Visual exploration of historical maps

Martin Reckziegel
Leipzig University, Leipzig, Germany

David Joseph Wrisley and Taylor Wright Hixson
New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

Stefan Jänicke
University of Southern Denmark, Odense, Denmark

Abstract

Historical maps tell rich stories, and they are also valuable data objects. They vary greatly in size, type, and context, as well as the kinds and density of information they contain. Historical maps are indeed objects that invite close reading, interpretation, and debate. Whereas a variety of environments exist for the annotation, manipulation, and representation of digital maps, or map-derived data, workflows in the spatial digital humanities can be complex and those environments are not often well integrated. In this article, we describe a prototype named 'MapFolder' for studying maps, its algorithms for calculating the areal distortion, its visual design for communicating that distortion, along with a scholarly workflow. We blend annotation practices common in the spatial humanities with the workflows of georeferencing in order to be able to visualize how historic cartographic documents compare with the geospatial representations we are familiar with today. The case studies we use to demonstrate 'MapFolder' are maps of the medieval period, a body of maps that are less often studied algorithmically and that are usually avoided in typical workflows of georeferencing. MapFolder is by no means a prototype designed to work exclusively with medieval maps, but since maps of this period are only partially geographic in their design, they offer a particularly fruitful opportunity to rethink the algorithmic manipulation of historical depictions of the world. Working with this complex data from the humanities allows us, as well, to propose the use of visualization for critical, comparative spatial analysis in pre-modern studies and beyond.

Correspondence:
Martin Reckziegel, Leipzig University, Leipzig, Germany.
E-mail:
reckziegel@informatik.uni-leipzig.de

1 Introduction: A prototype for close reading historical maps

Historical maps tell rich stories, and they are also valuable data objects. They vary greatly in size, type, and context, as well as the kinds and density of information they contain. Historical maps are indeed objects that invite close reading, interpretation, and debate. Whereas past study of historical maps may have been hindered by low resolution of print reproductions, increased numbers of digitized map archives mean that maps are more accessible than ever, and in

ii251

forms that can be manipulated and studied with computational methods. Whether by download of openly licensed files, or by image repositories compliant with the International Image Interoperability Framework (IIIF) with well-defined application programming interfaces (APIs), new modes of access to map collections are providing scholars with the ability to notice great detail and ascertain patterns in images. Whereas a variety of environments exist for the annotation, manipulation, and representation of digital maps, or map-derived data (Höhn, 2016), workflows in the spatial digital humanities can be complex and those environments are not often well integrated.

In this article, we describe a prototype named 'MapFolder' for studying maps, its algorithms for calculating the areal distortion, its visual design for communicating that distortion, along with a scholarly workflow. MapFolder is a 'prototype that argues' for bringing computation to historical cartography as a way of expanding how we close read maps (Galey and Ruecker, 2010). We blend annotation practices common in the spatial humanities with the workflows of georeferencing in order to be able to visualize how historic cartographic documents compare with the geospatial representations we are familiar with today. The case studies that we use to demonstrate 'MapFolder' are maps of the pre-modern period, a body of maps that are less often studied algorithmically and that are usually avoided in typical workflows of georeferencing. Our approach expands on a previous research that identifies a warped geographic grid of latitude and longitude in well-known medieval maps: the largest known medieval map on display at Hereford Cathedral in Hereford, England, dating to around the year 1300, and late medieval Gough map of Great Britain of uncertain dating and provenance (Tobler, 1966; Lloyd and Lilley, 2009). MapFolder is by no means a prototype designed to work exclusively with medieval maps (in fact, it can handle any type of raster map), but since maps of this period are only partially geographic in their design, they offer a particularly fruitful opportunity to rethink the algorithmic manipulation of historical depictions of the world (Kaplan *et al.*, 2014). Working with this complex data from the humanities allows us, as well, to propose the use of visualization for critical, comparative spatial analysis in pre-modern studies and beyond.[1]

2 Existing digital approaches to medieval maps

Medieval maps were indeed receptacles of geographic information, but they also contained details about cosmology, human history, and eschatology (Edson, 1997). It has been argued that mappae mundi, as they are called in Latin, were 'teaching rather than locational devices', created 'primarily to provide a visual narrative of Christian history cast in a geographical framework, not to communicate geographical or cosmographical facts' (Woodward, 1985). As such, in European mappae mundi one regularly finds Jerusalem symbolically located at the center with indications of Paradise and its four rivers as well as other imaginary people and places in the margins. It is commonly accepted that medieval maps did not have the same meanings as maps do today, and their spatio-temporality has been the object of significant scholarly consideration. In this article, we do not explore the temporal aspect of maps, but we do argue for a reconsideration through digital analysis of what scholars have dubbed their 'geographical framework' (Woodward, 1985) or 'cartographic veracity' (Lloyd and Lilley, 2009).

In recent years, medievalists working in digital humanities have come up with a variety of new approaches for scholarly interaction with maps. As we will summarize below, digital approaches to medieval maps have largely focused on annotation workflows of digitized copies of a map. By annotations, we understand a wide variety of historical practices of adding information to a document (Bradley and Vetch, 2007). The added information provided by annotation in the case of maps can be of several kinds: linguistic, such as transcriptions of a toponym on a map; semantic, such as a scholarly note of a textual source for a place or a region; or even cartographic, adding points, lines or vectors that correspond to map features of scholarly interest. Scholarly interest in annotating maps has traditionally been important for large maps that contain dense amounts of imagery and text, even in the pre-digital era. Below, we provide a selection of four examples of this general trend of digital environments facilitating scholarly annotation of maps with attention to their visual design.

First, a project from Leuphana Universität Lüneburg entitled Ebskart[2] has taken written annotations from the Ebstorf map and constructed an interactive image using Flash[3] with clickable features on the map indicating rivers, toponyms, text, and iconography. Upon clicking on zones of the text, one is able to view the project's scholarly annotations. This web-based exploration approach is particularly effective—as a kind of critical edition of the map—especially when the map is either large in scale or too difficult to read given the resolution of pre-IIIF web-based images. In such cases, annotation of the map reproduces a common activity found in print catalogues or reference works: creating equivalence tables that transcribe toponyms or features on the map, pairing them with historical information or present-day location of the places. The obvious advantage of the Ebskart map as a web object is found in the collocation of the modern annotation and the exact location on the historical map. It provides a solution for researchers who do not possess a high-quality image for close study of map features; but on the other hand, a clear limitation is the lack of zoom for verification or detailed examination.

Second, the Hereford Cathedral has produced an engaging web-based, annotated project known as Mappa Mundi.[4] In addition to annotations of myths and legends, biblical toponymy and ethnic geographies, Mappa Mundi can be said to expand on the Ebskart critical edition-like approach to the map by including elements of the material history of the document itself, providing interesting shelf notes and physical details about the Mappa Mundi: annotations about human alteration of the map, repairs that were made, even palimpsests where humans may have tried to scratch out a place altogether.

Third, the British Library's Virtual Mappa Project[5] using the Digital Mappa software[6] takes interactive annotations of thirteen medieval maps to a new level by providing an interface for user annotation of places on the maps, linking them to textual materials, as the ability to make connections to other medieval maps. Taking a linked-data approach the Digital Mappa software allows for people to annotate a full corpus of maps and develop them into searchable digital editions. In other words, the Virtual Mappa project allows scholars to carry out intertextual scholarly reading, focusing on the context of medieval mapmaking as connected to many other textual and visual materials.

Finally, similar to the Digital Mappa software, the web-based tool from the Pelagios Commons, Recogito,[7] allows for the creation of linked open data between polygonal annotations made on digitized map images with an option for what could be called social annotation of maps and geographic texts. Although Virtual Mappa and Recogito are valuable contributions in tool development for scholarly annotation of medieval documents, their focus lies in associating a delimited pixel box with a named space without aiming to relate if there is some kind of approximate spatial reference system within them.

3 Visualization and the pseudo-geographic elements of medieval maps

Woodward's assertion of medieval maps as a narrative form is qualified by his claim that they are nonetheless placed within a 'geographical framework' (Woodward, 1985). In this article, our case studies are the so-called complex medieval maps that blend somewhat conventional structures (such as a T–O structure) with pseudo-geographic detail. Rather than a modern coordinate system, we find in some of them notions of spatial orientation suggested by an abundance of detail (continents, rivers, peninsulas, seas, or islands) as well as geographic and named entities inscribed on the surface of the map. We argue that visualization can allow us to augment our historical geographical knowledge of the pre-modern organizational structure of maps by placing them within the context of modern coordinate systems. The applicability of our prototype is by no means restricted to being used with medieval maps, but the complexity of these cartographic documents allowed us to begin from the standpoint of significant difference between the spatial reference systems.

The visual design of topological map features is a key component of our work. Visualization, that we would define as the study of interactive visual representations of abstract data aiming to reinforce human cognition (Card, 1999), has been proven to be a valuable means for humanities scholars to gain new

insights into many different kinds of cultural heritage collections (Jänicke *et al.*, 2017; Windhager *et al.*, 2018). We aim to convey visually how the geographic qualities of medieval maps diverge from our modern coordinate systems. In this context, we generate a bridge between medieval mapping practices and geo-visualization (MacEachren and Kraak, 2011), to, on the one hand, preserve the spatial integrity of the medieval map, and, on the other hand, to provide a new perspective on how space was represented in the past. Our goal is not to 'correct' the medieval maps by placing them into contemporary map coordinates, but rather to create a screen-based means of inter-action, supporting exploratory analysis between both spatial perspectives. In this respect, the objective of visualization here is a comparative view, bringing to-gether medieval spatial representations and a variant of the Mercator projection—admittedly an old carto-graphic norm from the late sixteenth century with its share of limitations—but nonetheless ubiquitous in today's online street mapping platforms and unmis-takable to contemporary audiences.

By doing so, we aim to expand the modes of visu-alization available to scholars of historical cartography to include exploratory spatial analysis of maps. Our solution takes advantage of a common practice in Geographic Information Systems (GIS)—georectifi-cation—that calculates distortion between two images based on a set of human annotations. In our research, we have found that this practice allows us to situate such pre-modern maps on a spectrum ranging from the more topological and the more symbolic. In other words, in our visualization design the complex spatiality of the historical map is not overtaken by that of normative basemaps. In this respect, our interactive visualized distortion requires the user to think criti-cally about undistorted versus distorted spaces, to view historical maps with an eye to recognizing patterns of distortion, and to invoke perennial calls for spatial literacy, but with a historical twist (Grossner, 2014).

