Stratigraphic and tectonic control of deep-water scarp accumulation in Paleogene synorogenic basins: a case study of the Súľov Conglomerates (Middle Váh Valley, Western Carpathians)

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Abstract: The Súľov Conglomerates represent mass-transport deposits of the Súľov–Domaniža Basin. Their lithosomes are intercalated by claystones of late Thanetian (Zones P3–P4), early Ypresian (Zones P5–E2) and late Ypresian to early Lutetian (Zones E5–E9) age. Claystone interbeds contain rich planktonic and agglutinated microfauna, implying deep-water environments of gravity-flow deposition. The basin was supplied by continental margin deposystems, and filled with submarine landslides, fault-scarp breccias, base-of-slope aprons, debris-flow lobes and distal fans of debrite and turbidite deposits. Synsedimentary tectonics of the Súľov–Domaniža Basin started in the late Thanetian–early Ypresian by normal faulting and disintegration of the orogenic wedge margin. Fault-related fissures were filled by carbonate bedrock breccias and banded crystalline calcite veins (onyxites). The subsidence accelerated during the Ypresian and early Lutetian by gravitational collapse and subcrustal tectonic erosion of the CWC plate. The basin subsided to lower bathyal up to abyssal depth along with downslope accumulation of mass-flow deposits. Tectonic inversion of the basin resulted from the Oligocene–early Miocene transpression (σ1 rotated from NW–SE to NNW–SSE), which changed to a transpressional regime during the Middle Miocene (σ1 rotated from NNE–SSW to NE–SW). Late Miocene tectonics were dominated by an extensional regime with σ3 axis in NNW–SSE orientation.

Keywords: carbonate breccias, Súľov Fm., late Thanetian–Lutetian, mass-transport deposits, deep-water basin, subduction, tectonic erosion.

Introduction

The Súľov Conglomerates occur in the Middle Váh Valley area as coarse-grained lithosomes in the Súľov–Domaniža Basin (SDB). This basin is superposed on the frontal units of the Central Western Carpathians (CWC). The thickness of the Súľov Conglomerates is estimated between 750 m and 1200 m. Western and eastern belts of the Súľov Conglomerates are divided by the Prečín–Súľov fault, and separated by the Cretaceous formations of the Krížna and Manín Units cropping out in the Súľov window (Marschalko & Kysela 1980; Rakús & Hók 2003) — Fig. 1. In general, the tectonic structure of the area resulted from the Cretaceous nappe stacking (prior to Middle Turonian) of the CWC Fatric and Hronic nappe systems, post-nappe folding, gravitational collapse of the orogenic wedge and accommodation of the Late Cretaceous–Paleogene basins, and early Miocene transpression and transtension. Kinematic and paleostress analyses of brittle fault structures of the Mesozoic nappe units was performed in the western part of the Pieniny Klippen Belt (PKB) and Peri-Klippen zones (Kováč & Hók 1996; Bučová et al. 2010; Šimonová & Plašienka 2011, 2017). Current research has completed these tectonic investigations by structural analysis of the Paleogene formations of the Middle Váh Valley area, providing information about younger tectonic phases, which controlled the subsidence and inversion of the Súľov–Domaniža Basin.

The sedimentary formations of the Súľov–Domaniža Basin are divided into the Súľov Fm. (Andrusov 1965) and Domaniža Fm. (Samuel 1972). The Súľov Fm. consists of three lithostratigraphic units, which begin with basal conglomerates overlaying the Manín Unit and the higher Fatric and Hronic nappes (Svinské chlievy Mb. sensu Salaj 1993), followed by thick lithosomes of carbonate breccias and conglomerates (Súľov Conglomerates s.s.) and intraformational conglomerates in flysch-type sediments (Paština Závada Mb. sensu Buček & Nagy in Mello et al. 2011).

Stratigraphic assessment of the Súľov Conglomerates is constrained by their superposition above the Upper Paleocene to Lower Eocene limestones and carbonatic sandstones of the
Jablóvké Formation, as well as above the flysch sediments with blocks of biohermal limestones of the Hričovské Podhradie Fm. and their conglomerate lithosomes (Ovčiarsko Mb.). Their stratigraphic age was determined predominantly by using large benthic foraminifers from underlying formations (Samuel et al. 1972) and planktonic foraminifers from the overlying Domaníša Fm. (Samuel & Salaj 1968; Samuel et al. 1972). However, direct evidence for the stratigraphic age of the Súľov Conglomerates acquired by planktonic microfauna is still missing.

The paper presents new structural, sedimentological and biostratigraphic data gathered by investigation of the Súľov Conglomerates in the Middle Váh Valley area.

