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Prehistoric flint mine detection by airborne laser scanning (ALS). Experiences from Poland 2011–2015

Janusz BUDZISZEWSKI, Michał JAKUBCZAK,
Katarzyna RADZISZEWSKA & Michał SZUBSKI

Abstract

Research on flint mining in Poland has a long history. It started at the beginning of the twentieth century through the pioneering research by S. Krukowski and J. Samsonowicz. Over the years, successive generations of Polish researchers continued investigations of prehistoric extraction and distribution of rich siliceous deposits in the whole country. The advance of new methods of remote sensing opened the way to new research in this topic. The Institute of Archaeology of the University of Cardinal Stefan Wyszyński in Warsaw since 2011 has been researching prehistoric flint mining using airborne laser scanning (ALS, LiDAR). Within the projects, conducted in the years 2011 - 2015, we tested nondestructively a number of different mines from a chronological and geological point of view. At this time we have developed a research methodology, allowing remote sensing and verification of new sites and also increase our knowledge about mines already known.

Keywords: Flint mining, remote sensing, ALS, LiDAR.

Résumé

*Les recherches sur les minières à silex ont une longue histoire en Pologne. Elles ont débuté au début du XX*ème *siècle avec les recherches pionnières de S. Krukowski et de J. Samsonowicz. Au cours du temps, plusieurs générations de chercheurs polonais ont perpétué les recherches sur les sites d'extraction préhistoriques, ainsi que sur la répartition des roches siliceuses de bonne qualité, sur l'ensemble du territoire. Les avancées des nouvelles méthodes de télédétection ont ouvert la voie à de nouvelles recherches dans ce domaine. L'Institut d'Archéologie de l'Université Cardinal Stefan Wyszyński à Varsovie, a développé, depuis 2011, un projet de recherches sur les minières à silex préhistoriques en utilisant la détection laser aéroportée (airborne laser scanning, LiDAR). Dans ce projet qui s'est déroulé entre 2011 et 2015, il a donc été possible de travailler de manière non destructive sur différents sites miniers, sur les aspects géologiques et chronologiques. Aujourd'hui, nous avons développé une méthodologie qui nous permet la télédétection et la vérification de nouveaux sites, tout en approfondissant notre connaissance des sites déjà connus.*

***Mots-clés** : exploitation minière du silex, télédétection, ALS, LiDAR.*

1. Introduction

The first prehistoric flint mine in Poland was discovered by J. Samsonowicz and S. W. Krukowski in September 1921. This was the site 'Borownia' in Ruda Kościelna, Ostrowiec Świętokrzyski district. However, the explorers were not able to properly interpret all observed facts and found the site to be remnants of rich flint workshop (KRUKOWSKI, 1921, p. 162-163, fig. 10). A year later – July 19, 1922 – J. Samsonowicz discovered Neolithic mines of banded flint in Krzemionki, Ostrowiec Świętokrzyski district. This object, which was destroyed by limestone mining, enabled the observation of not only surface materials or relief of the spoil tips, but also underground mining. The observations made by J. Samsonowicz made it possible to reinterpret the site 'Borownia' discovered a year earlier and consider it as a remnant of prehistoric flint mine (SAMSONOWICZ, 1923, p. 23). The great and well-preserved site in Krzemionki in the interwar period was a centre of research on prehistoric flint mining in Polish Lands. S. Krukowski, who conducted his research at that time, noted that the relation between the types of underground excavation and mining heaps is so large, that a specific type of heap enables to infer the characteristics of the corresponding underground (KRUKOWSKI, 1939, p. 12, 27-33). However, creating accurate plans of large site of varied terrain relief was beyond the financial and organisational capacity.

2. History of topographic survey at flint mines in Poland

The first topographic plan of prehistoric flint mine was made in 1940 by W. Zelkewicz and T. Żurowski, under the supervision of S. Krukowski, in the area of much smaller site in range Zbuczi in the village of Łazariwka, located in the upper Dniester basin, in the present-day western Ukraine. The 1:1000 scale map, with a contour interval of half a metre, covered the whole site about 230 metres long and about 16 metres wide (SYTNIK, 2014). Unfortunately, this map has disappeared into war containment and the relief of the site has never been the subject of detailed analyses.

The contour plan of 'Krzemionki' mining field on a scale of 1:200 with a contour interval of 25 cm was created in 1947-1948 by the Councillor of the Central Office of National Measurements Ing. R. Gizowski (SAWICKI, 1948, p. 123). That plan was so large and complicated that was plotted only in 1953. Finally, it consisted of 45 sheets in a format close to B2, with 2480 pits, recognised as remnants of prehistoric shafts. It turned out, however, that the amount of information carried by such plan surpassed the analytical capabilities of the researchers. The idea of its detailed analysis crystallised only in the eighties of the last century (BUDZISZEWSKI, 1990). Such a task was undertaken by W. Borkowski in his doctoral dissertation in 1993 and published two years later (BORKOWSKI, 1995). At the beginning of the nineties, the researcher realised another similar project. In the newly discovered mine of erratic flints 'Rybniki-Krzemianka' in Kopisko, Białystok district, a detailed altitude situational plan of the site was created and analysed (BORKOWSKI, 2005).

The time-consuming nature of this type of work, with the simultaneous analytical limitations of poorly computerised level of technology, caused similar studies to be discontinued over the next dozen years. Back to them made only a breakthrough due to the development of airborne laser scanning (ALS, LiDAR).

3. Airborne laser scanning (ALS) as a new tool to investigate flint mines relief

Airborne laser scanning (ALS, LiDAR) is a method of acquiring spatial data using laser measurements for remote sensing and analysis of objects with preserved terrain relief. In archaeology this method is used recently, the first projects of this type date back to 2000. In recent years, with the development of technology and increasingly cheaper access to data, it has become the leading, non invasive method of archaeological research in wooden areas (CRUTCHLEY & CROW, 2010; DONEUS & BRIESE, 2011; HOLATA & PLAZAK, 2013; BANASZEK, 2015).

The ALS technology utilises interoperable devices – a laser beam emitter, a laser beam distribution module, a reflections detector and a GPS receiver as well as gyroscopic device to determine pitch, roll and heading of the plane correlated with GPS base station to determine the exact position of the scanner. This makes it possible to calculate the location in which the laser beam bounced off the obstacle surface and save it in the XYZ space coordinate system. As a result of post processing, a cloud of all points registered by the scanner is obtained (KURCZYŃSKI, 2015, p. 59-60). The next step is the point classification. It allows extracting the reflections that have reached the ground. In the case of archaeology, this is an extremely important element of the process, as part of the information on landform can be lost, or even false objects can be generated during the classification (OPITZ, 2016, p. 37-44).

