Marine and Petroleum Geology 18 (2001) 87–114

Marine and Petroleum Geology

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Sedimentology and hydrocarbon habitat of the submarine-fan deposits of the Central Carpathian Paleogene Basin (NE Slovakia)

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Received 28 August 1997; received in revised form 13 March 2000; accepted 19 May 2000

Abstract

The Central Carpathian Paleogene Basin accommodates a subsiding area of the destructive plate-margin. The basin history comprises marginal faulting and alluvial fan accumulation (E_2); transgressive onlap by shoreface sediments and carbonate platform deposits (E_2); glacio-eustatic regression induced by cooling (Terminal Eocene Event); forced regression, tectonic subsidence and growth-fault accumulation of basin-floor and slope fans (E_3); decelerating subsidence, aggradation and sea-level rising during the mud-rich deposition (O_1); high-magnitude drop in sea-level (Mid-Oligocene Event), retroarc backstep of depocenters and lowstand accumulation of sand-rich fans and suprafans (O_2–M_1); subduction-related shortening and basin inversion along the northern margins affected by backthrusting and transpressional deformation (O_2–M_1). The basin-fill sequence has poor (TOC $\leq$ 0.5%) to fair (TOC $<$ 1.0%) quality of source rocks. Maturity of OM ranges from initial to relic stage of HC generation. Paleogene rock-extracts display a good correlation with scarce trapped oils. The presence of solid bitumens and HC-rich fluid inclusions indicates overpressure conditions during HC generation and migration. Potential HC reservoirs can be expected in porous lithologies (scarp breccias), in basement highs and traps related to backthrusting, fault-propagation folding and strike–slip tectonics.

Keywords: Western Carpathians; Forearc basin; Submarine fans; Sedimentology; Sequence stratigraphy; Basin subsidence; Tectonogenesis; Hydrocarbon potential

1. Introduction

The Central Carpathian Paleogene Basin (CCPB) lies within the West Carpathian Mountain chain. The CCPB extends over an approximate area of 9000 km^2 having a sedimentary bulk of about 11 500 km^3. The basin is filled by several hundred up to thousand meters thick of flysch-like deposits. The CCPB experienced the Late–Middle Eocene transgression from the Peritethyan sea of the Outer Carpathian basins (Andrusov & Köhler, 1963). The basin lasted under submarine fan deposition till the Latest Oligocene–Early Miocene? (Sotak, Bebej, & Biron, 1996; Sotak, Spisiak et al., 1996).

Paleogene sediments of the CCPB have been investigated in numerous studies on sedimentology (e.g. Marschalko, 1966, 1970, 1975, 1981, 1987; Marschalko & Gross, 1970; Marschalko & Radomski, 1960; Picha, 1964; Radomski, 1958), regional geology (e.g. Gross et al., 1999, 1980, 1993; Nemcok, 1990), biostratigraphy (e.g. Blaicher, 1973; Dudziak, 1986; Gedl, 1995; Köhler, 1967; Marschalko & Samuel, 1960; Molnar, Karoli, & Zlinska, 1992; Olszewska & Wieczorek, 1998; Samuel & Bystricka, 1968; Samuel & Salaj, 1968; Samuel & Snopkova, 1962), basin analysis and paleogeography (e.g. Marschalko, 1981; Nemcok, Keith, & Neese, 1996; Samuel, 1973), structural geology (e.g. Mastella, Ozimkowski, & Szcesny, 1988; Nemcok, 1993; Ratschbacher et al., 1993; Sperner, 1996), geophysical research (e.g. Fusan, Biely, Ibrmajer, Plancar, & Rozloznik, 1987; Morkovsky, 1981), and organic geochemistry (Francu & Müller, 1983; Korab et al., 1986; Masaryk, Milicka, Pereszlenyi, & Pagac, 1995). Hydrocarbon potential of the CCPB was tested by deep drillings in Lipany and Plavnica prospects,

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0264-8172/01/$ - see front matter
PII: S0264-8172(00)00047-7

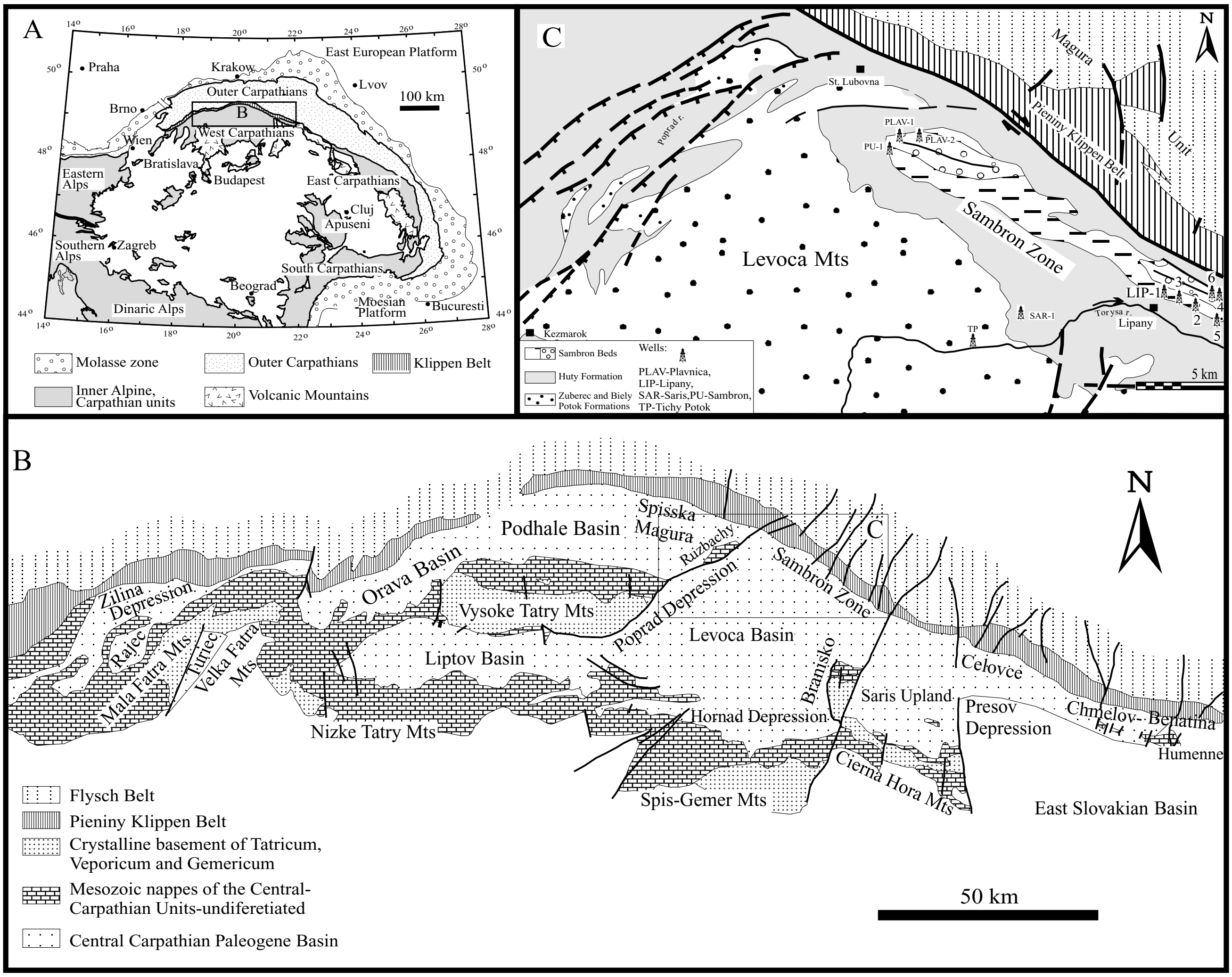

Fig. 1. Location of study area within the Alpine-Carpathian orogen (A); the CCP Basin system depicting structural sub-basins, basement massifs and surrounding units (B); geological sketch of the eastern Slovakia with situated wells studied (C).

including Lipany 1–6, Plavnica 1, 2, Sambron PU1 and Saris 1 wells. Indications of borehole hydrocarbon were recovered as methane, paraffinic oils, non-combustible gas, asphalts and nitrogen (e.g. Nemcok et al., 1977; Rudinec, 1989, 1992). Both oil and gas were trapped mostly in the breccia-type reservoirs.

In this paper we aim to present a new sedimentary model of the CCPB based on a facial analysis, sequence stratigraphy, subsidence history and hydrocarbon potential appraisal. In the attempt to derive a new model we, as the first step, introduce pre-existing and new data sets. These data sets comprise sedimentary, geochemical, structural and engineering geology data, frequently available in unpublished reports (e.g. Keith et al., 1991; Pereszlenyi, Milicka, & Vitalos, 1996; Sotak, Spisiak et al., 1996). As a second step, all databases are compared in order to derive critical parameters for a new model.

2. Geological setting

The CCPB represents the largest accumulation space of the submarine fan deposits in the Central Western Carpathians (Fig. 1). The CCPB was formed on the upper plate above the subducting oceanic slab attached to the European Platform (e.g. Royden & Baldi, 1988). The basin overlaps the basement units consolidated by pre-Senonian thrusting. The Paleogene sediments are preserved in several structural sub-basins, including the Zilina, Rajec, Turiec, Orava, Liptov, Podhale, Poprad and Hornad Depressions. The sedimentary cover of the CCPB surrounds crystalline basement massifs, like the Vysoke Tatry, Branisko and Mala Fatra Mts., which were uplifted during 22–10 Ma (Kovac, Kral, Marton, Plasienka, & Uher, 1994; Kral, 1977). The CCPB is bounded to the north by the Pieniny Klippen Belt, which represents a transpressional strike–slip zone related to plate boundary (Csontos, 1995;

