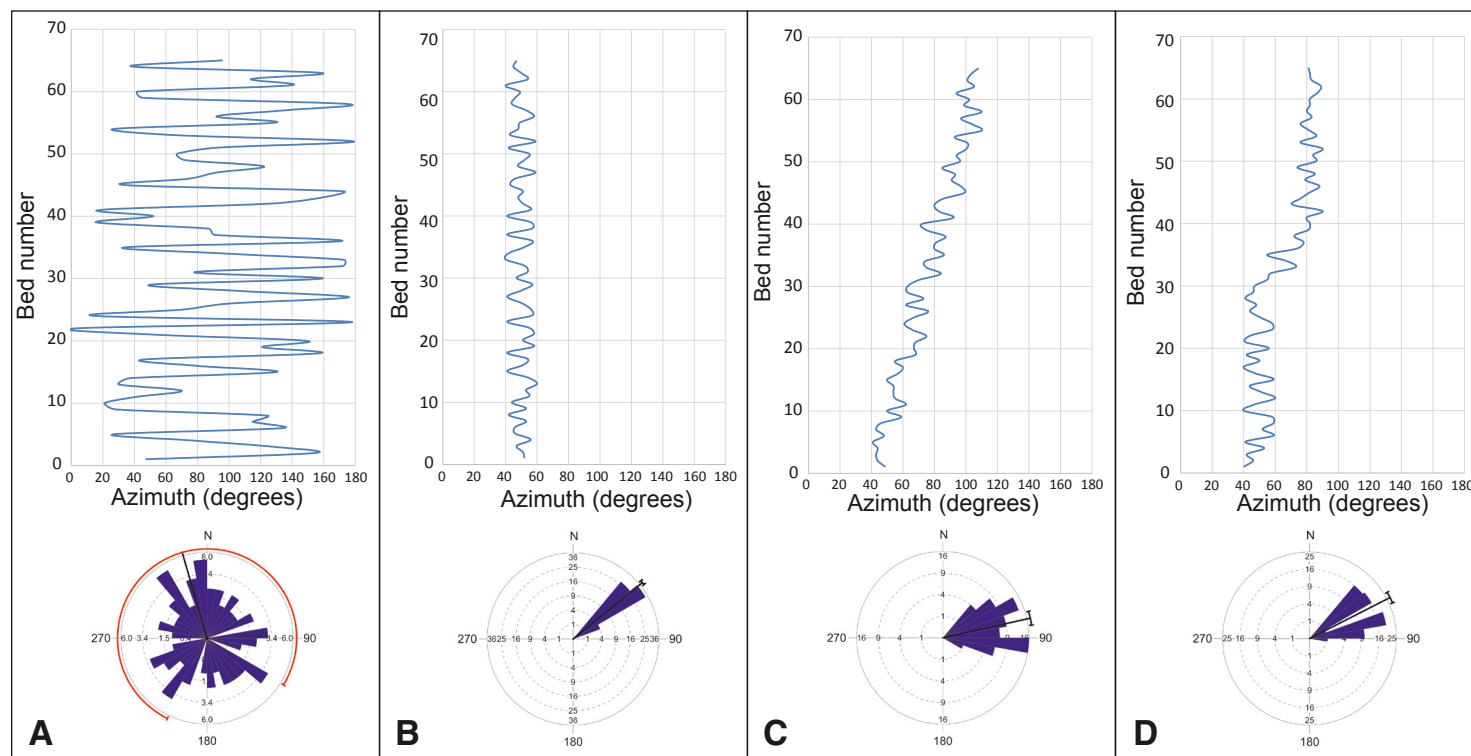


Figure 4. Directional end members plotted using the classic rose diagram and the proposed time-series diagram. Dataset is randomly generated in a spreadsheet. Labels on the concentric circular lines indicate the number of observations of the statistical population. (A) Randomly distributed paleocurrent data showing a sawtooth distribution in the time-series diagram and not providing a clear trend in the rose diagram. Red circle indicates the circular standard deviation of the statistical population. (B) Paleocurrent data concentrated within a narrow statistical distribution showing a clear unidirectional direction in both time-series and rose diagrams. (C) Paleocurrent data providing different information when plotted using a time-series versus a rose diagram. In the time-series diagram, it is possible to recognize a progressive change through time in paleocurrent direction, while the rose diagram reports only a bimodal distribution, being unable to provide any information on the stratigraphic evolution of the measured data. (D) Paleocurrent data displaying information in a rose diagram similar to that in C, while in the time-series diagram it is possible to see that there is a specific stratigraphic interval (between beds 30 and 35) recording a change in, e.g., the depositional process, basin physiography, or some other aspect. Before and after this event, paleocurrent data have a low statistical dispersion of the azimuthal distribution, suggesting stable depositional conditions.

