

## Research paper

## OATools: An ArcMap add-in for the orientation analysis of geological structures

Lenka Kociánová<sup>a,\*</sup>, Rostislav Melichar<sup>b</sup><sup>a</sup> Czech Geological Survey, Leitmerova 22, 602 00 Brno, Czech Republic<sup>b</sup> Department of Geological Sciences, Faculty of Science, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic

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## ABSTRACT

This paper describes Orientation Analysis Tools (OATools), a new add-in, which has been developed for ArcGIS software (ESRI) to allow the spatial analysis of structural data. These tools bring a complex approach to structural data analysis that highlights the spatial aspect of oriented data. In this paper we introduce the functionality of this add-in, which allows users to plot selected data in azimuthal projection, calculate and plot fold axes, construct density distribution diagrams and rose histograms, and create maps of spatial averages and fold axes. There is a link between projections and maps; therefore, it is possible to select point data in the projection and see their location on the map, and vice versa. Practical use of these tools is demonstrated in a case study of the Svatka and Polička crystalline units (Eastern margin of the Bohemian Massif, Czech Republic), where a large dataset was collected. Using OATools the structural conditions were explored. Major changes in foliation dip directions were detected and the axial surfaces of the folds were determined. We also demonstrate the benefit of applying these tools, together with the potential of GIS with respect to spatial data queries, storage, and visualization.

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## 1. Introduction

The geological mapping and structural investigation of deformed geological units give rise to large datasets of oriented data. Structural data are captured and stored systematically to enable further GIS processing and map compilation.

Geological observations are bound to the coordinates of control points, where structural measurements are made and from which other descriptive data are taken. The localization of these control points plays an important role in map creation. Therefore, data are stored in a spatial database and the use of GIS software is essential. GIS software provides useful functionality for spatial analysis, but there is a lack of tools suitable for the processing of oriented data typical of structural geology (Alberti, 2005).

This work was motivated by a need to unify the workflow of structural analysis in a single software environment dedicated to storage and visualization of spatial data. To this purpose, Orientation Analysis Tools (OATools) were created. This add-in for ArcMap brings new functionality to the most widely-used software in geological mapping – ArcGIS (ESRI, 2014) – and has the potential to be used also in other fields of study.

## 1.1. Existing software

A range of good quality software is available for plotting oriented lines and planes in azimuthal projection. Plotting functionality was implemented in ArcView 3.0 GIS by Knox-Robinson and Gardoll (1998) to investigate the spatial aspect of directional data. This module-GIS-Stereoplot-allows the plotting of structural data in either equal-area or equal-angle nets for the purpose of mineral exploration.

ArcView GIS 3.0 produced by the Environmental Systems Research Institute (ESRI) was a forerunner of the current ArcGIS software product line and is no longer developed and supported.

A spatial averaging routine was integrated in ArcMap (version 8.2) by Maxelon (2004). This tool is part of a macro Export Toolbox written in Visual Basic for Applications (VBA) focused on data export and structural data assessment.

Modern applications for spherical data processing include statistical functions as well as rotation and transformation functions. Examples are GEOrient (Holcombe, 1994), Spheristat, Stereonet for Windows, and OSXStereonet (Cardozo and Allmendinger, 2013) for Macintosh. Most of this software, however, is not able to analyze the spatial information associated with directional data and cannot work with the geospatial vector data format employed by modern GIS software. Consequently, structural analysis cannot be accomplished without moving back and forth between various software applications.

\* Corresponding author.

E-mail addresses: [lenka.kocianova@geology.cz](mailto:lenka.kocianova@geology.cz) (L. Kociánová), [melda@sci.muni.cz](mailto:melda@sci.muni.cz) (R. Melichar).