4 Georectification: contexts and goals

A common practice in spatial humanities is georecti-fying historical maps to generate rasters for use in GIS

(Clifford *et al.*, 2013). Georectification refers to the algorithmic transformation of an image into geospa-tial data for visualization and analysis. In this process, first, a set of control points is georeferenced in the image. An algorithm then uses these control points to 'rectify' and warp the whole image to match a well-defined map projection.[8]

Dependent on the application domain, this method is typically carried out with different levels of precision and with different goals in mind. Georectification is often applied to project satellite imaging data onto contemporary maps for context-ualization with other georeferenced data sources (Teo *et al.*, 2003; Yang and Li, 2004). In glaciology, the technique is used to determine fine-granular velocity fields of glacial flows (Messerli and Grinsted, 2015). Spatial humanities practitioners create basemaps for projects representing historical locations, a georecti-fied map is used to extract historical vector data for analysis, or they compare spatial representations of space over time. If we consider both, the historical map and the basemap as imperfect representa-tions—rather than reflections—of reality, the georec-tification process creates a spatial relation which must be used critically rather than instrumentally (Presner *et al.*, 2014). More often than not, however, the pro-cess of georectification is applied in situations where the historical map is basically close to the coordinate systems of modern cartographic practice.

In these cases, valuable historical information can be extracted from this process (Baiocchi and Lelo, 2005). Methods to algorithmically analyze and visual-ize the extent of distortion between a modern and a historic map have been proposed (Jenny *et al.*, 2007; Claeys Boùùaert *et al.*, 2016). The latter study presents a methodology to visualize areal and angular distor-tion using differential analysis for every point of the modern map as projected onto the historic map or vice versa, given an arbitrary, differentiable projection function. This helps identifying geometric inaccura-cies, and visualizing such divergence allows one to analyze historical cartographic technique. We take a step further to being able to analyze and visualize topological inconsistencies in complex cartographic documents, the mappae mundi.

Whereas the above-mentioned spatial humanities projects used georectification to create a basemap for map-based storytelling, this article takes a different

approach to employ the image transformation function of georectification in the geo-narrative process itself. As we are visualizing this transformation to understand the complexity of difference between the representation of places in a reference map (the Web Mercator map in our case) and the representation of places as assigned pixel values in a historic map image file, our approach differs from traditional most georeferencing workflows in that we do not only stretch the map to fit geographic space causing a warp in parts of the historic image, but we also proceed in the other direction, calculating how geographic space has to be stretched to align with the medieval map.

5 Annotation workflow

Our data consist of digitized images of maps or digitized reconstructions of lost maps (as in the case of the Ebstorf map). As with most georeferencing workflows, our goal is to 'fit' the historic map to the real-world by finding a number of anchoring control points.[9] Typically in georeferencing, one would pick the coordinate reference system of the historical map; however, we are working with maps that do not have such a systematic spatial organization.

Identifying control points on the historical map is a form of geographic annotation that links any particular feature or location with data about that place. As we have mentioned above, annotation platforms for digitized maps include Recogito where place names on digitized maps can be linked to geographic data in online gazetteers or Digital Mappa that allows us to 'highlight, annotate and link collections of digital texts and local, online and IIIF images', but neither platform provides an option for warping, georectification, or direct overlay of the annotated object with a modern web map. In order to do that, we could have used a GIS platform, but these are notoriously standalone environments. In the end, we decided on MapWarper for its social convenience: we could create sufficient accurate control points linked to Web Mercator maps as a team, host the maps with a persistent URL, share these annotated maps, rectify them with the desired method (thin-plate spline), and export the values to our international collaborators in visualization. One of our takeaways from working with this spatial humanities workflow was the extent to which georectification has been excluded from most web-based platforms for annotation.

Using MapWarper was the simplest tool for georeferencing as far as interface and collaboration was concerned; however, there were notable limitations of using MapWarper. Annotation choices were largely driven by the legibility of the toponyms on the map. Annotation is only point-based, and for annotating the toponyms found on historical maps, there are no dots marking an exact place, instead we would use an approximate center point in the part of the textual field marked by the toponym. Web Mercator is also the only projection provided in MapWarper. In the case of very large maps or very large files, MapWarper resizes the images and controlling the map pane is difficult. During annotation, for maximal legibility and identification of location, we used our university's library 3×3 video wall with the highest quality images we could find alongside MapWarper, as shown in Fig. 1. The larger screen allowed us to see particular zones of the map in high resolution without having to zoom in and lose the larger context of the place.

In the process of annotation, we aimed for as much coverage as possible on the digital image, a typical strategy for choosing control points in a georectification workflow. This strategy in the case of only pseudo-geographic maps was often limited because the annotatable geographic data at the margins of the maps are either sparse, imaginary, or unmappable. Without enough control points spread equally around the original map, the rectification algorithm produces limited results, suggesting distortion in places of data sparsity. With Western maps that are slightly more recent, such as portolan maps from the late fifteenth and early sixteenth century (Baletti, 2006), annotation coverage of the map would be a simpler proposition.

Since maps can be truly complex objects—and in some cases with abundant textual data as we see in the case of the Fra Mauro map in Fig. 1—during annotation we also used scholarly geographic sources for both the identification and the transcription of the place names.

Given the various strata of geographical knowledge of the period, the situation of medieval toponyms is a complex one. Previous scholarship that attempted to transcribe the toponyms on the maps in question was invaluable for not only identifying general debate about
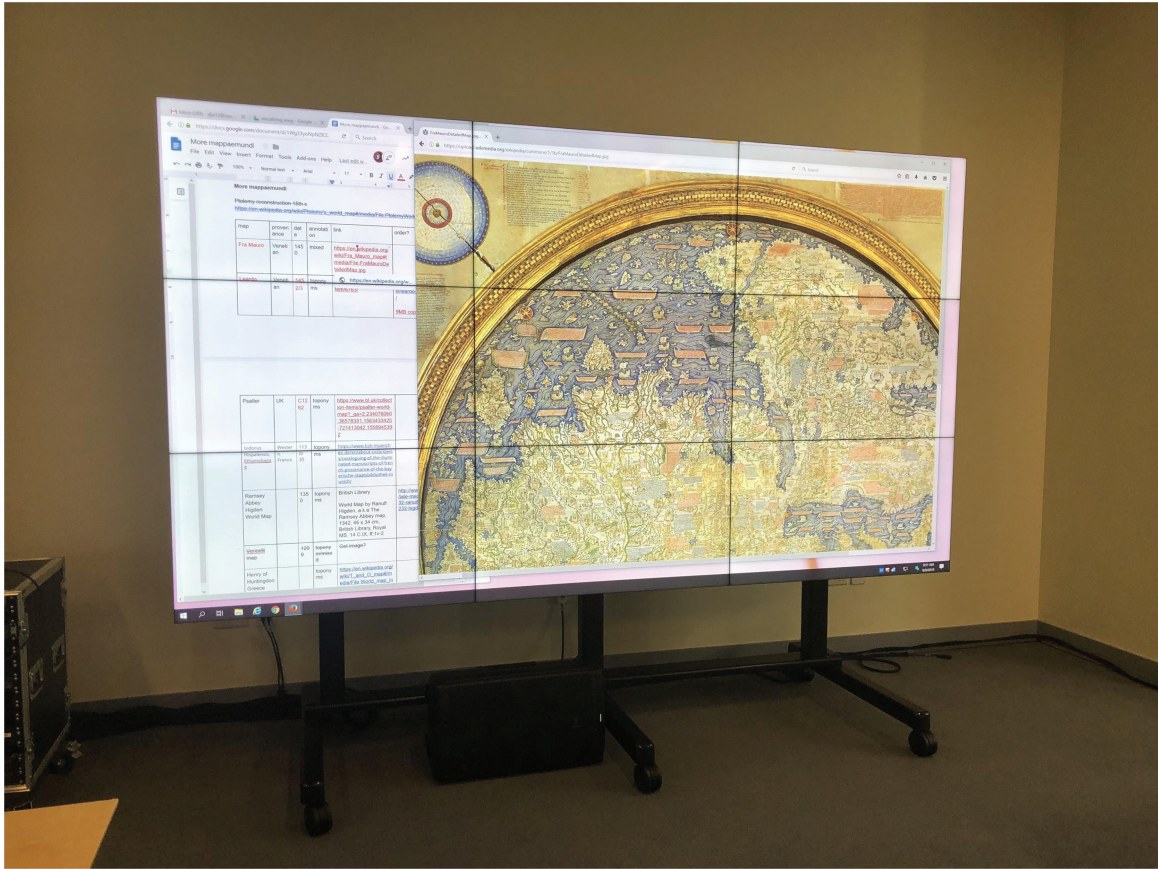
Fig. 1 Using the video wall at NYU Abu Dhabi in order to circumvent the challenges of the high-density large images and the usability of the MapWarper interface. Image partially shown on screen with other work documents: Biblioteca Nazionale Marciana, Fra Mauro map (c 1450).[10] Google and the Google logo are registered trademarks of Google LLC, used with permission

such toponyms and deciding on modern geographical locations to associate with them. Additionally, on a medieval map, one might find names of cities, names of regions or landmarks, river names, etc. all intermixed with symbolic and legendary place names. Many of the place names on the maps we dealt with have already been the object of study, although their geolocation has not necessarily been carried out.[11] Since the edit tab in MapWarper uses the OpenStreetMap[12] basemap with contemporary regional languages, a considerable amount of philological knowledge (e.g. the Arabic, Hebrew, and Russian alphabets) was required to translate historical toponyms into their contemporary locations. Using a combination of multilingual gazetteers such as GeoNames and Pleiades, we were able to identify about 180 historical places on eight maps. The images and the point annotations consisting of pixel values and corresponding geo-locations were communicated to the visualization team. We have published this data and a web map (Fig. 2) openly online.[13]

