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Comparison of the consistency of structural measurements made using the traditional method and with the use of point cloud from terrestrial laser scanning in a selected site of Radków Bluff (Table Mountains, SW-Poland)

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Abstract: The results from two methods of structural analysis of the morphological rock escarpment are presented – a conventional technique, based on cartographic projection and set of structural measurements, and one based on processed point cloud data obtained from terrestrial laser scanning of the site (TLS).
The results refer to one of the numerous sites located at the base of the nearly 40 km long vertical rock cliff (Radków Bluff) in Table Mountains, which locally reaches height of up to 50 m. The selected site in the area of so-called Radków Rocky Towers area is characterized by a complex and multi-stage structural pattern. A method of automatic and semi-automatic determination of discontinuity surfaces in the entire exposure was tested, with particular emphasis on zones of load induced fractures located at the base of the rock wall. The authors obtained a high convergence of the results generated from the point cloud analysis and those made by the traditional method using a geological compass. The paper suggests a correct and effective methodology for surveying and using data, as well as highlighting the benefits of documenting geological sites with the use of TLS. The analysis confirms the role and importance of fractures induced by a localized load in the process of destruction and retreat of morphological slopes.

Key words: rock cliffs and discontinuities, induced fractures, structural mapping, terrestrial laser scanner, Table Mountains

Introduction

The identification and measurement of structural phenomena are routine activities during the documentation of geological sites. In clastic sediments and sedimentary rocks, primary spatial phenomena include textures and sedimentary structures, both surficial and internal (e.g. lineation and imbrication of grains, trough, ridge or dome structures). Secondary spatial phenomena include post-depositional pre-consolidation deformation (e.g. load casts, folds and compaction structures) and post-consolidation deformation caused by redeposition or tectonic processes (fractures, faults, shear zones, folds). All the previously mentioned phenomena are related to movement, i.e. movement of material, and more broadly to transport processes, so they can conventionally be called geokinematic phenomena.

A separate group consists of phenomena related to the natural or forced geostatic situation in the rock. In natural conditions, the accumulation of static stresses most often occurs at the base of walls and morphological bluffs, which usually mark the boundaries of a lithological cover or slab. This is when local damage systems (e.g. fractures) can form, with scale, density and orientation closely related to the geometry of the morphological forms (Ollier 1978, Wojewoda, Ollier 2013). Authors consider that such forced geostatic destruction, which forms new fracture patterns, appears to play a fundamental role in the local destruction of the base of escarpment, and thus in the regional retrogradation of such landforms.

Table Mountains range in the Sudetes (Fig. 1), due to its platy geological structure, resulting directly from the distribution and migration of facial zones in the Cretaceous sea and thus from the primary sedimentary architecture of the sediments (clinoforms, sandstone lithosomes) (Fig. 2), is distinguished by a large number of long and high rock cliffs on the one hand (e.g. Radków Bluff, Batorów Cliff) and iso-

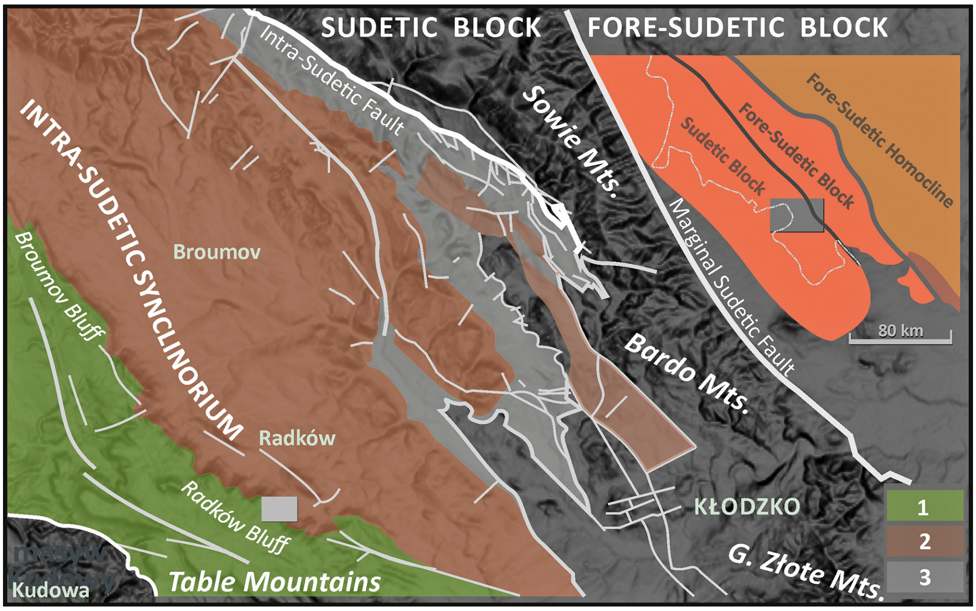

Fig. 1. The location of the study area and schematic geological structure of SE-part of Intra-Sudetic Synclinorium area. The post-Variscan sedimentary-volcanic cover: upper Cretaceous (1), lower Permian (2) and Carboniferous rocks constituting Intra-Sudetic Synclinorium (3)

lated massifs and rock formations on the other (e.g. Szczeliniec Wielki, Rocky Mushrooms) (Wojewoda et al. 2011). Over 50 years of structural studies in the area and especially last 3 decades of mainly sedimentological and tectonic field work, have provided numerous examples of the occurrence of forced geostatic phenomena at various scales (Jerzykiewicz 1968, Kosciak 2000, Cacoń et al. 2002, Wojewoda 2007, 2009, 2019, Cacoń et al. 2009, Wojewoda et al. 2010, Duszyński, Migoń 2015, 2017, Duszyński et al. 2015, 2016, Duszyński 2018). They are particularly common at the base of Radków Bluff – an almost ver-

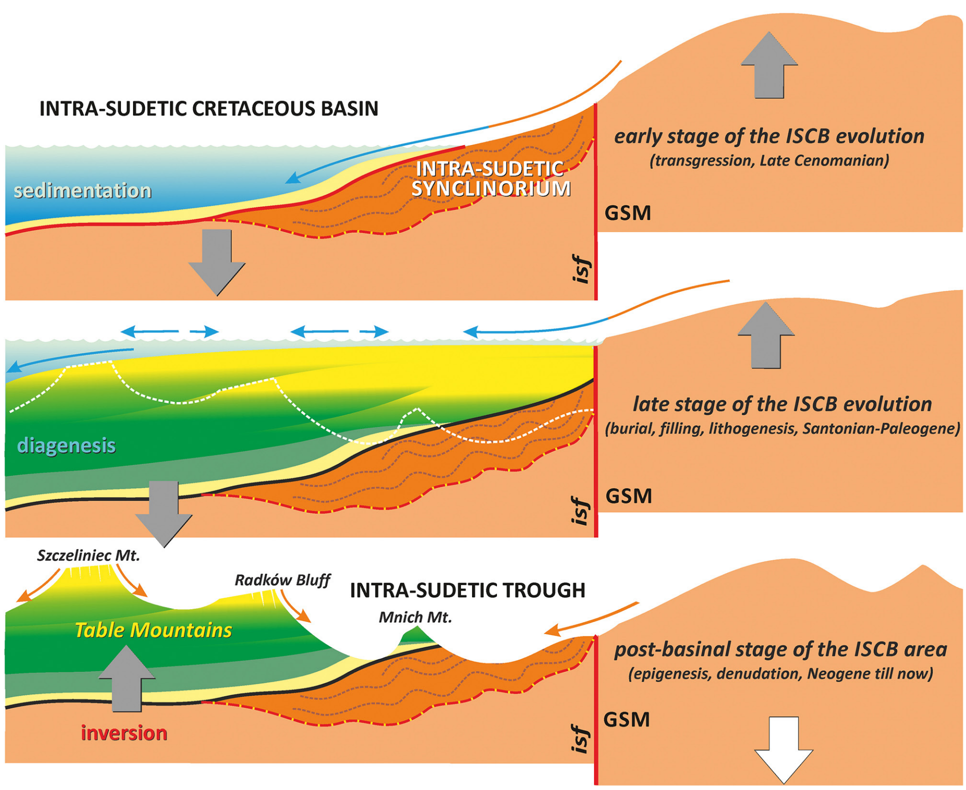

Fig. 2. Chronology of various phenomena and processes in Intra-Sudetic Synclinorium, isf – Intra-Sudetic Fault, GSM – Góry Sowie Massif (modified after Wojewoda 2020a)

tical morphological escarpment, locally more than 50 m high and almost 40 km long, developed in Middle Jointed Sandstone (*Inoceramus lamarcki* zone) (Wojewoda 2012, Wojewoda, Ollier 2013, Wojewoda, Kowalski 2016 (Figs 3, 4).

