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A visual analytics approach for deterioration risk analysis of ancient frescoes

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Abstract Mural paintings are precious and irreplaceable as cultural heritage components. At present, however, these paintings are subject to increasing various risks of deterioration. Thus, a visual analytics method based on risk management is proposed in this study to analyze these risks. A series of multi-scale analytic tools is designed and developed with multidimensional and multivariate visualization techniques to study single or multiple risks at the scales of sites, caves, walls, and specific risk areas from different perspectives. Several case studies that contain real data are presented and an expert review is conducted to evaluate the proposed method.

Keywords Cultural heritage · Mural paintings · Risk · Visual analytics

1 Introduction

A grotto fresco site is an integral cultural heritage component that is generally renowned for its valuable ancient mural paintings in caves. These precious ancient paintings and pieces of rock art are fragile and are typically subject to various risks (Stovel 1998; Li et al. 2013; Mckercher et al. 2005; Tidblad et al. 2009; Sabbioni et al. 2006). The risks to cultural heritage can be divided into three categories: natural hazard, deterioration, and anthropogenic risks. Deterioration risk is an unusual category for cultural heritages and is the risk category that is most relevant to cultural relics. The deterioration risk to ancient mural paintings mainly involves flaking, blistering, cracking, disruption, loss, detachment, and mold, among others. These risks are the main focus of the daily effort to conserve grotto fresco sites.

Considerable effort has been exerted to preserve cultural heritages, and preventive conservation is the most significant of such efforts in that this approach aims to identify and reduce the potential risks to such heritages. To this end, risks must be managed scientifically and rationally. Nevertheless, many challenges are encountered in the risk management of cultural heritages. First, the diversity of risks generates heterogeneous, multidimensional and multivariate features in risk data. Second, multiple types of risks are difficult to manage and analyze simultaneously on a unified platform. Finally, clarifying and examining overall risk distribution conveniently is complicated at site level. Therefore, tools that can manage and analyze risks on multiple scales from different perspectives must be developed.

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Much research effort is currently being exerted to capture, analyze, visualize, and model cultural heritage risk information. For example, Zarzo et al. (2011) developed a microclimate monitoring system that can collect and investigate microclimate risk information to preventively conserve the Renaissance frescoes in a cathedral. Chittaro et al. (2006) proposed a visual tool to simulate the effect of disasters on cultural heritage objects and discussed the experience of a museum in a gothic cathedral that was subject to a real disaster. These works focus on either environmental impacts or natural disasters, and to the best of our knowledge, no customized visual analytics approach has been developed for the management and analysis of deterioration risks to ancient mural paintings.

In the current work, we emphasize the use of visual analysis to study the deterioration risks to such paintings and present a visual analytics method that supports risk management process. This method involves risk identification, assessment, analysis, mitigation, and decision-making support. We focus on the Dunhuang Mogao Grottoes, which is an important World Heritage Site, although our results are also applicable to other similar cultural heritage sites. The main efforts of this study are summarized as follows.

– A visual analytics method based on risk management process is proposed to analyze various deterioration risks to mural paintings, which supports risk identifying, assessing, and analyzing.
– A series of visualization tools are designed and developed to analyze the deterioration risks at multiple scales from different perspectives.
– Several case studies that utilize real data are presented, and the proposed method is evaluated through an expert review.

The remainder of the paper is organized as follows. We first review related works from two aspects. Then, we introduce our methodological approach and design. Subsequently, we discuss several case studies and introduce the evaluation based on expert review. Finally, we present the conclusions of this work.

2 Related work

2.1 Risk study in cultural heritage

Cultural heritages are vulnerable and are subject to various risks (Agnew 1997, 2010; Giovagnoli et al. 2008; Zhao and Li 2003). Thus, risk management theory is ideal for preventive conservation of cultural relics (Waller 1994, 1995; Levin 1992). For example, Waller applied a risk management model for the preservation of movable cultural relics based on the study and practice of museum collection preservation. The model was continuously perfected in subsequent works (Waller 1994, 1995, 2002). Paolini et al. (2012) attempted to manage risks in the preventive conservation of an immovable cultural heritage in Amman. These works gradually introduced risk management into the field of cultural heritage research and attempted to enhance risk management theory through practice.

Many studies have also focused on risk monitoring and detection. Deterioration risk is commonly associated with imbalances in temperature and humidity as a result of different factors, such as heating, air conditioning, ventilation, and large numbers of visitors (Camuffo 1998). Given these complex risks, different microclimate parameters (e.g., temperature, relative humidity, and dew point, among others) were monitored in some studies (Bernardi 1990; Bernardi and Camuffo 1990; Camuffo et al. 2002). Hazard risk is another important risk category for cultural heritages. The probabilistic seismic risk assessment method based on history data is commonly used to study seismic hazards (D'Amico et al. 2012). D'Ayala et al. (2012) presented a methodology for assessing the effects of local site conditions on the seismic performance of cultural heritage buildings. Abruzzese et al. (2009) proposed a broad wireless sensor network system for monitoring and assessing vibration risk. Kheir et al. (2008) used geographic information systems (GISs), remote sensing, structural classification techniques, and decision-tree modeling to map erosion risks. Chau et al. (2005) presented two hybrid models based on artificial intelligence technology to forecast floods. These studies focus on microclimate factors or on hazard risk monitoring, and few works analyze deterioration risks.

2.2 Data visualization in cultural heritage

At present, significant progress has been made in collecting, analyzing, and visualizing cultural heritage information. GIS technologies are typically introduced into various applications related to cultural heritages. Petrescus survey indicated the application status of GIS technologies in cultural heritages (Petrescu 2006).

The methods that are commonly used to visualize architectural heritage are shape syntax-based methods (Özkar and Stiny 2009) that originated as manual drawings on paper and developed into modern computer-aided drafting-based drawings (Anastasiou et al. 1999). For example, Huang et al. (2005) applied shape grammar to examine cultural heritages.

Deufemia et al. (2012) proposed a visual analytics tool to examine large repositories and drawings. This tool aims to interpret new archaeological findings. Blaise et al. (2008) presented a methodological framework-labeled informative modeling based on the relationship between architectural modeling and information visualization. Huisman et al. (2009) also introduced a geo-visual analytics tool for archaeologists; this tool aims to investigate archaeological events. Zhang et al. (2013) proposed a visual analytics framework and approach for studying the degradation problems in grotto wall paintings by applying multidimensional visualization techniques.