6 Areal distortion and orientation calculation

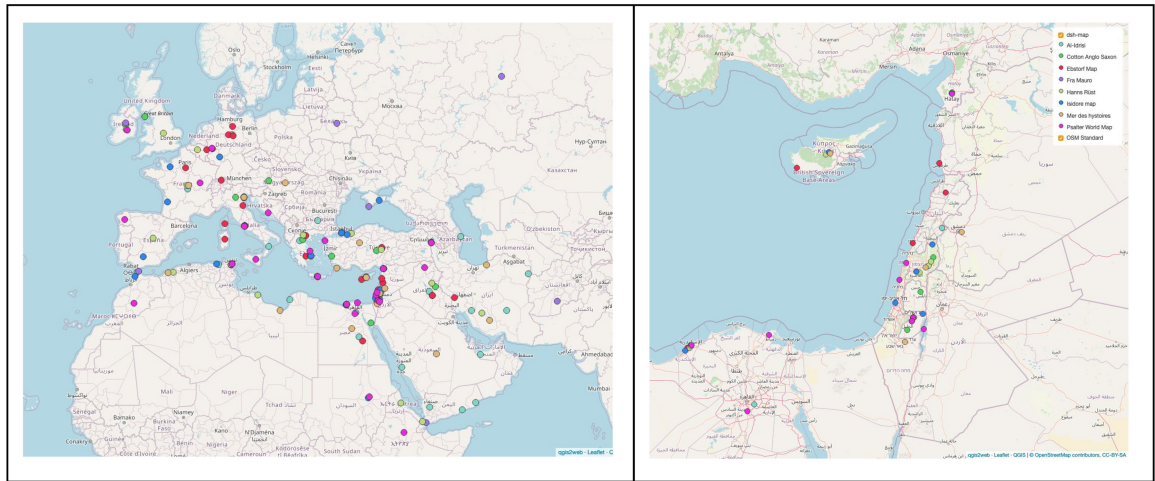Georectification can be implemented using different image transformation techniques. One of the

Fig. 2 A facetable web map of the aggregate of the map annotations done to the eight medieval maps in this article (left) with a detail of the density of locations in the Eastern Mediterranean (right)[13]

commonly available methods in modern GIS systems such as ArcGIS[14] or QGIS[15] are kth-order polynomial algorithms. Here, the coefficients of a polynomial function of order k are determined, such that the residual error between the resulting transformation function and the given control points is minimized. The higher the order, the more degrees of freedom and as such the more detailed curvature is allowed, still the transformation might not necessarily match the control points. Another common method is the thin plate spline (TPS) transformation. This 'rubber-sheet' method is guaranteed to match all control points. The space in between is locally deformed, such that the curvature necessary to maintain this property is minimal, or, in other words, that an imaginary thin metal plate bends according to the given control points.

As medieval maps do not follow the projections used in modern cartography, by georeferencing and georectifying them we do not expect a seamless, intuitive result. Instead, when projecting mappae mundi onto modern maps or vice versa, topological inconsistencies are likely to occur. As shown by the control points in the top illustration of Fig. 3a, an imaginary place A might be to the left of place B on the historic map, while their horizontal order is reversed on the modern map. Furthermore, the places C and D remain their order. The TPS method resolves this by

creating a 'folded' transformation of the historic map on the modern map as shown in the bottom illustration of Fig. 3a.

This fold is located where the topology of the historic map is different from that of the modern map and as such we promote folds as indicators for regions of different pre-modern organizational structure of historical maps. Another indicator of the organizational structure is the amount of image space a region is assigned to on the historic map. We relate this space to the reference map by locally calculating the areal scaling factor of the transformation from the historic to the modern reference map image.

The calculation for both folds and areal scaling are based on an established areal scaling factor formula (Claeys Boùùaert *et al.*, 2016). As Boùùaert *et al.*, we favor the TPS method for georectification for similar reasons. Principally, we expect the most accurate results in terms of topological analysis as TPS respects the user-defined control points. Based on those control points, the image transformation is performed by two functions $x(x', y')$ and $y(x', y')$. The first transforms an image point (x', y') in the historic map to the corresponding x-coordinate in the reference map, the second transforms (x', y') accordingly to the corresponding y-coordinate. To calculate the areal scaling factor σ for any point in the historic map, Boùùaert *et al.* use the four partial derivatives resulting in

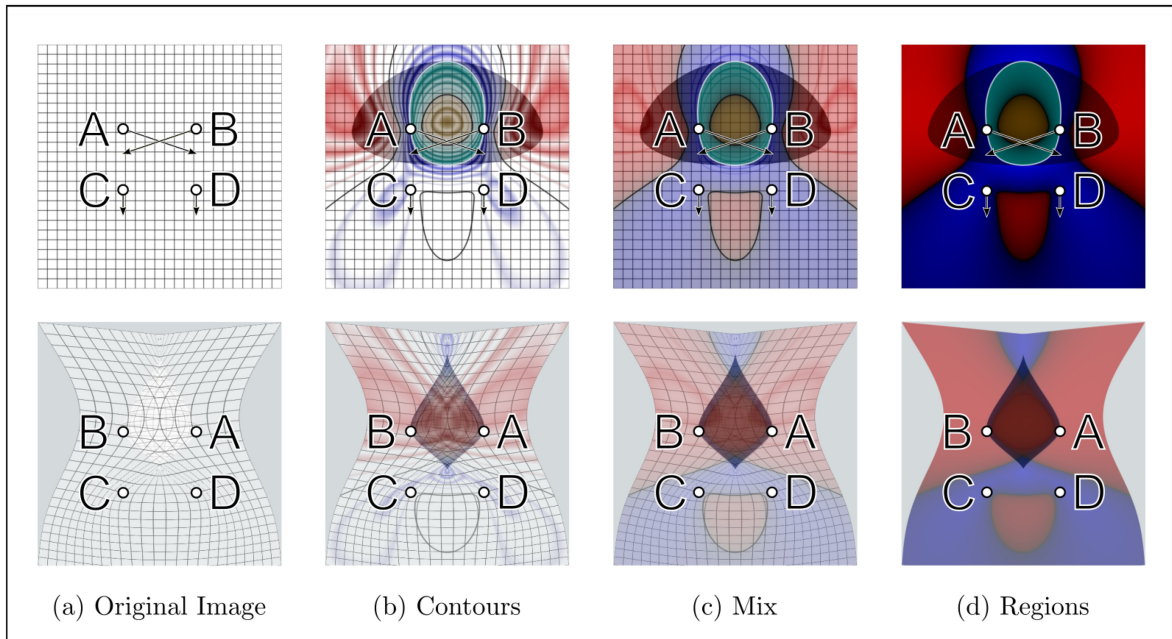| (a) Original Image | (b) Contours | (c) Mix | (d) Regions |

Fig. 3 Topological inconsistent rectification illustrated with our four visualization modes

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x(x',y') \\ y(x',y') \end{pmatrix} \quad a = \frac{\partial x}{\partial x'} \quad b = \frac{\partial y}{\partial x'}$$

$$c = \frac{\partial x}{\partial y'} \quad d = \frac{\partial y}{\partial y'}$$

$$E = a^2 + b^2$$
$$F = a \cdot c + b \cdot d$$
$$G = c^2 + d^2$$

$$\text{Eq(1)} \quad \sigma = \sqrt{EG - F^2}$$
$$\text{Eq(2)} \quad \sigma = \sqrt{(ad - bc)^2}$$

Fig. 4 Calculation of the areal scaling factor for a map image location using partial derivatives

Equation (1) (Fig. 4), which we can further simplify to Equation (2). σ is equal to the area of the parallelogram constructed by the partial derivatives of the Jacobian matrix J whose numerical calculation and behavior is illustrated in Fig. 5. The absolute value of the determinant of J reflects the ratio by which a small square at (x', y') is scaled, so that σ can be also defined by Equation (3).

By looking at the sign of the determinant, we can deduce the orientation of the image transformation. In the upper part of Fig. 5, the orientation at the examined location on the historic map remains the same when transformed onto the reference map. In such a situation, the determinant is positive in contrast to the lower part of the figure where the

orientation flips and the determinant becomes negative. With this method, we can compute regions where the historic map will be flipped that are regions where the map will be folded.

In both cases, folded or not, the absolute value of the determinant is the areal scaling factor σ. Despite the warping occurring at any given point, that factor also depends on the resolution of the historic map image as well as the general scale of the reference map and as such not easy to interpret. To overcome this problem, we normalize σ by the average or mean of all[16] occurring areal scaling factors. We define regions on the historic map where σ is above the average to be magnified in the reference map or the other way around that such region in the reference map is
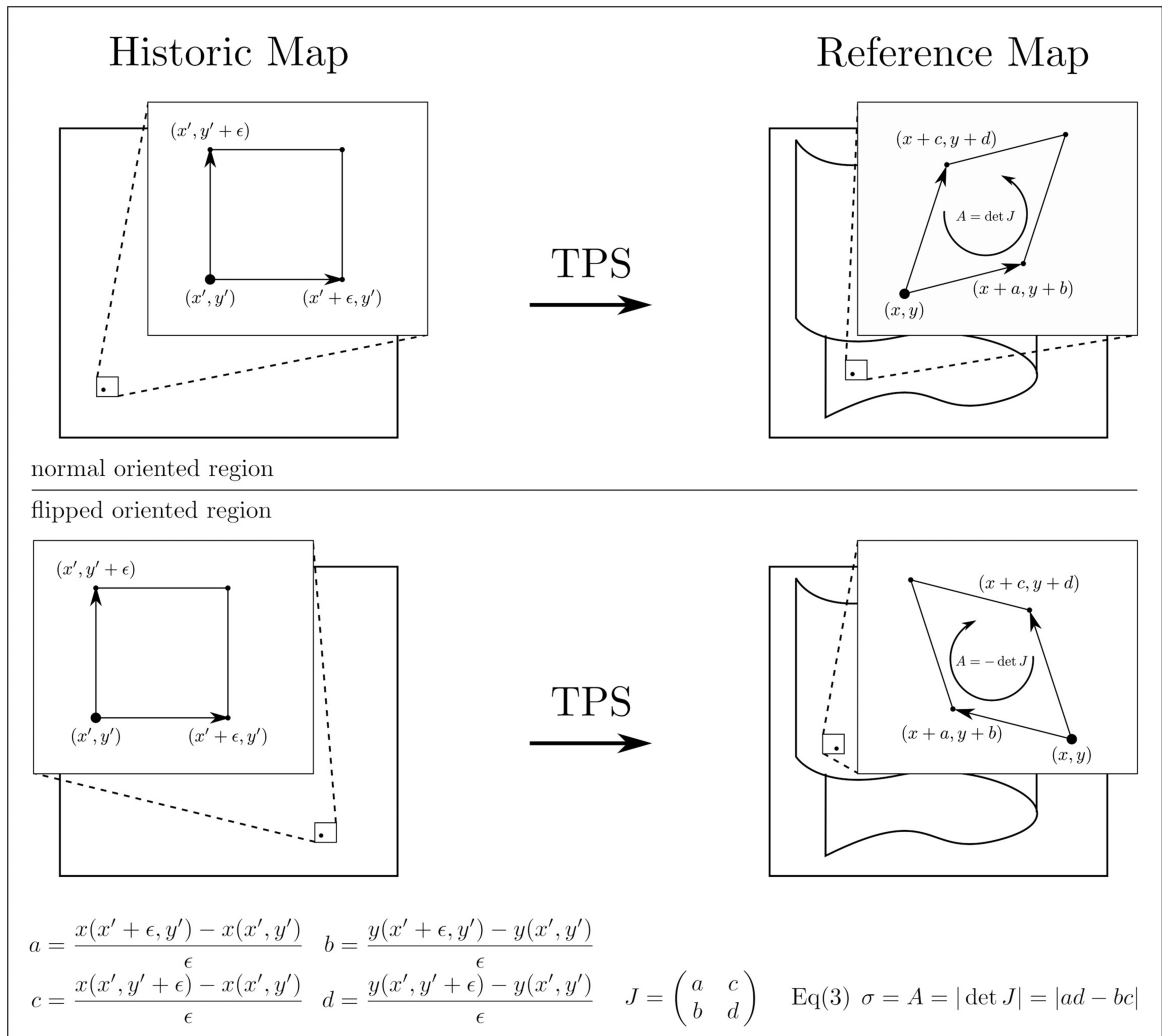
Fig. 5 Calculation of the areal scaling factor and the orientation of the transformation for a map image location using the Jacobian determinant