Regional geological setting

The geological structure of the Middle Váh Valley area (Fig. 1) is very complicated due to frontal thrust stacking of the Central Carpathian nappes and PKB Oravic units (Manin, Kostolec, Klape, Podháj, Podmanín units, etc. — Mello et al. 2011), superposed by Late Cretaceous flysch units, Gosau-type sediments (Rašov facies), and Paleogene sediments of the Hričov–Žilina belt and Súľov–Domaniža Basin ("flysch" means a regional widely used term for turbiditic deep-sea fan sediments in the Northern Apennines, Alps and Carpathians — for historical review see Mutti et al. 2009).

The tectonic position of the Mesozoic units has been a matter of debate for a long time. Different views concern especially the tectonic position of the Manín Unit, which was placed between the Tatricum and PKB (Andrusov 1938, 1945), or its attribution to a marginal development of the Tatric or Fatric units was proposed by Mahel (1946, 1948, 1950). The Manín Unit shows affinity to the PKB units by the presence of thick prisms of Albian flysch formations (Rakús & Marschalko 1997; Marschalko & Kysela 1980). The relationship of the Manín Unit to the Tatricum was preferred by Rakús & Hók (2005), considering the Turonian age of its youngest stratigraphic formations. Senonian formations of the Podmanin Group, which were formerly assigned to the Manin Unit (Kysela et al. 1982) or to the Podháj Unit (Salaj 1990), were included in a footwall unit close to the Klape and Oravic units (Rakús & Hók 2005). According to Plašienka & Soták (2015), the Senonian formations could represent a new sedimentary cycle after a nappe thrusting of the Manin and Klape units, so belonging to the Gosau Group (see also Salaj 2006).

During the Late Cretaceous to Paleogene tectogenesis, units of the Klippen Belt were folded and incorporated into the Mesoalpine accretion wedge. The geological structure of the Klippen and Peri-Klippen units in the Middle Váh Valley area has also been subject of current research (Kováč & Hók...
Carbonate conglomerates in the Middle Váh Valley area were introduced under the name Súľov Conglomerates by Štúr (1860). They form a complex brachysynclinal structure spreading in the NW–SE direction, which is underlain by the mid-Cretaceous formations of the Kostolec and Manín units (Hradná succession *sensu* Rakús & Hók 2005). Starting from the earliest research, the Súľov Conglomerates were considered as basal transgressive sediments of the Central Carpathian Paleogene formations (Uhlig 1903). Based on this position, a Middle to Late Eocene age of the Súľov Conglomerates and breccias was assumed (Andrusov 1965; Chmelík 1967). However, later studies found that the Súľov Conglomerates are developing from the Jablonové Fm., which proves to be of Ilerdian–Cuisian age (Samuel et al. 1972). That was a reason why an Early Eocene age (Cuisian=Ypresian) was also assigned to the Súľov Conglomerates. The conglomerates are overlain by turbiditic sediments of the Domaniža Fm., the Lutetian age of which was proven by planktonic foraminifers and nannofossils (Samuel et al. 1972; Peterčáková 1987). The transitional part of these formations is formed by the Paština Závada Mb., in which the conglomerates are intercalated with claystones and turbiditic deposits of the Domaniža Fm. (Buček & Nagy in Mello et al. 2011). Nevertheless, until now the exact age of conglomerates of the Súľov Fm. and Paština Závada Mb. has been documented only very rarely by planktonic microfauna (e.g., *Globigerina conglomerata*, *G. eocaena*, *Globorotalia cf. crassaformis*, etc.; Benešová in Maheľ et al. 1962).

The Súľov Conglomerates form rocky crests in two mountain belts. The western belt is formed by steeply SE-dipping up to subvertical (60°–80°) lithosomes of conglomerates in rocky cliffs at Baňa (662.5 m a.s.l.), Veľký Pezínok (416.2 m), Zámok (660.0 m), Brada (816.0 m) and Holy vrch (658.9 m) hills — Fig. 2A. Conglomerates of the western belt form a plunging syncline, which is steeply amputated and overthrust by the conglomerates of the eastern belt along the Prečín fault. The conglomerate lithosomes of the eastern branch are gently dipping (25°–40°), forming the rocky crests between Roháč (802.7 m) and Žibrid (867.0 m) hills (Fig. 2B), and extending to Lietava, Baňov and Peklína villages. Basinward to the Brezany and Domaniža–Pružina depressions, they form thick intraformational conglomerates of the Paština Závada Mb.

