ROCKMASS DEFORMATIONS CAUSED BY ZINC AND LEAD ORES MINING IN THE OLKUSZ REGION (SOUTHERN POLAND)

Jerzy CABALA, Leslaw TEPER and Tadeusz RUTKOWSKI

University of Silesia, Faculty of Earth Sciences, Bedzinska 60, PL 41-200 Sosnowiec, Poland,
Corresponding authors e-mail: cabala@us.edu.pl / teper@us.edu.pl, Fax +48-32-2915865

ABSTRACT
Results of study on continuous and discontinuous deformation are presented. Ground surface deformations formed in 1980-2002 period. Conical potholes, depressions, cracks, as well as edges like scarps and ridges have been observed. The depth of some structures reached 25 metres and their areal dimension achieved ca. 500 square metres. Continuous deformations can form as sag structures with subsidence ranging from 500 to 600 mm. Deformations were frequently filled up with Quaternary sands from the cover. A model of the deformation development has been adopted, which helped predict subsidence parameters for the part of the "Klucze" orefield scheduled to open in the future. Mining has influenced changes of physical features of the Triassic complex in the close vicinity of excavations. In this region, influence of groundwater drainage on the rockmass state is of major importance. Knowledge of the deformation growth helps to correct building development and to recognise the occurrence of new hydraulic connections of the Quaternary water horizon with the Triassic aquifer. Reclamation of post-mining areas will be particularly important after closing the last operating zinc and lead mine in this region what is expected in a few years.

KEYWORDS: sinkhole, discontinuous ground deformation, subsidence trough, continuous ground deformation, subsidence prediction, Zn-Pb ores, Silesian-Cracovian district

INTRODUCTION

In the Olkusz district silver and lead ores from shallow depths have been mined out since XIII century. Extensive underground mining operation of zinc and lead ores has been being carried out in the area continuously for last 30 years.

The "Pomorzany" mine is only one active nowadays from among three ore mines operating there since 1970s. Ore deposits from 60 to 150 metres deep have been extracted. Up to the middle 1990s room-and-pillar system with roof caving was used. Present-day exploitation is carried out using room-and-pillar and shortwall systems with hydraulic backfilling (Socha and Wnuk, 1998). Resulting from breaking down mining systems with a roof deflection support from the overlying strata has been removed causing them to disrupt and/or sag into the void space created. In response to ongoing mining land surface relief has been changed. In this way ground of about 15 square kilometres in area has been deformed around Olkusz, Bukowno and Boleslaw. Discontinuous deformation features of the surface caused by shallow Zn-Pb ore extraction were examined by Wilk et al. (1973), Jarosz (1975), Janusz and Jarosz (Kwiatek, 1998) and Tyc (1990) whereas Popiolek (1990) described continuous land subsidence forms. Subsidence troughs as well as scarps, pits, chimneys and potholes of various sizes appear at the surface over cavings. Disruptions are places where karst expands, debris or crush breccias sediment and new hydraulic contacts form.

Ore extraction is accompanied by intense groundwater pumping which will be stopped along with mine closing scheduled for 2008-2010 (Socha and Wnuk, 1998, Cabala, 2000). Mine flooding will result in revival of presently drained aquifers deformed due to ore removal. That implies a strong need to define the effect of mining on rockmass prior to mine abandonment. Reserves of easy accessible Zn-Pb ores of good quality documented in areas adjacent to the "Pomorzany" deposit will be crucial for its future prospects (Kicki and Saluga, 1999, Cabala, 2000). Present extraction approaches the "Klucze" deposit (Fig. 1) and sporadically enters the "Klucze" field whose ore are of better quality than in the "Pomorzany" (Gansdorfer, 1996). It means that recognition of the deformation pattern and knowledge of potential surface subsidence will be necessary for completing mining plans for the new parts of orefield.