Unfortunately, the accuracy of the earlier conventional measurement methods and the photographic documentation proved to be insufficient for the evaluation/measurement of possible displacements at specific sites and thus for a satisfactory explanation of the influence of the destruction of the escarpment base on its evolution over time. In order to test the previously postulated cause-and-effect relationship of induced fractures with the cliff geometry and its possible destruction and retrogradation processes, a field-documentation experiment was performed. For the purposes of this article, the results for the site located at the base of Radków Bluff (Radków Towers area) are further presented (Fig. 5). This area, apart from the spectacular zones of induced destruction, is characterised by a very distinct system of orthogonal joints, which further enhances the separation of both in the measurement plan.

Over many years of field work, the authors have collected a large amount of structural data from many sites located within Radków Bluff (Wojewoda, Kowalski 2016, 2017). However, the juxtaposition of even a large number of measurements obtained by traditional measurement methods with the use of a geological compass, does not allow the observation of the destruction process. Spectacular examples of phenomena initiated by the development of specific fractures, which authors describe in the outcrops at the base of Radków Bluff, are located in a site where

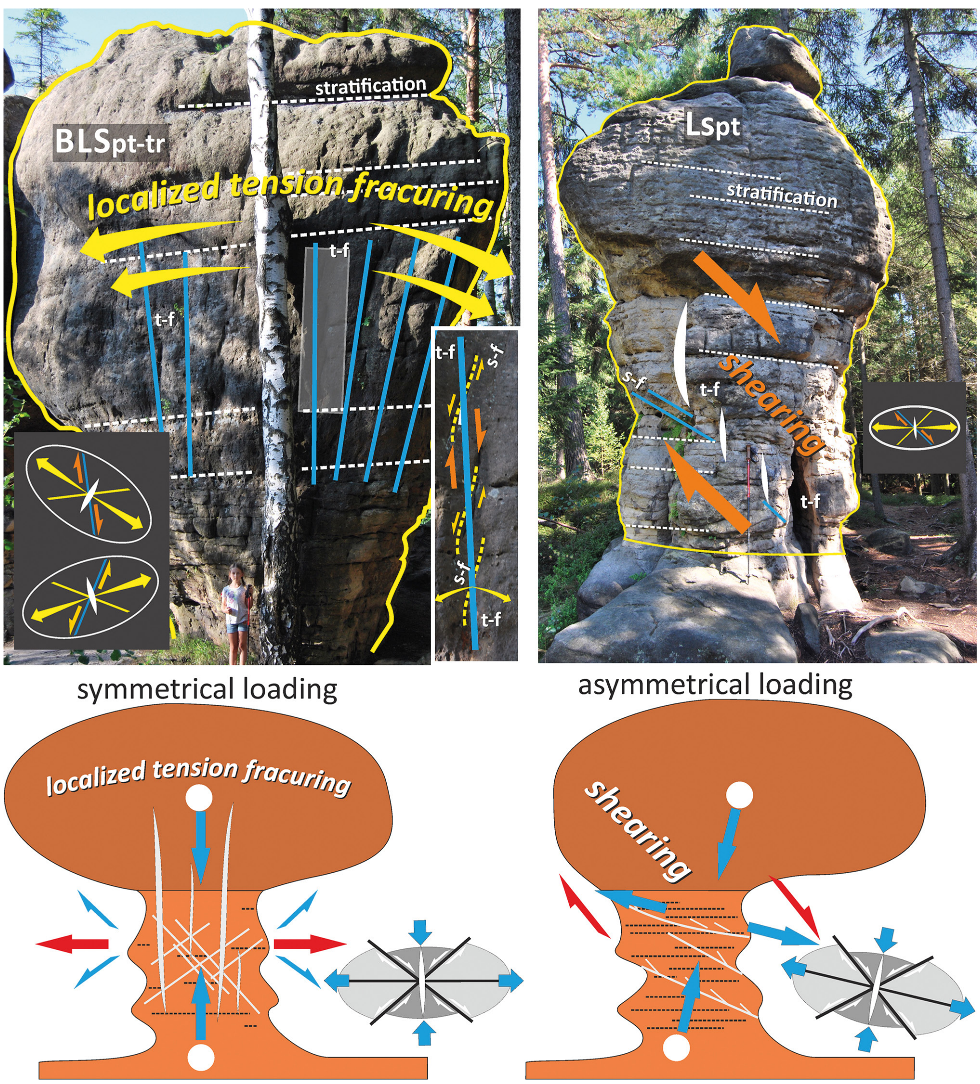

Fig. 3. Development of induced fractures in sandstone rock forms due to lithologically controlled selective erosion and, subsequently, overloading on the rock form bed. The fracture lines are symbolic, but most likely they represent P shears and conjugate Riedel shears R' (synthetic and antithetic, respectively, which are oriented orthogonally to each other (Davis et al. 2012). One of Rocky Mushrooms on the plateau above Radków Towers, BLSpt-tr – bioturbated, homogenous sandstones at the top of Radków Bluff Sandstone, LSpt – large-scale cross-bedded sandstones t-f – tension fracturing, s-f – shear fracturing (after Wojewoda, Ollier 2013, Wojewoda et al. 2022)

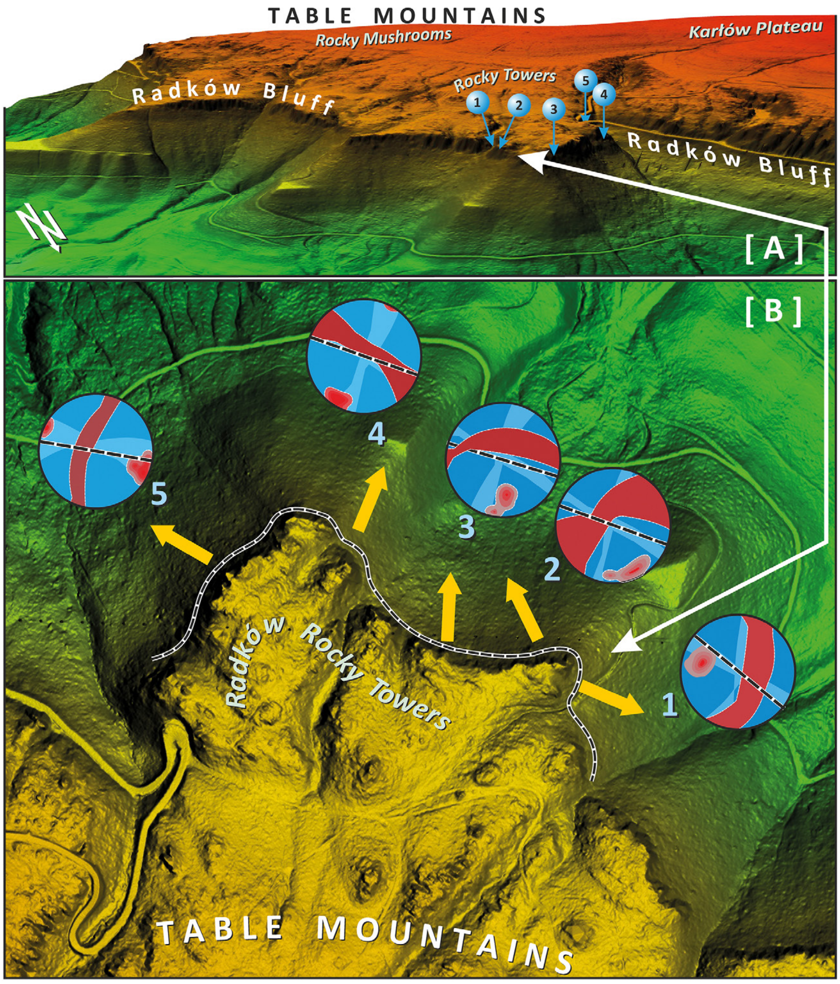

Fig. 4. The orientation of induced fractures at the base of Radków Bluff, at Radków Towers locality. A – the location of outcrops within Radków Bluff, B – results of structural analysis carried out conventionally. Aggregate projection diagrams were created based on at least 10 measurements, a total of more than 100 measurements at 5 sites. A total of 58 measurements were made with the compass at site no. 1, which were then compared with the results obtained from the point cloud. Colours explanation on the stereoplots: red lines show inclination of great circles of measured fractures; red spots refer to normal to fractures planes, black dashed lines refer to local topography, light blue show inclination of great circles of joints, blue is for background (modified after Wojewoda et al. 2022)

