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Geologos 30, 2 (2024): 71–80
https://doi.org/10.14746/logos.2024.30.2.08

GEOLOGOS

Young geodynamic activity in the marginal fault zone of the Sudetic Block – new data

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Abstract

A quarter of a century ago, during cartographic works using then-known field methods for measuring structural features, on the boundary of the Sudetic and Fore-Sudetic blocks, new phenomena were recognised; these were interpreted to be tectonic in nature and the result of left-lateral strike-slip movement in the subsurface. Grabens, half-grabens, shear zones and seismites in the gold-bearing sands and gravels that form the slopes of the valley of the River Kaczawa, are estimated to be of Pliocene and early Pleistocene age, having been interpreted as deposits of the pre-Kaczawa alluvial fan system. The natural exposures documented 25 years age have now all disappeared. In 2022, these levels became exposed again as a result of renewed gravel exploitation and phenomena described in the past reappeared. Field measurements were made again, this time using modern data-recording techniques, such as photogrammetry and terrestrial laser scanning. This work has enabled a comparison of field measurement methods with those obtained from the point clouds data. The results were found to be highly consistent. At the same time, precise reconstructions of the structures and their connection to the geodetic reference system make it possible to supplement previous geokinematic interpretations for this segment of the Sudetic Marginal Fault Zone (SMFZ). A formerly postulated left-lateral strike-slip regime in this zone was confirmed during the period of formation of the pre-Kaczawa alluvial fan deposits, but also probable is a kinematic inversion that must have occurred during, or just after, the early Pleistocene.

Keywords: Palaeogeography, neotectonics, strike slip, deformation, photogrammetry

1. Introduction

In the valley of the River Kaczawa, near the town of Złotoryja (sites: Rokitki, Kopacz), in levels belonging to the Neogene-Quaternary sedimentary succession of the Sudetes Mountains and the Sudetes Foreland, neotectonic movements of the Sudetic Marginal Fault Zone (abbreviated here as SMFZ) have been documented (Mastalerz & Wojewoda, 1990, 1993). The main outcrops are located on the slopes and near the border of the valley of the River Kaczawa in the section where it crosses the SMFZ (Fig. 1A). Based on the spatial distribution of these deposits, their sedimentological features and deformational structures in the sparse and scattered outcrops at that time, the authors proposed a geokinematic model for the SMFZ. In this model, an important role in the formation and offset of the alluvial fan system was assigned to sinistral strike slip movement within the major fault of this zone – the Sudetic Marginal Fault (SMF). It was then described as grabens and half-grabens, shear zones and seismites, indicative of the strike-slip and extensional nature of the SMFZ in this segment as well as of significant seismic activity.

Relatively recently, in 2021, at the geosite of Rokitki, aggregate exploitation was resumed with-

