Development history of Middle Jurassic neptunian dykes in the High-Tatric series, Tatra Mountains, Poland

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ABSTRACT:

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Neptunian dykes filled with Middle Jurassic sediments from the High-Tatric series in the Tatra Mountains are described. Six types of dykes, which constitute two groups, are distinguished, basing on the type of filling deposits, external shape of the systems and character of the walls. *Group I* embraces all of the dykes with sharp-edged walls and predominantly vertical structures. *Group II* consists of dykes with smooth walls and predominantly horizontal structures. The distribution of particular types of dykes in the High-Tatric tectonic units is discussed. The processes of the initiation of dykes, their development and filling with deposits are reconstructed. The distribution of the dykes of *Group I*, their orientation, shape, size and relationship to the host-rocks, indicate the mechanical nature of the initiation phenomena. The dykes of *Group II* underwent major reconstruction during the development stage, which made studies of their initiation impossible. Neptunian dykes belonging to *Group I* display features indicating the sole role of mechanical processes during their development. In the dykes of *Group II* chemical erosion played an important role. Different dykes were filled in different ways. Processes of injection of loose sediments into fissures opening in the solid substrate, rapid burying of open dykes by migrating dunes of crinoidal sand, and slow sieving of fine material into vast systems of voids, are proposed to explain the filling of dykes by various types of sediments. The interpretation of the formation of internal breccias at the footwall of a fault scarp is presented. The influence of pressure dissolution phenomena on the post-depositional history of the neptunian dykes is evaluated. Field and microscopic observations were complemented by isotopic analyses of the sediments and calcite cements filling the dykes. Paleogeographic conclusions based on the characters of the neptunian dykes are given.

Key words: Neptunian dykes, Origin of the cavities, Filling the cavities, Paleogeography, Tatra Mountains (Polish Carpathians), Middle Jurassic.

INTRODUCTION

The history of a neptunian dyke consists of three major stages: initiation, development, and filling, each of which influences its own specific set of features (SMART & *al.* 1987). Particular stages may be short and occur directly one after another, or may be separated by a considerable amount of time, during which environmental conditions have changed. The term neptunian dyke, indicating a marine origin, refers only to the time of filling. Therefore, the dykes may be initiated and develop in both subaerial and marine conditions. There are two major processes leading to the formation of neptunian dykes: mechanical fracturing, caused by extensional tectonics or gravity sliding, and chemical dissolution, either subaerial or subaqueous. Identification of the history of the dykes is very important in paleogeographic interpretations, as it often provides data otherwise unavailable in the rocks lying in normal stratigraphic position.

In the High-Tatric series dykes filled with various types of Bajocian and Bathonian deposits are common. Counterparts of their fillings in normal stratigraphic succession in most of the High-Tatric area are preserved only locally, in the form of laterally discontinuous, lenticular bodies, mostly as a result of post-Bajocian, Bathonian, and post-Bathonian erosion. Therefore, the dykes are valuable sources of information about those stages. Conclusions from the present studies of neptunian dykes are widely used in paleogeographic reconstruction of the High-Tatric series during the Middle-Jurassic (ŁUCZYŃSKI *in press*).

GEOLOGICAL SETTING

The High Tatra Mts. are the northernmost of the "core mountains" of the Central Western Carpathians. On its northern slopes, the Variscan crystalline massif is covered by Permo-Mesozoic sedimentary rocks, lying both in autochthonous and allochthonous positions. The sedimentary cover represents two major successions (or series), High-Tatric and Sub-Tatric, differing substantially in their facies development. The High-Tatric succession, exposed in the topographically upper part of the massif, is represented generally by relatively shallow-water facies, marked by numerous stratigraphic gaps. The Sub-Tatric series, exposed in the lower part of the massif, is of nappe character, is more complete and is composed generally of deeper-water facies.

The High-Tatric series consists of both autochthonous and allochthonous rocks. They belong to three major tectonic units (Text-fig. 1): the Kominy Tylkowe unit (autochthonous), and the Czerwone Wierchy and Giewont units (allochthonous or foldic). The allochthonous units have been detached from their basement and overthrust northward during the Alpine orogeny. Paleogeographically, they represent areas originally situated south of the autochthonous series.

In the Kominy Tylkowe unit, the stratigraphic succession is complete across the Triassic/Jurassic boundary and the lowermost Middle Jurassic (Aalenian) is represented by sandy carbonates of the Dudziniec Formation. In the Czerwone Wierchy and the Giewont units, a major stratigraphic gap occurs above the Middle Triassic (Anisian) limestone and dolomite sequence, which is penacordantly covered by Middle Jurassic deposits of the Smolegowa, Krupianka or even the Raptawicka Turnia formations (Text-fig. 2). The Smolegowa Formation and, particularly, the Krupianka Formation, are laterally discontinuous, lenticular bodies with thickness ranging from few dozen centimetres up to about 2 m. The same formations exposed in the autochthonous unit overlie the Dudziniec Formation,

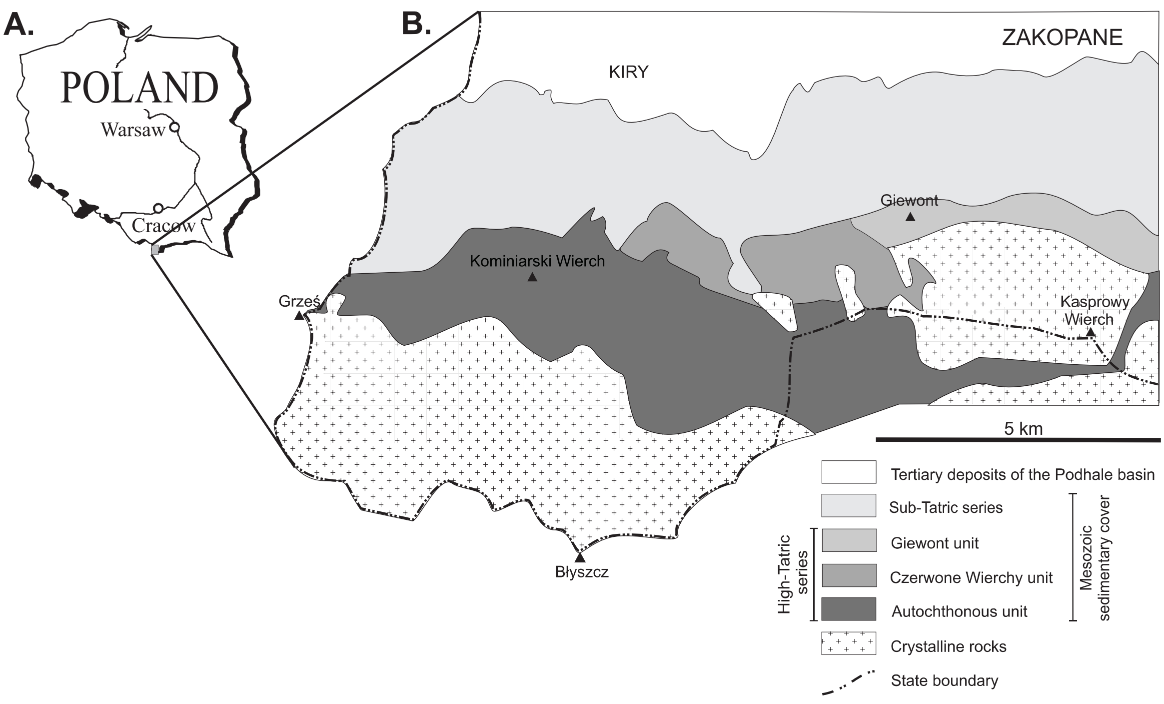

Fig. 1. Structural map of western part of the Polish section of the Tatra Massif (B), and its geographic location (A)

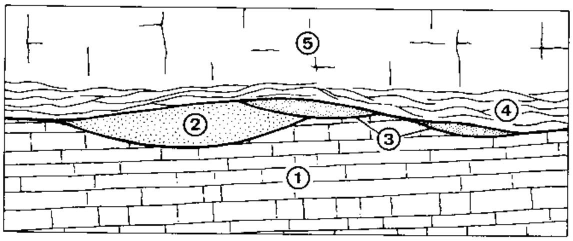

Fig. 2. Idealized spatial relations between the Middle Jurassic lithosomes in the High-Tatric foldic units; **1** – Middle Triassic limestones and dolomites, **2** – white coarse crinoidal limestones of the Smolegowa Formation (Bajocian), **3** – red ferruginous and crinoidal limestones of the Krupianka formation (Bathonian), **4** – Wavy bedded limestones of the Raptawicka Turnia Formation (Callovian), **5** – Massive limestones of the Raptawicka Turnia Formation (Oxfordian)

and are generally laterally continuous (up to a dozen or so metres thick).

The Smolegowa Formation, of Bajocian age (HORWITZ & RABOWSKI 1922; LEFELD & *al.* 1985), is uniformly developed as unbedded, white, light grey and pinkish, coarse crinoidal limestones. The sediments exhibit a range of features characteristic of *in situ* deposition of pelmatozoan material close to crinoidal meadows (GŁUCHOWSKI 1987).

