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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 (σ_1 rotated from NW–SE to NNW–SSE), which changed to a transpressional regime during the Middle Miocene (σ_1 rotated from NNE–SSW to NE–SW). Late Miocene tectonics were dominated by an extensional regime with σ_3 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 litostratigraphic units, which begin with basal conglomerates overlying the Manín Unit and the higher Fatric and Hronic nappes (Svinské chlievy Mb. *sensu* Salaj 1993), followed by thick lithosomes of carbonatic 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

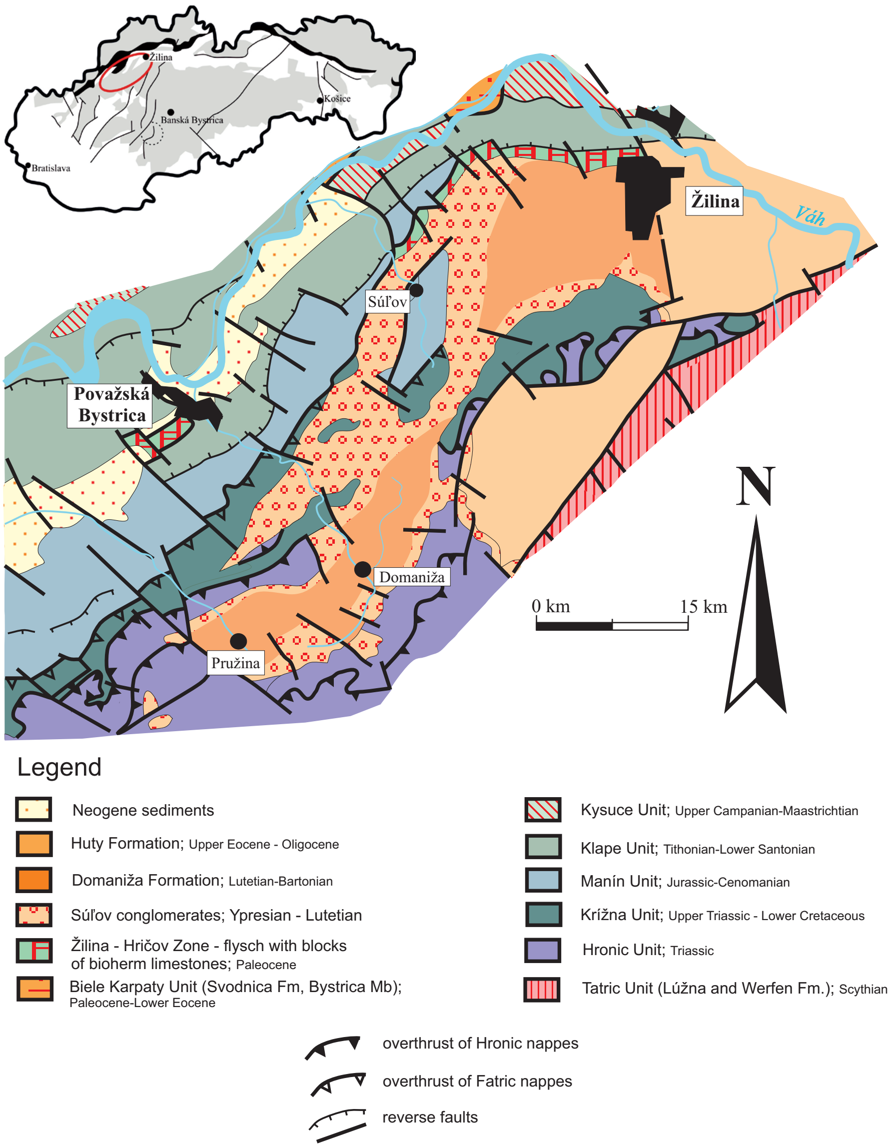

Fig. 1. Simplified geological map of the Middle Váh region showing the frontal nappe units of the Central Western Carpathians (Malenica, Manín, Hradná, Kostolec, and other units), Peri-Klippen zone (Klape, Podháj, Praznov–Jablonica and Hričov–Žilina units) and Pieniny Klippen Belt. These Mesozoic units are overlain by Paleogene sediments of the Súľov–Domaniža Basin, predominantly by thick formations of the Súľov Conglomerates (based on the maps by Biely et al. 1996 and Mello et al. 2011).

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 (Manín, Kostelec, 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 Maheľ (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 Podmanín Group, which were formerly assigned to the Manín 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 Manín 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 the subject of current research (Kováč & Hók

Jablonové 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 Domaniža 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.

1993; Bučová et al. 2010; Šimonová & Plašienka 2011, 2017; Plašienka 2012; Prokešová et al. 2012; Bučová 2013).

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 Holý 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, Babkov and Peklina 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 nappe and Klippen belt units (cf. Marschalko & Samuel 1993).

Fig. 2. Panoramic view of rocky crests built by the Súľov Conglomerates. **A** — Veľký Pezínok–Dolné Skálie group of rocky cliffs in the western belt of the Súľov Conglomerates; **B** — Roháč group of rocky cliffs in the eastern belt of the Súľov Conglomerates.