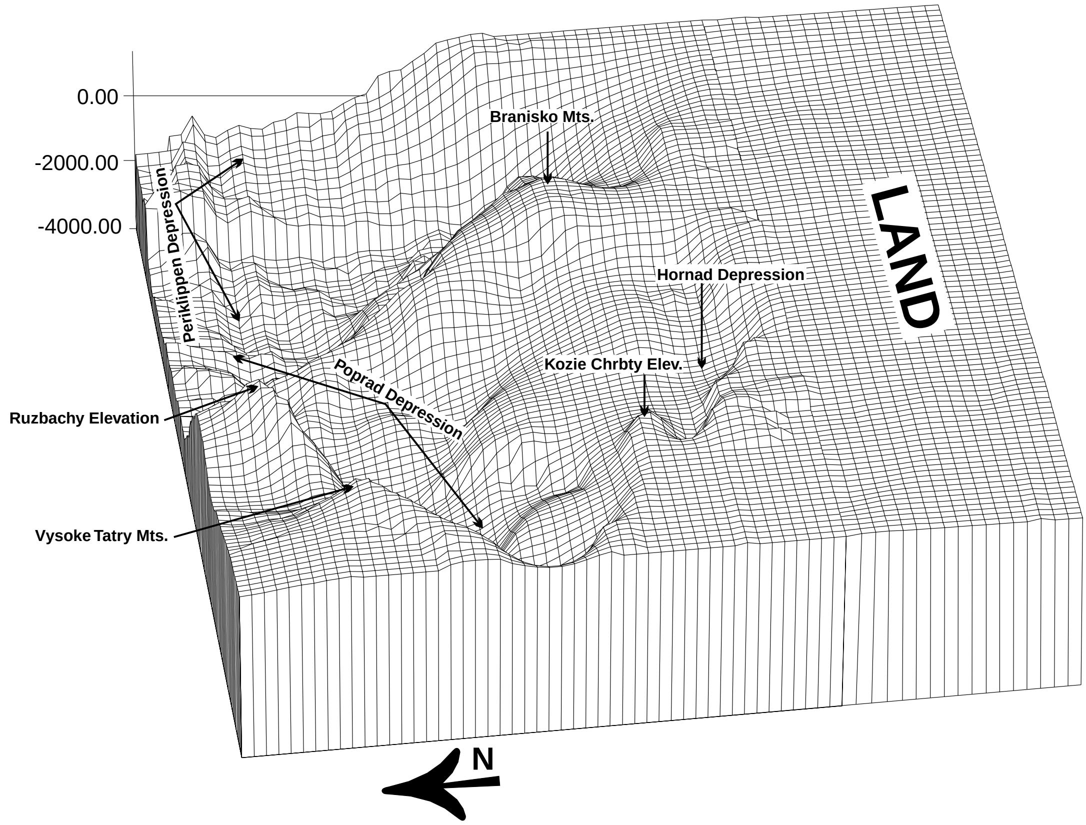

Fig. 2. Perspective diagram showing the bottom configuration of the Levoca Basin, as interpreted from the basal reflections of the Paleogene formations in seismic profiles.

Csontos, Nagymarosy, Horvath, & Kovac, 1992; Potfaj, 1998; Ratschbacher et al., 1993).

The sediments of the CCPB are commonly divided into lithostratigraphic formations of Subtatric Group (Gross, Köhler, & Samuel, 1984). From the base, the sedimentary sequence is developed as follows (Fig. 3A): *Borove Formation* (including Tomasovce Mr., Hornad Mr., Vitkovce Breccias sensu Filo & Siranova, 1996, 1998) — basal transgressive facies consisting of breccias, conglomerates, polymictic sandstones to siltstones, marlstones, organodetrital and organogenic limestones; *Huty Formation* (including Sambron Beds sensu Chmelik, 1957) — claystone/siltstone lithofacies less frequently with interbeds of fine- to medium-grained sandstones and "Menilite"-type shales; *Zuberec Formation* (including Kezmarok Mr. sensu Gross, 1998) — sandier, medium-rhythmical flysch sediments; *Biely Potok Formation* — massive sandstone banks. Each of the CCPB formations contains coarse clastic fans named the Pucov Member. Their thickness is highly variable depending on bottom configuration and differential subsidence. The stratigraphical range of the CCPB formations has been limited to Bartonian–Lower Oligocene (e.g. Gross et al., 1993; Samuel & Fusan, 1992). However, their nannoplankton stratigraphy has to be extended to the Latest Oligocene or even to the Early Miocene? (Olszewska & Wieczorek, 1998; Sotak, 1998a,b; Sotak, Spisiak et al., 1996).

The CCPB shows an asymmetic profile inclined toward the north (Fig. 2). Therefore, the Upper Eocene–Lower Oligocene formations of the CCPB get thicker toward the marginal (Periklippen) depression, and the Upper Oligocene formations toward the hinterland (e.g. Levocske vrchy Mts.). The greatest thickness of the flysch sediments occurs in the Sambron Zone, which is an antiformal structure that brings Upper Eocene formations of the CCPB to the surface (Sambron Beds — shaly and thin- to medium-rhythmic flysch deposits with intraformational bodies of conglomerates and breccias). The Sambron Zone is a belt of tectonically disturbed flysch sediments in the northern flank of the CCPB about 5 km wide, near the junction with the Pieniny Klippen Belt.

The structural pattern of the CCPB includes basement-involved fault zones, like the Margecany and Muran Faults, extensional structures, like halfgrabens and listric and antithetic faults in the Hornad, Periklippen and Poprad Depressions, and structures related to retro-wedge thrusting, transform faulting and strike–slip tectonics in the Sambron Zone (Kovac & Hok, 1996; Marko, 1996; Nemcok, 1993; Nemcok et al., 1996; Nemcok & Nemcok, 1994; Plasienka, Sotak, & Prokesova, 1998; Ratschbacher et al., 1993; Sperner, 1996).

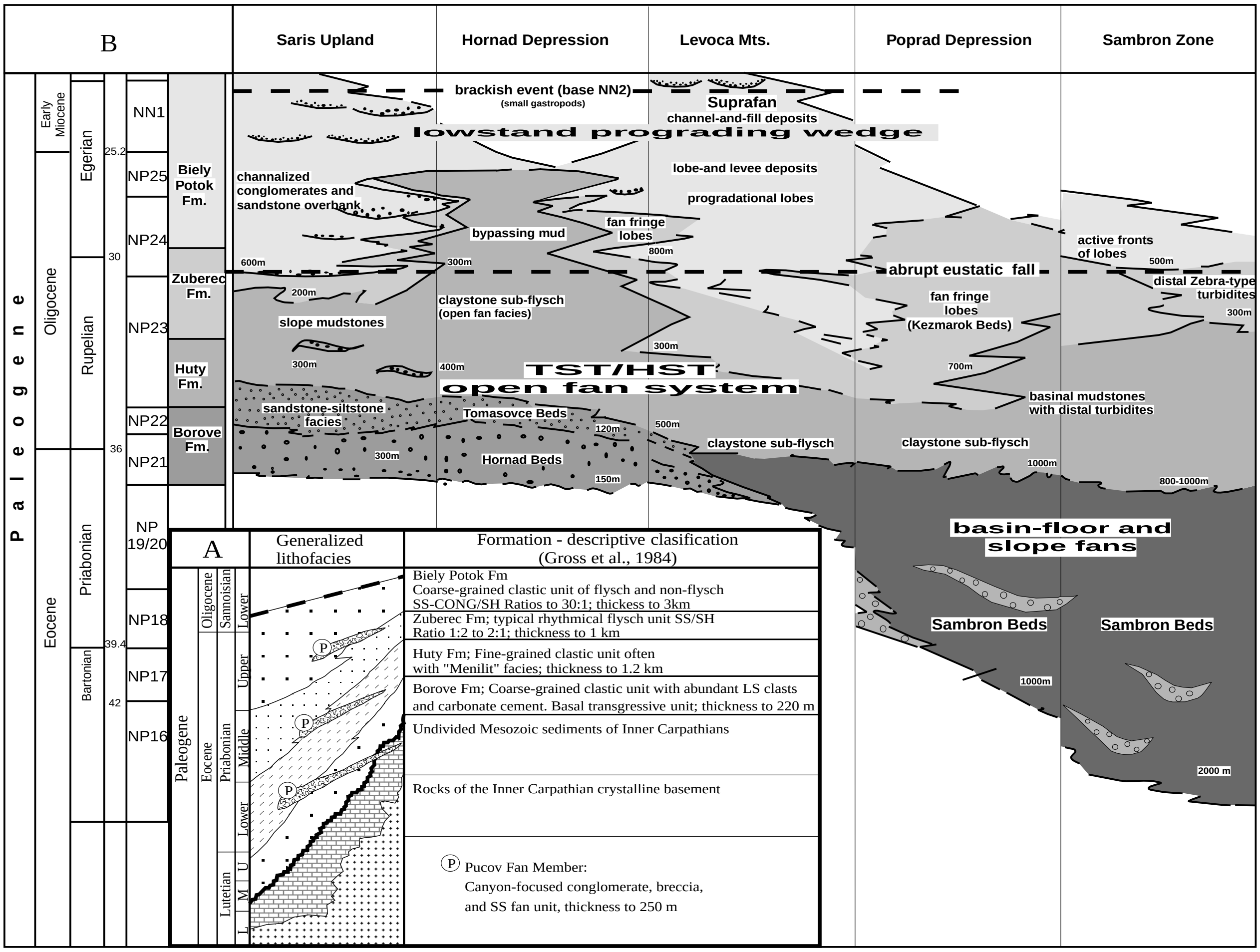

Fig. 3. Descriptive lithostratigraphy of the CCPB after Gross et al., 1984 (A) and depositional systems of the Levoca Basin, interpreted as facies tracks of submarine fans and sequence components (B). Time scale after Haq et al. (1988).

3. Facial analysis and sedimentology

Sedimentary formations of the CCPB are classified with respect to dominant lithologies. In fact, the formations represent sediments from different submarine fan environments, because their lithology appears as identical. Therefore, the claystone lithology of the Huty Fm. corresponds to various mud-rich deposits, such as basinal mudstones, overspilled muds and levees, slope mudstone drapes, bypassing muds and muddy hypopycnal deposits. However, there are also cases when different lithologies have been defined as the same lithostratigraphic unit. For instance, the Biely Potok Fm. defines mostly massive sandstones from the middle-fan area (suprafan lobe and channel-and-fill deposits after Janocko, Hamrsmid, Siranova, & Jacko, 1998; Sotak, 1998a; Sotak, Bebej, & Biron, 1996), but also conglomerates from the slope-fan area (e.g. Saris Upland). In this sense, CCPB formations should be interpreted as facies tracts of submarine fans (Figs. 3B, 4 and 5).

The lowermost formation of the CCPB contains sediments of alluvial fans, defined as the Hornad Member (Filo & Siranova, 1998). They consist of conglomerates (Fig. 6a), poorly sorted sandstones and boulder breccias, which are indicative of rockfall avalanches, stream flows, fluidal surge flows, debris flows, traction currents and high-density turbidite currents (Barath & Kovac, 1995; Marschalko, 1970). Floodplain sediments of fan deltas of the lowermost formation are represented by parallel-stratified and cross-stratified sandstones with dispersed gravel patches or landslide failure breccias, defined as the Chrast Member with Vitkovce Breccias (Filo & Siranova, 1998). The accumulation of alluvial fan deposits was controlled by marginal faulting like halfgraben or ancient river valley (Marschalko, 1970).