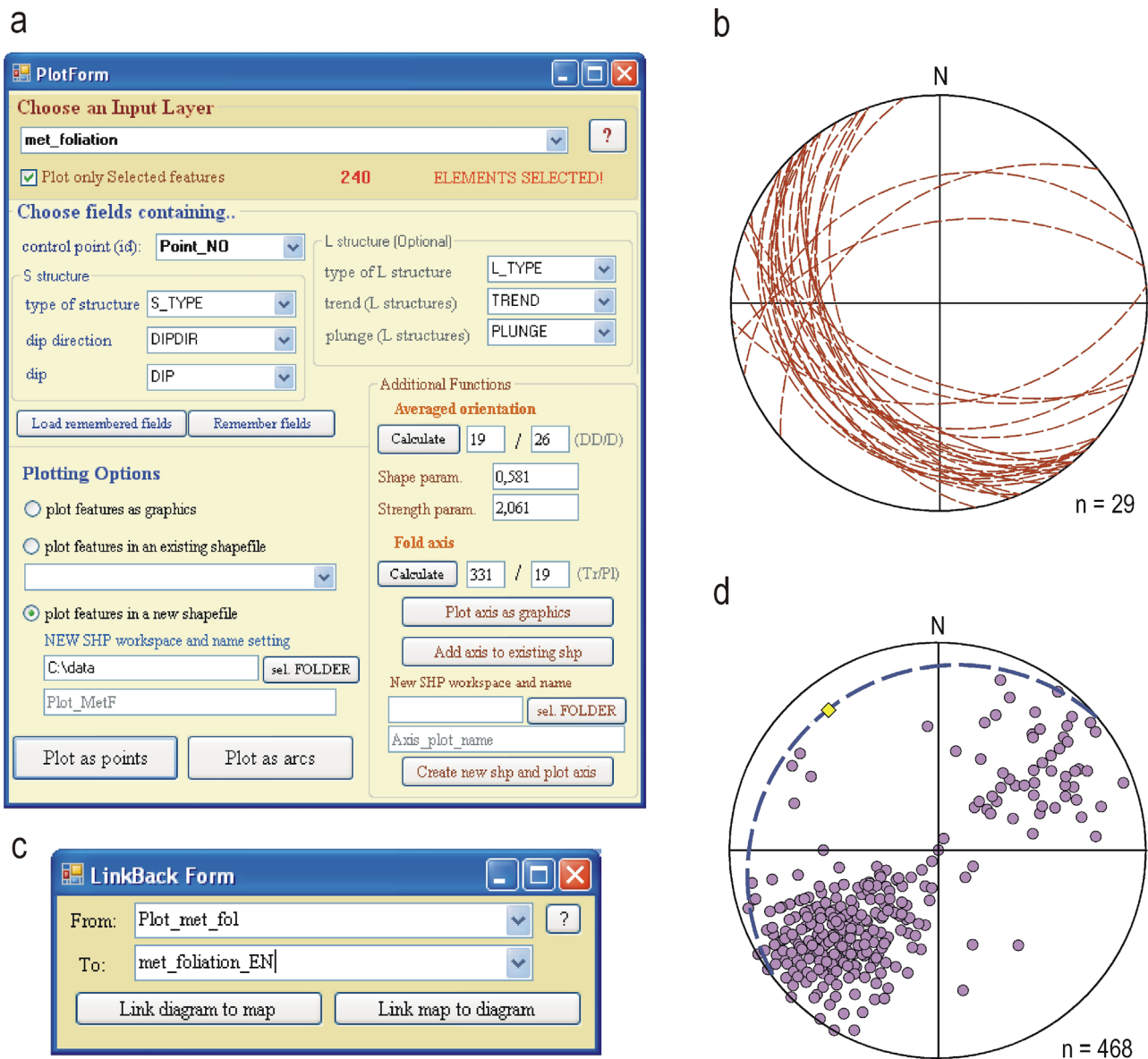
## 1.2. OATools geospatial functions

The tools presented here combine orientation analysis techniques with GIS functionality. Data are analyzed on the basis of their regional geological setting, topographic position (e.g. area of interest), and/or attributes stored in the spatial database. The GIS selection tools enable this selection to be made by location or by attributes as well as by spatial and non-spatial relationships. OATools read the selection from the dataset which is to be processed.

The functions of OATools offer methods of oriented data visualization in spherical azimuthal projections (equal-area) and statistical analyses such as the creation of density distribution diagrams and the calculation of mean vector and fold axis. Equal-area projection is used, because it is suitable also for density distribution diagrams (the density of plotted points is distorted by equal-angle projection). Data in the projection and on the map can be linked. Another function enables the representation of the spatial distribution of lines and planes in a rose histogram.

Further functions include data interpolation methods. These tools create a grid of interpolated orientations with a user-defined interval and radius of influence. The user can then recognize possible attitude variations and changes in the context of the geological setting.

Working interactively with both map and equal-area projection facilitates the determination of regions (structural domains) where geological structures have certain geometrical characteristics (types of distribution). The foliations of such domains should share common axes (Vollmer, 1990). The subdivision of a geological map into structural domains is a useful method of analyzing complex structures (Ramsay and Huber, 1987; de Kemp, 1998).



**Fig. 1.** (a) "Plot" tool dialog box. Fields for dip direction and dip are filled in the "S-structure" section. Fields for orientation of lineation can be set in the "L-structure" section. (b) Example of a great circle diagram (beta diagram). Great circles are projected on a plane of equal-area projection. (c) Dialog box of the "Link Back" tool. The button used sets the direction of the link. (d) Foliations from the SE sector of the Svatka crystalline unit (poles to planes), fold axis (yellow diamond), and fold axial surface (great circle) are plotted. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 2. Functionality and implementation

### 2.1. General interface

OATools are an add-in for ArcMap version 10.2, which is part of the ArcGIS software package. The add-in is applicable also to a higher version of ArcGIS (10.3). The tools were created in Visual Basic.NET (VB.NET) using Microsoft Visual Studio (2010) with ArcObjects, a developer kit for ArcGIS. They are easy to share and install on a computer (just by double clicking on the esriAddIn file). No administrative rights are required and no other license or extension is needed.

These tools appear in ArcMap as a toolbar. The graphical user interface (GUI) is composed of interactive dialog boxes (Fig. 1a), where the user can set the input data and parameters, perform and display calculations with numerical results, and start the computation producing new data that are added into the ArcMap application.

### 2.2. Input data

Input data for all OATools are in a geographical format (an ESRI shapefile or feature class in geodatabase). Tabular data (e.g. xls, dbf) containing  $X$ ,  $Y$  coordinates can be added to the map and saved as a shapefile or feature class. The table should contain a field for the control point ID and fields for either a planar structure (type of structure, dip direction, dip) or a linear structure (type of structure, trend, plunge). The fields are defined in the input dialog box. The field for type of structure is used to distinguish different structures plotted in one shapefile, as well as the calculated fold axis plotted in this shapefile. This attribute can then be used to set the symbology—different colors are used for different types of structure. The setting of field names can be saved as a text file for future use. OATools require the coordinates of a planar coordinate system that uses a measurement system to locate features, not angular units (latitude and longitude).

### 2.3. Spherical projection

The initial step in using OATools is to define a new azimuthal projection using the “New Projection” button on the toolbar. An azimuthal lower hemisphere equal-area projection appears. This projection is added to the map document of the ArcMap application as a new data frame. It is switched simultaneously to Layout View in order to see both the projection and the map.

#### 2.3.1. Point and great circle diagram

The “Plot” tool button on the OATools toolbar opens an interactive dialog box (Fig. 1a). The layer containing structural data is chosen (only layers from an active data frame are in the list) and fields for planar and (or) linear structures are set. The plotting options include the output in the form of graphical markers for fast plotting or (which is recommended) a vectorial output, i.e. a shapefile. The shapefile can be symbolized on the basis of attributes and linked back to the map through the ID field. This is achieved using the “Link Back” tool from the OATools toolbar.