Material and methods

The Súľov Formation consists of monogenic 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 herein). Interpretation of debris-flow deposits also differs in two distinct models: viscoplastic and inertial grain flow models (see Sohn 2000 for the review). Debrites 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,

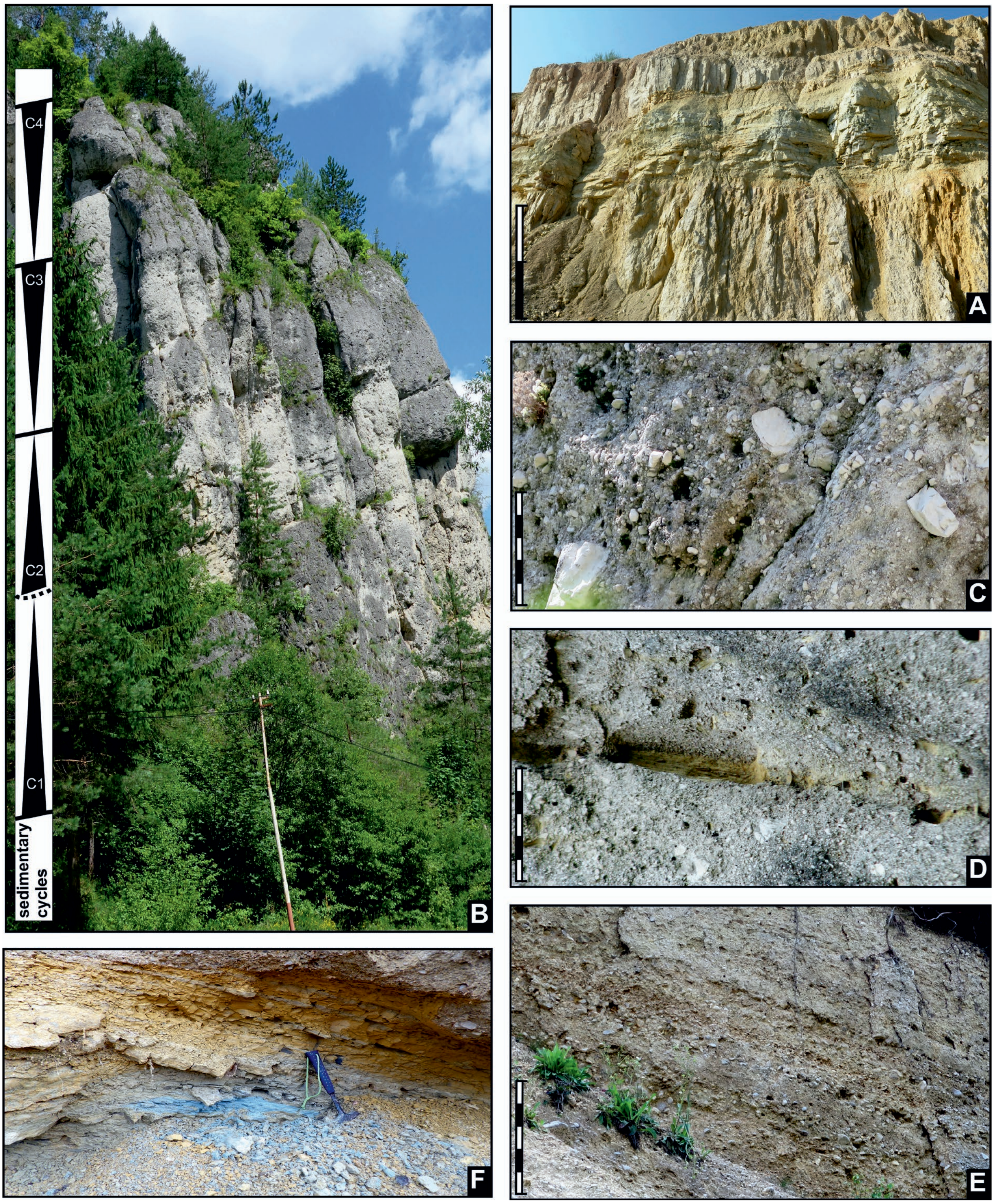

Fig. 3. Sedimentary sequences of the Súľov Fm. **A** — Transgressive basal sediments of the Súľov Fm., which discordantly overlie the Triassic dolomites of the Fatric Krížna Unit. Dolomites are superposed by horizontally bedded calcarenites with parallel lamination and oscillatory ripple marks, which 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 skala 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 skala 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. Súľov 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.

1991, 1997) is more reliable. This model interprets the debris flow deposition by grain collisions, shear stress and dispersive pressure, which drops leading to "freezing" of the flow. Therefore, coarse-grained sediments, like those in the Súľov Fm., can include both debrites of cohesive flows (with Bingham plastic rheology) and non-cohesive flows (non-Newtonian dilatant fluid rheology — *sensu* Gani 2004).

Biostratigraphic data come from planktonic foraminiferal microfauna, which has been obtained from claystones in basal parts of the Súľov Fm. (loc. Pažice in Hradná 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 microfauna has been analysed using systems of taxonomic classification and biostratigraphic 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 biostratigraphic 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 paleostress 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 Křížna unit and Kostolec–Manín units (Hradná succession), Ilerdian–Cuisian formations (Jablonové, Riedka), Súľov Conglomerates and Paština Závada Member (Lutetian). There were very rare possibilities to identify successive deformational phases from intersection of slickenside structures observed on the fault plane. Our data on brittle tectonic structures in the Súľov Conglomerates have been combined with previous structural works of other authors (e.g., Šimonová & Plašienka 2011, 2017; Bučová 2013).