The alluvial fans are overlain by sediments of marine transgression. They are developed mostly as shoreface sandstones (Fig. 6b and c), offshore bars, longshore nummulitic banks and fore- and back-bank facies (Bartholdy, 1997; Bartholdy, Bellas, Cosovic, Fucek, & Keupp, 1999; Kulka, 1985). In the Levoca Mts., the Nummulite Eocene transgression overlapped the seaward depression within the Sambron Zone, which was followed by backstepping of shoreline on the land during the Early Oligocene. The

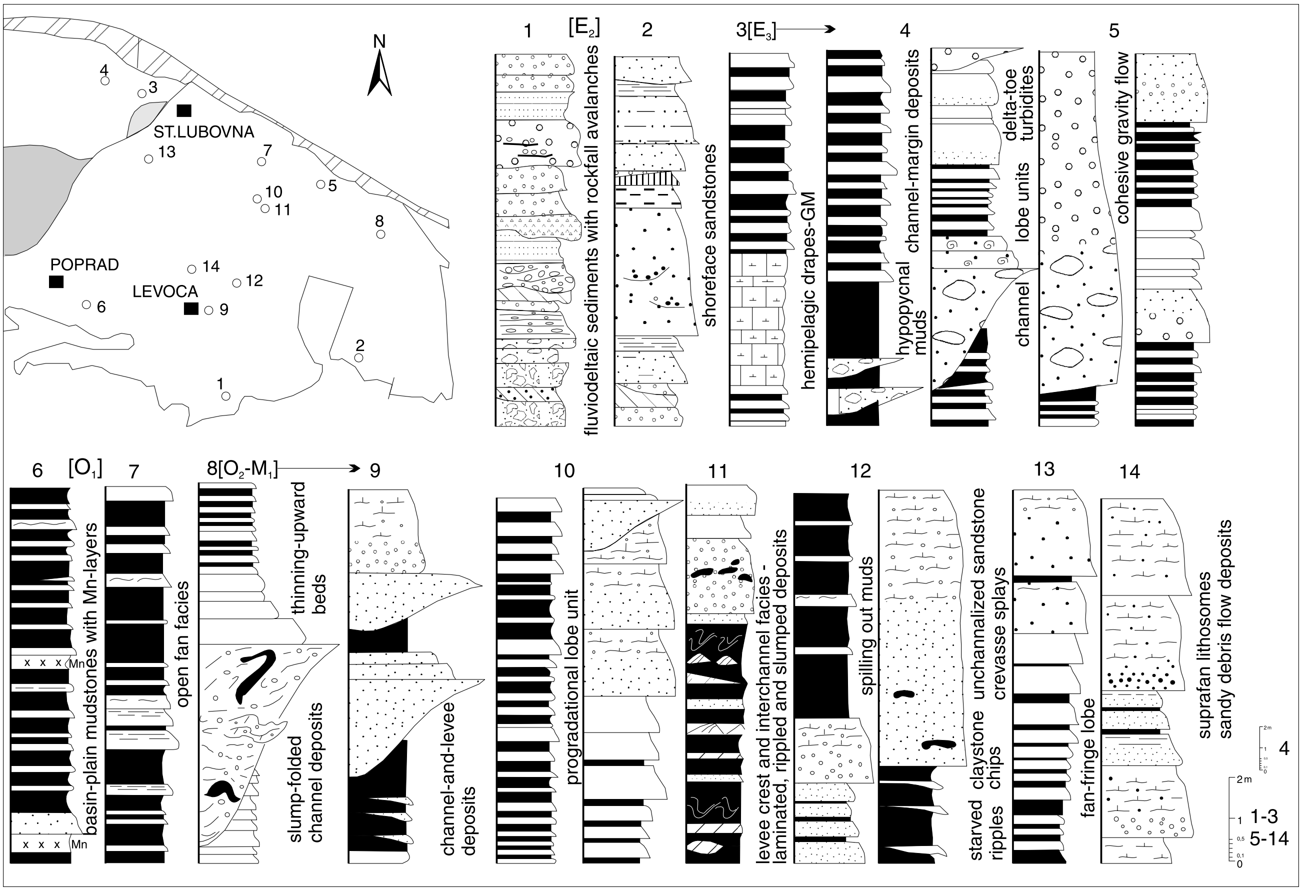

Fig. 4. Representative logs of sedimentary facies in the CCPB (Levoca Basin), illustrating the successive development of fluviodeltaic sediments (1), shoreface sediments (2), slope drape mudstones and hemipelagic deposits (3), canyon-fill deposits (4), channel-margin deposits and delta-toe turbidites (4), mass-movement deposits (5), open-fan and basin-plain deposits (6,7), lobe deposits (10,13), levee crest and interchannel deposits (11), channel-and-fill deposits (8,9) and suprafan lithosome deposits (14). Abbreviations: GM — Globigerina Marls, Mn — manganese layers, E_2 — Middle Eocene, E_3 — Upper Eocene, O_1 — Lower Oligocene, O_2–M_1 — Upper Oligocene up to Early Miocene.

nummulitic strata are covered by hemipelagic drapes of the Globigerina Marls or directly overlain by dark claystones and wispy-laminated muds, known as mud blankets beneath the Sambron Beds. The Sambron Beds consist of submarine fan sediments extended in the Podhale-Spis Magura area (Szaflary Fm.), and piled up in the thrust structure of the Sambron Zone. They show a marginality to laterally entering canyons, which served as multiple point-source feeders for the Sambron, Tokaren, Pucov and Szaflary Fans. These canyons and related fans indicate their shelf-margin connection to a delta (units 1–2 sensu Janocko & Jacko, 1998). Sedimentary formations of the Sambron Beds are formed by black shales and thin- to medium-bedded sandstones (Fig. 6d), which are indicative of debris flow deposition through freezing in laminar state or transformation to turbulent flows, muddy hypopycnal plumes and delta-toe turbidites, known as amalgamated megabeds in the Spis Magura area (shingled turbidites sensu Mitchum, Sangree, Vail, & Wornardt, 1993). Claystone/sandstone sediments of the Sambron Beds are intercalated with conglomerates and talus breccias (Fig. 6e), which are up to 500 m in the Sambron PU-1 well (Fig. 13). They form either sharply based intraformational bodies deposited via cohesive slide-flows or chaotic accumulations driven by en masse movement, like pebbly mudstones or slurry slumps. Accumulation of large blocks within the Sambron Beds, like in the Spis Magura Mts. and Ginoc creek near Sabinov, indicates the submarine landsliding. The Sambron Beds contain practically no trace fossils. Sedimentary successions of the Sambron Beds reach a thickness of up to 3000 m.

The Upper Eocene Sambron Beds are overlain by claystone lithofacies, which indicate enormous amounts of mud entrained into the CCPB and low efficiency of feeder channel systems. The formation is developed in alteration of thin sheet-like or pinching out sandstone beds, which are coupled with thick mudstone caps and hemipelagic drapes. Internal stratification of turbidite beds reveals flow-stripping processes in the upper flow regime. They form mostly base-missing, distinctly laminated and convoluted layers, defined as Bouma's T_{bcd} divisions. Sandstone beds frequently show a dominance of dune phase, observed in the cross-stratified bedforms with downcurrent migration of ripples (Fig. 6f). A

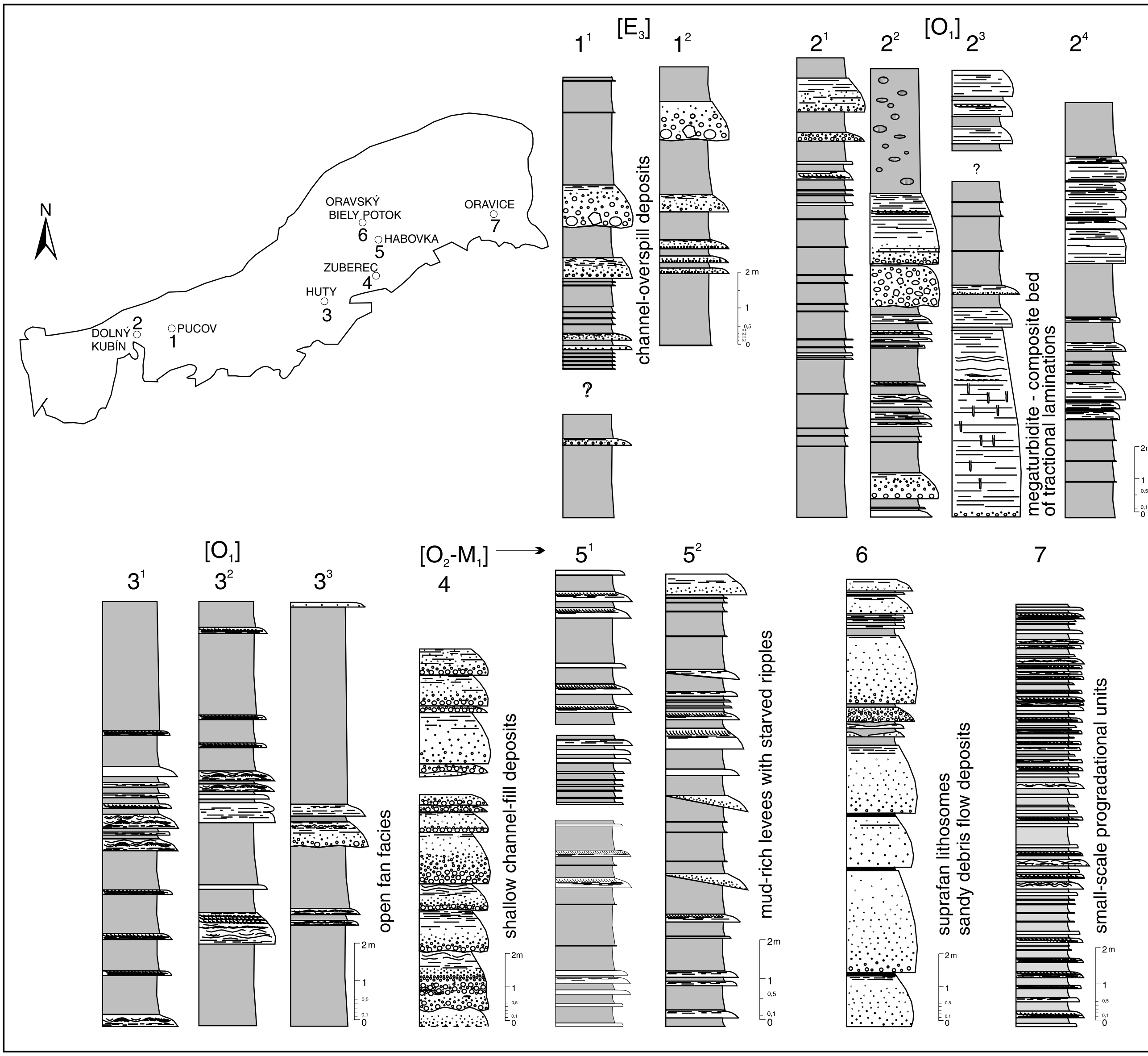

Fig. 5. Representative logs of sedimentary facies in the CCPB (Orava Basin) showing the distribution of submarine fan facies, known as channelized conglomerates with mud overspills (1), mudstone-dominant deposits with megaturbidites (2), open-fan deposits (3), channel-fill deposits (4), mud-rich levee deposit (5), lobe deposits (7) and suprafan deposits (6). Abbreviations: E_3 — Upper Eocene, O_1 — Lower Oligocene, O_2–M_1 — Upper Oligocene up to Early Miocene.