The Krupianka Formation, of Bathonian age (PASSENDORFER 1935, 1938), occurs in three major limestone lithofacies: crinoidal, ferruginous and nodular (ŁUCZYŃSKI *in press*). Its common features are: intensive red colour, occurrence of more-or-less abundant pelmatozoan debris, and a relatively abundant, coarse terrigenous admixture of quartz, limestone, dolomite and ferruginous clasts. Crinoidal limestones are exposed mainly in the Giewont unit. The poor preservation state of the pelmatozoan ossicles, the occurrence of the abundant clastic admixture and the characteristic lenticular shape of the lithosomes, are considered to indicate allochthonous deposition of the crinoidal debris in the form of megaripples (JENKYNS 1971). In the Czerwone Wierchy unit, the crinoidal limestones pass laterally into ferruginous limestones, generally not exceeding 30 cm in thickness. Stromatolites are common in both the crinoidal and the ferruginous limestones (SZULCZEWSKI 1963, 1968). In the majority of sections in the Kominy Tylkowe unit, the limestones of the Krupianka Formation exhibit a well-developed stylonodular structure. The differences

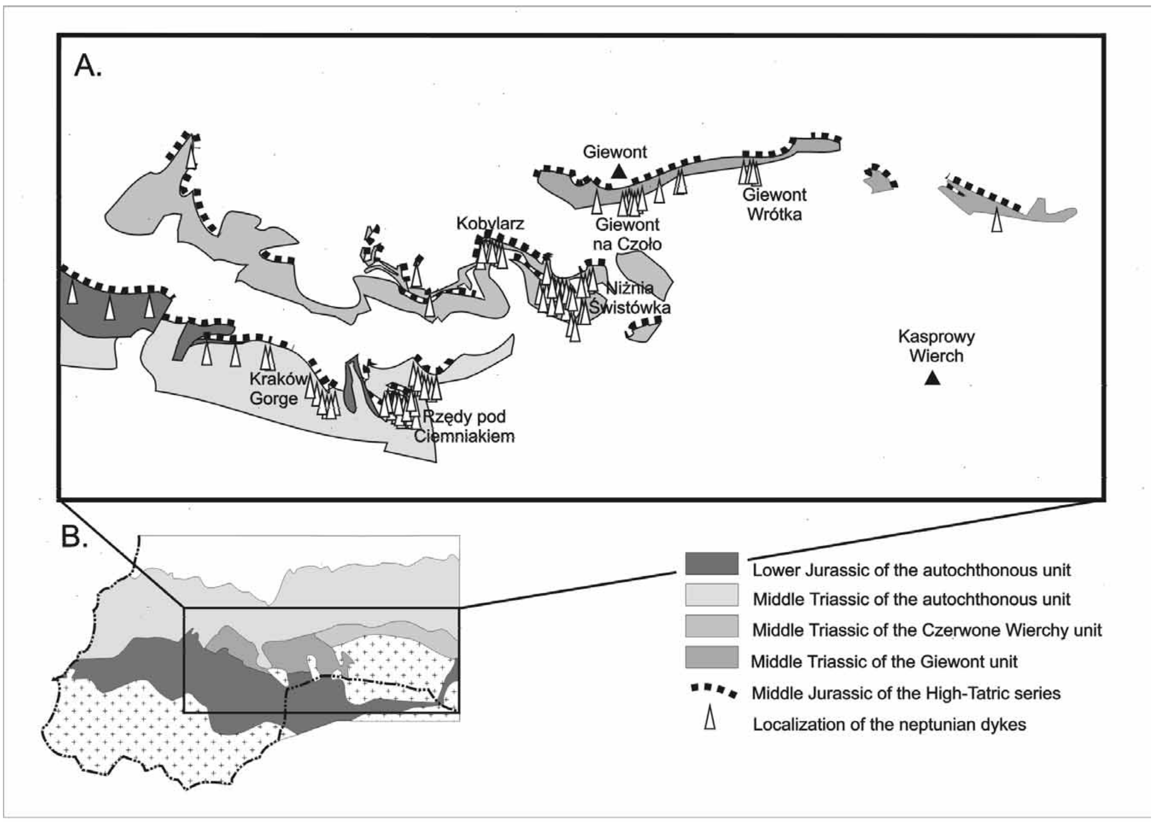

Fig. 3. Distribution of the neptunian dykes filled with Middle Jurassic sediments penetrating the Lower Jurassic and the Middle Triassic of the High-Tatric series (A) and their location (B). Symbols used in (B) are given in Text-fig 1

between the three Bathonian lithofacies are to a large extent an effect of late diagenetic pressure dissolution and compaction (ŁUCZYŃSKI 2001).

The Krupianka limestones are overlain by the Raptawicka Turnia Formation, which begins with wavy-bedded limestones of Callovian age (HORWITZ & RABOWSKI 1922; PASSENDORFER 1935, 1938).

Neptunian dykes filled with Middle Jurassic deposits occur in all three tectonic units of the High-Tatric series (Text-fig. 3). They cut the Middle Triassic limestones and dolomites, and rarely, in the autochthonous unit, they also cut the Lower Jurassic.

CLASSIFICATION, DESCRIPTION AND DISTRIBUTION OF NEPTUNIAN DYKES

One of the basic features of the distribution of the neptunian dykes in the High-Tatric series is their occurrence in distinct concentrations. A separate group of interconnected dykes, or dykes situated close to each other, characterized by a range of common features of the filling sediments and of the character of the walls, is referred to herein as **a system of neptunian dykes**, and is treated as a unit in all quantitative considerations.

Individual systems show various shapes and sizes. They may be homogeneous or may consist of parts connected to each other but filled with different deposits. Commonly, a once-formed set of fractures was later reopened, resulting in formation of dykes with multi-stage filling. Reference of such dykes to a particular system was arbitrary. They were either referred to the distinctly dominant type, or were treated as two or more independent systems.

Eighty-seven systems of neptunian dykes filled with Middle Jurassic sediments have been recognized in the High-Tatric series. They are classified here into six types, constituting two groups:

- Group I:

- *dykes filled with Smolegowa limestones* (8),
- *dykes filled with Krupianka limestones* (26),
- *dykes filled mostly with calcite cements* (6),
- *internal breccias* (15),

- Group II:

- *dykes filled with red micrite* (13),
- *dykes associated with pressure solution structures* (19).

Group I. Dykes belonging to this group are characterized by the prevalence of sharp-edged walls. They occur in distinct, isolated systems, consisting mainly of vertical structures. Sharp-edged host-rock fragments are commonly incorporated into the sediments filling the dykes. The deposits are generally coarse-grained.

Dykes filled with Smolegowa limestones (Pl. 1, Fig. 1), *dykes filled with the Krupianka limestones* (Pl. 1, Fig. 2) and *dykes filled mostly with calcite cements* (Pl. 1. Fig. 8) most commonly consist of wide (up to 125 cm), vertical dykes with sharp-edged walls, rapidly thinning-out downwards, and of short sills (< 2 m) branching from them. The penetration depth ranges from 4 to 13 m. Only these 6 systems of *dykes filled mostly with calcite cements*, which are partly filled with marine sediments, were taken into account. The *dykes filled with Krupianka limestones* show relatively complicated shapes. They consist generally of broadly branching dykes, up to a few dozen centimetres thick. Their orientation varies; the thickest dykes are generally vertical, whereas the narrower ones are commonly oblique and parallel to the bedding planes of the host-rock. The d*ykes filled with Krupianka limestones* and *dykes filled with Smolegowa limestones* are commonly connected with other types of dykes.

The *internal breccias* are also included into *Group I*. Although these are not dykes in the strict sense of this word, and they are characterized by different architecture, the co-occurrence and common origin of the dykes and some internal breccias is widely recognized (BLENDINGER 1986; LEHNER 1991; Winterer & *al.* 1991; JONES 1992; MICHALIK & *al.* 1994).

A specific feature of *internal breccias* (Pl. 1, Figs 6-7) is the abundance of sharp-edged host-rock fragments in the filling. The clasts are of various size - from very fine, to lithoclasts exceeding 10 cm in diameter. The shapes of the bigger clasts generally fit well to the surrounding walls. Most commonly the breccias are monomictic, but some dykes contain clasts of various lithology. The *internal breccias* generally form irregular caverns in places where the host-rock is particularly intensively fractured. The caverns are of various sizes, with diameters ranging from a few centimetres up to more than a metre. They penetrate the Triassic substratum to depths exceeding 40 m and are commonly associated with *dykes filled with Krupianka limestones*.

Group II. The walls of the dykes of *Group II* are smooth and devoid of sharp edges. The systems tend to be vast and to consist mainly of sills. The filling is fine, and is commonly distinctly laminated, indicating slow sedimentation.

