Acta Geologica Polonica, Vol. 63 (2013), No. 1, pp. 137–151
DOI: 10.2478/agp-2013-0005

VERSITA

Character and structural evolution of the Mała Łąka Fault in the Tatra Mts., Carpathians, Poland

MAGDALENA DĄBROWSKA[1] AND EDYTA JUREWICZ[2]

[1]*Faculty of Geology, University of Warsaw, Al. Żwirki i Wigury 93, PL-02-089 Warsaw, Poland.*
present address: EFENDI – Internet Domains, Białowieska 1/44, PL-04-063 Warsaw, Poland.
[2]*Faculty of Geology, University of Warsaw, Al. Żwirki i Wigury 93, PL-02-089 Warsaw, Poland.*
E-mail: edyta.jurewicz@uw.edu.pl

ABSTRACT:

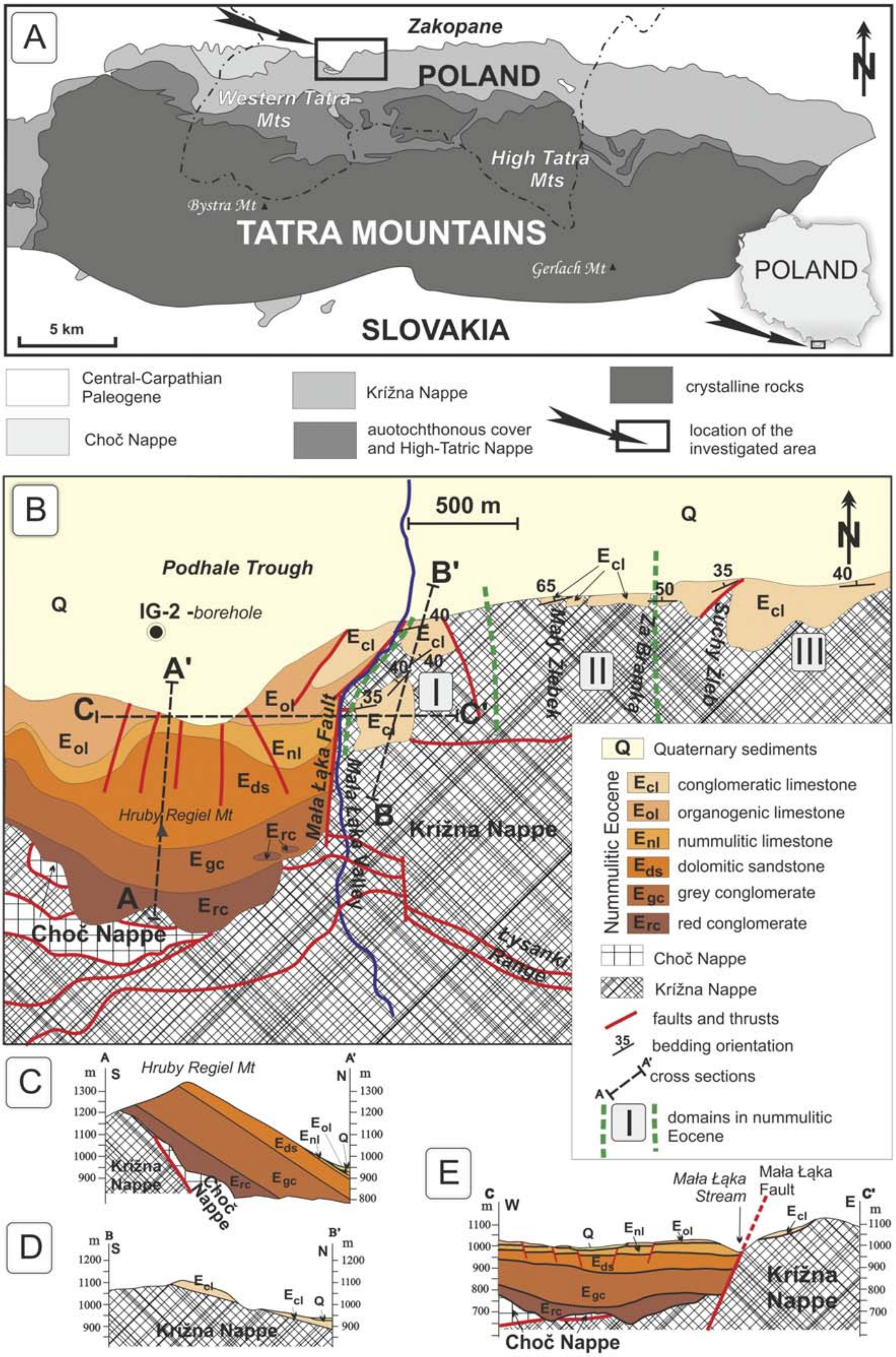
Dąbrowska, M. and Jurewicz, E. 2013. Character and structural evolution of the Mała Łąka Fault in the Tatra Mts., Carpathians, Poland. *Acta Geologica Polonica*, **63** (1), 137–151. Warszawa.

The Mała Łąka Fault in the Tatra Mts. is a synsedimentary normal fault responsible for the variable thickness of Eocene deposits in the area. Its main activity took place in the interval from the sedimentation of red conglomerates to the appearance of nummulitic limestones. The estimated throw is up to 350 m. Near the northern margin of the Tatra Mts., the trend of the fault changes from N–S to NE–SW. This part of the fault could have been activated during the Neogene uplift of the Tatra Mts. and rejuvenated as a sinistral fault. In the upper reach of the Mała Łąka Stream, the fault trend does not follow the course of the Mała Łąka Valley. Here, the flowing stream waters used extensional fractures within a damage zone associated with the Mała Łąka Fault rather than the lithological boundary at the tectonic contact between the Triassic dolomites and the Eocene conglomerates. The fault has a hinge-like character; its hinge was located in the present-day Kościeliska Valley, c. 2.5 km west of the Mała Łąka Valley.

Key words: Synsedimentary fault; Nummulitic Eocene; Conglomerate; Tatra Mts.; Podhale Trough.

INTRODUCTION

This paper is focused on solving the controversies linked with the Mała Łąka Fault (Text-fig. 1) in the Tatra Mts. Its presence is reflected in significant differences in the thickness of the Eocene nummulitic facies (Borové Formation *sensu* Gross *et al*. 1984), particularly its conglomeratic series, which reach a total of 350 m on the Hruby Regiel Mt. (Sokołowski 1959; see*:* Borecka 2007), compared to only several metres and a discontinuous cover on the eastern side of the fault (Text-fig. 1). Sokołowski (1959) considered that the differences in the thickness and development of the Eocene deposits reflected the variable morphology of the basement that persisted until the sedimentation of the Podhale Flysch. According to Bac-Moszaszwili (1971), the Mała Łąka Fault was formed due to the activation of an older structure, i.e. the overthrust of the western part of the Sub-Tatric Nappes onto their Zakopane part. As a result, rejuvenation of the basement structures caused an overthrust of younger Eocene deposits onto Triassic rocks. In contrast to this interpretation, Jurewicz (2005) considered that the Eocene deposits on Hruby Regiel were not overthrust onto the Tatra nappe structures and that the Mała Łąka Fault was a normal fault, throwing down the western block


