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RECOGNITION OF GEOLOGICAL STRUCTURES AT STARUNIA PALAEONTOLOGICAL SITE AND VICINITY (CARPATHIAN REGION, UKRAINE) BASED ON GRAVITY SURVEYS

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Abstract: In the early 20th century, relics of Pleistocene mammals were found near the village of Starunia. Gravity surveys performed in the place of the discovery revealed a low-density bed in the Miocene Vorotyshcha salt-bearing beds. The lowered density resulted from high halite content and probably an increased number of ozokerite veins. The localization of zoological relics can be attributed to the existence of this bed. Surface gravity surveys enabled scientists to determine its course and horizontal range. Gravity surveys also confirmed the existence of the Rinne fault. In the western part of the study area gravity modelling showed an interface between Miocene Vorotyshcha salt-bearing beds and Sloboda Conglomerates, differing in average bulk density. Geologic data indicate that this interface may have the form of an overthust rather than of a fault.

Key words: Starunia, Carpathian region, Ukraine, Miocene Vorotyshcha salt-bearing beds, geophysics, gravity, gravity modelling.

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INTRODUCTION

Gravity surveys were part of an interdisciplinary research project focused on a study of the Starunia area. In the years 2006–2009 interdisciplinary investigations were made in an abandoned earth wax (ozokerite) mine in Starunia (Kotarba, 2009), about 130 kilometres southeast of Lviv, Ukraine (Fig. 1), where remnants of a mammoth and three woolly rhinoceroses, and one nearly completely preserved carcass of rhinoceros were found in 1907 and 1929. The discovery of large Pleistocene mammals in the Starunia ozokerite mine was a spectacular scientific event on the World’s scale. A unique combination of oil and brine within the Pleistocene clayey mud, into which the animal had sunk, resulted in a nearly perfect preservation of this specimen.

General information covering history of the area and details about geology and results of the earlier research works conducted in the area are described in a special monograph devoted to Starunia (Kotarba, ed., 2005) and recent works (Kotarba & Stachowicz-Rybka, 2008; Sokołowski *et al.*, 2009; Sokołowski & Stachowicz-Rybka, 2009; Stachowicz-Rybka *et al.*, 2009).

Reconnaissance gravity surveys in 2004 (Madej & Porzucek, 2005) enabled determination of the general properties of geologic structure of the place where fossil remains of mammals had been discovered. The aim of the present study was a more detailed description of the geologic setting in this area, especially establishing the course of the low-density bed, which was probably a result of high halite and ozokerite content within the Miocene Vorotyshcha salt-bearing beds. The relics were found above this bed, within the Pleistocene clays, therefore, it can be assumed that the fossil animals search area can be limited to the sub-Quaternary subcrop of the layer.

GRAVIMETRIC METHOD

Gravity surveys encompass measuring relative values of gravity, which correspond to changes in acceleration of gravity with respect to a reference station. The gravity is measured with gravimeters. The measured values are used for calculating gravity anomalies, which illustrate its changes as the gravity value is not constant. Measured gravity values (unlike other negligible elements) reflect a spatial system of masses in a rock formation, corresponding to the bulk density distribution, called “density” in this paper.

The distribution of gravity anomalies calculated from gravity can be correlated with the site of geological structures and forms, differing in bulk density from the neighbouring rocks. Gravimetric method is applicable in all places where a density contrast between studied objects and the surrounding rocks can be observed. Geological elements made of rock material having a negative density contrast are