A plane can be depicted as pole to plane (Fig. 1d). The distance from the diagram center (in equal-area projection) is computed according to

$$Xd = r \cdot x / \sqrt{(1+z)} \quad (\text{E.1a})$$

$$Yd = r \cdot y / \sqrt{(1+z)}, \quad (\text{E.1b})$$

where  $x$ ,  $y$ ,  $z$  are components of the directional vector and  $r$  is the

radius of the diagram (Melichar, 2005).

The second option is to plot the plane as a great circle (Fig. 1b). For equal-area projection, the representation of a plane is a non-circular curve – a quartic equation (Hobbs et al., 1976). A segment of the true circle, which is an approximation of this curve, is used instead of the curve, since deviation from it is small (Richter and Krejci, 1994). The radius and the center point of the true circle are determined (Knox-Robinson and Gardoll, 1998).

#### 2.3.2. Fold axis and averaged orientation

The “Additional Functions” section of the dialog box of the “Plot” tool offers calculation of the fold axis, the averaged orientation, and the shape and strength parameters, which are parameters useful in discriminating girdle-type distributions from clustered distributions (Fisher et al., 1987). These statistical functions use the orientation matrix, whose components are the sums of the direction cosines of selected orientations (Scheidegger, 1965; Fisher et al., 1987; Lisle, 1989). This is a useful indicator of fabric shape (Woodcock, 1977; Vollmer, 1990). Computed eigenvalues and eigenvectors are used. The shape and strength parameters are functions of the eigenvalues. The maximum eigenvector corresponds to the mean axis of the data; the minimum eigenvector is the direction of the fold axis, the  $\pi$ -pole. The calculated orientation of the fold axis can be plotted in the projection.

#### 2.3.3. “Link Back” tool

The “Link Back” tool dynamically links the map and projection data. The link works through the FID field. This field is added to a newly created shapefile (as an “N” field) and filled with the FIDs of the original data. The direction of the link is chosen in the dialog box (Fig. 1c).

The “Link Back” tool can be used to determine the location of oriented structures that deviate from the expected type of distribution.

#### 2.3.4. Density distribution

The “Density Distribution” tool calculates the density in the diagram representing the projection of the spherical surface, where places with the same density are drawn with the same color intensity.

The “Density Distribution” tool on the OATools toolbar opens an interactive dialog box (Fig. 2a) where input parameters and the output workspace are set. The smoothing parameter defines the level of detail in which the contours of the density distribution are drawn (the smaller the value of the parameter, the less detailed the contours). A recommended value is displayed, which depends on the size of the dataset. This value is empirical and is determined in order to produce a diagram comparable to that created by the Schmidt method (Schmidt, 1925). A color ramp and the number of color classes can be set in the Appearance tab (Fig. 2b).

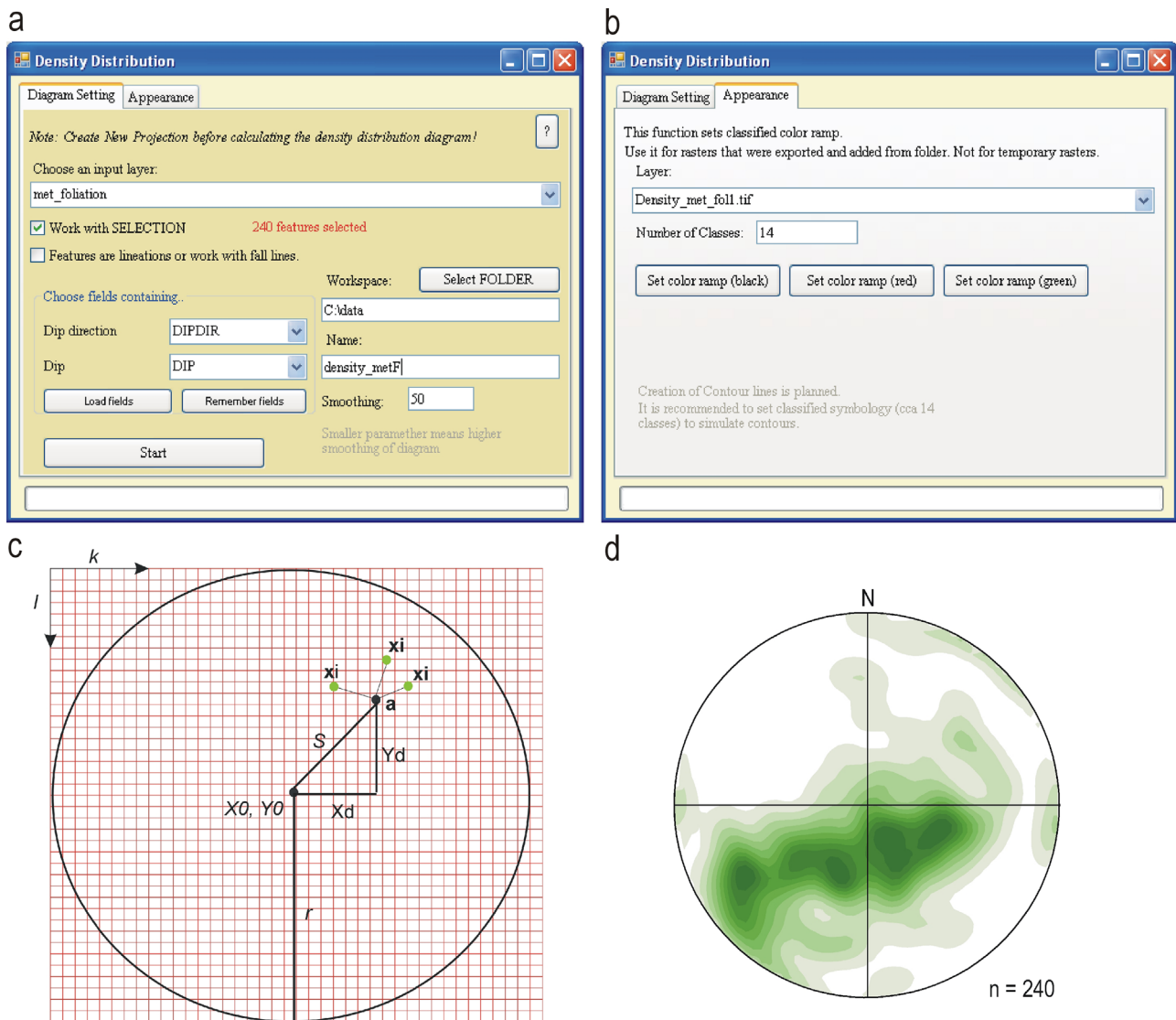
A raster dataset is created in the selected workspace and the density is calculated for each cell of the raster in the  $X$ ,  $Y$  position. The dip ( $\varphi$ ) and dip direction ( $\alpha$ ) that correspond to the cell position in the equal-area projection (Fig. 2c) are calculated (Melichar, 2005) according to