A
Zakopane
POLAND
Western Tatra Mts
High Tatra Mts
Bystra Mt
TATRA MOUNTAINS
Gerlach Mt
POLAND
5 km
SLOVAKIA
N
Central-Carpathian Paleogene
Choč Nappe
Krížna Nappe
auotochthonous cover and High-Tatric Nappe
crystalline rocks
location of the investigated area
B
500 m
Q
Podhale Trough
IG-2 -borehole
A'
C
C'
B'
B
A
Ecl
Eol
Enl
Eds
Erc
Egc
Hruby Regiel Mt
Mała Łąka Fault
Mała Łąka Valley
Krížna Nappe
Choč Nappe
Łysanki Range
Mały Żleb
Za Bramką
Suchy Żleb
I
II
III
65
50
35
40
Q Quaternary sediments
Nummulitic Eocene
Ecl conglomeratic limestone
Eol organogenic limestone
Enl nummulitic limestone
Eds dolomitic sandstone
Egc grey conglomerate
Erc red conglomerate
Choč Nappe
Krížna Nappe
faults and thrusts
bedding orientation
cross sections
domains in nummulitic Eocene
C
A
A'
S
N
m
Hruby Regiel Mt
1300
1200
1100
1000
900
800
Krížna Nappe
Choč Nappe
Erc
Egc
Eds
Enl
Eol
Q
D
B
B'
S
N
1200
1100
1000
900
Ecl
Q
Krížna Nappe
E
C
C'
W
E
Mała Łąka Stream
Mała Łąka Fault
1100
1000
900
800
700
Q
Enl
Eol
Eds
Egc
Erc
Ecl
Choč Nappe
Krížna Nappe

(hanging wall). According to Borecka (2007), the Mała Łąka Fault is synsedimentary in character. The change of bedding orientations near the Mała Łąka Valley indicates a strike-slip character of the fault, the activity of which was linked with Middle Miocene horizontal compression responsible for the formation of large dislocation zones in the Podhale Trough (Borecka 2007).

GEOLOGICAL SETTING

The Tatra Mts. are a fragment of the western Central Carpathians, which are a part of the Alpine Orogen. They are composed of a crystalline core, a para-autochthonous sedimentary High-Tatric cover and overthrust High-Tatric and Sub-Tatric (Krížna and Choč) nappes (e.g. Kotański 1963; Andrusov 1968; Passendorfer 1983; Mahel' 1986; Plašienka *et al.* 1997; Nemčok *et al.* 1998). The nappe structure of the area was formed as a result of Late Cretaceous tectonic activity (e.g. Plašienka *et al*. 1997; Lefeld 2009).

In the Middle Eocene, marine sediments of the so-called Central Carpathian Palaeogene Basin (CCPB) started to form on a folded and eroded Mesozoic basement (Passendorfer 1958; Bieda 1959; Halicki 1963; Marschalko 1968; Roniewicz 1969; Gross *et al.* 1984). Palaeogene deposits from the Podhale area comprise two members differing in lithology and facies: a lower, carbonate complex, known as the nummulitic Eocene (e.g. Bieda 1959, 1963) and an upper flysch complex, referred to as the Podhale Flysch and Oligocene in age (e.g. Blaicher 1973; Olszewska and Wieczorek 1998; Gedl 2000; Garecka 2005). The nummulitic Eocene is a transgressive facies, consisting mainly of carbonate breccia, organogenic to organodetrital limestone and polymict sandstone, deposited in shallow-water (e.g. Passendorfer 1958; Roniewicz 1969; Olszewska and Wieczorek 1998). According to Gross *et al.* (1984), they belong to the Borové Formation, being a part of the Subtatric Group, passing upwards into flysch deposits of the Huty (Zakopane) Formation.

According to Soták *et al.* (2001), the CCPB was formed as a marginal sea of the Peri-Tethyan basin and shows a fore-arc position developed in the proximal zone of the Outer Carpathian accretionary prism. It is not clear whether the Tatra Mts. formed part of the morphology of the basin bottom or formed an island in the period preceding Eocene transgression and sedimentation. According to Passendorfer (1958) and Passendorfer and Roniewicz (1963), at least during the sedimentation of the Zakopane beds (the oldest part of Podhale Flysch), the Tatra Mts. could have been an island, whereas Marschalko and Radomski (1960) suggested that the axis of the CCPB passed through the massif.

A subsequent tectonic stage in the history of the Tatra Mts. is linked with the uplift of the massif along the Sub-Tatric Fault located at their southern margin (Uhlig 1899; Andrusov 1959). As a result, the autochthonous sedimentary cover with the overthrust Sub-Tatric and High-Tatric nappes was tilted to the north (Sokołowski 1959), which caused strong erosion of its southern part (Bac-Moszaszwili 1997). The uplift had a rotational character (Piotrowski 1978). The rotation axis was horizontal and W–E-oriented (Jurewicz 2005). According to various authors the rotation angle was: 20° (Piotrowski 1978), 30–35° (Bac-Moszaszwili 1997) or 40° (Jurewicz 2005). The Podhale Trough, with the nummulitic Eocene and the Podhale Flysch, was formed between the uplifted Tatra Massif to the south and the Pieniny Klippen Belt to the north. Nowadays, a larger part of the Podhale Trough, particularly the Zakopane Cuphole, is covered with Quaternary sediments (Text-fig. 1B)

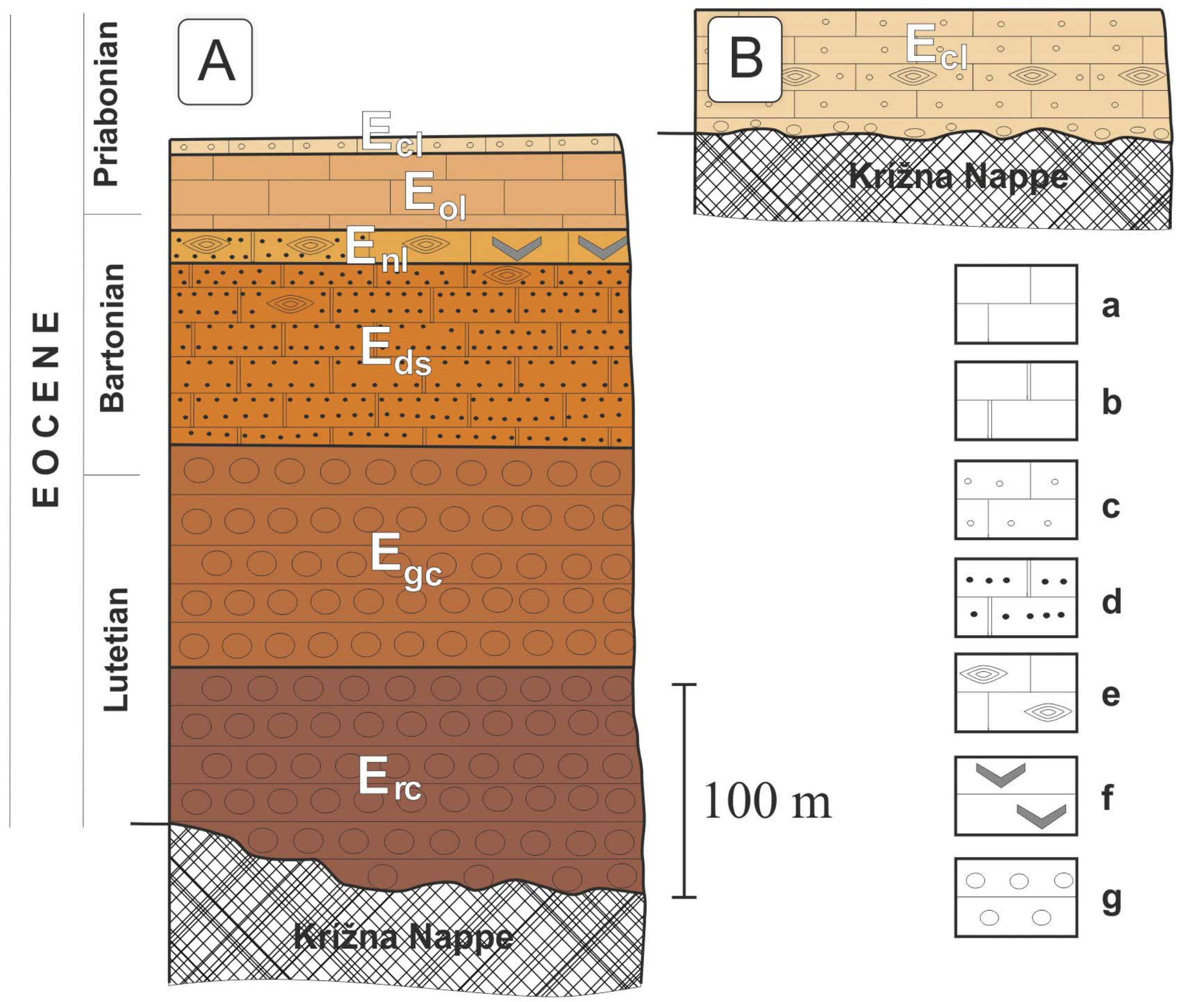
Nummulitic Eocene in the Mała Łąka Valley region