GEOLOGICAL AND MINING CONTEXT

The lower Triassic ore-bearing dolomites have been exploited. They resulted from limestones epigenetic replacement. Ore beds are covered by weak dolomites of the middle Triassic age, further by plastic, argillaceous and carbonate sediments of the Keuper and finally by 50-60 m thick Quaternary sands (Cabala and Konstantynowicz, 1999). Zn-Pb ores occur mostly in forms of irregular pockets that vary in size, or in stratabound bodies elongated horizontally in the Pomorzany tectonic graben where productive
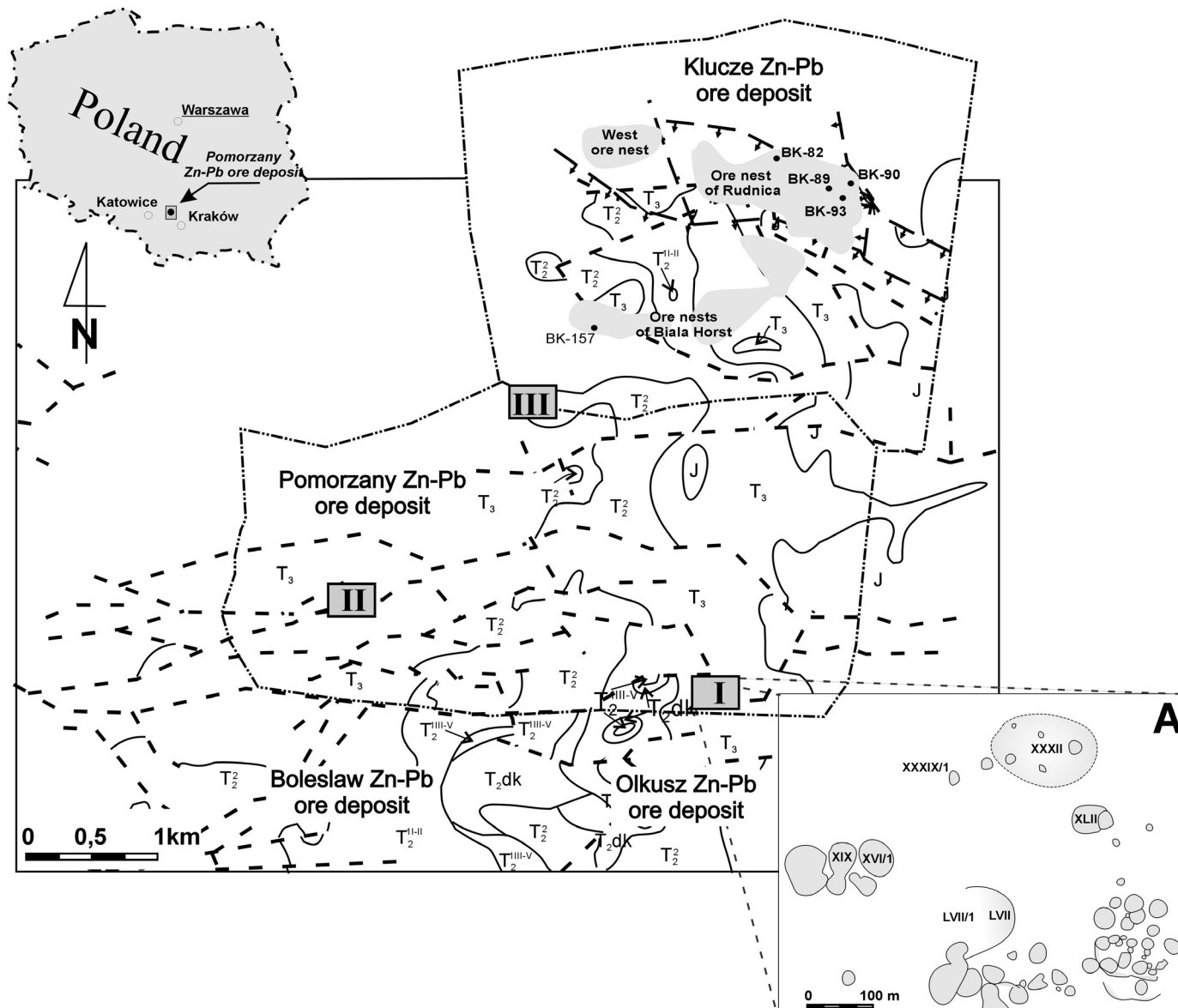
Fig. 1 Sketch map of the "Pomorzany" Zn-Pb orefield near Olkusz with study area location.
Q – Quaternary, J – Jurassic, Triassic: T_3- Keuper, T_2^2 - Diplopora Dolomites, T_2^{1III-V} - KTG Limestones, T_2^{II-II} - Gogolin limestones, T_2dk - Ore-bearing Dolomites, T_1^3 - Roet dolomites, $T_1^{2.1}$- Lower Bunter Sandstone, P – Permian, C – Carboniferous, I, II, III – test sites. Inset A – discontinuous subsidence features of site I.
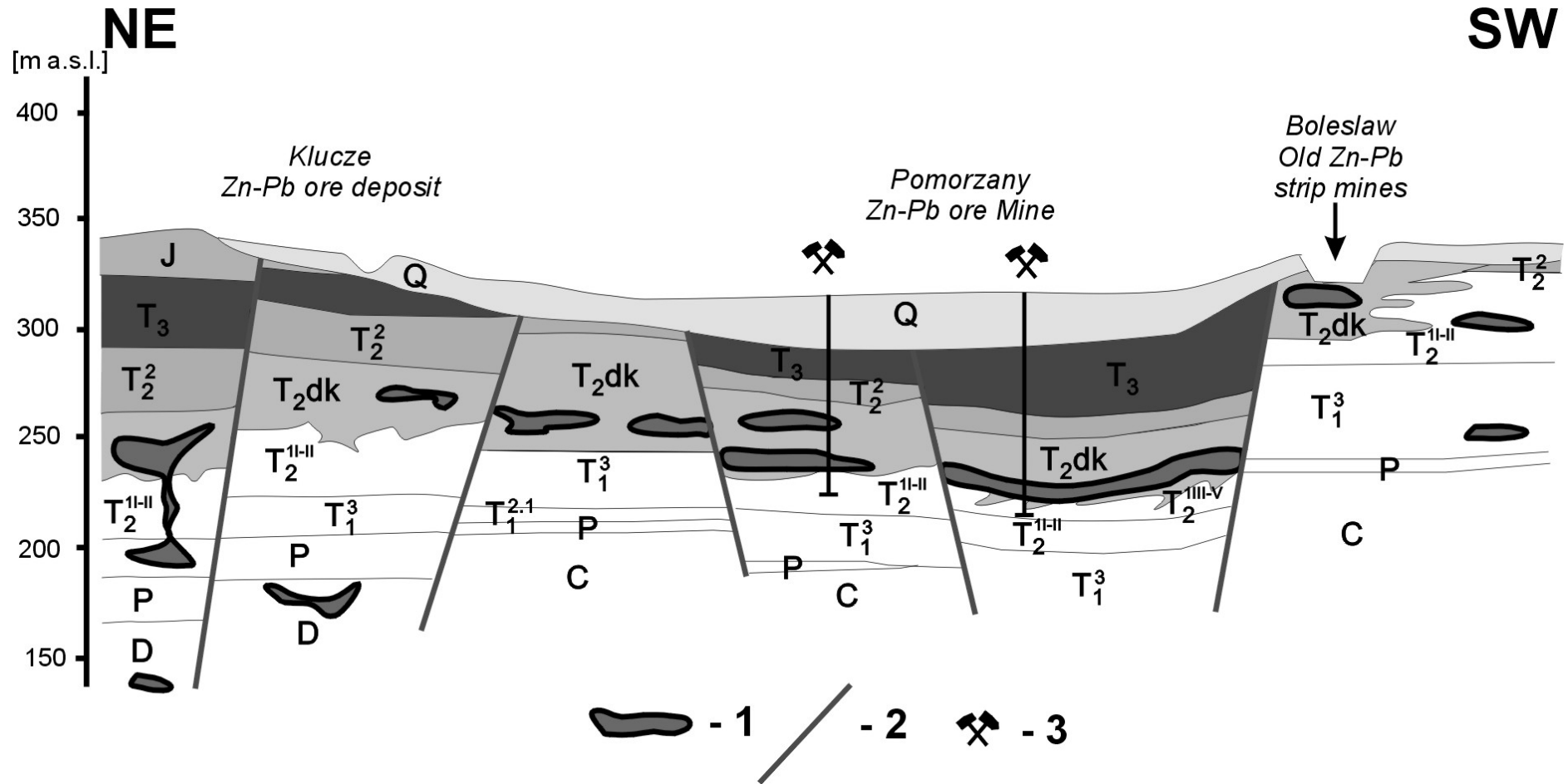
Fig. 2 Synthetic geological cross-section of the "Pomorzany" deposit (horizontal dimension out of scale).
1 – Zn-Pb ore-bearing zone, 2 – faults, 3 – pit shafts, for further explanation see Fig. 1.