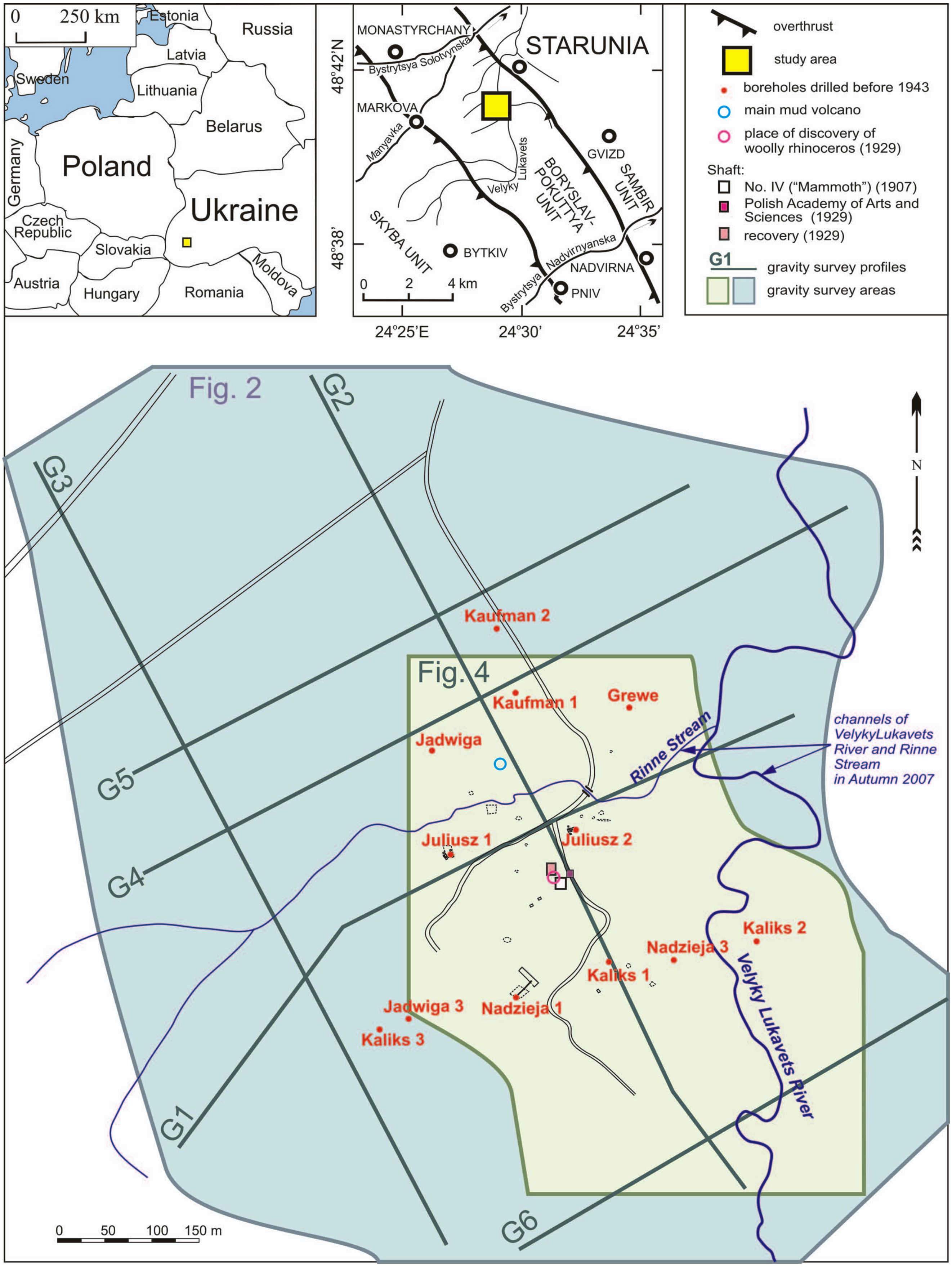

Fig. 1. Sketch map of the Starunia palaeontological site and surrounding area (Carpathian region, Ukraine) showing the location of the gravity surveys

visible in the form of relatively negative gravity anomalies; the positive contrast results in relatively positive anomalies formation. The amplitude and horizontal range of anomaly coming from a studied geological element depends on the density contrast, size of the element, and depth of its deposition.

Gravity surveys in Starunia area were made with a Scintrex gravimeter Autograv CG-3 with the high accuracy of ±0.01 mGal and repeatability of ±0.005 mGal.

FIELD MEASUREMENTS

The first stage of gravity recognizing geological setting of the region where zoological relics were found near Starunia, Ukraine were performed in 2004 (Madej & Porzucek, 2005). Five profiles 700 to 1200 m long were made there (G1–G5) (Fig. 1). These measurements reveal the existence a considerable relatively negative gravity anomaly, which was related to the existence of the low-density bed. For closer recognizing the course of the structure and shallow geological setting in more detail gravity surface surveys were made in two stages. In 2007 the surveys covered an area of ca. 10 ha and measurements were made in a grid of 12.5 m mesh; in 2008 ca. 10 ha of area was surveyed in a lattice of 10 m mesh (Fig. 1). Additionally the sixth profile G6 530 m long, transversely cutting the analysed structure, was established.