The Mała Łąka Valley represents the boundary between the so-called western part and Zakopane part of the Sub-Tatric Nappes (Bac-Moszaszwili 1998). The area located to the east of the Mała Łąka Valley, i.e. the Zakopane part of the Sub-Tatric Nappes (Łysanki Range), is built of dolomites and limestones belonging to the Krížna Nappe (Text-fig. 1B), the age of which was determined by Kotański (1963) as Middle Triassic (Anisian and Ladinian). To the west, within the western part of the Sub-Tatric Nappes, besides rocks of the Krížna Nappe, occur Jurassic limestones of the Choč Nappe. To the west of the Mała Łąka Valley, the nummulitic Eocene deposits located on the Hruby Regiel covering the Tatra Massif from the north, are structurally linked with flysch sediments of the Podhale Trough. However, due to their high resistance to weathering, they have been included orographically into the Tatra Massif (Roniewicz 1969). At the valley boundary, development of the nummulitic Eocene changes radically (Sokołowski 1959). To the east these sediments occur only locally, mainly near the northern margin of the Tatra Mts. and as an isolated lobe near the Mała Łąka Valley (Text-fig. 1B). Lithology in this

Text-fig. 1. A – Main geological tectonic structures of the Tatra Mts.; B – Geological map of the Mała Łąka Valley area with similar areas (domains) marked. Based on Bac-Moszaszwili *et al.* (1979), Borecka (2007), Guzik *et al.* (1958; 1975) and our own studies. C – cross-section through the western wing of the Mała Łąka Fault; D – cross-section through the eastern wing of the Mała Łąka Fault; E – cross-section perpendicular to the fault strike area is relatively uniform and the thicknesses are not great (not more than some dozen metres). To the west of the valley, on Hruby Regiel, the Eocene deposits reach a thickness of up to 350 m (Text-fig. 2A), these being the greatest thicknesses in the Polish part of the Tatra Mts (Sokołowski 1959). They begin with red conglomerates lying unconformably on a Mesozoic basement, which pass upwards into grey conglomerates (Kuźniar 1910; Roniewicz 1969; Olszewska and Wieczorek 1998). The basal part of these conglomerates is probably freshwater in origin and their red colour could be connected with karst processes (Głazek and Zastawniak 1999; Gradziński *et al.* 2009; Jach et al. 2011). Above the conglomerates occur dolomitic sandstones, passing up gradually into a limestone complex (Sokołowski 1959; Roniewicz 1969).

Western block – Hruby Regiel

On Hruby Regiel the succession of Eocene deposits (Text-fig. 1, 2A) commences with red conglomerates (E_{rc}), infilling a local depression in the basement. The basal part of conglomerates is probably freshwater in origin and gradually passes upward into marine deposits. Their red colour is believed to be linked with karst processes (Głazek and Zastawniak 1999; Głazek 2000; Gradziński *et al.* 2009) but initially it was thought that the red colour could be connected with the occurrence of iron-bearing rocks in the basement (Wyczółkowski 1959), comprising Liassic limestones with haematite of the Choč Nappe and Jurassic limestones and radiolarites of the Krížna Nappe (Roniewicz 1969; Kulka 1985). Clasts of these rocks



Text-fig. 2. Lithological logs of the nummulitic Eocene: A – Hruby Regiel (based on Guzik *et al.* 1958; Borecka 2007 and Jach *et al.* 2011; simplified); B – northern slope of the Łysanki Range (based on our own studies). E_{rc} – red conglomerates; E_{gc} – grey conglomerates; E_{ds} – dolomitic sandstones; E_{nl} – dolomitic limestones, detritic limestones, sandy limestones, nummulitic limestones (so-called "jarzec"), limestones with plant detritus; E_{ol} – organogenic limestones, nummulitic limestones, discocycline limestones, limestones without nummulites; E_{a} – conglomeratic limestones, nummulitic limestones with clasts. a – limestones; b – dolomites; c – conglomeratic and organodetritic limestones; d – dolomitic sandstones; e – nummulitic limestones; f – limestones with plant detritus; g – conglomerates are found in the red conglomerates. Other clasts in the conglomerates include Cretaceous limestones of the Krížna Nappe and Triassic dolomites of the Choč Nappe. The matrix is clayey-carbonate-ferruginous (Roniewicz 1969; Kulka 1985).

The conglomerates are poorly sorted, particularly in the basal part of the succession. The clasts vary in size from a few centimetres to blocks over 50 cm in diameter. Thin intercalations of medium- and thin-bedded sandstones occur sporadically (Borecka 2007). The thickness of the red conglomerates on Hruby Regiel reaches up to 100 m (Text-fig. 2A) whereas to the north of Hruby Regiel Mt, up to 135 m of conglomerates were proved in the the Hruby Regiel IG-2 Borehole (Głazek 2000; see Chowaniec *et al* 1975).

Reflecting the change in environmental conditions, the red conglomerates pass upwards into grey conglomerates (E_{gc}; Text-fig. 2A). In places where the passage is gradual, yellow conglomerates have also been noted locally (Sokołowski 1959). The grey conglomerates are characterized by a more distinct bedding; the clasts are better sorted and more rounded, and their diameter decreases upsection (Borecka 2007). The clasts are dominated by Triassic dolomites from the Sub-Tatric Nappes. The matrix is calcareous (Roniewicz 1969). On Hruby Regiel the grey conglomerates reach their maximum thickness of up to 120 m.

Higher upsection occur dolomitic sandstones (E_{ds}; Text-fig. 2A), with well sorted fragments of Middle Triassic dolomites and dolomitic limestones cemented with a carbonate matrix (Wyczółkowski 1956). As in the conglomerates, the sizes of these rock fragments decrease upwards. Within the topmost part of the dolomitic sandstones nummulites appear (Borecka 2007). The thickness of the sandstones on Hruby Regiel reaches 60–120 m (Roniewicz 1969).

