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The largest giant gypsum intergrowths from the Badenian (Middle Miocene) evaporites of the Carpathian Foredeep

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The Badenian (Middle Miocene) evaporite deposits of the Carpathian Foredeep in Poland, Ukraine and Czech Republic, contain large bottom-grown primary gypsum crystals (selenite) which are some of the largest in the world. The 0.5–3.5 m long crystals are arranged in a palisade manner and create specific intergrowths similar to the contact swallow-tail {$\bar{1}$01} twins known in other areas. They occur in one stratigraphical interval that is several metres thick. The largest specimens were found near Busko in Southern Poland. The selenite crystals are commonly 1–1.5 m long, but specimens exceeding 2.5 m in length are present but are rare and poorly documented. Some years ago one specimen approaching 3.5 m in length was recognized at Bogucice-Skałki and seems to be the largest known and existing mineral crystal in Poland. Recently another *ca.* 3.5 m long selenite specimen was exposed at nearby Gacki. Both these crystals are partly damaged, and one is not fully exposed, and therefore it is difficult to establish which is (or was) actually the largest one.

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INTRODUCTION

One of the largest selenite crystals in the mineral world occurs in the Middle Miocene (Badenian) gypsum deposits in the northern Carpathian Foredeep (Kasprzyk, 1993*a*, *b*; Peryt, 1996). The gypsum crystals represent a primary coarse crystalline evaporite deposit (selenite). The very largest crystals show specific intergrowths similar to {$\bar{1}$01} contact gypsum twins (Bąbel, 1991). The crystals are arranged in a palisade manner and form a layer, up to several metres thick, occurring at the base of the Badenian gypsum deposits spread along the northern margin of the Carpathian Foredeep in Poland, the Czech Republic and Ukraine. The giant intergrowth layer is entirely composed of the large crystals commonly 0.5–1.5 m in size, and in places approach and exceed 2.5 m in size. In Poland this layer is best exposed near Busko in the Nida River valley, south of the Holy Cross Mountains. Although many former investigators described crystals more than four metres long from this area they did not supply convincing documentation (see critical review in Bąbel, 2002). Many earlier outcrops of the giant intergrowths have been destroyed by quarrying and the very large crystals reported there were not convincingly authenticated. Present-day outcrops reveal countless crystals of 1–2 metres length but only a few examples approaching 3 m in size.

Some years ago it was recognized that the largest gypsum crystal in these outcrops is exposed in the abandoned quarry at Bogucice-Skałki, 9 km west of Busko (Fig. 1). The length of this crystal, which is partly damaged and not fully exposed, is estimated at about 3.5 m. This specimen was indicated as the largest known and existing natural crystal in Poland and possibly one of the largest such crystals in Europe (Bąbel, 2002). It has been suggested that even larger specimens can be discovered in future among the crystals of the giant gypsum intergrowths in the Nida region during subsequent studies.

The aim of the present paper is to document a new, so far unrecorded giant gypsum crystal of comparable size to the specimen from Bogucice-Skałki. Its comparison with the other mineral giants occurring on Earth, and with gypsum in particular, is presented, with emphasis on the specimens which are still preserved.