The Súľov Conglomerates belong to the Súľov Fm. of the Myjava–Hričov Group (Danian–Middle Lutetian). This formation started to develop by the Early Eocene transgression (Mello et al. 2011). The transgressive conglomerates overlay the Upper Paleocene–Lower Eocene organodetritic limestones in the Pružina area (e.g., Riedka locality) and Hričov–Jablonové area. The synclinal belts of the Súľov Conglomerates exhibit no conformity with basement structures of the Paleogene basin. This points to a structural discordance between the Súľov–Domaniža Basin and the Mesozoic klippen belt units (cf. Marschalko & Samuel 1993).

**Material and methods**

The Súľov Formation consists of monogenetic carbonate breccias and conglomerates (Fig. 3). The term *breccia* is valid for very poorly sorted to unsorted, coarse-grained sediments composed of angular, often shard-like clasts of limestones and dolostones (Eyles & Januszczak 2007). Breccias and conglomerates of the Súľov Fm. represent various types of gravity flow deposits (Marschalko & Samuel 1993). However, the classification and terminology of gravity flow deposits is purely constrained. Different authors emphasized manifold parameters in their classification schemes, like sediment concentration, fluid turbulence, rheology and physical properties of the flows (Gani 2004, and references therein). Interpretation of debris-flow deposits also differs in two distinct models: viscoplastic and inertial grain flow models (see Sohn 2000 for the review). Debris are commonly regarded as sediments of cohesive flows (e.g., Lowe 1982). For genetic classification of the Súľov Conglomerates, as dominantly mud-free deposits, an inertial grain flow model proposed by Takahashi (1978, 1993; Bučová et al. 2010; Šimonová & Plašienka 2011, 2017; Plašienka 2012; Prokešová et al. 2012; Bučová 2013).
Fig. 3. Sedimentary sequences of the Súľov Fm. A — Transgressive basal sediments of the Súľov Fm., which discordantly overlie the Triassic dolomites of the Fatric Krížna Unit. Dolomites are superposed by horizontally bedded calcarenites with parallel lamination and oscillatory ripple marks, which pass into carbonate breccia beds and chaotic breccias higher up in the section (locality Baranova quarry near Veľká Čierna village), scale bar: 7 m. B — Decametre-scale sequence of the Súľov Conglomerates consisting of breccia and conglomerate megabeds with normal grading (C1–C2 cycles), channelized units (C2 cycle), bed-base stratification and inverse grading (C3–C4 cycles). Loc. Farská skală near Lietava, electrical column for scale; C — Unsorted breccia layer with large floating clasts implying influence of dispersive stress and frictional freezing during a mass-flow deposition of the Súľov Fm., Loc. Farská skală near Lietava, scale bar: 1 m; D — Platy claystone intraclasts and chips in thick conglomerate bed generated by erosion of cohesionless debris-flows with grain pressure and flow friction. Loc. Šuľov strait, Hradná creek, scale bar: 50 cm; E — Conglomerates with stratified gravels in sandy-rich matrix deposited from hyperconcentrated density flows. Loc. Lietava village, scale bar: 1 m; F — Interbeds of greyish-blue mudstones with deep-water agglutinated foraminifers (DWAF) in sandy and gravelly sediments of the Súľov Fm. (Paština Závada Beds). Loc. Lietava village, hammer for scale.

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Biostatigraphic data come from planktonic foraminiferal microfana, which has been obtained from claystones in basal parts of the Súľov Fm. (loc. Pažice in Hrdná creek, 220 m SE above the Jablonové quarry (N 49°10'32.2"; E 18°34'20.2"), from claystone interbeds within the Súľov Conglomerates at the locality Čierny potok Creek (N 49°09'0.3"; E 18°33'38.7"), Lúka pod hradom (N 49°10'43.1"; E 18°35'13.1"), and from the Paština Závada Beds at the locality Lietava (N 49°10'7.7"; E 18°40'34.6"), Lietavská Závada (N 49°10'46.7"; E 18°37'42.6") and Prečín (N 49°08'5.1"; E 18°51'51.6"). The microfana has been analysed using systems of taxonomic classification and biostatigraphic zonation of Paleogene foraminifers (Blow 1979; Berggren & Miller 1988; Olsson et al. 1999; Berggren & Pearson 2005; Pearson et al. 2006; Wade et al. 2011). The age data were constrained on the basis of foraminiferal index species, marked by their lowest and highest occurrences (LO, HO).