The dolomitic sandstones are covered by a rock complex comprising organogenic dolomitic limestones, dolomitic sandstones, detrital limestones, sandy limestones with nummulites and nummulitic limestones (Sokołowski 1958; Borecka 2007) (E_{nl}; Text-fig. 2A) Due to the mass accumulation of foraminifer tests resembling barley grains, some parts of this complex are known as "jarzec" (barley in the local dialect). Foraminifers constitute the dominant rock-forming component. They include mainly representatives of the genus *Nummulites*, particularly *N. perforatus* (Bieda 1959). Mass accumulations of foraminifers, comprising *Discocyclina* and microscopic sized forms (Bieda 1963; Olempska 1973), as well as brachiopod shells are also encountered (Roniewicz 1969). The highest beds in the complex contain plant detritus (Sokołowski 1959; Jach *et al.* 2011).

The nummulitic Limestones are overlain by another carbonate complex – organogenic limestones (E_{ol}; Text-fig. 2A). These rocks also contain large foraminifers belonging to the genera *Nummulites* and *Discocyclina*, which in this case are accompanied by bivalves, brachiopods, bryozoans and annelids (Roniewicz 1969). In most of the study area these deposits end the succession of the nummulitic Eocene.

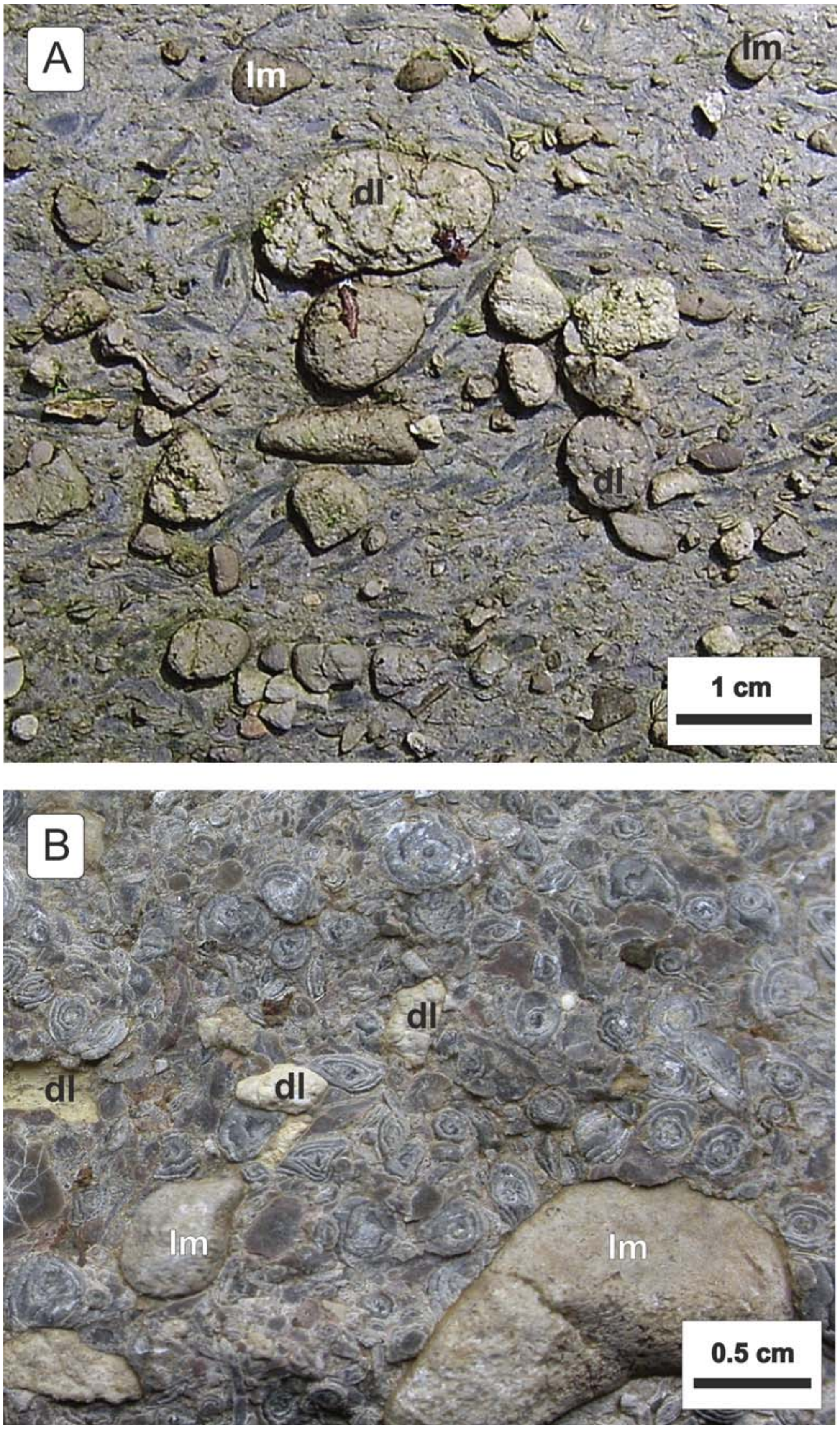
The last complex is composed of conglomeratic limestones (E_{cl}) which are seen on the eastern slope of Hruby Regiel (Borecka 2007). They include dark grey, thick-bedded limestones with clasts of limestones and dolomites. Sedimentation of these beds preceded a sudden change connected with the intensification of tectonic activity in the CCPB. In consequence, a new stage of tectonic evolution linked with flysch sedimentation started in this area (Kulka 1985).

Eastern block – Łysanki

The development of the nummulitic Eocene in the area located on the northern slope of the Łysanki Range (to the east of the Mała Łąka Valley) is significantly different from the succession on Hruby Regiel. The Eocene deposits are much thinner here, with fewer lithologies represented (Text-fig. 2B). Sokołowski (1959) correlated the Eocene deposits that occur to the east of the Mała Łąka Valley with the youngest rocks on Hruby Regiel.

The lithological variability is the highest on the north-western slope of the Łysanki Range. Conglomeratic deposits lie at the base of the southern part of an isolated lobe of Eocene deposits and occur discontinuously along the entire northern margin of the Tatra Mts. Their matrix is calcareous and the clasts comprise dolomites and limestones that probably derive from the Mesozoic basement (Kotański 1963). The size and amount of clasts vary (Text-fig. 3A). The matrix content in the conglomerates increases upsection, and the conglomerates gradually pass into thick-bedded conglomeratic limestones. Nummulites occur sporadically in the matrix, but larger accumulations are also encountered.