On the basis of classified point cloud, a digital terrain model (DTM) is generated. This is a numerical representation of the terrain surface that allows determining the height of each point upon the topographic surface. The model can be generated in two ways – as a grid of squares (GRID) and as irregular triangles (TIN). In the case of the TIN model, the points are not subjected to interpolation –

so it is more 'real' land mapping (BORKOWSKI, 2015, p. 110-111). Archaeological analyses use different DTM visualisation methods. Apart from the standard hillshading, which involves lighting the 3D model from any chosen direction, other algorithms are also used. They represent a terrain relief illuminated from multiple directions at the same time or completely independent of light, using geometric relationships between adjacent measurements (KOKALJ & HESSE, 2017).

In order to know the quality of a scan, the most commonly used is the nominal number of measurements per square metre. As our current experience shows, four points are enough for the archaeological application. However, this problem is much more complex. The most important is the number of measurements that have reach the ground surface. It depends on the scan parameters and the type of forest cover. As the scan is made more perpendicular to the surface, the greater is the penetration of the laser. However, reducing the scan angle increases its price because more flights are required. Typically, a scanning angle of 20 to 30 degrees from the vertical is used. Another important value is the size of the laser spot - the greater is the better for the penetration of the plant cover. Later, however, a terrain model with a pixel size smaller than the spot diameter used for scanning cannot be generated. A scan with a speckle diameter of about 40 cm is considered as a good compromise. In addition to scanning parameters, a vegetative cover also has impact on the data quality. Therefore, its term should be chosen in such a way that the least possible obstacles appear in the way of the laser beam. In Central Europe, it is early spring or eventually late autumn.

The additional information that can be obtained from the ALS data is the laser return beam intensity (Fig. 1). This method is applicable

Fig. 1– Chocolate flint mining field 'Przyjaźń' in Rzeczków, Radom district. Comparison of digital terrain model (a) and visualisation showing intensity of laser return beam (b) on the site with a ploughed surface. The line is indicating the area where flint artefacts are present.

for open area analysis, also for remote sensing of archaeological objects, similar to vegetative changes in aerial photography (CHALLIS *et al.*, 2011). Unfortunately, in spite of good efficiency in the analysis of geological structures, this method is not effective for archaeological sites (BENNET, 2014, p. 31- 32).

In the realities of Polish archaeology, besides costly commissioned flights, the data provided under the governmental project IT System of the Country's Protection Against Extreme Hazards (ISOK) may be used. The primary goal of this project, co-funded by the state and the European Union, was to create a flood risk map based on precision altitude data obtained by airborne laser scanning (MAŚLANKA & WĘŻYK, 2015). However, the interest in the data obtained during it turned out to be so great that in the course of implementation it was decided to extend it and cover the entire territory of the country. Scan quality is 12 points per square metre in urbanised areas and four or six points per square metre in other areas. Most of Poland's surface, including forested areas of flint outcrops, are scanned in the standard with parameters: ≥ 4 points per m², scanning angle ≤ 25°, laser beam spot diameter ≤ 0.5 m (KURCZYŃSKI *et al.*, 2015, p. 31-32). Data provided within the ISOK project can be purchased (or obtained free for educational and scientific purposes) in the form of a LAS point cloud that can be further processed. By the middle of 2017 ALS data for the area of 92 % of Poland was made available in this way (Fig. 2). The data derived from the ISOK program is available in the public domain: http://mapy.geoportal.gov.pl/wss/service/WMTS/guest/wmts/ISOK - a raster image of the simplified DTM of the area of Poland, allowing for the initial insight into micro-topography of archaeological sites before taking any fieldwork.

Fig. 2 – Location of surveyed areas of the prehistoric flint mining conducted by the Institute of Archaeology of the University of Cardinal Stefan Wyszyński in Warsaw in the years 2011-2015, in the background range of available airborne laser data provided by the ISOK project. Circle – grant project (ordered scans); rhomb - self project (ISOK data).

4. ALS SURVEY OF THE POLISH FLINT MINES

Taking advantage of emerging opportunities at the Institute of Archaeology of the Cardinal Stefan Wyszyński University in Warsaw, a number of tasks were implemented in the years 2011-2015 using the effects of airborne laser scanning. First – in 2011 – was examined the outcrop of banded flints in the Central Poland over the lower Kamienna River, under the grant of the Ministry of Culture and National Heritage (MKiDN): Research of the prehistoric flint mines using LiDAR. In 2013 another grant of the MKiDN was completed: Cataloguing of prehistoric flint mines in different environmental conditions. In its framework an area of chocolate flint exploitation from Upper Jurassic limestone of Central Poland and Cretaceous erratic flint from Quaternary moraines in north-eastern Poland (Knyszyn Forest) were compared. Scanning in the above projects was performed by the Polish company MGGP Aero. Remote sensing measurements were made using the Lite Mapper 68000i system. Scanning standards assumed a sample density of 4 pts/m² with the accuracy of altitude measurement ≤ 15 cm and continuous reflection readings for four ranges. On the basis of such data, the digital terrain model (DTM) in GRID ASCI format was created, at a resolution of 0.5 m and altitude accuracy of h ≤ ± 0.25 m, as well as digital surface model (DSM) of the same parameters. In the next two years, as a part of research were analysed the remnants of early modern Jurassic flint mining in the vicinity of Cracow and traces of sedimentary siliceous rocks (siliceous marls) exploitation in Cergowa, Carpathian Mountains. In both cases the basis of the study was the data obtained from the ISOK program. In 2015, an attempt was also made to carry out a detailed analysis of the topography of the 'Borownia' banded flint mining field. All these works allow for an initial assessment of the capabilities of airborne laser scanning for the studies on prehistoric flint mining.