mineralization is found between 210 and 290 m above sea level (Fig. 2). In the elevated area of the Klucze horst, orebodies have more complex geometry and usually considerable vertical extent reaching down to the bedrock formation built of the Devonian carbonates. The highest Zn-Pb percentage occurs several meters above the limestone-dolomite contact (Fig. 2). This horizon is noticeable thanks to well-developed karst forms, sporadically filled with cave breccias.

Horizontal position of productive strata enables extraction by room-and-pillar and shortwall methods where 2-20m thick ore panels are mined by driving a series of 1-3 sublevels advancing horizontally in step-like arrangement. Isolated rich ore nests are taken out by stoping. In horst areas, where huge orebodies lie at shallow depths, removal can result in a prominent deformation of overlaying rocks. Ultimately, this process affects the surface, causing the ground to sag, and crack and holes to form.

ANALYTICAL METHODS

Ground surface sinking in the "Pomorzany" orefield was examined at three test sites (Fig. 1):

- Site I - a block of about 0.5 km^2 in area where shallow ore removal using roof caving made subsidence pits, chimneys and potholes of various sizes and shapes appeared at the surface over voids.

- Site II – a rockmass of ca. 0.2 km^2 in area where hydraulic backfilling technique was adopted. Safety pillars of ore were left in place to support the roof of the mine and a surface feature. Ground settling is controlled by three geodetic traverses.

- Site III – a block of about 0,2 km^2 in area, partly beyond northern limit of the "Pomorzany" field, where mining with hydraulic filling is planned for the 2004-2005 period. Information obtained from previous sites has been used to predict subsidence hazard at this site.

Dynamics of deformation was analysed using data from three level lines established for ground subsidence monitoring carried out by the geodetic survey of the "Pomorzany" mine during 1979-2002. Drill core tests provided data for drawing maps of potential roof surface configuration of separate geologic units in overburden (Rutkowski, 2003). Subsidence prediction was made using "Szkody 4.0" software developed by the Polish Central Institute of Mining, Katowice. Calculations are based on Budryk-Knothe theory (Jedrzejec, 2002). Results have been compiled in the form of subsidence parameter maps (Rutkowski, 2003) using Surfer 7.0 software.

SINKHOLE SUBSIDENCE - DISCONTINUOUS FEATURES

The Triassic complex is susceptible to fracturing. Natural features developed by spontaneous karst voids filling confirm such rockmass behaviour. Cave breccias and unconsolidated material, which are washed into the voids observed over karst occurring in ore-bearing interval, are reported elsewhere (Wilk et al., 1973, Sas-Gustkiewicz and Socha, 1982, Cabala, 1993).

Caving method of ore removal used at site I resulted in abundance of disruptions in rockmass and ground surface. 56 potholes, crown holes and chimneys, 8 subsidence pits, 7 cracks and one edge were documented. All the pits, chimneys and potholes are usually circular in shape with vertical walls or bell-shaped walls, but can be of different diameters and depths. The deepest features reach 25 m whereas the largest incorporate ground of ca. 500 square metres in area. Holes formed concurrently with the ore recovery as caving allowed voids to migrate upward from the mine workings. Small secondary disruptions appeared within the features several years later. Mine workings were driven at a depth of 67-80 m. To avoid out-of-control roof collapse, caving was artificially generated at times. In some excavations spontaneous abrupt roof failure succeeded within hours removal of the pillar.

Where poorly fractured middle Triassic diplopora dolomite or nonfractured Keuper mudstone cover ore-bearing dolomite cavities called Weber voids form (Fig. 3) resulted from delamination of strata overlaying zone of collapse (Szpetkowski, 1995). After cessation of mining, subsidence may stop for a time period, to be followed by failure at some later date. Then the Weber voids remain long lasting. Once the zone reactivates, new subsidence features can form. Two discontinuous deformations arose in such a manner 5 years after the extraction had been completed at site I. Subsidence equilibrium is reached fast as speed of the settling is controlled by the rockmass structure. Failure of the roof strata produces collapse and relocation of the overburden material consisting of the ore-bearing dolomite, the diplopora dolomite as well as clays, mudstones and carbonates of the Keuper age. Finally, Quaternary sands are washed into the pit and then into the mine forming a kind of natural hydraulic filling. Plants, even small trees transported with surfacial material can be found in underground openings that are located next to caving zones (Fig. 4).

In the same Triassic carbonate horizons, karst system occurs occasionally filled by cave breccias due to collapse of roof rocks. Karst forms are developed mostly in the floor level of the ore-bearing dolomite having considerable lateral extent while their vertical dimension is rather small. Collapse zones related to paleokarst had not reached ground surface; i.e. the roof of the Triassic rocks had not been deformed then.