On the northern slope of the Łysanki Range, nummulitic limestones crop out (Text-fig. 3B). They are exposed in the northern part of an isolated lobe of Eocene deposits and in the neighbourhood of the boundary between the Tatra Mts. and the Podhale Trough (Text-fig. 1B). They comprise dark grey, resistant limestones, in which foraminifer tests belonging to the genus *Nummulites* are the main rock-forming element. Fragments of Triassic limestones and dolomites are also present. The small clasts have a


A
lm
lm
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dl
1 cm
B
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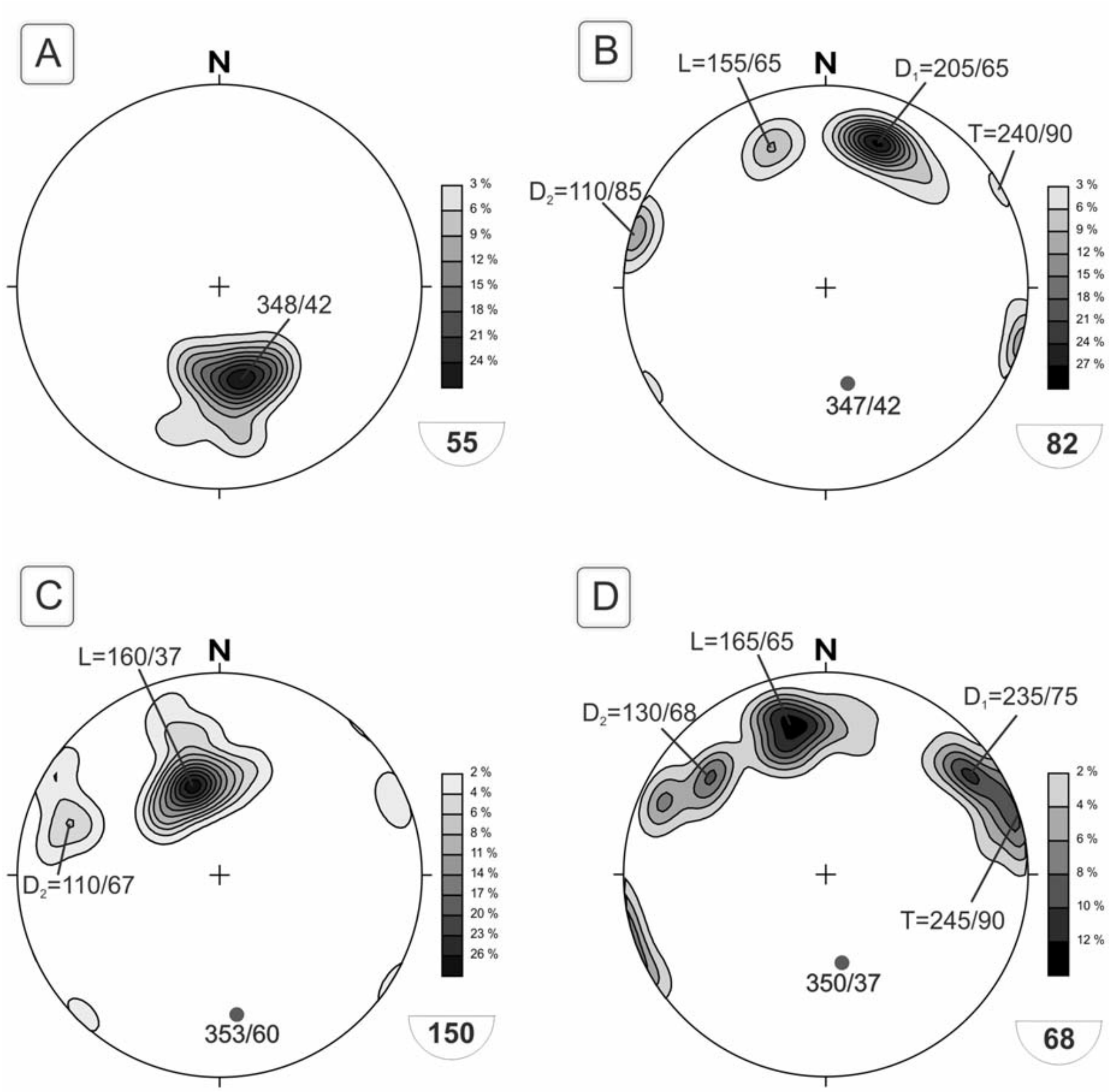
variable degree of rounding. The clast content in the rock is generally low and the clasts range in size from a few millimetres to c. 10 cm. In some exposures (e.g. near the Za Bramką Valley), a decrease in clast size is observed upsection. Nummulite tests occur sporadically in the matrix, and in some cases in larger accumulations. Discocyclines are also present, sometimes in high abundance (Text-fig. 3B). The total thickness of the nummulitic Eocene on the northern slope of the Łysanki Range reaches c. 50 m.

TECTONICS

Bedding orientation

On the basis of the bedding orientation of the nummulitic Eocene (Text-fig. 4), the area between the Mała Łąka and the Strążyska valleys can be subdivided into three areas (domains – Text-fig. 1A). Domain I is the area of the Mała Łąka Valley, where the dominant orientation is 347/42 (Text-fig. 4B). There is also a



Text-fig. 4. Stereoplots of the nummulitic Eocene for the area between the Mała Łąka and Strążyska valleys: A – bedding orientation; B-D – fracture orientations for three domains; B – eastern slope of the Mała Łąka Valley (domain I); C – Mały Żlebek and Za Bramką Valley area (domain II); D – Suchy Żleb and the western slope of the Strążyska Valley (domain III). See Text-fig. 1B for domain locations. Points mark poles to the average bedding orientation of the nummulitic Eocene in the particular domains. L – longitudinal fractures; D_1 and D_2 – two sets of diagonal fractures, T – transverse fractures. Pole to planes; lower hemisphere; based on Stereonet software

Text-fig. 3. A – Conglomeratic limestones; matrix with high abundance of foraminifers belonging to the genus *Discocyclina*; B – Nummulitic limestones with clasts of Triassic dolomites (dl) and limestones (lm); eastern block, northern slope of the Łysanki Range, near the boundary with the Podhale Trough sub-dominant orientation at 325/40. NE–SW strikes are observed in the lower part of the Mała Łąka Stream, near the northern Tatra margin. A similar change in bedding orientation was noted by Borecka (2007) on the western side of the Mała Łąka Valley, near Hruby Regiel, where the dip directions vary between 310–340/25–42, with 326/36 being dominant.

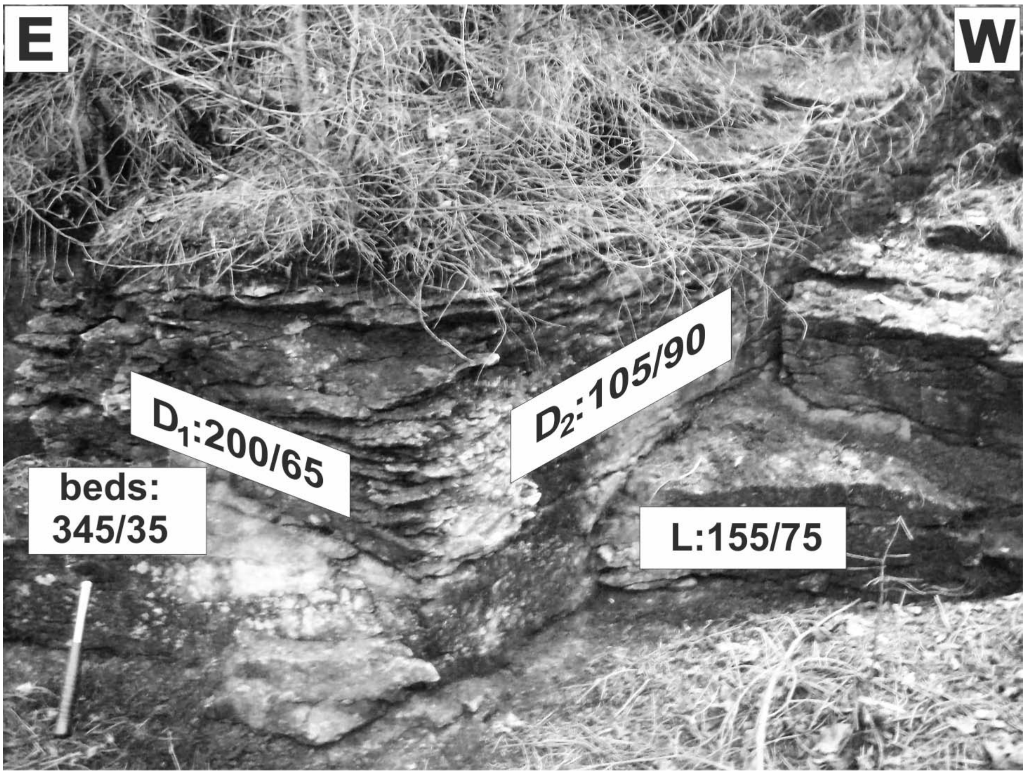
Domain II is the area between Mały Żlebek and the Za Bramką Valley, encompassing also the eastern part of the Mała Łąka Valley. Strikes of the Eocene strata are variable here (Text-fig. 4C), but the deviations do not exceed 20° from the generally latitudinal trend. Much higher dip values, usually exceeding 50°, are characteristic of this domain.