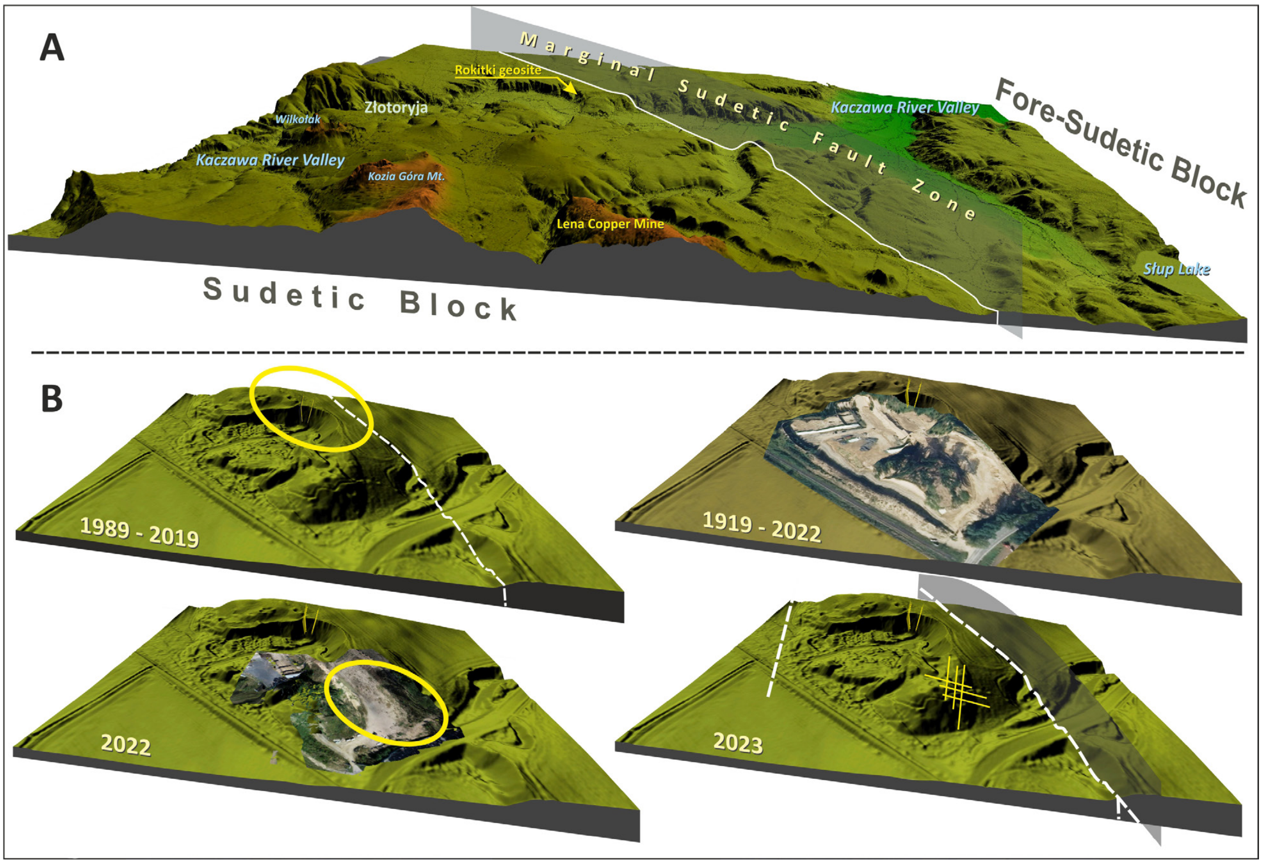

Fig. 1. A – Location of the Rokitki geosite in relation to the approximate course of the Sudetic Marginal Fault Zone on the LiDAR terrain model (dated 2014); **B** – Recent changes in the geosite area during 2019–2023, as a result of renewed gravel exploitation.

in a gravel pit. These works have now permitted a new description and documentation, this time supplemented by photogrammetry and terrestrial laser scanning of the excavation sites and a more detailed interpretation (Fig. 1B) of new data sets. The aim of the present paper is primarily to compare the results obtained by using old and novel methodologies, but also to present the possibility of using the acquired data directly to map the spatial structure of the rock mass. Moreover, new techniques complement the previous geokinematic model for this segment of the SMFZ.

1.1. Age of sediments

The sediments of the Neogene-Quaternary succession, first recognised and mapped by German cartographers in the early 20th century (1903–1916), were assigned a Miocene age (Kühn & Zimmermann, 1929; Zimmermann, 1936). They were similarly classified by Polish cartographers (see Jerzmański, 1958; Kozdrój et al., 2005, 2009). Subsequent detailed studies of the lithology and distribution of these deposits, based on palynological dating, have confirmed their late Neogene age (e.g. Oberc & Dyjor, 1969a, b; Dyjor, 1993, 1997). In the vicinity of Złotoryja, the Neogene-Quaternary sedimentary succession includes three of the four sedimentary units distinguished formerly in the Sudetes, differing in lithology (according to Wojewoda in Wojewoda et al., 1995; August et al., 1995). The lower series consists mainly of whitish quartz sands with a high content of dispersed clay material (mainly kaolinite) and intercalations of kaolinitic tills. The middle one consists of sands and gravels, mostly quartz-silica, containing material exclusively of Sudetean provenance, while the upper series consists of gravels and lithic sands containing mixed rock material, both of Sudetic and Scandinavian provenance. All series are separated by erosional surfaces, with the surface separating the lower and middle series having a large, over-regional extent.

The lowest levels in this area rest directly on crystalline rocks of the Fore-Sudetic Block or on the residual kaolinites (saprolites) that covering these. The latter have been documented in several boreholes near the area discussed. The sediments themselves, however, are also kaolinitic and constitute the youngest sedimentary formation in the Sudetes (Gozdnica Formation), of Pliocene age (Dyjor & Sadowska,1986; Piwocki et al., 2004). The same age was also indirectly confirmed by research of heavy and accessory minerals by Grodzicki (1963, 1972). The middle series is referred to locally as "preglacial" or "eopleistocene" (Wroński, 1974, 1975), while the upper series consists of fluvioglacial deposits, related to the oldest glaciation of the Sudetes Foreland area, i.e. with the South-Polish Glaciation, which, as estimated, reached present-day altitudes of 330–350 m a.s.l. (Przybylski, 1998; Badura & Przybylski, 1998).

