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Indicators of recent geodynamic activity in the Książ Castle area (Świebodzice Unit, Sudetes) in the light of structural analysis and geodetic measurements

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Abstract. Indicators of recent geodynamic activity in the Książ Castle area are registered by the measuring instruments of the SRC PAS (Space Research Centre of Polish Academy of Sciences) Geodynamic Laboratory at Książ. Over 40 years of continuous observations from quartz horizontal pendulums (since 1974) and over 10 years of observations from water-tube tiltmeters (since 2002) have documented irregularly repeatable strong signals related to the relative displacement of blocks in the rock substrate, on which Książ Castle is located. These signals have dip (rotational) and vertical strike-slip components. Also, the presence of a horizontal strike-slip component is evidenced by geometric anomalies (deformations) of the shape of the Pełcznica river valley, which directly correspond to the orientation of the main faults in the area. Recent geodynamic activity is documented by destruction of the construction elements in the castle complex. Instrumental indicators of movement, geodetic measurements and structural analysis of the rock massif have allowed for constructing a model showing the main unconformity surfaces in the analysed rock massif. Sinistral, NE–SW and ENE–WSW-oriented strike-slip faults prevail in the laboratory corridors, along with perpendicular WNW–ESE and NW–SSE-oriented dextral and normal faults. Most dislocations are accompanied by zones of intense cataclasys, secondary silification, and Fe and Mn mineralization. Generally, the faults were formed due to reactivation of joint fractures cutting the steeply N- and S-dipping (at 75–90º) deposits of the Książ Conglomerate Formation.

1 Introduction

The Świebodzice Unit (Sudetes, SW Poland) belongs to parts of Poland with recent geodynamic activity. This activity was confirmed by multiannual measurements with application of instruments working in the underground Space Research Centre of Polish Academy of Sciences (SRC PAS) Geodynamic Laboratory (GL) at Książ Castle, i.e. quartz

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horizontal pendulums (HP) and water-tube tiltmeters (WT). The registered phenomena are incidental in character, reflecting in form of relative dislocation of rock blocks and substrate tilting [1-5]. The dislocations take place in the Książ massif mainly along of the discontinuoity surfaces, i.e. faults within the massif. These include strike-slip and oblique-slip faults, but also low-angle thrusts, documented in the underground excavations of the GL and in natural exposures in the vicinity of Książ Castle.

One of the most probable indicators of geodynamic activity in the vicinity of Książ Castle are well-documented shape anomalies of the Pełcznica river valley [5]. These anomalies are most probably caused by the kinematics of the rock substrate, along fault surfaces, which constrained the modification of the river valley shape [6]. The idea of tectonic foundation of the Pełcznica valley and other river valleys incising the Świebodzice Unit (e.g. Czyżynek, Szczawnik and Lubiechowski Potok valleys) was confirmed by morphometric analyses conducted by Wojewoda [7]. These analyses, including determination and quantification of indicators of river channels torsion, have indicated the presence of numerous structural anomalies in the valley shapes, which correspond both in range and orientation to faults determined by mapping surveys in the Świebodzice Unit by other authors.

This paper presents the results of geodetic measurements and structural analyses, which indicate that the concept of the tectonically-induced development of the Pełcznica river valley and the Książ Castle area is correct. The obtained results indicate that the confirmed faults and fault zones were formed due to reactivation of pre-existing joint sets cutting the sedimentary rocks of the Książ and Chwaliszów formations. These faults indicate recent activity.

2 Characteristics of the study area

The Świebodzice Unit (ŚU), in older literature referred to as depression, trough, synclinorium or basin [7-10], is a small, rhomb-shaped, regional geological structure with an area of about 100 km^2, located in the Central Sudetes between Wałbrzych to the south, Strzegom to the north and Świdnica to the east (Fig. 1). The Świebodzice Unit is composed mainly of Carboniferous sedimentary rocks, traditionally assigned to the Pogorzała, Pełcznica, Chwaliszów and Książ formations. Blocks of Upper Devonian rocks, forming isolated and likely allochthonous rock bodies of various sizes, subordinately occur in the ŚU structure. From the south, the ŚU bounds with the Sowie Mts. Gneiss Massif along the Szczawienko Fault; from the east and north it is separated from the Fore-Sudetic Block by the Sudetic Marginal Fault; and from the west it adjoins with the Intra-Sudetic Synclinorium along the Strumyk (Struga) Fault. From the north, the boundary of the ŚU with the metamorphic rocks of the Kaczawa Complex (Cieszów Unit) is not defined precisely [7, 11, 12] and is most probably a system of smaller, generally sinistral strike-slip faults [12]. According to Teisseyre [13], the sedimentary rocks forming the ŚU are locally strongly folded, and the particular mesofolds have approximately W-E-oriented axes. The ŚU was for the first time distinguished as a separate structural element of the Sudetes in the 1950-ties [14, 15]. Authors of older geological maps concluded that the ŚU is an integral part of the Intra-Sudetic Synclinorium [16, 17].