Domain III is the area to the east of the Za Bramką Valley, encompassing the area of Suchy Żleb and continuing into the Strążyska Valley. The strikes differ slightly from 90° and are usually c. 80°. The dips are low, with an average value of 35° (Text-fig. 4D).

Fracture orientation

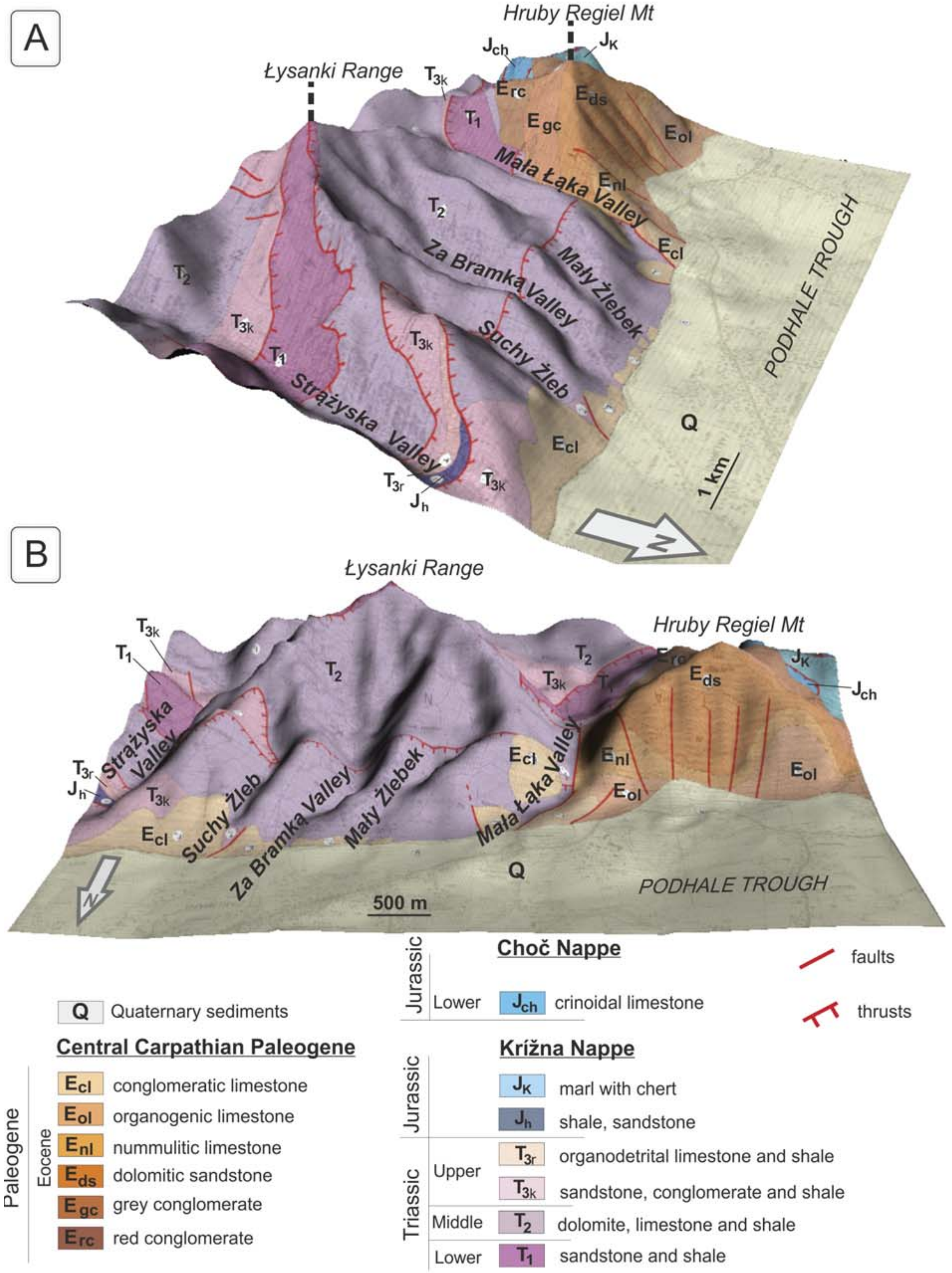
In the Podhale Trough the fracture network is relatively regular (e.g. Halicki 1963; Mastella and Ozimkowski 1979; Ludwiniak 2010). Fracture sets were determined based on their orientation with respect to the regional extent of the Podhale Trough. Within the nummulitic Eocene deposits, as in the entire Podhale Trough, several fracture sets can be distinguished in the area between the Mała Łąka and Strążyska valleys, (Text-fig. 5): a set of longitudinal fractures (L), two sets of diagonal fractures (D_1 and D_2), and a set of transverse fractures (T). All of these sets, albeit variably recorded, can be distinguished in each domain (Text-fig. 4B–D). With only a few differences, they reveal similar characteristics and orientation to those distinguished by Borecka (2007) to the west of the Mała Łąka Valley. Analysis of stereoplots shows (Text-fig. 4C) that in domain II the set of longitudinal fractures (L) is more distinct and the fractures more numerous. Field studies indicate that in this area this set could represent cleavage. It shows considerable regularity and ubiquity.