1.2. Outline of Sudetes palaeogeography during the Neogene/Quaternary transition

Neogene sediment patches cover almost the entire area north of the SMFZ. In places where the northern border of the Sudetes (i.e., SMFZ) is cut by valleys of larger rivers, the range of Neogene formations locally reaches even more than 8 km inside the Sudetes, for example in the valleys of the rivers Kaczawa, Bystrzyca and Nysa Kłodzka. Such a distribution of Neogene and lower Pleistocene deposits on the Lower Silesian Block prompted Dyjor (1997) to present the hypothesis that they were deposits of alluvial fans formed at the outlets of the ancient largest Sudetean rivers named "pre-rivers". In his palaeogeographical scheme, he distinguished, among others, the position of "pre-Kaczawa" alluvial fan, which, however, he limited to the Fore-Sudetic Block area, as if this fan was "cut off" from the front of the Sudetes (see Fig. 2A, B).

Cartographic identification of locations of exposures of Neogene sediments (as above) and their sedimentological description by Mastalerz & Wojewoda (1990, 1993) clearly indicated that the deposits of the Lower Pliocene Gozdnica Formation occur north of, within, and south of the zone of marginal faults of the Sudetic Block (Fig. 2B). Nowadays, using a detailed numerical LiDAR terrain model, this can be shown in a cross-section to the axis of former pre-Kaczawa fan outcrop belt (Fig. 2C), where the top surface of the above-mentioned lower series is convex up, with culmination in a point with approximate co-ordinates 51˚08′30″ (N) and 15˚57′00″ (E). Approximately, this place was indicated by the authors cited above as the location of the apex of one of the alluvial fans of "pre-Kaczawa River" (see Mastalerz & Wojewoda, 1993, fig. 10C).

2. Data sources

2.1. Geological field research

Field work was carried out in the autumn of 2022 and in the spring of 2023, comprising photographic documentation of phenomena observed in the faces of a disused gravel pit (currently a sports shooting range), which now cover the area adjacent to the sites investigated in 1989 (Mastalerz & Wojewoda, 1990, 1993; Wojewoda et al., 1995) (Figs. 1, 4A). In total, over 300 measurements of various types of structural surfaces were made using the Freiberg geological compass and the compass in the FieldMoveClino smartphone application, which were compiled on stereographic diagrams and which, for selected structures, mainly fault surfaces, shear surfaces and zones, and near-fault fractures, were presented in a simplified, schematic form along with measurements averaged for a specific structure or group of structures in Figure 4B.

2.2. Analysis of existing cartographic and LiDAR materials

The oldest cartographic document that contains information on the lower part of the deposits discussed here is sheet no. 2821 (4861) Złotoryja (German: Goldberg), mentioned earlier (Kühn & Zimmermann, 1929). The authorship of this subdivision, which featured on the map and in the map explanations, belongs to Kühn, who studied the area of the Kaczawa Valley in person. In the northern and southern slopes of the valley, near the present-day suburb of Złotoryja Rokitki (German: Reisicht) and the village of Kopacz (German: Kopatsch), respectively, near the mouth of a local stream called Śnieżny Potok (German: Schneebach), Kühn described these sediments as "white clayey sands" and dated them as Miocene. He considered the gravels overlying these to be glacial deposits formed at the mountain foothills. After World War II, on the oldest renewed map sheet Złotoryja M33–32Db as part of the series Detailed Map of the Sudetes at a scale of 1:25,000 (made in 1955, published three years later), these sediments were also marked by Jerzmański (1958) as Neogene. A similar interpretation of the age and genesis of these strata to that presented in papers by Mastalerz & Wojewo-