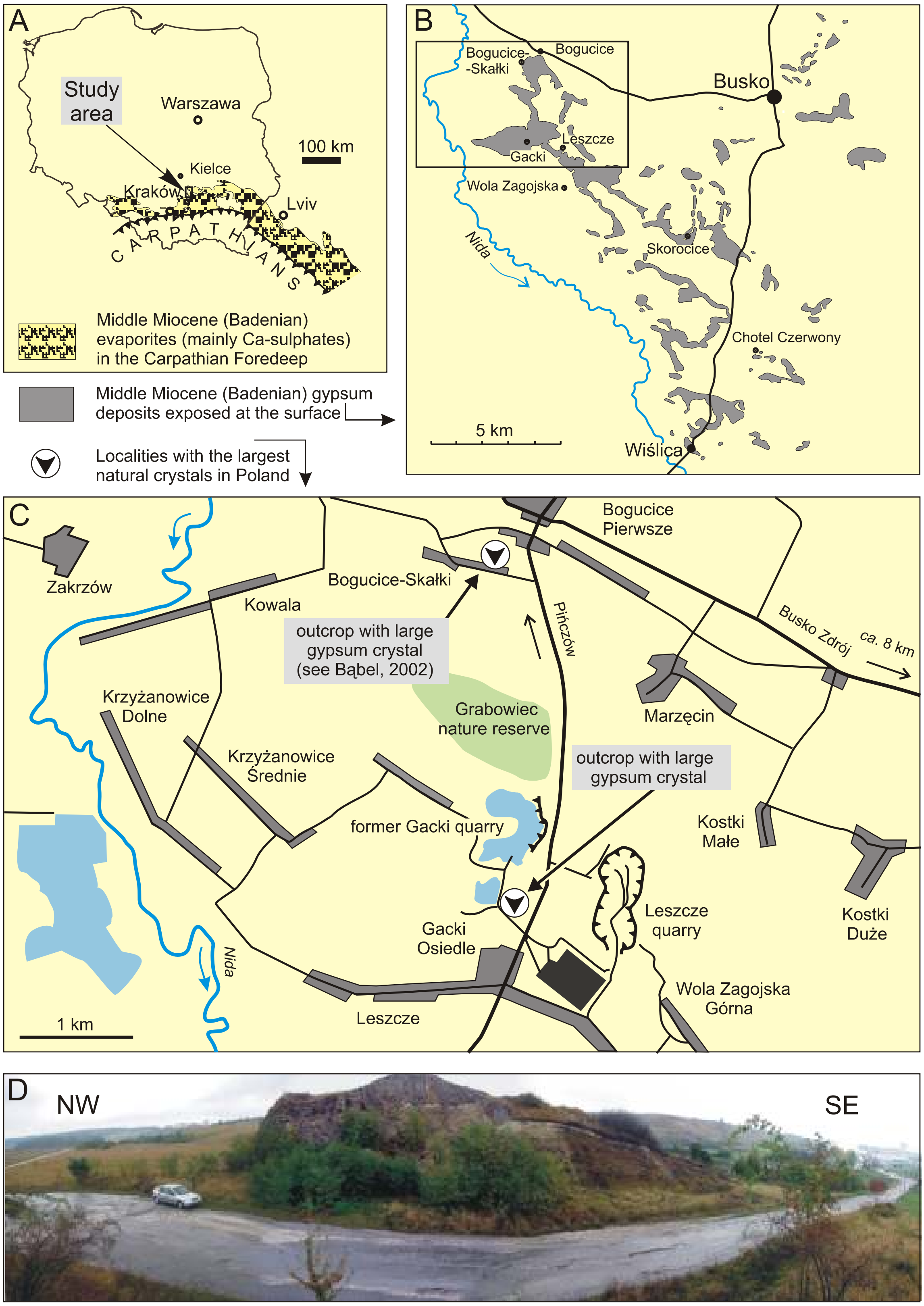

Fig. 1A – location of the study area of the Badenian (Middle Miocene) evaporites; B – exposures of the Badenian gypsum deposits in the Nida River valley (after various sources and the authors' own data); C – location of the exposures with the largest gypsum crystals; D – panoramic view on the gypsum hill with exposure of the giant gypsum crystal at Gacki

GEOLOGICAL BACKGROUND

Metre-size gypsum intergrowths are a natural curiosity because of the large sizes of the crystals, uncommon among minerals within sedimentary rocks. They are the product of gypsum crystals growing directly on the bottom of a brine-filled evaporite basin (in this case of Badenian age) in a manner similar to the gypsum crystals growing, in compact pavements, in recent marine saltwork pans. The large sizes of the Badenian crystal intergrowths are apparently the result of even longer periods of continuous growth taking place in somewhat deeper brine, protected from dissolution. The sedimentary environment of these peculiar giant-crystalline deposits has been interpreted in detail by many authors (e.g., Kreutz, 1925; Kasprzyk, 1993*a*, *b*; Peryt, 1996; Bąbel, 2007, with references) comparably to the analogous selenite deposits from other basins (Ortí Cabo and Shearman, 1977; Shearman and Ortí Cabo, 1978; Rodríguez-Aranda *et al.*, 1995*a*, *b*; Warren, 2006; Ayllón-Quevedo *et al*., 2007). The giant crystals in this setting show a palisade structure and are oriented more or less normally to the depositional surface, which is a typical feature of crystals growing on a substrate and has been interpreted as a result of the competitive growth effect (Shearman and Ortí Cabo, 1978; Bąbel, 1987).

The intergrowths are also a crystallographical curiosity (Kreutz, 1925; Bąbel, 1991) and differ from the gypsum twins so far described in other ancient evaporite deposits (Ortí Cabo and Shearman, 1977; Shearman and Ortí Cabo, 1978; Rodríguez-Aranda *et al*., 1995*a*, *b*). They also display an unusual primary skeletal structure rarely present in selenite deposits (Schreiber, 1978).

THE OUTCROP WITH THE GIANT CRYSTAL

The crystal bed is exposed on the small hill through which the entry road entering the former Gacki quarry was cut (Fig. 1). Gacki quarry was closed some years ago. Its area was recultivated and the lakes infilling the previous quarry are now recreation sites. The hill is a valuable geological exposure of the Badenian deposits, taken under protection of law in 1986–1987 (point no. 212 on the territory of the Nida Region Landscape Park, and Alicja Kasprzyk was involved in the project leading to the preservation of this outcrop). A regionally important fault, with a throw 13 m, is also seen in this exposure (Fig. 2; Krysiak, 2000). The west footwall side of the fault is composed of the so-called “sabre” gypsum deposits (containing crystals having sabre shapes) representing the middle part of evaporite section (Fig. 2A, B). The section on the eastern side of the fault contains the marine pre-evaporitic Badenian marls overlain by the giant gypsum intergrowths at the base of the evaporite section (Fig. 2). These Badenian gypsum deposits are known as the Nida Gypsum deposits in the Nida River region, and as the Krzyżanowice Formation in the Polish part of the Carpathian Foredeep and the Tyras Formation in the Ukrainian part.

The basal surface of the giant gypsum intergrowths shows irregular undulations with an amplitude of up to 0.5 m (Figs. 2 and 3). The knobbly irregularities at the base of the crystal clusters are load structures formed when gypsum crystals started to grow on the soft muddy substrate as separated clusters. Due to their increasing weight these clusters gradually sank into the bottom, squeezing the loamy material to the side and up. The initial growth of gypsum crystals was associated with influx of clay material which was deposited mainly in between the crystal aggregates. During continued growth the aggregates coalesced into one compact coarse-crystalline layer and the load deformation of the muddy substrate ceased (see Bąbel, 1987, fig. 6). Similar load structures are known from Messinian gypsum as selenite nucleation cones (Dronkert, 1985) and are also present in the sabre gypsum facies in the same exposure (at the top of layer h). The outcrop has been illustrated by Osmólski *et al.* (1978, pl. 1, fig. 7), Petrichenko *et al.* (1997), Krysiak (2000, pl. 1, fig. 1), Urban (2008, fig. 16), and mapped by Lipka *et al.* (2007).