RESULTS AND DISCUSSION

The detailed gravity surveys performed in 2007 to 2008 in relation to the base station of 2004 enabled linking of both measurement series. Numerous boreholes were drilled, reaching the top of the Miocene series at a maximum of 17 m of depth (Sokołowski *et al.*, 2009). The geologic data enable precise assessment of the average bulk density of near-surface deposits, i.e. 2.1 g cm^{-3}. The density was assumed for calculating the Bouguer correction, accounting for attraction of flat and parallel plate between gravity station and the assumed reference level. Measurements of 2004 were also re-calculated using the above density value.

By combining measurements of 2004 and 2007–2008 it was possible to find a more accurate distribution of Bouguer gravity anomaly in the analysed area (Fig. 2). The obtained distribution of Bouguer anomaly generally corresponds to the distribution of 2004 (Madej & Porzucek, 2005). The main remaining element is the relatively negative gravity anomaly of amplitude more than 1 mGal. The reconnaissance surveys of 2004 revealed that the anomaly is generated by a significantly tilted low-density bed. The tilting corresponds with geologic investigations made by Mitura (1944). This bed belongs to the Miocene Vorotyshcha salt-bearing beds, and its lowered density (as compared to the neighbouring rocks) may have two causes. The first one is a high halite content, and the other one the existence of ozokerite veins in its near-surface area.

The distribution of Bouguer anomaly also enables the distinguishing two high gravity horizontal gradient zones (I and II). The character of gravity distribution in these zones shows the existence of an interface of rock deposits, considerably differing in density. Zone I is related with the Rinne fault described by Mitura (1944). Traces of zone II should be attributed to the Vorotyshcha salt-bearing beds and Sloboda Conglomerates interface, which may have a character of an overthrust. The Miocene strata are sandstone-claystone breccia with halite, potassium-salt, gypsum and calcite layers, and veins of ozokerite (Mitura, 1944; Korin, 2005). The density of Vorotyshcha salt-bearing beds is lower than that of Sloboda Conglomerates built of sandstones and conglomerates. The existence of zone II can be proved by increased horizontal gravity gradient, and also has a characteristic distribution of gravity anomaly typical of a situation when two faults are merging. A similar distribution of gravity anomalies had been observed and modeled, and then confirmed by boreholes during gravity surveys used for recognizing sulphureous deposits (Fajklewicz *et al.*, 1994). A characteristic distribution of anomalies can be seen in the NW part of the analysed area, between profiles G2 and G4, and proved by measurements in profile G5. The boundary of the east bank of the Velyky Lukavets River is congruent with the observed course of zone II.

For determining parameters of the low-density bed and localization of Vorotyshcha salt-bearing beds and Sloboda Conglomerates contact, a quantitative interpretation was made. Generally, the interpretation enables finding a relationship between the measured distribution of gravity anomaly and the magnitude, location and bulk density of the searched geologic form or structure responsible for the gravity effect (Fajklewicz, 2007). The parameters were determined on the basis of gravity modelling in a selected profile.

Surface surveys enable determining the strike of the bed, thanks to which the gravity values could be selected for modelling from a profile cutting the bed perpendicularly. The profile was so situated as to make it longest and thus the obtained distribution of anomalies most informative. The selected profile is running SW to NE (Fig. 2), and the distribution of gravity anomalies in the profile is presented in Fig. 3. The asymmetric distribution of anomalies shows to the tilting of the modelled bed.

As the results of quantitative interpretation are evidently equivocal, therefore Mitura's geologic data (Mitura, 1944) have been employed to make the results more precise. Modelling was also based on reconnaissance surveys of 2004 (Madej & Porzucek, 2005). The above materials reveal that the profile is cutting the system of beds tilted to the west. On this basis a gravity model was constructed, Fig. 3.

The modeling improved the model of 2004 and increased its accuracy (Madej & Porzucek, 2005). This confirmed the existence of a low-density bed, which probably results from a high halite and light ozokerite content. The density of the bed is lower than that of the neighbouring formation by –0.24 g cm^{-3}. Basing on the results of modelling (Fig. 3), the probable course of lines determining the range of the sub-Quaternary subcrop of the bed was established.