Compared with our work, most of these works focus on archaeological research of cultural heritage, whether GIS technologies or shape syntax-based methods. Few works study the degradation of relics using visualization techniques. Nevertheless, these works do not combine risk management with visual analytics in deterioration risk analysis.

3 Method and design

3.1 Visual analytics method overview

In practice, risk management process of cultural heritage is derived from risk management theory. Firstly, deterioration risks are monitored by field surveys, and risk events are identified by processing monitoring data. Subsequently, risk magnitude is quantified through risk assessment. Then, domain experts conduct a risk analysis to determine risk patterns, causes, and mechanisms. Appropriate risk mitigation strategies are developed based on risk analysis results, and suitable risk treatment measures are adopted. Thus, risk causes and resources can be obtained through risk analysis, and then they can be prevented or stopped in time to mitigate risks by risk treatment. As a result, the goal of preventive conservation for cultural heritage can be achieved under the guidance of risk management. However, risk management is challenging and inefficient given the nature of risk data as multidimensional, multivariate, heterogeneous, and a type of big data. Thus, an intuitive and convenient analytic tool must be developed to support risk identification, assessment, and analysis.

Our method is designed on the basis of the risk management process, which consists of risk identification, assessment, analysis, and treatment. The method is shown in Fig. 1. This method aims to facilitate risk management as well as to provide intuitive and effective analysis of risk data. The proposed method emphasizes risk analysis, which is the core of risk management. The results of visualization-based risk analysis can also support risk reasoning and be regarded as visual evidence in decision-making related to risk mitigation. The proposed method has four components: risk analysis tools for visualizing the overall risk distribution of multiple caves at site scale, risk analysis tools for visualizing detailed risk information at cave scale, risk analysis tools based on risk clustering, and semiautomatic risk marking and accessing tools.

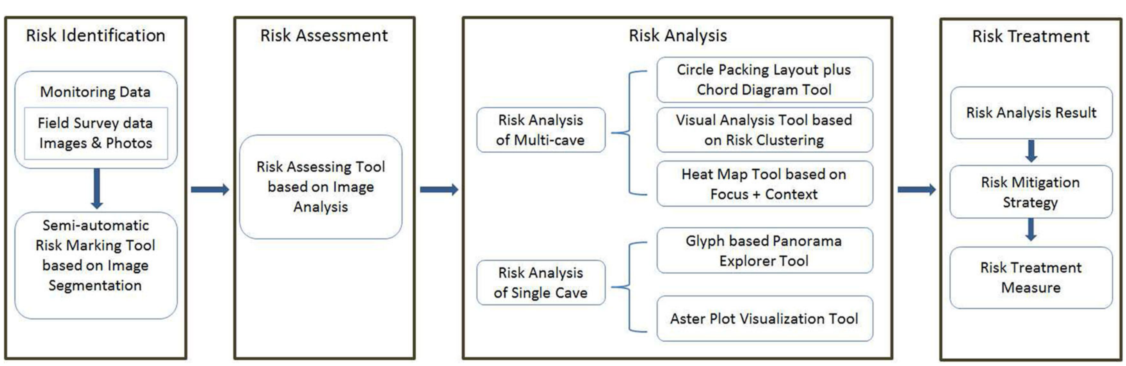

Fig. 1 Proposed multi-scale analytics method for deterioration risks to mural paintings based on risk management process

3.2 Risk analysis tools for multiple caves

Risk analysis is an essential process in risk management. Clarifying and analyzing the overall risk distribution in all caves is vital to this analysis in that domain experts can determine risk patterns and obtain knowledge by studying global risk distribution. Thus, visual analytic tools must be developed for visualizing and analyzing overall site-level risk distribution. The site-level risk analysis tools for our method perform three functions: overall risk distribution visualization, the visualization of the spatial distribution of overall risk, and the visual analysis of risk correlation.

3.2.1 Visualization of overall risk distribution with the circle packing layout + chord diagram

The cultural heritage site contains many caves. Hence, scalability must be favorable for site-level visualization tools to visualize overall information. Furthermore, all caves are classified into bottom, middle, and top floor caves because the position of a cave on the cliff is a sensitive factor in risk analysis. Caves near the ground belong to the bottom floor; caves near the cliff top are top floor caves; and the remaining caves belong to the middle floor. A circle packing layout is adopted for the caves in our design to facilitate space efficiency. The three floors of caves are mapped to three circular groups (Fig. 2a); the purple, green, and yellow circle groups represent the caves at the bottom, middle, and top floors, respectively. The size of each circle corresponds to the risk magnitude of each cave.

The next step involves encoding all types of risk and cave-level information into site-level visualization. In this work, risks are represented by arcs that form a large circle around circle groups (Fig. 2b). Each arc represents one type of risk and is filled with a corresponding color. The length of each arc corresponds to the sum of the magnitudes of one type of risk for all caves. These arcs are arranged in descending order according to the magnitude of risks; the arcs are drawn in a clockwise direction from the top middle point. The chord visualization method is also used to visualize cave-level risk data. Furthermore, the arcs are split into a number of segments, and each segment represents one type of risk for one cave. The segment length corresponds to the risk magnitude. If one cave is subject to certain risks, then the circle is linked to the