$$\varphi = \pi/2 - 2\arcsin(S/2) \quad (\text{E.2a})$$

$$\alpha = (2 - \text{sign}(Yd) - \text{sign}(Xd \cdot Yd))\pi/2 + \text{atan}(Yd/Xd), \quad (\text{E.2b})$$

where  $S$  is the direct distance of the cell from the diagram center and  $Xd$ ,  $Yd$  are the components of this distance in the  $X$  and  $Y$  directions. The dip and dip direction are expressed as vector  $\mathbf{a}$  ( $x_a$ ,  $y_a$ ,  $z_a$ ).

Density is determined using the Watson density (Watson, 1983)



**Fig. 2.** (a) Dialog box of the “Density Distribution” tool. The number of selected objects is displayed. The smoothing parameter is optional, but a recommended value is provided. (b) Appearance tab. The color scale and number of classes for the density distribution diagram are set here. (c) Cell array ( $k$ ,  $l$ ). Each cell represents a position on the surface of a sphere.  $S$  is the distance of a particular cell from the diagram center ( $X_0$ ,  $Y_0$ ). The  $\mathbf{x}_i$  direction is a vector expression of orientation that has an influence on the density calculated in the  $\mathbf{a}$  direction. (d) Example of a density distribution diagram. A color scale with 12 classes is set. The smoothing parameter is 65. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for axial data (e.g. directions with an unknown stratigraphic facing), ensuring that all measurements of orientation fall within the lower hemisphere of the azimuthal projection.

The density in the  $\mathbf{a}$ -direction is the sum of  $W$  (Fisher et al., 1987) according to

$$W(\mathbf{a} \cdot \mathbf{x}_i) \approx \exp^{Cn(\mathbf{a} \cdot \mathbf{x}_i)^2}, \quad (\text{E.3})$$

where  $\mathbf{x}_i$  is the directional vector of the  $i$ th orientation obtained from dip and dip direction in the input table.  $Cn$  is the smoothing parameter.

The resulting density distribution diagram is shown in Fig. 2d. This diagram can be implemented in the orientation analysis of structural data as well as other types of oriented data (e.g. rock slopes).

### 2.3.5. Rose histogram

The “Rose Histogram” tool enables the representation of the frequency of orientations of geological structures in the geological map. Orientations are read from point geometry data (orientations

are in the attribute table) or are calculated from the geometry of line data. The “Rose Histogram” tool on the OATools toolbar opens a dialog box (Fig. 3a) where the point or line layer is chosen.

The routine reads dip directions from an attribute table of point data and converts them to strikes. In the case of lines, the averaged orientation of line segments is found (the arithmetic mean). Orientations are matched to one of the 10 degree classes, which is the most common convention (Munro and Blenkinsop, 2012). The length of the class with the highest frequency equals the diagram radius. Other classes are relative to it. A new polygon shapefile is created (its shape is determined by the lengths of the classes) and added to the ArcMap document. This polygon forms the rose shape (Fig. 3b).

### 2.4. Interpolation tools

Interpolation tools analyze structural data in space; therefore, changes in their direction can be observed and related to other geological features. This functionality can be used in structural analysis, structural domain definition, and cross section

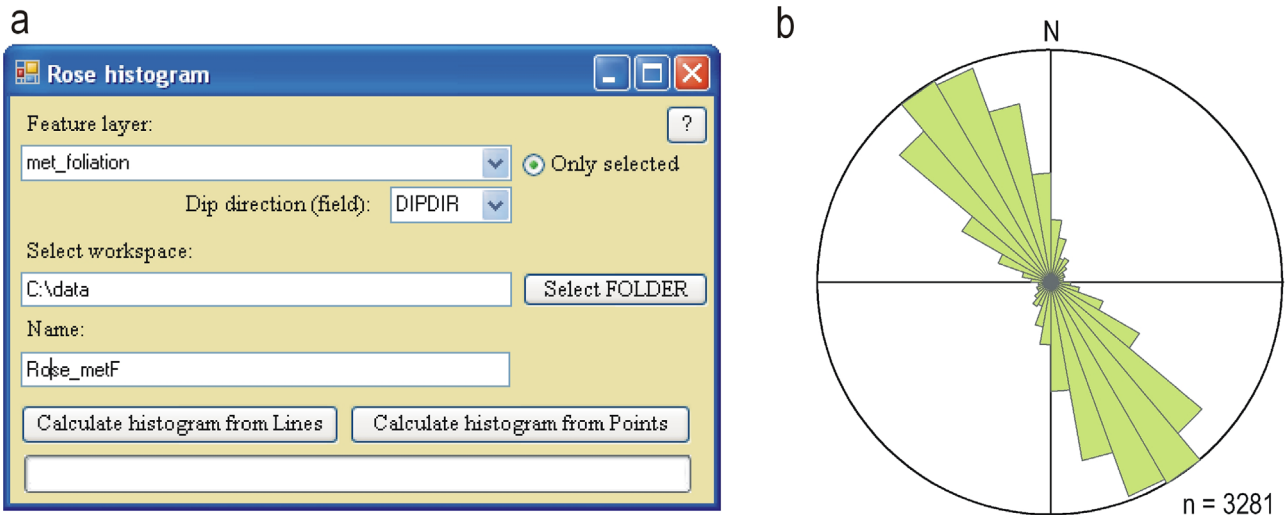


Fig. 3. (a) “Rose Histogram” tool dialog box. Input is the point or line layer. (b) Example of a rose histogram. The length of 10° classes represent the frequency of particular strikes.

construction.