case of antidunes with upcurrent migration of ripples with respect to basal flutes has also been recorded (e.g. Revistne, Roskovany). Hydroplastic deformations, like cylindrical or isoclinal folds in convolute lamination, are common owing to a high volume of suspended load. Complete T_{a-e} turbidites are reduced in bed thickness, which is about 0.5 m. The claystone formation occasionally, like in the Bysterec section in Orava, contains 3–4-m-thick composite beds of megaturbidites with multiple T_b intervals of tractional lamination (Fig. 6g). Their internal structures, like inversely graded laminae (S_2 flow type sensu Lowe, 1982), indicate the traction-carpet deposition within the small-scale submarine channel. Interturbidite deposits of claystone formation comprise mostly homogenous mudstones deposited from muddy fallout. Claystones are associated with manganese beds, like in the Svabovce-Kisovce prospect, pelocarbonates and occasionally also with tuffite intercalations. They are richer in traces of ichnofossils and bioturbation, observed in mottled mudstones. Claystone formation represents a simple depositional system of mud-rich fans with open-fan facies, basinal mudstones, small-scale lobes, large leveed channels, starved ripples, Zebra-type facies, washload spills and slumped overbank deposits. The formation is considered to be the Lower Oligocene subflysch, which precedes the main flux of turbidite systems into the CCPB.

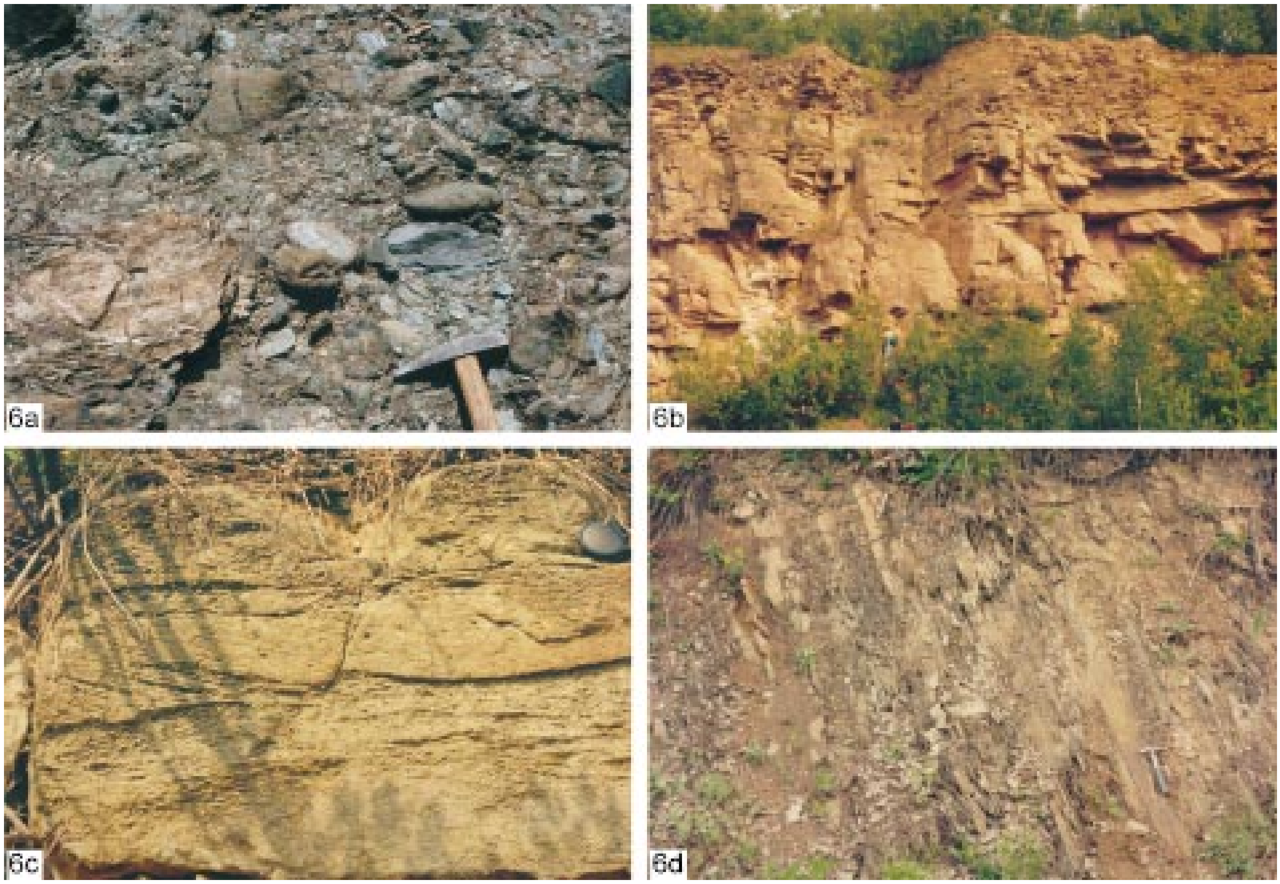

Fig. 6. (a) Coarse-grained conglomerates of alluvial-fans in lowermost formation of the CCPB (Hornad Mr.). (b) Massive sandstones of transgressive formation (Tomasovce Mr.) exhibiting a large-scale tabular cross-stratification with pebble lags. (c) Cross-stratified sandstone with small-scale sets of inclined ripples and erosional lower bounding surface. Transgressive shoreface deposits of the CCPB. (d) The Sambron Beds formed by shaly and fine turbiditic deposits. The sequence is intercalated by conglomerates and scarp breccias. (e) Carbonate breccia with green-coloured matrix from the Sambron Beds. Note the symmetrical pressure shadows of slickenfibre chlorite/smectite aggregates, developed as white rims around the clasts. (f) Turbiditic beds in mudstone-dominant formation (Huty Fm.). Sandstone shows a well-developed duna phase of cross-stratification, formed by downcurrent migration of ripples. (g) Megaturbidite in mudstone-dominant formation (Huty Fm.), observed as a composite sandstone bed with multiple T_b intervals of tractional lamination. Scale bar is about 1 m. (h) Well-developed channel in submarine fans of the CCPB (Levoca Basin). Channel forms deep scours filled up by coarse-grained sandstones with rafted claystone chips in the top of amalgamated beds (high-density turbidites). It incised the previous sequence of silty mudstones with pinching-out ripples (levee-overbank deposits). Erosional structures in scours indicate mass vasting fill of channels (giant groove casts). (i) Slump-folded deposits of submarine-fan channels in the CCPB. The channel was filled up by slumps, pebbly mudstones and distorted sandstone beds and then overflow and abandoned, as indicated by thinning-upward development of sandstone-fill sequence. Scale bar is about 0.5 m. (j) Lobe deposits of submarine fans showing the tabularity of sandstone beds and progradational development of thickening-upward sequence. (k) Fan-fringe deposits of submarine fans (Kezmarok Mr.) with less conspicuous progradational development of lobe sequences. (l) Abundant ichnocoenosis with *Fucoides graphicus* (like *Taphrhelmintopsis*-rich ichnocoenosis) in the Oligocene sediments occurring in responce to bottom oxygenation and renewed circulation of the CCPB. (m) Levee facies of submarine fans, observed as markedly laminated and rippled deposits. They are intimately intermixed with lobe, channel and interchannel deposits. The current-laminated structures resulted from overbanking processes related to submarine fan lobes and channels. (n) Levee deposits with lenticular bedding and cross-ripple stratification (like flasser-type bedding). (o) Slump-folded sediments of levee crest deposits indicating its steeper slopes toward the interchannel areas. (p) Rip-up clasts derived from levee mudstones and incorporated into the basal portion of overlying channel-fill deposits. (r) Sandstone-dominant sequence of suprafan deposit in the CCPB (Biely Potok Fm.). They are observed as unchannelized massive sandstones showing a great lateral extent in bed thickness and tabularity (suprafan lobes). (s) Massive sandstone of suprafan lithosomes, observed as markedly graded bed with parallel stratification of pebbly "tracers" and laminar flow structures in the top. Their internal stratification indicates the deposition from sandy debris flows (planar fabric, floating granules, preservation of fragile rafted clasts, etc.).

During the Late Oligocene the CCPB was filled up by sand-rich fans. They form large elongated fans with counter-directional paleocurrent orientation proceeding from E and SE to W and NW (Levoca Mts., Saris Upland, Hornad and Poprad Depressions) and from W and SW to E and NE (Orava, Podhale and Spis Magura Mts.). Both paleocurrent systems exhibit a downfan distribution of submarine fan facies (Fig. 7). In accordance with paleocurrent direction the bed-thickness logs decrease and vertical arrangement of flysch sequences changes from the thinning-upward trend in the upper fan zone to mostly a thickening-upward trend in the zone of depositional lobes and to a non-cyclic trend in the distal facies. The slope facies of the submarine fans occurs as markedly channelized and

Fig. 6 (*continued*).

slump-folded deposits (Fig. 6h and i), known in the Saris Upland, but unknown in the Orava region ("wild flysch" after Marschalko, 1966). Channels are filled by conglomeratic and chaotic accumulations nivellated by thinning-upward sandstone beds. Interchannel facies are developed as levee overbanks, comprising thin- to medium-bedded turbidites, unchannelized sandstones of crevasse-splays, or spilled-out muds.

Further down, for example in the Levoca or Skorusina Mts., the slope facies of submarine fans pass into the zone of depositional lobes. Lobe deposits show a great tabularity of beds, which are vertically stacked with a thickening-upward tendency (Fig. 6j). They start as thin-bedded turbidites, which become thicker upward and progressively pass into massive and homogenous turbidites. The thickness of individual lobe cycles ranges from 5 to 30 m. Lobe cycles either follow each other successively or are intercalated by lobe-and-levee and channel-and-levee deposits. Levee crest facies indicate deposition from dilute suspensions and fine turbidites spilled out from distributary lobe channels. They are commonly mudstone-rich and remarkably laminated, rippled and slumped (Fig. 6m and o). Levee deposits exhibit various wave-current structures such as flat, climbing-ripple and starved-ripple lamination, lenticular bedding, cross-ripple stratification, load-casted ripple marks, convolute lamination and flaser-type bedding (see Mutti, 1977).