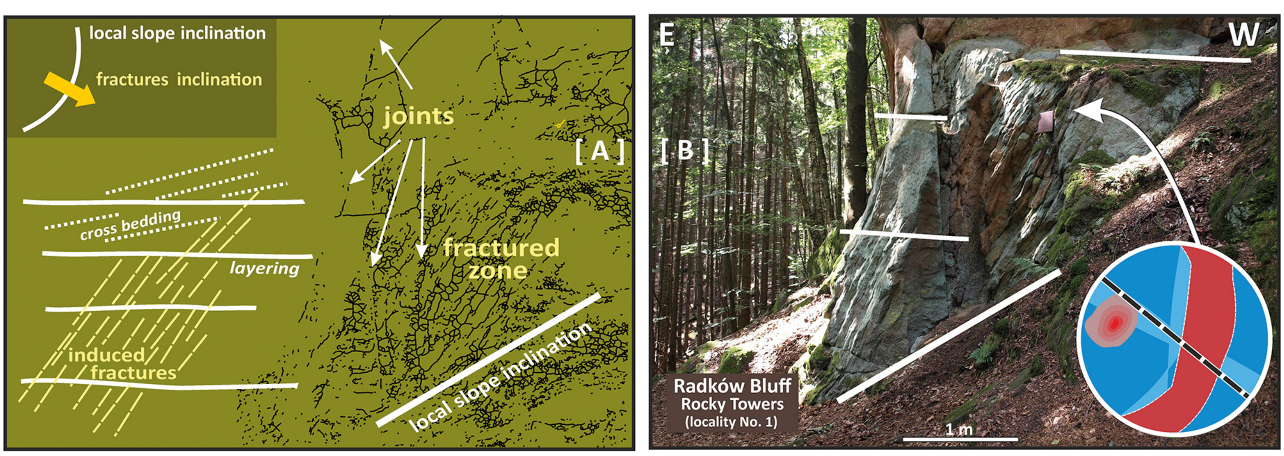

Fig. 5. Radków Towers site (Radków Bluff, Table Mountains), A – an example of traditional documentation of structural phenomena – faulting, layering, joints and induced fractures, B – photograph view of the outcrop. A and B show a view of the outcrop from the same spot

it was possible to use modern measurement techniques based on terrestrial laser scanning (Sokalski, Wojewoda 2022).

The aim of the authors' research was primarily to compare the consistency of traditional measurement methods with modern tools based on terrestrial laser scanning (TLS). The authors also tested the possibility of capturing the process of destruction, taking place at the base of Radków Bluff on differential scans over an observation period of almost two years.

Terrestrial Laser Scanning in Geological Applications

Terrestrial Laser Scanning (TLS) is a quick and accurate, optical measurement method (e.g. Pfeifer, Briese 2007) that allows detailed documentation and inventory of objects in three-dimensional (3D) space. The scanner measures angles and distances with help of a laser beam that travels from the device to objects, where it reflects and goes back to the scanner. The coordinates (XYZ) and other information (e.g. the reflectance of the laser beam) are acquired from multiple points on the scanned objects (or terrain surface) and a point cloud, based on the collected information, is created (Vosselman, Maas 2010). TLS also allows measurement in the fourth dimension. Proper survey methodology allows monitoring and capturing processes that change over time (e.g. Vos et al. 2022). TLS is used in many fields, ranging from civil engineering, forestry, forensics, to open-pit and underground mining (e.g. Pagounis et al. 2006, Dassot et al. 2011, Kankare 2015, Lipecki, Thi Thu Huong 2020, Kekeç et al. 2021, Wu et al. 2022, Kumar Singh et al. 2023). It also finds applications in geology, where it offers much broader possibilities than just structural characterization of geological sites.

Terrestrial laser scanning makes it possible to extend the scope of geological documentation with additional elements, especially in large sites, with various metric measurement possibilities (e.g. Buckley et al. 2008, Telling et al. 2017, Bistacchi et al. 2022). For example, in sediments and sedimentary rocks, depending on the lithology and resolution of the scan, it is possible to measure the thickness of, e.g. sets of layers (sometimes individual layers), or the size of characteristic rock elements such as the size of pebbles or rock voids. It is possible to measure any chosen/set distance and thus surface area and volume. The point cloud can be fitted into a local geodetic reference system, including a numerical terrain model. Based on the scanning data, a characterization of a specific geological phenomenon in the scan space or an overall structural analysis of the site (object) can be performed/established.

Over the past two decades, in parallel with the development and fast improvement of laser scanning techniques and digital photography, significant progress has been made in the use of advanced algorithms for the analysis of point clouds obtained from laser scanning and photogrammetry. A large number of methodological studies have been published on the structural characterization of rock masses based on automatic or semi-automatic methods for the determination of surfaces (planes), fractures and linear structures (e.g. Kemeny, Donovan 2005, Kemeny et al. 2007, Ferrero et al. 2009, Lato et al. 2009, Sturzenegger, Stead 2009, Gigli, Casagli 2011, Lato, Vöge 2012, Vöge et al. 2013). The vast majority of studies and methods have been developed for applied purposes – for geotechnical needs in relation to geohazards causing damage to the rock mass at public utility sites such as railways and roads.

The development of laser scanners in the last few years has made it possible for these devices to reflect geological objects in the form of a very dense, high-resolution point cloud with much shorter measurement times than even 10 years ago. In addition, more and more new functionalities of existing software are being made available. For geologists working in the field, but also for specialists dealing with rock mass mechanics and geohazards, tools have been developed to acquire structural data from hard-to-reach or hazardous exposed sites in a way that ensures relatively high convergence of results obtained from conventional geological compass measurements and the processed and analysed point cloud data (cf. Assali et al. 2014, 2016, Dewez et al. 2016, Thiele et al. 2017, Chen et al. 2018, Riquelme et al. 2018, Pan et al. 2019, Wu et al. 2021).

Study site – geological structure and evolution

Radków Bluff reflects the exhumation and inversion of the relief during the post-basin phase in Central Sudetes. While the area located north and northeast of the current Table Mountains, i.e. today's massifs of Sowie and Bardo Mountains, but also most of Fore-Sudetic Block, supplied Cretaceous Intra-Sudetic Basin with material, since the Cenomanian to the Coniacian (see, among others: Jerzykiewicz, Wojewoda 1981, 1986, 1997, 2020a, b, Biernacka, Józefiak 2009, Biernacka 2012, Wojewoda et al. 2022). Currently, the relatively elevated Table Mountains supply material to Ścinawa River valley in the northeast. It is worth noting that the oldest sediments containing Cretaceous material are of late Pliocene age (lower part of so-called Gozdnica Formation), which dates the beginning of Cretaceous denudation in the Neogene. It is also worth emphasizing that Cretaceous sandstones have undergone deep residual chemical weathering, as evidenced by common kaolinization of feldspars. Such material could not have been preserved as a primary substance in the high-energy, mainly beach-coastal sediments of Cretaceous sea (cf. Wojewoda et al. 2022). Relics of residual weathering that occurred during the Oligocene and Miocene in Sudetes and Carpathians are widely distributed, among others in the form of saprolites covering extensive etchplain, but also as redeposited weathered material (cf. August et al. 1995, Wojewoda et al. 1995, Migoń 2001, 2002). These facts quite clearly indicate a radical landscape inversion and exposition of the Cretaceous sedimentary succession at the earliest in the Pliocene, and the process initiated then most likely continues to this day.

The issue of the joints penetrating the whole cretaceous sandstone massif has not been clearly resolved, although many facts prove that it was an early process, already during the sedimentation of the oldest members of the Cretaceous succession. This is evidenced, for example, by phenomena such as the common occurrence of complementary shears of the kink band type which penetrate Turonian and Coniacian sediments (e.g. Solecki 2011), but also by helicoidal fracture zones that are penetrated by *Dominichnia* type trace fossils, as for example *Ophiomorpha* (e.g. Wojewoda 2020a, Wojewoda et al. 2022). In turn, a high seismotectonic activity is already evidenced during the deposition of Cretaceous sediments, e.g. by numerous seismite structures, including some of the first ones described in the Sudetes (Wojewoda 1987). The youngest tectonic activity is documented by numerous and significant regional shear zones. These are sets of fractures with meso-structural features typical of strike slip zones, which range in width up to over 200 m and a length of over 5 km (see Wojewoda 2020a, 2020b, Leszczyński et al. 2022, Wojewoda et al. 2022). The formation of the latter is associated with the tectonic activity of the most important tectonic zone in Sudetes – Intra-Sudetic Shear Zone (Wojewoda 2007).

Another phenomenon common in Table Mountains are epigenetically forced fractures, referred to induced fractures. The term was originally introduced by Ollier (1978), and then by Wojewoda (2012) and Wojewoda, Ollier (2013). These fractures occur locally on the plateaus of rock massifs disintegrating due to selective weathering. They often accompany rock mushrooms and towers (cf. Fig. 3).

At the foot of the escarpment under Radków Towers, at the end of the rock headland, a damage zone in the sandstone of Radków Bluff is observed (Fig. 5). These recently discovered and described fractures show how the basal rock breaks down when it is isolated from the rest of the rock massif. This dense fracture network is created under the pressure of hundreds of tons of weight, illustrating how a block of rock, isolated from the main massif, destroys its own base. These fractures are considered non-tectonic induced fractures. Their spatial orientation almost exactly aligns with the outline of the rock headland of Radków Towers (cf. Fig. 5) (Wojewoda, Kowalski 2017, Sokalski, Wojewoda 2022). Studied outcrop constitutes an example of how damage caused by load arises and evolves at the base of high morphological escarpments, mainly within rock blocks separated from the main rock massif.