Biostratigraphic data and depositional age

Planktonic foraminiferal microfauna 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, Hradná creek, 220 m above the Jablonové quarry). Claystones are poor in planktonic foraminifers, which comprise *Globanomalina pseudomenardi*, *Acarinina mckannai*, *A. nitida, A. caoligensis*, *Morozovella acuta, M. praeangulata*, *Subbotina triloculinoides, 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).

Claystones from lower part of the Súľov Conglomerates were sampled in the Čierny potok Creek around the forest road from Súľov to Vrchteplá. They occur in turbiditic interbeds within thick conglomerate lithosomes. The microfauna 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*), subbotinids (*Parasubbotina inaequispira*, *Subbotina triangularis*, *S. ex gr. velascoensis*) and rare other planktonic foraminifera (e.g., *Igorina broedermanni*). 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-westward 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 pseudotopilensiss*, *A. aspensis, A. cuneicamerata, A. wilcoxensis, A. pentacamerata* and *Acarenina collactea*. The acarininid species are associated with *Turborotalia frontosa*, *Subbotina patagonica, S. eocaena, S. roesnaensis* and *Catapsydrax unicavus*. Foraminiferal microfauna 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 claystone- and flysch-type sediments of the Domaniža Basin

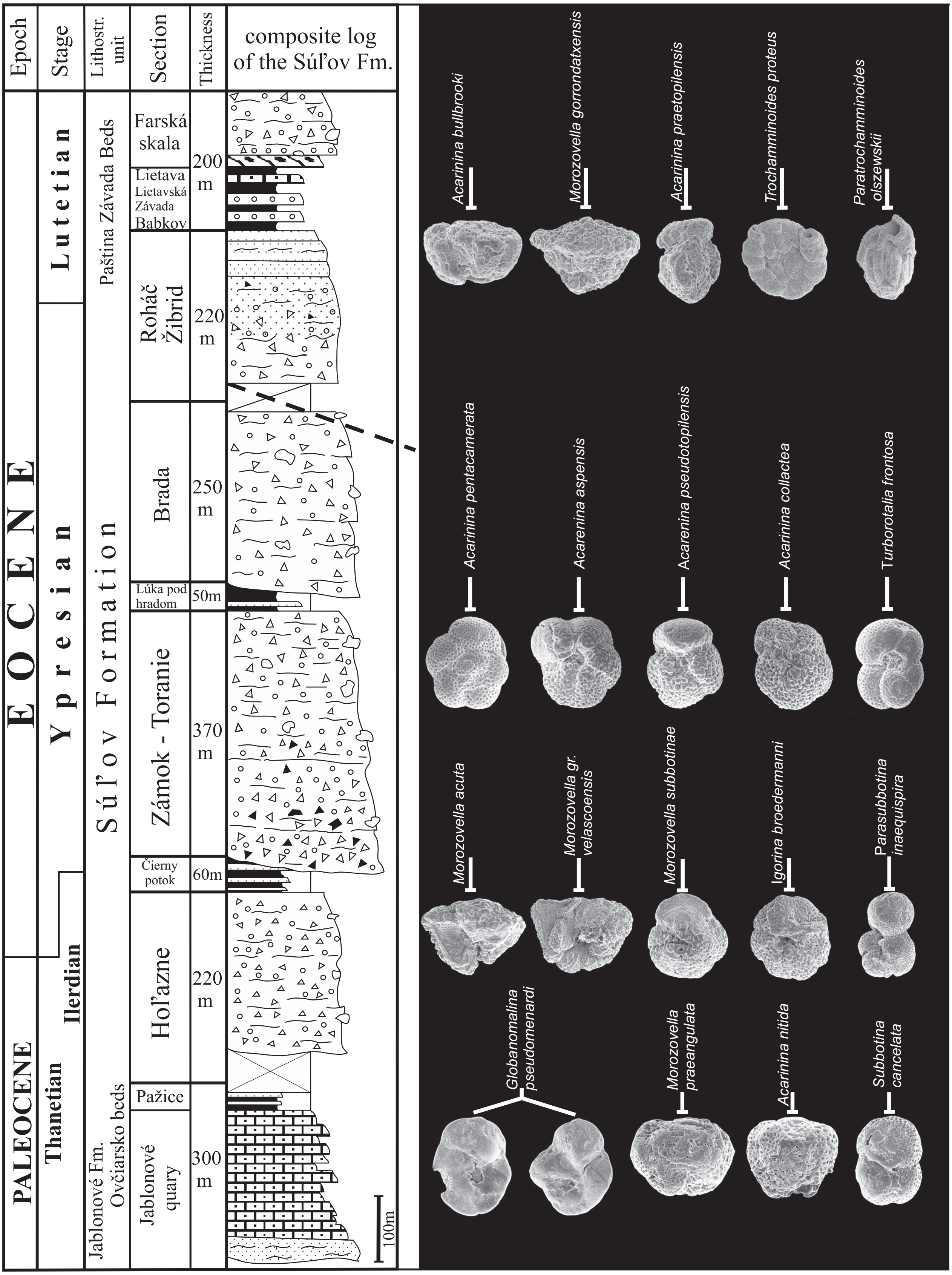

Fig. 4. Composite log of the Súľov Fm. with conglomerate lithosomes, hemipelagic interbeds and their microfauna. Foraminiferal species imply the late Thanetian–early Ypresian (Ilerdian) up to early Lutetian age of conglomerate formation and deepening-upward sequence with DWAF-type association in the uppermost part of the Súľov Fm.