Lobe successions with occasional channel-and-levee deposits grade upward into sand-rich lithosomes. These lithosomes are tabular bodies of massive amalgamated sandstones that lack interbedded shales (Fig. 6r). Sandstones are commonly developed as normal or inverse graded beds with lamination in the top portion. Their sedimentary structures are indicative of high-density turbidity currents or sandy debris flows (sensu Shanmugam, 1996). Sandstone lithosomes are characterized by sharp contacts, typical for the freezing of high-density currents, by buoyancy of coarser grains, known as pebbly "tracers" (Fig. 6s), by rafted clasts in the form of claystone chips (Fig. 6p) and

Fig. 6 (*continued*).

by transition to laminar intervals, defined as tractional lamination. Sandstone lithosomes of the Levoca and Skorusina Mts. represent the final stage of the submarine fan deposition, defined as the "suprafan" (sensu Normark, 1970). Their tabularity recalls the suprafan lobes that aggrade to form a suprafan bulge. The suprafan area of the Levoca Mts. is eroded by braided distributory channels filled up by pebble-sandstone and conglomerate accumulations. Lobe-fringe facies of the suprafan show less conspicuous progradational trends (Fig. 6k). They are developed either as medium-rhythmic bedded formations in Spis Depression (Kezmarok Member sensu Gross, 1998) or as Zebra-type turbidites containing a high amount of the ophiolite detritus and some tuffites in the Sambron Zone (Sotak & Bebej, 1996).

4. Sequence stratigraphy

The CCPB has undergone two third-order cycles of initial transgression (TA 3.5–3.6 sensu Exxon cycles), which were followed by two second-order cycles of deposition (TA4 and TB1 sensu Exxon cycles). The initial transgression was preceded by deposition of alluvial-fan and delta-fan sediments. Alluvial suites show upward change from subaerial to subaqueous deposits (Barath & Kovac, 1995). The evidence of the first marine incursions is present in the uppermost strata of these suites, including the appearance of oysters, gastropods and bivalves (Volfova, 1962). Later on, fluviodeltaic sediments of the CCPB were flooded to the coastal zone and then overlain by shoreface sands, as indicated by the Tomasovce Member (Filo & Siranova, 1996), and carbonate platform deposits. The Upper Lutetian transgression in the CCPB (Andrusov & Köhler, 1963) led to the shallow-marine deposition of nummulitic banks, developed in two third-order cycles (Bartholdy, 1997). Nummulitic cycles of the CCPB, like a large foraminifera demise (Hallock, Premoli-Silva, & Boersma, 1991; Hottinger, 1997), disappeared because of the inversion of the Middle Eocene warm climate to cooler climate in the beginning of the TA4 supercycle. Climatic changes culminated in the "Terminal Eocene Event" (Figs. 8 and 10), which corresponds to the global cooling and glacio-eustatic regression related to the Antartic cryosphere expansion (Robert & Kennett, 1997; Van Couvering et al., 1981). Consequently, the extensive carbonate deposition on broad warm shallow shelves was suffocated by terrigenous sedimentation on bypassed shelf areas, in accordance with observation of the latest nummulites in the CCPB that survived until the Zone P16 (Köhler, 1998). The sediments from above the nummulitic limestones are depleted in $CaCO_3$ and enriched in organic matter owing to continental

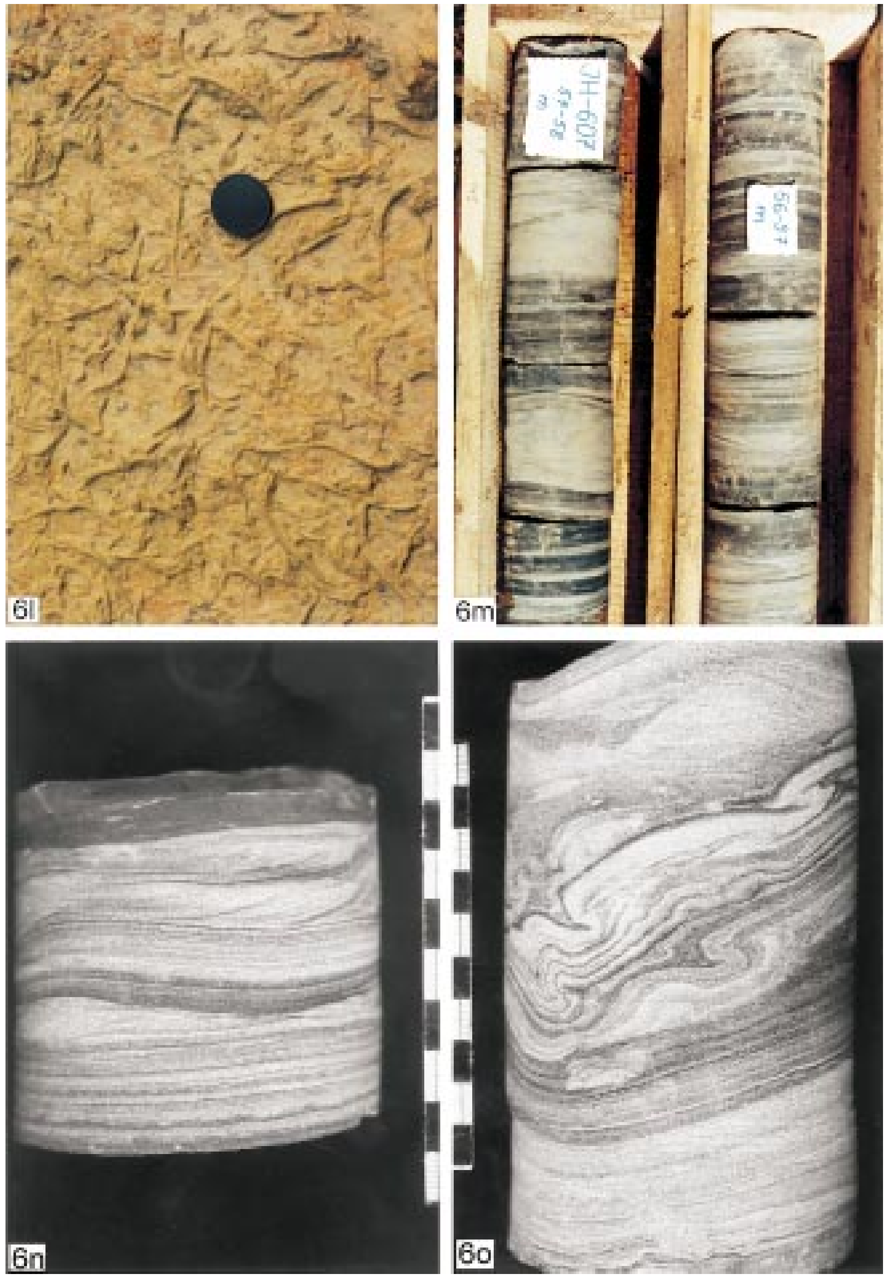

Fig. 6 (*continued*).

runoff of land plants. They contain abundant cool-water cocoliths, like *Isthmolithus recurvus*, *Zigrablithus bijugatus*, diatom oozes in Menilite facies, *Globigerina*-rich fauna in the Globigerina Marls and nectonic fishes (Amphisile Shales sensu Suess, 1866). A small-scale intercalation of non-calcareous black shales and Menilite facies with Globigerina Marls indicates short pulses of the high carbonate productivity during the terminal Eocene fertility crisis (Pomerol & Premoli-Silva, 1986). The fluctuations in productivity provide the evidence of climatic changes driven by precessional cyclicity (Krhovsky, 1995; Krhovsky, Adamova, Hladikova, & Maslowska, 1993; Leszczynski, 1997).

The climatic control of depositional changes in the CCPB became less significant during the period of forced regression (Figs. 9–11). Nevertheless, the cool-water influx into the CCPB led to the carbonate depletion and anoxicity in the Sambron Beds, as indicated by non- or weakly calcareous claystones, anoxic facies, scarcity of microfossils and sulphide-rich black shales. The appearance of the Globigerina Marl in deep-water siliciclastic deposits of the Sambron Beds indicates the CCD drop that occurred near the Eocene/Oligocene boundary (Thunell & Corliss, 1986). The falling stage of relative sea-level is recorded by a Type-1 sequence boundary on shelves (between carbonate platform deposits and overlying formation), which

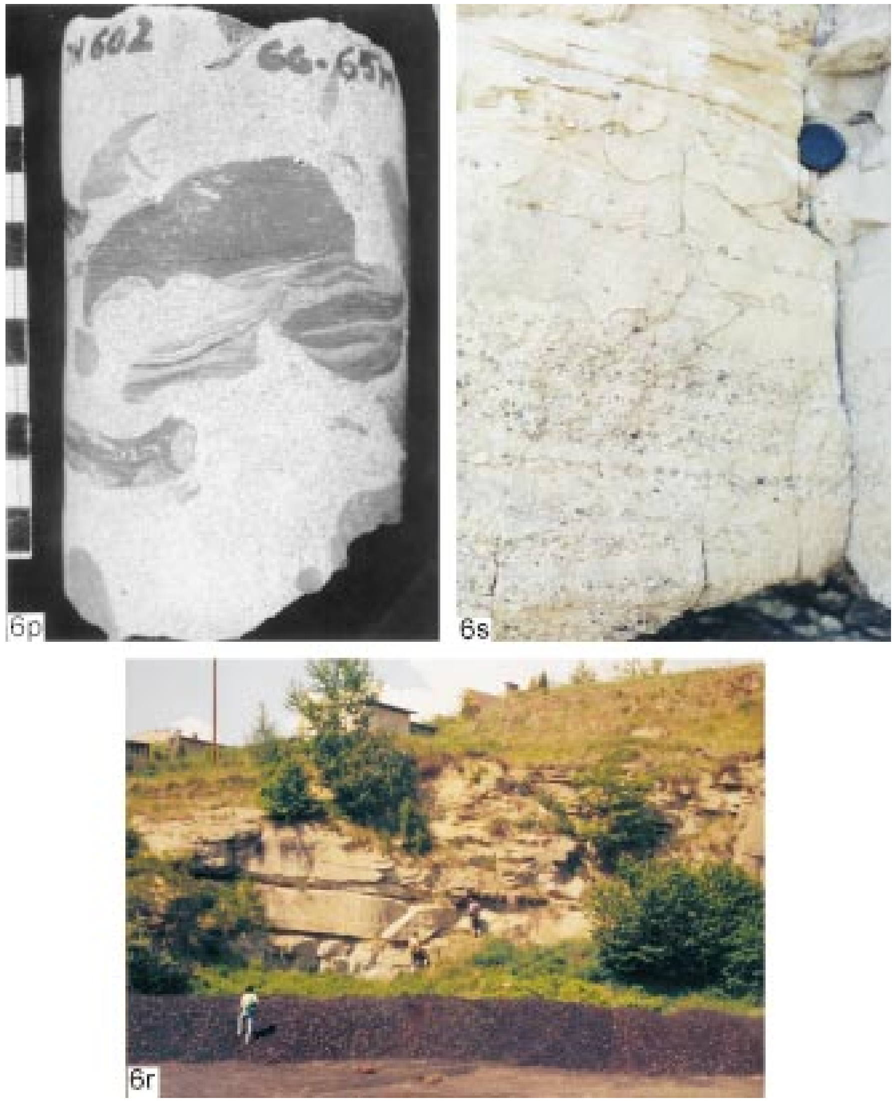

Fig. 6 (*continued*).