The wall of giant crystals was probably exposed since quarry operations began and has been known to the authors since the late 1970s. The giant crystal was, however, unseen at that time, until a rock fall took place between 1999 and 2006 (Figs. 2 and 3). Then the new segment of the gypsum wall was exposed and the crystal became evident (Fig. 3B).

The giant gypsum intergrowth layer breaks easily and splits along vertical planes. The fractures form along the strongest {010} gypsum cleavage planes, which are usually vertically and subvertically oriented, and along the relatively flat sub-vertical composition surfaces, i.e. the surfaces along which one component crystal forms an oriented intergrowth with the adjacent crystals. The cohesion of the intergrowths along the composition surface is very weak or absent. Therefore, in the walls of exposures, the giant crystals are commonly seen as the large {010} cleavage surfaces, shining in the sunlight like big mirrors, or as composition faces (the crystalographically oriented surfaces of the component crystals adjoining each other and creating together the composition surface of the intergrowth). The size of crystals can be thus easily recognized by tracing these two kinds of surfaces. The {010} cleavage is oriented more or less normal to the composition surface of the intergrowths. A great many of such exposed giant crystals are seen in this gypsum wall (Fig. 2C).

DESCRIPTION OF THE GIANT CRYSTAL FROM GACKI

The largest crystal is evident along the side of its composition face (Fig. 4). An adjacent, equally large component crystal was destroyed during the rock fall. The composition face of the giant intergrowth shows specific fan-like relief resulting from serial splitting of the apex of the intergrowth into a cluster of apices (each of which can be considered as a subcrystal). These apices grew upwards creating flat sub-vertical fields separated by steps. These steps, going up the composition surface, increased in height from a few mm to several cm. The composi-