(*sensu* Buček & Nagy in Mello et al. (2011). Claystone interbeds with foraminiferal microfauna were found in conglomerates at two localities. Greyish-blue and brown clays occur at the Lietava locality within poorly stratified sandy-gravelly sediments. Their microfauna differs in predominance of planktonic foraminifers in brown clays and agglutinated foraminifers in greyish-blue clays. Planktonic assemblage comprises the species *Acarinina bullbrooki*, *A. punktocarinata*, *A. coaligensis, A. praetopilensis*, *Morozovella gorrondatxensis*, *M. gracilis*, *Igorina wartsteinensis*, *I. salisburgensis*, *Subbotina senni* and *Parasubbotina hagni*. The species *Acarinina bullbrooki* is regarded as a marker of the early Lutenian Zone in the Western Carpathians (=*Acarinina crassata densa* Zone *sensu* Samuel & Salaj 1968). Morozovellid foraminifers are also present including early Lutetian species, like *M. gorrondatxensis* (Orue-Etxebarria et al. 2014). Further species of igorinids and subbotinids are known from the lower Lutetian formations of the Helveticum, Betic Cordillera, etc. (e.g., Rögl & Egger 2012; Gebhardt et al. 2013; Gonzalvo & Molina 1998). Summary data from planktonic foraminiferal microfauna of the uppermost part of the Súľov Conglomerates (Paština Závada Mb.) provide evidence for an early Lutetian age (Zone E8–E9).

Claystones from all interbeds of the Súľov Fm. contain agglutinated foraminifers, as well. Their associations comprise *Psammosiphonella cylindrica*, *Bathysiphon gerochi*, *Nothia robusta*, *Trochamminoides subcoronatus, T. contortus, T. proteus*, *T.? dubius*, *Paratrochamminoides olszewski, P. deflexiformis*, *Haplophragmoides excavates, H. horridus, Ammodiscus cretaceus*, *A. serpens, Psammosphaera irregularis* and *P. cf. fusca*. Increasing content of agglutinated foraminifers from the early Ypresian to early Lutetian reveals an initial collapse subsidence of the basin to bathyal depth and its deepening-upward to abyssal depths with DWAF-type microfauna of agglutinated foraminifers in the uppermost part of the Súľov Fm. (Paština Závada Mb.).

Structural analysis and paleostress reconstruction

Bedding of the Súľov Conglomerates is oriented in the NNE–SSW direction and SE-ward tectonically inclined by 65° to 85°. The most steeply dipping bedding planes were observed in fine-grained conglomerates in the Súľov area (mean of 78°) and gently dipping in the Lietava area (ranging from 9° to 30°).

The synsedimentary tectonics of the Súľov–Domaniža Basin are recorded by fissures in the carbonate complexes of the underlying Hronic unit. The fissures are bounded by subvertical scarps and filled by structureless carbonate breccias (Fig. 5A — Baranova near Veľká Čierna). The fissures and related normal faults form a conjungate system with NW–SE and NE–SW orientation (Fig. 5D — Kardošova Vieska). They were formed by extensional collapse during the initial D0 phase of basin tectonics, when maximum stress axis was vertical (Table 1).

Marginal faulting of the Súľov–Domaniža Basin is recorded in fault-bounded talus aprons of basal conglomerates (Riedka, Svinské chlievy). This system of E–W trending normal faults, which controlled progressive steepening of basinal slopes, was formed during WNW–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 NNW–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 WNW–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; Kováč & Hók 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 (Hók et al. 1998; Rakús & Hók 2003). That is also a case of reverse faults with thrusting of Aptian sediments of the Fatric Unit over Paleogene sediments in the Veľká Fatra Mts. (Krpeľany, TK-3 borehole; Pulišová 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 (σ_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; Kováč & Hók 1996; Fodor et al. 1999; Šimonová & Plašienka 2011, 2017; Bučová 2013).