2.4.1. Spatial averaged map and map of fold axes

The “Spatial Averaging” and “Map of Fold Axes” buttons on the OATools toolbar open interactive dialog boxes where input data are set (Fig. 4a). A selection from the dataset is read after the input layer is chosen. Fields for dip and dip direction are defined in the drop-down menu or loaded from a text file (created by the “Remember Fields” button in the previous use). The user can modify two parameters: the interval of the grid of averaging stations and the radius of influence (Fig. 4b). The radius of influence is the radius within which structural data are included in the calculation.

The routine determines the extent of the data and subsequently the width and height are divided by the interval to find the number of averaging stations in the X and Y directions.

Therefore, the number of stations depends on the extent of the data. This value in both directions, and the width and height of the area are displayed in the tool dialog box. This information helps to determine whether the interval is adequate. The interval is the same in both directions—the squared grid prevents the misrepresentation of results.

The sum of orientation matrices weighted by distance from the averaging station is calculated according to (Scheidegger, 1965)

$$\mathbf{M} = \sum \mathbf{M}_k \cdot w_k \tag{E.4}$$

where  $w_k$  is the weight of a particular orientation corresponding to the inverse distance from the averaging station and the matrix  $\mathbf{M}_k$  equals the columnar vector multiplied by the transpose, i.e. the row vector of the  $k$ -th orientation (the dyadic product).

Eigenvalues are derived and used to obtain the averaged

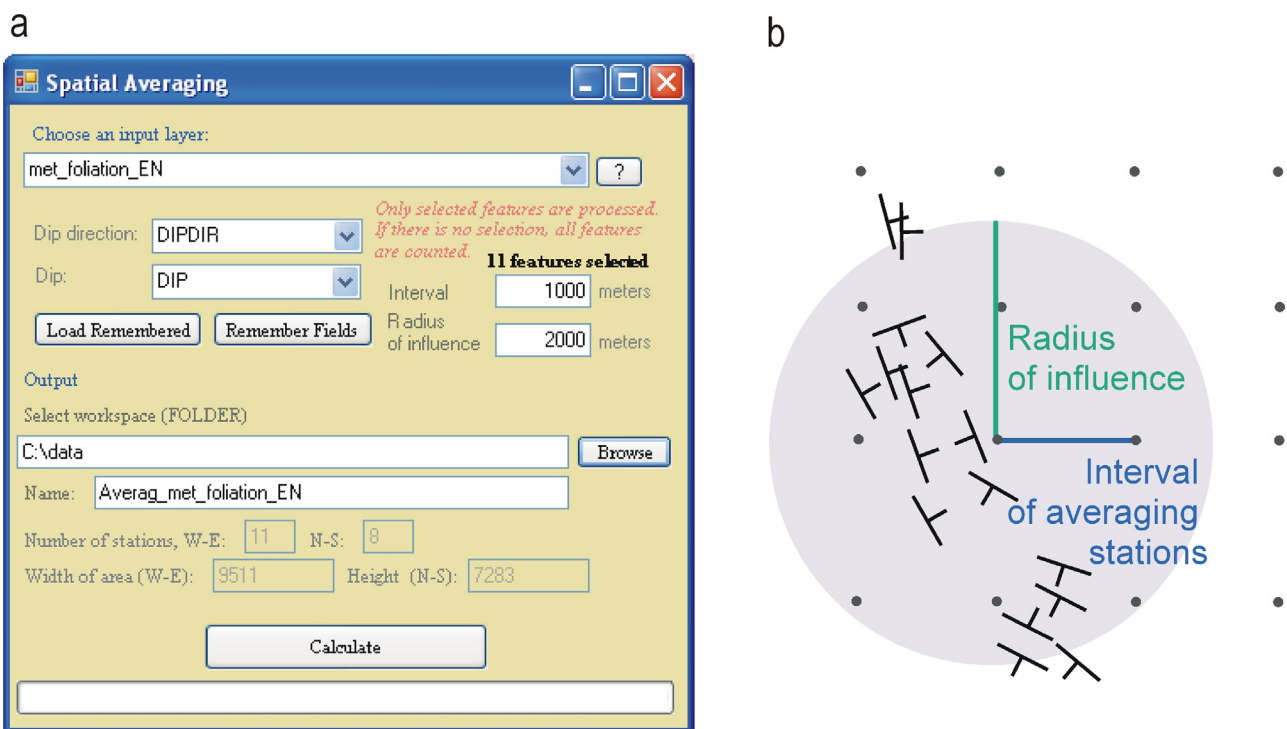


Fig. 4. (a) Dialog box of the “Spatial Averaging” tool. The number of selected objects is displayed. The number of stations in the X and Y directions as well as the extent of the data are provided. (b) Optional parameters of spatial averaging: interval of the grid and radius of influence.

orientation and the orientation of the fold axis. The result is a point geometry shapefile with a coordinate system identical to that of the original data.