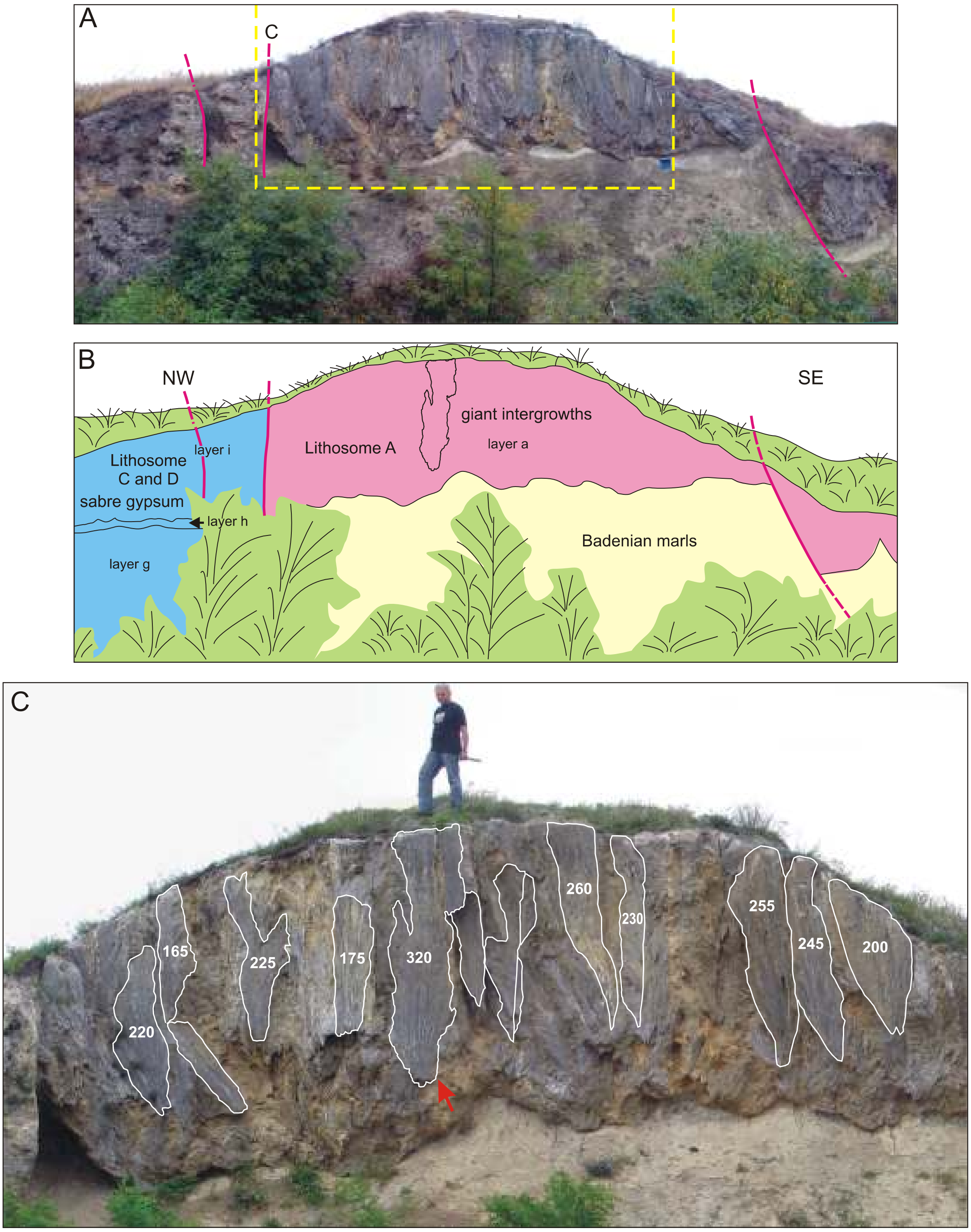

Fig. 2A – the outcrop of the Badenian (Middle Miocene) deposits at Gacki, with the studied giant gypsum intergrowths at the top of the hill; B – sketch explaining the geology and stratigraphy of the outcrop; gypsum layers and lithosomes lettered according to regional stratigraphical code (see Bąbel, 2007, with references); C – enlarged view of the giant gypsum intergrowths with the exposed largest crystals outlined and their maximum length given in cm, photo taken by J. T. Bąbel

tion face is slightly concave and its curved shape is the primary growth feature visible also in the other composition surfaces of the intergrowths in this locality (Fig. 5). Such a feature of the composition surfaces is rarely present, and most commonly they are very flat. The composition face in this particular case is elongated vertically and is about 70 cm wide in the lower part and about 80 cm wide in the topmost part (Fig. 4A, B). The uppermost part of the crystal is uneven and therefore the long axis of the crystal can be measured along different directions. It is about 3.15 m long when measured more or less vertically but is 3.20 m long when measured obliquely to the right topmost part of the crystal (Fig. 4B). This 3.20 m size is the maximum length of the existing crystal.

The crystal was originally longer and its lowermost part was apparently destroyed (Fig. 4C). This lowermost part was the "nucleation" site of the crystal (and the intergrowth), the

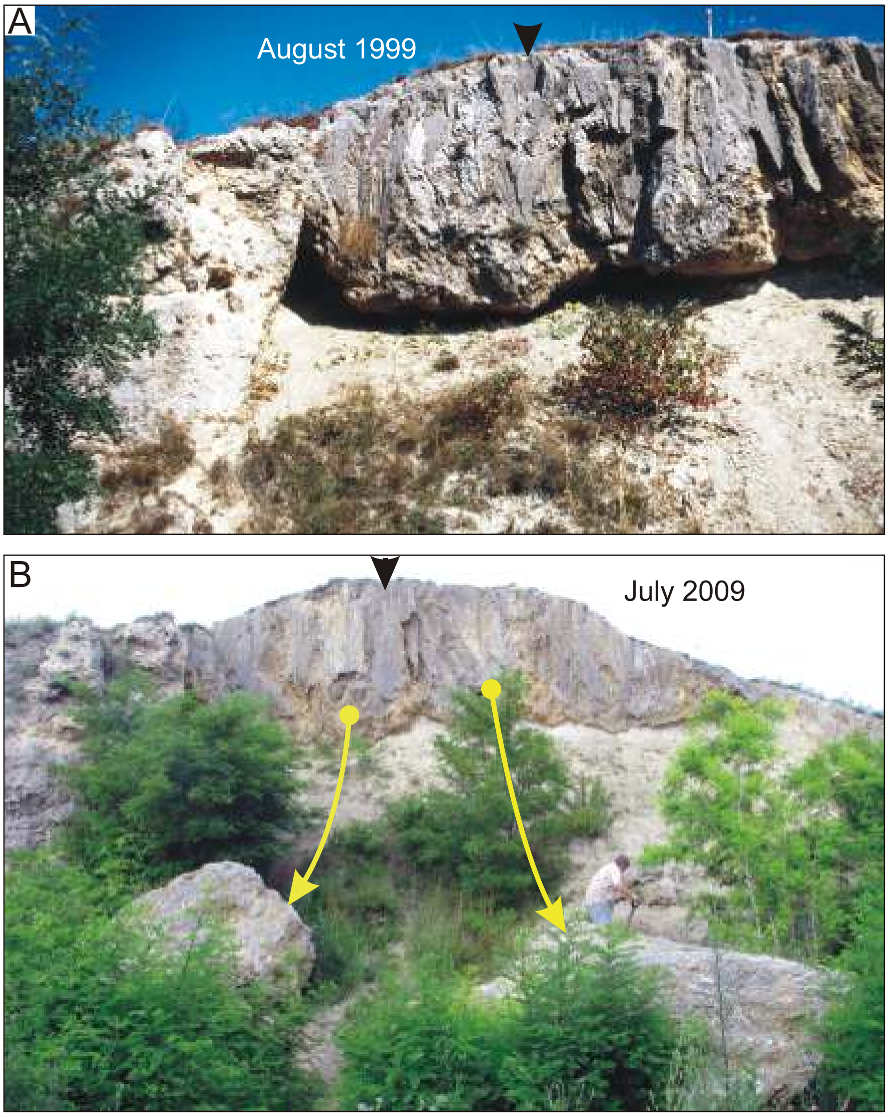

Fig. 3. The view of the exposure at Gacki before (A) and after the gypsum rock fall (B)