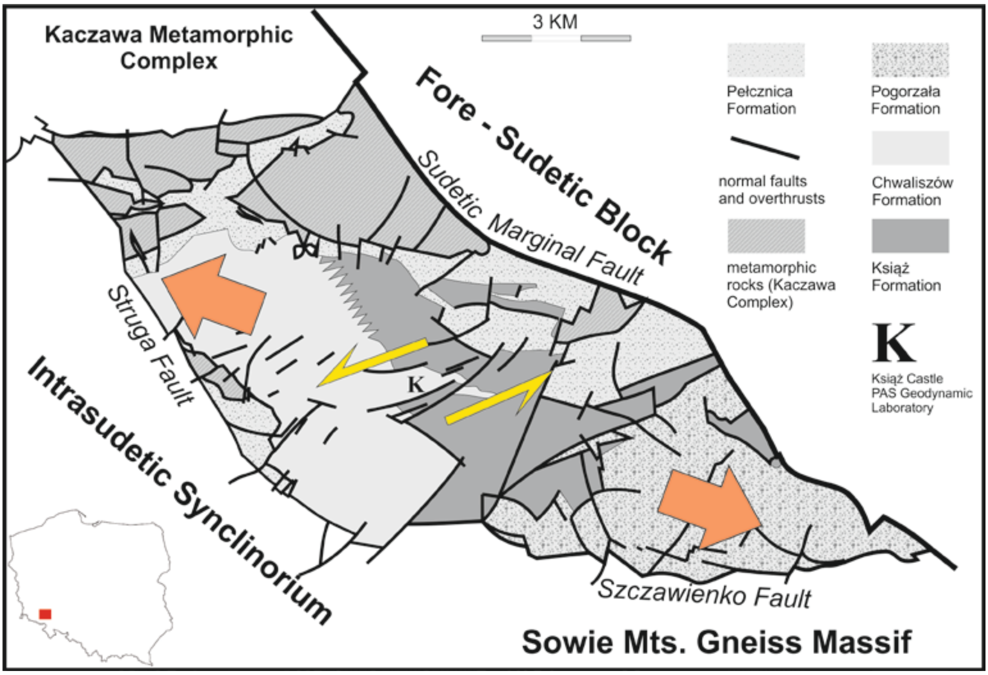


Fig. 1. Simplified geological map of the Świebodzice Unit [5].

The SRC PAS Geodynamic Laboratory at Książ is located within the Książ massif (Książ morphological elevation), situated in the central part of the ŚU.

2.1 Underground Geodynamic Laboratory at Książ

The Geodynamic Laboratory at Książ, belonging to the Space Research Centre of the Polish Academy of Sciences has been established in the underground excavations under the Książ Castle courtyard (Fig. 2). The corridors were excavated for military purposes at the end of World War II by the Nazi Todt Organization [18-20]. After World War II, the object was managed by the Silesian Military District, and in the 1970-ties was made available to the Polish Academy of Sciences for scientific research.

The first research laboratory in the underground of the Książ massif, the Geophysical Observatory of the Institute of Geophysics, Polish Academy of Sciences, was established following the initiative of Prof. Roman Teisseyre, who installed seismographs at Książ. In 1974, owing to Prof. Tadeusz Chojnicki, the research activity was extended to studies of tidal signals with application of quartz horizontal pendulums. In the early 2000s, thanks to Prof. Marek Kaczorowski, the underground SRC PAS Geodynamic Laboratory was established. New instruments were constructed, allowing for expanding the range of the research onto non-tidal processes, including e.g. kinematic effects in the rock massif [5, 21, 22].