After the routine is performed, this shapefile is added to the ArcMap document. Symbols are rotated according to the dip direction. An attribute table of the shapefile contains information taken from the original data (dip, dip direction, and – if present – the control point ID and type of structure). This routine also incorporates a check on the extent of the data, which prevents extremely long processing times resulting from mistakes in the coordinates in the original table. The spatial averaged map and map of fold axes give an overview of structural conditions in the geological map (Fig. 6a and b).

### 3. Case study: Svatka and Polička crystalline units (eastern margin of the Bohemian Massif)

OATools were tested on field data from the Svatka and Polička crystalline units, the Bohemian Massif, Czech Republic (Fig. 5a). This region was selected to demonstrate the potential of OATools because of the presence of a large-scale folded structure (brachyantiform), where, in particular, interpolation tools can be demonstrated effectively and the regional structure explored.

A large dataset was collected from the Svatka and Polička crystalline units (Melichar, 1995). This dataset contained more than 3000 orientations of metamorphic foliations and associated lineations. The data extent was approximately 40 km × 50 km. Structural data were plotted and rotated symbols were set

(Fig. 5b). A geological map with a scale of 1: 500,000 was used as the basemap (Czech Geological Survey (2014)). This map was also used to define geological units (Fig. 5a).

#### 3.1. Geological setting

The Svatka crystalline unit is a metamorphic complex of pre-Variscan age (Mísař, 1983) formed mostly by leucocrate migmatite and mica schist with granitic intrusions of Cambrian age (Schulmann et al., 2005). The complex was deformed and metamorphosed during the Variscan orogenesis. Now, granite forms a large body of orthogneiss in the central part of the unit. This body is elongated in the NW–SE direction, more or less along the metamorphic foliation. The Polička crystalline unit lying in the hanging wall of the Svatka unit consists of different types of paragneiss with early Variscan (Schulmann et al., 2005) intrusions of granite, tonalite and older diorite. The tonalite bodies were strained and foliated, so their shape is also subparallel to the regional direction of foliation. Contact with the underlying Svatka unit is marked by a narrow discontinuous belt of amphibolites and was slightly reworked by younger steep NNW–SSE striking normal faults (Hanzl et al., 2011). These units have more or less the same structural pattern and so it was possible to process all the data together. Data taken from rigid metamorphosed iron rich sediments forming large boudins in a lower part of the Svatka crystalline unit were excluded from the analysis, because they exhibit an old deviated orientation of foliation in comparison to the surrounding rock.