Methods

Geological documentation of the outcrops located at the base of Radków Bluff was carried out in the traditional manner – sketches of the outcrop including a structural sketch were made and delineated zones of discontinuities were measured with a geological compass. Photographic documentation was also carried out (cf. Figs 4, 5).

For the spatial measurements a Riegl VZ400i pulse terrestrial laser scanner was employed. The device features a pulse repetition rate of up to 1200 kHz, which results in an effective measurement rate of 500,000 points/s. The laser beam operates in the near infrared (1550 nm wavelength). The 3D positioning accuracy is 3 mm at a distance of 50 m and 5 mm at a distance of 100 m. The minimum distance from the measured object is 0.5 m. Data was processed and analysed in Riegl's dedicated RiScan Pro software (v. 2.14.1), which can be extended with an additional LIS GeoTec Plug-In tool for the analysis of structural phenomena (Riegl Laser Measurement Systems 2022).

The primary aim of the measurement was to document the zones of induced fractures that are developed at the base of the rock headland that builds up a section of Radków Towers. At the base of Radków Towers there is a footpath, which is severely limited by the steep slope, resulting in relatively little field to position the scanner. For this reason, measurements were taken at a distance of 3–5 m from the rock face. Such a short distance from the scanned object ensures minimal divergence of the laser beam that allow for increased resolution and a finer detailed image of the irregularities of the outcrop. The key lower part of the outcrop (up to 3–5 m) of total length of about 50 m was captured on the scan. In order to obtain a dense point cloud, scanning was carried out at the maximum frequency of the laser pulse (1200 kHz). For the first measurement epoch a very high mapping accuracy along the entire length of the outcrop was achieved by scanning from 13 scan sub-stations spaced at maximum 5 m intervals to minimize the effect of occlusion (as much as possible). Reference targets were used for the registration of the first measurement epoch. The registration process was performed in two stages:

1. the coarse registration carried out by the function *Automatic Registration 2*; the registration error (expressed in standard deviation) measured few cm after this step,
2. fitting plane patches generated on the basis of given parameters from sub-station point clouds (such as: minimum point count, maximum standard deviation, maximum deviation, minimum reflectance) was conducted by the function *Multi Station Adjustment*; fitting of plane patches was then improved in an iterative process whose parameters were changed step by step until the minimum error (expressed in standard deviation) was achieved; after this step it measured 2.1 mm.

The authors conducted three measurement series performed at 10-month intervals. The purpose of such a procedure was to try to capture the destruction process in the zone of induced fractures on differential images (scans). In the second measurement epoch, the entire outcrop was captured from 23 scan sub-stations, and the third was recorded using 17 scan sub-stations. However, for the second and third measurement epochs, the scanning resolution was decreased by reducing the frequency of the laser beam to 600 kHz. The procedure for registering the scans of the second and third measurement epochs was similar to that of the first measurement epoch, except that reference targets were not used for registration. For the second and third measurement epochs, the error of *Automatic Registration 2* did not exceed a few cm in both cases. In the next step (*Multi Station Adjustment*) in both epochs, it was possible to align the scans in such a way that the registration error (expressed as a standard deviation) was in the range of 2 to 3 mm. Subsequently, the registered scans from each measurement epoch were combined into a single point cloud, and were then aligned using the *Multi Station Adjustment* tool. The alignment error (expressed as standard deviation) totalled 3.9 mm.

The next step was to remove vegetation from the point cloud. Due to the vertical rock walls and dense tree cover, the RiScan Pro built-in vegetation removal filter proved to be unusable, as it also removed parts of the rock surfaces from the point cloud. Consequently, all vegetation was removed manually by editing the point cloud in RiScan Pro. In the next step, the data were filtered by the attributes of the returning laser beam (reflectance, deviation) and to simplify the structure of the point cloud (octree filter). Some parts of the point cloud were further filtered to apply advanced 3D visualization effects. The structural analysis tool requires additional filtering to give each point of the point cloud coordinates that define the position of the scanner. The processed data after registration, basic filtering and combining into a project consisting of three point clouds representing three measurement epochs has approximately 250 million points.

The LIS GeoTec structural analysis software tool is a RiScan Pro Plugin for geotechnical analysis of scanned rock surfaces. The tool classifies the point cloud in terms of dip and dip direction angles to create contour diagrams for the dominant sets of discontinuity surfaces. The analysis is performed in 2 steps. Step 1 consists of extracting the normal surfaces for each point and then segmenting areas with the same surface orientation. Step 2 is the analysis of surfaces for a cluster with a specific orientation and the calculation of dip and dip direction angles with respect to the selected target coordinate system. The result of the analysis is then plotted onto the contour diagram (Riegl Laser Measurement Systems 2022). The tool allows for automatic surface detection and/or additional parameter definition, which an experienced field geologist can modify in order to obtain the most reliable measurement results.

Results

The study carried out by the authors confirmed good consistency between the results obtained by traditional geological compass measurements and by using a semi-automatic algorithm to determine the orientation of the discontinuity surfaces based on point cloud analysis.

Zone of induced fractures is clearly manifested on a structural sketch and a photograph shown in Fig. 5. The white line shows the slope angle, while the yellow lines show the interval in which the horizontally overlying sandstone layers are cut by a fracture system. A projection diagram that summarizes the collective results of 58 measurements taken with a geological compass (Fig. 5B) shows an averaged orientation of induced fractures at 106/72. The measured dip direction angle of the fracture plane is coincident and closely related to the slope direction in this part of the outcrop.

Structural analysis based on the point cloud (Fig. 6A) was performed by manually selecting the input parameters for the algorithm responsible for identifying the planes. This is a necessary procedure for exposures with highly complex fracture systems. It was possible to confirm the effectiveness of the method by comparing the results of the measurements with those made conventionally (with a geological compass). Fig. 6B, showing the above discussed fragment of the rock headland in a slightly vertically rotated side view, confirms the quality of the point cloud measurements by obtaining coincident results for the two sets of joints marked in red (40/85) and yellow (140/85), as well as for the surfaces of induced fractures marked in blue (118/68) (Fig. 6C). The remaining colours (green, orange and purple) highlight less significant sets of surfaces with identical orientations.