The fourth deformation phase is expressed by σ_1 rotation in a NNE–SSW direction with perpendicular extensional axis to maximum compression (Fig. 6; Table 1). Transpressional faulting was changed to transtensional 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 paleo-valleys, karst forms (red-stained conglomerates) and riverine channels. Coastal onlap of bedrocks and scarp breccias is

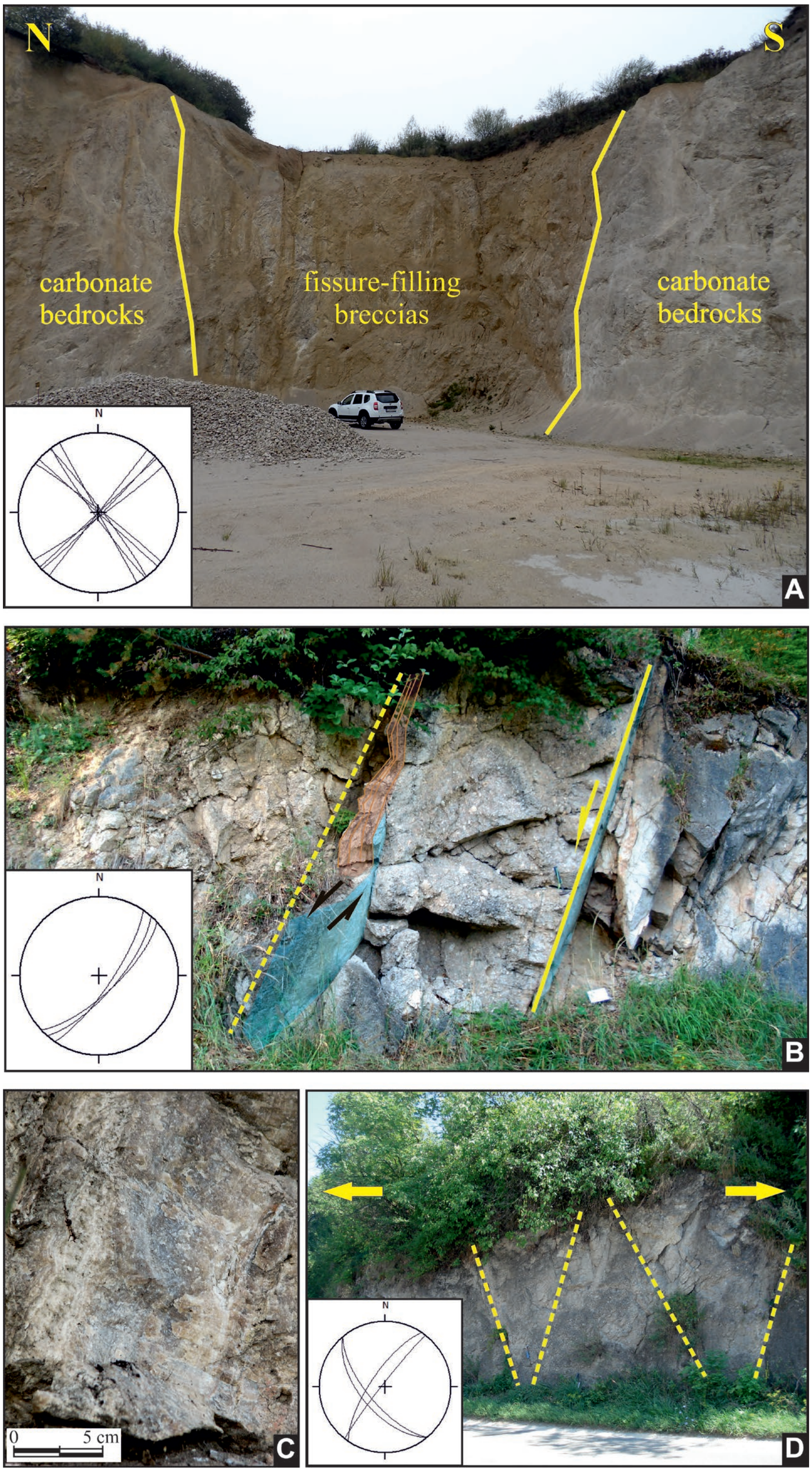

Fig. 5. Structures of synsedimentary tectonics and normal faulting in the Súľov Conglomerates. **A** — Large-scale tensional fissure filled by Paleogene breccias in the Triassic complexes of the Krížna Unit. These fissures were formed by NNW–SSE extension and filled with material derived from steep fault scarps and (Loc. Baranovo near Veľká Čierna); **B** — Normal faults in basal conglomerates of the Súľov Fm. with down-dip lineation 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–Domaniža Basin (Loc. Svinské chlievy, Ostrá Malenica Hill); **D** — Conjugate sets of normal faults in conglomerates of the Paština Závada Mb. (Loc. Kardošova Vieska).

Table 1: Homogenous fault groups recorded in area studied. Explanations: n — number of fault-slip data; σ_1, σ_2, σ_3 — principal stress axes in format azimuth/dip (in degrees); R — stress ratio $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$; R´ — tensor type; F5 (α) — 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.