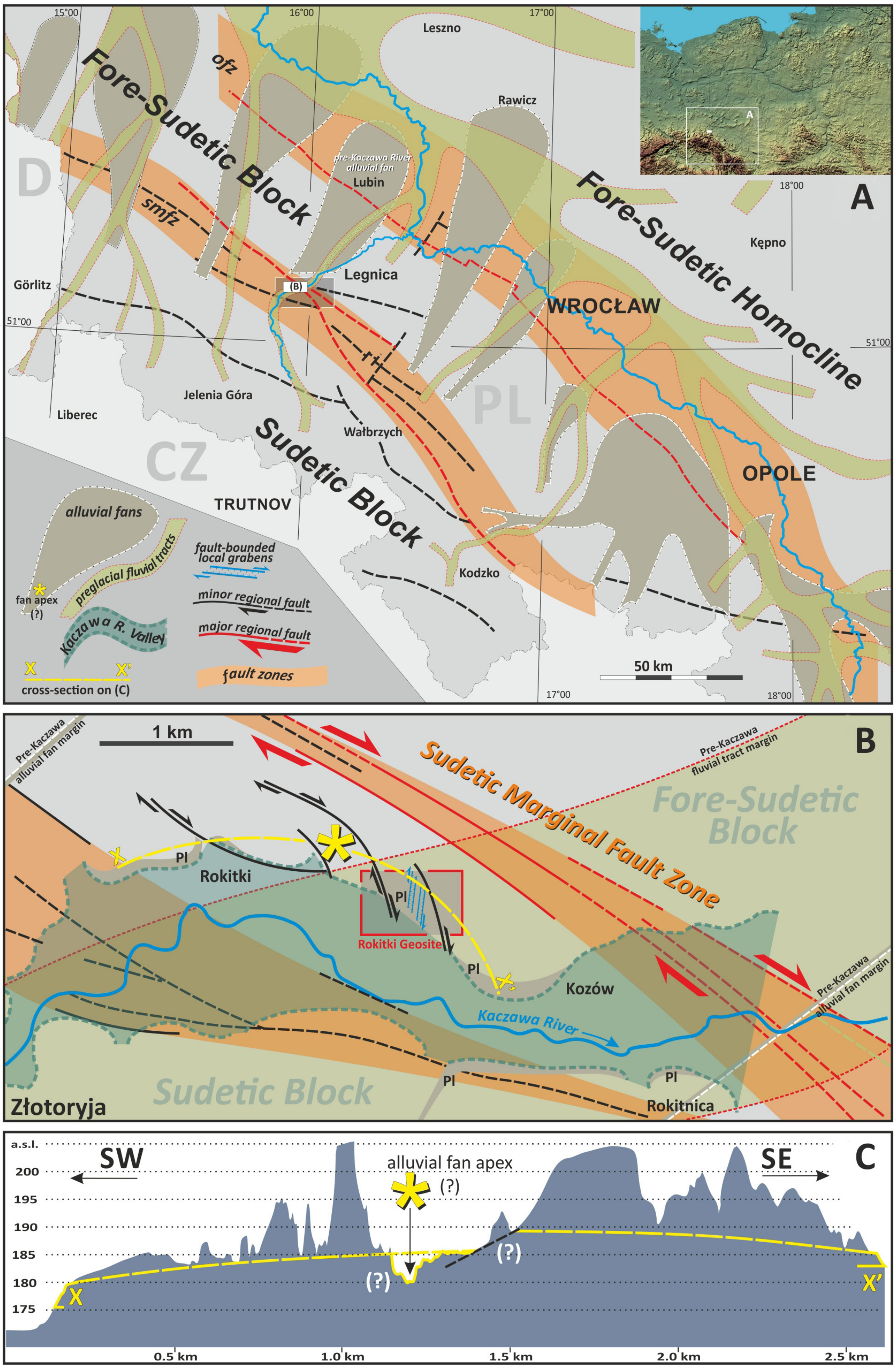

Fig. 2. A – Location of the study area: regional palaeogeographical context for the Pliocene and Pleistocene (according to Oberc & Dyjor, 1969a, b; Dyjor, 1993, 1997; August et al., 1995; Wojewoda et al., 1995, modified and supplemented); **B** – Local tectonic and geokinematic context; **C** – Cross-section of the top surface of the gold-bearing clayey sands made along the line as marked above (B). The culmination point marked probably corresponds to the apex of one of the former lobes of the pre-Kaczawa alluvial fan. Abbreviations: smfz – Sudetic Marginal Fault Zone, ofz – Odra Fault Zone

da and others, and supported by meticulous analysis of the premises, can be found in the explanations to map sheet Złotoryja 759 (M-33-32-D) of the series Geological Map of Poland at a scale of 1:50,000 (Kozdrój et al., 2009).

Completely new data were provided by LiDAR imaging, which is now widely used in cartographic works. Apart from the possibility of very precise mapping of terrain surfaces, this allows to combine data obtained in other ways (e.g. as a result of terrestrial laser scanning) into a complete spatial database. The 2.5-D cloud imaging also allows the use of very useful morphometric techniques. Here we present, as an example, the use of data from a digital terrain model to calculate polynomial trend surfaces (Fig. 3), for this purpose, standard procedures offered by the Microdem application (version 2011.1, 2020) by Professor P.L. Guth (Guth, 2009). First-, 2nd-, 3rd-, 5th-, 7th- and 8th-order trend surfaces (Fig. 3B–G) were made for a slightly enlarged area that included the one presented in Figure 2B.

2.3. Photogrammetric point cloud documentation

Photogrammetric mapping was also performed at the study site. Figure 3A shows two selected diagrams illustrating the spatial situation. Figure 4B contains geological documentation of one of the slopes based on an orthogonal projection of the slope containing the example of a tectonic structure presented below, which in the photographic mosaic (Fig. 4D) was tentatively interpreted as a graben, one of few identified previously nearby. In turn, Figure 4C, E are local projections approximately orthogonal to the measured surfaces, initially interpreted as the boundary faults of this "graben".

The inventory measurement of the Rokitki geosite was carried out using the photogrammetric technique. This task was performed using a DJI Phantom 4 drone equipped with 20 Mpix non-metric CMOS camera. The photogrammetry mission was planned in the Pix4D capture environment. The parameters for mission planning were set to 80% frontal and 70% side overlap in mission grid at different AGL heights (above ground level). In order to develop a continuous 3D model representing the surface of the entire geosite three photogrammetric missions were performed:

- (1) mission grid at 60 m AGL
- (2) mission grid at 35 m AGL
- (3) additional oblique photos at 20 m AGL.