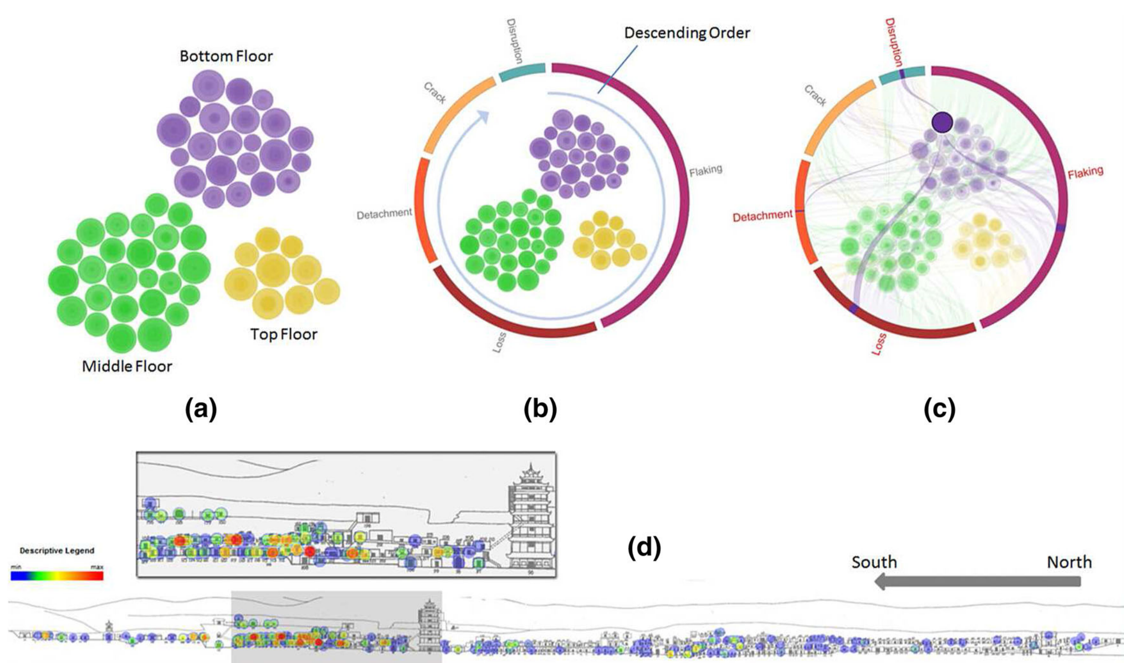

Fig. 2 Site-level visualization with the *circle packing* layout + chord diagram tool and heat map. **a** Three floors of the Mogao Grottoes as encoded by a three-group *circle packing* layout. **b** Risks are encoded by arcs that form a large circle around these groups. **c** *Circles* are linked to arc segments by chords. **d** Spatial distribution of overall disruption risk based on a heat map with focus + context visualization

corresponding arc segments by chords (Fig. 2c). The chord width represents risk magnitude. By applying the aforementioned visualization tools, we can determine the type of risks in a cave and the caves that are subject to one or several given risk types.

3.2.2 Visualization of the spatial distribution of overall risk with heat map based on focus + context

Another important aspect of site-level risk analysis is the visualization of the spatial distribution of risk because the geographical environment is an important element in risk analysis. However, detailed spatial information is lacking given that the caves are encoded in accordance with the circle packing layout. Thus, a heat map is introduced into our method to visualize the spatial distribution of risk given the relative position information of each cave (Fig. 2d). An orthophoto map of the cliff facade is used as a base map. The caves are represented by dots on the base map that are filled with different colors, and the colors of the dots represent risk severity. Considering that the orthophoto map is long and narrow, focus + context visualization is applied to provide users with both an overview and details. The entire heat map is shown in the context view, and the selected area is displayed in focus view with a zoomed-in version. In addition, a heat map is combined with the circle packing layout + chord diagram tool. The heat map shows the aggregated risk distribution of all caves if none of caves or risks has been selected in the circle packing layout + chord diagram tool. If a risk or a cave is chosen, the heat map depicts the distribution of the selected risk type or the selected cave.

3.2.3 Visual analysis of risk correlation through scatter plot matrix

The correlations among different types of risks are often related to risk mechanisms, and the exploration of these correlations is an important task in site-level risk analysis. A scatter plot matrix (Fig. 10) is introduced into our method as a useful complementary tool for analyzing the correlations between two different risk types. The scatter plot matrix is a matrix of all the pairwise scatter plots among different risk types and represents a simple but effective technique for viewing all pairwise relationships among the risks.

3.3 Risk analysis tools for single cave

Domain experts derive macro understanding and risk patterns from site-level risk analysis. To validate these findings, experts must check the detailed information of single caves, such as risk type, severity, area position, appearance features, and orientation. Therefore, analyzing the risks of every single cave is an important part of risk analysis.

In our method, we design several tools to visually analyze deterioration risks at the scale of the cave, wall, and specific risk area in compliance with existing practices. In this work, a panorama is utilized to visualize the detailed risk information of a single cave (Fig. 3). A set of symbols that are familiar to domain experts is used to mark different types of risks on the images semiautomatically (as described in Sect. 3.5). The marked images are used to construct the cave-level panorama. Users can therefore check detailed information (such as risk type, risk area size, position, and orientation) regarding each specific risk area in an immersive manner through the panorama of a single cave.

Although the detailed risk information of a single cave has been visualized intuitively, we must still determine the overall risk situation of such a cave. For this purpose, Aster plots are introduced in our work. Examples are shown in Fig. 4. This plot is a common but effective approach to high-dimensional data visualization. Risk magnitude data are normalized within the range of 0.0 to 1.0 so that experts can compare the risks of different caves based on the Aster plots. In fact, users can jump to the corresponding panoramic view by clicking this plot. The Aster plot tool is also combined with site-level tools and views.

3.4 Risk analysis tools based on risk clustering

All the caves are subject to different risk types of various severities. Nevertheless, there are similarities among the caves in terms of the risk type and severity. Analyzing the features of caves under similar risks