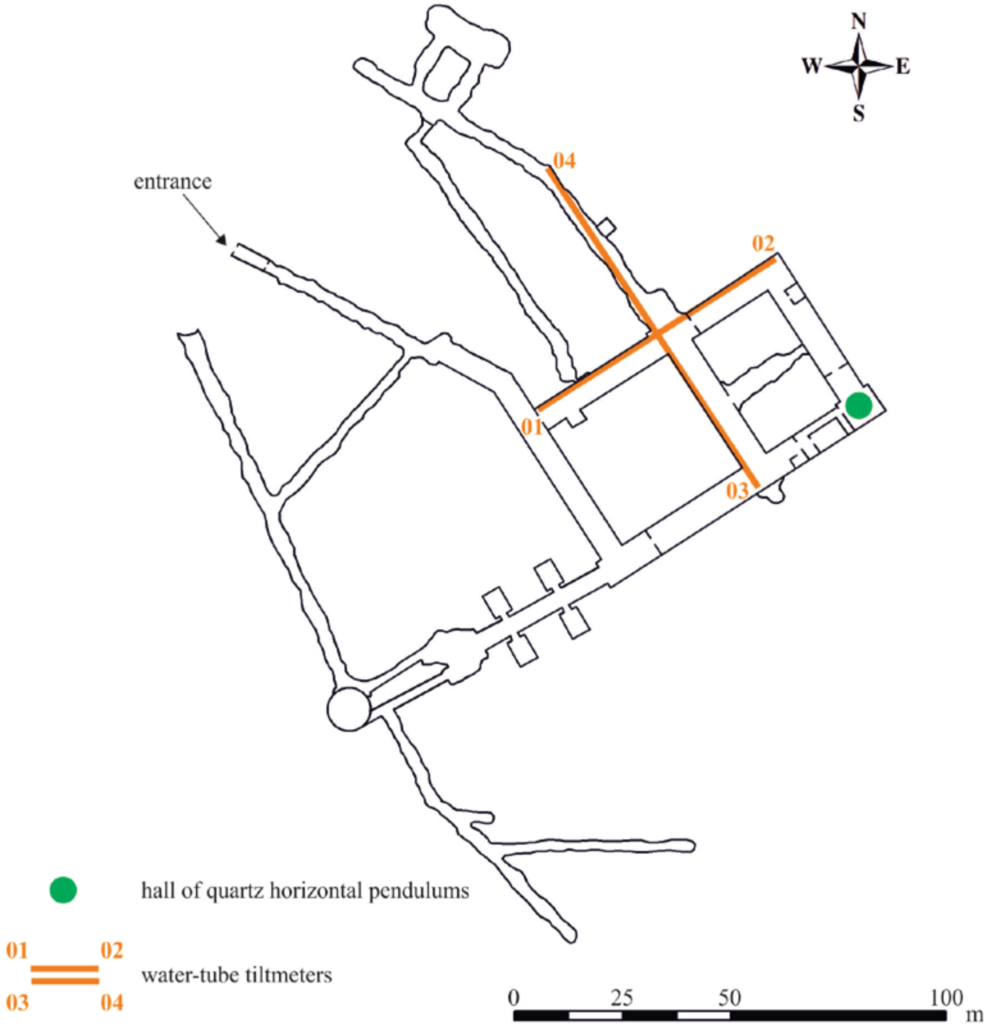


Fig. 2. Sketch-map of the underground excavations under the Książ Castle courtyard.

3 Indicators of recent geodynamic activity

Data on the effects of geodynamic activity in the Książ area are supplied by the GL measuring instruments. At first, they were quartz horizontal pendulums. The over 40-year continuous record of data indicates the presence of relatively short-term periods, when the pendulums relatively rapidly changed their measuring azimuths. This phenomenon was interpreted as being resulted from tilting of the rock massif (lithosphere fragment), on which the horizontal pendulums were installed, caused by relative displacement of tectonic nature [1]. Effects of geodynamic processes were confirmed in the Książ massif after the installation of subsequent instruments – water-tube tiltmeters. At present these instruments supply the most precise information in terms of quality and quantity on the short-term kinematic phenomena in the Książ massif.

3.1 Water-tube tiltmeter – composition and measuring principle

The water-tube tiltmeter is composed of two main elements: a hydrodynamic system (pipe), half-filled with water, and two interference gauges measuring the change of fluid level at its ends [2]. The instrument works on a principle that uses the hydrodynamic property of water attempting to attain hydrodynamic equilibrium [23]. When deformation effects occur, caused e.g. by Earth tides, symmetric changes of water level take place at the ends of the hydrodynamic system as a result of change of vertical. Using algorithms [3], the values of these changes are calculated to vertical movement. In the case of the GL at Książ, the hydrodynamic system (WT) is cut by several, recently active unconformity surfaces [5, 24].