To obtain a metric photogrammetric model, 6 GCP (Ground Control Points) were marked. GCPs were measured by an independent satellite GNSS RTN measurement technique in the ASG-EUPOS system.

The photogrammetric mission yielded 448 photograms. To process the model, Structure from Motion algorithms implemented in Metashape PRO software were used. The first stage of work was the image matching. Non-metric photographs were aligned to the photogrammetric matrix as a result of terratriangulation of the model on 6 GCPs. After the adjustment, a dense point cloud consisting of nearly 30 million points was created.

Data processing was carried out in the PL2000/5 co-ordinate system as well as EVRF2007 height system with a horizontal accuracy of mXY = 1.5 cm and height accuracy of mH = 2 cm. The result of this study was a point cloud representing the bare earth surface (ISPRS class 02 grounds). The point cloud was processed into a digital terrain model DTM. Export of measurement data was made in the ISPRS *.las format. Additionally, in the process of photogram orthorectification, an orthomosaic of the AoI (Area of Interest) and an orthomosaic of the slope analysed in oblique and vertical projection have been performed.

3. Results and discussion

The first issue, being one of the goals of the present project, was the possibility of objective and reliable spatial documentation of geosites, the importance of which has or may have factual significance for our knowledge of the geology on a local to regional and even supra-regional scale. Current techniques allow to obtain a virtually unlimited amount of point information about surfaces, which is usually the starting point for correct 3D recognition of geological objects. Of course, this is possible by combining methods for modelling the external surface of objects with their physical properties and their variability inside the objects. In any case, the combination of such data allows to create reliable and predictive models that constitute the basis for knowledge of 3D geological space.

Unifying data in terms of resolution is just one of the difficulties encountered when modelling. Another difficulty results from the prosaic fact of a geologist's comprehensive knowledge and experience. Hence, there is still a great need to teach methods of description, measurement and interpretation of specific structural phenomena, necessarily in connection with the local geodetic reference system.