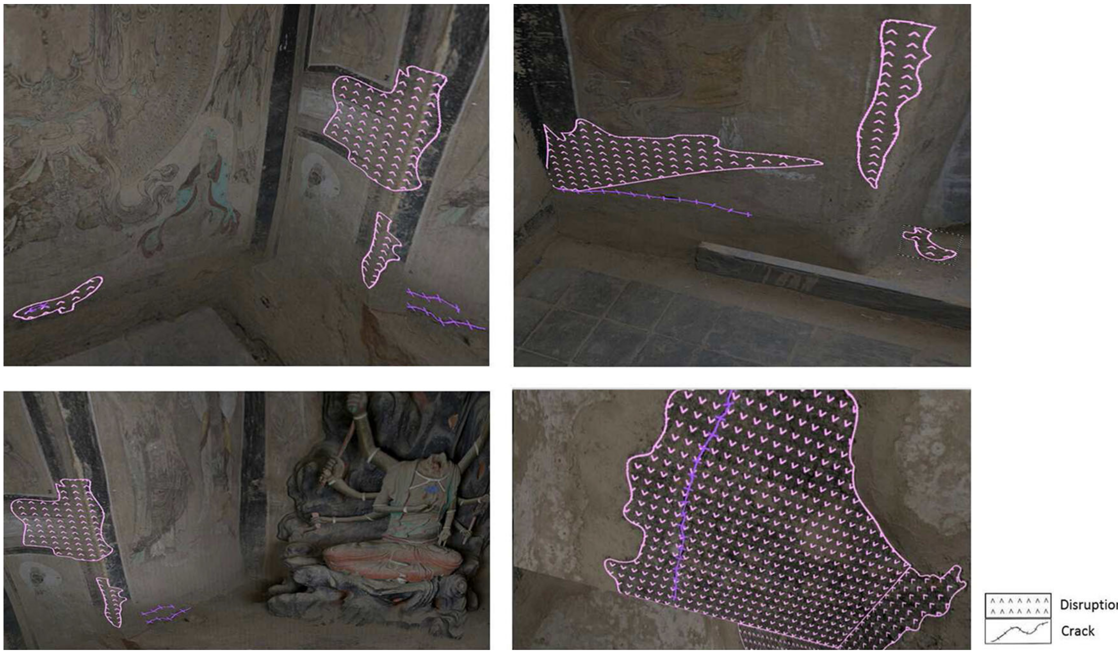

Fig. 3 The glyph-based panorama tool

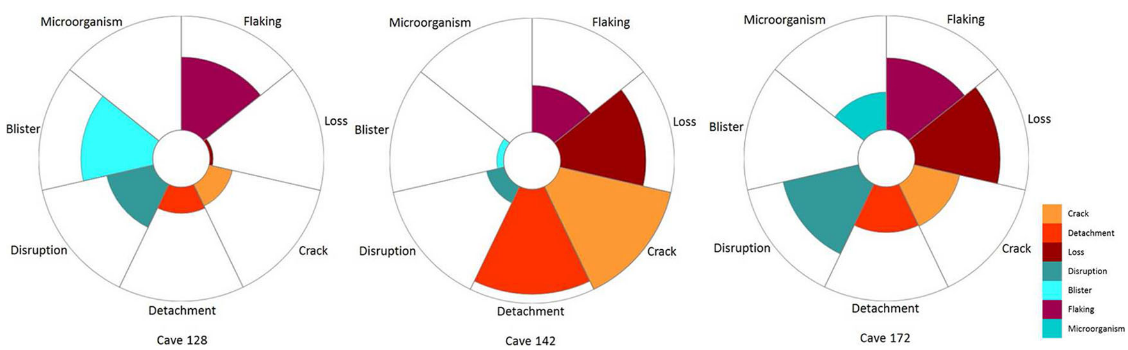

Fig. 4 Visualization of the Multi-risk data of a single cave using aster plots. Each sector is marked by a *certain color* and represents one type of risk and its magnitude

effectively reveals risk patterns and imparts knowledge to domain experts. Therefore, this process is meaningful for risk analysis. Clustering is introduced into our method to identify similar caves. Furthermore, a comprehensive analysis tool is designed to analyze risk features based on the clustering results.

The k-means clustering algorithm (MacQueen 1967) is used in our clustering study. The risk data are characterized by high dimensionality given the diversity of risks. Thus, principal component analysis (Kambhatla and Leen 1997), which is a dimension reduction method, is conducted to process these data. The clustering results are interesting in that nearly every cluster exhibits a completely different risk characteristic. Thus, risk analysis based on risk clustering is significant.

To facilitate intuitive understanding, clustering results are visualized through a force layout (Fig. 5). On this basis, we design a comprehensive tool to study risk patterns based on risk clustering. Grouped and stacked bar charts (Fig. 5) are added to this tool as a supplement in the analysis of the risk severity and spatial distribution of each cluster. A heat map is incorporated into this tool to generate visual spatial location information. Users can select a specific cluster to filter the caves through interactions.

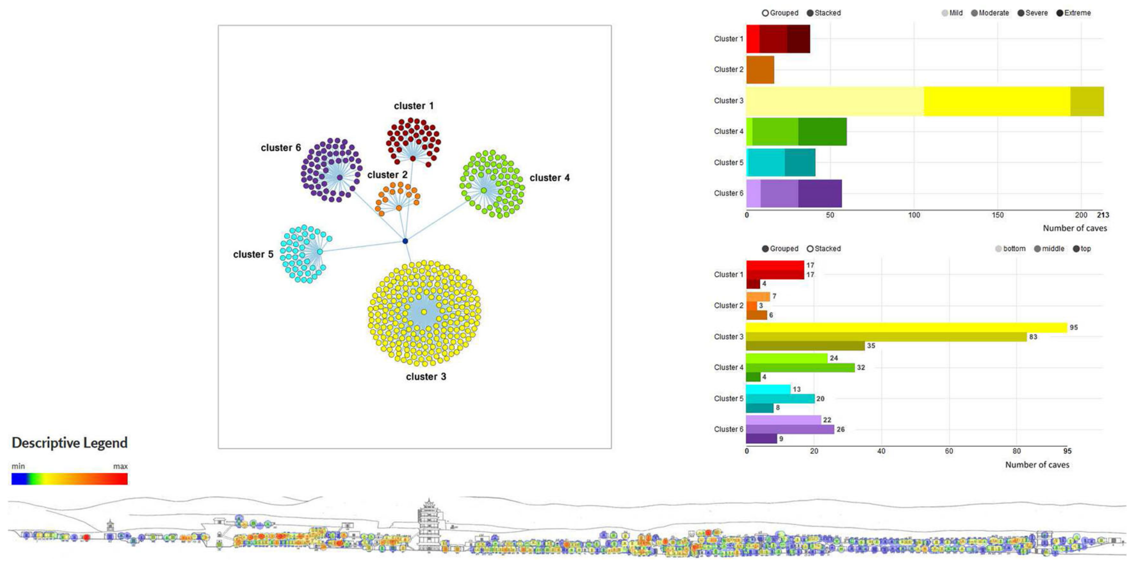

Fig. 5 Comprehensive visual analysis tool based on risk clustering. Clusters are visualized by force layout. The grouped bar chart and stacked bar chart are used as assistant tools to analyze risk from the clustering perspective. A heat map is also integrated into this tool to analyze the spatial distribution of risk clusters

Simultaneously, the heat map is regenerated to show the spatial distribution of risk in the selected cluster. This tool can also work together with the cave- and site-level tools to analyze risk patterns.