It turned out, that the ALS digital terrain model (DTM) identifies many geological structures. While the possibility of observing the course of rocks in the Carpathians is easy to account, it is difficult to explain the fact that DTM also maps the course of layers of Jurassic limestone on the north-eastern margin of the Świętokrzyskie Mountains. Jurassic rocks are covered there by a thin (1-2 m) layer of Quaternary formations, which should result in ground levelling and hide the eroded rock surface. Nevertheless, there are slight patterns of successive limestone layers of varying resistance, unnoticeable on the surface but perfectly clear in the micromorphology of the terrain (Fig. 3). In this situation it is easy to track the layers containing flints and look for traces of their prehistoric exploitation. It is also easy to record all the disturbances in the course of layers that reveal even minor tectonic faults. This allows to clarify and to verify a number of previous views on the geological structure of this area. For example, it turned out that the detailed reconstruction of the geological structure of the 'Krzemionki' reserve area (MICHNIAK, 1992; BORKOWSKI, 1995, p. 41-53) resulting from the research in early nineties, in many crucial points is quite erroneous. All of the faults slitting the mining field that were supposed to have meridian run actually run latitudinal.

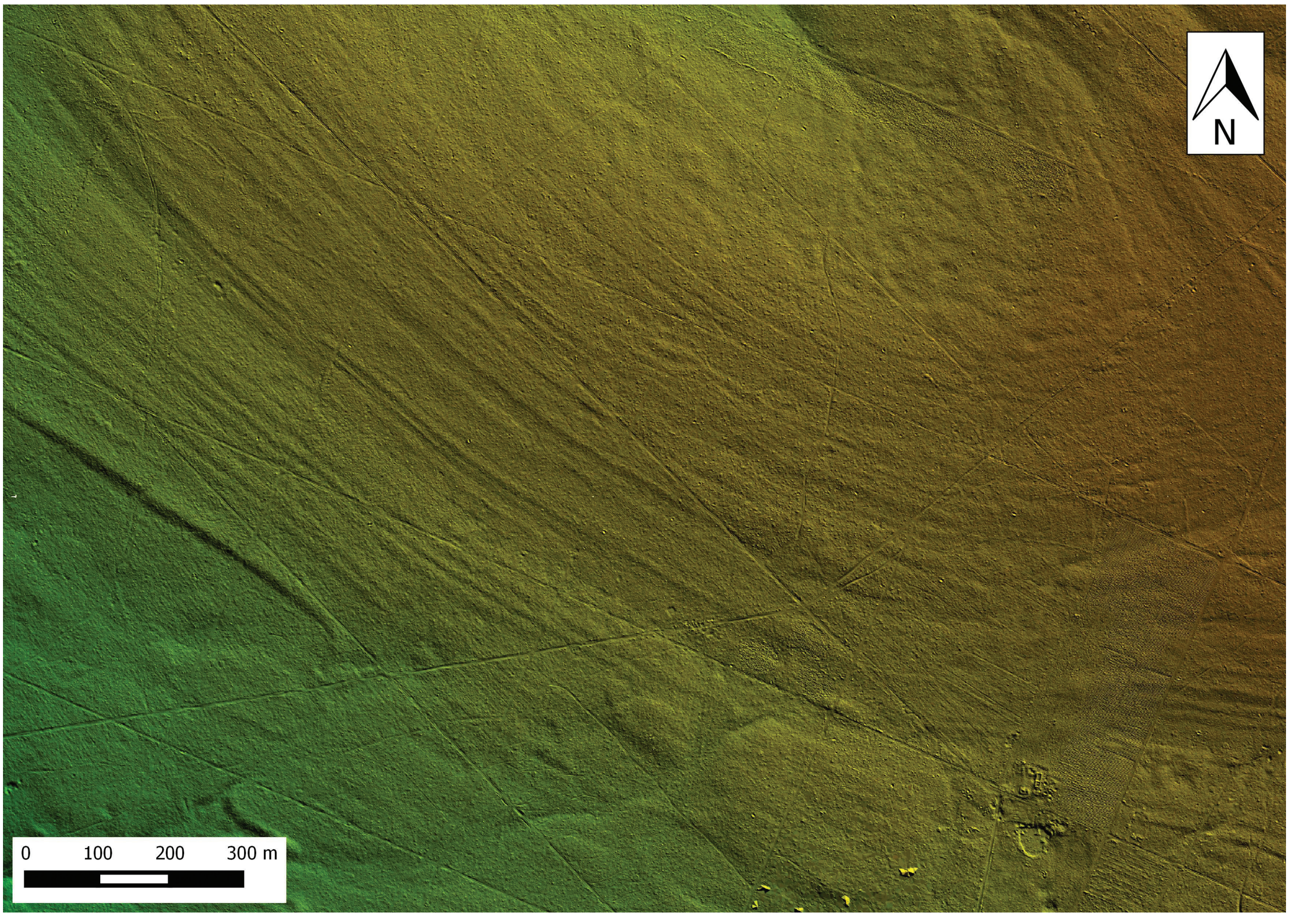

Fig. 3 – Digital terrain model of south-eastern part of Magonie-Folwarczysko basin showing the Oxfordian and Kimmeridgian limestone layers course containing banded and chocolate flints.

The data on geological structure was obtained not only from the analysis of surface microrelief of the area. They also appear in the visualisation of reflection intensity. For example, the anomalies observed in the vicinity of the 'Zele' mining field of chocolate flints in Wierzbica, Radom district, look like Pleistocene polygonal structures.

The digital terrain model obtained by airborne laser scanning allows identification of various types of flint mining remains. The simplest to interpret are large, isolated mines, such as the chamber mines on 'Krzemionki' mining field (MIGAL, 1997, p. 318-319, 322-324). They have round heaps reaching up to one metre in height and scattering up to over a dozen metres from the centre of the shafts (Fig. 4). Sometimes they are not omnipresent, but consist of two half-shed heaps of different heights. Several of such objects were excavated (ŻUROWSKI, 1962; BORKOWSKI & MIGAL, 1988; BĄBEL, 2015, p. 63-86), therefore we know that the heap size is limited because most of the debris was deposited in the mine's underground. Generally, the relief of this type of objects is similar to the medieval and modern metal ore mines (CASAGRANDE, 2013; CEMBRZYŃSKI & LEGUT-PINTAL, 2014; KAPTUR, 2014).