Dykes filled with red micrite (Pl. 1, Figs 3-4) and *dykes associated with pressure solution structures* (Pl. 1, Fig. 5) commonly find their way along the heterogeneities of the host-rock; particularly, they tend to run

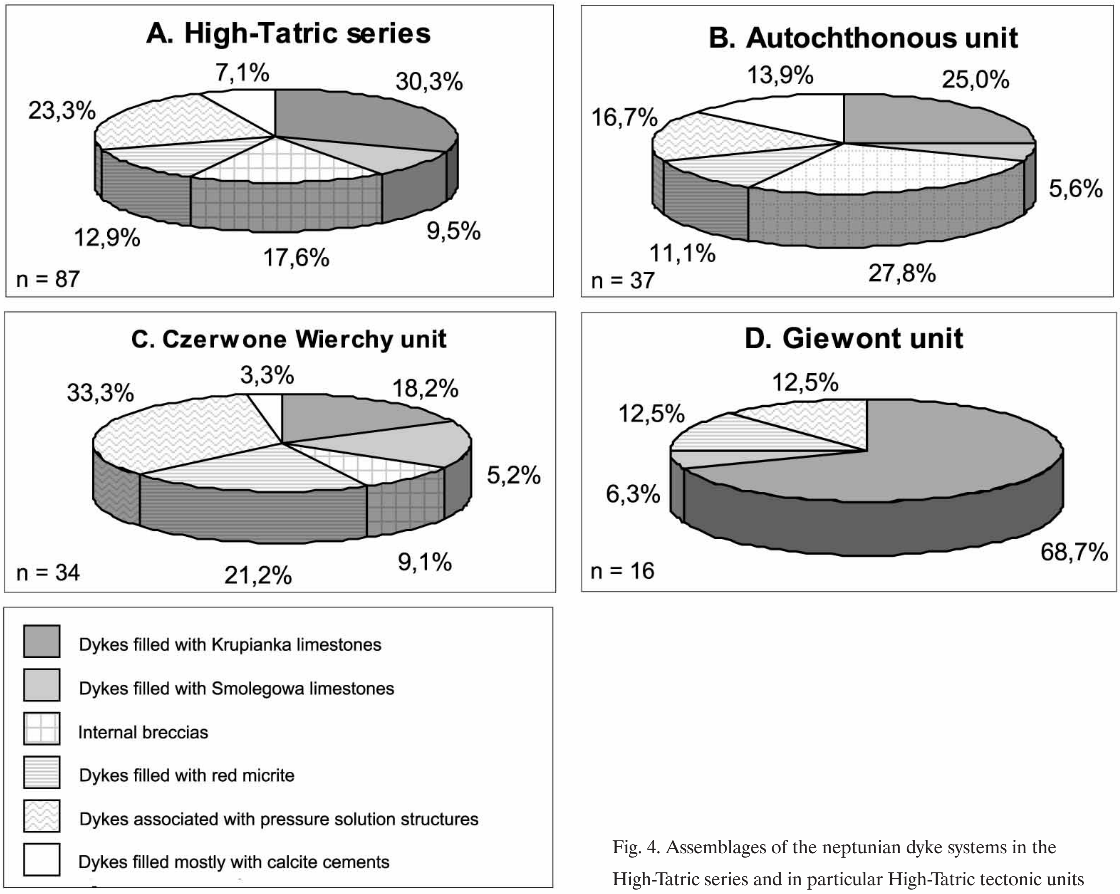

Fig. 4. Assemblages of the neptunian dyke systems in the High-Tatric series and in particular High-Tatric tectonic units

along bedding planes. Individual sills are thin; from few millimetres to a few centimetres (rarely exceeding 10 cm). In contrast to the other types of dykes, their walls are smooth and no host-rock fragments are found in the filling. The systems penetrate the basement to depths of more than 150 m.

In *dykes associated with pressure solution structures* the filling shows the character of a solution residuum. It is a concentration of ferruginous and clay minerals, and of clasts resistant to pressure dissolution (mainly quartz). Only these systems, which beside residual material also contain marine sediments, the latter preserved generally only in their broader parts, are considered here. Most commonly (in 15 dykes) it is red micrite, but Smolegowa and Krupianka limestones also occur (in 1 and 3 dykes respectively). The dyke walls coincide with stylolites and clay seams.

The adoption of a ”system of neptunian dykes” as a unit in quantitative analysis caused some methodical problems. A single *dyke filled with Smolegowa limestones*, which penetrates the basement to a depth of a few dozen centimetres, if occurring alone, was considered a separate system, at the same hierarchical level as a set of *dykes filled with red micrite*, outcropping in an area of several tens of square metres. Nonetheless, a clear picture of a different distribution pattern of various dykes appeared from this investigation.

Particular tectonic units contain different assemblages of neptunian dykes (Text-fig. 4). The proportion obtained for the whole High-Tatric series is taken here as a reference point. The autochthonous unit is marked by the highest proportion of *internal breccias* and of *dykes filled mostly with calcite cements*. The Czerwone Wierchy unit is characterized by a particularly high content of systems belonging to *Group II* and of *dykes filled with Smolegowa limestones*. The Giewont unit is dominated by *dykes filled with Krupianka limestones*.

ORIGIN OF NEPTUNIAN DYKES

Initiation of voids

Analysis of the processes of void initiation is based on the observations of distribution and orientation of the systems, their shape, size, and relation to the host-rock.

Orientation of dykes

Studies of dyke orientation were possible in only a few places. A surface best suited for the measurements – the top of the Triassic sequence, which corresponds to the sea floor, from which the dykes penetrated, is well exposed in only a few places, as most of the exposures occur on anti-dip slopes. The studies were carried out on Kobylarz and in Niżnia Świstówka (Text-fig. 3) in the Czerwone Wierchy unit (4 systems), and in Rzędy pod Ciemniakiem in the autochthonous unit (3 systems). Palinspastic reconstruction was limited to rotation of the host-rock bedding planes to horizontal.

Directional analysis was made exclusively for vertical and steeply oriented dykes, as only they cut the host-rock across heterogeneities such as bedding planes, and only their orientation depends directly on the initiation process. Sills that run along bedding planes make use of structures that already existed. Therefore, only *dykes filled with Smolegowa limestones*, *dykes filled with Krupianka limestones* and *dykes filled mostly with calcite cements* were taken into consideration here.

Summarized projections of all data obtained from the particular tectonic units (Text-fig. 5) show the lack of any predominant dyke orientation. Different situation emerges for particular systems, where all the vertical dykes are generally parallel. *Dykes filled with the Krupianka limestone* show the most uniform orientation.

The following conclusions can be drawn from the above analysis.

a) The lack of a predominant dyke orientation in particular tectonic units is an effect of intensive tectonic deformations, which took place after the formation of the dykes.
b) Similar orientation of the dykes belonging to particular systems can be interpreted as an effect of a single act of mechanical strain perpendicular to the surfaces of the dykes.
c) The most regular orientation of the *dykes filled with Krupianka limestones* is probably caused by the fact that these are the youngest of the analysed systems. The other systems were subjected to subsequent reactivation and consequent changes of orientation.

Distribution of dykes

The distribution of the studied dykes is very uneven. A particularly dense concentration of dykes occurs in the Rzędy pod Ciemniakiem (Text-fig. 4), where 24 systems have been distinguished in an area not exceeding 300 metres in diameter. Many features at this locality, such as prevalence of dykes with sharp-edged walls, high content of *internal breccias*, and of *dykes filled mostly with calcite cements*, resemble structures forming at the foot of fault scarps (VACHARD & *al.* 1987; MIŠIK & *al.* 1994). Less numerous concentrations, (mainly of *dykes filled with Smolegowa limestones* and *dykes filled with Krupianka limestones*) occur in few other places of the High-Tatric series (Kraków Gorge - 6, Kobylarz - 8, Giewont na Czoło - 7). Along with vast areas without neptunian dykes (e.g. Zawrat Kasprowy), it points for a very inhomogeneous distribution.

A locality with an especially dense occurrence of neptunian dykes is Niżnia Świstówka, where 21 individual systems crop out in a relatively small area (>0.5 km^2). Most of them belong, however, to *Group II* and cannot be directly linked with fault activity.

Overall shapes of neptunian dyke systems

In some dykes, the shapes of the systems depend solely on the process of their initiation. Such is mostly the case with dykes filled directly after opening of the fissures.

Preservation of original shape by a neptunian dyke is indicated by:

- brittle character of walls,
- simple shape, domination of vertical structures and limited depth of penetration;
- orientation consistent with regional paleostress directions;
- features indicating rapid, unreiterated filling.

These criteria markedly limit the list of dykes, where the final shape can be treated as the result of the initiation process. Voids of *Group II* and *internal breccias* do not meet the basic, above-listed conditions. *Dykes filled mostly with calcite cements* exhibit features revealing long exposure of their walls after opening. Among the *dykes filled with Smolegowa limestones* and *dykes filled with Krupianka limestones,* some of the systems are filled with more than one type of deposit, or contain abundant sharp-edged fragments of host-rock. Therefore, finally preservation of original post-initiation shape has been assumed in only 11 dyke systems.