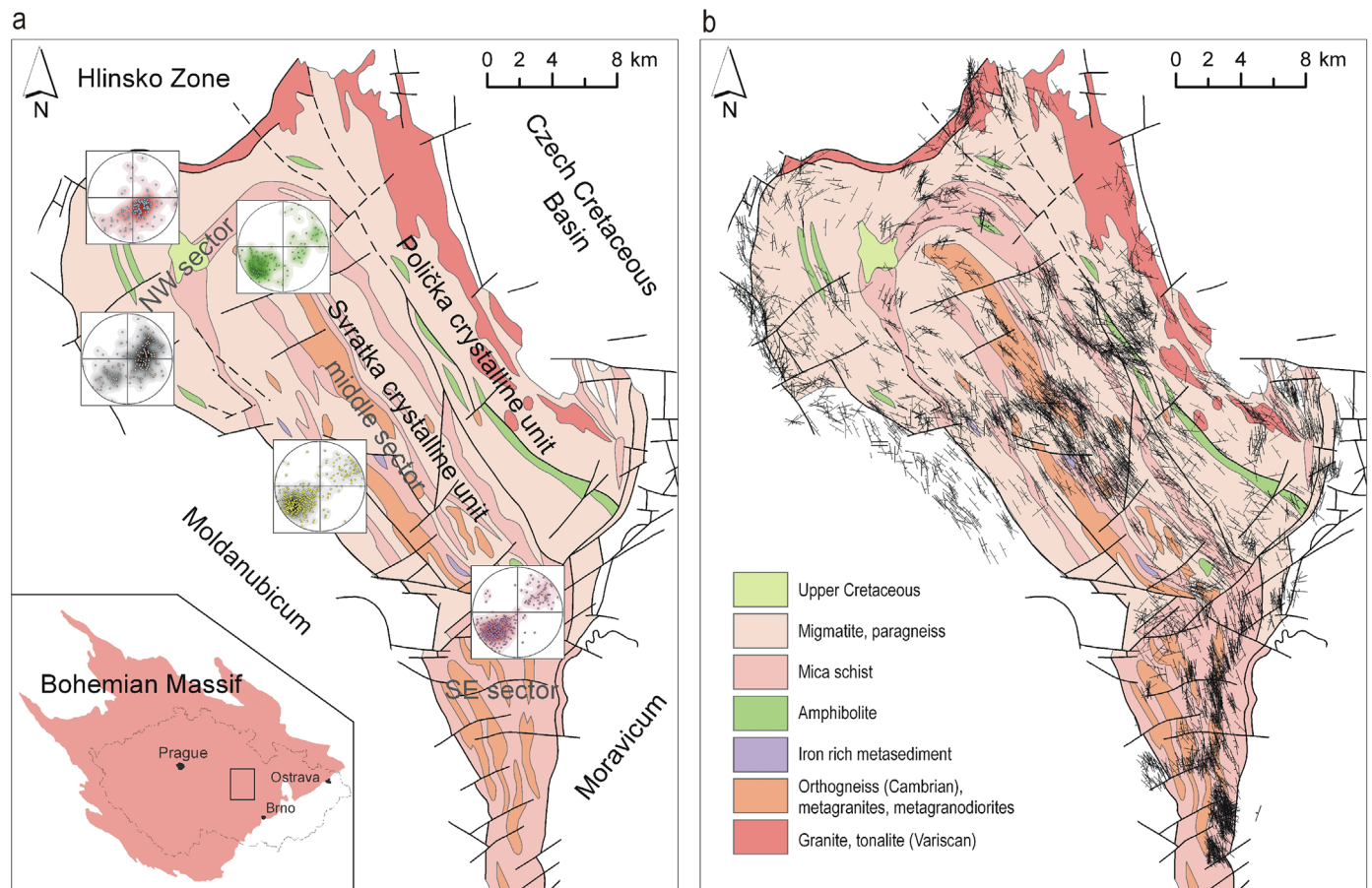
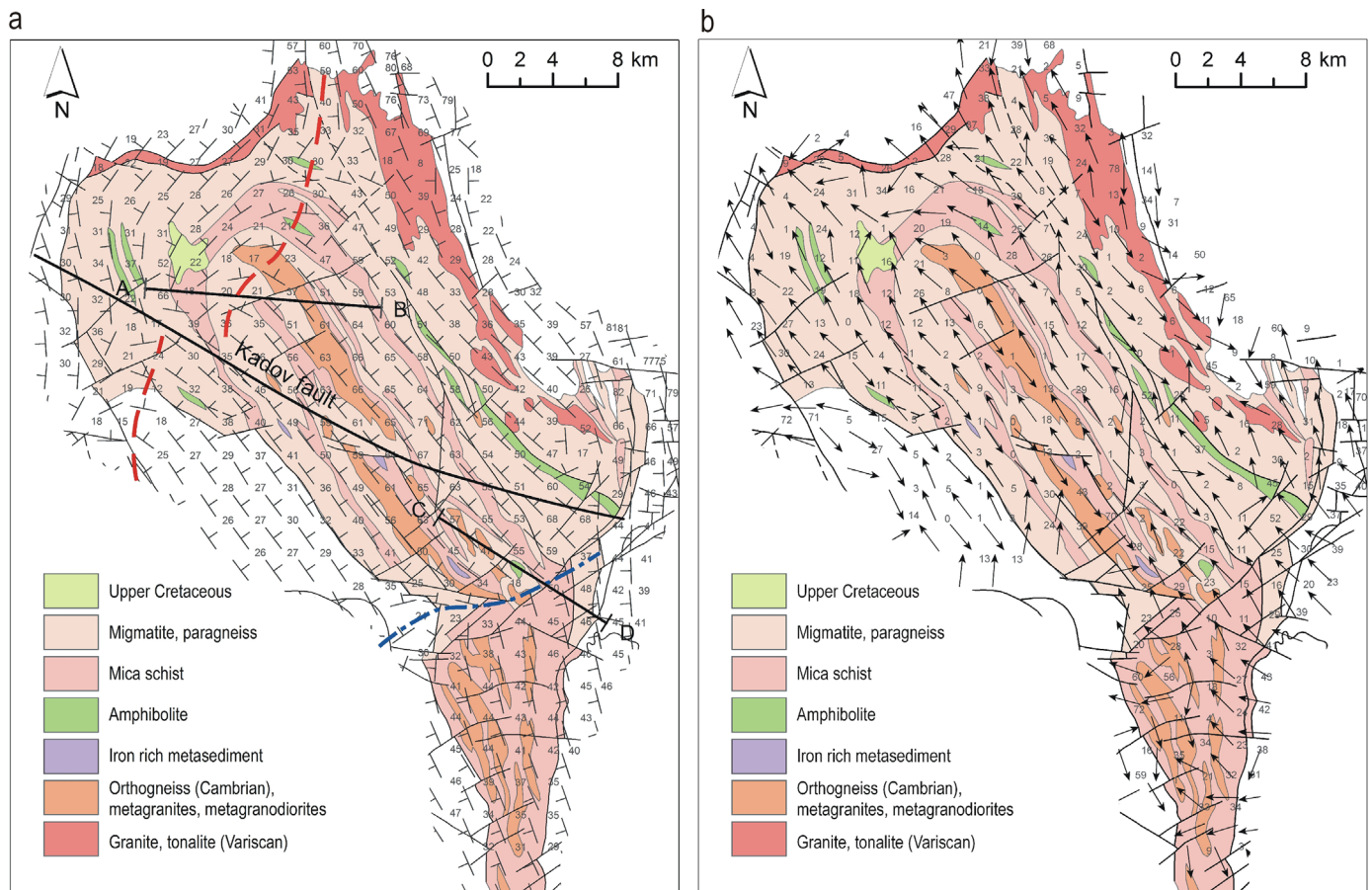


Fig. 5. (a) Svatka and Polička crystalline units in the Bohemian Massif (Czech Republic). Metamorphic foliation plotted in azimuthal projections (equal-area) for particular sectors (Geological map 1: 500,000, Czech Geological Survey (2014)). (b) Field data collected by Melichar (1995): metamorphic foliation (Geological map 1: 500,000, Czech Geological Survey (2014)).



**Fig. 6.** (a) Spatially averaged data on a 1:500,000 scale geological map (Czech Geological Survey (2014)). Red dashed line: trace of the axial surface of the brachyantiform duplicated by tectonics (Kadov fault). Blue dash-dotted line in the SE sector: trace of the axial surface of the overturned fold. Lines of cross sections are indicated. (b) Map of fold axes (Geological map 1:500,000, Czech Geological Survey (2014)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### 3.2. Performed analysis

The “Spatial Averaging” and “Map of Fold Axes” tools were used for dataset analysis. The radius of influence was set to 5000 m. Such a value for this parameter can eliminate local fluctuations and highlight the main structure (Fig. 6a and b). The interval of the averaging stations was 2000 m; the grid consisted of  $20 \times 26$  stations.

On the basis of the spatially averaged data (Fig. 6a), three sectors of the regional structure were distinguished: the north-west, middle, and south-east sectors (Fig. 5a). The “Plot” tool was used to plot data from these sectors. The poles to planes of metamorphic foliation were plotted as vector shapefiles. The use of a vector format for the data enabled links between points in the azimuthal projection and their location on the map to be established. Therefore, the location of the deviated orientations could be observed. Density distribution diagrams were calculated (Fig. 5a).