shrunk in the historic map. Accordingly, regions on the historic map where σ is below the average are diminished in the reference map.

With these calculations, we can divide the historic map into regions where the map is folded and where it is not, as well as regions of magnification or shrinkage, giving an approximate sense of distortion compared to modern geographic maps. That is to say, we can calculate the amount of scaling and its orientation at any location and it is this abstract data that we aim to

visualize in order to support an understanding of the complexity of medieval mapping practices.

7 Web-based prototype

We designed the web-based prototype MapFolder[17] for interactive exploration of the spatial complexity of historic maps by visualizing the distortions calculated above. In addition to a number of predefined

maps for exploration (described in the next section), users can select to import their own data. The corresponding workflow is illustrated in Fig. 6. The first step concerns creating annotations for the historic map image. As described in the annotation workflow, we use the MapWarper[18] tool for that purpose. It generates a set of control points that can be exported to a comma-separated value (CSV) file, which is then imported along with the historic map image into MapFolder. However, other means than MapWarper are thinkable to produce the required CSV file, even a manual georeferencing of historic map image pixels. The prototype interface is depicted in Fig. 7. The pane surrounded by the red dotted lines supports the import process. The full data set is named and loaded into the tool. Below that can be found an options pane (orange dotted lines), and the main part of the interface consists of two views (green dotted lines). The left pane displays the historic map image with superimposed visualizations while the right pane shows the reference map image: that is, the historic map georectified and layered on top of a Web Mercator basemap. Below the main visual field of the interface a legend (blue dotted lines) provides a key for the colors used in the visualizations. In addition to being able to explore the provided views, the user can annotate both the computed fold-feature areas and the imported control points. Finally, MapFolder offers the possibility of exporting

all data (historic map, control points, folded areas, annotations) in a GeoJSON file, which in turn can be reused as import data for MapFolder.

7.1 Visualization design

We designed four visualization modes that can be selected from the options panel (highlighted in orange in Fig. 7). They are best described using the illustrative example above in Fig. 3. The top row of that figure corresponds to the historic map view, and the bottom row to the respective reference map view, that is, the georectified, transformed map image.

In the Original image mode shown in Fig. 3a, the historic map and its georectified version are shown unchanged in their corresponding views.

In the Contours mode shown in Fig. 3b, the historic map is superimposed with a contour map showing the areal scaling which can be read like a traditional mountain map; the higher the mountain, the larger the scaling factor of the image. Each contour line in the visualization represents a region in which the scaling is identical. The wider such contour line is drawn, the smaller the gradient is, that is, the smaller the change of scaling is at that location. The more saturated the lines are, the larger the magnification or shrinkage is with respect to the mean scaling. The colors of the lines are used to discriminate the different types of regions calculated. The color blue indicates a factor smaller, and the color red a factor greater
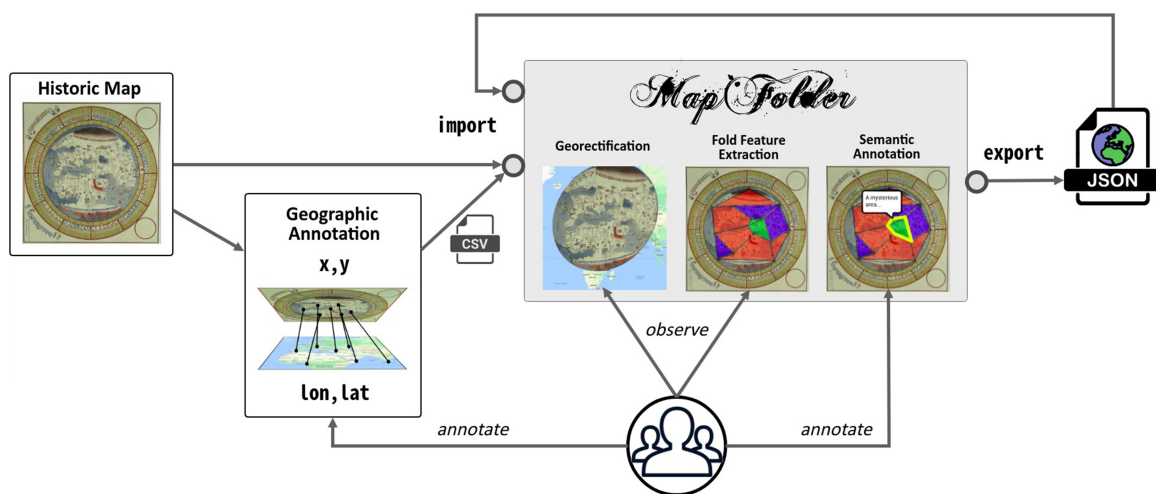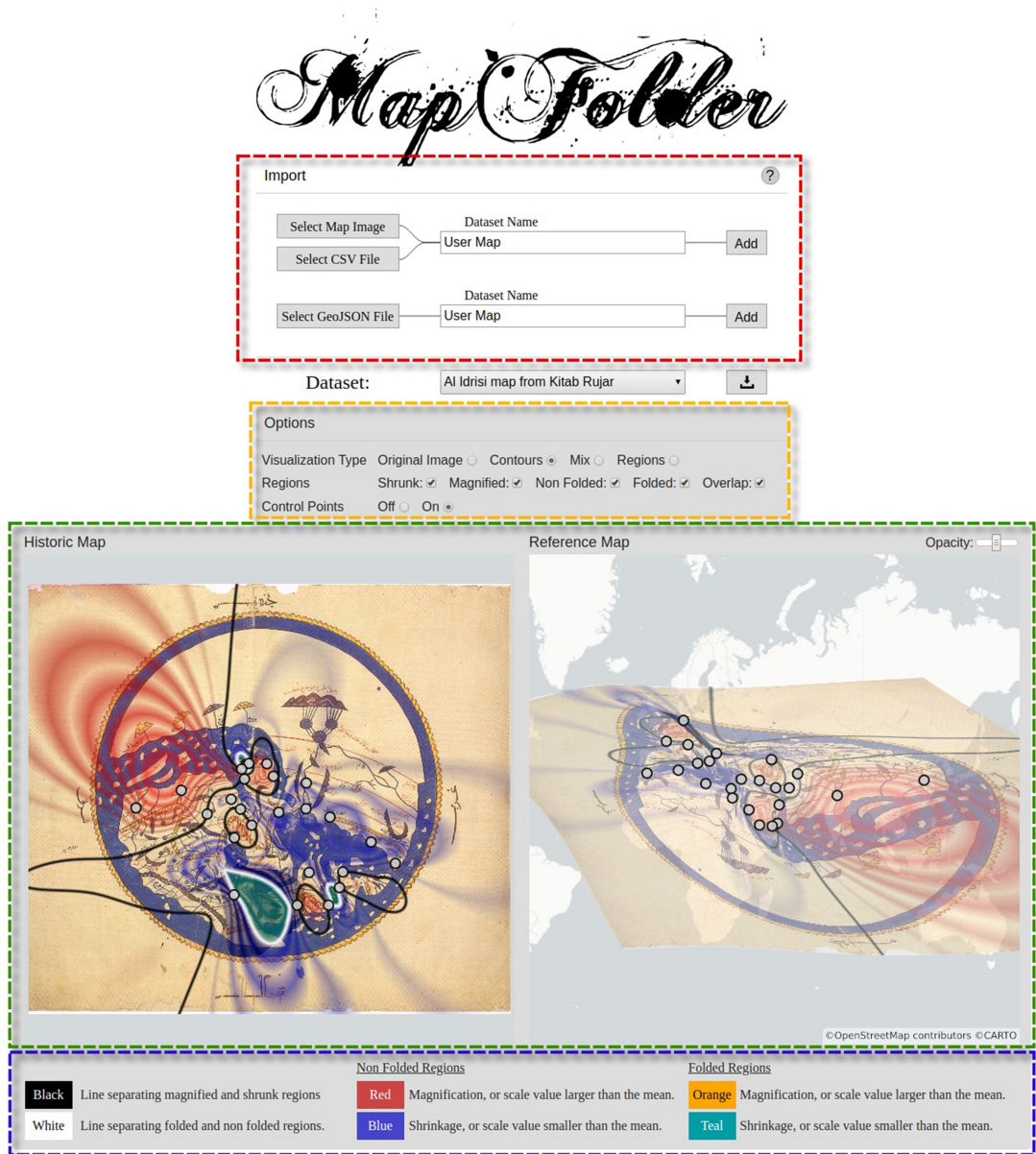

Fig. 6 The MapFolder workflow

Fig. 7 The web-based prototype MapFolder to compare a historic map (left) to a reference map (right), illustrating the 1456 al-Idrisi map in Arabic. The four parts of the interface are highlighted by rectangles in colored dotted lines. Original visualization based on Oxford, Bodleian Library MS. Pococke 375 fol. 3v-4[19]

than the mean in a nonfolded region. Turquoise and yellow indicate shrinkage and magnification in a folded region, that is, where the orientation of features of the historic map is flipped. The white contour line

represents the crease of the fold, separating flipped versus nonflipped regions. The black contour line represents the mean scaling, separating magnified from shrunk regions. Both lines are drawn with uniform

width in contrast to the other for improved recognizability. In addition to the contour lines, a shadow in regions that will overlap due to the occurring folding is drawn in this as well as in the two final visualization modes.