Shapes of the studied systems vary together with the material filling the dykes. No major differences have been observed between dykes belonging to the same type from different tectonic units. All of the basic features of the selected systems, such as their shape, predominance of vertical structures and brittle character of the walls, correspond well with the features postulated for dykes that were initiated mechanically (BLENDINGER 1986; LEHNER 1991). The only peculiar feature is the depth of penetration, which is greater than could be expected (a dozen or so, instead of few metres).

Conclusions

Reconstruction of the process of void initiation, based on dyke orientation, shape and distribution, points to its mechanical, most probably tectonic nature.

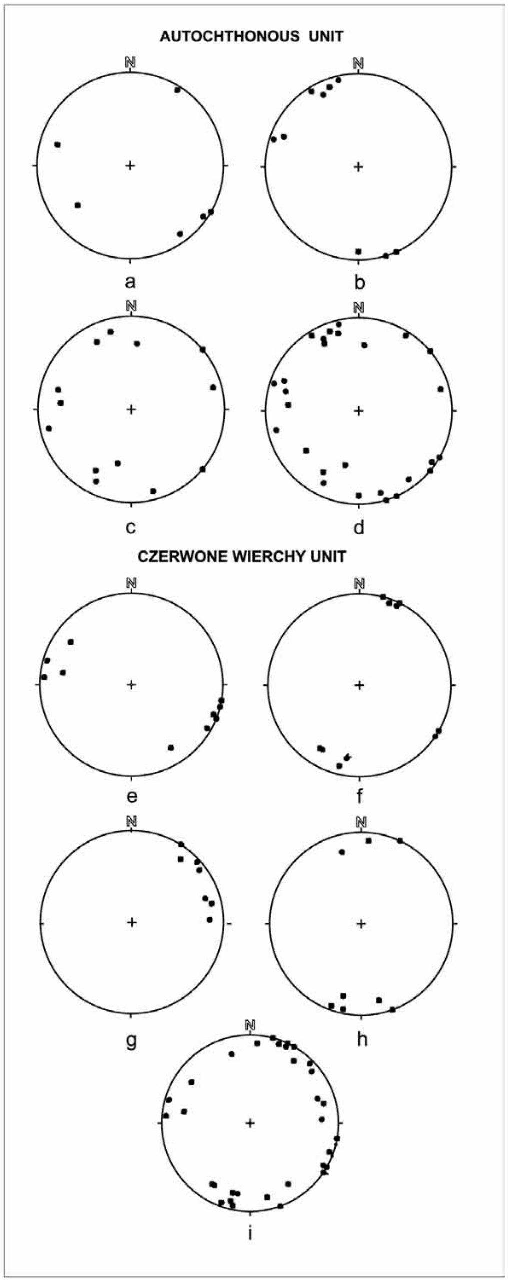

Fig. 5. Orientation of the neptunian dykes. Projection of normal to the dyke planes on the lower hemisphere; **a, b, c, e, f, g, h** – orientation of fissures constituting particular systems of neptunian dykes, **d** – total of a, b and c (orientation of all fissures measured in the autochthonous unit), **i** – total of e, f, g and h (orientation of all fissures measured in the Czerwone Wierchy unit)

The most convincing feature is the orientation pattern of selected systems of dykes; a distinct preference for one or more directions indicates tectonic origin of neptunian dykes (WENDT 1971; WINTERER & *al.* 1991), even when other features, such as e.g., character of walls, point to influence of chemical processes in their development (JONES 1992). A tectonic origin is also suggested by patchy distribution of dykes, and by their concentration in definite groups close to normal faults, (VERA & *al.* 1984; BRAITHWAITE & HEATH 1992). The association with normal faults may be of various nature and origin. It is closest when the dykes are formed by filling open spaces in tectonic screes at the fault's footwall by sediments actually deposited on the sea floor (MIŠIK & *al.* 1994; VACHARD & *al.* 1987). This process often leads to the creation of internal breccias. Scarp fault breccias are commonly accompanied by neptunian dykes running parallel to a fault (WIECZOREK & *al.* 1994, 1995; BÖHM & *al.* 1995). During the Bajocian and the Bathonian, the Rzędy pod Ciemniakiem area was probably situated at the footwall of a repeatedly reactivated fault scarp, where internal breccias have formed. Also the shapes of selected systems, to which a preservation of original post-initiation form is ascribed, correspond well to the descriptions of structures that were definitely initiated by tectonic processes (BLENDINGER 1986; LEHNER 1991).

Structures similar to those described above have also been interpreted as effects of gravity sliding phenomena (FÜCHTBAUER & RICHTER 1983; FÜCHTBAUER & *al.* 1984; WINTERER & SARTI 1994). In the High-Tatric area, strain resulting from gravitation or relaxation of a massif in the external parts of elevated blocks may also have played an important role in the creation of fissures. However, no indicators of gravity sliding, such as lenticular open spaces, scoop-shaped blocks or association with listric faults (WINTERER & SARTI 1994) have been observed. Moreover, the deposition of the host rocks and the formation of neptunian dykes were separated by a long time-gap (roughly 50 Ma). In the Middle Jurassic, the Middle Triassic substrate must already have been strongly lithified and thus rather unsusceptible to gravity sliding.

Development of voids

The analysis of void development is based on observations of: character of walls, shape and size of the systems, and of some aspects of sediment arrangement, which indicate recurrent movements inside the fissures.

Character of dyke walls

5 basic types of dyke walls have been distinguished in the systems studied.

Sharp walls. Clean, covered neither by calcite cements nor by ferruginous encrustations, sharp-edged walls, (Pl. 2, Figs 1, 3, 5).
Gradational walls. Walls of thin, anostomosing dykes intensively penetrating host-rocks. It is difficult to delimit such boundaries precisely. Individual grains and other host-rock elements are commonly incorporated in the sediments filling the dykes (Pl. 2, Fig. 8).
Walls covered by calcite cements. Walls covered by radiaxial and palisade calcite cements growing from dyke walls towards its centre, accompanied by blocky cements generally occupying central parts of the voids (Pl. 2, Figs 4-6).
Walls covered by ferruginous encrustations. Walls covered by ferruginous (hematite) encrustations, in the form of laminated crusts and endostromatolites (Pl. 2, Figs 2, 7).
Walls running along pressure solution structures. Several variants occur here:
– stylolitic boundary (Pl. 2, Fig. 3),
– boundary with residuum of resistant grains (mainly quartz),
– boundary covered by dissolution seams (Pl. 2, Fig. 8),
– boundary covered by microstylolites and horsetail stylolites.

Sharp walls, *walls covered by calcite cements*, and *walls covered by ferruginous encrustations* constitute together a group of “**brittle**” walls. *Gradational walls* and *walls running along pressure solution structures*, are referred to as “**smooth**” walls.

Various wall types coexist within single systems, with no major differences between particular tectonic units. The only exception is an extraordinarily high content of *smooth* walls in the systems in the Czerwone Wierchy unit. The proportions of groups of *brittle* and