The largest gypsum crystal is arrowed

site from where it started to grow up in competition with the other adjacent intergrowths. This "nucleation" site can be reconstructed by tracing down the triangular shaped composition face (in a similar way as was done in case of the giant crystal from Bogucice-Skałki; Bąbel, 2002). The triangular shapes of the composition faces and the span of the lower acute angle of these triangles is usually constant and characteristic for each particular intergrowth cluster (Fig. 4D, E). Assuming the constant span of this acute angle the destroyed part of the crystal can be estimated as a minimum of 20 and a maximum of 25 cm long (Fig. 4C). This estimation is much more precise and certain than in the case of the crystals from Bogucice because the crystal from Gacki is better exposed and available for investigation. Thus the total length of the crystal, before it was partly destroyed, can be estimated as a minimum of 3.40 m and a maximum of 3.45 m. The total length of the crystal from Gacki can be additionally extended taking into consideration that the topmost part of this crystal is also partly removed. The top of the crystal was exposed at the surface of the hill long before the rock fall and was and still is subjected to erosion and karst dissolution. Thus it is reasonable to estimate that the crystal approached 3.4–3.5 m in length.

The surface area of the composition face of the crystal from Gacki, together with the reconstructed lower part, can be roughly estimated as about 2.01 m^2. The third dimension of this crystal, perpendicular to the composition face, in unknown. By analogy to the adjacent crystals, it can be assumed that it is not larger than 0.5 m. Assuming that it is 20 cm on average, the crystal volume equals *ca*. 0.402 m^3 and its mass is *ca*. 933 kg (for the density of gypsum – 2.32 g/cm^3).

COMPARISON WITH THE GIANT CRYSTAL FROM BOGUCICE-SKAŁKI

Both crystals are exposed in the same way – from the side of the composition face (Fig. 6). Both show spectacular characteristic fan-like relief typical of the composition faces of giant gypsum intergrowths.