Field investigations were focused on the structural analysis of tectonic deformation of the Súľov Conglomerates in the Middle Váh Valley area, and on sampling of sections for biostatigraphic research. The structural research involves kinematic interpretation of joints, fault planes and shear-sense indicators on fault planes (fault striae, Riedel shears, accretionary mineral steps). The measured fault data have been processed by the paleostress inversion method (Angelier 1994) and P–T axis method, using software package TENSOR (Delvaux 1993; Delvaux & Sperner 2003).

The field data give a structural record of several successive deformation events. In order to determine individual deformation phases, it was necessary to perform paleoearth analysis in rocks of different ages. Therefore, the structural data were measured in Triassic complexes of the Hronic Ostrá Malenica and Považie nappes, mid-Cretaceous formations of the Fatric Krížna unit and Kostolec–Manín units (Hradná succession), late Paleocene biozones (P 3–P 4 sensu Berggren & Pearson 2005). This indicates that the underlying sediments of the Jablonové Fm. should not be younger than Thanetian, and the overlying conglomerates of the Súľov Fm. should not be older than early Ypresian (i.e. late Ilerdian).

Claystones from lower part of the Súľov Conglomerates were sampled in the Čierny potok Creek around the forest road from Súľov to Vrchtepľa. They occur in turbiditic interbeds within thick conglomerate lithosomes. The microfana of the claystones is very rich in morozovellid foraminifers, comprising species of Morozovella acuta, M. ex gr. velascoensis, M. aequa and M. subbotinae. They are associated with acarininids (Acarinina nitida, A. strabocella, A. coalingensis, A. mckannai), subbotinitids (Parasubbotina inaequispirina, Subbotina triangularis, S. ex gr. velascoensis) and rare other planktonic foraminifera (e.g., Igorina brodermanni). These foraminifers provide evidence for Late Paleocene–Early Eocene age, based on last appearances of morozovellid species of M. velascoensis group and M. acuta (Zone E2) and first appearances of M. subbotinae (Zone P5) and Parasubbotina inaequispira (Zone E1). Considering that, the claystones from basal parts of the Súľov Conglomerates belong to the late Thanetian–early Ypresian (Ilerdian).

A monotonous sequence of conglomerates and breccias is interbedded by claystones in the middle part of the Súľov Fm. They crop out in the saddle “Lúka pod hradom” north-west of Súľov village. The claystones are yellow-brown in colour and rich in planktonic foraminifers or radiolarians (loc. Prečín). Their foraminiferal associations markedly differ from those in basal part of the Súľov Conglomerates by almost complete absence of morozovellids (only M. cf. subbotinae) and predominance of acarininids, belonging to the species Acarenina pseudotopifensis, A. aspensis, A. cuneicamerata, A. wilcoxensis, A. pentacamerata and Acarenina collactea. The acarininid species are associated with Turborotalia frontosa, Subbotina patagonica, S. eocaena, S. roesnensis and Catapsydrax unicusus. Foraminiferal microfana from this locality contains index species of middle Ypresian to early Lutetian biozones (e.g., Acarenina pseudotopilensis), and those appearing in Zone E5 (A. wilcoxensis, A. pentacamerata) and Zone E7 (T. frontosa). Therefore, the age of conglomerates of the middle part of the Súľov Fm. is constrained to the middle Ypresian to early Lutetian.

The uppermost part of the Súľov Fm. belongs to the Paština Závada Mb., defined as Súľov-type conglomerates in clast- and flysch-type sediments of the Domaníža Basin

Biostratigraphic data and depositional age

Planktonic foraminiferal microfana has been obtained from five localities in different parts of the Súľov Fm. (Fig. 4). Basal part of the formation occurs in turbiditic beds between the Súľov Conglomerates and Jablonové Fm. (loc. Pažice, Hrdná creek, 220 m above the Jablonové quarry). Claystones are poor in planktonic foraminifers, which comprise Globanomalina pseudomenardi, Acarinina mckannai, A. nitida, A. coalingensis, Morozovella acuta, M. praeangulata, Subbotina triloculinoidea, S. triangularis and S. cancellata. Some of these species are important in foraminiferal biostratigraphy, having their highest occurrences in the Late Paleocene (Globanomalina pseudomenardi, Morozovella praeangulata). Therefore, they represent marker species of the Late Paleocene biozones (P 3–P 4 sensu Berggren & Pearson 2005). This indicates that, the underlying sediments of the Jablonové Fm. should not be younger than Thanetian, and the overlying conglomerates of the Súľov Fm. should not be older than early Ypresian (i.e. late Ilerdian).
**Fig. 4.** Composite log of the Súľov Fm. with conglomerate lithosomes, hemipelagic interbeds and their microfauna. Foraminiferal species imply the late Thanetian–early Ypresian (Ilerdian) up to early Lutetian age of conglomerate formation and deepening-upward sequence with DWAF-type association in the uppermost part of the Súľov Fm.