3.5 Risk marking and assessment tools

Risk identification and assessment are important parts of risk management. To this end, a semiautomatic tool is designed to assist domain experts in marking risk areas on images using familiar symbols. The tool is combined with image segmentation technology and can perform the aforementioned task automatically as well as fill the corresponding symbols in the area (Fig. 3). Subsequently, domain experts can adjust and modify border shape manually to enhance accuracy. The marked images can also be used to build the panorama (described in Sect. 3.3). Then, risk measuring indicators (such as length, width, area, and depth) can be obtained by analyzing the marked images with image analysis techniques. Risk events can be identified and risk magnitude quantified based on these measuring indicators.

3.6 Interaction design

Risk analysis is a complex process that requires users to switch between different scales. Thus, all multi-scale visualization layouts and tools must be combined in operation. Three main interaction types are observed in our method: cave selection, risk selection, and dynasty and cluster filtering.

When a cave is selected, the corresponding circle, the arcs that represent the risks in the selected cave, and the chords that link the circle to the arc segments are all highlighted first (Fig. 2c). Meanwhile, the heat map view shows the selected cave as a colored dot at the corresponding position. By double-clicking the cave, users navigate to the Aster plot and panoramic views.

Subsequently, we can select one or several types of risks. Then, the caves with the chosen risks and the related chords are highlighted, and the heat map view shows the spatial distribution of the risk in question. Meanwhile, the arcs that represent the selected risks are split into three parts that are denoted by three colors (Fig. 6a). The purple, green, and yellow arc segments correspond to the sum of the magnitudes of the selected risk in the caves on the bottom, middle, and top floors, respectively.

Third, caves can be filtered by dynasty and cluster. The size of circles will decrease and the arcs, chords, and heat map will be recalculated and redrawn based on the filtered caves.

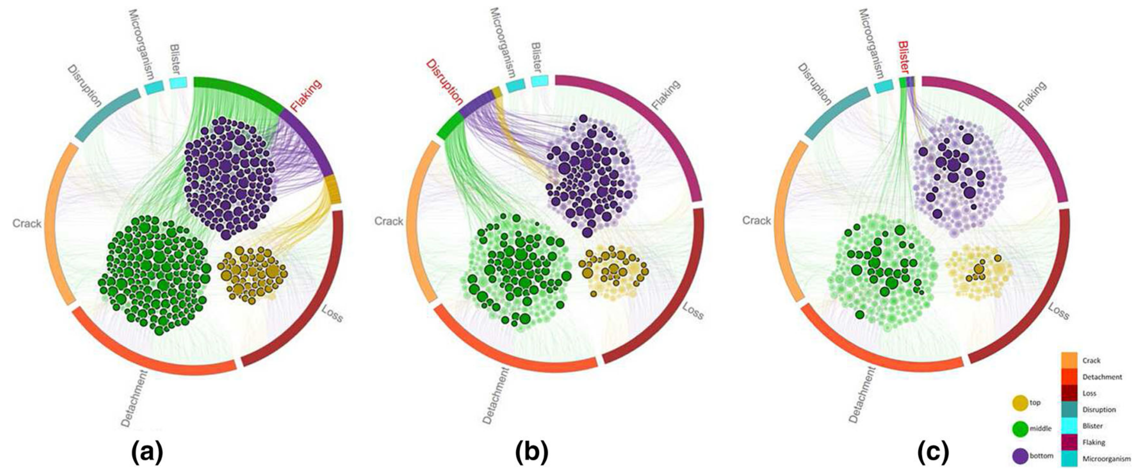

Fig. 6 Overall risk spatial distribution pattern. **a** Flaking risk is the most common risk for all the caves. **b** Disruption risk mostly occurs in the middle and lower floors. **c** Blistering risk mostly occurs in the middle and lower floors.

4 Applications and case studies

4.1 Study background

Our study is mainly based on the Mogao Grottoes, which is a World Heritage Site located 16 miles southeast of the center of Dunhuang, Gansu Province, northwest China. The Mogao Grottoes are distinguished by their exquisite murals and sculptures of Buddhist art. The grottoes have 735 caves, 45,000 square meters of murals, and 2415 painted sculptures. The mural paintings have always been threatened by various risks over the past centuries. In recent years, risk management has been gradually introduced into the Mogao Grottoes and domain experts have attempted to apply risk management practices to cultural heritage conservation.

4.2 Risk spatial distribution pattern

Globally, the most severe deterioration risks are flaking, loss, detachment, and cracking. As shown in Fig. 6a, when flaking risk is selected, the vast majority of the circles that represent the caves are highlighted. The same finding is also applicable to loss, detachment, and cracking risks. Such result indicates that most of the caves are facing these four types of risks. Based on statistics, the percentages of caves that are exposed to flaking, loss, detachment, and cracking risks are 83, 80, 85, and 89 %, respectively. Moreover, the arc lengths of these four types of risks show that they are not only the most common, but also the most severe, types of risks to mural paintings.

When risks are filtered, several interesting patterns emerge. For example, in Fig. 6b, c, when disruption and blistering risks are selected, the highlighted circles are mostly green and purple, which indicates that these types of risks mostly appear on the middle and bottom floors. Therefore, these mural risks must be associated with the height of a cave above the ground. Panorama tools for a single cave (Fig. 3) are used to investigate the causes of these risks. The detailed positions of the areas that are facing disruption and blistering risks can be seen clearly in the panoramic views. These areas are mainly located on the lower part of the walls. Therefore, disruption and blistering risks possibly occur on sections that are close to the ground. In particular, statistics show that 86.2 and 85.6 % of the caves that are facing blistering and disruption risks, respectively, are located on the bottom and middle floors. Some causes may explain why these two risks follow such an obvious principle, and domain experts have provided some explanations. Disruption and blistering risks are both associated with a change in humidity. Humidity is high in the caves that are close to ground, which makes these caves vulnerable to these two types of risks. Another pattern is that the caves with the most severe disruption risk are concentrated in the south area, as revealed in the heat map view (Fig. 2d). This phenomenon can be attributed to the fact that the southern part of the Mogao Grottoes is located considerably lower than the northern part. Other types of risks do not present such a regular visual pattern, and thus, they are not definitely associated with humidity.