SINKHOLE SUBSIDENCE PREDICTION

To predict a sinkhole subsidence Janusz and Jarosz model (Jarosz, 1975, Kwiatek, 1998) was applied. It is based on relations between the largest thickness of collapsed rocks ($h_{z\ max}$), maximum height
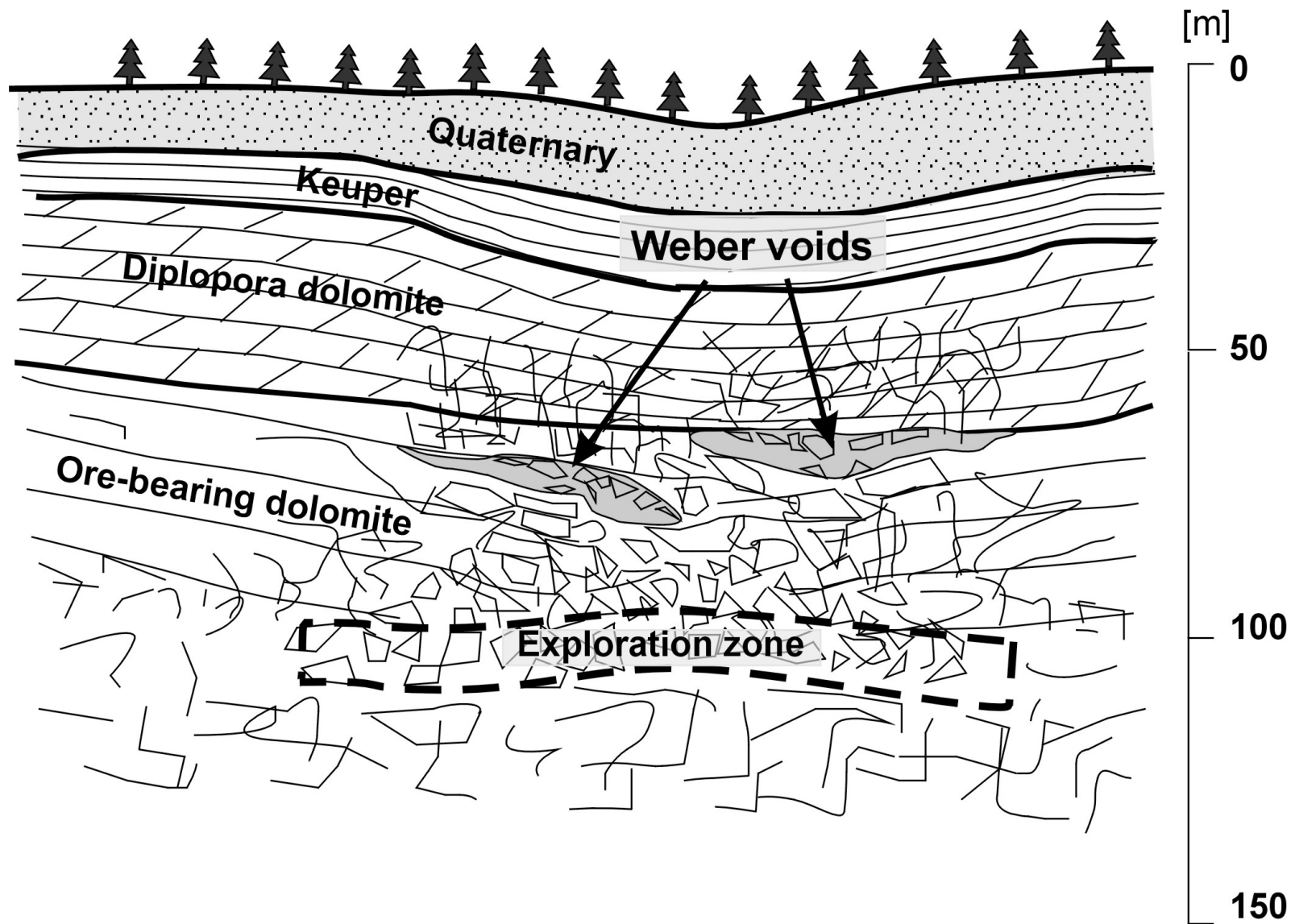
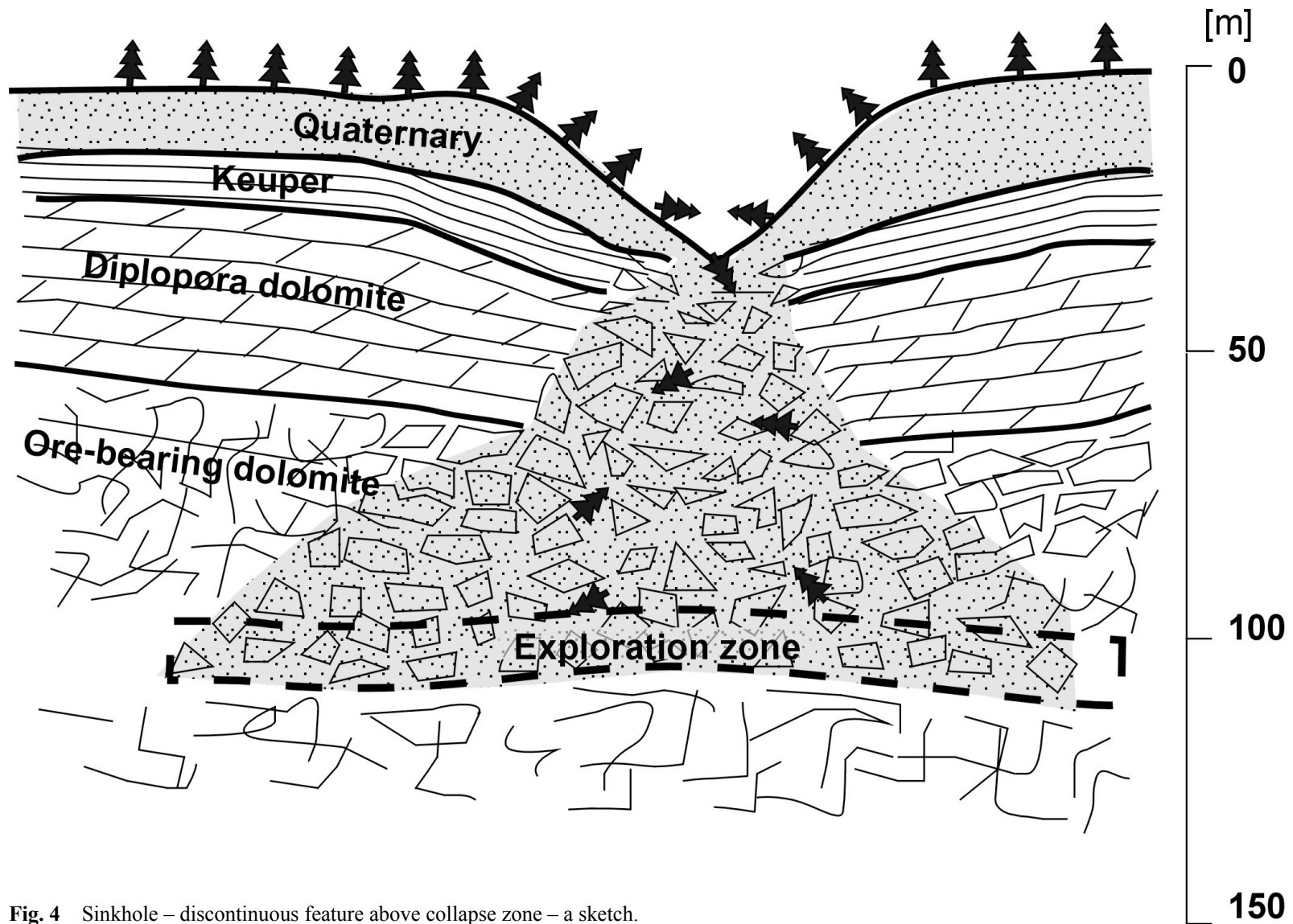**Fig. 3**   Weber voids in collapse zone above Zn-Pb deposit – a sketch.