Equally obvious is the form of small quarries facing the slope, where the heaps were naturally dropped down. Such objects were identified in the DTM of the north-eastern part of the mining field of banded flint 'Skałecznica Duża' in Teofilów, Opatów district (JAKUBCZAK, 2012). They range from a few to over a dozen metres wide, with niches of less than one metre deep. Several similar objects have also been identified to the north-western extremity

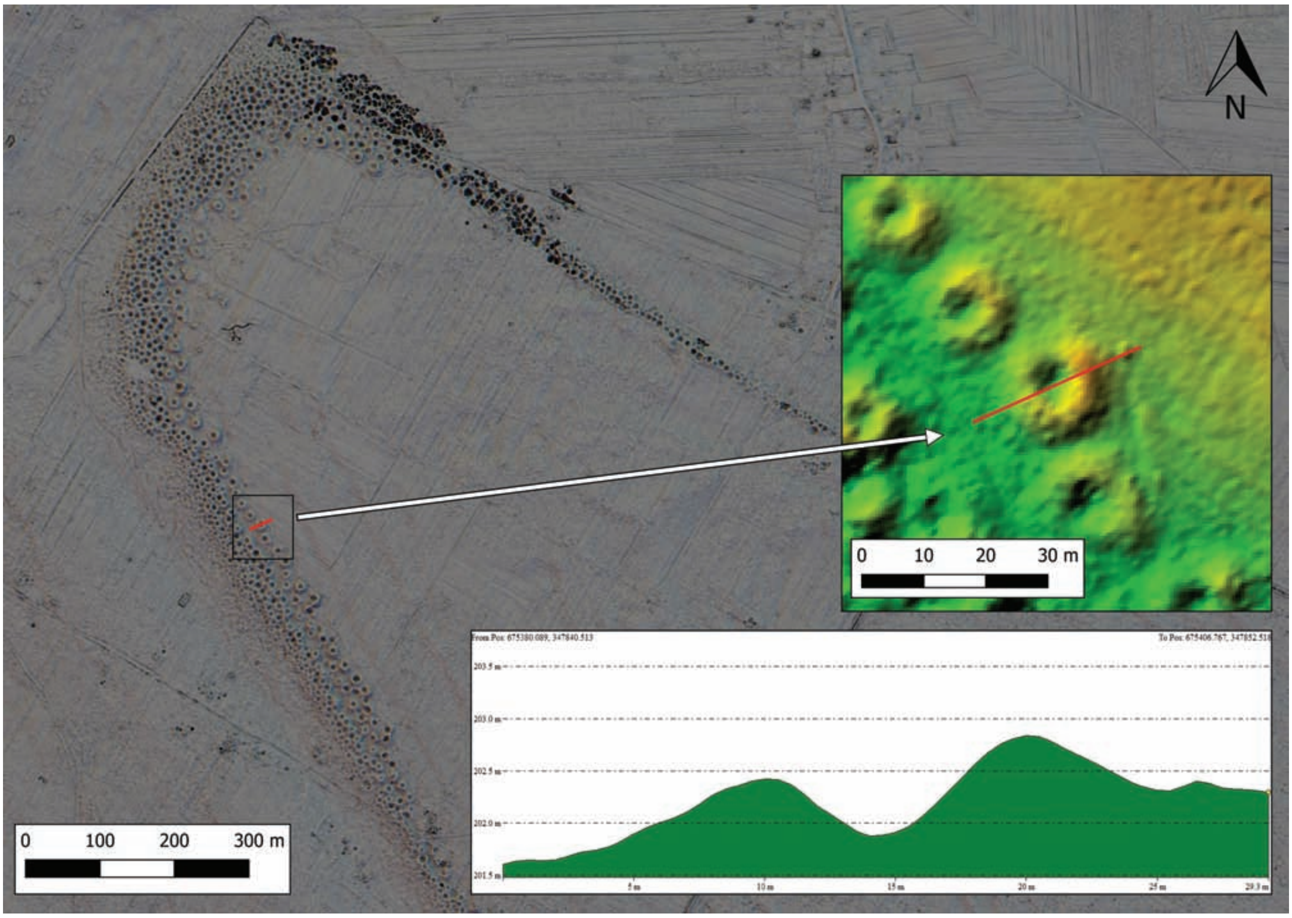

Fig. 4 – Digital terrain model of banded flint mining field 'Krzemionki', Ostrowiec Świętokrzyski district. Visualisation of chamber mines surface relief.

of the Rybniki-Krzemianka mining field in Kopisk, Białystok district, where Cretaceous flints from Quaternary moraine were exploited (BORKOWSKI, 2005; SZUBSKI, 2016). Analogous objects, but of a much more pronounced form, are also known from the modern Jurassic Cracow flint quarries, mining for the purposes of gunflint production in Mników (Fig. 5) and the northern rim of Zelków, Krakow district.

With a completely different relief we are dealing on sites related to the exploitation of banded flint in mines with large niches or in chamber and pillar mines (MIGAL, 1997, p. 317-323). We know them from the sites of 'Krzemionki', 'Borownia' and 'Korycizna', Ostrowiec Świętokrzyski district. At the first of these sites, several of such objects were excavated (SAŁACIŃSKI, 1988; BĄBEL, 2015, p. 56-66), so we have come to know the relation between the method of exploitation and surface relief. The heaps of mines create here a relatively high, several-centimetre embankment, which depicts the depressions of particular shafts (Fig. 6). Such image is very impressive, but not easy to explain in detail, because many of the observed hollows raise doubts whether they are the remnants of shafts or accidental forms at the contact of several heaps. There is also no certainty that heaps do not mask some of the older shafts.

From the outcrops of the banded flint we know one more kind of surface micromorphology of the prehistoric flint mine. These are low, several dozen centimetres in height embankments, stranded out from the environment like scabs. They have a weak surface relief, in which it is impossible to separate the depressions of particular mining objects. Such relief characterises sites 'Krunio' (Fig. 7)