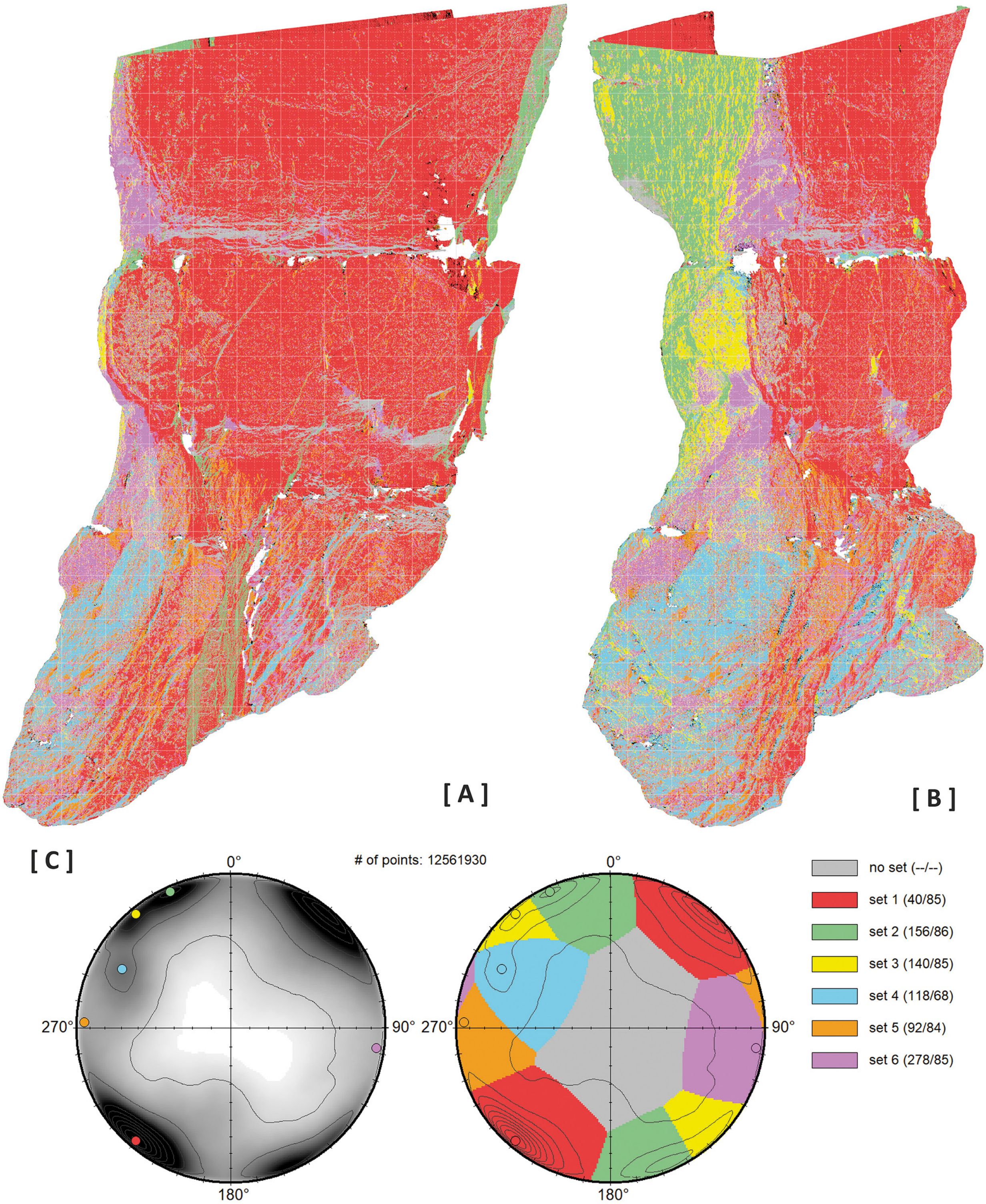

Fig. 6. Semi-automatic algorithm was applied to the point cloud data of an outcrop with the zone of induced fractures: six sets of discontinuities marked with different colours were distinguished. A: side view of the part of the outcrop with clearly manifested zone of induced fractures (cf. Figs 5B and 7B), B: rotated side view of the outcrop to visualize the course of the fractured planes in the induced fractures zone, C: structural analysis of more than 12.5 M of points, which distinguished 6 sets of discontinuities and put them onto the contour diagram

Despite a detailed analysis of point clouds obtained from three measurement epochs over a period of about 20 months, it was not possible to observe the destruction process in the most predisposed zones, i.e. in the zones of induced fracturing.

Disscussion

During the fieldwork, the authors made dozens of conventional measurements throughout the analysed outcrop. Compass measurements require some knowledge and experience from the operator and sometimes even intuition to correctly assess whether the measured orientation of the surface is due to its real orientation in geological space or whether it is a falsified intersection image. This is particularly important especially when measuring structures such as induced fractures, where orientation of the fracture plane is variable even within a single (large) outcrop and depends on the geometric form and orientation relative to the slope of a given rock headland part. In addition, induced fractures zones manifest themselves as a dense network of parallel but also irregularly aligned fracture planes that do not form clearly distinguishable planes from the rock face – in contrast, for example, to joint sets that form clear and unambiguously easily identifiable, flat, vertical, regular surfaces.

The point cloud view (Fig. 7A) in the side view analogous to Fig. 5B, shows an almost photographic image of the object. The fracture surfaces are just as clearly visible as in the photograph, and with the appropriate filtering and display it is possible to highlight and emphasise the most interesting parts of the object. Furthermore, because this section of the point cloud consists of more than 15 million points, very accurate metric and angular measurements are possible. Because objects are scanned from multiple perspectives (i.e. from aligning scans captured at sub-stations), it is possible to freely rotate and view objects in 3D space. Positioning a section of the rock headland in a more vertically rotated view (Fig. 7B) allows even better imaging of induced fracture surfaces. In this case, filtering was applied to identify planes with similar orientations. For this section of the point cloud, surfaces with orientations corresponding to the joint system are highlighted in light red, while those corresponding to induced fractures are highlighted in light green. Analysis of the point cloud in terms of the structural setting of the object is undoubtedly a very valuable addition to the geological documentation of the exposure.

In the case of structural analysis performed on a point cloud, using tools for automatic or semi-automatic determination of sets of discontinuities with the same (and similar) orientation, the risk of incorrect measurement as a result of compass application according to the subjective, not always accurate, assessment of the operator is practically eliminated. The algorithm for automatic determination of surfaces identifies them very well in the case of regular and homogeneous fracture surfaces or layering (e.g. joint sets). If the surfaces are more irregular, additional smoothing of the point cloud is sometimes needed. This results in a uniformity of the surface that allows it to be more clearly assigned to a set of surfaces with a specific orientation. However, it is important to bear in mind that the iterative application of the smoothing algorithm results in the loss of an increasing amount of detail, so if its application is necessary, its effect on the discontinuities sets determination algorithm should be checked in steps (Vöge et al. 2013).

The algorithm for distinguishing surfaces with the same orientation also makes it possible to identify surfaces in complex fracture zones where:

1. the surface orientation is not unambiguous or difficult to identify due to the separation of only an edge or a small part of the fracture surface from the rock face, or additionally
2. there are fracture systems from different stages of development of a given structure/object next to each other.

In such cases, it may be necessary to assign appropriate parameters to the algorithm determining the discontinuity surfaces. In the case of (1), it may be important to match a sufficient number of neighbouring points to determine surfaces with similar orientation. In contrast, in case (2) it is important to set appropriate:

a) tolerance angles for normal points identified within a single surface,
b) tolerance angles for identified planes assigned to a set of surfaces with same orientation, and
c) the search radius for the Kernel Density Estimator.

Such an initial procedure also requires an experienced geologist to select the appropriate parameters depending on the complexity of the site or test approach by selecting parameters until the results are satisfactory, i.e. coincide with those obtained from conventional measurements.

An important aspect of the point cloud-based structural analysis process is to perform the measurements in accordance and consistently with the approved methodology (e.g. Kemeny et al. 2007), i.e. by selecting the appropriate scanning resolution, location and number of sub-stations, so as to exclude or minimise dead zones and occlusion effects on the surfaces targeted by the scan. The point cloud must be also properly prepared before structural analysis. It is crucial to remove vegetation and weathering cover, which strongly bias the image when automatically identifying discontinuity surfaces. This is also important for semi-automatic delineation of discontinuity surfaces in large sites located on slopes, (Lukačić et al. 2023), where there may be fractures with surfaces oriented parallel to the slope. The population of measurements may then be falsely augmented by measurements from point cloud fragments representing weathered cover.

An undoubted advantage of structural analysis carried out on a point cloud is the identification of additional sets of discontinuities. This adds value to the documentation of the site, as some of the less important structures are omitted in the description when structural analysis is carried out conventionally. In addition, structural analysis based on the point cloud can help to select sites for more detailed field investigation. Fig. 6B shows a side view of the section of the rocky headland, where the blue colour (corresponding to induced fractures) also indicates a section in the higher part of the headland than the zone of clearly visible induced fractures occurring in