Fig. 4   Sinkhole – discontinuous feature above collapse zone – a sketch.

of failure zone ($h_{s\ max}$) and thickness of hard rocks overlaying a cavity (h). The maximum collapse zone is a rockmass section where weakening and destruction of rocks occur, which results in relocation of rock particles accompanied by increase of rock volume.

The maximum vertical extent of collapse zone ($h_{z\ max}$) depending on the height of underground excavation (w) is given by

$$h_{z\,max} = w\left[\frac{6}{\Pi(k-1)} + \frac{1}{4}\right], \tag{1}$$

where k is a parameter expressing a change of the mechanical properties of the rockmass in the course of deformation. For the Triassic complex in the Olkusz Zn-Pb ore district k mean value is equal to 1.25 (Popiolek, 1990). Assumed $h_{s\ max} \cong 1{,}5\ h_{z\ max}$.

To simplify the model, one can assume that a sinkhole is to form on the ground surface in case of $h \le h_{z\ max}$ while for $h_{z\ max} \le h \le h_{s\ max}$ ground subsides in the sag form.

Values of the deformation coefficients were calculated for the sinkhole-type discontinuous subsidence that was observed at test site I (Table 1). Parameters assembled in the table show why potholes and subsidence pits have to form in examined rockmass conditions. Note that the hard rock level thickness (h) is lesser than $h_{z\ max}$ as well as $h_{s\ max}$. In addition, geostatic pressure, which originates from the Quaternary sands over 40 metres thick, accelerates the deformation process resulting in a sinkhole-type surfacial subsidence.

Based on the presented model, the subsidence over the "Klucze" prospect orefield was predicted (Table 1), where deposit hosted in both Triassic and Devonian systems is of greater vertical extent. Apparently, a hypothetical room-and-pillar method with roof caving would not result in any effects on ground surface in case of extraction of thin ore-bearing levels. In contrast, sinkhole subsidence would occur, if isolated rich ore nests located at various depths were recovered using a series of stopes with the roof forced or allowed to cave. Deformation growth depends on local geology and mining factors (Fig. 5). Cavity width (l) and height (w) play crucial role here. When failure zone above the cavity has its vertical extent (f) larger than the secure roof thickness sinkhole-type discontinuous feature will arose. The value of f can be evaluated from equation

$$f = a - \frac{w}{2}. \tag{2}$$

The height of a roof pressure arch is denoted as a (Fig. 5), which can be obtained from the formula

$$a = \frac{l}{2}(m-1), \tag{3}$$

where $m = 5$ is inverse of a Poisson ratio.

A discontinuous feature will form when the vertical extent of fractured zone does not exceed the maximum height of collapse zone, i.e. when $f < h_{z\ max}$. The theoretical values of cavity largest width l_{max} range from 15.1 m to 22 m depending on cavity height and secure roof thickness. Violation of the l_{max} limit value results in caving.

Where ore is removed from shallow depth, ground deformation forms regardless how thick the

Table 1 Sinkhole subsidence (discontinuous deformation) parameters for the test site I compiled with values predicted for the "Klucze" prospect orefield, using model of Janusz and Jarosz (Jarosz, 1975, Kwiatek,1998).

Sinkhole (Fig. 1A) or drilling (Fig. 1) symbols		Excavation height w [m]	Collapse zone max. height $h_{z\,max}$ [m]	Solid rocks thickness h [m]	Fractured zone max. height $h_{s\,max}$ [m]	Extraction depth [m]	Radius of surfacial feature r [m]	Surface depression [m]	Volume of depression V [m³]
The Pomorzany Zn-Pb ore deposit	XXXII	20	157.8	33.4	236.8	78.4	95	3.3	9900
	XLII	18	142.0	27.0	213.1	72	25	10	1750
	XVI/1	24	189.4	30.6	284.1	76.5	19	7	592.5
	XIX	11	86.8	33.5	130.2	76	11	15	1900
	LVII	24	189.4	32.0	284.1	76	50	15	39250
The Klucze Zn-Pb ore deposit	BK-157	10	78.9	28	118.4	108.4	Sinkhole to form*		
	BK-89	8	63.1	100	94.7	147.5	No effect on ground surface*		
	BK-82	16	126.3	175.6	189.4	225.6	Subsidence trough to form*		
	BK-93	41	323.6	90	485.4	138.1	Sinkhole to form *		
	BK-90	50	394.6	130	592	178	Sinkhole to form *		