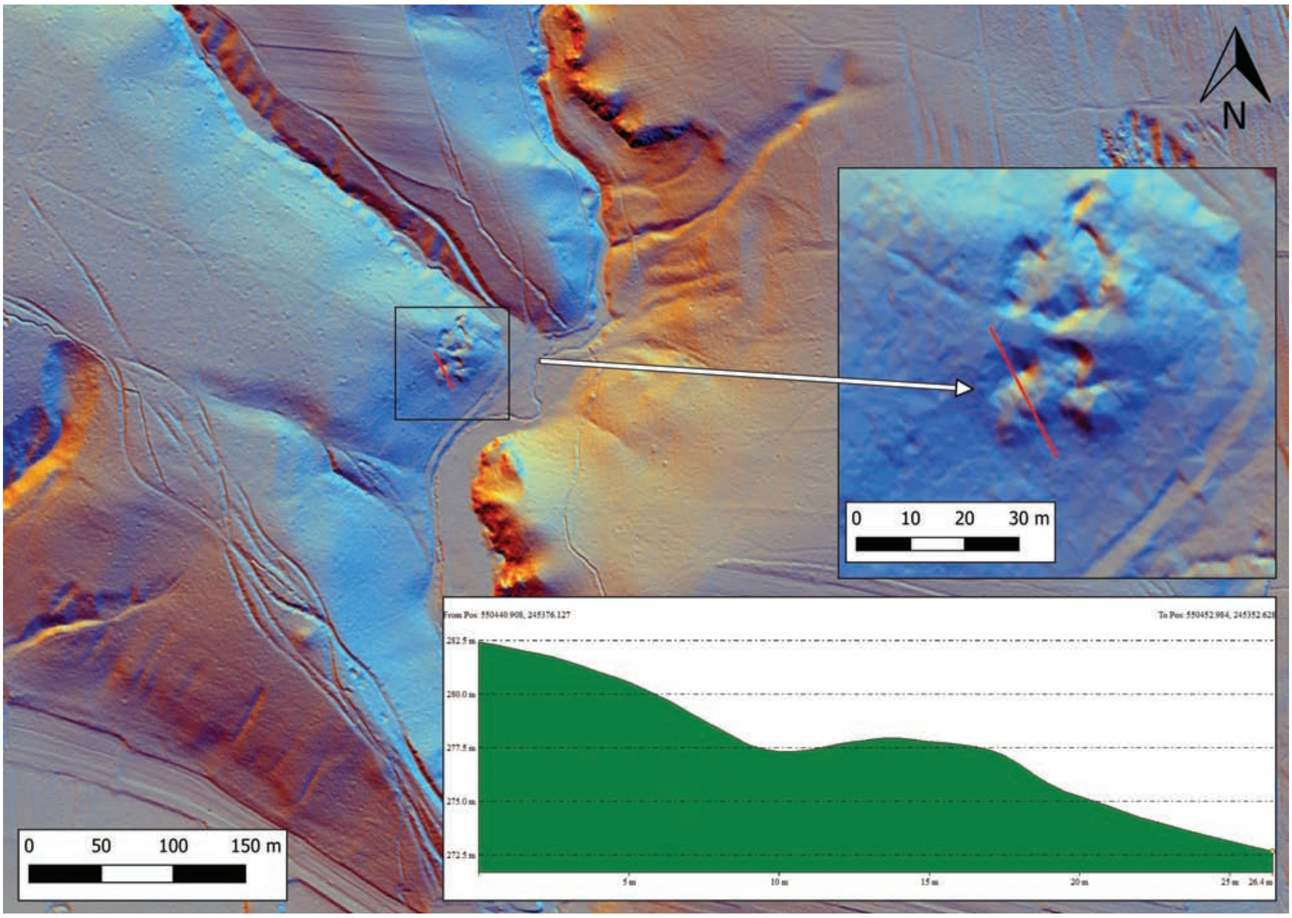

Fig. 5 – Digital terrain model of modern Jurassic Cracow flint quarries in Mników, Kraków district. Visualisation of present surface relief with modest quarries.

and 'Nowa' in the Ostrowiec Świętokrzyski district. It is impossible to say today whether this relief is the result of some specific method of exploitation, local deposit conditions or subsequent damage by the agriculture.

It seems that the most frequently observed anthropomorphic relief on the sites related to the flint sourcing is the surface of extremely varied but not very deep relief. Among local hills and hollows, regular circular depressions appear as if they are the scars of the youngest generation of objects. However, for most areas, a digital terrain model generated by scanning at a resolution of four dots per square metre does not allow for reliable localisation of particular mines, and it may not be possible even with more accurate plans. Such relief was probably created during the exploitation of raw materials in small pit mines. We know it from sites with very different geological conditions. Both, from the sites related to the exploitation of flints from Quaternary moraines (SZUBSKI, 2016; Fig. 8), as well as banded flint from Jurassic limestone in most of the 'Skałecznica Duża' area (JAKUBCZAK, 2012) or Jurassic flint near Kraków in early modern mines in Karniowice, Kraków district.

The types of anthropogenic relief of flint mines surface identified in research practice of Institute of Archaeology of Cardinal Stefan Wyszyński University in Warsaw certainly do not exhaust all possibilities. The only published analyses of this type of sites, conducted using airborne laser scanning imaging in the south-western Pyrenees in Spain reveal a picture unknown from Polish sites (TARRIŃO *et al.*, 2011; ORÚE BELTRÁN DE HEREDIA, 2013; TARRIŃO *et al.*, 2014). It can therefore be presumed that the above-mentioned catalogue will have to be supplemented many times.

It is important to note that the anomalies observed in the digital terrain model must