Within the nummulitic Eocene deposits, the fracture network is rather well developed. Most of the fractures are normal to the bedding, indicating that they were formed before the beds were tilted. Only the transverse fractures are vertical, and therefore could



Text-fig. 5. Fractures in the nummulitic Eocene deposits. Exposure on the eastern slope of the Mała Łąka Valley. Fracture sets L, D_1 and D_2 are visible

Text-fig. 6. DEM (Digital Elevation Model) with different sun shading directions; based on Kościelisko sheet 1:10 000 topographic map and geological map (Bac-Moszaszwili *et al.* 1979), simplified. A – View from NE, sun shading from W; the morphology shows distinct faults on Hruby Regiel. B – View from N, sun shading from SW; note change of valley orientations near the contact between the Sub-Tatric Nappes and the Podhale Trough


A
Hruby Regiel Mt
Łysanki Range
J_{ch}
J_K
T_{3k}
E_{rc}
E_{ds}
T_1
E_{gc}
E_{ol}
Mała Łąka Valley
E_{nl}
T_2
Za Bramką Valley
Mały Żlebek
E_{cl}
Suchy Żleb
Strążyska Valley
T_{3r}
J_h
PODHALE TROUGH
Q
1 km
N
B
Łysanki Range
Hruby Regiel Mt
500 m
PODHALE TROUGH
Jurassic
Lower
Choč Nappe
J_{ch} crinoidal limestone
faults
thrusts
Q Quaternary sediments
Central Carpathian Paleogene
Paleogene
Eocene
E_{cl} conglomeratic limestone
E_{ol} organogenic limestone
E_{nl} nummulitic limestone
E_{ds} dolomitic sandstone
E_{gc} grey conglomerate
E_{rc} red conglomerate
Krížna Nappe
Jurassic
J_K marl with chert
J_h shale, sandstone
Triassic
Upper
T_{3r} organodetrital limestone and shale
T_{3k} sandstone, conglomerate and shale
Middle
T_2 dolomite, limestone and shale
Lower
T_1 sandstone and shale

have been formed after tilting of the Eocene strata. Fractures of this set are usually open, and the fissures are usually several millimetres wide; there are also wider fissures, reaching up to several centimetres in width. In the area investigated in this study, mineralization of fissures was not observed, albeit to the west of the Mała Łąka Valley, fractures of this set are very often filled with calcite (Borecka 2007). Calcite mineralization of this set was also observed in the nearby Strążyska Valley.

DEM analysis

It is difficult to collect a sufficient number of fault orientation measurements in the area between the Mała Łąka and the Strążyska valleys to be able to use them for statistical analysis. Faults, particularly those assumed to be synsedimentary, are unclear and difficult to observe directly. Therefore, digital elevation model (DEM) analysis using the Surfer 8 software was applied. Using different light directions (Ozimkowski 2010), structures linked with morphology and tectonics are enhanced (Text-fig. 6A). This enables, for example, determination of the course of minor faults on Hruby Regiel that were not visible on older maps (Sokołowski 1959; Bac-Moszaszwili 1979), but which had been pointed out by Borecka (2007).

The DEM image shows variation in the course of each valley (Text-fig. 6B), which near the northern margin of the Tatra Mts. change their strike from S–N to SW–NE. The Mała Łąka Stream, as well as streams in valley and gulleys lying more to the east, shows a distinct change in orientation to the NE. Such a change in the course of the valley could be a result of streams using a fault set typical of the Podhale Trough, rather than those present within the Tatra Massif. These NE–SW faults must have been younger than the earlier formed beds of the nummulitic Eocene, the bedding orientations of which are clearly disturbed (Text-fig. 1B). This fault set is clearly visible throughout the entire area of the Podhale Trough (e.g. Mastella and Ozimkowski 1979; Ludwiniak 2010).

EVOLUTION OF THE MAŁA ŁĄKA FAULT

Stage 1.

In the western block of the Mała Łąka Fault there was a local depression which was gradually filling up by debris flow. Their basal parts were probably deposited under freshwater conditions (Gradziński *et al*. 2006; Jach *et al.* 2011). Red conglomerates (E_{rc}) were deposited on the uneven surface of the karsted Mesozoic basement. The morphological escarpment linked with the Mała Łąka Fault, which supplied clastic material to the conglomerates that were deposited below it, probably already existed at this stage (Text-fig. 7A).

Stage 2.

The approaching sea flooded the area of the present-day Hruby Regiel Mt. The Mała Łąka Fault throwing up the footwall block was still active. Within the western block, grey conglomerates (E_{gc}) were deposited throughout the Hruby Regiel area (Text-fig. 7B).

Stage 3.

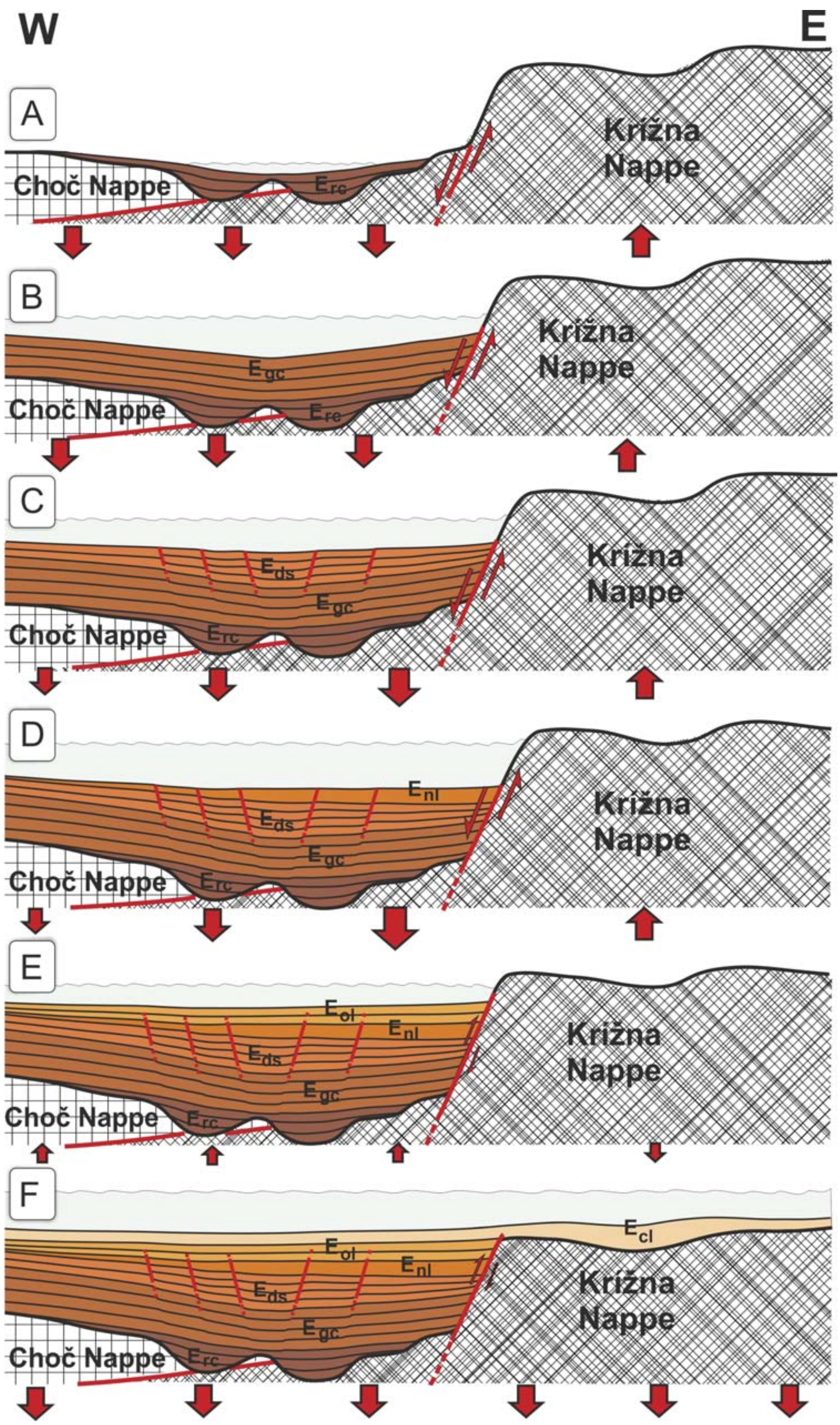
Due to the proceeding marine transgression, the size of the clasts gradually decreased. Dolomitic sandstones (E_{ds}) were deposited on the western side of the Mała Łąka Fault. A series of synsedimentary faults linked with the rough basement morphology and uneven compaction of the earlier formed sediments was formed during their sedimentation. They caused an increase in the thickness of the sandstone in the area of Hruby Regiel. The activity of the Mała Łąka Fault caused tilting of its western wall, which resulted in a greater thickness of the deposits in the direct vicinity of the fault (Text-fig. 7C).