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Marginal faulting of the Súľov–Domaniža Basin is recorded in fault-bounded talus aprons of basal conglomerates (Riedka, Sviské chlív). This system of E–W trending normal faults, which controlled progressive steepening of basin slopes, was formed during NW–ESE to W–E compression and perpendicular extension (Fig. 6; Table 1 — D1a, D1b, D1c homogeneous groups). Their original direction prior to the Miocene counterclockwise rotation has been restored as NW–SSE to N–S trending (e.g., Marko et al. 1995, Márton et al. 2016, Šimonová & Plašienka 2017). Marginal faulting and block tilting also led to opening of intraformational fissures, which were filled with banded crystalline calcite veins known as the Malenica onyxites (Salaj 1991; Fig. 5B,C). The vein systems exhibit a structural predisposition to NW–ESE trending normal faults with dip-slip striations on the fault planes.

Post-sedimentary deformation of the Súľov conglomerates started with compressional to transpressional tectonics during the Oligocene to Early Miocene (cf. Marko et al. 1995; Kovač & Hők 1996). The compressional stress axis was oriented in the NW–SE direction with perpendicular extensional axis. There are three homogeneous groups of faults recognized in this phase (D2a, D2b, D2c; Fig. 6, Table 1). D2a group consists of sixteen dextral strike-slip faults, which are oriented in the ENE–WSW direction. Homogeneous group D2b is formed by fifteen sinistral strike-slip faults with N–S direction. The last homogeneous fault set, which is related to the first deformational phase, belongs to the D2c group. This group is represented by twenty four reverse faults with NE–SW directions. Likely during this phase, the Paleogene sediments of the Peri-Klippen zone, Rajec Basin and Turiec Basin were also deformed (Hők et al. 1998; Rakúš & Hők 2003). That is also a case of reverse faults with thrusting of Aptian sediments of the Fatic Unit over Paleogene sediments in the Veľká Fatra Mts. (Kupeľany, TK-3 borehole; Pulíšová et al. 2015). Transpressive deformation resulted from collision of the Western Carpathians and North European Platform, which culminated during the Late Oligocene–Early Miocene, also leading to inversion of the fore-arc basins (Kováč 2000).

The next deformation phase (D3) succeeded a transpressional tectonic regime (Fig. 6; Table 1). Our data allowed selection of three homogeneous groups of faults (D3a; D3b; D3c) in the Súľov Conglomerates. Twenty two sinistral strike-slip faults with NNE–SSW orientation (D3a group), seventeen reverse faults (D3b group) and eight normal faults generally oriented in NNE–SSW direction (D3c group) were recorded. The maximum compressive stress axis ($\sigma_1$) of the D3 phase was oriented in a NNW–SSE direction, like that, which operated during the Ottnangian to Lower Badenian (Marko et al. 1995; Kovač & Hők 1996; Fodor et al. 1999; Šimonová & Plašienka 2011, 2017; Bučová 2013).

The fourth deformation phase is expressed by $\sigma_1$ rotation in a NNE–SSW direction with perpendicular extensional axis to maximum compression (Fig. 6; Table 1). Transpressive faulting was changed to transensional tectonic regime. It was possible to choose four homogeneous groups of analysed faults. There are four dextral strike-slip faults with NW–SE
orientation (D4a), completed by sixteen sinistral strike-slip faults with NE–SW orientation (D4b), seven inverse faults with NW–SE orientation (D4c) and twelve normal faults with NE–SW orientation (D4d). Transtensional fault systems of ALCAPA were activated from the middle to late Badenian (Csontos et al. 1991). The next deformational phase D5 (Fig. 6; Table 1) continued in a transtensional tectonic regime during the Sarmatian (cf. Marko et al. 1995; Kováč & Hók 1996; Fodor et al. 1999). The compressional component of the paleostress field rotated to a NE–SW direction with perpendicular extensional stress axis. During this tectonic regime, new systems of dextral strike-slip, sinistral strike-slip and normal faults were generated. Dextral strike-slip faults were oriented in a N-S direction (D5a), sinistral strike-slip faults were oriented generally in WNW–ESE direction (D5b). Their systems were related to NE–SW normal faults (D5c).

Transtensional deformation of the Súľov Conglomerates was finally changed to an extensional tectonic regime (Fig. 6, Table 1). Extensional stress axes were oriented in a NNW–SSE direction, as is recorded by normal faults with an ENE–WSW orientation (D6) and extensional joints with a NE–SW orientation and 60°–70° inclination (Fig. 6). Faults with a similar orientation were found by Králiková et al. (2010), Pešková et al. (2009) and Vojtko et al. (2008), corresponding to extensional tectonics, which probably operated during the Pliocene (Šimonová & Plašienka 2011; Šimonová 2013).