In the Regions mode shown in Fig. 3d, the scaling factor is visualized using continuous color map without showing the historic map image. The coloring is the same as for the Contours mode and the saturation of the colors correspond to the value of the scaling factor. However, instead of allowing for an accurate feel of the amount of scaling, this mode is intended to visualize the location and spread of the qualitative different types of regions introduced above.

The Mix mode shown in Fig. 3c represents a compromise between the contours and regions mode. Besides the regions the underlying historic map image is still visible as well as the contours for very large respective small scaling factors.

7.2 Interaction design

The visualization modes can be selected from the options panel and both map views update accordingly. Both, the different types of regions (folded, nonfolded, magnified, shrunken, or overlapping), and the control points can be switched off, preventing their superimposition on the historic map image to reduce visual clutter. In order to explore the transformation on different zoom levels, both map views offer zooming and panning as commonly available in map visualizations. The user can also reduce the opacity of the transformed historic map for improved visibility of the underlying basemap.

We further introduce 'coordinated cursors': with the mouse position in one of the map views we show the corresponding transformed location in the other one using crosshair styled cursors. When hovering over the historic map view, only one location of the reference map corresponds to the current mouse position; however, when hovering over the reference map in overlapping regions, multiple locations correspond to the current mouse position as shown in Fig. 11. As an addition to the static visualizations, we found these coordinated cursors particularly helpful in understanding the geometric transformations between both map views.

Users can click on the historic map image to either select the control point or region underneath as shown

in Fig. 8. A selected region is highlighted in both views, so that its extent can be seen in the reference map. We decided for a white, slightly transparent hatch pattern as visual indicator for the selection as there are already enough colors used in the visualizations. Further, we decided against the possibility to click a feature in the reference map, as one point in that map may intersect with more than one region, introducing the complexity of dealing with an ambiguous selection. With a feature selected, a resizable annotation editor is shown in the bottom half of the historic map view. This editor allows to annotate any control point or region with attribute-value pairs of text.

7.3 Data import and export

Finding an appropriate data format for our prototype was not straightforward. We aim to store all features—the control points and the computed regions together with their attribute-value annotations—in both the historic map image coordinate system as well as the geographic coordinates system linked together. Projects dealing with the annotation of historic maps often develop tools and data models for project-specific needs (Höhn, 2016). Furthermore, resources are not maintained after project end or documentation is not available. As such, we were unable to find an existing, well documented, and widely used suitable data format. Although building upon the Web Annotation Data Model[20] would be one option, we decided to extend the GeoJSON[21] format. We store the geographic coordinates of the features as standard GeoJSON Feature objects, while adding the image coordinates and annotations as properties to those objects. Additionally, we add the image in the form of a URL to the top level FeatureCollection object to be able to link map images externally or internally using the 'data' URL scheme.[22] This pragmatic decision allows the exchange of the geographic aspects of the features with standard compliant GeoJSON software while maintaining machine readability of the image aspects. Figure 9 shows the exported GeoJSON for the al-Idrisi map rendered by Github. The prototype is able to import and export this data format in addition to importing an image/CSV file pair. Specifications for the CSV column format as well as the GeoJSON format can be found in the public MapFolder repository.[23]
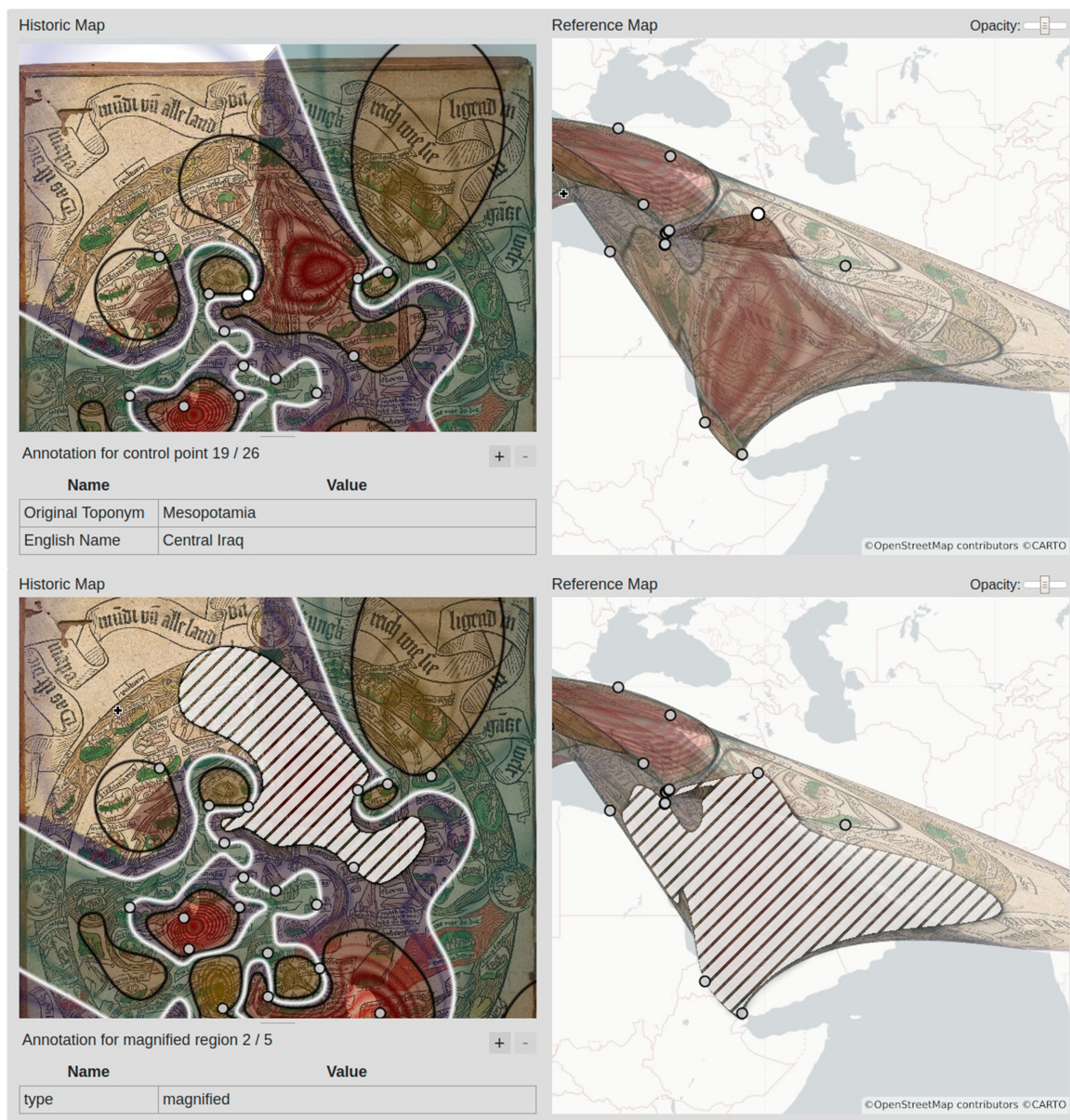
Fig. 8 The selection of one feature highlights its shape in both views and opens the annotation editor, in which attribute-value paired annotations can be viewed and edited. In the top half, a control point is selected, in the bottom half an entire region. Original visualization based on an incunable, Pierpont Morgan PML 19921[24]

8 Maps studied

Our research dealt with eight medieval maps of diverse provenance and type. Table 1 presents what each map is known as, its place of production, approximate date of creation, medium, and location. Perhaps significant to our choice is the fact that half of them date from the fifteenth century, a moment in which a
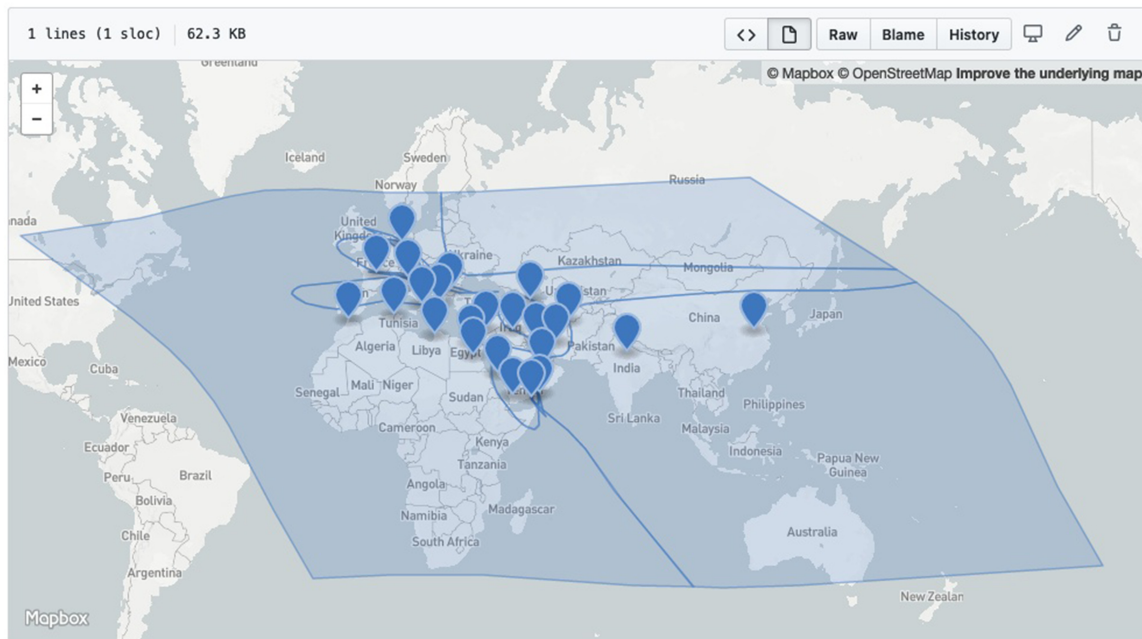
Fig. 9 A rendering of our GeoJSON data in the MapFolder Github repository[25]

geographical consciousness typical of Renaissance maps and an age of exploration and European expansion of trade routes might be said to be found in them (Brotton, 1997).