Very steep foliations were shown to occur in the SE sector. The fold axis was computed from the data in this sector by the “Plot” tool and plotted in the projection. Using the direction of the trace of the axial surface, the axial surface could be calculated and plotted as a great circle (Fig. 1d).

### 3.3. Interpretation

The map of spatial averages from the foliations shows two dominant flections: a brachyantiformal closure dislocated by the Kadov fault in the NW sector and a foliation overturning at the

Věstín Fan in the SE sector, (Zapletal, 1934).

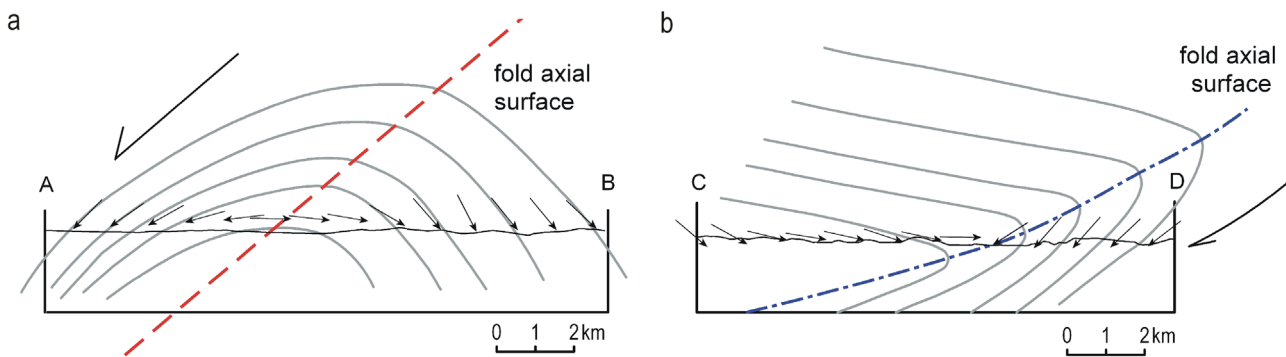
#### 3.3.1. A regional brachyantiformal closure in the NW sector

The brachyantiformal closure in the NW was described by Rošival (1895) and Beneš (1962) as the closure of an isoclinal overturned fold. New findings show that the trace of the axial surface is bent parallel to the boundary of the Svatka gneisses and the Hlinsko Zone (Fig. 6a). This was caused by normal shearing that took place within the contact zone (Pitra et al., 1994). The fold has the character of an open fold (Fig. 7a).

The map of spatial averages reveals not one antiformal structure, but two. One is developed in the NW sector of the Svatka and Polička units. The other is situated at the NW boundary with the Moldanubicum (Figs. 5a and 6a). The trace of the axial surface ends on the Kadov fault and the continuation is shifted along the fault.

The Kadov fault is of the late Variscan age (Melichar, 1995) and was identified on the basis of detailed mapping at a scale of 1:50,000. There are bands of amphibolites and marbles split by the fault. On the 1:500,000 scale map, only a large orthogneiss body appears to be divided by the fault (Fig. 6a). This dextral normal fault resulted in the dislocation of the NE limb of the brachyantiform (the middle sector) into two parallel parts (Fig. 6a).

The axial surface disappearing at the Kadov fault and the duplicated limb with NE dips led previous authors to the idea of an isoclinal fold, but, in fact, the Svatka and Polička crystalline units comprise a single NE-dipping limb duplicated by the movement along the fault.



**Fig. 7.** (a) Open fold character of the brachyantiform in the NW sector. Apparent dips of spatially averaged foliations in the direction of cross-section A–B are plotted. (b) Large overturned fold of the Věstín Fan in the SE sector. The orientations of apparent dips of metamorphic foliations form the shape of a “fan” (cross-section C–D).

### 3.3.2. A change to the opposite dip direction in the SE sector – the Věstín Fan, (Zapletal, 1934)

The change in dip direction in the SE sector is concentrated into a narrow belt that separates the SE fold limb with an inclination of 30–40° to the SW and the NW limb dipping towards the NE at between 50° and 60°. Steep foliations were observed in this belt, indicating that the Věstín Fan is, in fact, a large overturned fold. The orientation of the fold axial surface was determined by combining the fold axis and the bearing of the trace of the axial surface, and found to be 322/15 (Fig. 1d). The geometry of the fold is sketched in Fig. 7b.

## 4. Conclusion

OATools unify the processing of structural data into a single environment and remove the need to export data to different formats. The proposed add-in enhances the functionality of ArcMap 10.2 for the purpose of geological mapping. Now, ArcMap can be used not only for visualizing geographical position of oriented data, but also for orientation analysis. Therefore, spatial aspects of the data can be considered when performing structural analyses.

The user should consider factors that can influence the result, such as the relevance of the data to be processed, for example, in order to avoid mixing different types of structures; s/he should also consider the boundaries between geological units of different genesis, etc. In addition, the radius of influence has a significant impact on the calculation: the higher the value, the fewer the number of local fluctuations that are apparent.

Further development of these tools is focused on the incorporation of the OATools functions into an extended add-in depicting the intersections of geological structures with the plane of cross section. An upgrade of OATools to higher versions of ArcGIS is also planned.

## Acknowledgment

OATools add-in for ArcMap (ESRI) version 10.2 can be downloaded at <http://is.muni.cz/www/lenka.koc/OATools.html>. A detailed guide is included. The application source code is shared under the GPL-3 license.

OATools are still being improved and any comments or suggestions would be appreciated particularly with respect to functionality.

We thank Matthew Nicholls for proofreading the manuscript and all our reviewers for their contributions in improving the overall quality of the article.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.cageo.2015.12.005>.

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