Discussion

Sediment gravity flows and their deposits

The Súľov Formation (sensu Andrusov 1965) is formed by conglomerates of different continental, basin slope and deep-water settings. Continental margin sediments are represented by talus breccias and alluvial fan, braided stream and fan-delta conglomerates that filled paleovalleys, karst forms (red-stained conglomerates) and riverine channels. Coastal onlap of bedrocks and scarp breccias

Fig. 5. Structures of synsedimentary tectonics and normal faulting in the Súľov Conglomerates. A — Large-scale tensional fissure filled by Paleogene breccias in the Triassic complexes of the Krížna Unit. These fissures were formed by NNW–SSE extension and filled with material derived from steep fault scarps and (Loc. Baranovo near Veľká Čierna); B — Normal faults in basal conglomerates of the Súľov Fm. with down-dip linearization and veins of banded crystalline calcite (Fig. C for detail). Normal faulting and vein dilatation refers to a layer-parallel extension related to block tilting and tectonic subsidence of the Súľov–Domaníža Basin (Loc. Svinské chlievy, Ostrá Malenica Hill); D — Conjugate sets of normal faults in conglomerates of the Paština Závada Mb. (Loc. Kardošova Vieska).
Homogenous fault groups recorded in area studied. Explanations: n — number of fault-slip data; \( \sigma_1, \sigma_2, \sigma_3 \) — principal stress axes in format azimuth/dip (in degrees); \( R \) — stress ratio (\( \sigma_1 - \sigma_3; (\sigma_1 - \sigma_3)/\sigma_3 \)); \( R' \) — tensor type; F5 (\( \alpha \)) — mean slip deviation (angle between observed and computed slip directions, in degrees); Q (Qrw) — World Stress Map project quality ranking as defined in Sperner et al. (2003) from A — best to E — worst.

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Subsidence history

Gravitational movement and mass-transport deposition of the Súľov Conglomerates revealed a steep marginal escarpment, which could have been active as a master fault for the tectonic subsidence. Initial subsidence and syntectonic deposition started from 56 Ma, which is dated by HO of Gl. pseudomenardi, and recorded by accumulation of about 300 m thick conglomerate lithosomes. Their occasional pelagic interbeds indicate a rapid deepening to upper bathyal depth (cca 600 m). Based on biostratigraphic data (HOs of M. acuta and M. subbotinae, LO of I. broedermanni), this subsidence phase lasted approximately 2 Ma during the early Ypresian.

Tectonic subsidence increased during the middle Ypresian, when the basin reached a bathyal depth and was filled with up to 620 m of carbonate debris flow sediments. The duration of this phase is approximated between 54 and 50 Ma, implying an accumulation rate of 155 m/Ma. The age of the upper lithosomes of this cycle is dated to the late Ypresian, based on FOs of Turborotalia frontosa and the acarininid assemblage-zone (A. pentacamerata, A. pseudotopilensis, A. aspersis). Bathymetric data indicate the subsidence rate of 300 to 700 m/Ma, which is roughly the same value as in fore-arc basins governed by subduction tectonic erosion (von Huene & Lallemand 1990, Wagreich 1995).

Tectonic subsidence of the Súľov–Domaniža Basin was not followed by a significant thermal subsidence, since the basin-fill sediments did not record a higher grade of thermal alteration. The lack of thermal subsidence is a typical feature of...
Collapse basins developed on orogenic wedges, in which the overthickened crust prevents a rise in temperature (Séguret et al. 1989; Wagreich 1995).

The sedimentary load of mass-wasting deposits in the Súľov–Domaniža Basin led to the flexural subsidence and progressive deepening to abyssal depths (>2000 m). Lower Lutetian sediments of the Súľov Formation contain greyish-blue and ochre mudstones with deep-water agglutinated foraminifers (DWAF), *Scolicia*-type ichnofossils and even rich radiolarians. Considering that, the basin attained the CCD, which during the Eocene occurred at depths of 3200 to 3600 m in the global oceans (e.g., Rea & Lyle 2005; Slotnick et al. 2015).

The deepening of the SDB culminated during the middle Lutetian with deposition of red and variegated non- or weakly calcareous claystones with *Reticulophragmium amplectens*. These agglutinated foraminifers indicate an abyssal basin below the CCD with the paleo-depth around 4000 m (Pälike et al. 2012; Uchman et al. 2006). Accordingly, the Súľov–Domaniža Basin was the deepest depozone in the basinal systems of the Central Western Carpathians in the Middle Eocene times.