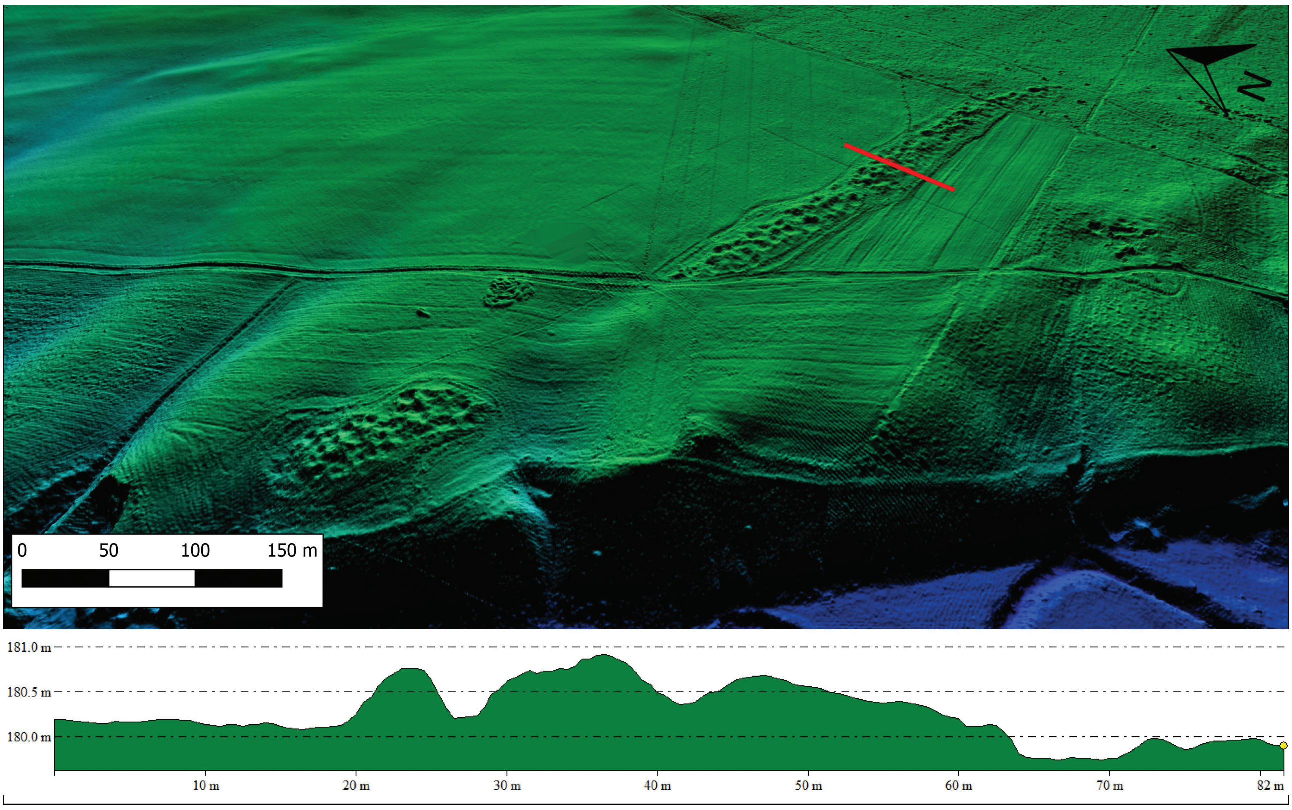

Fig. 6 – Digital terrain model of banded flint mining field 'Borownia' in Ruda Kościelna, Ostrowiec Świętokrzyski district. 3D visualisation of prehistoric flint mines surface relief.

always be verified in the field. Objects with a very similar surface microrelief may be formed not only by the use of flint sourcing, but also by the activity of animals. Similar in form are also, for example, the complexes of badger sets. Luckily, they are usually smaller in size than the prehistoric mining sites. However, from the Knyszyn Forest in north-eastern Poland a complex of badger sets of 50 x 25 metres is known.

An additional difficulty in identifying the relief of the prehistoric mining sites is that we must take into account not only the differences arising from various types of mining activity or deposit conditions, but also differences in the degree of damage caused by later economic activity, mainly agricultural. Observations made during our work revealed that anthropogenic relief is impermanent and easily can be totally destroyed. By far the most known sites related to the exploitation of flint show a relief completely aligned with later ploughing!

Reflecting on the combination of the flint mining sites relief images and its difference with the remnants of other stone materials exploitation, we must note that in the flint mines a small amount of material is obtained in relation to the size of the work being carried out. While as a result of the exploitation of sand, clay or limestone there are distinct niches in exhausted deposits, in the case of flint we rather observe the increase in volume of heaps resulting from the fragmentation of gangue. Certainly, the remains of the siliceous layer rocks exploitation will be different. Some ideas can result from the studies on Neolithic exploitation of metabasalts, conducted in recent years in the Jizera Mountains in Czech Republic (PROSTŘEDNIK *et al.*, 2005; ŠIDA *et al.*, 2013; ŠIDA, 2014).

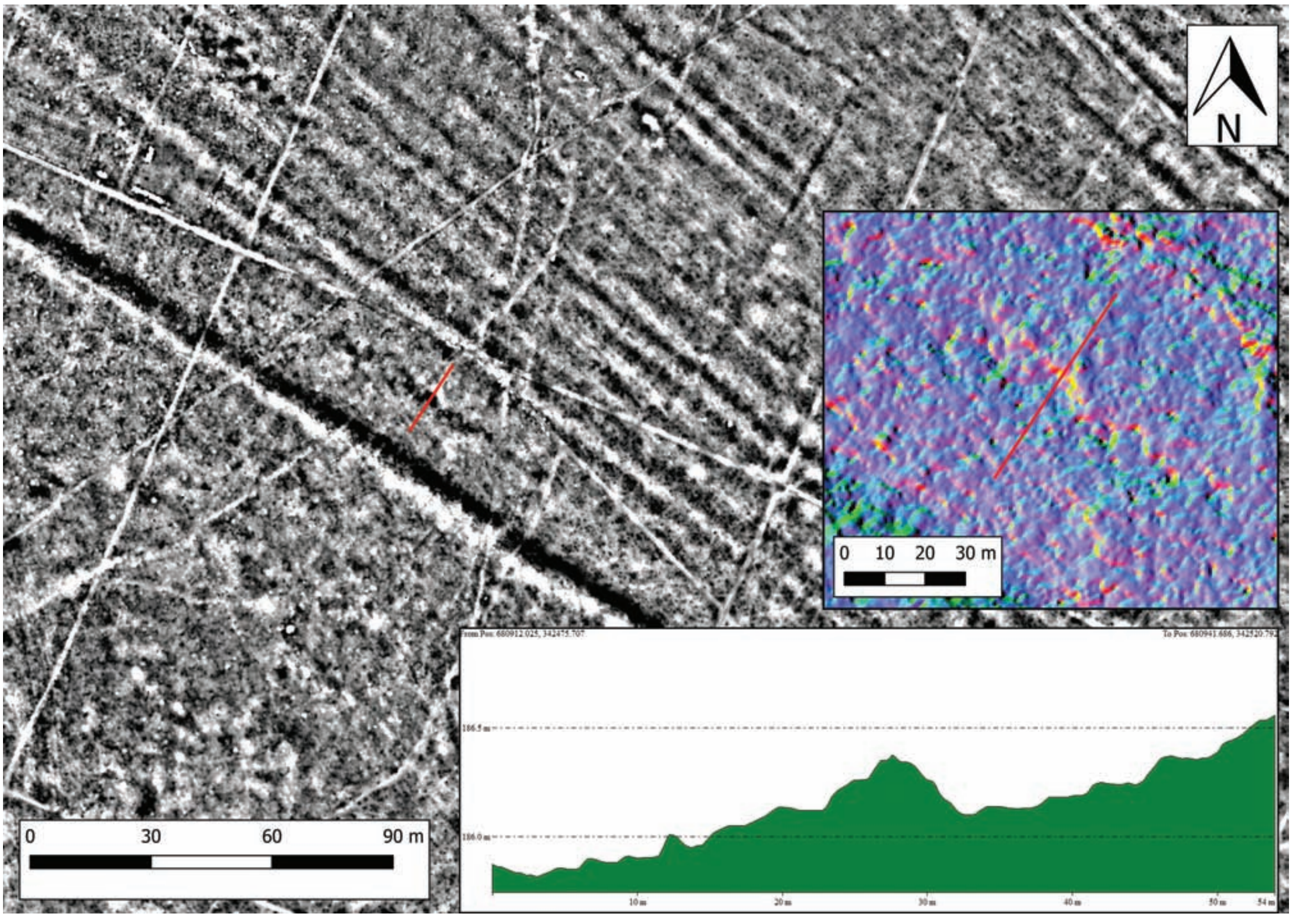

Fig. 7 – Digital terrain model of banded flint mining field 'Krunio' in Łysowody, Ostrowiec Świętokrzyski district. Visualisation of prehistoric flint mines surface relief.