The distribution of the gravity effect from this bed would not coincide with anomaly values in Fig. 3. The southwest part of the anomaly would be fitted. To fit the

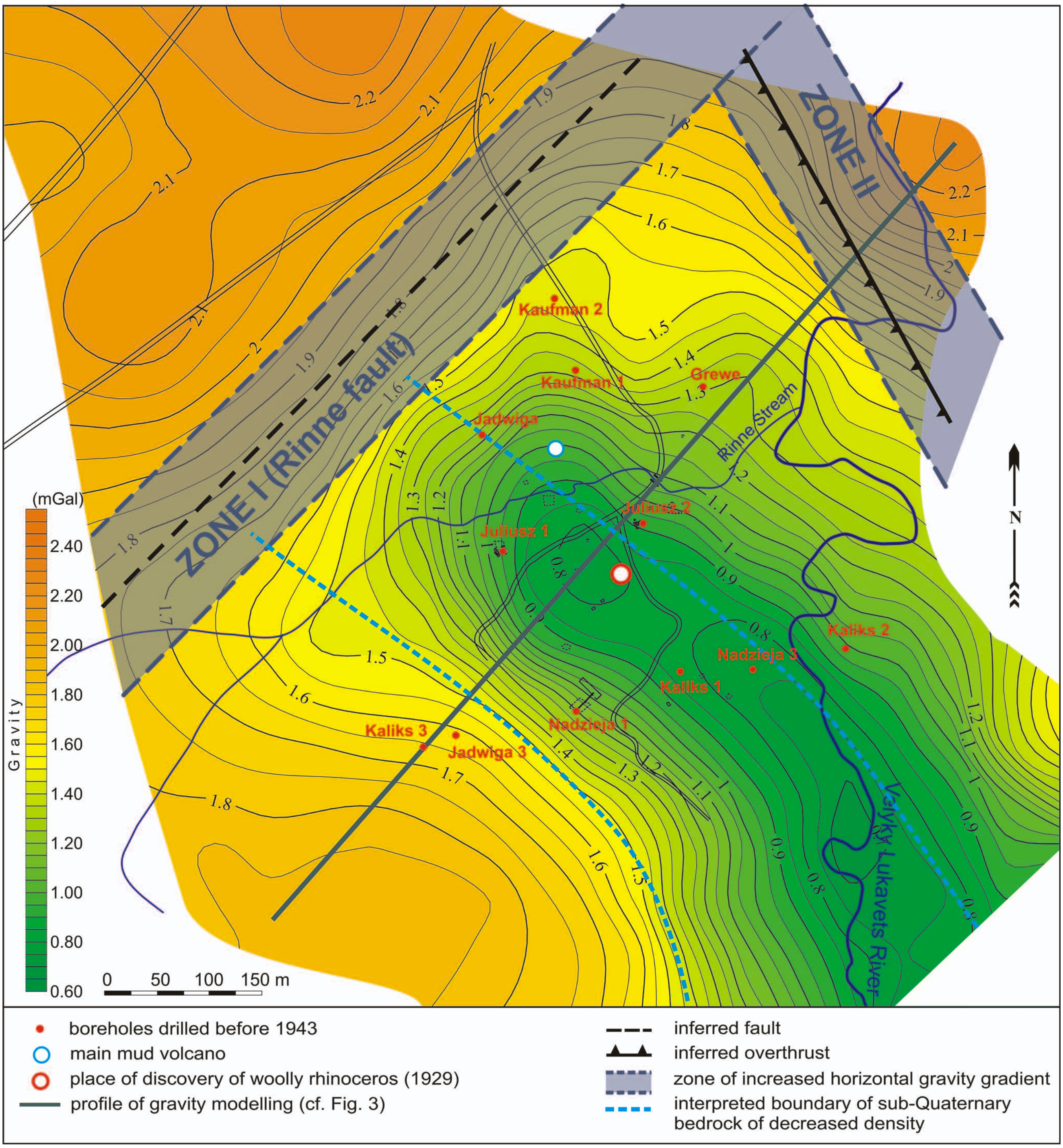

Fig. 2. Surface distribution of the gravity anomalies (surveys 2004–2008)

northeastern part of the anomaly it was necessary to add to the model a bed having a higher density than that of the neighbouring formation by +0.10 g cm^{-3}. Geologically, the bed should belong to the Sloboda Conglomerates, which are built of more dense material than the Lower Miocene Vorotyshcha salt-bearing beds. The interface may have a form of an overthrust, which has been marked in Fig. 2. The localization of the overthust may be slightly different in reality, and this is due to the too short NE profile and the resulting difficulties in modelling. Unluckily, elongation of the profile would not be possible because of the terrain conditions (hilly area overgrown with forest).