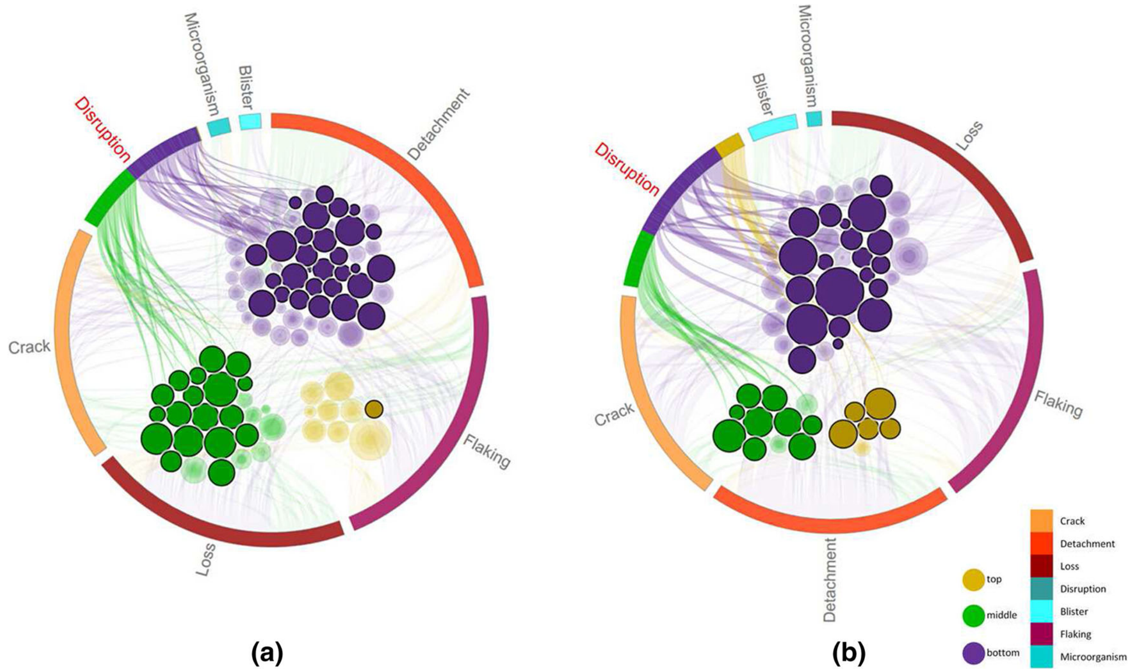

Fig. 7 Disruption risk pattern with construction dynasty. **a** Disruption risk distribution of the High Tang Dynasty. **b** Disruption risk distribution of the Late Tang Dynasty

4.3 Risk pattern for construction dynasty

The caves and mural paintings of the Mogao Grottoes were built and maintained by several dynasties. Caves built during different dynasties exhibit many differences, such as painting materials, processes, and technologies used, cave position, surviving time, and historical experiences. Many of these factors influence the formation of deterioration risk, and thus, construction dynasty is a significant analysis perspective in risk analysis.

In general, the risk distribution of caves built during different dynasties presents distinct characteristics. The Sui Dynasty, High Tang Dynasty, and Late Tang Dynasty are selected as examples in this study. When filtered by construction dynasty, that is, by comparing the lengths of arcs, we determine that the most severe risk is detachment risk for the caves of the Sui Dynasty and the High Tang Dynasty. Meanwhile, the biggest threat to the caves of the Late Tang Dynasty is loss risk. The cracking risk is more serious than the flaking risk for the caves of the Sui Dynasty, but the opposite is true for the caves of the High Tang Dynasty. Moreover, the disruption risk to the caves of the High and Late Tang Dynasties is significantly more severe than that to the Sui Dynasty. Based on the heat map view, a large portion of the caves of the High and Late Tang Dynasties is located at the south side of the Mogao Grottoes. Given that the south part of the Mogao Grottoes is considerably lower than the north, the caves built during these two dynasties are more vulnerable to disruption risk because humidity is higher in the area.

To analyze the aforementioned risk pattern, the High and Late Tang Dynasties are selected as examples. As shown in Fig. 7a, 9 caves are located on the top floor (yellow circles) among the 94 caves of the High Tang Dynasty, and only 1 of these caves is facing disruption risk. Obviously, the occurrence frequency of disruption risk on the bottom and middle floors is considerably higher than that on the top floor. In Fig. 7b, disruption risk is mainly observed in caves on the middle and bottom floors (represented by green and purple disruption arc segments, respectively). Statistics show that 86.2 % of disruption risk occurs in caves on the middle and bottom floors, with 56.6 % occurring in caves on the bottom floor. We believe that these findings are related to humidity because the caves on the lower floors are closer to the ground. In addition, some of the caves on the top floor are also exposed to disruption risk. Domain experts suppose that this phenomenon is likely associated with rainwater infiltration from the top of the cliff.

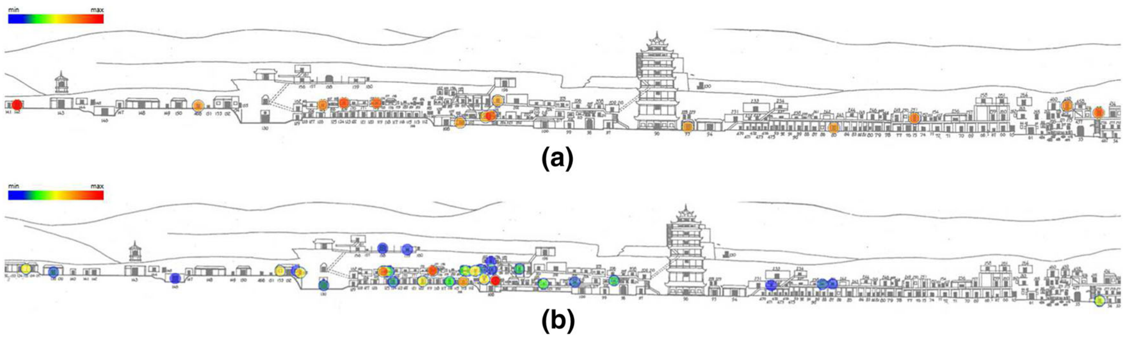

Fig. 8 Spatial Distribution of risks based on risk clustering. **a** Aggregated spatial distributions of risks for cluster 2. **b** Spatial distribution of disruption risk for cluster 1