Tensor name	n	σ_1	σ_2	σ_3	R	R´	F5 (α)	Q (Qrw)	Stress regime
D1a	10	084/21	283/68	176/06	0.56	1.44	6.84	E	pure strike-slip
D1b	7	274/07	006/17	162/71	0.44	2.44	5.31	E	pure compressional
D1c	6	165/88	271/01	001/02	0.5	0.5	8.38	E	extension
D2a	16	116/07	325/82	206/04	0.41	1.59	10.57	E	pure strike-slip
D2b	15	126/01	026/83	216/07	0.46	1.54	19.39	E	extensional strike-slip
D2c	24	117/02	027/01	273/88	0.52	2.52	10.07	E	pure compressional
D3a	22	162/01	268/85	072/05	0.44	1.56	7.48	E	pure strike-slip
D3b	17	339/08	247/07	117/80	0.5	2.5	5.36	E	pure compressional
D3c	9	135/85	351/04	261/03	0.66	0.66	17.03	E	extension
D4a	4	002/08	145/80	271/06	0.55	1.45	4.95	E	pure strike-slip
D4b	16	198/04	032/86	288/01	0.69	1.31	9.34	E	extensional strike-slip
D4c	7	208/06	118/00	024/84	0.5	2.5	2.44	E	pure compressional
D4d	12	202/55	029/35	269/03	0.5	0.5	2.07	E	extension
D5a	8	257/04	053/85	166/02	0.55	1.45	4.58	E	pure strike-slip
D5b	6	043/14	134/06	247/75	0.54	1.52	11.7	E	pure strike-slip
D5c	18	186/80	051/07	320/07	0.43	0.43	7.98	E	extension
D6	20	117/68	261/18	355/12	0.57	0.57	20.11	E	extension

developed as a flat-bedded or clinostratified sequence of calciclastic shoreface sediments with parallel lamination and oscillatory ripples (Fig. 3A).

Extrabasinal sources supplied the SDB with monogenic clastic material from the Triassic carbonate complexes, but there are also some components with intrabasinal origin (e.g., Paleocene reefal limestones of the Kambühel Fm.). The clastic supply was enhanced by slope oversteepening and gravity flow accumulation of thick conglomerate lithosomes in the Súľov–Domaniža Basin. Their coarse-grained particles, poor sorting and thick structureless megabeds (Fig. 3B) imply a fast accumulation of debris avalanches and cohesive debris flows, which came to be frozen "*en masse*" after reaching a deep basin (see Marschalko & Samuel 1993). Unlike megabeds, there are also lithosomes stacked by conglomerate units, which are amalgamated, internally truncated, channelized (dish structures), graded or laminated (frictional lamination) and upwardly penetrated by large clasts and claystone chips (Fig. 3B,C). It seems, that these conglomerates were deposited from non-cohesive debris flows with basal friction, incremental aggradation, erosion and dispersive grain pressure (rafted and floated clasts). Downslope movement and transformation of debris flow was facilitated by their dilution and reducing a drag on the sea-floor by hydroplaning (e.g., Mohring et al. 1998). The conglomerates of uppermost lithosomes (Paština Závada Mb.) are increasingly sorted, horizontally stratified, matrix-supported and intercalated by mudstones (Fig. 3E, F). They were deposited from frictional (non-cohesive) up to hyperconcentrated density flows in deep-water slope channels and base-of-slope lobes.

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. aspensis*). 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