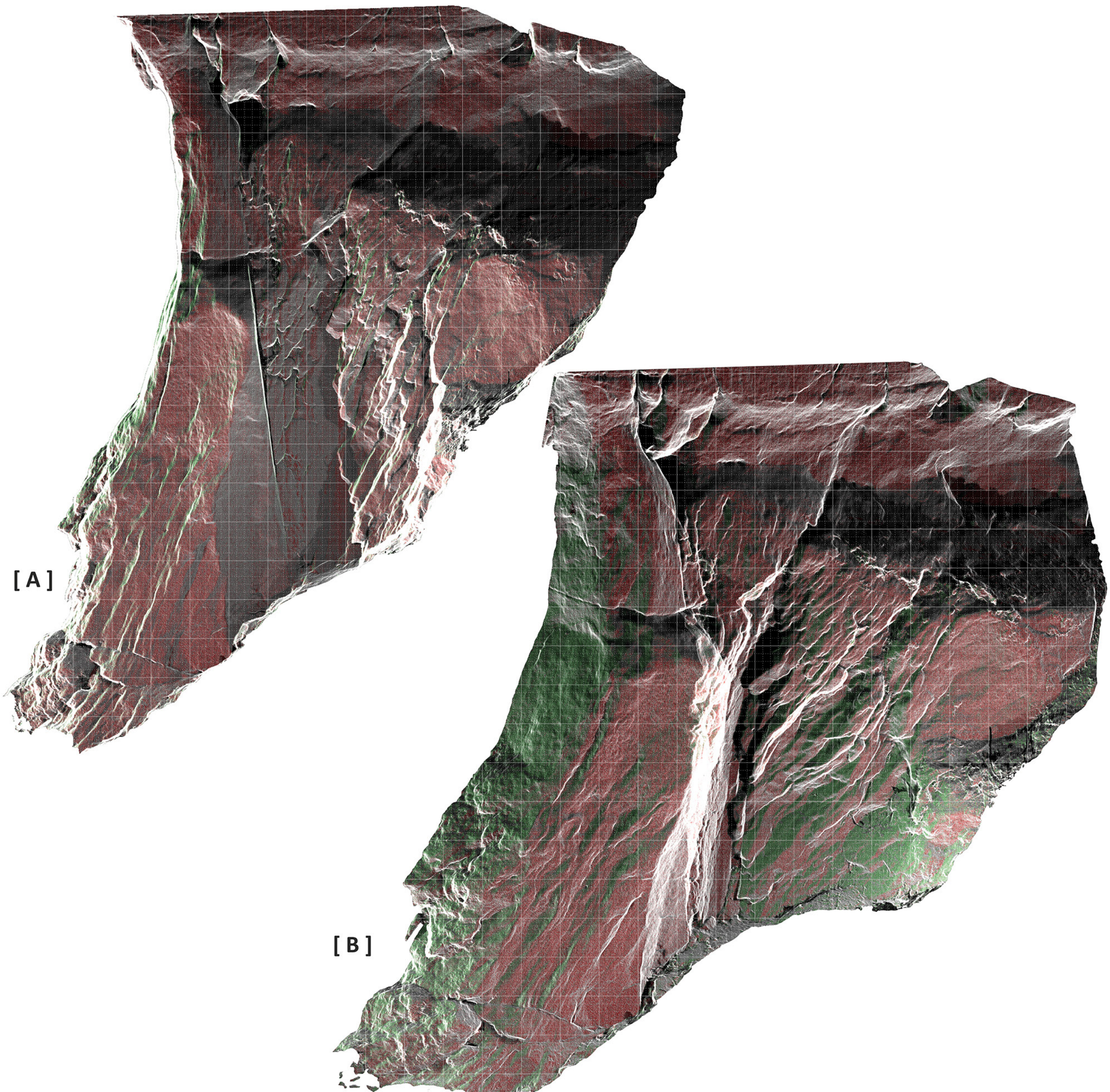

Fig. 7. A: Side view of site no. 1 (cf. Fig. 5B), B: vertically rotated view of a part of exposure with zone of induced fractures. Green colour marks induced fractures surfaces, while with red colour one of joint set is marked. The positioning of the object in Fig. 7A is intended to be the same as in Fig. 5B. The slight rotation of the object in Fig. 7B is intended to better visualize the induced fractures zone. For better visualization of the damage zone, semi-transparency of the points in the cloud (controlled by the operator) was used, which in this case gives better results than shading the point cloud from a certain direction (hillshading), however, it may cause some loss of image depth

its lower part (at the base). This part of the headland is in contact with the rock mass and may also be the zone where the initial development of induced fractures takes place. Point cloud data analysis allows this hypothesis to be verified in the field work.

Summary

With a database of measurements taken conventionally using a geological compass in their disposal, the authors were able to test a structural analysis procedure using a point cloud to determine sets of surfaces with similar orientation in both the automatic and semi-automatic approaches discussed above. The conducted experiment confirmed the relatively high efficiency of the used tool. At the same time, the tested method still requires the involvement of an experienced geologist, who is necessary for the correct setting of parameters in the case of sites characterised by complex and multi-stage structure. Nevertheless, the method is very much in development and it is very likely that, in the coming years, tools in service will make use of artificial intelligence and machine learning algorithms to identify discontinuities surfaces more unambiguously (cf. Mammoliti et al. 2022). It is already quite common to combine structural analysis on the basis of clouds acquired from various sources, e.g. terrestrial laser scanning and modern photogrammetric techniques of the SfM type (eng. *Structure-from-Motion*, cf. Pagano et al. 2020), or even using images taken with modern smartphones (cf. Riquelme et al. 2021). The presented method has another important advantage which is the safety of surveying. This is crucial in the case of hard-to-reach parts of the rock mass and dangerous sites, where there is a risk of mass movements phenomena. It is to be expected that in the future, automation processes will aim to reduce the role of man even further in data acquisition for structural analyses.

It is worth emphasizing the common occurrence of the induced fractures at the foot of almost vertical walls of jointed sandstone in Radków Bluff. This indicates their important role in the destruction of the bluff and sheds new light on the mechanism of destruction of the rocky walls and thus the frontal retrogradation of the Cretaceous plate in the area of Table Mountains. This may also indicate a slightly different mechanism of destruction and denudation of these rocks than the one proposed in recent years by Duszyński et al. (2015, 2016), Duszyński, Migoń (2015, 2017), Duszyński (2018). Certainly, long-term monitoring of the damage described above using a terrestrial laser scanner has a chance to bring us closer to a better understanding of the physical side of this process in the future.

Conclusions

The authors present the phenomenon of non-tectonic, epigenetic induced fractures that can be observed at the base of several tens of meters high rock walls of Radków Bluff. Over couple of years of field work, a detailed documentation of several sites at the base of the bluff was carried out, supported by a set of structural data acquired by the traditional survey method using a geological compass. The results of this work can be summarized in the following conclusions:

1. The possibility of using TLS as a method that allows very detailed documentation of geological exposures is presented, which can furthermore be supplemented by characterization of structural features of the rock mass.
2. Comparison of measurements made in the traditional way and using semi-automatic algorithms to identify sets of different surfaces with the same orientation (e.g. discontinuities, layering) gives consistent results.
3. The accuracy of the TLS measurements at the resolutions and time interval applied by the authors is insufficient to capture significant changes in the surveyed sites over the two-year measurement period and thus confirm the rate of the destruction process, which was also one of the objectives of the study.

Moreover, the authors think that at the current stage of validity and reliability of applications to identify and especially interpret the results obtained by the TLS method, it is still advisable at least to consult an experienced structural geologist who will have the ability to control the input parameters to the algorithms currently used to process point cloud data.

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Author's contribution

DS determined the parameters of experiment, took part in TLS data acquisition and processing, analysed data and made the interpretation, created figures and drafted manuscript. JW conceived the study, designed the experiment, carried out the field work, created figures and co-drafted the manuscript. All authors participated in contributing to text and the content of the manuscript. All authors approve of the content of the manuscript and agree to be held accountable for the work.

References

Assali P., Grussenmeyer P., Villemin T., Pollet N., Viguier F., 2014. Surveying and modeling of rock discontinuities by terrestrial laser scanning and photogrammetry: Semi-automatic approaches for linear outcrop inspection. Journal of Structural Geology 66: 102–114. DOI: 10.1016/j.jsg.2014.05.014.

Assali P., Grussenmeyer P., Villemin T., Pollet N., Viguier F., 2016. Solid images for geostructural mapping and key block modeling of rock discontinuities. Computers & Geosciences 89: 21–31. DOI: 10.1016/j.cageo.2016.01.002.

August C., Awdankiewicz M., Wojewoda J., 1995. Trzeciorzędowe bazaltoidy, wulkanoklastyki i serie osadowe wschodniej części bloku przedsudeckiego. In: S.Cwojdziński (ed), Geologia i ochrona środowiska bloku przedsudeckiego. Przewodnik do LXVI Zjazdu PTG, Rocznik Polskiego Towarzystwa Geologicznego: 241–254.

Biernacka J., 2012. Provenance of Upper Cretaceous quartz-rich sandstones from the North Sudetic Synclinorium, SW Poland: Constraints from detrital tourmaline. Geological Quarterly 56: 315–332.

Biernacka J., Józefiak M., 2009. The Eastern Sudetic Island in the early-to-middle Turonian: Evidence from heavy minerals in the Jerzmanice sandstones, SW Poland. Acta Geologica Polonica 59: 45–565.

Buckley S.J., Howell J. A., Enge H.D., Kurz T. H., 2008. Terrestrial laser scanning in geology: data acquisition, processing and accuracy considerations. Journal of the Geological Society 165(3): 625–638. DOI: 10.1144/0016-76492007-100.

Cacoń S., Mierzejewski M., Wojewoda J., 2002. Lite podłoże skalne i jego przemieszczenia w parkach narodowych i rezerwatach Sudetów. In: J.Pijanowska, B.Jaroszewicz, B.Jędrzejewska (eds), Nauka w Parkach Narodowych. Kosmos 51(4): 399–406.

Cacoń S., Wojewoda J., Kapłon J., 2009. Geodynamic studies in the Góry Stołowe National Park area. Acta Geodynamica et Geomaterialia 6(3): 230–238.

Chen S., Walske M.L., Davies I.J., 2018. Rapid mapping and analysing rock mass discontinuities with 3D terrestrial laser scanning in the underground excavation. International Journal of Rock Mechanics and Mining Sciences 110: 28–35. DOI: 10.1016/j.ijrmms.2018.07.012.

Dassot M., Constant T., Fournier M., 2011. The use of terrestrial LiDAR technology in forest science: Application Fields, Benefits and Challenges. Annals of Forest Science 68: 959–974. DOI: 10.1007/s13595-011-0102-2.

Davis G.H., Reynolds S.J., Kluth C.F., 2012. Structural Geology of Rocks and Regions (3rd Edition). John Wiley & Sons Inc.

Dewez T., Girardeau-Montaut D., Allanic C., Rohmer J., 2016. Facets: a CloudCompare Plugin to Extract Geological Planes from Unstructured 3D Point Clouds. ISPRS – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLI-B5: 799–804. DOI: 10.5194/isprsarchives-XLI-B5-799-2016.