3.2 Characteristics of the registered tectonic phenomena

The effects of kinematic phenomena during periods of increased activity in the Central Sudetes [25] are recorded as asymmetric changes of the signal representing water level oscillations at both ends of the water-tube tiltmeters. This asymmetry is caused by dislocation of blocks along unconformity surfaces, i.e. faults of the Książ massif [5]. Since their installation, the WT at Książ have registered several tens of phenomena with amplitudes several times exceeding tidal amplitudes (from 0.05 to 1.5 mm; Fig. 3). Moreover, these effects occurred during different intervals in the year and had different durations.

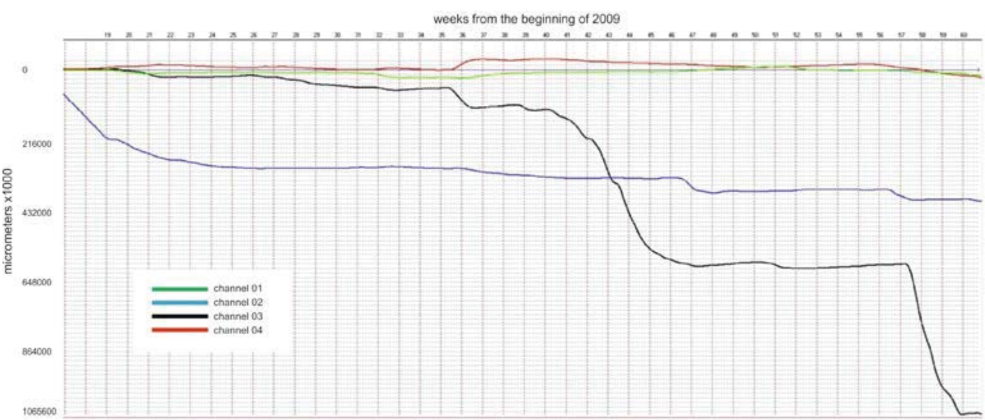


Fig. 3. Records from four measuring channels of water-tube tiltmeters from 2009.

4 Methodology of geological research

Mapping surveys in the Pełcznica river valley and the vicinity of Książ Castle were conducted in 2010–2017. They comprised the documentation of natural exposures and observations in the GL underground excavations. Structural measurements included bedding planes, fractures and faults. Particular attention was drawn on expressions of hydrothermal mineralization related with fault zones. Field measurements on the surface were made with application of Nomad Trimble and Columbus V-900 GPS receivers. Measurements of structural elements were marked on shaded relief maps based on the LiDAR digital terrain model (DTM), being the effect of aerial laser scanning conducted in Poland in 2011–2014. MicroDEM, Global Mapper 15.0 and Surfer (Golden Software) v. 9.0 software were used. The mapping materials and geological data were worked out and processed in the PUWG 1992 projection.

Measurements of dislocation zones, whose orientation is visible in the GL underground corridors, were made using geodetic techniques. An oriented total station with stabilized points of the horizontal control network was used for fault measurement. Spot heights locating each fault in the GL corridors (their coordinates) were also processed in the PUWG 1992 projection. The minimum number of spot heights necessary for determining the strike and dip of a fault zone is 3. Depending on the measurement conditions (complexity of the zone visible on the sidewalls and ceiling, presence of screens), the number of measured points varied from 3 to 9. As a result, a cloud of points representing spot heights along particular dislocation zones was obtained for each zone. During determination of directional parameters of each fault, an assumption was made that within the corridor cross-section the fault surface may roughly correspond to a plane. Accordingly, determination of the fault zone parameters was reduced to determining the plane equation in R^3. The plane equation was determined from the levelling of the set of spot heights at a condition of the minimum sum of squares of the distance of measured spot heights in each fault to the calculated plane [24]. The effect of these actions is presented in Fig. 4.