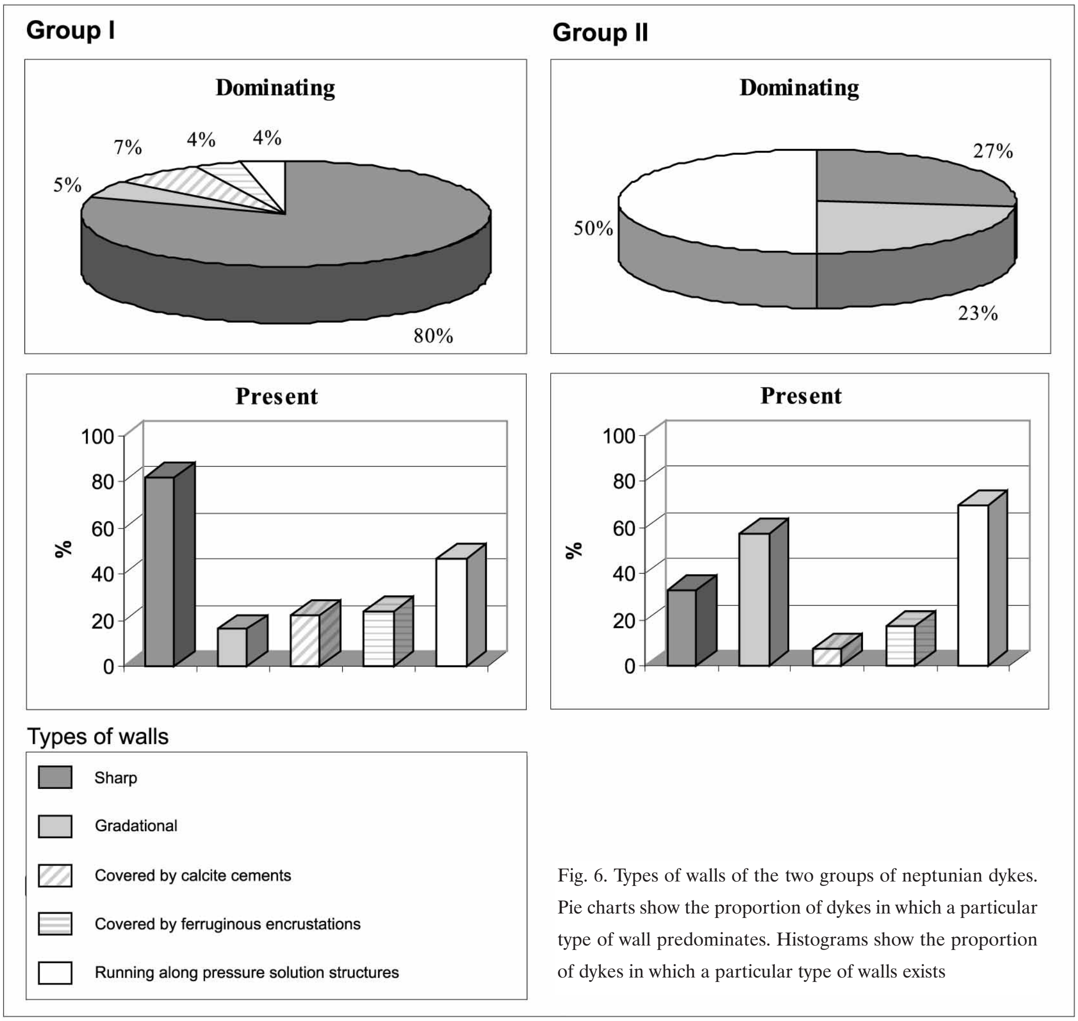

Fig. 6. Types of walls of the two groups of neptunian dykes. Pie charts show the proportion of dykes in which a particular type of wall predominates. Histograms show the proportion of dykes in which a particular type of walls exists

smooth walls vary greatly in the two groups of dykes distinguished. *Group I* is characterized by a predominance of *sharp* walls and the occurrence of walls *running along pressure solution structures* in less than 50% of the systems (Text-fig. 6), with other wall types found in less than a quarter of dykes. *Group II* is characterized by similar proportion of *brittle* and *smooth* walls.

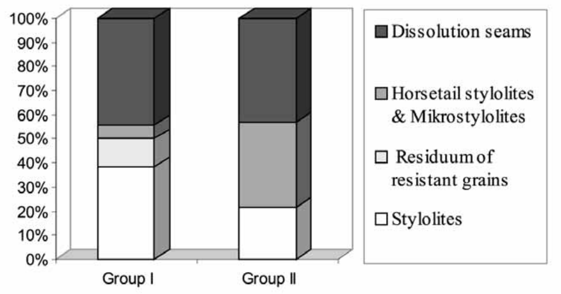

Fig. 7. Proportion of various types of wall running along pressure solution structures in the two groups of neptunian dykes

The only wall type occurring frequently in both groups of dykes is that *running along pressure solution structures*. They were noted in 47% of the dykes from *Group I* and in 70% of the dykes from *Group II*. Pressure solution phenomena develop preferentially along lithological boundaries (WANLESS 1979; BRAITHWAITE & HEATH 1992; RAILSBACK 1993). Commonly they run along walls of horizontal sills (MIŠIK 1998*). Walls running along pressure solution structures* display quite a variety of types. Such walls are included into the group referred to as smooth. Some of them are, however, both genetically and structurally closer to brittle walls.

Four varieties of walls running along pressure solution structures can be divided into two groups – **sutured** (stylolites and boundaries with a residuum of resistant grains), related to brittle walls, and **non-sutured** (dissolution seams and horsetail stylolites/microstylolites), related to smooth walls. The proportions of their occurrences in the two groups of dykes distinguished is markedly different (Text-fig. 7.). In *Group I sutured* and *non-sutured walls* occur in more or less equal numbers, whereas in *Group II non-sutured walls* predominate.

Evidence of recurrent movement inside the fissures

Simple subdivision of neptunian dyke history into initiation, development, and filling stages, does not always reflect the actual sequence of processes. Especially in dykes of tectonic origin, minor recurrent movements led to reactivation of already existing fissures.

Multiple filling, where Smolegowa limestones coexist with Krupianka limestones, occurs mainly in the Czerwone Wierchy unit. This tectonic unit contains most of *dykes filled with Smolegowa limestones*, and probably was the longest subjected to the processes of fissure opening. In many systems, the concurrence of different deposits is limited to the various lithofacies of the Krupianka Formation; however, only those systems, in which different sediments are in juxtaposition along vertical boundaries, are considered to be indicators of recurrent movements.

Another indication of recurrent movements within the neptunian dykes is the process of breaking away of sharp-edged host-rock fragments. The intensity of this process and appropriate architecture of voids led to the formation of *internal breccias*. However, fragments of surrounding rocks are commonly incorporated also into the *dykes filled with Smolegowa limestones* and the *dykes filled with Krupianka limestones*.

Intimately connected with reactivation and recurrent movements are the *internal breccias*. Most commonly the breccias are monomictic (BLENDINGER 1986; JONES 1992), but in some breccias the clasts are more variable (CLARI & *al.* 1995). Co-existence of various clasts may result from falling into the void of material coming directly from the sea-bottom or from higher parts of the stratigraphic column cut by the dyke. The co-existence of clasts of different origin is typical of the High-Tatric systems of *internal breccias*, particularly those found in the Rzędy pod Ciemniakiem area.

Shapes and sizes of neptunian dykes

The shapes and sizes of systems differ markedly between the two groups of dykes distinguished.

Group I. *Internal breccias* have their own characteristic architecture. Other systems belonging to *Group I* consist generally of a vertical dyke (dykes) penetrating downwards from a discontinuity surface, and of sills branching from it. The sills are relatively short, which results in the whole system being limited to a narrow vertical section, with a width not exceeding a few metres. The dykes to sills ratio ranges between 1:5 to 1:10, but as the dykes are generally much longer than the sills, the respective length ratio varies between 1:2 to 3:1. Due to the greater width of the vertical dykes than the sills, the volume ratio ranges between 1:1 and 1:4 in favour of the dykes. The depth of basement penetration varies to a large extent, but in most areas it does not exceed 10 m.

Group II. Systems of dykes belonging to *Group II* penetrate the Triassic carbonates to great depths, which at

Niżnia Świstówka exceed 100 m. The sills distinctly predominate, intensively penetrating the host-rocks in the form of frequently branching, parallel, thin fissures, passing laterally into pressure solution structures. Although these systems are extensive, their vertical structures are not well developed. Sills are locally connected by short vertical dykes. Size of the systems does not enable the dyke to sill ratio to be evaluated, as was possible for the systems of *Group I*. Nonetheless, all respective values (number, length and volume) are at least a few dozen times higher in favour of the sills.

Conclusions

Analysis of dyke walls, of phenomena indicating recurrent movements inside the fissures, and of the shapes and sizes of the systems, indicates that the two groups of dykes show a markedly different development history.

In the systems belonging to *Group I*, the main role has been played by mechanical processes. This is shown by the predomination of clean, *brittle* walls, pointing to rapid deposition inside the dykes (WENDT 1971; BRAITHWAITE & HEATH 1992), and by the common incorporation of sharp-edged host-rock fragments into the filling deposits (BLENDINGER 1986; JONES 1992). Dykes of this group also contain numerous structures indicating their reactivation, such as filling by different sets of deposits in juxtaposition along vertical boundaries (WENDT 1965; MIŠIK & *al.* 1995). Moreover, the typical shapes of the systems correspond well to the descriptions of neptunian dykes of an unequivocal tectonic origin (BLENDINGER 1986; LEHNER 1991). The features described were most probably the result of recurrent tectonic processes, however, gravity sliding may also have played a substantial role, especially in the development of internal breccias (WINTERER & SARTI 1994).

The dykes belonging to *Group II* display some features suggesting the influence of chemical erosion on their development. The walls are commonly *smooth*, which is characteristic of voids subjected to karstic dissolution (POTY 1980; VERA & *al.* 1984, 1987), and the filling material commonly contains insoluble host-rock elements. No structures pointing to dyke reactivation were found. The influence of chemical processes is suggested, moreover, by the overall shapes of the systems (SMART & *al.* 1987) and by the predominance of horizontal sills over vertical dykes (CHERNS 1982). The most probable explanation for the features described seems to be karstic dissolution. The supposition of subaerial exposure is in accordance with data from the normal stratigraphic succession, such as the occurrence of stratigraphic breaks and abundant admixture of terrigenous material (ŁUCZYŃSKI *in press*). However, it must be admitted that no unequivocal indicators of emergence, such as speleothems, vadose silts or stable isotope data (see below), confirm such an interpretation. Similar features have also been interpreted as the effects of subsolution (WINTERER & SARTI 1994), while neptunian sills are also described as openings of horizontal parts of listric faults (WINTERER & *al.* 1991), which form without any necessity of subaerial exposure. The length and abundance of the High-Tatric sills seem, however, to contradict such a possibility.