of paleocurrent data. Figure 4B represents a case of unidirectional distribution of paleocurrent data (e.g., de Weger et al., 2020, see their fig. 2). In this case, the trend is clear, and both graphs (i.e., rose diagram and time series) provide similar information. The rose diagram exhibits a clear maximum around the N40°–N60° direction with a low amount of statistical dispersion, whereas the proposed time-series diagram representation shows a straight trend along a N40°–N60° orientation. Lin and Bhattacharya (2021, see their fig. 5d) recently published a set of rose diagrams of paleocurrents measured from current ripples showing a bidirectional to random distribution of the directional data. Due to the anomalous nature of such rose diagrams, it would be interesting

to apply the method proposed here to evaluate time-related trends. Figure 4C introduces a statistical population of paleocurrent data showing a gradual change in orientation from northeast to east. In this case, the rose diagram is characterized by a maximum along the northeast direction with a high level of statistical dispersion. Rose diagrams presented in Figures 4C and 4D are quite similar, highlighting a well-defined bimodal distribution of the data, like in Figure 1D. However, this type of representation can hide crucial information about abrupt or subtle modification of the paleocurrent orientations related to external factors such as change in the paleotopography or basin physiography. Conversely, the proposed method (i.e., time-series diagram) is able to

detect a clear linear trend of directional data related to a progressive change in paleocurrent orientation from N40° to N90° (Fig. 4C) or an episodic change (i.e., between beds 30 and 35, Fig. 4D) referable to a geological event to be carefully investigated and understood, separating two more stable trends positioned at two different azimuths (N40°–N60° versus N90°–N100°). This type of evolution can be clearly recognized in the time-series diagram (Fig. 4D), as documented in the proposed example of the Catanzaro Strait (Fig. 3).

■ DISCUSSION AND CONCLUDING REMARKS

We propose the use of a simple graphical method of visualization and analysis of paleocurrent data that is complementary to the classical representation of directional data using rose diagrams. Rose diagrams are an effective graphical representation of orientation data, especially for displaying spatial variation of preferred orientation (e.g., main trends of stratigraphic elements in different sectors of a geological map). Conversely, the recognition of different orientation clusters or subgroups in a rose diagram is commonly problematic due to the bin-size issue, which could generate an overlap of different directional trends. The preliminary individuation of preferential orientation and the relative construction of different rose diagrams for each recognized interval require the application of statistical tests, which can fail to show significance in highly dispersed directional data or in the presence of gradual temporal changes in paleocurrent data. We tested the usefulness of our method in a Plio-Pleistocene tectonic basin of southern Italy that records a well-constrained syndepositional block rotation. Paleocurrent analysis based on the rose diagram of the tested example (Fig. 2) highlights a highly dispersed and bimodal trend along N80°–N170° orientations, but inspection of the diagram did not allow the individuation of the well-defined gradual changes in paleocurrent orientations along the sedimentary succession. Our method overcomes the limitations of rose diagrams and can represent an effective and easy-to-use approach for the identification of “anomalous” intervals in a stratigraphic sequence. In particular, we argue that it can be useful for portraying progressive changes in paleocurrent data in an easier and more effective way than traditional representation of directional data. Indeed, the proposed method permits visualization of progressive small- and large-scale variations in the plotted data, highlighting any anomalous shift in the distribution of the data, although it is difficult to define the exact start and end of the anomalous interval. Accordingly, potential changes in the basin physiography or setting are emphasized without the need for previous understanding of the geology of the area, removing any possible bias. However, because it is only a technique for presenting information graphically, additional studies need to be performed in order to assign the anomalies to a potential specific geological process. In the example from the Catanzaro Strait, it is possible to recognize an anomaly between bed numbers 32 and 48 (Fig. 3), where paleocurrent data change from N90°–N110° to N140°–N150°. Based on previous study in the area, this anomaly can be interpreted as related to the Pleistocene clockwise rotation of the Calabrian arc recorded by paleomagnetic data (Mattei et al., 2007). The so-called “anomalous” intervals from

the paleocurrent distribution point of view may hide very valuable information useful for reconstructing the regional evolution of the basin.

It is important to highlight that the proposed method is applicable only to stratigraphic successions recording the same sedimentary environment and in which it is possible to isolate the allogenic factors that control sedimentation (climate, eustasy, tectonism) to identify the factor responsible for the “anomalous behavior”. Accordingly, it would be important for this condition to be clearly established in advance to avoid possible use of the method in inappropriate examples, leading to erroneous conclusions.

The benefits of our proposed method relative to the typical rose diagrams are: (1) it is easy to apply to existing data sets because they do not need any prior manipulation; (2) it permits easy recognition of anomalies in the distribution of the data through time; (3) recognized anomalies can be linked to known geological events or can open new avenues of research to identify the trigger mechanism behind the anomalies; (4) it removes any potential bias in the interpretation because data are plotted following the stratigraphic order, and results clearly show anomalies, where present, without any previous geological knowledge; and (5) it can be easily applied to other sources of data, such as azimuthal comparison of relationships between tectonic lineaments and fluvial net geometry.

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