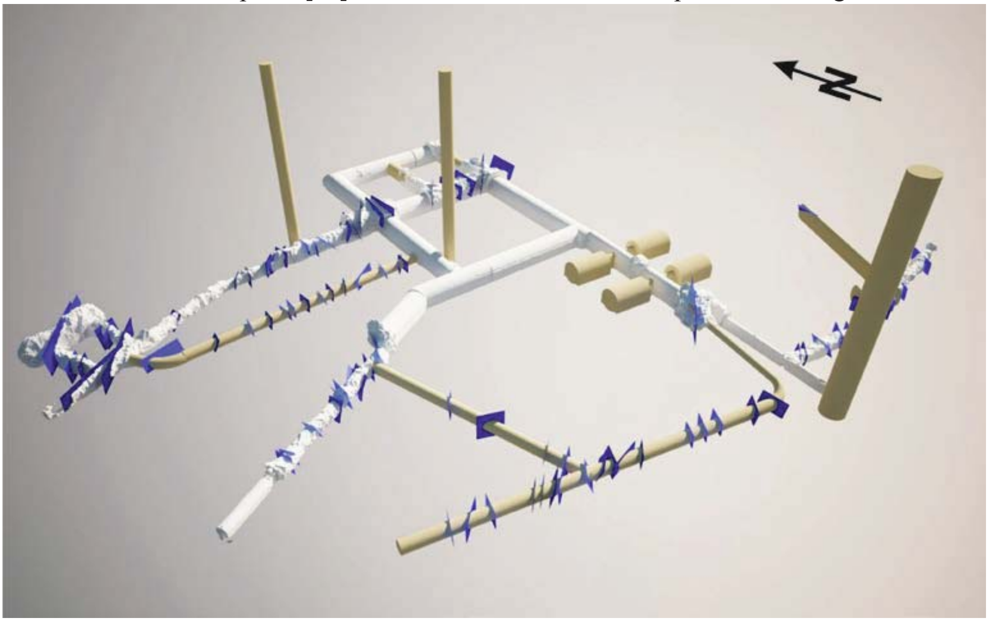


Fig. 4. Visualisation of the determined fault planes (blue) in the underground corridors of the Geodynamic Laboratory (grey and yellow).

5 Mapping survey in the Książ massif – results of structural analysis

Carboniferous deposits assigned to the Książ and Chwaliszów formations are well-exposed in the vicinity of Książ Castle. The Książ Formation mostly consists of coarse-grained, poorly-sorted conglomerates with single clasts that reach maximally up to 2 m in diameter. Most of the framework grains constitute gneisses, migmatites and granites with an admixture of sub-angular limestone clasts. In close vicinity of Książ Castle, conglomerates of the Książ Formation pass laterally to the north into deposits of the Chwaliszów Formation [9, 10], which consists of poorly-sorted, polymictic conglomerates interbedded with lithic sandstones. Deposits of the Książ and Chwaliszów formations that crop out in the Książ massif are strongly deformed (Figs. 5, 6). The bedding planes of the conglomerates and sandstones are W−E-trending and with steep dips (65−90º) to the N−NNW and S−SSE (Fig. 7A). This produces a visual effect of the presence of fold structures in the study area [9]. The investigated rocks are cut by joints of three main sets (j1, j2 and j3 respectively, cf. Fig. 7C, 7D), NW−SE and W−E-oriented dextral faults, and NE−SW-oriented sinistral faults (Fig. 7B). Numerous minor (secondary) fault-related structures were documented. They included mesostructural kinematic indicators [26] associated with brittle and strike-slip tectonics. Slickensides, grooves, hackles, striated ridges, low-angle R (Riedel) shears, *en echelon* cracks and high-angle antithetic R' shears were measured and documented (Fig. 6). Numerous extensional, NE−SW-trending extensional fractures associated with faults are filled with clay gouge, sometimes calcitified and impregnated with hematite mineralisation. This mineralisation is probably linked with the youngest stage of faulting. The measurements were plotted using a stereographic projection on the lower hemisphere.