4.4 Risk pattern for risk clustering

In this case study, we analyze risk features based on risk clustering. All the caves are grouped into six clusters (Fig. 5), and several interesting patterns have been discovered by analyzing risks through the interactions (Sect. 3.6) that support the analysis from the perspective of the clustering result in our method. Based on the interactions, we can filter the caves by cluster and select specific risks to study their distribution. In Fig. 8a, the heat map shows that all 16 caves that belong to cluster 2 are represented by a red or orange circle on the heat map, which indicates that they are exposed to serious risk. The bar charts (Fig. 5) also show that all the caves in cluster 2 suffer from an extremely severe risk level. In addition, the heat map (Fig. 8a) shows that only 4 caves are located on the middle floor among the 16 caves included in cluster 2. Most of the caves that face the highest severe risks are located on the top and bottom floors. This finding indicates that the geographical environment is an important factor that determines deterioration risks. Based on the knowledge of experts, this finding can be partially explained by the following causes. The low position of a cave does not only indicate high humidity but also the likelihood of flooding. The caves located on the top floor are likely to suffer from rainwater infiltration or leaking water, whereas the caves on the middle floor are located in a relatively good geographical environment.

In addition, to analyze the pattern of disruption risk, cluster 1 is selected as an example because it faces the most serious disruption risk. By investigating the spatial distribution of disruption risk in the heat map view (Fig. 8b), we determine that most caves that are experiencing serious disruption risk are located on the lower floor in cluster 1. Meanwhile, the bar charts (Fig. 5) show that only 4 caves located on the top floor and 34 of the 38 caves located on the lower floor are facing disruption risk. In addition, most of the caves in cluster 1 are located at the south side of the Mogao Grottoes, as indicated in the heat map (Fig. 8b). These visual findings strongly demonstrate the same pattern on disruption risk.

4.5 Risk coupling pattern

Based on practical experiences, associations occur among different types of risks because of common sources or causalities of risks. Studying the relationship among risks can provide domain experts with insights into risk mechanisms. In this section, we study the correlations among different types of risks. In Fig. 9a, b, the caves (circles) with cracking and detachment risks are highlighted separately. In Fig. 9c, the caves with both cracking and detachment risks are highlighted. The distribution of highlighted caves in Fig. 9c is highly similar to those in Fig. 9a, b. This result indicates that most of the caves with one of these two types of risks also have the other type. Statistics show that 87 % of the caves have cracking risk, 83 % have detachment risk, and 77 % have both types of risks. Thus, we suppose that a coupling relationship exists between cracking and detachment risks. To gather further evidence, scatter plot matrices are used to analyze the correlations among risks. In Fig. 10, most of the dots are concentrated in the area near the diagonal line in the scatter plot of cracking and detachment risks. This observation implies that the degrees of severity of these two types of risks present a positive correlation in most situations. Furthermore, by exploring cave-level panoramic views to observe risk areas on the walls, we determine that the locations of areas with cracking and detachment risks are close to each other or even overlap with each other. Based on

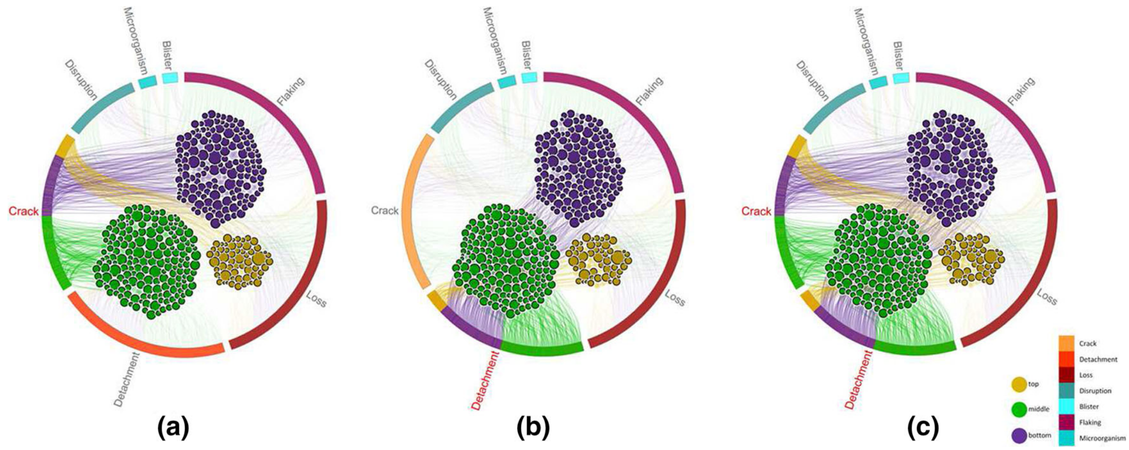

Fig. 9 Risk coupling analysis. **a** Cracking risk distribution. **b** Detachment risk distribution. **c** Cracking and detachment risk joint distribution

the aforementioned visual discoveries, we can assume that a coupling relationship exists between cracking and detachment risks.

Domain knowledge provides an explanation for this phenomenon. The configuration layers of ancient mural paintings are generally composed of (from bottom to top) the support, plaster, grounding, and paint layers. Cracking risk is caused by the dislocation, overlying, and even cracking of the plaster layer as a result of the instability of the support layer. Meanwhile, the cause of detachment risk is the partial separation of the plaster layer from the support layer. Obviously, the instability of the support layer is one of the reasons why the plaster layer separates from the support layer. Therefore, cracking and detachment risks are both associated with the instability of the support layer. Thus, the correlated causes of risks result in the risk coupling phenomenon between cracking and detachment risks.