Duszyński F., 2018. Mechanizmy i uwarunkowania rozwoju progów morfologicznych Gór Stołowych = Mechanisms and controls of escarpment evolution in Poland's Stołowe Mountains. Przegląd Geograficzny 90(1): 7–33.

Duszyński F., Migoń P., 2015. Boulder aprons indicate long-term gradual and non-catastrophic evolution of cliffed escarpments, Stołowe Mts, Poland. Geomorphology 250: 63–77.

Duszyński F., Migoń P., 2017. Zespół skalny Dziedzińca na płaskowyżu Skalniaka w Górach Stołowych. Przyroda Sudetów 20: 199–218.

Duszyński F., Migoń P., Strzelecki M.C., 2015. The origin of sandstone boulder aprons along the escarpments of the Stołowe Mountains: are they all rockfall-derived? A new insight into an old problem using the CONEFALL 1.0 software. Bulletin of Geography. Physical Geography Series 8: 19–32.

Duszyński F., Migoń P., Kasprzak M., 2016. Underground erosion and sand removal from a sandstone tableland, Stołowe Mountains, SW Poland. Catena 147: 1–15.

Ferrero A.M., Forlani G., Roncella R., Voyat H., 2009. Advanced Geostructural Survey Methods Applied to Rock Mass Characterization. Rock Mechanics and Rock Engineering 42: 631–665. DOI: 10.1007/s00603-008-0010-4.

Gigli G., Casagli N., 2011. Semi-automatic extraction of rock mass structural data from high resolution LIDAR point clouds. International Journal of Rock Mechanics and Mining Sciences 48(2): 187–198. DOI: 10.1016/j.ijrmms.2010.11.009.

Jerzykiewicz T., 1968. Uwagi o genezie i orientacji ciosu w skałach górnokredowych niecki śródsudeckiej. Geologica Sudetica 4: 465–478.

Jerzykiewicz T., Wojewoda J., 1986. The Radków and Szczeliniec sandstones: An example of giant foresets on a tectonically controlled shelf of the Bohemian Cretaceous Basin (Central Europe). In: R.J.Knight, J.R.McLean (eds), Shelf Sands and Sandstones. Canadian Society of Petroleum Geologists Memoir 11: 1–35.

Kankare V., 2015. The prediction of single- tree biomass, logging recoveries and quality attributes with laser scanning techniques. Dissertationes Forestales 195. DOI: 10.14214/df.195.

Kekeç B., Bilim N., Karakaya E., Ghiloufi D., 2021. Applications of Terrestrial Laser Scanning (TLS) in Mining: A Review. Türkiye LİDAR Dergisi 3(1): 31–38.

Kemeny J., Donovan J., 2005. Rock mass characterisation using LIDAR and automated point cloud processing. Ground Engineering 38: 26–29.

Kemeny J., Turner K., Norton B., 2007. LIDAR for Rock Mass Characterization: Hardware, Software, Accuracy and Best-Practices. In: F.Tonon, J.T.Kottenstette (eds), Laser and Photogrammetric Methods for Rock Face Characterization: Report on a workshop held June 17–18, 2006 in Golden, Colorado.

Kościak B. 2000. Rock movement analysis of the monument of inanimate nature table hill – Szczeliniec Wielki. Szczeliniec 5: 3–39.

Kumar Singh S., Pratap Banerjee B., Raval, S., 2023. A review of laser scanning for geological and geotechnical applications in underground mining. International Journal of Mining Science and Technology 33(2): 133–154. DOI: 10.1016/j.ijmst.2022.09.022.

Lipecki T., Thi Thu Huong, K., 2020. Technologia Laserowego Skanowania Naziemnego Zastosowania w Szybie Pionowym w Polsce. Inżynieria Mineralna 1(2). DOI: 10.29227/IM-2020-02-36.

Mammoliti E., Di Stefano F., Fronzi D., Mancini A., Malinverni E.S., Tazioli A., 2022. A Machine Learning Approach to Extract Rock Mass Discontinuity Orientation and Spacing, from Laser Scanner Point Clouds. Remote Sensing 14(10): 2365. DOI: 10.3390/rs14102365.

Migoń P., Lidmar-Bergström K., 2001. Weathering mantles and their significance for geomorphological evolution of central and northern Europe since the Mesozoic. Earth-Science Reviews 56: 285–324.

Migoń P., Lidmar-Bergström K., 2002. Deep weathering through time in central and northwestern Europe: problems of dating and interpretation of geological record. Catena 49: 25–40.

Lato M., Diederichs M.S., Hutchinson D.J., Harrap R., 2009. Optimization of LiDAR scanning and processing for automated structural evaluation of discontinuities in rockmasses. International Journal of Rock Mechanics and Mining Sciences 46(1): 194–199. DOI: 10.1016/j.ijrmms.2008.04.007.

Lato M., Vöge M., 2012. Automated mapping of rock discontinuities in 3D LiDAR. International Journal of Rock Mechanics and Mining Sciences 54: 150–158. DOI: 10.1016/j.ijrmms.2012.06.003.

Leszczyński S., Chrząstek A., Halamski A.T., Nemec W., Wojewoda J., 2022. Cretaceous of the North Sudetic Synclinorium (southwestern Poland): Stratigraphy, origin and economic importance. In: J.Todes, I.Walaszczyk (eds), Cretaceous of Poland: 144–190.

Lukačić H., Krkač M., Gazibara S.B., Arbanas Ž., Mihalić Arbanas S., 2023. Detection of geometric properties of discontinuities on the Špičunak rock slope (Croatia) using high-resolution 3D Point Cloud generated from Terrestrial Laser Scanning. IOP Conference Series: Earth and Environmental Science 1124: 012006. DOI: 10.1088/1755-1315/1124/1/012006.

Ollier C.D., 1978. Induced fracture and granite landforms. Zeitschrift fur Geomorphologie N.F. 22(3): 249–257.

Pagano M., Palma B., Ruocco A., Parise M., 2020. Discontinuity Characterization of Rock Masses through Terrestrial Laser Scanner and Unmanned Aerial Vehicle Techniques Aimed at Slope Stability Assessment. Applied Sciences 10(8): 2960. DOI: 10.3390/app10082960.

Pagounis V., Tsakiri M., Palaskas S., Biza B., Zaloumi E., 2006. 3D laser scanning for road safety and accident reconstruction. In: Proceedings of the XXIII International FIG congress, 8: 13–27.

Pan D., Li S., Xu Z., Zhang Y., Lin P., Li H., 2019. A deterministic-stochastic identification and modelling method of discrete fracture networks using laser scanning: Development and case study. Engineering Geology 262: 105310. DOI: 10.1016/j.enggeo.2019.105310.

Pfeifer N., Briese C., 2007. Laser scanning – principles and applications. GeoSiberia 2007 – International Exhibition and Scientific Congress. DOI: 10.3997/2214-4609.201403279.

Riegl Laser Measurement Systems, 2022. Riegl VZ-400i and LIS GeoTec datasheets.

Riquelme A., Tomás R., Cano M., Pastor J.L., Abellán A., 2018. Automatic Mapping of Discontinuity Persistence on Rock Masses Using 3D Point Clouds. Rock Mechanics and Rock Engineering 51: 3005–3028. DOI: 10.1007/s00603-018-1519-9.

Riquelme A., Tomás R., Cano M., Pastor J.L., Jordá-Bordehore L., 2021. Extraction of discontinuity sets of rocky slopes using iPhone-12 derived 3DPC and comparison to TLS and SfM datasets. IOP Conference Series: Earth and Environmental Science 833: 012056. DOI: 10.1088/1755-1315/833/1/012056.

Sokalski D., Wojewoda J., 2022. Analiza strukturalna zniszczeń zlokalizowanych górotworu z wykorzystaniem naziemnego skanera laserowego (TLS) – wybrane przykłady z wyrobiska podziemnego O/ZG Rudna i Progu Radkowa (Góry Stołowe). Conference 65. Rocznica odkrycia złoża rud miedzi na monoklinie przedsudeckiej. Wrocław-Krotoszyce.

Solecki A. 2011. Structural development of the epi-Variscan cover in the North Sudetic Synclinorium area. In: A.Żelaźniewicz, J.Wojewoda, W.Ciężkowski (eds), Mezozoik i Kenozik Dolnego Śląska, WIND, Wrocław: 19–36.

Sturzenegger M., Stead D., 2009. Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts. Engineering Geology 106(3–4): 163–182. DOI: 10.1016/j.enggeo.2009.03.004.

Telling J., Lyda A., Hartzell P., Glennie C., 2017. Review of Earth science research using terrestrial laser scanning. Earth-Science Reviews 169: 35–68. DOI: 10.1016/j.earscirev.2017.04.007.