Gravity surveys of 2007 to 2008 also enabled more detailed recognition of the course of a bed generating the relatively negative gravity anomaly (Fig. 2). Starting from the Rinne fault, the bed axis was running NW to SE, and turned southwards, just like the Velyky Lukavets River valley does.

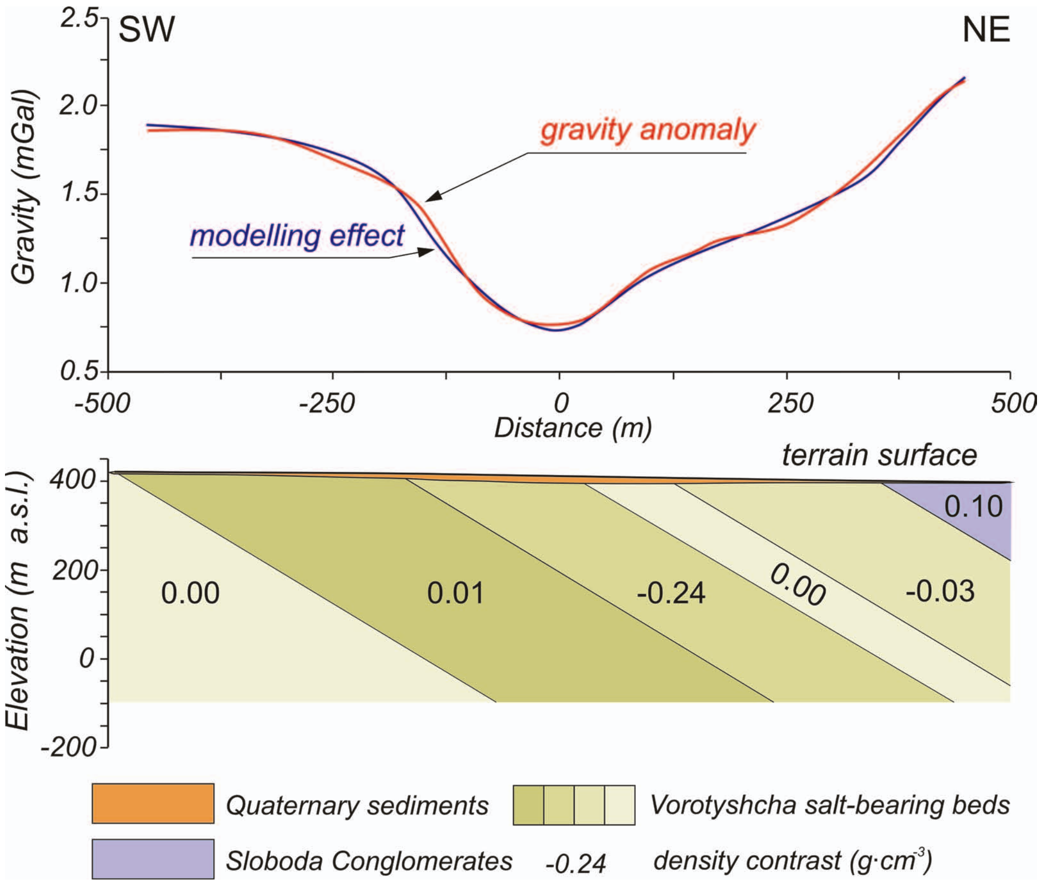

Fig. 3. Gravity modelling of geology. Location cf. Fig. 2

Fig. 4 gives a distribution of gravity anomaly obtained from the results of measurements of 2007 to 2008. The surface gravity surveys enabled finding a local gravity anomaly. The surface range and density of gravity stations enabled tracing the rock formation to a few tens of metres of depth. Five local gravity anomalies A to E can be distinguished (Fig. 4). All these anomalies are connected with the existence of a salt-bearing bed having lower density as compared to the neighbouring rocks. Anomalies B, C, D and E follow the low-density bed's axis, whereas anomaly A is at its border, near the Rinne fault. All these anomalies are relatively negative, which speaks for their lower density rock formation in the anomalous areas.

The shape and amplitude of local anomalies B, C and E are very similar. These anomalies have a relatively great surface range, and their amplitude does not exceed 0.04 mGal. Such anomalies are probably formed from small density changes in the surface part of rock formation (a dozen metres of depth).