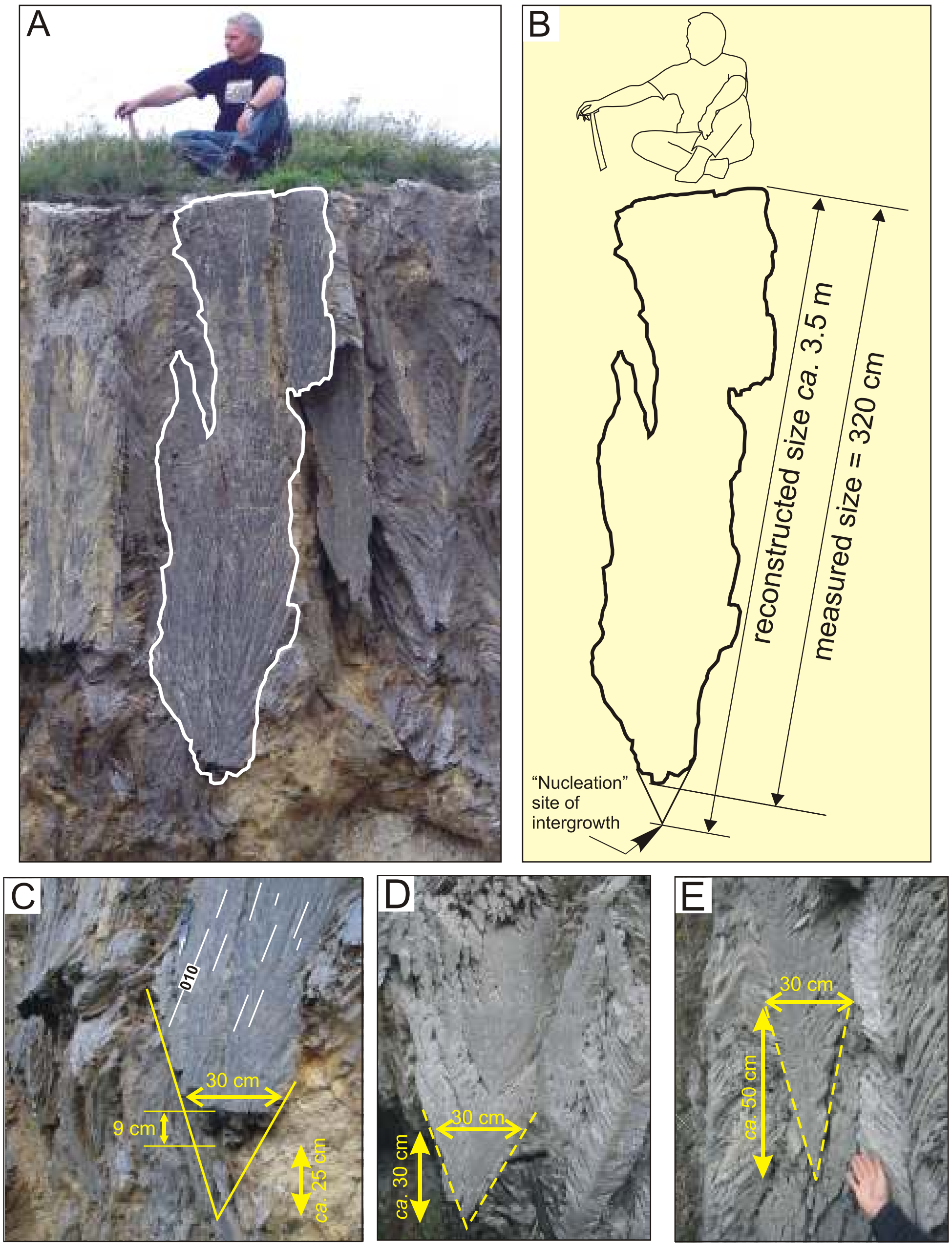

Fig. 4. The sizes of the giant gypsum crystal from Gacki

A – the crystal seen from the side of the composition face (outlined), photo taken by J. T. Bąbel; **B** – the measured and restored sizes of the crystal; **C** – mode of the reconstruction of the lowermost destroyed part of the giant crystal, traces of {010} cleavage planes are marked; **D**, **E** – triangular shapes of the composition faces of the exemplary intergrowths from Bogucice-Skałki, with the preserved lowermost parts and "nucleation" sites of the intergrowths; note fan-like growth relief of the composition faces of the crystals; further explanations in the text; photos on figures D and E courtesy of S. Lugli

The composition face of the crystal from Bogucice-Skałki is about 2.05 m^2 (Bąbel, 2002) and it is slightly larger than the composition face of the specimen from Gacki. The visible length of the crystal from Bogucice-Skałki is 3.15 m and in its middle part it is about 1 m wide. The crystal from Gacki is 3.20 m long and about 70–80 cm wide so it is 20–30 cm narrower (Fig. 6C). These lengths are not the total length of the crystals. The topmost parts of both crystals are partly obliterated by karst dissolution. The lowermost part of the crystal from Gacki has been destroyed, and the same part of the crystal from Bogucice is covered. In both cases the total length was reconstructed in a similar way – from the triangular shape of the composition face. In the case of the crystal from Bogucice the total length was estimated as a minimum of 3.4 m, and a maximum of 3.55 m; in the case of the crystal under discussion it is a minimum of 3.4 m, and a maximum of 3.45 m (in both cases ignoring erosion of the crystal tops). It is difficult to state unequivocally which crystal is (was) actually the longest (their minimum sizes are similar). Also it is unknown which of them is actually larger in volume or weight, because the third dimen-

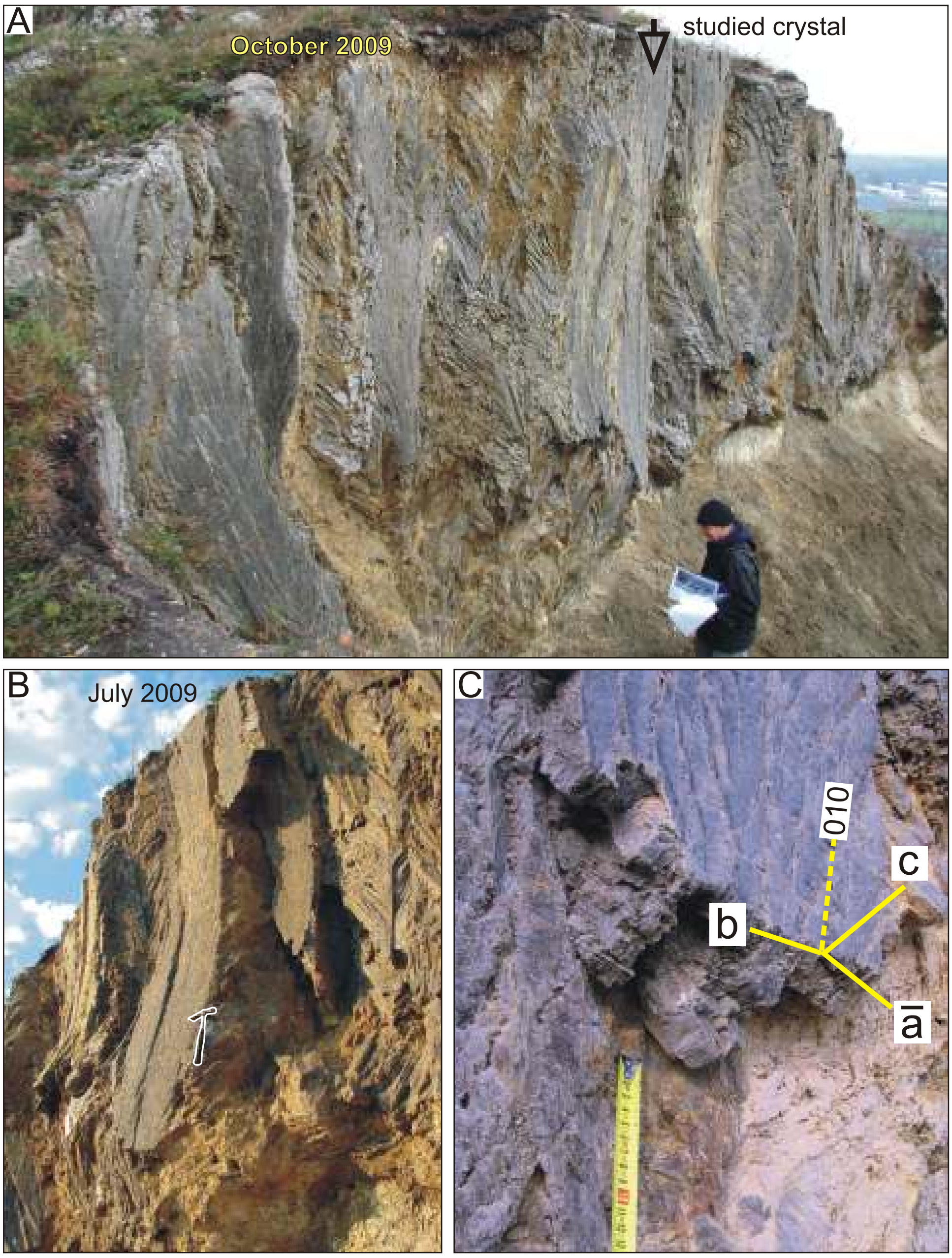

Fig. 5. The giant gypsum crystal from Gacki with a slightly curved composition face seen from the west (A) and from the east side (B), and details of the lower, partly destroyed part of the crystal (C)