5 Evaluation

An expert review is performed to evaluate the proposed method. The evaluation team is a professional multidisciplinary team that is composed of risk management experts, conservators, chemists, geologists, and microclimate researchers. Our questionnaire consists of five sections: visualization, interaction, esthetics, application value, and usability. Based on the results of the questionnaire, the evaluation opinions are summarized as follows.

First, most of the experts agree that our method is consistent with practical experiences, and thus, users will easily accept these tools and be comfortable in operating them when studying risks. Second, the experts are satisfied with our visualization technique and its esthetic characteristics, but they offer some advice to improve our visualization technique and make it more intuitive for domain experts. Third, the experts believe that the interaction methods are sufficient to support complex risk analysis tasks; however, they also suggest that other helpful information, such as tool tips, should be provided to users. Finally, the domain experts believe that the application value of our method is high because it does not only provide new risk analysis perspectives but also offer domain experts the capability to identify, assess, and analyze risks conveniently and efficiently. For the time being, risk management experts and conservators suggest that the functions of risk reasoning and decision-making support should be enhanced because risk reasoning and treatment still depend mainly on experts. The microclimate researchers also suggest that we can integrate the analysis of microclimate monitoring data into the method to assist in automatically analyzing and discovering risk causes and sources.

In summary, most of the experts consider our work to be valuable for studying and managing risks to cultural heritage. Moreover, they believe that our work integrates visual analytics with cultural heritage conservation and risk management, which is an innovative combination.

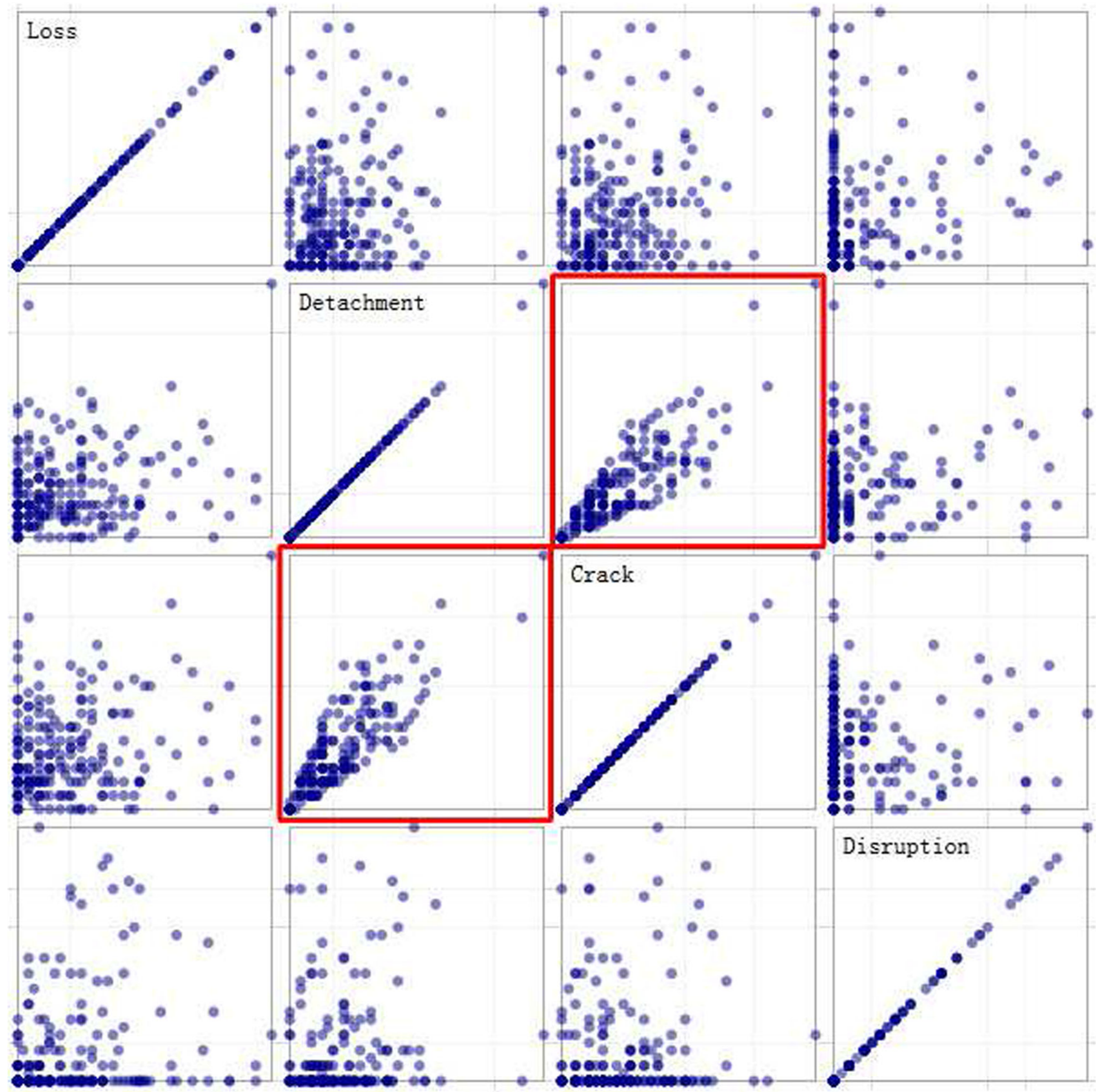

Fig. 10 Part of the scatter plot matrix for risk correlation analysis

6 Conclusions

A new visual analytics method for analyzing and visualizing the deterioration risks to ancient mural paintings based on risk management and conservation practices is proposed in this study. A series of visualization tools is designed and developed, including a circle packing layout + chord diagram tool to visualize overall risk distribution at site scale, a heat map based on a focus + context visualization tool to obtain spatial information on risks, a scatter plot matrix tool to explore correlations among different types of risks, a comprehensive analysis tool with a bar chart and a heat map based on risk clustering to discover risk features of similar caves, a glyph-based panorama tool, and an Aster plot tool to check for detailed cave-level risk information. Furthermore, several case studies are performed. New risk patterns are discovered through visual analytics. Finally, an evaluation based on expert review is performed.

The risks faced by cultural heritage are not limited to deterioration risks. In fact, many categories of risks threaten cultural heritage, including hazard risks. In the future, we can design a new framework that can analyze deterioration and hazard risks using a unified platform based on this work.

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