were eroded by fluvial channels entering the basin through marginal delta-fed fans (Janocko & Jacko, 1998). Therefore, the eroded nummulitic limestones and Globigerina Marls are common in the slope fan conglomerates of the Sambron Beds. During the forced regression, the basin slopes were actively tilted and incised by submarine canyons, which fed the basin-floor and slope fans. The Sambron Fan, like the Tokaren, Pucov and Szaflary Fans, represents lowstand system tracts consisting of channel-fill, spillover and mass-failure deposits (Gross, Köhler, & Borza, 1982; Janocko & Jacko, 1998; Sotak, 1998a; Sotak, Bebej, & Biron, 1996; Wieczorek, 1989). Successive stages of the normal regression in the Sambron Beds are indicated by progradational stacking of lobe sequences. The latest stage of the relative sea-level lowering is marked by an amalgamated sandstone unit, observed, for example, in the Bachledov Valley. This unit corresponds to shingled turbidites that represent sandy toeset deposits of shelf-margin deltas. The lowstand deposition of the Sambron Beds took place from 39–36 Ma, giving a high accumulation rate of flysch lithologies.

The TA4 supercycle tended toward the gradual rise of relative sea level during the Early Oligocene (Figs. 8–11). Successive formation of the CCPB during the deposition of the Huty Fm. corresponds to transgressive and highstand system tracts. The transgression is marked by ravinement surfaces detectable as the unconformity between Eocene Nummulitic banks and middle Rupelian sediments of the NP 23 Biozone in the southern Orava region. Ravinement surfaces provided a large amount of detrital components, like nummulites, for turbidite clastics of transgressive deposits. The sequence boundary at the base of the transgressive formation is locally developed as an unconformity between the growth fault systems tract of the Sambron Beds and the overlying sequence of mud-rich fans (tectonically enchanced sequence boundary sensu Vail, Audemard, Bowman, Eisner, & Perez-Cruz, 1991). Basal sediments of the transgressive formation still show the cool-water

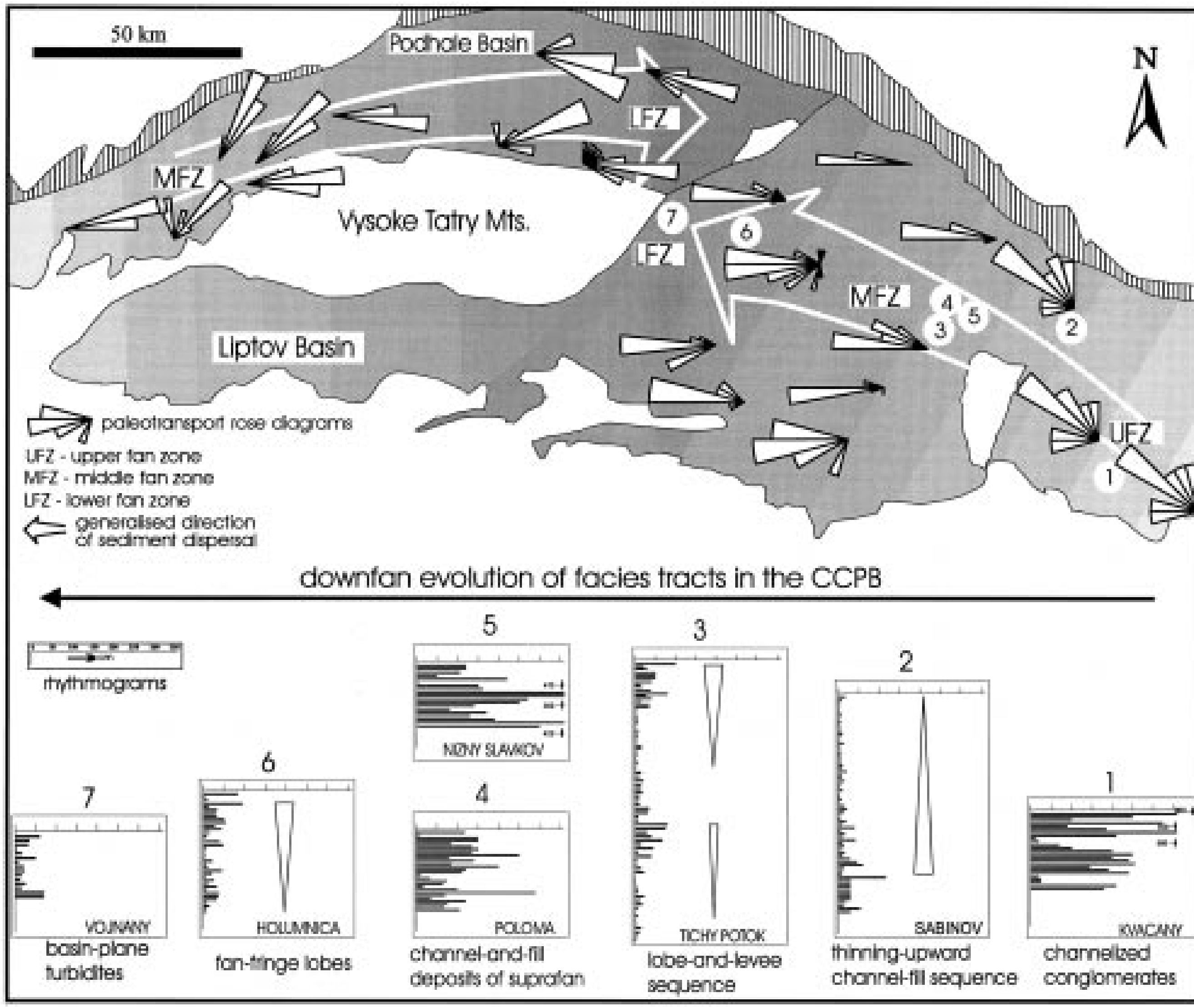

Fig. 7. Paleogeographic sketch of submarine fan systems in the CCPB during the Late Oligocene, as is shown by paleocurrent directions, distribution of facial zones and downfan evolution of facies tracts. Note two systems of submarine fans with counter-directional paleocurrent orientation. Paleocurrent data for the Podhale basin taken from Marschalko and Radomski (1960) and Radomski (1958).

influence, salinity decrease and semi-isolation, as indicated by wetzeliellacean dinoflagellates, inprints of diatoms, brackish nectonic fish and ostracods (South Orava region). Higher in the section, the carbonate-free sequence reveals the first pulses of nannofossil blooms, characterized by reticulofenestrids of NP 23 Biozone, which flourished because of sea-level rising and renewed circulation. Evidences come from Tylawa-like limestones in the Zuberec Formation (Gross et al., 1993). The Lower Oligocene transgression rose to the highest sea-level at 32 Ma (Haq, Hardenbol, & Vail, 1988), which restored the Paratethyan circulation (Baldi, 1984). Consequently, the CCPB became reoxygenated, which led to the increase in carbonate precipitation, productivity and fertility. Higher nutrient and paleo-oxygen content in the basin is inferred from bottom colonization by trace-fossil pioneers, like *Zoophycos* beds in the Jakubovany section. The maximum flooding of this sequence falls into horizons of manganese layers, which occur in the Orava region and Rajec and Poprad Depressions (Andrusov, Bystricka, & Köhler, 1962; Marschalko, 1959; Picha, 1961). Manganese layers represent a condensed section of the marine transgression. Their condensation is also expressed by a relative abundance of biota, like cyclicargoliths and bathypelagic fish fauna, glauconite-rich arenites, as against lowstand turbiditic sandstones of the Sambron Beds and Upper Oligocene sediments, pelocarbonates and sporadically also tuffaceous intercalations (Prosiek Valley, Bajerovce and Plavnica). Successive formation of mud-rich deposits indicates a low-energy environment of highstand phase. The late highstand of this formation is recorded by small-scale progradational events and megaturbidite beds in the