Approximate position of crystallographical axes $\bar{a}$, b, c, and traces of the {010} cleavage planes of the gypsum crystal are marked on C; see Bąbel (2002) for more details

sion of the crystals is unseen. However, the crystal from Bogucice is undoubtedly the longest existing crystal among the so far recognized and authenticated gypsum specimens and natural crystals from Poland. The new crystal from Gacki is the largest as far as the visible crystal length is taken into account.

COMPARISON WITH SOME OTHER GIANT MINERAL CRYSTALS

What is (or was) really the largest in size mineral crystal ever found on Earth remains controversial. It could be the colossal microcline from Devils Hole Beryl Mine in Colorado, USA, with dimensions of 49.4 × 36.0 × 13.7 m, which was mined out and remains unauthenticated (see Rickwood, 1981). A better candidate is the giant beryl from the pegmatite at Malakialina, Malgasy Republic, 18 m long and 3.5 m in diameter, also removed and poorly documented (Rickwood, 1981; Bąbel, 2002). The longest crystal which has been accurately measured and documented photographically is a spodumene 14.23 m long and 0.80 m wide from Etta Mine in the Black Hills, South Dakota, USA (see Jahn, 1953; Rickwood, 1981). Although this crystal was destroyed during mining other crystals several metres long are still to be seen in the abandoned quarries in this area

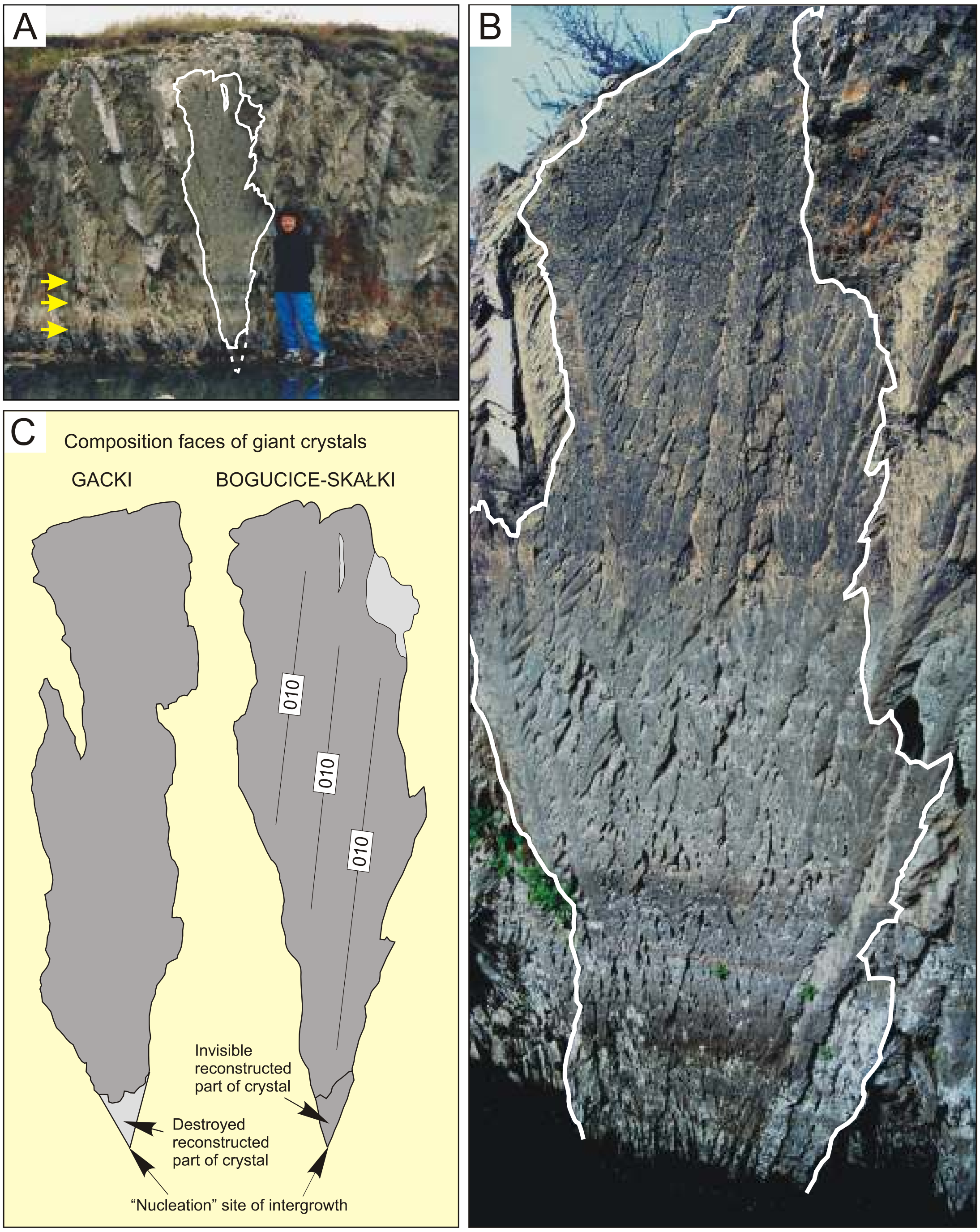

Fig. 6. The largest gypsum crystal from Bogucice-Skałki, fully exposed (in A, outlined) and flooded with water (in B, outlined) and its comparison with the specimen from Gacki (C)