8.1 Distinctive geographic features of our map corpus

Medieval maps in the T–O style often have distinctive features. Two of them include a circular structure, and an orientation where Asia sits along the top half and the bottom quarters are shared with Europe to the left and Africa to the right as illustrated in Fig. 10. The division of the world creates a shape like the letter T inside of the letter O.

In the maps studied for this article, most followed this general orientation while exhibiting some distinct features. However, the al-Idrisi and Fra Mauro maps were oriented differently. They both exhibit Africa primarily along the top, with Asia in the bottom left and Europe in the bottom right.

Bodies of water were another distinctive geographic feature in the maps studied. In most of them, there was a distorted, though recognizable, Mediterranean region with features such as the Pillars of Hercules/ Straights of Gibraltar and the Italian peninsula (Fra Mauro, Psalter, al-Idrisi, Isidore, Ebstorf, Cotton Anglo-Saxon, Hanns Rüst). Fra Mauro had the most defined and recognizable Mediterranean region, including Northern African coastal features. The Mer des Hystoires map was unique in featuring all toponyms as individual islands, so there were no distinguishable real large bodies of waters; one might qualify this as a combination of a T–O and a list map. The Red Sea, while present in all maps studied, was distinguished in red in more than half of the maps (Psalter, Isidore, Ebstorf, Cotton Anglo-Saxon, Hanns Rüst).

Medieval maps in the T–O style are often shaped so that the Holy Land is located at the center of the map. The Ebstorf, Hanns Rüst, Mer des Hystoires, and Psalter maps all have a focus on the Holy Land at the exact center of the map with distinct toponyms and/or large iconography. The Isidore and Fra Mauro maps both have increased importance or prominence of the Holy Land, but the area is not the focus of the

Table 1. The eight medieval maps used in this article with relevant metadata

Known as	Place of production	Language	Date	Size/medium	Reference
Fra Mauro	Venice	Latin	1450	$223 \times 233\,cm^2$ wall mounted	Biblioteca Nazionale Marciana, Venice
Psalter World Map	Westminster	Latin	1262 or later	9.5 cm high, in vellum manuscript	London, BL Add MS 28681, fol. 9r
Al-Idrisi's world map from Kitab Rujar/ Book of Roger	Cairo	Arabic	1456	Miniature in paper manuscript	Oxford, Bodleian MS. Pococke 375 fol. 3v-4
Mer des Hystoires World Map	Paris	French	1491	Printed book	Brocardus, de Monte Sion. (Paris, 1543). La Mer des Histoires.
Isidore Map of the world with the Red Sea	Western France	Latin	c. 1130–35	Miniature in Vellum manuscript	Munich, BSB MS Clm 10058, fol. 154v
Ebstorf map	Northern Germany	Latin	c. 1235	$3.6 \times 3.6m^2$ vellum	not extant
Cotton Anglo-Saxon map	Canterbury, England	Latin	1025–50	Unknown	London, BL, Cotton MS Tiberius BV
Hanns Rüst woodcut map	Augsburg, Germany	German	c. 1480	16×11.5 inches, Woodcut print	New York, Pierpont Morgan PML 19921

map in that it is at the precise center of the circle. The Cotton Anglo-Saxon map does not place the Holy Land features at the center of the map at all.

A distinct geographic feature in the al-Idrisi map is the red lines across the map that could be interpreted as lines of latitude given the map represents the 'known world from the Equator to the Baltic Sea'.[26] The Mer des Hystoires map is unique in its placement of toponyms on what can be described as hills or islands. This map also includes many legendary and nongeographic places along the top of the map, a common distinctive feature of some medieval maps. The Isidore map often features buildings, which may be representative of places of worship, along with the toponyms. Though a nongeographic feature, the Psalter map has Christ and two angels taking up a third of the manuscript map. Artistic additions such as this make for interesting distortion when warped to a coordinate system.

9 Observations about maps using visualization

In what follows, we offer some remarks about using MapFolder on three use cases.

9.1 Use Case #1: The Psalter map

In the Psalter map, there is a lot of folding at its center—clearly marked as Jerusalem with many Holy Land cities in close vicinity (Fig. 11). Concentrated folding in the map could indicate an area with symbolic importance. Hovering over the reference map, it is possible to see how a location in a folded area transforms into multiple in the historic map caused by the folding. The coordinated mouse control is crucial to understand which parts are folded together. This example allows us to assess more critically the fact that many mappae mundi contain Jerusalem at their center.

9.2 Use Case #2: Fra Mauro

The Fra Mauro map clearly demonstrates the shrinkage and magnification in the maps studied. When using the Mix or Regions facets, one can more clearly recognize the regions present in shrinkage, magnification, and folding, whereas using the Contours mode, it is possible to see what may be considered the epicenter of the distortions. Faceting allows us to further investigate distortions. For example, the large swath of magnified space in the right in the historic map view highlighted in red in Fig. 12 demonstrates that much of Europe is given less geographic significance historically. This example allows

Fig. 10 A modern orthographic map in the T–O style with Jerusalem at the center, with the south-east pointing up.[27] Asia is shown in the top half of the map, while Europe is shown in the bottom left and Africa in the bottom right quarters

us to assess, in the case of T–O maps, how much of Africa and Asia is actually represented on the map.

9.3 Use Case #3: Isidore map of the world with the red sea

The Isidore Etymologies Map has an intriguingly high amount of distributed folded regions. One particularly curious folded region is near the control points in the region of present day France and Germany (Fig. 13). Different reasons may be the cause of the folded areas in this example; for example, the placement of the toponyms by the original map maker, which were used as anchor locations for the georectification, or imprecise placement of control points. If the analysis of a map with MapFolder results in a high degree of distributed folded regions,

regardless of their cause, one may want to consider that a fold could potentially be resolved by changing the annotation method or making a slight change in where the control points are placed on the historic map. This use case demonstrates how the MapFolder interface should be used heuristically, as a method of hypothesis generation, rather than an absolute accurate tool to numerically verify hypotheses of significance of places represented in medieval maps.

10 Discussion and limitations

As our last use case demonstrates, we propose MapFolder as an explorative tool suitable for
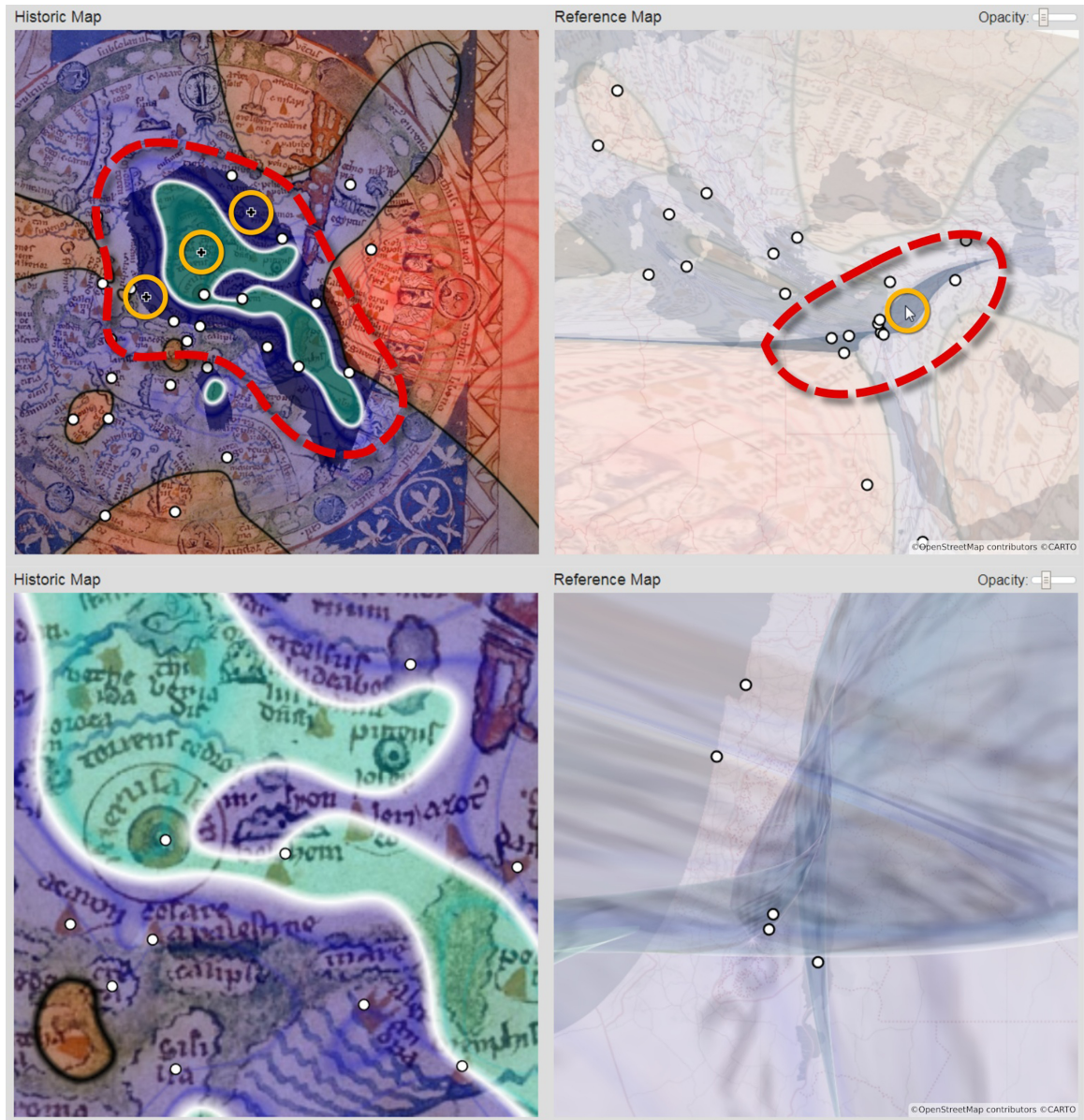
Fig. 11 The top two images demonstrating the Mix visualization mode showing folded regions in the center of the Psalter map corresponding close to Jerusalem (highlighted in red), as well as coordinated cursors showing the image transformation for a position in an overlapping region (highlighted in orange). More details can be revealed by zooming in as demonstrated by the bottom two images. Original visualization based on the mappae mundi found in The British Library, Additional MS 28681, fol. 9r[28]

hypothesis generation. We encourage its use to generate supportive evidence for existing hypotheses or to open new pathways of inquiry into pre-modern map making or, more generally, into analyzing maps of any