**Basin tectogenesis**

Tectonic collapse of the Súľov–Domaniža Basin is recorded by fault-scarp breccias, fissure-filling breccias and veins.

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**Fig. 6.** Synoptic table of successive deformational phases D1 to D6 observed in all localities of the Súľov Mts. Each homogenous group of faults is presented by a stereogram (the fault planes are plotted as great circles with observed slip senses using stereographic projection — Schmidt net, lower hemisphere).
Basal breccias and conglomerate lags often occur at scarps generated by tilting and synsedimentary normal faulting (Figs. 5B, 5D). Open fissures are occasionally infilled by gravitational breccias with material derived from the fissure walls (Fig. 5A). Layer-parallel extension was accompanied by opening of discrete fissures filled with banded veins of the Malenica onyxites, which were erroneously interpreted as lacustrine sediments in conglomerates of the Svinské Chlievy Mb. (Salaj 1991, 1993, 2002) — Fig. 5A, B. Their lacustrine origin was already questioned by Buček & Nagy (in Mello et al. 2011). The Malenica onyxites are formed by syntaxial overgrowth of palisade, fibrous and prismatic crystals, similar to those from pre-Eocene karst flowstones in the Tatra Mts. (Jach et al. 2016) or Late Eocene sedimentary dykes in the Buda paleoslope (Fodor et al. 1992). The flowstone deposits in fissures were precipitated from descending meteoric waters or ascending fluids with elevated temperature. It is possible, that the driving mechanism for fluid flow might have been seismic pumping (see Roberts & Steward 1994). Syntectonic origin of the flowstones is documented by their occasional fragmentation due to renewed fold activity and by carbonate clasts derived from fault gouge. The coastal fault-blocks probably emerged in the vadose zone, because such flowstones could have been precipitated in bedrocks uplifted above the water-table (Tucker & Wright 1990; Roberts & Stewart 1994). Accordingly, the Súľov–Domaniža Basin experienced a high topographic differentiation with active fault scarps and raised mainland drainage for providing a huge amount of carbonate gravity-flow breccias (Fig. 7). Gravitational collapse, bathyal to abyssal deepening and mass-transport deposition in the Súľov–Domaniža Basin could have been controlled by the subduction tectonic erosion, which is a prominent process in most convergent plate-margin systems (e.g., von Huene & Lallemand 1990; von Huene & Ranero 2003; von Huene et al. 2004a; Vannucchi et al. 2001, 2004). Subcrustal tectonic erosion of the Austroalpine microplate was also considered as a driving mechanism for rapid subsidence and deep-water sedimentation of the Gosau basins in the Eastern Alps (Wagreich 1993, 1995; Wagreich & Marschalko 1995; Kázmér et al. 2003). The Súľov–Domaniža Basin began to develop when the Oravic ribbon continent entered the subduction zone, which resulted in an overthickened orogenic wedge with supercritical taper (Plašienka & Soták 2015). Enormous uplift of the plate margin could occur due to buckling of the ribbon continent in the subduction zone. This was followed by basal erosion of the upper plate, which led to gravitational collapse and seaward tilting of basin slopes (Fig. 8). The steep marginal escarpment of the upper plate above a ribbon buttress led to submarine landsliding and mass-wasting of scarp breccias and conglomerates in deep-water basins (Figs. 7, 8). Mass-transport deposition in the Súľov–Domaniža Basin could be forced by seismotectonic activity, since subduction of seamounts creates a highly potential for earthquakes (e.g., von Huene et al. 2004a). That is
the reason why the mass-transport deposits are frequently connected with seismic activity (e.g., Ratzov et al. 2010; Gamberi et al. 2011).

**Conclusions**

Our structural and biostratigraphic evaluation of the Súľov Conglomerates has come to the following conclusions:

- The Súľov–Domaniža Basin started to develop in the latest Paleocene to Early Eocene by gravitational collapse of an overthickened orogenic wedge, which is recorded by fissure-filling breccias, scarp breccias and fault-related veins of onyxites. Initial subsidence led to accumulation of talus breccias derived from extrabasinal sources and intrabasinal highs (e.g., the Kambühel Lms.), submarine landsliding and rapid deepening of basinal depocentres to bathyal depth. The subsidence continued during the Middle Eocene with deepening around the CCD (DWAF, radiolarians) and accumulation of gravelly and sandy debris-flow lobes in the abyssal basin. The coarse-grained slope system was connected with deep-sea fans, which are represented by distal turbidites of Domaniža Fm. Maximum deepening of the SDB is recorded by non-calcareous red-beds with *Reticulophragmium amplectens*.