Photo in figure A was taken in 1992; note fan-like growth relief of the composition face of the crystal and traces of water levels (arrowed in A); further explanations are in the text and in Bąbel (2002)

(http://giantcrystals.strahlen.org/america/etta.htm). Because all such record crystals, like many other mineral giants, have been destroyed, the question arises as to what is the largest known and still existing natural crystal on Earth?

Behr and Horn (1982) and Behr *et al.* (1983) noted the occurrence of a quartz crystal 50 m (!) in size from pegmatite in the Hakos Mountains, SW of Windhoek in Namibia, and the other authors illustrated crystals several metres long from this site (Marais *et al.*, 1995). One of the illustrated crystals is estimated as 12 m in length (see Behr and Horn, 1982, fig. 5b; Rykart, 1995, Abb. 206, p. 323; and http://giantcrystals.strahlen.org/africa/verloren.htm). Pavlyshyn and Dovgyi (2008) illustrated a 10 m long quartz crystal found at the Akdjailau ore deposits in Kazakhstan. These findings, like many other similar occurrences (Deleff *et al.*, 2004), are still awaiting better documentation and authentication.

At present the best candidate for the largest known existing natural crystal is among the giant gypsum (selenite) crystals discovered in 2000 at Naica silver mine, SE of Chihuahua, in Mexico. The largest crystal or crystals are from the famous Cave of Crystals (Cueva de los Cristales), about 350 m below the surface, and attain 11 m (36 ft.) in length (García-Ruiz *et al.*, 2007*a*, *b*), although some other authors suggested less (10 m; Herrera *et al.*, 2002), and the others even larger maximum sizes (>12 m; Lazcano Sabagun and Winchell, 2001; and >13 m; Forti and Sanna, 2010). The crystals from Naica grew from the low salinity subsurface solutions, at temperature of *ca*. 46–56°C, and at very low supersaturation levels (García-Ruíz *et al.*, 2007*a*, *b*, 2008; Garofalo *et al.*, 2010).

COMARISON WITH SOME OTHER GIANT GYPSUM CRYSTALS

The 11 m long crystals from Naica are at the head of the list of the largest known gypsum crystals on Earth. This mineral occurrence commonly creates very large specimens. Crystals similar in origin and appearance to those from Naica have long been known from the El Teniente copper mine in Chile (Lindgren, 1933). They occur in caverns of a volcanic ore body (Braden Pipe Breccia) and are over 4 m in length (Floody, 2000 *fide* Skewes *et al*., 2002). According to the visitors of the mine they attain lengths up to 6 m (Tunks, 2002; Cannell *et al.*, 2005) or even 7 m (García-Ruiz *et al.*, 2008). Other large gypsum crystals that are several metres in length are known from Eocene gypsum deposits explored at Debar underground mine in Macedonia (http://giantcrystals.strahlen.org/europe/debar.htm).

Equally long crystals remain to be found and authenticated within the Messinian (Late Miocene) evaporite selenite deposits in the Mediterranean region, particularly those having {100} twins. Two localities are the most remarkable; near Favara on Sicily where Richter-Bernburg (1973) noted 6 m long twinned crystals, and the environs of Eledhiou in Cyprus, from where twins of various sizes, from 4.5 to 7 m long, were reported (Schreiber, 1978; Rouchy, 1982; Robertson *et al.*, 1995). Probably a great many other, undescribed outcrops of Messinian giant selenite crystals, common around the Mediterranean, await explorers ready to find them. And a short time ago Aref (2003) noted the occurrence of 1.8 m long selenite twins in Upper Miocene (Messinian?) evaporites at the Al-Barqan quarry, 70 km south-east of El-Alamein in Egypt. The growth of all these giant evaporite gypsum crystals, also those in the studied Badenian ones, as with the crystals from Naica, presumably required persistent and relatively low supersaturation states necessary for elimination of any spontaneous nucleation during the growth (Bąbel, 2007).

CONCLUSIONS AND FINAL REMARKS

The new giant gypsum crystal exposed at Gacki in the Nida River valley is comparable in length to the formerly recognized, record specimen from Bogucice-Skałki. Both the crystals are partly damaged, and the crystal from Bogucice is not fully exposed, and therefore their maximum size can not be determined precisely. Both the crystals can be estimated as at least 3.4 m in length. They are the largest mineral crystals so far documented (localized and described) and still existing in Poland. Although the crystal from Bogucice-Skałki is *ca*. 5 cm smaller in visible length than the specimen from Gacki, it still remains the largest known and existing natural crystal because its invisible “additional” lowermost part is surely more than 5 cm long and is undestroyed.

These large gypsum crystals from the Badenian evaporites of Poland are considerably smaller in size than the largest known gypsum crystals on Earth. They are, however, among the rare giant specimens that are still preserved and available for visitors, and their natural and extraordinary beauty is easy to see and to admire.

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