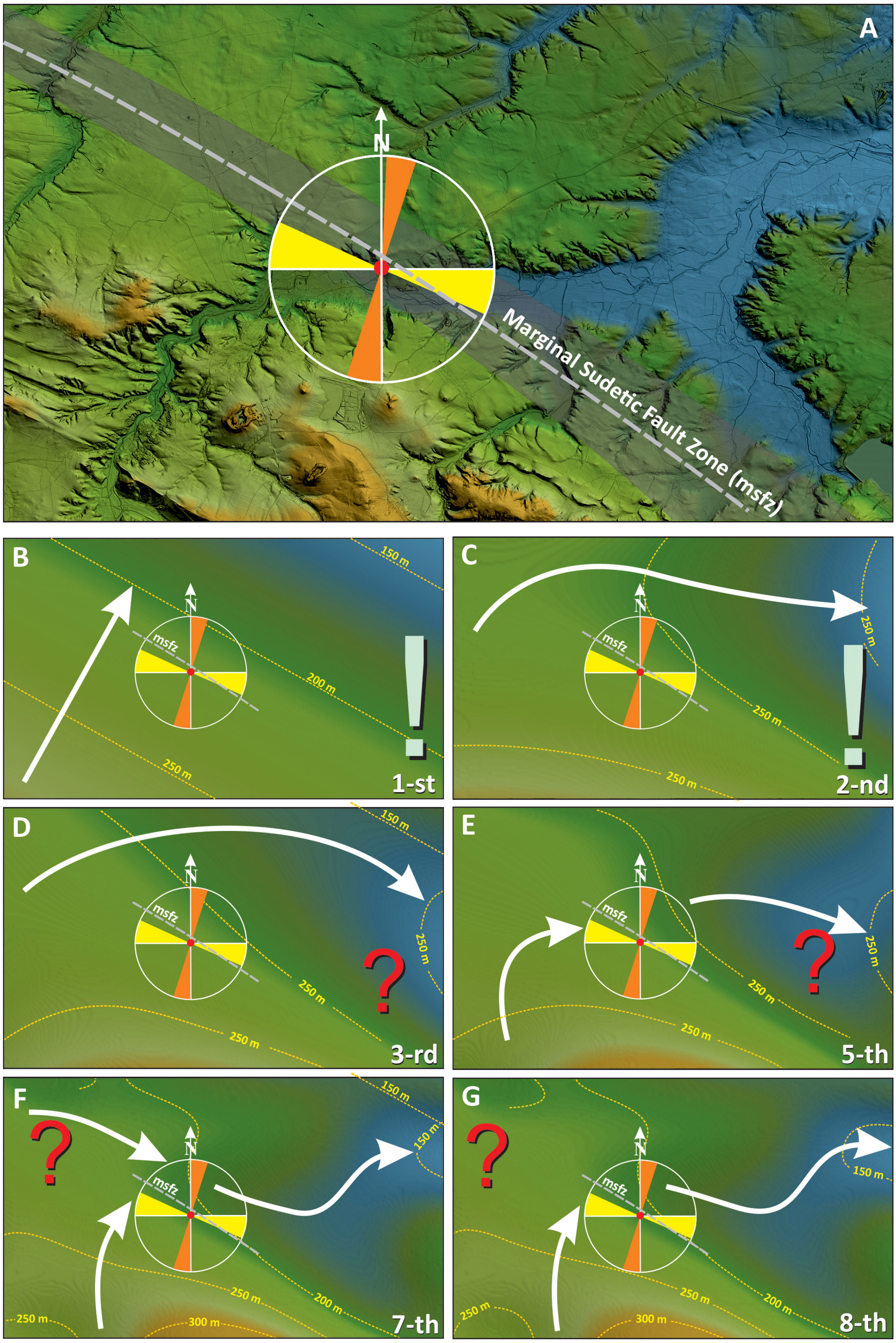

Fig. 3. A – Location of the Rokitki geosite within the general course of the SMFZ with a simplified diagram of the strike of the boundary surfaces of tectonic grabens and half-grabens, as well as listric surfaces within these (orange and yellow, respectively, see Fig. 5); **B–G** – Trend surfaces of the first, 2nd-, 3rd-, 5th-, 6th- and 8th- order made for the area selected. White arrows mark the main drainage axes for particular trend surfaces.

The Rokitki geosite has been known for a long time, not only to geologists, because some of the deposits described from here have long been known as gold-bearing sands and gravels. Due to their occurrence in the valley of the River Kaczawa, estimated from approximately 25 m below the valley floor to > 19 m above (compare Grodzicki, 1996,1998; Kozdrój et al., 2009), the most intense exploitation, even in the Middle Ages, took place at the base of the valley slopes, where the material was less waterlogged than in the valley itself. Intensive exploitation means, in fact, the destruction of the original structure of the rock or soil mass. Therefore, when neotectonic phenomena were recognised in these sediments in the past, they concerned the highest parts of the section, because only there was a natural slope preserved, while the entire remaining area was one large landslide, which, incidentally, was also included in the cartographic documentation of this area (see, among others, Kozdrój et al., 2009). From 1989 to 2019, virtually all traces of the places where geological documentation had been made at that time disappeared (Mastalerz & Wojewoda, 1990). A very uncomfortable situation occurred, because unique phenomena documenting local geokinematics, cited in many publications, including textbooks, as indicators of tectonic phenomena in unconsolidated sedimentary material, had been lost. If it were not for the combination of various events and progress in spatial measurement and mapping techniques, the whole matter would probably have remained a story from the past.

Meanwhile, renewed gravel exploitation here has resulted in the removal of most of the redeposited and internally deformed material, and in exposure of undisturbed sediments, not only at the highest level, but also in the lower part of the section. This time, both spatial measurements were made using both traditional methods and modern mapping techniques. Figure 4B is a simplified documentation of the phenomena identified on the best-preserved excavation face. All blue diagrams represent an averaged geological compass measurement, while the phenomena interpreted as being tectonically induced are marked in yellow.

A portion of the face has also been highlighted and is presented in detail in the photograph below (Fig. 4D). In the "flat" view from the front, the first assessment led to the assumption that this was a tectonic graben, the edges of which were bounded by two listric fault surfaces. However, compass measurements have contradicted this working hypothesis. After "separating" both fault surfaces in the photogrammetric cloud, it turned out that they had a completely different geometry than would result from the view of the face (Fig. 4C, E). The surfaces were divided into measurement segments, for which the average resultant vectors were determined in the geometric centre of each section (measurements in two-part notation are presented next). Moreover, for individual measurements their significance was estimated as depending on the differences in the shape of the surface within each sector (i.e. surface roughness). The higher risk that the measurement is uncertain (red colour) practically excluded the measurement from the set as it was completely random. However, simplified stereographic diagrams made for measurements from the point cloud show very good agreement with those made of measurements using the traditional method by geological compass.

Therefore, in this particular case, photogrammetric documentation of such objects can certainly be highly useful, especially in terms of detailed spatial interpretation of selected structural phenomena. Moreover, periodic repetition of documentation in the same geodetic reference system may, in the case of actively exploited slopes, lead to *de facto* 3D recognition of the geological structure of the rock mass monitored.

Constant access to the acquired data and a much greater accuracy (resolution) of recognition – all this makes it possible to repeat calculation procedures many times, depending on our understanding of geological phenomena. Moreover, it presents opportunities to recreate geological space after it has completely disappeared or been destroyed – a genuine geological time machine.