age not following a strict grid system. Its purpose is not to produce resilient statistics. The TPS method, on which the distortion and fold computation are based, minimizes a hypothetical bending energy, or, in other
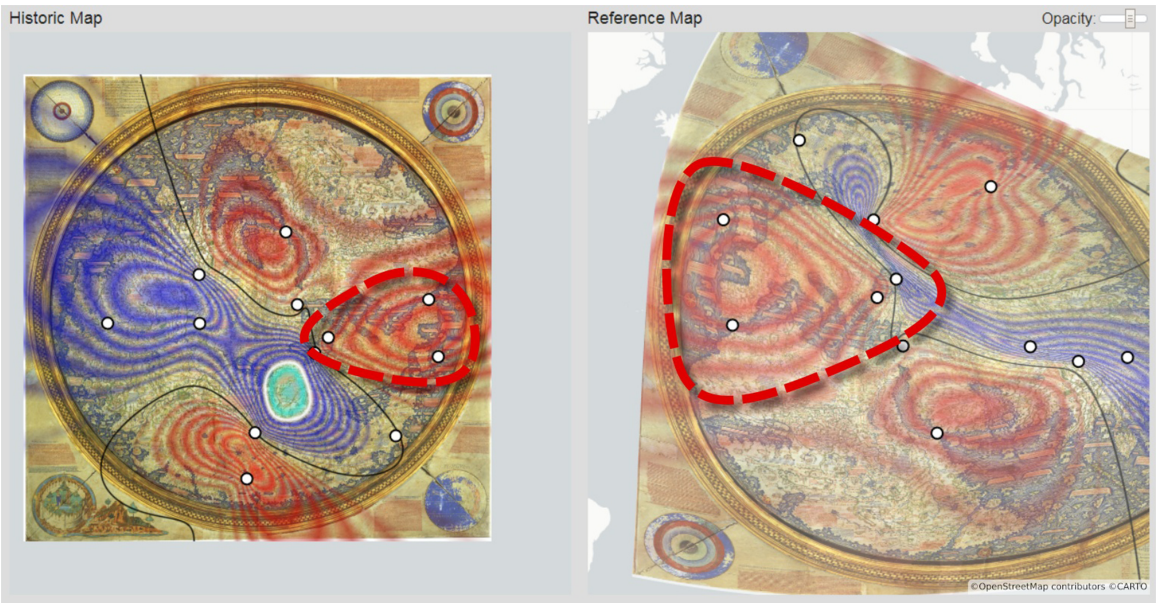
Fig. 12 The Contours visualization mode showing the Fra Mauro map with a magnified region in the right of the historic map highlighted in red corresponding to large portions of Europe. Original visualization based on Biblioteca Nazionale Marciana, Fra Mauro map (c 1450)[29]
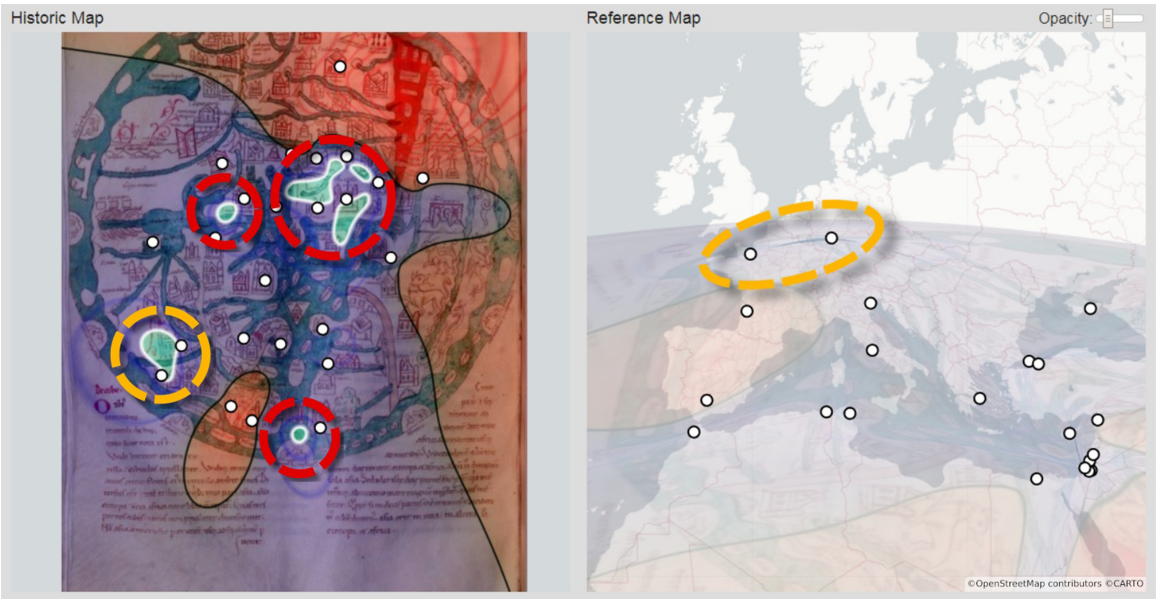

Fig. 13 The Mix visualization mode showing the Isidore map with distributed folds (highlighted in red). One particular fold (highlighted in orange) maps to two control points in today's France and Germany. Original visualization based on Munich, BSB MS Clm 10058, fol. 154v

words, the method will try to smooth out necessary distortions as much as possible.

Figure 14 demonstrates how quickly the visualization can change if only one of the control points would be removed. As the position of the green highlighted control point is no longer a constraint, the TPS moves it to another location in the reference map, as can be seen in the bottom half of Fig. 14, contributing to a release in bending stress. This results in the removal of one of the folds and the expansion of the other. The changes in the visualization, however, are only locally significant. The farther away from the removed point (in terms of control points lying in between), the less noticeable the change. We can draw some general observations about this behavior. The outcome of the visualization depends on the number and quality of the control points. The more control points are provided, the more folds and local distortions can be captured, and in turn the more refined their areas will be. Also, small changes in the placement of control points, for example, by inaccurate annotations, have a larger impact in areas with a low density of control points. Apart from the technical nature of this behavior, a practical limitation exists. The precision of our visualization is limited by the number of point-based features (e.g. toponyms) identifiable in a historic map.

11 Conclusions and future directions

We showcased how 'folds' in historical maps can be determined and visualized referring to contemporary geographical knowledge. Our workflow resembles, but it is fundamentally different from traditional practice of georeferencing in GIS, in as much as it separates the space of annotation from the interface of visual output. We have demonstrated how MapFolder can assist in the close reading of medieval mappae mundi that exhibit so many different scales and folds across the surface of the map. Far from asserting a normative approach that the medieval maps contain geographic errors, our prototype allows anyone interested in historical maps—the map historian, the medievalist, the student of GIS—access to a means of analysis of various zones on the map with sufficient precision. We

also proposed a spatial humanities workflow that offers a synergistic blend of elements of annotation and computational analysis of map images. As opposed to previous solutions, our workflow supports a more sophisticated feature detection and visual analysis of historic maps. With respect to these tasks, the development of standardized data formats for storing and linking georeferenced map images enriched by annotations as well as the inclusion of established data formats like IIIF into existing tools would be important future contributions outside the scope of MapFolder.

In order to improve our approach and the MapFolder tool in the future, we envision a series of adaptations. First, we aim to address the problem of unannotated 'dead spaces', in which our algorithm currently approximates space anticipating a well portrayed geographical area. We will account for this problem by allowing the user to annotate the estimated accuracy of areas in-between control points, hindering our algorithm to approximate space when inappropriate. We would also like to enable users to specify levels of uncertainty for a control point annotation that could be taken into account when determining the distortion, but also being visually communicated. Second, we ideally would offer more sophisticated means of annotation. By also incorporating line and polygonal annotations addressing geographic features that do not bear toponyms, we hope to further increase the accuracy of the folded map visualization. Third, we suggest reversing the transformation direction by projecting the reference map onto the historic map, giving an alternative view on how geographic grid representation space can be compared with the mappae mundi. Fourth, we would like to support using arbitrary reference maps, either standardized map projections or other historic maps that could be used as a point of reference.
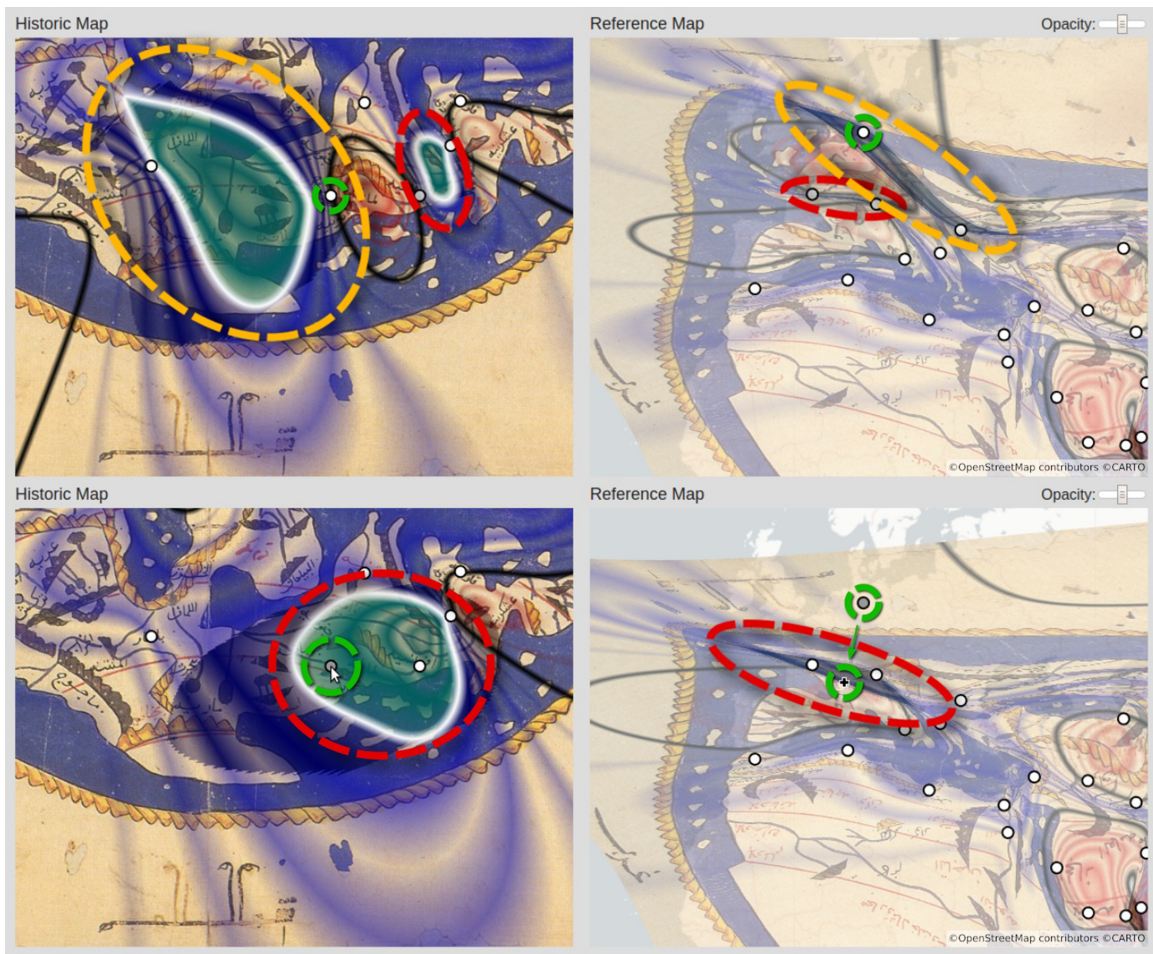
Acknowledgements