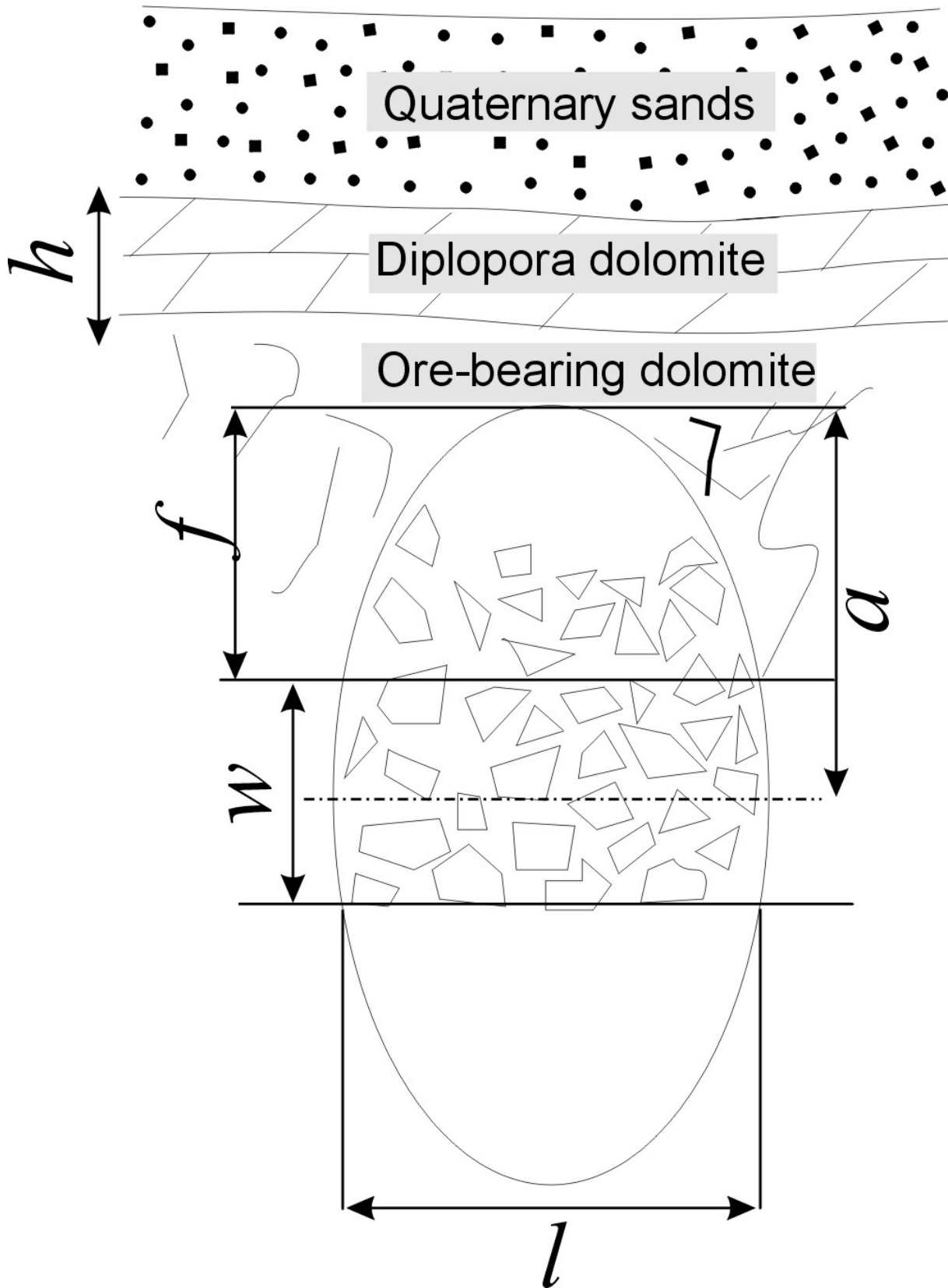* for theoretical case of a room-and-pillar extraction with roof caving

Fig. 5 Stress ellipsoid parameters referred to excavation width *l* and height *w*.

Triassic hard rocks and the Quaternary sands are. However, the thickness ratio of overburden lithologies still influences type and shape of evolving feature.

TROUGH SUBSIDENCE - CONTINUOUS FEATURES

Subsidence troughs over abandoned mine workings usually occur when the overburden sags downward due to the failure of remnant mine pillars, or by placing the pillars into a soft mine roof or floor. The resultant surface effect is a large, shallow, yet broad, depression in the ground, which is usually elliptical or circular in shape. As the ground sags, it pulls away from the edge of the trough and creates tension cracks around the perimeter. Correspondingly, the ground is compressed in the centre of the trough and a small ridge can form. The surface tilts where the ground curves into the trough. This activity produces vertical movement and results in horizontal tension and compression and tilt of the ground surface.

Dynamics of subsidence trough development was surveying at test site II (Fig. 1) where three to four ore slices were withdrawn and openings were fully filled. The lower level was mined using room-and-pillar method, the upper slices were taken out by shortwall system.

Ground relief underwent the biggest changes during 1986-1992. Observed subsidence troughs are atypical being irregular or at least asymmetric in shape. The maximum subsidence occurred above the openings with the maximum total height. Vertical ground displacement reached 559 mm where complete excavation was 15 metres high, which resulted in 37.2 mm of the ground downward movement per each meter of the void height. The last parameter increased in value up to 45 mm when measured for excavations lower than 10 metres. Abrupt increase of vertical displacement was recorded twice at measurement points established next to tectonic faults. Presumably, this may be related to either geological situation or void incomplete backfilling.

In general, extraction with full backfilling produce small or no ground deformation. However, the subsidence observed in the surveyed area is accompanied by major changes of hydrograpfic pattern. Flow of the streams is altered or disrupted. Intensive drainage draws down the watertable, which results in sinking of the surface water.