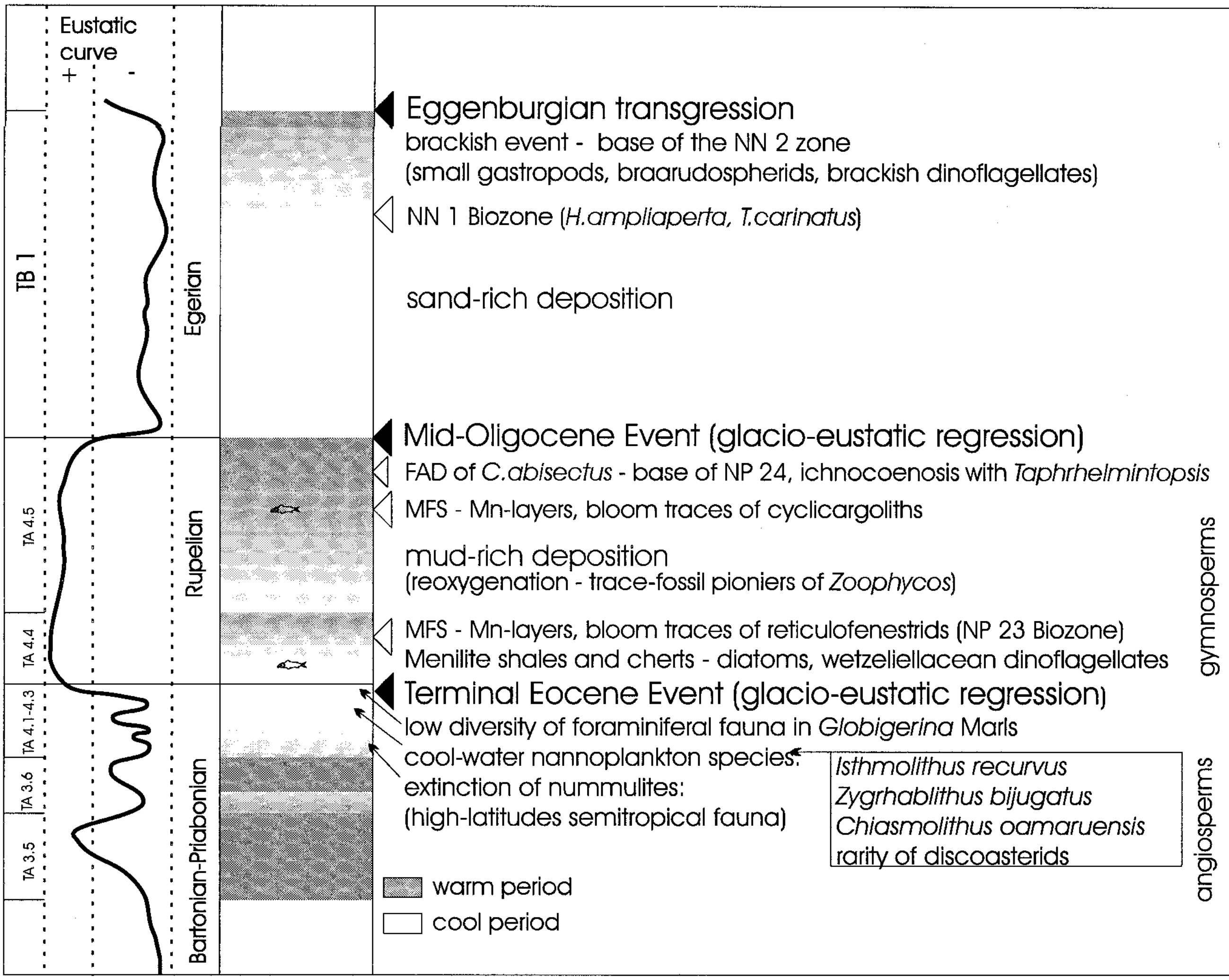

Fig. 8. Climatic changes in sequence-stratigraphy development of the CCPB, as inferred from inversion of the Middle Eocene warm climate, later cooling culminated in the Terminal Eocene Event and continued during the Early Oligocene, upwardly tended to eustatic rise of sea-level and then its drastic lowering due to glacio-eustatic regression in the Mid-Oligocene Event. Climatic changes are evidenced by extinction of semitropical fauna, foraminiferal abundance and bloom traces of nannofossils, inprints of diatoms (Menilite facies) and brackish dinoflagellates.

Orava region. Such deposition with progradational events (falling stage system tracts) terminated till the FAD of *Cyclicargolithus abisectus* on the base of NP 24 biozone, where the oxygen-related ichnocoenosis (Fig. 6l) with Fucoides and Taphrhelmintopsis began to appear already in flysch lithologies (Taphrhelmintopsis unit sensu Pienkowski & Westwalewicz-Mogilska, 1986). The Early Oligocene highstand sedimentation in the CCPB is in accordance with relative sea-level rise in the Outer Carpathian Basin. Supra-Menilite sediments and associated nanno-chalk horizons in the Outer Flysch Carpathians, like the Jaslo, Zagorz and Folusz Limestones and the Stiborice Marl, were deposited during the coeval sea-level highstand in the Late Rupelian (Krhovsky, 1995; Krhovsky & Djurasinovic, 1993). The composite sequence deposition of the Huty Fm. lasted for about 5 Ma (35–30 Ma). It indicates a slow accumulation rate of about 80–160 m/Ma for mudstone dominant litologies.

The TB1 supercycle was introduced by the Intra-Oligocene regression (Figs. 8–11). It is in accordance with an abrupt sea-level fall at around 30 Ma (Mid-Oligocene Event), determined as a distinctive drop in sea-level during the major glaciation in Antartica and subsequent cooling in the Northern Hemisphere (Kennett & Barker, 1990; Poag and Ward, 1987; Robin, 1988; Zachos, Lohmann, Walker, & Wise, 1993). At this time, the CCPB started to fill up by sand-rich turbidite systems of submarine fans, as a frequency of related turbidite currents essentially increased during glaciation (Eberli, 1991; Shanmugam & Moiola, 1982). Therefore, the deposition of the Upper Oligocene submarine fans in the CCPB appears to be forced by global eustasy. The falling stage of the Late Oligocene regression in the CCPB is expressed by offlap break of pre-existing highstand sediments, which were eroded and reworked into conglomerate-slope accumulations of submarine fans (Fig. 9). The example cases are blocks of Mn carbonatic

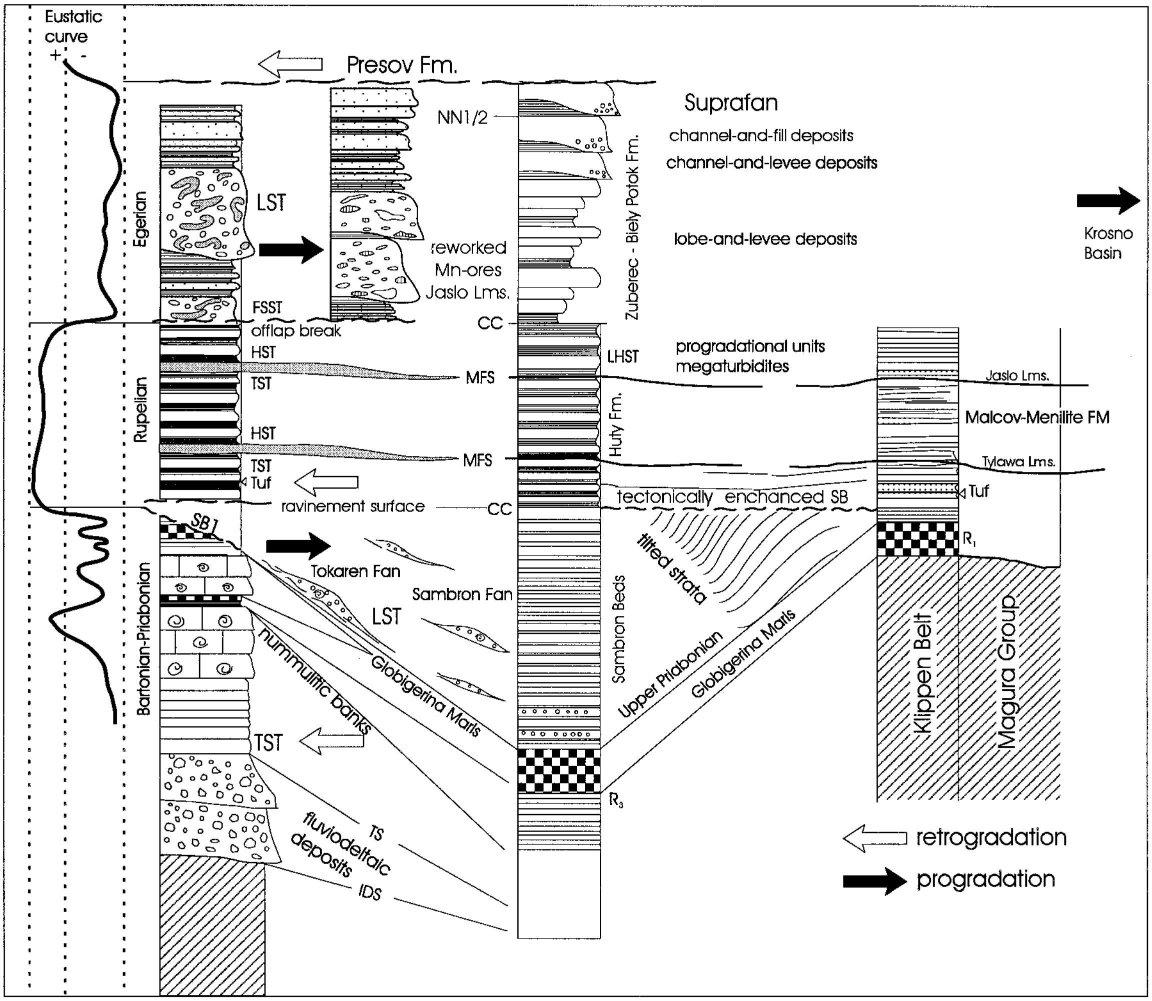

Fig. 9. Composite logs of system tracts in the CCPB interpreted in terms of sequence stratigraphy. Abbreviations: IDS — initial depositional surface, TS — transgressive surface, TST — transgressive system tract, HST — highstand system tract, LST — lowstand system tract, LHST — late highstand sytem tract, FSST — falling stage system tract, MFS — maximum flooding surface, SB1 — Type 1 sequence boundary, CC — correlative conformity.

ores (Marschalko, 1966). The erosional truncation of upper fan zones becomes less obvious basinward, where it is inferred as correlative conformity between mud-rich and sand-rich fans. During the Late Oligocene, the CCPB was filled up by the progradational wedge of submarine fans, which is developed from the sandy-weak turbidite system of the Zuberec Fm. to the sand-rich turbidite system of the Biely Potok Fm. The sand-rich deposition of the CCPB lasted until Early Miocene, as indicated by nannofossils like *Helicosphaera scissura*, *H. kamptneri*, *H.* cf. *carteri*, *H.* cf. *ampliaperta*, *Reticulofenestra* cf. *pseudoumbilica*, *Triquetrorhabdulus* cf. *carinatus*? (Nagymarosy, Hamrsmid, & Svabenicka, 1996) and some foraminifera (Molnar et al., 1992). However, the Early Miocene age is more apparent from sequence stratigraphy correlations. The global eustasy, which occurred under a distinctive regression during the Late Oligocene–Early Miocene, led to gradual shallowing and brackishing of Paratethyan basins. The Late Oligocene regression in the CCPB is recorded by the Biely Potok Fm., while shallowing and decrease of salinity is indicated by appearance of braarudospherids in nannoplankton associations (e.g. Blatna dolina) and brackish dinoflagellates in phytoplankton (Hudackova, 1998). The regressive trend of the Late Oligocene–Early Miocene deposition reached the maximum lowstand on the base of the NN2 Biozone, when the brackish fauna started to appear (Steininger, Senes, Kleemann, & Rögl, 1985). Such a brackish event, indicated by small gastropods and some gyrogonites (characeans?), has been traced in sandstone lithosome sediments of the Levoca Mts. According to this evidence, the deposition of the Biely Potok Fm. probably lasted till the Early Eggenburgian (Late Egerian sensu Berggren, Kent, Swisher, & Aubry, 1995). It should terminate to the lowstand phase at the beginning of the NN2 zone, which preceded the next transgressive cycle TB 2.1 (sensu Haq, 1991), and occurred at the base of the Presov Fm. (Kovac & Zlinska, 1998). In fact, gastropod-bearing sandstones and overlying sandstone lithosomes of the Biely Potok Fm., which are about 300 m thick in the Levoca Mts., cannot be defined as "flysch", but rather as molasse sediments, deposited during a