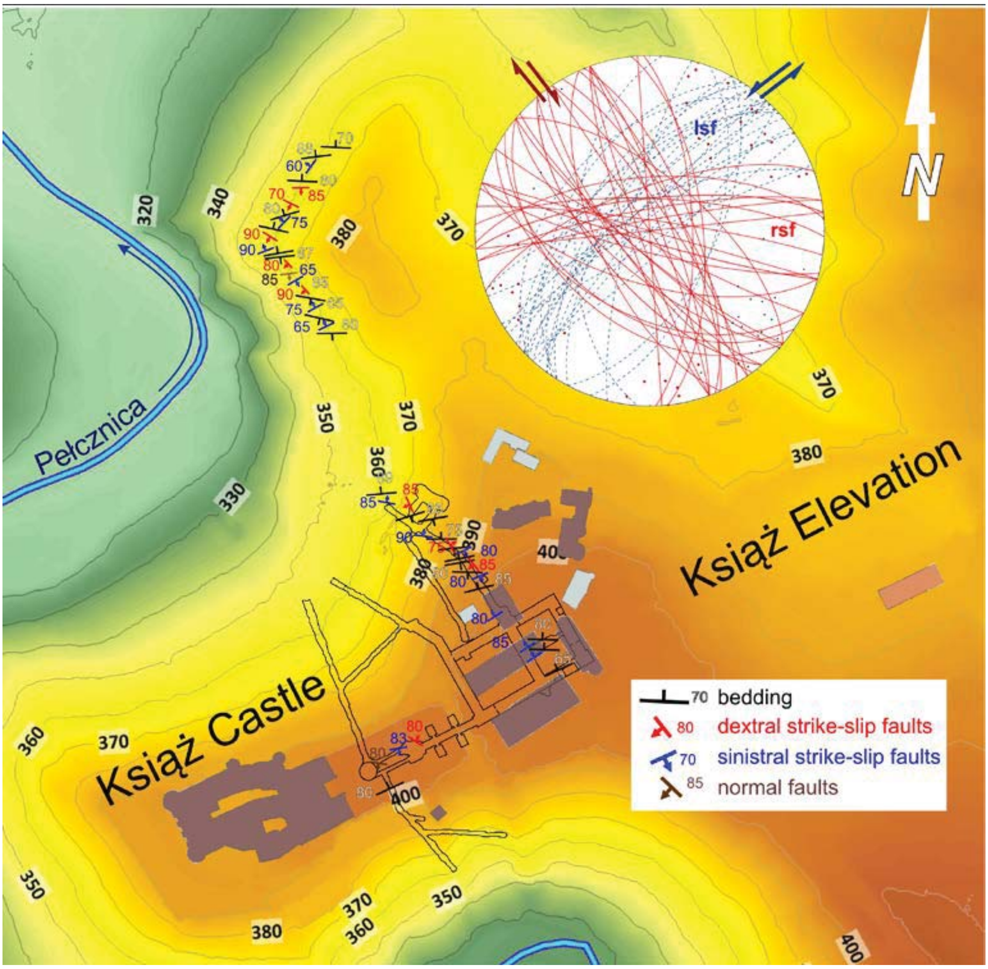
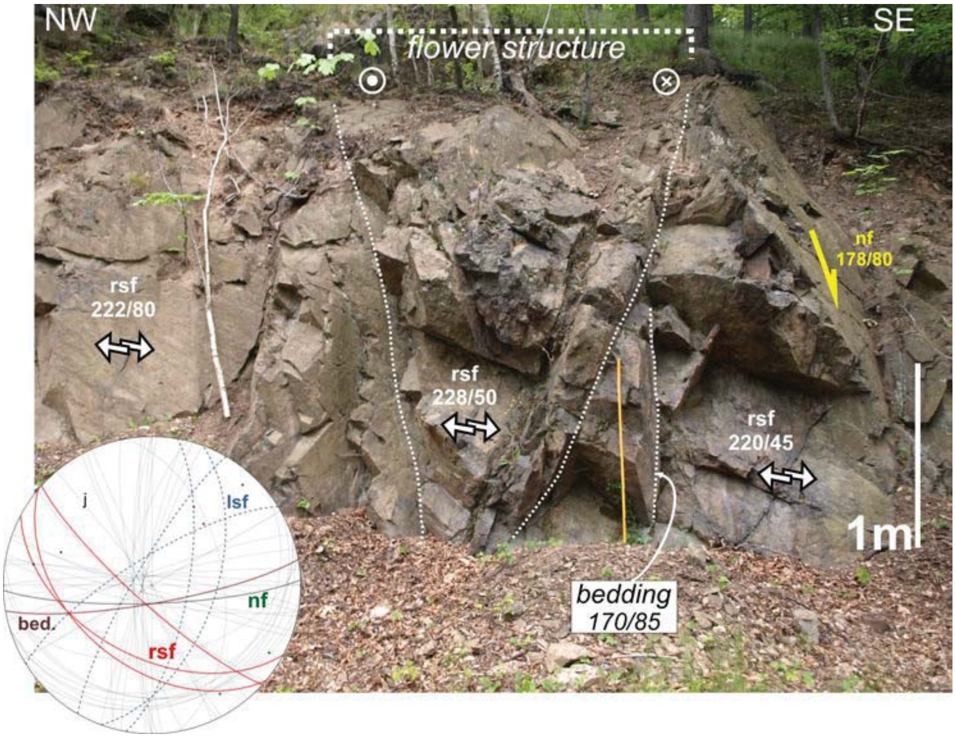


Fig. 5. Map showing the orientation of bedding planes in the deposits of the Książ Formation, and of the main fault structures in the Książ massif. Upper right diagram (Schmidt net, lower hemisphere) presents the orientation of the planes of dextral strike-slip faults (rsf, red) and sinistral strike-slip faults (lsf, blue), determined in the underground excavations of Książ Castle and in exposures on the surface.