TROUGH SUBSIDENCE PREDICTION

Diversity of the geometry of existing subsidence troughs and their influence on both surveyed land surface and rockmass underlaying the sags, invite to analyse parameters of continuous deformation expected in orefield sections scheduled to extract. Anticipated effects on ground subsidence were assessed for the test site III (Fig. 1), which is planned for mining during 2004-2005. Values of parameters of ground displacement and deformation were calculated using Szkody 4.0 software (Jedrzejec, 2002). Calculations were based on data derived from detailed surveying of the orefield geology. The prognostic calculation results have been presented by means of maps (Figs 6 and 7). The complete set of the maps representing spatial distribution of resultant subsidence (w), resultant horizontal displacement (u), resultant slope (T), extreme vertical curvatures (K_{max} and K_{min}) as well as greatest tensile (ε_{max}) and compressive (ε_{min}) deformations, was worked out by Rutkowski (2003). The resultant values correspond to the conditions when the full subsidence trough will form. Additionally, the extreme values given in Table 2 calculated adopting exploration coefficient a equal to 0.1, which corresponds to stowing material falling into the 3rd category. Extreme values would be half as large assuming a use of filling sands that met the 1st category standard. The recalculation is needed because the value of a decreases to 0.05 in such a case. The calculation of the subsidence measures (Tab. 2) was verified using Kwiatek's (1998) method. It confirms the prediction results. Some differences concerning K and ε values may be explained by possible existence of supplementary stresses in examined rockmass.

According to the prognosis, the maximum vertical displacement is expected in the central part of the trough. It will progressively decrease until the limit of the surface area will be reached (Fig. 6). The most significant deformation will occur around the trough perimeter where the largest prognostic values were calculated for resultant horizontal displacement (Fig. 7), resultant slope and vertical curvatures, both positive and negative. The carbonate and argillaceous and carbonate rocks overlying examined section of Zn-Pb ore deposit will be subject to extensive discontinuous damage.

Obtained results, matched up with subsidence hazard classification used in coal mining industry (Kwiatek, 1982), allow rating of an examined land surface among 4th or 5th categories of mining areas. Application of the best kind of stowing material (a = 0.05) in abandoned workings would help with improving surfacial conditions, particularly by decreas-

Table 2 Maximum values of subsidence parameters calculated for test site III (symbols are explained in text)

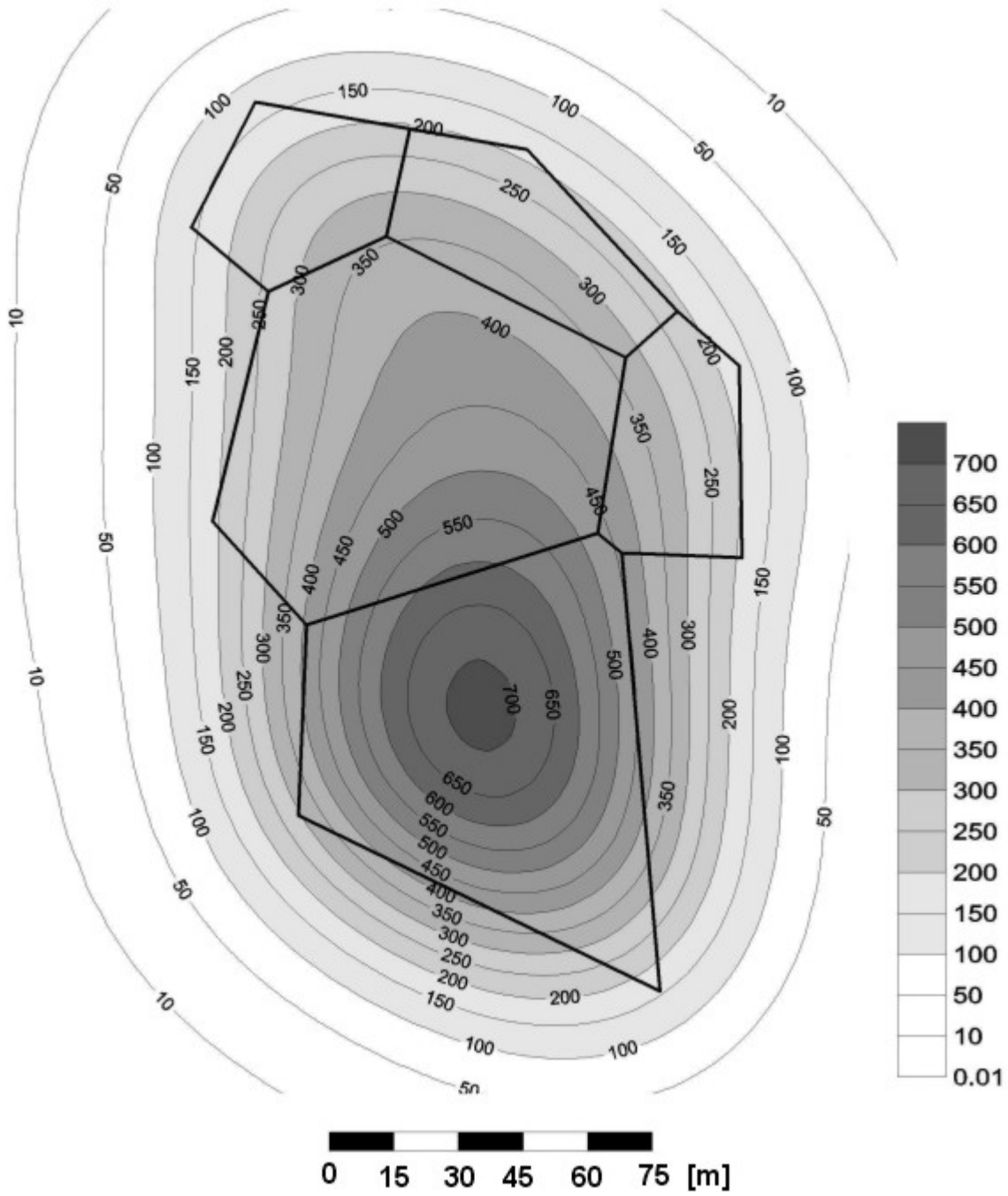| Coefficient	w_{max} [mm]	u_{max} [mm]	T_{max} [mm/m]	ε_{max} [mm/m]	ε_{min} [mm/m]	K_{max} [1/km]	K_{min} [1/km]
max	715.3	265.4	12.43	6.15	-10.86	0.508	-0.288