Filling of dykes

Sedimentation inside a dyke may be similar to that on the sea bottom or may be specific only for the voids. Its character depends mostly on the connection of dykes with the external environment, on their orientation and extent, and on the character and rate of marine deposition.

Comparison of the Middle Jurassic deposits in the neptunian dykes with the normal stratigraphic succession

Direct comparison of deposits filling the dykes with sediments of normal stratigraphic succession was possible only in the *dykes filled with Smolegowa limestones* and *dykes filled with Krupianka limestones*. All of the other types represent accumulation processes that are specific for the dyke environment.

Smolegowa limestones filling the dykes and occurring in normal stratigraphic sequence are practically indistinguishable. Minor differences are as follows:
- dyke fillings are less variable and lack greater amounts of shell debris,
- crinoid material is more disintegrated in dykes,
- in some places, the crinoidal limestones in the dykes show orientation of their elements, a feature that is absent in the deposits in normal stratigraphic position,
- coarse terrigenous admixture (>1 cm), sporadically present in the Bajocian deposits lying in normal position, does not occur inside the dykes.

Krupianka limestones. There are few features distinguishing the Krupianka limestones occurring in the neptunian dykes from those in normal stratigraphic position:
- more common subtle lamination of sediments occurring in dykes,
- more common occurrence of pressure solution structures in the normal stratigraphic position than in the deposits filling the dykes,

– absence in the dykes of ammonites, belemnites and extraclasts of diameter exceeding 1 cm, which are common in deposits occurring in normal stratigraphic position.

Character of deposition inside the voids

A. *Dykes filled with Smolegowa limestones* and *dykes filled with Krupianka limestones*. As discussed above, the Krupianka and particularly the Smolegowa limestones filling the dykes and cropping out in normal stratigraphic position are almost identical. The main differences relate to the orientation of sediments. The longer axes of non-isometric elements in the dykes are generally oriented parallel to the walls. As the dykes predominate over the sills, it leads to a prevalence of vertical lamination. The Smolegowa limestones do not show any differentiation regarding their position inside the systems, while the more branched systems of *dykes filled with Krupianka limestones* show gradual downward elimination of coarser elements.

Of the various models explaining the occurrence of identical deposits in the dykes and on the sea bottom, two can be applied to High-Tatric Middle Jurassic. The first one applies to filling the dykes by crinoidal limestones. JENKYNS (1971) compared lenticular accumulations of crinoidal limestones to sand dunes. According to this model, megaripples, moving on the sea bottom, reach open fissures and the crinoid sand fills the voids. The accumulation is abrupt and the process does not lead to segregation of various sediment fractions and components. Material deposited in this way shows no lamination and does not differ in composition from the deposits of crinoid dunes accumulated on the sea bottom.

The second process that can be applied here is hydrostatic injection of deposits (WENDT 1971; FÜCHTBAUER & RICHTER 1983; LEHNER 1991). Brittle fracturing, leading to fissure opening, takes place here only in lithified basement rocks, with loose material lying on the sea bottom acting in a plastic or friable way. In the High-Tatric neptunian dykes, the non-lithified Bajocian and/or Bathonian deposits were aspired to fractures opening beneath them, which formed in the Triassic substrate. Such a process does not cause changes in the composition and texture of the accumulated deposits. It is, in fact, an example of redeposition of the whole rock.

The two processes described above, and their effects differ in a number of aspects, which enable them to be distinguished.

(a) The megaripple model can be applied only to dykes filled with the Bathonian crinoidal limestones, the accumulation of which was allochthonous.

(b) The injection model assumes that the neptunian dykes have never been fissures open on the sea bottom. Therefore, their walls could not have been subjected to the influence of external factors, such as incrustations, etc.

(c) The two processes lead to different orientation and distribution of host-rock fragments. In the case of crinoidal material transport, the fragments fall onto the fissure's bottom. Assuming a paracontemporaneous filling of the fissures with their opening due to injection, the fragments are incorporated into the sediments filling the dykes in their whole volume, with a possibility of vertical orientation.

(d) Crinoid sediments poured into open fissures do not show any lamination. Dykes filled by injection are characterized by a specific bending of layers near the walls and by vertical lamination (LEHNER 1991; FELISIAK 1995).

(e) Pouring of the crinoid material into open fissures is much more predestined for a recurrent, pulsative character, than deposition by sediment injection.

(f) Injection of non-lithified deposits accumulated on the sea bottom should lead to thickness reduction of source rocks in the direct vicinity of the larger systems of dykes.

(g) Injection does not allow a 'sieve effect' to occur.

None of the models can explain the filling of all of the systems of *dykes filled with Smolegowa limestones* and *dykes filled with Krupianka limestones*. The two processes coexisted in various systems, in different parts of the same system, or even followed one another in the same dyke.

Dykes filled with Smolegowa limestones show numerous features indicating their filling by the process of sediment injection. A lamination parallel to the dyke walls has been discovered in 3 systems (out of 7). The sieve effect did not take place. Host-rock fragments commonly occur throughout the dykes. Calcite cements present on some dyke walls represent older calcite veins, along which the fracturing took place. Moreover, the accumulation of pelmatozoan material of the Smolegowa limestones was interpreted as characteristic of autochthonous sedimentation (GŁUCHOWSKI 1987; ŁUCZYŃSKI *in press*). These sediments do not fit the presumptions of the megaripplemark model. Therefore, it seems that *dykes filled with Smolegowa limestones* were filled mostly by the process of sediment injection.

Some of the *dykes filled with Krupianka limestones* show numerous indications of wall exposure, such as calcite cements or ferruginous incrustations, pointing against the injection model. In the larger systems, a sieve effect is visible, revealed mainly by downward disappearance of terrigenous material and crinoid ossicles, indicating a gradual dyke filling (WIEDENMAYER 1963), rather than by a single act of deposition. This all testifies to dykes opening on the sea bottom and their filling by crinoid sand transported as megaripples. However, *dykes filled with Krupianka limestones* show also attributes in favour of the injection model. Lamination parallel to the walls occurs in 10 out of 26 systems. Moreover, the host-rock fragments do not form distinct concentrations at the bottom of systems, but are spaced irregularly. All these indicate that, at least partly, *dykes filled with Krupianka limestones* were also filled by rapid injection, which took place mainly in the thicker and less branched dykes.

B. *Dykes filled with red micrite* and *dykes associated with pressure solution structures*. Filling of mostly horizontal *dykes filled with red micrite* and *dykes associated with pressure solution structures* took place in a different manner from that in vertical dykes (WENDT 1963, 1971, 1988; HSÜ 1983; BLENDINGER 1986). Fine sediment was slowly flown by waters circulating in open systems. A very fine fraction and a common lack of microfossils are generally explained as an effect of sieving in vast systems of thin voids (WIEDENMAYER 1963; WINTERER & *al.* 1991; MIŠIK & *al.* 1994, WINTERER & SARTI 1994). The d*ykes associated with pressure solution structures* analysed here are mainly sills that originally were filled with red micrite and were later subjected to dissolution, compaction and concentration of the pressure solution residuum. Therefore, the process of their filling was similar to that of *dykes filled with red micrite*. The ferruginous deposits of the Krupianka Formation were the most probable source rocks for the red micrite filling the dykes.

C. *Internal breccias.* Systems of *internal breccias* are filled by sediments characteristic of other types of dykes. The character of filling of particular caverns varied depending mainly on their shapes, position in the whole system and communication with the sea bottom (BLENDINGER 1986; LEHNER 1991; ČINČURA 1992).

In most *internal breccia* systems*,* red micrite is the main matrix. Host-rock fragments, detached from the walls, lie predominantly on the floors of the caverns, which indicates that during their deposition the voids were not filled with sediment. The same is confirmed by the arrangement of the laminae in the matrix, commonly coating the clasts. The upper parts of the systems, directly communicating with the sea bottom, and in many places adopting a form of a “cemented scree”, were filled directly after the opening of the fractures. However, their remote parts remained unfilled until buried by sieving downward of red micrite, originating from the Krupianka limestones deposited in the systems’ upper parts. Voids that were not completely filled with sediments were sealed by late calcite cements.

Walls of the caverns and of host-rock fragments incorporated into the matrix are clean and, with few exceptions, devoid of early calcite cements, ferruginous encrustations etc. It indicates that they were not subjected to external factors, and were probably filled by deposits directly after opening, or were isolated from the sea bottom. The filling did not, however, take place under hydrostatic conditions, because of too intensive substrate fracturing. Sediment supply was probably assured by the localisation of the *internal breccia* systems at the foot of an active fault scarp.

D. *Dykes filled mostly with calcite cements.* The sediments *of dykes filled mostly with calcite cements* are typical of the other types of dykes. The voids are sealed by radiaxial, palisadic and fibrous cements, growing from the dyke walls towards its centre, where they create a suture. Calcite cements occur in those dykes or in those parts that were isolated from the sea bottom and could not be filled by external sediments (FISCHER 1964; KENDAL 1985; WINTERER & SARTI 1994; CLARI & MARTIRE 1996). The central parts of thicker dykes are filled with blocky cements, which developed in places that opened too fast to allow growth of radiaxial cements.