5. AN ATTEMPT OF DETAILED STUDY OF FLINT MINE RELIEF

The effects of airborne laser scanning also have been recently tried for a detailed analysis of a single mining field. This test was carried out on the banded flint exploitation site 'Borownia' in Ruda Kościelna, Ostrowiec Świętokrzyski district (RADZISZEWSKA, 2015). Although this is the first prehistoric mining site discovered in Poland, it was never excavated. Among the surface materials dominant are the remnants of bifacial axes production in the Early Bronze Age. The exploitation field extends for 700 metres long and 30-50 metres wide, and is centred on a north-west – south-east axis (BUDZISZEWSKI & MICHNIAK, 1983/1989, p. 164-166). The estimated area of the entire mining field is about 2.7 hectares, of which an anthropogenic post-mining relief has been preserved in an area of approximately 1.5 hectares (Fig. 6).

Standard ALS data (4 pts/m^2, dot Ø 0.5 m) allowed the creation of a three-dimensional model of the site, related to the global coordinate grid. As a result, 192 depressions that could be identified as remnants of prehistoric mining shafts were identified on fragments of the field with preserved mining relief. Referring to the work of W. Borkowski (1995, p. 101-124) Thiessen polygons were applied to the visualisation of the terrain (Fig. 9a). On the basis of obtained results, the neighbouring shafts were determined and the distance between them was calculated. Subsequently, the maximum exploitation range was calculated by measuring the distance from the nearest concavity of adjacent shaft, as well as the maximum exploitation range by the average distance between adjacent shafts, the area of particular mining units, and volume (Fig. 9b) and maximal height of heaps (RADZISZEWSKA, 2015, p. 85-155). In order to determine the numerical representations of shafts for the resulting object

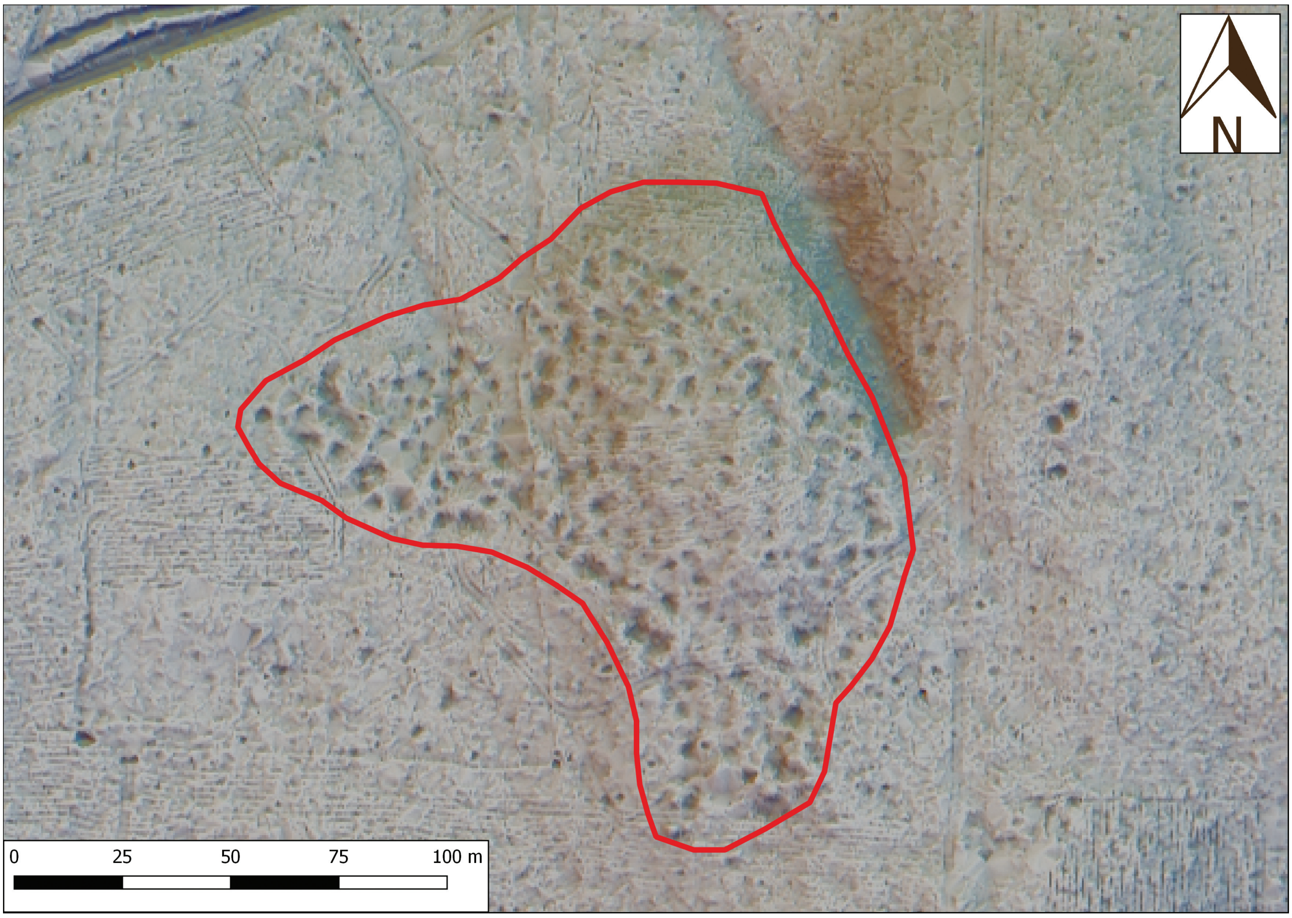

Fig. 8 – Digital terrain model of Quaternary moraine flint mining field 'Ogrodkowo I' in Kopisk, Białystok district. Visualisation of prehistoric flint mines surface relief.

classes, statistical methods were used. Performed analyses in conjunction with the results of ground penetrating radar sensing and electrical resistivity tomography has allowed presenting a number of hypotheses regarding the character of the whole site.