Fig. 14 The top half shows a part of the Al Idrisi map with two folds, highlighted in red and orange. In the two images in the bottom half the control point highlighted in green is disabled, resulting in removal of the orange fold and expansion of the red fold. This is caused by the relaxation of the underlying TPS 'bending' according to which the position of the disabled control point moves in the reference map. Original visualization based on Oxford, Bodleian Library, Pococke 375, fol. 3v-4[30]

mappamundi found in the manuscript of Isidore (Munich, MS Clm 10058, fol. 154v.). For all visualizations in this article showing a 'Reference Map', we use the CARTO Positron without labels basemap[31] based on OpenStreetMap[32] data. The screenshot in Fig. 1 is used with permission from Microsoft.

References

Baiocchi, V. and Lelo, K. (2005). Georeferencing the historical maps of Rome between the seventeenth and eighteenth centuries. In: *CIPA 2005 XX International Symposium*, 26 September–01 October, 2005, Torino, Italy.

Baletti, C. (Winter 2006). Georeference in the analysis of the geometric content of early maps. *e-Perimetron*, **1**: 32–42.

Bradley, J. and Vetch, P. (2007). Supporting annotation as a scholarly tool—Experiences from the online Chopin variorum edition. *Literary and Linguistic Computing*, **22**(2): 225–41.

Brotton, J. (1997). *Trading Territories: Mapping the Early Modern World*. London: Reaktion Books.

Card, M. (1999). *Readings in Information Visualization: Using Vision to Think*. San Francisco: Morgan Kaufmann.

Chamberlin, W. and Grosvenor, G.H. (1950). *The Round Earth on Flat Paper: Map Projections Used by Cartographers.* Washington: National Geographic Society.

Claeys Boùùaert, M., De Baets, B., Vervust, S., Neutens, T., De Maeyer, P., and Van de Weghe, N. (2016). Computation and visualisation of the accuracy of old maps using differential distortion analysis. *International Journal of Geographical Information Science*, **30**: 1255–80.

Clifford, J., MacFadyen, J., and Macfarlane, D. (2013). *Georeferencing in QGIS 2.0. Programming Historian.* https://programminghistorian.org/en/lessons/georeferencing-qgis (accessed 25 April 2019).

Duchon, J. (1977). Splines Minimizing Rotation-Invariant Semi-Norms in Sobolev Spaces, in: Schempp, W., Zeller, K. (eds), *Constructive Theory of Functions of Several Variables, Lecture Notes in Mathematics.* Berlin Heidelberg: Springer, pp. 85–100.

Edson, E. (1997). *Mapping Time and Space: How Medieval Mapmakers Viewed Their World.* London: British Library.

Galey, A. and Ruecker, S. (2010). How a prototype argues. *Literary and Linguistic Computing*, **25**(4): 405–24.

Grossner, K. (2014). Concepts and principles of spatial literacy In *Space in Mind: Concepts for Spatial Learning and Education.* Cambridge, Massachusetts: MIT Press, pp. 239–62.

Höhn, W. (2016). Georeferencing, annotation, and analysis tools for old maps: An overview. In van Dijk, Thomas; Schommer, Christoph (eds), *Proceedings of the 2nd International Workshop on Exploring Old Maps.* Würzburg: University of Würzburg.

Jänicke, S., Franzini, G., Cheema, M. F., and Scheuermann, G. (2017). Visual text analysis in digital humanities. *Computer Graphics Forum*, **36**(96): 226–50.

Jenny, B., Weber, A., and Hurni, L. (2007). Visualizing the planimetric accuracy of historical maps with MapAnalyst. *Cartographica*, **42**: 89–94.

Kaplan, F., Fournier, M., and Nuessli, M.-A. (2014). *L'historien et l'algorithme.* Le Temps des Humanités Digitales, Editions FYP, pp. 49–63.

Lloyd, C. and Lilley, K. (2009). Cartographic veracity in medieval mapping: analyzing geographical variation in the gough map of Great Britain. *Annals of the Association of American Geographers*, **99**(1): 27–48.

MacEachren, A. and Kraak, M.-J. (2011). Exploratory cartographic visualisation: Advancing the agenda. *The Map Reader: Theories of Mapping Practice and Cartographic Representation*, **23**: 83–8.

Messerli, A. and Grinsted, A. (2015). Image georectification and feature tracking toolbox: ImGRAFT. *Geoscientific Instrumentation, Methods and Data Systems*, **4**(1): 23–34.

Miller, K. (1928). *Weltkarte des Idrisi vom Jahr 1154 n. Ch., Charta Rogeriana.* Stuttgart.

Paul, N.L. (2018). *Introducing the Oxford Outremer Map. Fordham Medieval Digital Projects.* https://medievalomeka.ace.fordham.edu/exhibits/show/oxford-outremer-map/mpcontext (accessed 25 April 2019).

Presner, T.S., Shepard, D., and Kawano, Y. (2014). *Hypercities: Thick Mapping in the Digital Humanities.* Cambridge: Harvard University Press.

Teo, Y. M., Low, S. C., Tay, S. C., and Gozali, J. P. (2003). Distributed geo-rectification of satellite images using grid computing. In *Proceedings of the 17th International Symposium on Parallel and Distributed Processing (IPDPS '03)*, IEEE Computer Society, Washington, DC, USA.

Tobler, W. (1966). Medieval distortions: The projections of ancient maps. *Annals of the Association of American Geographers*, **56**(2): 351–60.

Windhager, F., Federico, P., Schreder, G., Glinka, K., Dörk, M., Miksch, S., and Mayr, E. (2018). Visualization of cultural heritage collection data: State of the art and future challenges. *IEEE Transactions on Visualization and Computer Graphics*, **25**(6): 2311–30.

Woodward, D. (1974). The study of the history of cartography: A suggested framework. *American Cartographer*, **1**: 101–15.

Woodward, D. (1985). Reality, symbolism, time, and space in medieval world Maps. *Annals of the Association of American Geographers*, **75**(4): 510–21.

Yang, W. and Di, L. (2004). An accurate and automated approach to georectification of HDF-EOS swath data. *Photogrammetric Engineering & Remote Sensing*, **70**: 397–404.

Notes

1 Other potential applications that we have not yet tried might include other kinds of documents that have a somewhat geographic quality: indigenous maps, topological maps, sketch maps, or mental maps.
2 https://www2.leuphana.de/ebskart/
3 https://www.adobe.com/products/flashplayer.html
4 https://www.themappamundi.co.uk/mappa-mundi/
5 http://sims.digitalmappa.org/workspace/#965fe731
6 https://www.digitalmappa.org/
7 https://recogito.pelagios.org/

8 It is worth acknowledging that amongst practitioners in GIS and the spatial humanities there is some ambiguity in the terms used for adding geo-information to image raster. Some do not use the term 'georectification' since it seems to assert the transformation of an image into a normative grid and the judgment that the original image did not constitute a legitimate spatial frame. We use the term to signify this transformation, but without asserting the correctness or the primacy of the Web Mercator system. We use the term georeferencing to signify the choice of control points and establishing their geographic coordinates.

9 For basic georeferencing workflows, see https://geo.nls.uk/urbhist/guides_georeferencing.html

10 https://commons.wikimedia.org/wiki/File:FraMauroDetailedMap.jpg

11 For example, in order to identify regions represented on the Ebstorf map that was destroyed in the Second World War, we relied on the annotations of the Ebskart project that reproduces sketches made from early photography of the map in 1891: http://www2.leuphana.de/ebskart/. For the Idrisi map, in addition to Miller (1928), we queried Twitter users and received many identifications of places: https://twitter.com/DJWrisley/status/117168669823072256. Our thanks to those who responded to our call.

12 https://www.openstreetmap.org/

13 The repository can be found at https://github.com/djwrisley/dshmap and the web map at https://djwrisley.github.io/dshmap/webapp/#4/40.11/33.40

14 https://www.arcgis.com

15 https://www.qgis.org

16 This term refers to a finite set of values - the set of scaling factors determined at each pixel of the historic map image. In the continuous case we would need to use the integral of the areal scaling function.

17 https://www.informatik.uni-leipzig.de/~reckziegel/mapfolder

18 https://mapwarper.net

19 https://commons.wikimedia.org/wiki/File:Al-Idrisi's_world_map.JPG

20 https://www.w3.org/TR/annotation-model

21 https://geojson.org

22 https://tools.ietf.org/html/rfc2397

23 https://github.com/MapFolder/MapFolder

24 https://www.themorgan.org/incunables/145336

25 https://github.com/MapFolder/MapFolder

26 This phrase is taken from the Bodleian Library's catalog description of the al-Idrisi map: https://digital.bodleian.ox.ac.uk/inquire/p/cc2debab-70f5-4b82-9bab-7235fdb89e43

27 https://commons.wikimedia.org/wiki/File:Orthographic_T%26O.png

28 https://www.bl.uk/collection-items/psalter-world-map

29 https://commons.wikimedia.org/wiki/File:FraMauroDetailedMap.jpg

30 https://commons.wikimedia.org/wiki/File:Al-Idrisi's_world_map.JPG

31 https://carto.com/help/building-maps/basemap-list/, https://github.com/CartoDB/basemap-styles

32 https://www.openstreetmap.org