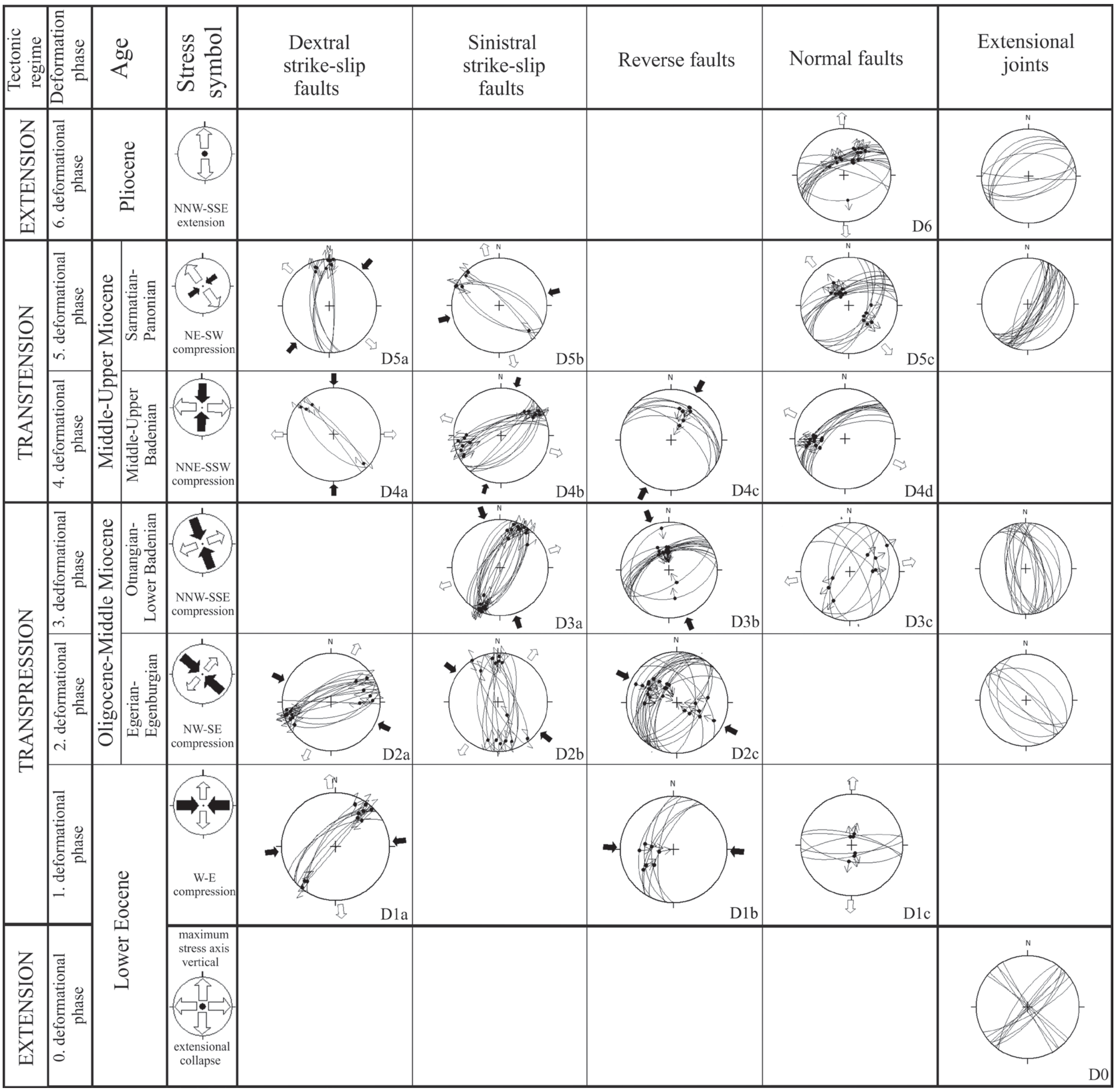

Fig. 6. Synoptic table of successive deformational phases D1 to D6 observed in all localities of the Súľov Mts. Each homogenous group of faults is presented by a stereogram (the fault planes are plotted as great circles with observed slip senses using stereographic projection — Schmidt net, lower hemisphere).

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

(Fig. 5). 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 basinal 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

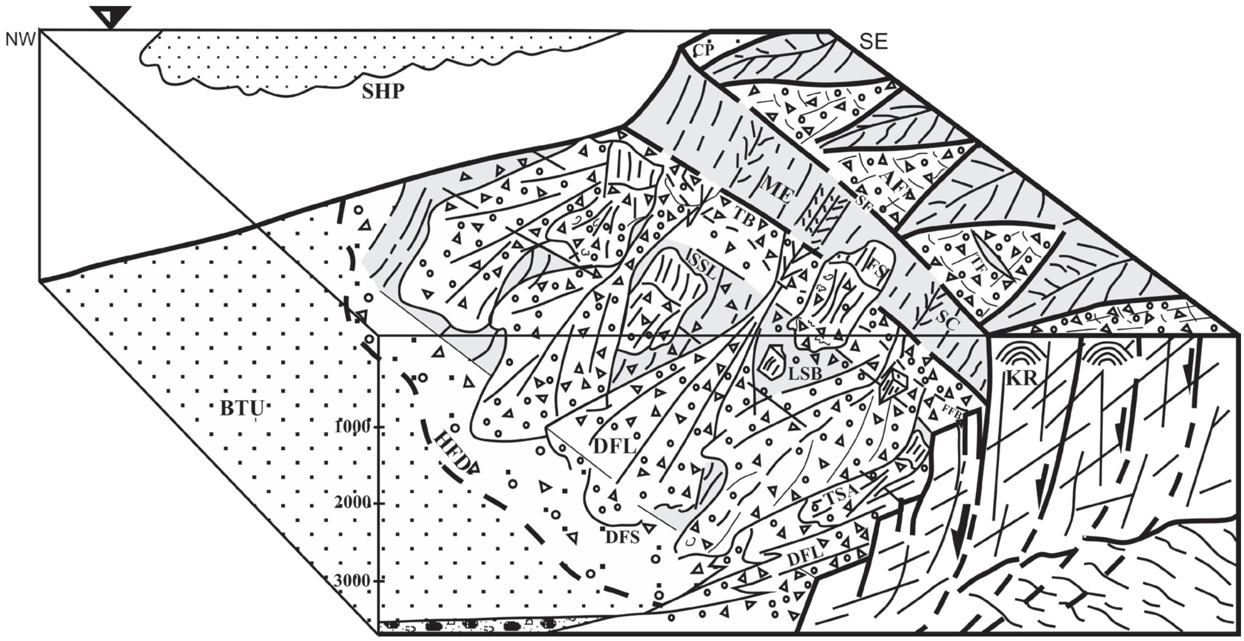

Fig. 7. Conceptual model for mass-transport deposition of breccias and conglomerates in the Súľov–Domaniža Basin. The model is designed as a fault-bounded deep-water basin with alluvial systems (AF), coastal plain (CP), eroded reef buildups (Kambühel Lms. — KR), reduced shelf (SF), marginal escarpment (ME), TF — tension fissures (TF), failure slopes (FS), landslide scarp blocks (LSB), scours and slumps (SSL), fissure-filling breccias (FFB), talus breccias (TB), slope conduits (SC), toe-of-slope aprons (TSA), debris flow lobes (DFL), seafloor debris-flow sheets (SF), hyperconcentrated flow deposit (HFD), basinal turbidites (BTU) and surface hemipelagic plume (SHP). Basin topography and sedimentary architecture reflects the basins on the active plate margins affected by slope failure and submarine mass-transport deposition (e.g., von Heune et al. 2004b; Gamberi et al. 2011; Loucks et al. 2011; Posamentier & Martinsen 2011; Principaud et al. 2015; Ruh 2016).