Most of the studied systems of *dykes filled mostly with calcite cements* occur at the Rzędy pod Ciemniakiem, where they coexist with *internal breccias*, which is probably not accidental. In this area, a particularly intensive fracturing of the substrate took place, and part of the dykes remained isolated from the sediment influx. In the following fracturing episodes some fragments of the dykes gained connection with other systems, and were buried mainly by deposits of the Krupianka formation.

OXYGEN AND CARBON ISOTOPIC COMPOSITION OF DEPOSITS AND CEMENTS FILLING THE NEPTUNIAN DYKES

Sixteen oxygen and carbon isotope analyses were performed on deposits and cements filling the neptunian dykes. The following samples were analysed: crinoidal limestones of the Smolegowa and the Krupianka formations (3 samples), red micrite (4 samples), pressure solution residuum (1 sample), radiaxial and palisadic calcite cements covering the dyke walls (4 and 2 samples respectively), and blocky calcite cements from the central parts of dykes (2 samples). Moreover, in order to estimate the influence of pressure dissolution processes on the isotopic composition, analyses of nodule and matrix of the Bathonian stylonodular limestones, cropping out in normal stratigraphic position, were also performed. All values are presented versus the PBD standard.

$\delta^{13}C$ values vary between 2.4‰ and 3.3‰ (Text-fig. 8). The spectrum of $\delta^{18}O$ is wider and ranges between –2‰ and –8‰. A distinctly lower result was obtained only from the pressure solution residuum. Analysed samples, particularly those with the red micrite, in relation to Middle Jurassic neptunian dykes from other regions, are depleted in heavy oxygen isotope $\delta^{18}O$ (e.g. WINTERER & *al.* 1991; WINTERER & SARTI 1994; MIŠIK & *al.* 1994). In the case of cements and all other types of deposits except red micrite, the $\delta^{13}C$ and $\delta^{18}O$ values fall within the range characteristic of marine waters of normal temperature and salinity (e. g. GRANT GROSS 1964; HUDSON 1977; HOFFMAN & *al.* 1991; GRUSZCZYŃSKI 1998), or are slightly lower. Such isotopic composition indicates good communication between the dykes and the sea bottom. Similarly, distinctly positive results of $\delta^{13}C$ for radiaxial and palisadic calcite cements covering the dyke walls, and for blocky calcite occurring in their central parts, indicate that their precipitation took place in waters of normal salinity, which excludes their speleothem origin (WINTERER & *al.* 1991; WINTERER & SARTI 1994). Similar isotopic values of early radiaxial cements covering the walls, and of late blocky cements closing up the voids, can be treated as evidence of similar conditions and of a continuing good communication with marine waters.

Oxygen and carbon isotopic composition is greatly influenced by diagenesis (HUDSON 1977; GRUSZCZYŃSKI 1998). In the studied material late diagenesis resulted in major depletion of the pressure solution residuum in the heavy oxygen isotope. To a lesser extent, this process also took place in the red micrite and in the calcite cements. The influence of pressure solution processes on isotopic composition is confirmed by results obtained for the nodule and the matrix of stylonodular limestones. The matrix, abounding in pressure solution structures, is characterized by a distinctly lower $\delta^{18}O$ value than the neighbouring nodule, which is devoid of such structures.

The isotopic composition of the deposits and cements filling the dykes of *Group I* confirms their mechanical origin. The isotopic composition of the red micrite indicates that its deposition took place under marine pelagic conditions, instead of a subaerial terra-rossa type accumulation.

PALAEOGEOGRAPHIC CONCLUSIONS

The detailed palaeogeographic history of the High-Tatric domain during the Middle Jurassic is the subject of a separate paper (ŁUCZYŃSKI *in press*). Only some major implications of the distribution and development of the neptunian dykes are presented in this paper.

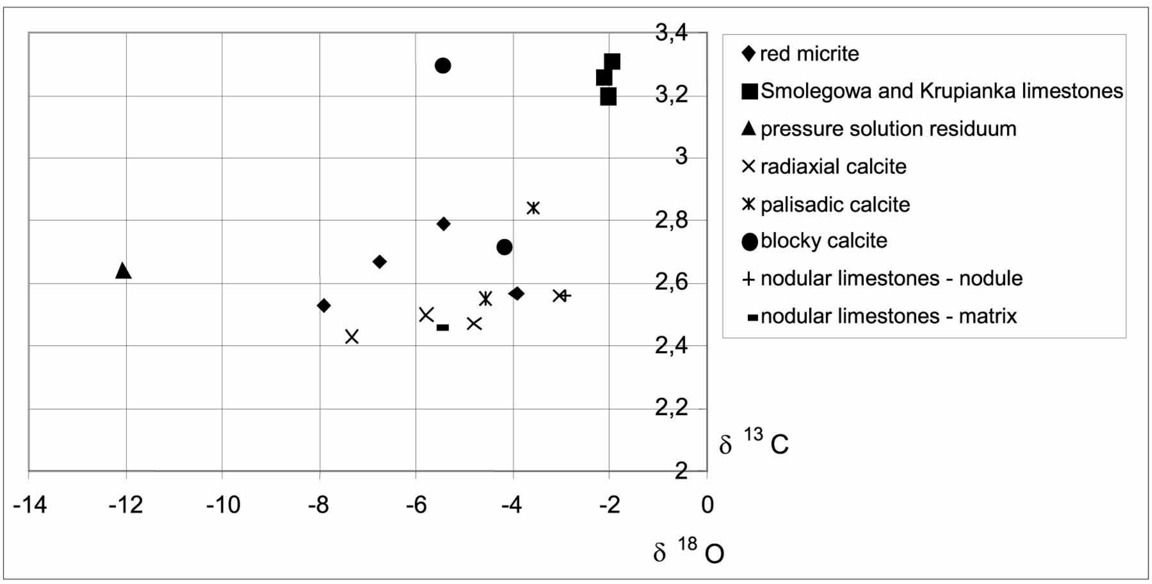

Fig. 8. $\delta^{13}C$ and $\delta^{18}O$ composition of the deposits and cements filling the neptunian dykes and of the Krupianka Formation nodular limestones (results given versus the PDB standard)

The periods of formation of neptunian dykes belonging to *Group I* mark episodes of intensive substrate fracturing, most probably associated with extensional tectonic movements. At least two such episodes took place in the High-Tatric area during the Middle Jurassic. The first followed the deposition of the Smolegowa limestones (Bajocian), and led to filling the fissures, which opened in solid Triassic substrate, by loose crinoidal sands lying on the sea bottom. The process was most intensive in the Czerwone Wierchy unit, where most of the dykes filled with Smolegowa limestones occur. The second episode took place during sedimentation of the Krupianka limestones (Bathonian), and resulted in the burying of the dykes by migrating dunes of crinoidal sands.

Neptunian dykes *filled with Smolegowa* and *with Krupianka limestones* commonly occur also in the areas, where these deposits are absent in normal stratigraphic succession (e.g. most of the Czerwone Wierchy unit). This proves that during the Bajocian and the Bathonian, marine deposition took place in the whole area of the High-Tatric series. On the other hand, the concentration of dykes of *Group II* in the Czerwone Wierchy unit, with evidence of the influence of chemical dissolution on their development, suggests a prolonged emergence of this area, separating the sedimentation of the Smolegowa from the Krupianka limestones.

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PLATE 1

Types of neptunian dykes filled with Middle Jurassic sediments in the High Tatric series

1 – Fragment of a neptunian dyke filled with coarse crinoidal limestone of the Smolegowa Formation; Kraków Gorge, autochthonous unit.
2 – Fragment of a neptunian dyke filled with crinoidal limestone of the Krupianka Formation, with sharp-edged fragments of the host-rocks incorporated into the sediments filling the dykes; Giewont Massif, Giewont unit.
3 – Parallel sills filled with red micrite; Niżnia Świstówka, Czerwone Wierchy unit.
4 – Distinctly laminated red micrite filling one of the larger voids; Rzędy pod Ciemniakiem, autochthonous unit.
5 – Parallel horizontal neptunian dykes associated with pressure solution structures; Niżnia Świstówka, Czerwone Wierchy unit.
6,7 – Internal breccia with sharp-edged limestone (A) and dolomite (B) clasts and with red micrite matrix; Rzędy pod Ciemniakiem, autochthonous unit;
8 – Neptunian dykes filled mostly with calcite cements forming a “cemented scree”; Rzędy pod Ciemniakiem, autochthonous unit.