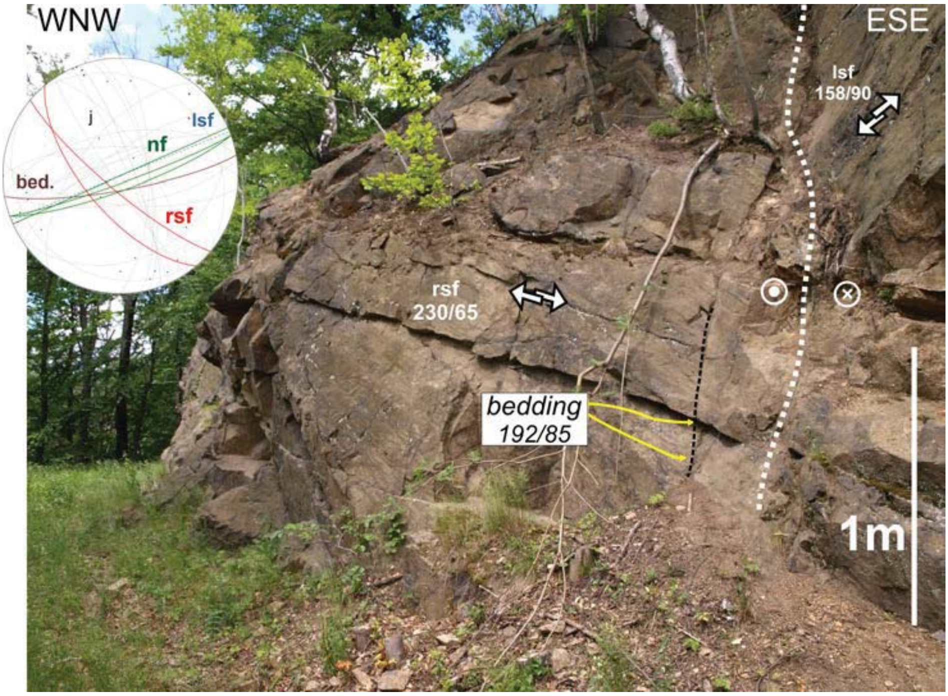


Fig. 6. Exposures of the Książ Formation to the north of Książ Castle. Explanations: bed. - bedding, j – joints, nf – normal faults. For other explanations see Fig. 5.