The shape of local anomaly D is more elongated than this of the previously discussed ones, and its amplitude is slightly higher. This reveals the existence of a shallow low-density bed in the place of the anomaly; the lowering is bigger than in the case of anomalies B, C and E. Anomaly D may be related with the existence of a closed "Nadzieja 3" well in its centre. According to oral communications, there were failure incidents accompanying oil production from this well, and they may be the cause of rock looseness and disintegration of the near-surface zone.

Anomaly A in the NW part of the gravity surface distribution has a different character than other described anomalies. It is located in the zone of increased horizontal gradient related with the Rinne fault. This anomaly is visible in the form of lowered horizontal gradient of gravity, and after removing the regional factor it would assume a concentric shape. The range of the anomaly does not exceed ca. 40 m, which is an evidence of the near-surface cause of its origin.

CONCLUSIONS

Gravity surveys performed in 2007 to 2008 greatly contributed to a detailed description of the fossil mammal finding sites. The surveys revealed the existence of a low-density bed, determined its range and sub-Quaternary range of the subcrop. The relics were found above this bed, within the Pleistocene clays, therefore it can be assumed that the fossil animals search area is perspective in the sub-Quaternary subcrop of the layer. Gravity surveys confirmed the existence of the Rinne fault, and also localized the Vorotyshcha salt-bearing beds and Sloboda Conglomerates interface, which may have the character of an overthrust. Rela-