Stage 4.

The sea level rose again and the carbonate stage of sedimentation began. To the west of the Mała Łąka Fault, nummulitic limestones, the so-called "*jarzec*" (E_{nl}), were formed. Synsedimentary faults that formed during sandstone deposition were still active, but began to fade out. The western wall was tilted further, causing an increase in the thickness of the nummulitic limestones in the vicinity of the Mała Łąka Fault (Text-fig. 7D.).

Stage 5.

The activity of faults formed during the sandstone sedimentation terminated. Organogenic limestones started to form (E_{ol}), gradually filling the depression to the western side of the Mała Łąka Fault. At this stage, the fault faded out or was rejuvenated as a reverse fault. The eastern wall was thrown down, and the western wall upthrown, which caused compensation of morphology in both fault walls (Text-fig. 7E).



Text-fig. 7. Stages of evolution of the Mała Łąka Fault (explanations in text). E_{rc} – red conglomerates; E_{gc} – grey conglomerates; E_{ds} – dolomitic sandstones; E_{nl} – nummulitic limestones (so-called "*jarzec*"); E_{ol} – organogenic limestones; E_{cl} – conglomeratic limestones

Stage 6.

This reverse trend of movement of the fault probably continued during the next stage of sedimentation because the thickness of the conglomeratic limestones (E_{cl}) was higher in the eastern than in the western fault wall (Text-fig. 2). The type of sedimentation changed due to increased tectonic activity, and conglomeratic limestones (E_{cl}) were formed throughout the area (Text-fig. 7F).

DISCUSSION

The study area is characterized by the occurrence of many map-scale faults. They were distinguished based on topography, DEM analysis, lithological differences, changes in the morphology of particular units, as well as bedding orientation. The most important fault of the area is the Mała Łąka Fault. Detailed structural analysis of Eocene deposits between the Mała Łąka and Strążyska valleys aided in determining the character of the dislocation in the Mała Łąka Valley as a synsedimentary normal fault. This fault probably had pre-Eocene origins because in the hanging wall there are preserved fragments of the Choč Nappe (the higher of the two Sub-Tatric Nappes), which are missing in the footwall to the east of the Mała Łąka Valley (Text-fig. 1B–E). The Mała Łąka Fault showed the highest activity during the interval from the sedimentation of the red conglomerates (E_{rc}) to the organogenic limestones (E_{ol}). Reconstruction of the development stages has shown that the fault array on Hruby Regiel is gravitational and forms a complex graben. The formation of these faults was linked with uneven sedimentation and compaction on an irregular basement resulting from the local preservation of slices of the Choč Nappe and from the karst processes documented by Głazek (2000). This diverse morphology influenced the thickness of the sandstones (E_{ds}), which are thinner on the slopes of Hruby Regiel than in its central part. The total displacement estimated from the cross-section (Text-fig. 1E) is up to 350 m. Taking into account that the influence of the fault on sedimentation decreases rapidly to the west, it can be assumed that the fault has a hinge-like character and that its “hinge” was probably located near the present-day Kościeliska Valley, i.e., c. 2.5 km west of the Mała Łąka Fault. The hinge-like character of the fault is also evidenced by the increasing thickness of nummulitic limestones (E_{nl}) towards the fault plane demonstrated by mapping (Text-fig. 1B, 7D; Bac-Moszaszwili *et al.* 1979; Tomaszczyk *et al*. 2009).

As shown on the map (Text-fig. 1B) and DEM (Text-fig. 6), the Mała Łąka Fault has a N–S-orientation in its southern part, whereas near the northern margin of the Tatra Mts. its orientation changes to SW–NE. The northern part of the Mała Łąka Fault is probably younger, which can be assumed from the change of bedding orientation in the conglomeratic limestones (E_{cl}) on the eastern slopes of the Łysanki Range (Text-fig. 1A). According to the DEM image, this situation is repeated in several neighbouring valleys, the northern parts of which are NE–SW-oriented, using for their course faults with this orientation. Their formation could have been linked with the Neogene tectonic processes that caused the rotational uplift of the Tatra Mts. and the formation of the Podhale Trough. The change in the course of valleys near the northern margin of the Tatra Mts. is accompanied by a drag zone that may indicate a strike-slip component. Such an interpretation as a sinistral fault was presented by Bac-Moszaszwili (1998), who indicated a possible post-Palaeogene translocation within the Zakopane part of the Sub-Tatric Nappes. The directions of tectonic transport are also concordant with the palaeomagnetic analysis of Grabowski (1995, 1997). According to the studies of Marko *et al.* (1995) and Jurewicz (2000), such a change in orientation may have resulted from clockwise rotation of the stress field or counter-clockwise rotation of the basement during the Palaeogene–Neogene evolution.

Another issue is the fact that the Mała Łąka Valley does not follow the course of the fault exactly (Text-fig. 1B). In its southern part (to the east of the Hruby Regiel summit), the valley axis runs within Triassic deposits of the Sub-Tatric Nappes. In this part, the Mała Łąka Fault runs on the western slope of the valley. This situation may be explained by the presence of a damage zone associated with the fault. Such a damage zone is evidenced mainly by tectonic breccia and a higher density of vertically-oriented open fissures linked with the transverse fractures (T). The flowing stream waters were able to cut down more effectively into the extensionally fractured rocks than into the tectonic contact between the Triassic dolomites and the nummulitic Eocene deposits. In the axial part of the Mała Łąka Valley these fractures are poorly visible due to the presence of alluvia but they are analogous to those in the Strążyska Valley, where numerous extensional fractures filled with calcite occur. Their course is parallel to the course of the valley and perpendicular to the structure orientations of the Podhale Trough and the Tatra Mts. as well. These fractures are distinctly younger than the remaining fractures and could have been linked with the Neogene uplift of the Tatra block.

CONCLUSIONS

The Mała Łąka Fault in the Tatra Mts. is a synsedimentary normal fault with an estimated throw of up to 350 m. The fault probably had pre-Eocene origins.

The fault has a hinge-like character; its hinge was located in the present-day Kościeliska Valley, c. 2.5 km west of the Mała Łąka Valley.

The Mała Łąka Valley does not follow the course of Mała Łąka Fault exactly but uses instead extensional fractures within a damage zone associated with the fault rather than the lithological boundary at the tectonic contact between the Triassic dolomites and the Eocene conglomerates.

The Mała Łąka Fault, like the faults in adjacent valleys, change its course near the northern margin of the Tatra Mts.; the trend of the fault changes from N–S to NE–SW. This part of the fault could have been activated during the Neogene rotational uplift of the Tatra Mts. and formation of the Podhale Trough.

Acknowledgements

We are grateful to the Directorate of the Tatra National Park for permission to conduct fieldwork. Thanks are also due to Michał Gradziński for helpful remarks and Chris Wood and Anna Żylińska for linguistic advice.

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Manuscript submitted: 30th November 2011
Revised version accepted: 15th September 2012