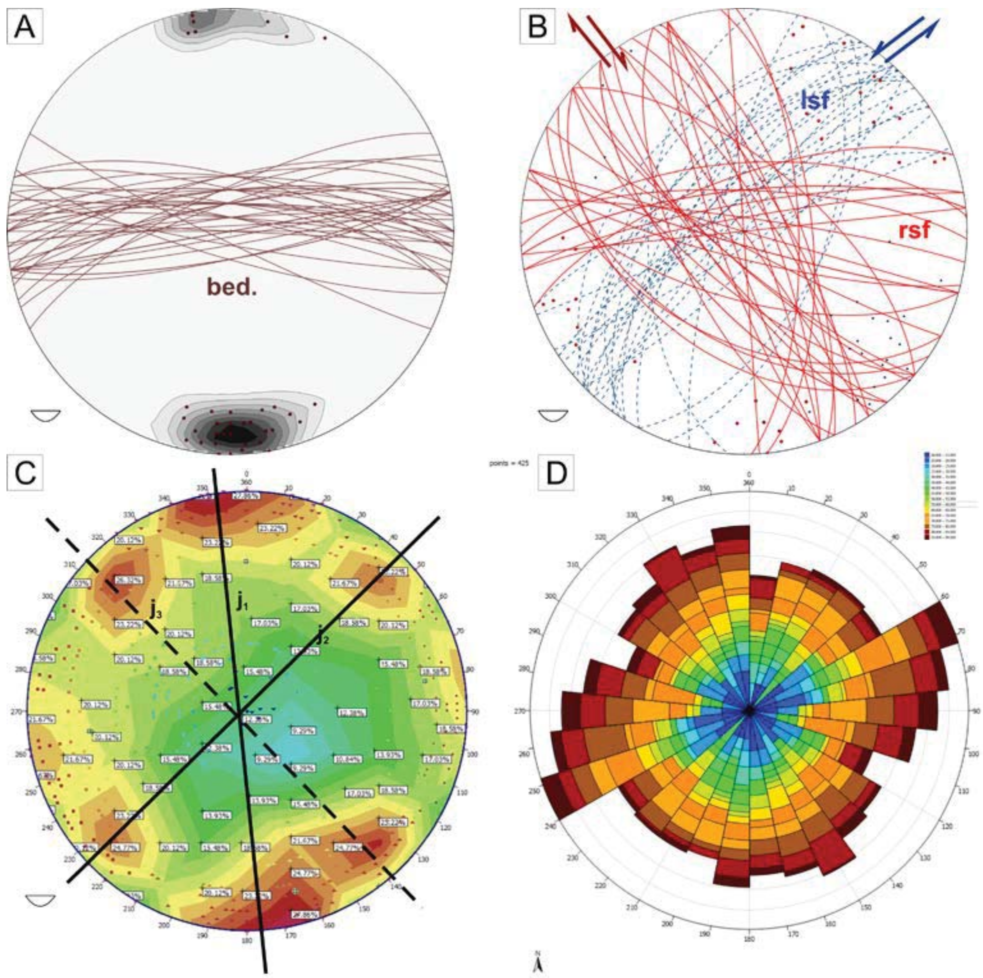


Fig. 7. Diagram showing the orientation of bedding planes (A; Schmidt net, lower hemisphere), strike-slip faults (B), joint fractures j1, j2, j3 (C), and composite rosette diagram of fractures in the Książ massif (520 measurements). Colour scale corresponds to the percentage contribution of particular classes of the fracture plane dip angles. For other explanations see Figs. 5, 6.

5 Discussion of the results

The presented investigations indicate the prevalence of oblique-slip and dip-slip faults in the formation of the central part of the Świebodzice Unit, at an insignificant contribution of thrusts and reverse faults. This conclusion is supported by morphometric analyses and sedimentological studies conducted in the ŚU by Wojewoda [7, 10]. Although our studies confirm the general kinematic scheme presented for the ŚU by Porębski [27] (simple, dextral shear along the bounding W–E and NW–SE-oriented dislocations), there is no evidence for the change of tectonic regime at the Frasnian to Famennian/early Tournaisian boundary from transtension to transpression, especially in relation to the new age-determinations for the deposits filling the Świebodzice basin [10]. Porębski [27] pointed to the significant role of the Intra-Sudetic Fault, interpreted as the major strike-slip zone controlling the Świebodzice basin, which did not find confirmation in mapping surveys.

The prevalence of strike-slip and normal zones points to the passive evolution of the central part of the ŚU (Książ elevation), mainly linked with transtension, and in consequence with the formation of an intra-basinal high in the area of the present day vicinity of Książ Castle. The process of formation of morphological and structural intra-basinal elevations within pull-apart basins was documented in experiments [28] and postulated for the ŚU by Wojewoda [7]. The main dislocations of the Książ massif are sinistral, NE–SW-oriented strike-slip faults, interpreted here as high-angle R' faults, complementary to the bounding dislocations of the ŚU. Sinistral strike-slip faults are reflected in the structural anomalies of the Pełcznica river valley determined during mapping surveys and DTM LiDAR morphometric analyses [10]. Although the determination of the exact time of the Pełcznica valley formation and of the largest activity of strike-slip and normal faults is difficult based on structural analyses, this process was most likely related to the stage of the last tectonic inversion (Neogene) in the Sudetes. Furthermore, the results of geodetic measurements indicate the recent tectonic activity of this area [1-4]. This activity was induced by sharp movement of the fault walls of both strike-slip and normal faults [25]. At the same time, the influence of rock massif collapse was also eliminated [29], as well as the effects of surface deformation of areas linked with former mining activity [30, 31] in the neighbouring areas (Wałbrzych Coal Basin).

6 Conclusions

Geodetic and geological investigations conducted in the Geodynamic Laboratory at Książ Castle supply new data on the displacement mechanism of blocks of the rock massif, on which the castle complex is built. Results of structural analyses and kinematic indicators recognized within the fault structures confirm the general kinematic trend proposed for the central part of the Świebodzice Unit by Wojewoda [7, 10]. Furthermore, field investigations conducted on the surface and in the underground excavations of Książ Castle confirm that the currently registered tectonic phenomena result from displacement along the dislocation zones that were active also in the past. These dislocations contributed to the formation of the present-day form of the Pełcznica river gorge, modified the channel course of this river, and influenced the present-day seismic activity of the area.

Noteworthy, indicators of the neotectonic activity are dangerous for the stability of the construction elements of the Książ Castle complex, recently deweloping its damages. Analysis of the above presented 3D model of the Książ massif structure confirms that part of the main, currently active dislocations zones run directly below the castle complex. Further geodetic surveys and structural investigations will aim at recognizing dislocation zones that may pose potential hazard to the Książ Castle.

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