According to geophysical studies, the dip angle of rock layers in the area of the mining field was determined to be 5-10 degrees in the north-east direction (MIESZKOWSKI *et al.*, 2014, p. 127-128). The mines found here reached a depth of 5-6 m (MIESZKOWSKI *et al.*, 2014, p. 128). There was only one case of anomaly that could be a reflection of a mining pit with a depth of 8 m (WELC *et al.*, 2014, p. 154). The maximum exploitation range, calculated according to the distance from the concavity of the adjacent shaft, ranged from 1 to 6 m. However, it is worth mentioning that only for 24 shafts this value was over 4 m, and only 5 of them were assigned a value exceeding 5 m (RADZISZEWSKA, 2015, p. 119-126).

The results of the analyses, compiled with the results obtained in 1993 by W. Borkowski for the 'Krzemionki' mining field (BORKOWSKI, 1995), suggest that in the case of 'Borownia' we are dealing with the occurrence of pit and niche exploitations. The existence of pillar and chamber mines can be excluded (RADZISZEWSKA, 2015, p. 156-157).

A summary of all the data shows that the shaft system is not compatible with the course of the natural layers documented by geophysical surveys on the mining field. The objects are grouped on parallel lines of cuts, as the arrangement of several shaft units with similar characteristics, which are often located around larger objects. In the north-western part of the site clearly stands out a division of the area into three such concentrations (Fig. 9), in the south-eastern part 8-10 groups can be distinguished. J. Samsonowicz in his classic geological studies postulated the existence of a fault dislocation located alongside the Kamienna River, in the immediate vicinity of the mining field 'Borownia' (SAMSONOWICZ,

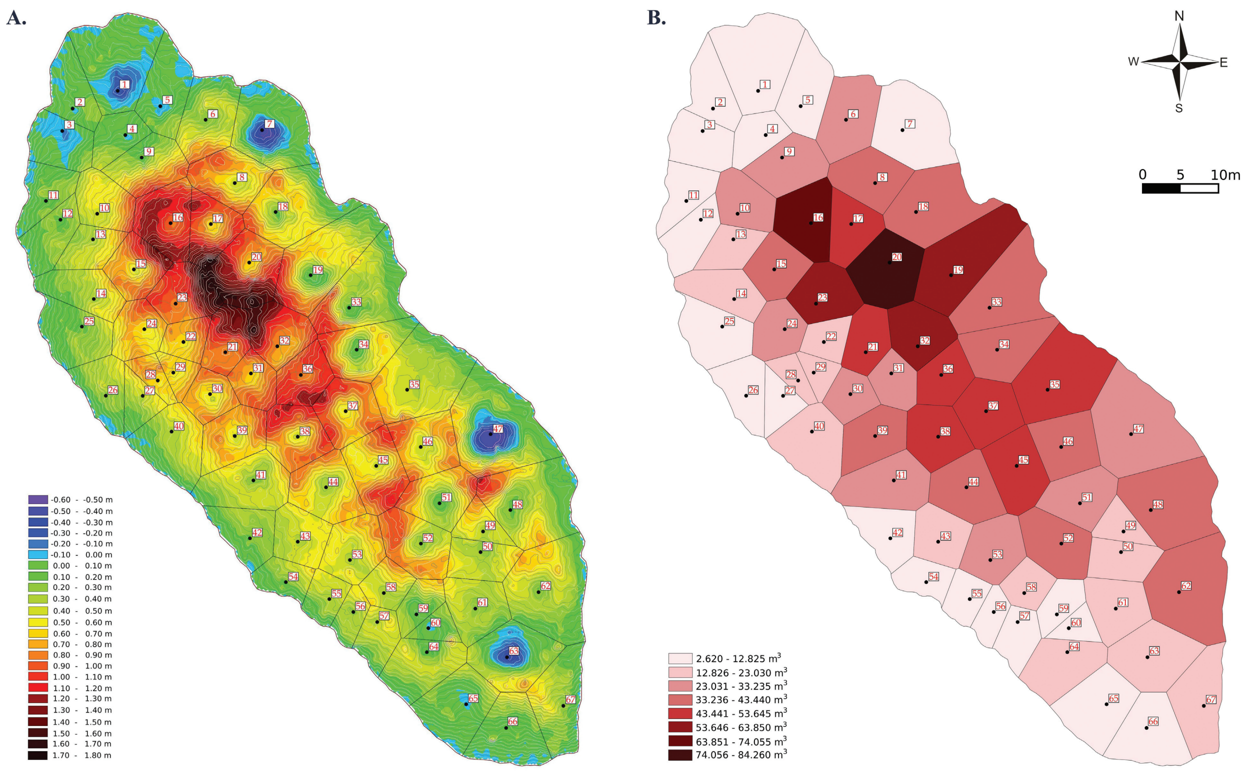

Fig. 9 – North-western part of banded flint exploitation field 'Borownia' in Ruda Kościelna, Ostrowiec Świętokrzyski district. Thiessen polygons overlying 3D surface model (a) and volume measurement of the individual heaps (b).

1934). Such a fault must be accompanied by a series of small transverse dislocations, running latitudinaly. Possibly, karstic processes running inside modified the rock mechanics conditions at the discussed site. This can only be confirmed by more accurate geophysical studies or excavation.

6. CONCLUSIONS

Studies conducted by the Institute of Archaeology of Cardinal Stefan Wyszyński University in the years 2011-2015 revealed that the data obtained by the ALS allow evaluating the geological conditions and identifying the remains of prehistoric and modern flint mining in various geological-environmental conditions. In spite of the technological advances, detection of the prehistoric siliceous rocks exploitations remains a task requiring certain qualifications, and distinguishing them from the traces of other human or even animal activity is possible only during field verification. Detailed analysis of the surface relief of the prehistoric mining sites allows hypothesising the methods used in their exploitation; however, such analyses usually require scanning in higher than the standard resolution.

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Authors' addresses:

Janusz BUDZISZEWSKI
Michał JAKUBCZAK
Katarzyna RADZISZEWSKA
Michał SZUBSKI
Institute of Archaeology
University of Cardinal Stefan
Wyszyński in Warsaw
ul. Wóycickiego 1/3, bud. 23
01-938, Warsaw, Poland
budziszewski.janusz@gmail.com
michal.jakubczak87@gmail.com
radziszewska.k@gmail.com
michal.szubski@gmail.com