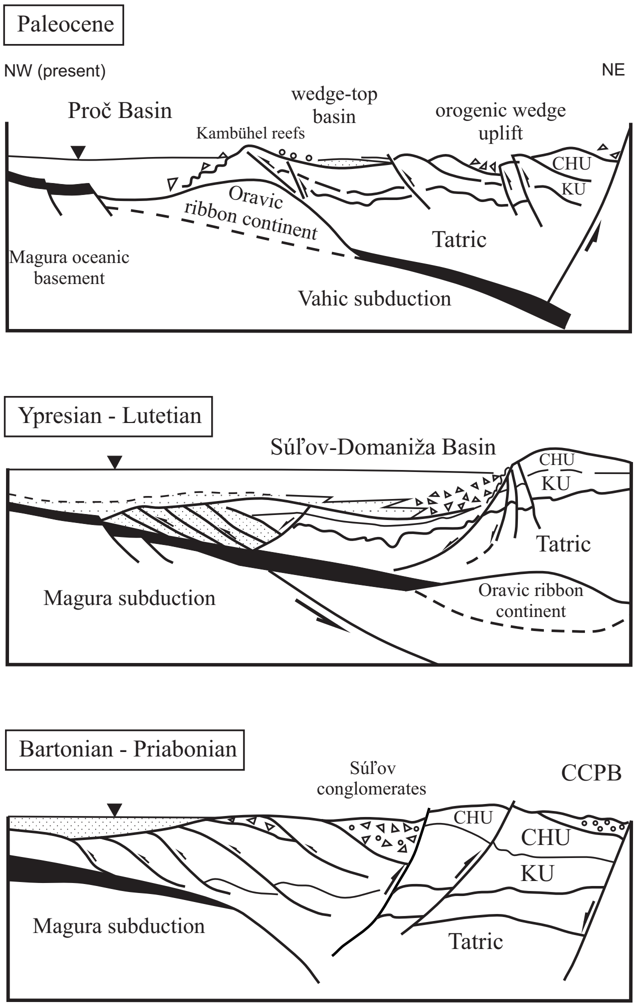

Fig. 8. Diagrammatic sections of the CWC orogenic wedge and subducting Oravic ribbon continent by using of seamount subduction model by von Huene et al. (2004b). This model seems to be appropriate for interpretation of tectonic erosion, upper plate weakening, gravitational collapse, marginal and mid-slope faulting, rapid tectonic subsidence, mass-transport wasting and abyssal deepening of the Súľov–Domaniža Basin. Abbrevations: KU — Križna Unit; CHU — Choč Unit; CCPB — Central-Carpathian Paleogene Basin. Modified after Plašienka & Soták (2015).

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 is filled with upper Thanetian–lower Ypresian (Ilerdian) to lower Lutetian carbonatic scarp breccias and conglomerates, which were accumulated in response to collapse subsidence, slope instability, downslope sliding and mass-transport wasting. The coarse clastics and scarp breccias moved downward across a narrow or missing shelf and steep slope into the basin. They were further transported by gravity-driven flows, which became largely frozen "*en-mass*" in a deep-water basin.
- 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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Appendix

Checklist of foraminiferal species mentioned in the text:

Acarinina aspensis (Colom, 1954)
Acarinina bullbrooki (Bolli, 1957)
Acarinina caoligensis (Cushman & Hanna, 1927)
Acarenina collactea (Finlay, 1939)
Acarinina crassata densa (Cushman, 1925)
Acarinina cuneicamerata (Blow, 1979)
Acarinina mckannai (White, 1928)
Acarinina nitida (Martin, 1934)
Acarinina pentacamerata (Subbotina, 1947)
Acarinina praetopilensis (Blow, 1979)
Acarenina pseudotopilensis Subbotina, 1953
Acarinina punktocarinata 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
Globanomalina pseudomenardi (Bolli, 1957)
Globigerina conglomerata Schwager, 1866
Globigerina eocaena, Guembel, 1868
Globorotalia crassaformis (Galloway & Wissler, 1927)
Haplophragmoides horridus (Grzybowski, 1901)
Haplophragmoides excavates Cushman & Waters, 1927
Igorina broedermanni (Cushman & Bermúdez, 1949)
Igorina salisburgensis (Gohrbandt, 1967)
Igorina wartsteinensis (Gohrbandt, 1967)
Morozovella acuta (Toulmin, 1941)
Morozovella aequa (Cushman & Renz, 1942)
Morozovella gorrondatxensis (Orue-Etxebarria, 1985)
Morozovella gracilis (Bolli, 1957)
Morozovella praeangulata (Blow, 1979)
Morozovella subbotinae (Morozova, 1939)
Morozovella ex gr. velascoensis (Cushman 1925)
Nothia robusta (Grzybowski, 1898)
Parasubbotina hagni (Gohrbandt, 1967)
Parasubbotina inaequispira (Subbotina, 1953)
Paratrochamminoides olszewskii (Grzybowski, 1898)
Paratrochamminoides deflexiformis (Noth, 1912)
Psammosiphonella cylindrical (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 roesnaensis Olsson & Berggen, 2006
Subbotina senni (Beckmann, 1953)
Subbotina triangularis (White, 1928)
Subbotina triloculinoides (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)