Thiele S.T., Grose L., Samsu A., Micklethwaite S., Vollgger S.A., Cruden A.R., 2017. Rapid, semi-automatic fracture and contact mapping for point clouds, images and geophysical data. Solid Earth 8: 1241–1253. DOI: 10.5194/se-8-1241-2017.

Vöge M., Lato M., Diederichs M.S., 2013. Automated rockmass discontinuity mapping from 3-dimensional surface data. Engineering Geology 164: 155–162. DOI: 10.1016/j.enggeo.2013.07.008.

Vos S., Anders K., Kuschnerus M., Lindenbergh R., Höfle B., Aarninkhof S., de Vries S., 2022. A high-resolution 4D terrestrial laser scan dataset of the Kijkduin beach-dune system, The Netherlands. Scientific Data 9: 191. DOI: 10.1038/s41597-022-01291-9.

Vosselman G., Maas H.-G., 2010. Airborne and Terrestrial Laser Scanning. Whittles Publishing, Caithes.

Wojewoda J., 1986. Fault scarp induced shelf sand bodies in Upper Cretaceous of the Intrasudetic Basin. In: A.K.Teisseyre (ed), 7 IAS Regional Meeting Guidebook, Excursion A-T: 1–30.

Wojewoda J., 1987. Seismotectonically induced sediments and structures in the Upper Cretaceous sandstones of the Intrasudetic Basin. Przegląd Geologiczny 4: 169–175.

Wojewoda J., 2007. Neotectonic Aspect of the Intrasudetic Shear Zone. Acta Geodynamica et Geomaterialia 4: 1–11.

Wojewoda J., 2009. Žďarky–Pstrążna Dome: a strikeslip fault-related structure at the eastern termination of the Poříčí–Hronov Fault Zone (Sudetes). Acta Geodynamica et Geomaterialia, 6: 273–290.

Wojewoda J., 2012. Joints in Cretaceous sandstones of the Góry Stołowe Mountains: tectonic and non-tectonic. In: 13th Czech–Polish Workshop on Recent Geodynamics of the Sudety Mts. and Adjacent Areas, Wrocław–Pawłowice, Abstracts: 57–58.

Wojewoda J., 2019. The Intrasudetic Basins and Synclinorium in the extensional model of the Sudetes evolution – environmental and paleogeographic schemes. In: 20th Czech–Polish Workshop on Recent Geodynamics of the Sudeten and the Adjacent Areas, Jakuszyce, Abstracts: 23–28.

Wojewoda J., 2020a. Geoatrakcje pogranicza – Góry Stołowe i Broumowskie Ściany. B. Kokot vel Kokociński, Nowa Ruda.

Wojewoda J., 2020b. Mapa geoatrakcji Krainy Gór Stołowych i Broumowskich Ścian. Wydawnictwo Turystyczne PLAN.

Wojewoda J., Ollier C., 2013. Weathering induced fractures, examples from the Góry Stołowe Mts. In: M.Krobicki, A.Feldman-Olszewska (eds), Głębokomorska sedymentacja fliszowa, sedymentologiczne aspekty historii basenów karpackich. POKOS 5'2013, V Polska Konferencja Sedymentologiczna, Żywiec, Abstrakty: 57–58.

Wojewoda J., Kowalski A., 2016. The role of the South-Sudetic Shear Zone in the evolution of the Sudetes. In: J.Wojewoda, A.Kowalski (eds), Przewodnik do Wycieczek Kongresowych, 3. Polski Kongres Geologiczny, Wyzwania polskiej geologii. wycieczka 2.3: 21–43.

Wojewoda J., Kowalski A., 2017. Gravity-induced fractures ('epigenetic fractures') from the Radków Bluff (Stołowe Mountains) – structural evidence of the progressive sandstone scarp retreat. In: On Recent Geodynamics of the Sudety Mts. and Adjacent Areas, Szklarska Poręba.

Wojewoda J., Migoń P., Krzyszkowski D., 1995. Rozwój rzeźby i środowisk sedymentacji w młodszym trzeciorzędzie i starszym plejstocenie na obszarze środkowej części bloku przedsudeckiego: wybrane aspekty. In: S.Cwojdziński (ed), Geologia i ochrona środowiska bloku przedsudeckiego. Przewodnik do LXVI Zjazdu PTG: 315–331.

Wojewoda J., Koszela S., Aleksandrowski P., 2010. A kilometre-scale low-angle detachment related to strike-slip faulting in upper Cretaceous mudstones of the Table Mountains (Central Sudetes, SW Poland). In: 8th Meeting of the Central European Tectonic Group Studies (CETeG), Abstracts: 127.

Wojewoda J., Białek, D., Bucha M., Głuszyński A., Gotowała R., Krawczewski J., Schutty B., 2011. Geologia Parku Narodowego Gór Stołowych wybrane zagadnienia. In: T.Chodak, C.Kabała, J.Kaszubkiewicz, P.Migoń, J.Wojewoda (eds), Geoekologiczne Warunki Środowiska Przyrodniczego Parku Narodowego Gór Stołowych. WIND, Wrocław: 53–96.

Wojewoda J., Chrząstek A., Sokalski D., 2022. Late Cretaceous geodynamics in the Middle Sudetes area (sedimentary and ichnological record). In: J.Todes, I.Walaszczyk (eds), Cretaceous of Poland: 191–241.

Wu X., Wang F., Wang M., Zhang X., Wang Q., Zhang S.A., 2021. New Method for Automatic Extraction and Analysis of Discontinuities Based on TIN on Rock Mass Surfaces. Remote Sensing 13: 2894. DOI: 10.3390/rs13152894.

Wu C., Yuan Y., Tang Y., Tian B., 2022. Application of Terrestrial Laser Scanning (TLS) in the Architecture, Engineering and Construction (AEC) Industry. Sensors 22(1):265. DOI: 10.3390/s22010265.

ERRATUM

Dominik Sokalski, Jurand Wojewoda (2023). Comparison of the consistency of structural measurements made using the traditional method and with the use of point cloud from terrestrial laser scanning in a selected site of Radków Bluff (Table Mountains, SW-Poland). Landform Analysis 42: 37–49. doi: 10.12657/landfana-042-003

given as

Fig. 4. The orientation of induced fractures at the base of Radków Bluff, at Radków Towers locality. A – the location of outcrops within Radków Bluff, B – results of structural analysis carried out conventionally. Aggregate projection diagrams were created based on at least 10 measurements, a total of more than 100 measurements at 5 sites. A total of 58 measurements were made with the compass at site no. 1, which were then compared with the results obtained from the point cloud. Colours explanation on the stereoplots: red lines show inclination of great circles of measured fractures; red spots refer to normal to fractures planes, black dashed lines refer to local topography, light blue show inclination of great circles of joints, blue is for background (modified after Wojewoda et al. 2022)

Fig. 5. Radków Towers site (Radków Bluff, Table Mountains), A – an example of traditional documentation of structural phenomena – faulting, layering, joints and induced fractures, B – photograph view of the outcrop. A and B show a view of the outcrop from the same spot

Acknowledgements

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Fig. 4. The orientation of induced fractures at the base of Radków Bluff, at Radków Towers locality. A – the location of outcrops within Radków Bluff, B – results of structural analysis carried out conventionally. **The figure 4B uses measurements taken by A. Kowalski (Wojewoda, Kowalski 2017).** Aggregate projection diagrams were created based on at least 10 measurements, a total of more than 100 measurements at 5 sites. A total of 58 measurements were made with the compass at site no. 1, which were then compared with the results obtained from the point cloud. Colours explanation on the stereoplots: red lines show inclination of great circles of measured fractures; red spots refer to normal to fractures planes, black dashed lines refer to local topography, light blue show inclination of great circles of joints, blue is for background (modified after Wojewoda et al. 2022)

Fig. 5. Radków Towers site (Radków Bluff, Table Mountains), A – an example of traditional documentation of structural phenomena – faulting, layering, joints and induced fractures, B – photograph view of the outcrop. **The figure 5B uses photo and measurements taken by A. Kowalski (Wojewoda, Kowalski 2017).** A and B show a view of the outcrop from the same spot

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I, Jurand Wojewoda, as a co-author of the article, declare that without any ill will, I used measurements and a photograph taken by Aleksander Kowalski, PhD as part of joint scientific research to create Fig. 4B and Fig. 5B. These materials were previously presented as joint material in a conference presentation (Wojewoda, Kowalski 2017). Despite citing this source in the article, I used these materials without obtaining Aleksander Kowalski's consent, which is a violation of good manners on my part and for which I sincerely apologize to Aleksander Kowalski, PhD. My neglect is not changed by the fact that the work carried out at that time was conducted on my initiative and under my supervision, and its purpose was to demonstrate the research hypothesis I had previously given. I would also like to emphasize that my co-author, Dominik Sokalski, MSc., had no knowledge of the history and authorship of the materials I used.

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