- The Upper plate margin of the CWC collapsed due to subduction and underthrusting of Oravic ribbon continent, which led to a supercritical taper of the orogenic wedge, subsequently followed by the subcrustal erosion and gravitational collapse along an extensional master fault escarpment. The marginal deep-seated escarpment was able to accumulate a high volume of scarp and slope-apron breccias and conglomerates derived from the Hronic carbonate complexes of the CWC orogenic wedge. Gravitational movement and mass-transport wasting of the Súľov Conglomerates was probably enhanced by the seismotectonic activity, since earthquakes generated by ridge subduction can lead to huge slumping on the active continental margins (e.g., von Huene et al. 2004b; Hühnerbach et al. 2005). This was likely the case of the Oravic ribbon subduction, as well.

- Tectonic inversion of the Súľov–Domaniža Basin started with intra-wedge shortening under NW–SE directed compression, Late Eocene–Oligocene uplift and post-Lutetian denudation (Kováč et al. 2016). During these events, the Paleogene sediments in the Rajec Basin and Turiec Basin were deformed, as well (Hók et al. 1998; Rakús & Hók 2003; Pulišová et al. 2015).

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References


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Appendix

Checklist of foraminiferal species mentioned in the text:

- Acarinina aspensis (Colom, 1954)
- Acarinina bullbrooki (Bolli, 1957)
- Acarinina caoligensis (Cushman & Hanna, 1927)
- Acarinina collactea (Finlay, 1939)
- Acarinina crassata densa (Cushman, 1925)
- Acarinina cuneicamerata (Blow, 1979)
- Acarinina mecknannai (White, 1928)
- Acarinina nitida (Martin, 1934)
- Acarinina pentacamatera (Subbotina, 1947)
- Acarinina pseudotopilensis Subbotina, 1953
- Acarinina punctocarinata Fleischer, 1974
- Acarinina strabocella (Loeblich & Tappan, 1957)
- Acarinina wilcoxensis (Cushman & Ponton, 1932)
- Ammodiscus cretaceous (Reuss, 1845)
- Ammodiscus serpens (Grzybowski, 1898)
- Bathysiphon gerochi Mjatliuk, 1966
- Catapsydrax unicavus Bolli, Loeblich & Tappan, 1957
- Globigerina congleromata Schwager, 1866
- Globigerina eocaena (Guembel, 1868)
- Globorotalia crassaformis (Galloway & Wissler, 1927)
- Haplophragmoides horridus (Grzybowski, 1901)
- Haplophragmoides excavates Cushman & Waters, 1927
- Igorina brodermanni (Cushman & Bermúdez, 1949)
- Igorina salisburgensis (Gohrbandt, 1967)
- Igorina wartsteinensis (Gohrbandt, 1967)
- Morozovella acuta (Toulmin, 1941)
- Morozovella aqua (Cushman & Renz, 1942)
- Morozovella gordonixensis (Oru-Etxebarria, 1985)
- Morozovella gracilis (Bolli, 1957)
- Morozovella praegordoni (Blow, 1979)
- Morozovella subbotinae (Morozova, 1939)
- Morozovella ex q. velascoensis (Cushman 1925)
- Notia robusta (Grzybowski, 1898)
- Parasubbotina hagni (Gohrbandt, 1967)
- Parasubbotina inaequispira (Subbotina, 1953)
- Paratrochamminoides olzewskii (Grzybowski, 1898)
- Paratrochamminoides deflexiformis (Noth, 1912)
- Psammophalina eocaena (Glaessner, 1937)
- Psammosphaera irregularis (Grzybowski, 1898)
- Psammosphaera fusca Shulze, 1875
- Reticulophragmium amplectens (Grzybowski, 1898)
- Subbotina cancellata Blow, 1979
- Subbotina eocaena (Guembel, 1868)
- Subbotina patagonica (Todd & Kniker, 1952)
- Subbotina roesnajensis Olsson & Berggen, 2006
- Subbotina senni (Beckmann, 1953)
- Subbotina triangularis (White, 1928)
- Subbotina triloculinae (Plummer, 1926)
- Subbotina ex gr. velascoensis (Cushman, 1925)
- Trochamminoides subcoronatus (Grzybowski, 1898)
- Trochamminoides contortus (Karrer, 1866)
- Trochamminoides proteus (Karrer, 1866)
- Trochamminoides? cf. dubius (Grzybowski, 1901)
- Turborotalia frontosa (Subbotina, 1953)