Fig. 6   Prediction of resultant vertical displacement *w* [mm] for test site III.
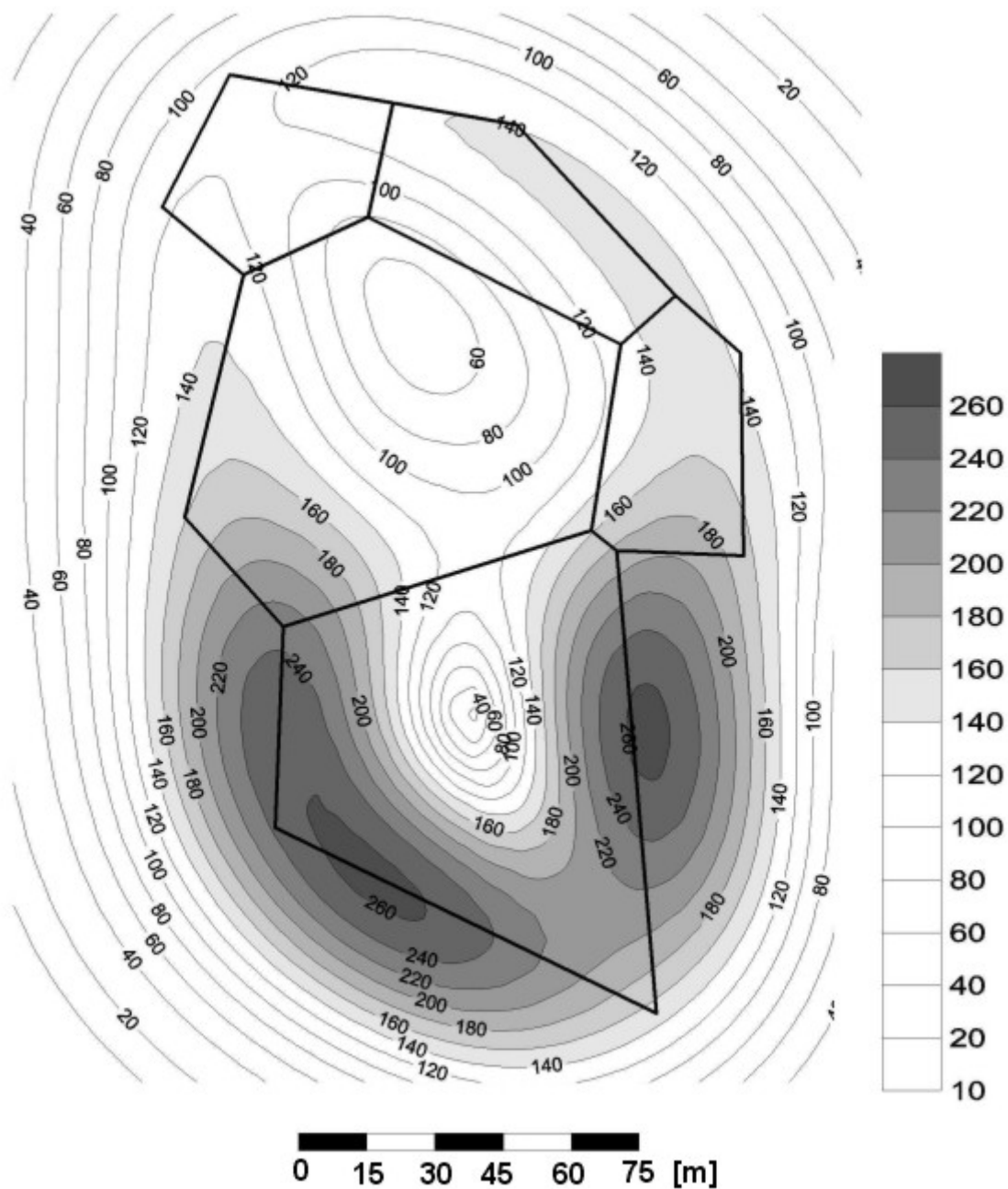
Fig. 7 Prediction of resultant horizontal displacement *u* [mm] for test site III.

ing horizontal deformation and resultant slope, and the area could fall into 3rd category in mentioned classification. Concluding, available data and completed investigation allow to predetermine that ground surface of test site III will be suitable to building development not earlier than 5 years after completing intended ore recovery.

FINAL REMARKS

Growth of the sinkhole-type discontinuous deformation is mostly controlled by methods of both ore extraction and mine openings management. Reactivation of the sinkholes observed several years after cessation of mining is subsequent to non-full caving, which means that the Weber voids form in a short time after recovery and collapse later on. Collapse zones of similar character found above karst cavities occurring in environs of the Olkusz ore district confirm susceptibility of the middle Triassic dolomites to this type of damage. Extraction with roof collapse is not advisable in the "Klucze" prospect orefield as predicted caving zones reach ground surface regardless of depth of mining.

Prognostic continuous features are rapidly appearing depressions with small vertical subsidence. According to predetermined parameters of ground deformation, particularly resultant slopes and horizontal displacements, the examined site has been identified as subsidence hazard area, which should temporarily not be taken into consideration for housing development.

Intensive groundwater discharge has an additional influence on dynamics of the Triassic complex deformation, especially on activation and reactivation of the settling. It is noteworthy that peak water inflow to underground openings is here about 260 m^3 per minute (Tyc, 1990). Thereby, the "Pomorzany" can be numbered among the most endangered by water mines all over the world. Mine closing will result in flooding its workings by groundwater whereas sinkholes will channel descension of precipitation and surface waters. Some of the collapse zones will favour hydraulic connection between the Quaternary and Triassic water-bearing horizons. This may be an essential future aspect of surveyed subsidence pattern as the Triassic aquifer is the principal underground reservoir of potable water for the extremely dense populated Upper Silesian urban area.

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