The second issue that arose from the possibility of much more detailed identification of the structures occurring at the site was the relationship between their spatial form and regional geological structures, and in this case, to the course of the SMFZ. The Rokitki geosite is located practically in the centre of this zone, for which regional tectonic activity dates back several million years. Therefore, all structural phenomena with tectonic features that occur here in Neogene (and younger) formations are a direct indicator of the activity of this zone. Measurements put together allowed for the creation of a probable 3D model of a structure that, at first glance, was considered a tectonic graben. It turns out that this is in fact a half-graben (Fig. 5), the orientation of which, in relation to the course of the SMFZ in this place, documents the dextral direction of displacement in the zone. This is the opposite direction to that documented by the offset of Pliocene alluvial fan sediments (compare Mastalerz & Wojewoda, 1990).

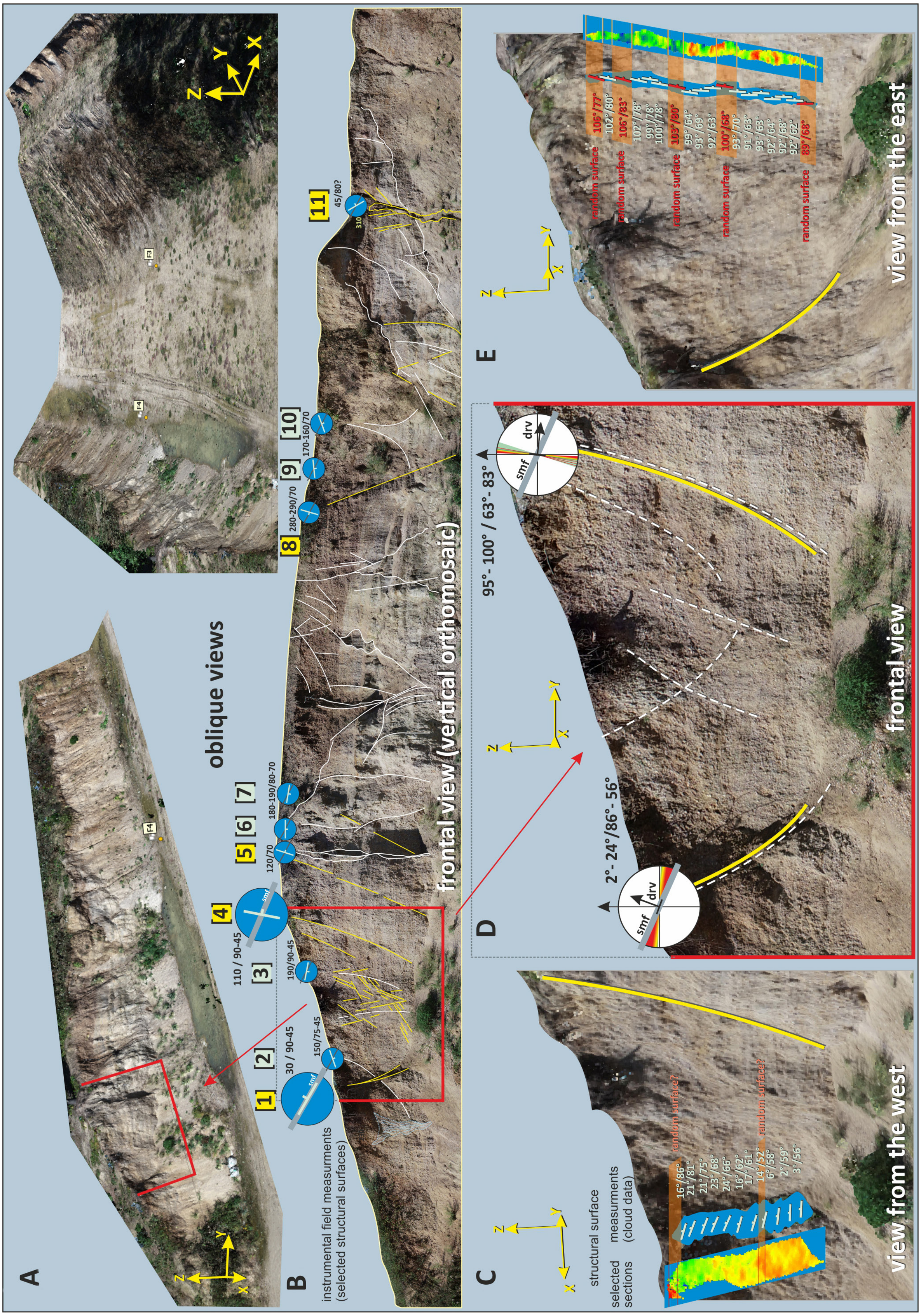
A
oblique views
B
instrumental field measurements
(selected structural surfaces)
[1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11]
30 / 90-45
150/75-45
190/90-45
110 / 90-45
120/70
180-190/80-70
280-290/70
170-160/70
45/80?
frontal view (vertical orthomosaic)
C
structural surface measurements (cloud data)
selected sections
random surface?
view from the west
D
2°- 24°/86°- 56°
95°- 100° / 63°- 83°
smf
drv
frontal view
E
random surface
view from the east