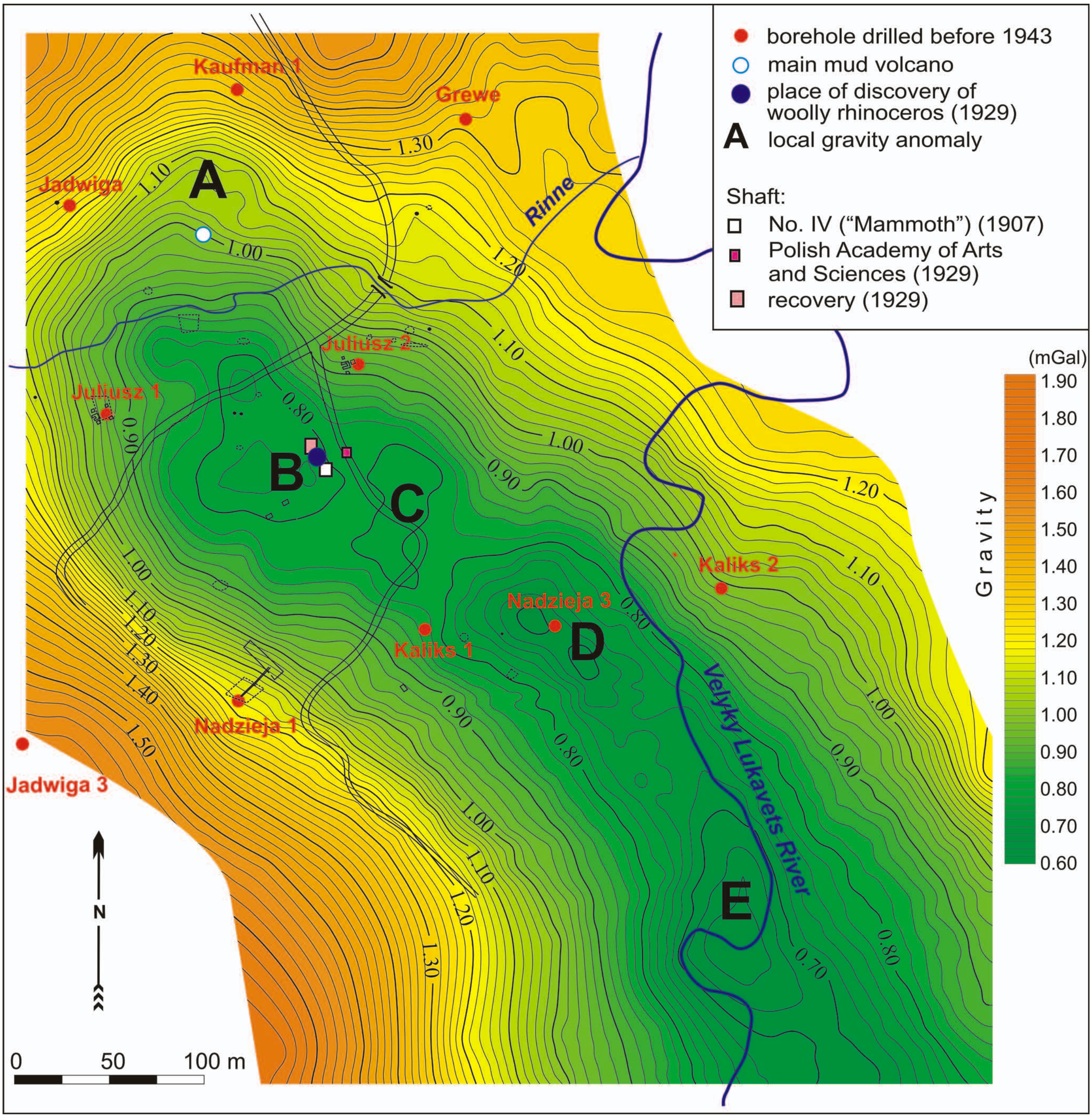

Fig. 4. Surface distribution of the gravity anomalies (surveys 2007–2008)

tively negative gravity anomalies were localized within this bed, which are indicative of loosening in the shallow near-surface geological setting.

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REFERENCES

Fajklewicz, Z., 2007. *Grawimetria stosowana* (In Polish). Uczelniane Wydawnictwa Naukowo-Dydaktyczne, Kraków, 433 pp.

Fajklewicz, Z., Madej, J. & Radomiński, J., 1994. Poszukiwanie metodą grawimetryczną kontynuacji złoża siarczanów w północnym bloku Lubichowa. (In Polish). Konferencja: "*Problemy geologii i ekologii w górnictwie podziemnym*", Szczyrk 12-14 październik 1994; 139–152.

Korin, S. S., 2005. Miocene salt-bearing Vorotyshcha Beds in the Starunia area, fore-Carpathian region, Ukraine. In: Kotarba, M. J. (ed.), *Polish and Ukrainian geological studies (2004–2005) at Starunia – the area of discoveries of woolly rhinoc-*

eroses. Polish Geological Institute and Society of Research on Environmental Changes "Geosphere", Warszawa–Kraków: 79–86.

Kotarba, M. J. (ed.), 2005. *Polish and Ukrainian geological studies (2004–2005) at Starunia – the area of discoveries of woolly rhinoceroses*. Polish Geological Institute and Society of Research on Environmental Changes "Geosphere", Warszawa–Kraków, 218 pp.

Kotarba, M. J., 2009. Interdisciplinary studies at Starunia palaeontological site and vicinity (Carpathian region, Ukraine) in the years 2006–2009: previous discoveries and research, purposes, results and perspectives. *Annales Societatis Geologorum Poloniae*, 79: 219–241.

Kotarba, M. J. & Stachowicz-Rybka, R., 2008. Wyjątkowe stanowisko paleontologiczne i środowisko osadów plejstoceńskich, w których znaleziono nosorożce włochate w Staruni (Karpaty Wschodnie). (In Polish). *Przegląd Geologiczny*, 56, 6: 442–452.

Madej, J. & Porzucek, S., 2005. Elements of geological setting of former ozokerite mine based on gravity survey in Starunia, fore-Carpathian region, Ukraine. In: M. J. Kotarba (ed.), *Polish and Ukrainian geological studies (2004–2005) at Starunia – the area of discoveries of woolly rhinoceroses*. Polish Geological Institute and Society of Research on Environmental Changes "Geosphere", Warszawa–Kraków: 115–124.

Mitura, F., 1944. *Geologia złoża wosku w Staruni*. (In Polish). Unpublished report, Archive of the Jagiellonian University, Kraków, 18 ms. pp.

Sokołowski, T. & Stachowicz-Rybka, R., 2009. Chronostratigraphy and changes of environment of Late Pleistocene and Holocene at Starunia palaeontological site and vicinity (Carpathian region, Ukraine). *Annales Societatis Geologorum Poloniae*, 79: 315–331.

Sokołowski, T., Stachowicz-Rybka, R. & Woronko, B., 2009. Upper Pleistocene and Holocene deposits at Starunia palaeontological site and vicinity (Carpathian region, Ukraine). *Annales Societatis Geologorum Poloniae*, 79: 255–278.

Stachowicz-Rybka, R., Granoszewski, W. & Hrynowiecka-Czmielewska, A., 2009a. Quaternary environmental changes at Starunia palaeontological site and vicinity (Carpathian region, Ukraine) based on palaeobotanical studies. *Annales Societatis Geologorum Poloniae*, 79: 279–288.