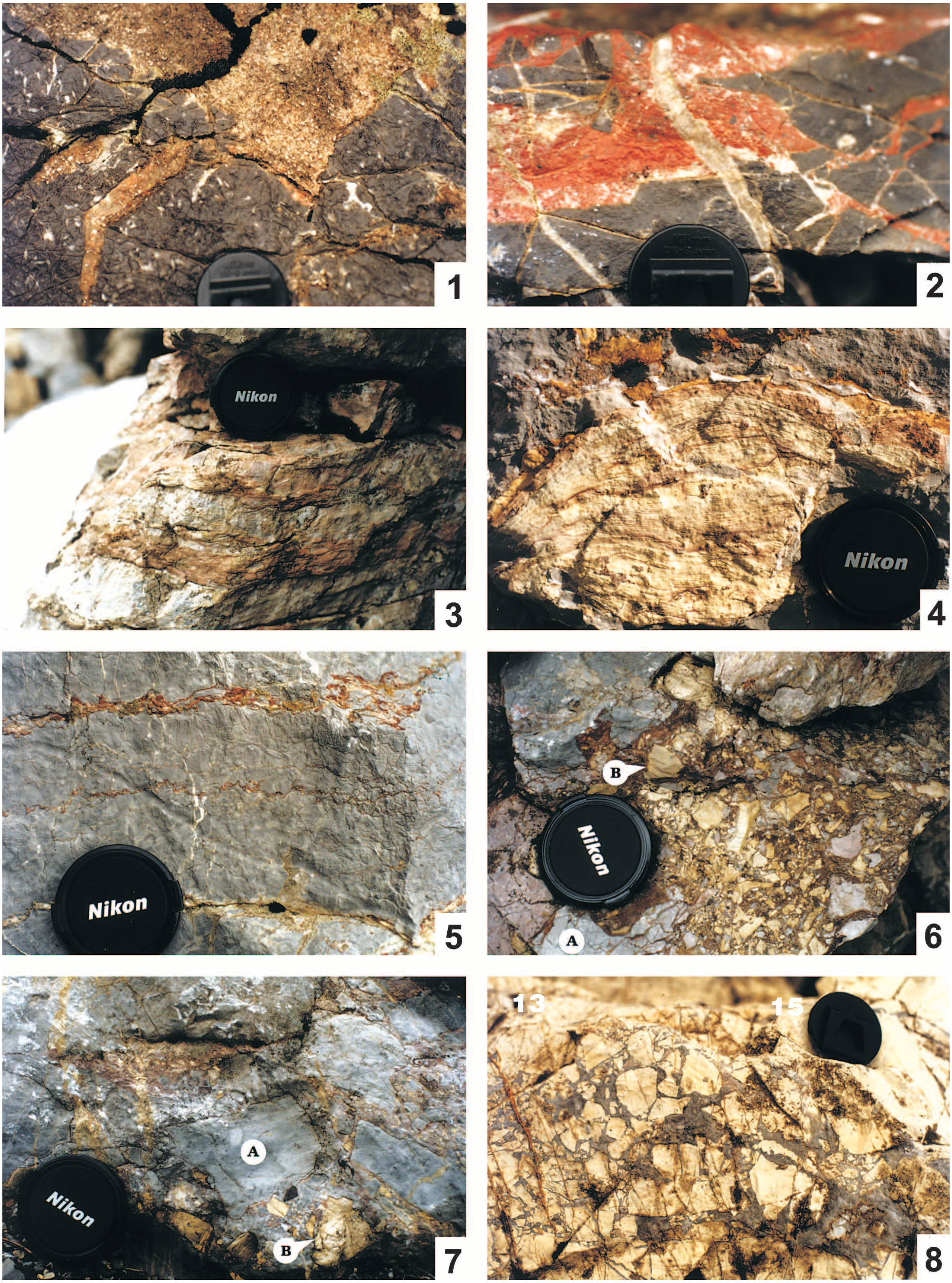
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PLATE 2

Major types of walls of neptunian dykes filled with Middle Jurassic sediments in the High-Tatric series

1 – Neptunian dyke with a sharp wall filled with red micrite (A), penetrating Triassic micritic limestone (B), cut by a thin dyke filled with red micrite and calcite cements (C); Wąwóz Kraków gorge, autochthonous unit; × 4.

2 – Neptunian dyke with a wall partly covered by ferruginous encrustations, filled with Krupianka limestone (A) penetrating Triassic micritic limestone (B); Rzędy pod Ciemniakiem, autochthonous unit; × 4.

3 – Neptunian dyke with a sharp and stylolitic wall filled with Krupianka limestone (A) penetrating Triassic micritic limestone (B) with sharp-edged fragments of host-rocks (arrows) and rounded dolomite clasts (C); Giewont massif, Giewont unit; × 4.

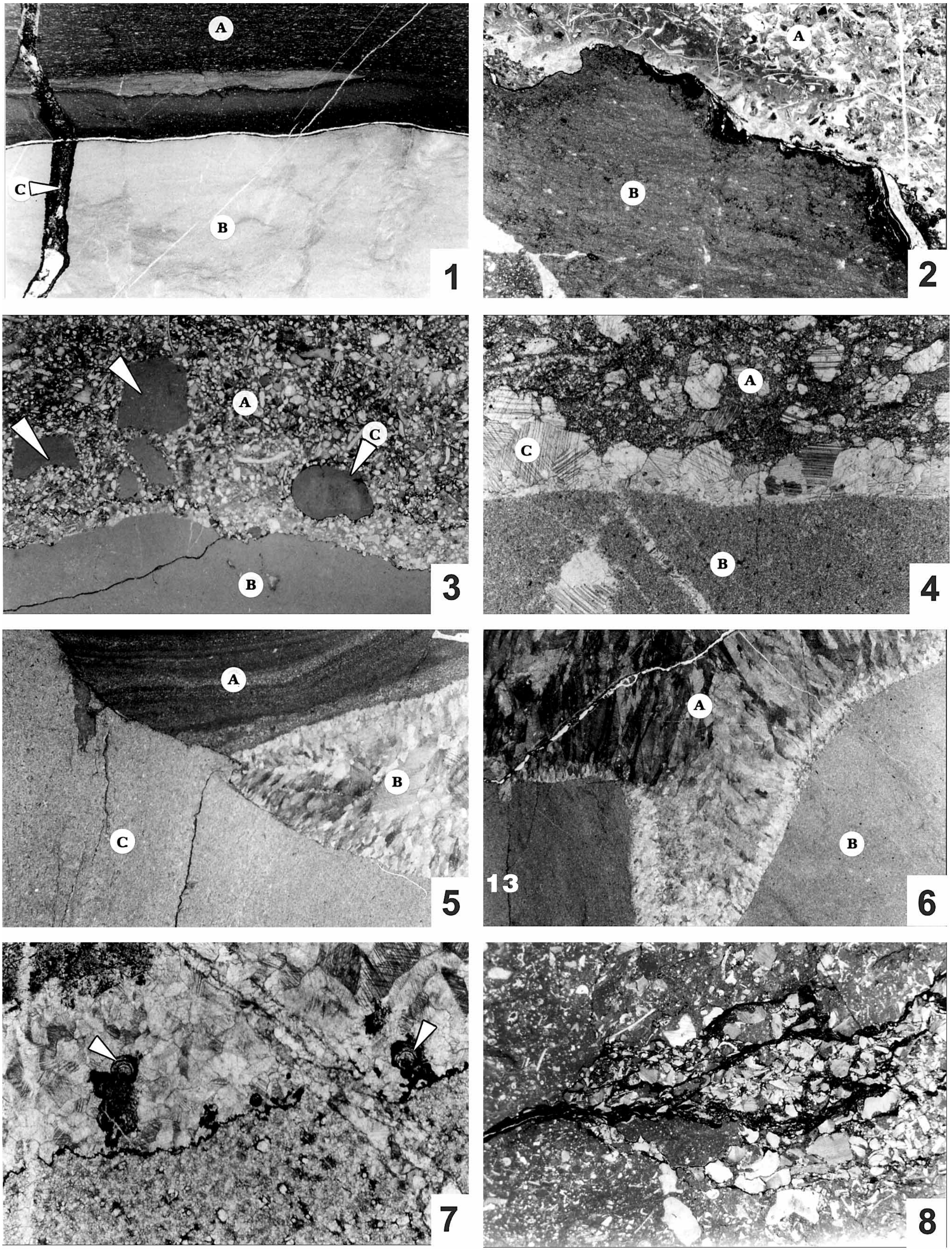
4 – Neptunian dyke filled with Krupianka limestone (A) penetrating Triassic micritic limestone (B) with a wall covered by calcite cements (C); Giewont massif, Giewont unit; × 15.

5 – Neptunian dyke with a sharp wall, filled with laminated red micrite (A) and calcite cements (B) penetrating Triassic micritic limestone (C); Rzędy pod Ciemniakiem, autochthonous unit; × 4.

6 – Neptunian dyke filled with radiaxial calcite cements (A) penetrating Triassic micritic limestone (B); Rzędy pod Ciemniakiem, autochthonous unit; × 5.

7 – Endostromatolites (arrows) in a neptunian dyke filled with Krupianka limestones; Rzędy pod Ciemniakiem, autochthonous unit; × 20.

8 – Neptunian dyke with a gradational boundary passing laterally into a dissolution seam; Niżnia Świstówka, Czerwone Wierchy unit; × 4.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