Fig. 4. Documentation of selected structural surfaces at the Rokitki geosite; **A** – Geographically oriented views (X for northing) of the northern part of the gravel pit; the location of the detail described below (B to E) and in Fig. 5 marked in red; **B** – orthophotomosaic obtained from a point cloud with marked measurements of tectonic surfaces (yellow) and other surfaces (white), measured with a classic geological compass; **C** –measurements of selected listric surface extracted from the point cloud inside the half-graben; **D** – Combined measurements of both surfaces on the photographic image of the half-graben; **E** – Measurements of the western face of the half-trench extracted from the point cloud.

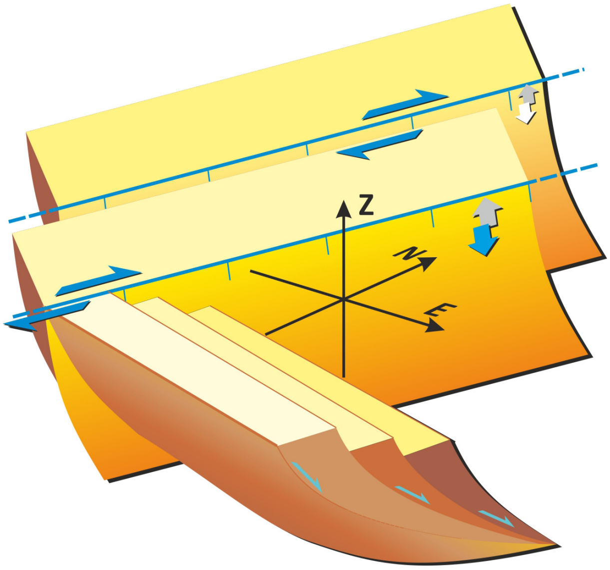

Fig. 5. Spatially oriented 3D model of the structure of the tectonic half-graben at the Rokitki geosite (as of July 2023).

There may be three reasons for the inconsistency presented above may. Firstly, it is related to the fact that the spatial structure of the pre-Kaczawa alluvial fan deposits was incorrectly interpreted or, secondly, that structural phenomena in the past were incorrectly measured or interpreted geokinematically. Finally, it could be that phenomena currently documented with modern tools have been incorrectly recognised or interpreted. Basically, this last possibility can be ruled out quickest, for many reasons presented here (see above). In turn, an offset of Pliocene alluvial fan deposits seems to be confirmed by cartographic images, as well as 1st^{t}- and 2nd-order morphological trend surfaces, which have been generated. The first one is a general signal of the original palaeoslope inherited from the period closely after the last planation of the area of both Sudetic and Fore-Sudetic blocks. This occurred for the first time prior to the marine transgression during the Late Cretaceous, and then again during the Miocene. The second-order trend surface indicates a dominant regional geotectonic component, which is clearly emphasised by the change in reconstructed palaeo-outflow direction, that refers to the proposed directions and the fan offset mechanism in the area of the Fore-Sudetic Block, and confirms the anti-clockwise (sinistral) strike slip regime inside the SMFZ. A similar mechanism for the westward-shifting pre-Kaczawa alluvial deposits is suggested by the present-day location of the morphological culmination of Pliocene deposits obtained based on the LiDAR model of the land surface (see Fig. 2B, C). Therefore, the most probable cause of the inconsistency cited above is the imprecise spatial identification of tectonic phenomena in relation to the geodetic reference system. It is worth mentioning that attempts have been made to verify old measurements in or near the places where they were taken, and documented in publications (Mastalerz & Wojewoda, 1990; Wojewoda et al., 1995). Unfortunately, these attempts have turned out ineffective.

4. Conclusions

New measurement and documentation techniques and high-resolution LiDAR imaging of the land surface confirm previous theses on the formation of the architecture of alluvial fan sediments in the strike slip tectonic zone during the late Cenozoic, but also verify the geokinematic scheme in subsequent periods of activity in this zone. While alluvial sedimentation occurred within the SMFZ during the Pliocene, and perhaps also in the early Pleistocene in the geokinematically dominant left-lateral strike slip regime, later, after this time, a kinematic inversion occurred, into a right-lateral one, which is documented here by identified and measured tectonic phenomena existing within the entire sequence of Pliocene and Quaternary deposits.

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Manuscript submitted: 8 March 2024
Revision accepted: 3 June 2024