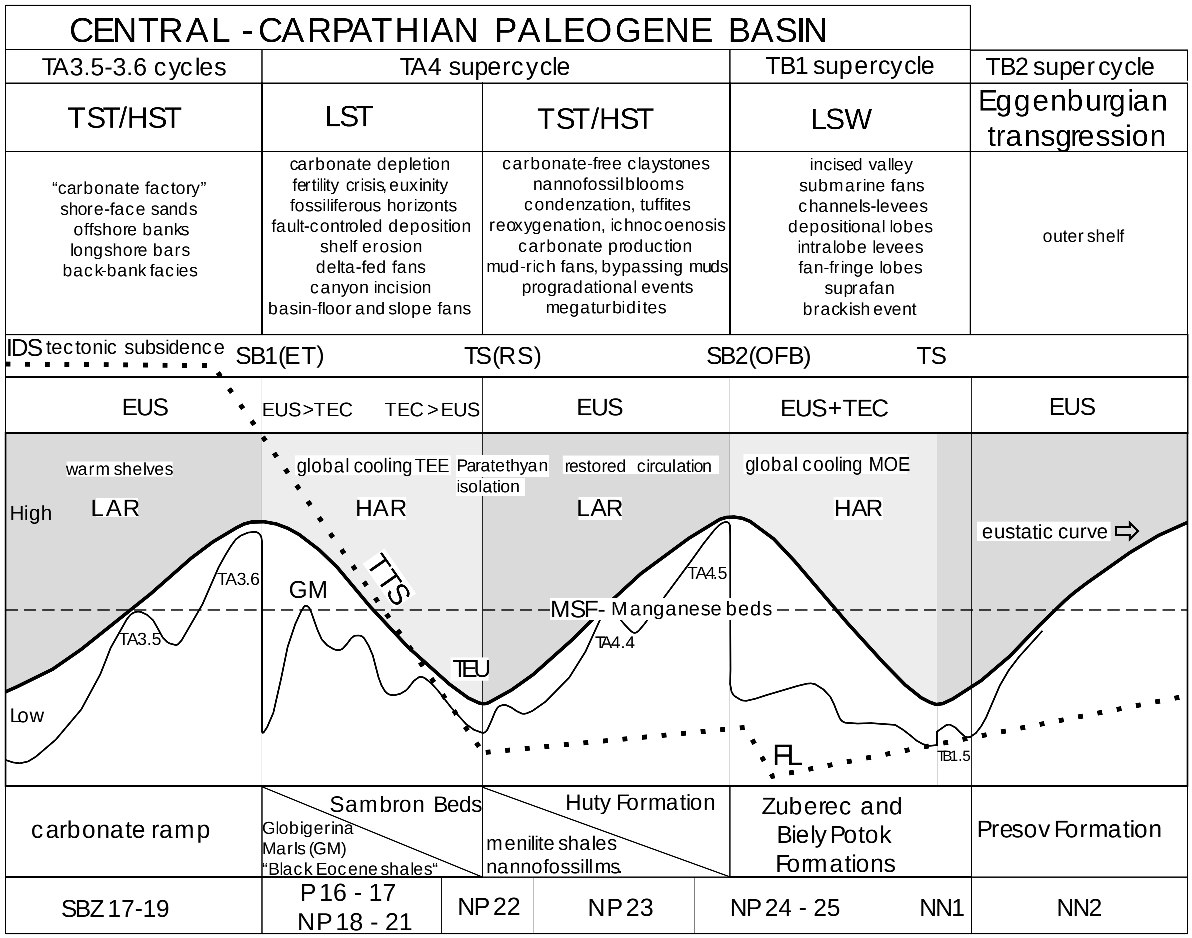

Fig. 10. Sequence-stratigraphy development of the CCPB, as appeared in correlation with Exxon cycle chart (Haq et al., 1988), subsidence history, climatic changes and depositional system tracts. Abbreviations: TST — transgressive system tract, HST — highstand system tract, LST — lowstand system tract, LSW — lowstand wedge, IDS — initial depositional surface, SB1 — Type 1 sequence boundary, ET — erosional truncation, TS — transgressive surface, RS — ravinement surface, SB2 — Type 2 sequence boundary, OFB — offlap break, MFS — maximum flooding surface, GM — Globigerina Marls, EUS — eustasy, TEC — tectonics, LAR — low accumulation rate, HAR — high accumulation rate, TEE — Terminal Eocene Event, MOE — Mid-Oligocene Event, TTS — tilted tectonic subsidence, FL — flexural loading.

retrogressive stage of the basin evolution. Nevertheless, the vitrinite reflectance and illite-smectite diagenesis data from near-surface sediments of the Levoca Mts. indicate that up to 2.5 km of this sequence is missing. Thus, the Late Oligocene–Early Miocene cycle of the lowstand deposition in the CCPB lasted for about 7 Ma (29–22.5 Ma), characterized by a high accumulation rate of sand-rich deposits of 320–370 m/Ma. Coeval deposition in the Outer Flysch Carpathians also occurred in the lowstand setting, as indicated by the Krosno Facies, including the Zdanice-Hustopece event (Krhovsky & Djurasinovic, 1993).

5. Basin subsidence and inversion tectonics

The CCPB began to subside because of active stretching under SW–NE directed minimum principal compressional stress σ_3 (Marko, 1996; Sperner, 1996). The basin subsidence was driven by structural tilting toward the Periklippen Depression and oblique listric and anthitetic faulting toward the Poprad depression. Asymmetric extension is indicated by the rapid tectonic subsidence in northern depressions and slow offshore subsidence along the southern CCPB margins. The subsidence record of basinal depressions is characterized by a steep hinge zone between 39 and 36 Ma (Fig. 12). The tectonic subsidence was followed by a high accumulation rate of up to 3000-m-thick Sambron Beds. The tectonic subsidence mode of the CCPB is in accordance with basins formed on active-plate margins, where basins are related to gravitational collapse owing to basal erosion of the overriding plate (Wagreich, 1995). Therefore, the initial tectonic subsidence of the CCPB could also have been induced by subcrustal erosion of marginal parts of the ALCAPA plate (sensu Csontos, 1995). The increase in tectonic subsidence of the CCPB should have been followed by the thermal phase, as indicated by the reflectance/depth curves in borehole profiles (Fig. 13), where the R_o values strongly increase from 0.7 to 1.8% between 2 and 3 km (Masaryk et al.,

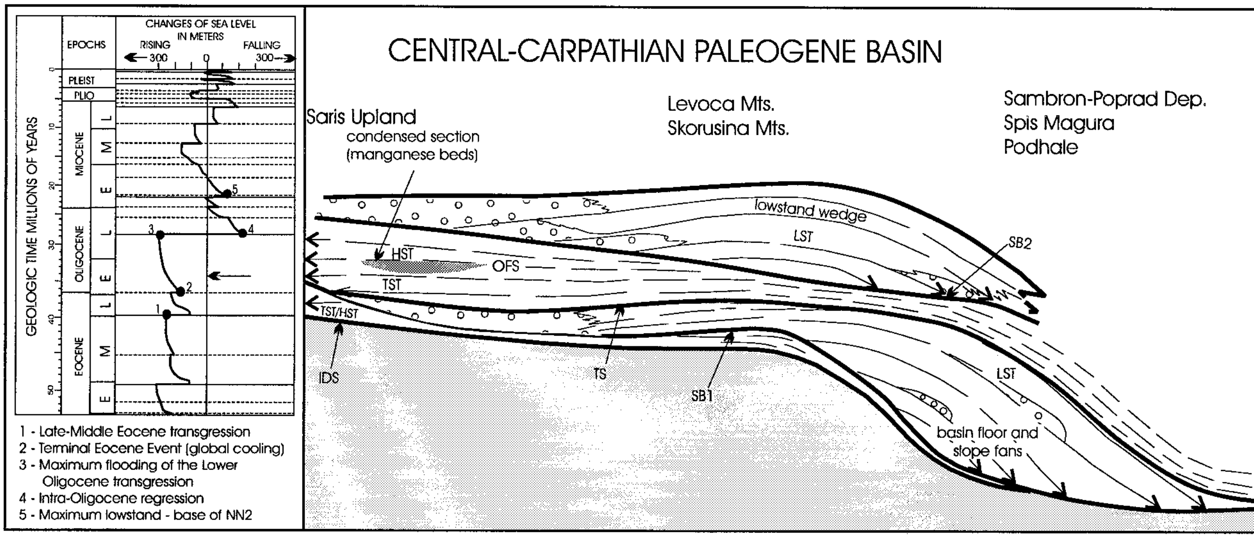

Fig. 11. Diagrammatic sketch of system tracts in the CCPB showing the initial transgressive onlap and successive accumulation of basin-floor and slope fan complex (Sambron Beds), open-fan complex with transgressive and highstand mud-rich deposition and maximum condensation in manganese beds (Huty Fm.) and wedging out of sand-rich and suprafan complex (Zuberec and Biely Potok Fms.). Sequence boundary SB2 coincides with the abrupt sea-level fall at about 30 Ma, indicated by Tertiary eustatic curve on the left. Abbreviations: IDS — initial depositional surface, SB1 — Type 1 sequence boundary, SB2 — Type 2 sequence boundary, TS — transgressive surface, LST — lowstand system tract, TST — transgressive system tract, HST — highstand system tract.

1995). This perturbation in R_o values indicates the increase in paleothermal gradient at about 50°C km^{-1}, provided which, a subcrustal heat for tilting tectonic subsidence of the CCPB is required (see Kooi, 1991). After the tectonic phase of subsidence, the CCPB underwent a post-rift relaxation, which resulted in the underfilled basin stage. The accommodation space of the basin was enlarged by slowly increasing subsidence and sea-level rise. The basin was supplied by mud-rich deposits, which overlapped syn-rift sediments of the Sambron Beds or bypassed basinal space-added slopes.

The subsidence of the CCPB began to differentiate during the Late Oligocene. The differentiation reflected the onset of shortening along the northern basin margin of the Sambron Zone. The deformation of the Sambron Zone indicates antiformal stacking and backthrusting, observed as fault-propagation anticlines, kink- and chevron-type folds and imbricated duplexes (Fig. 14a and b). In response to the

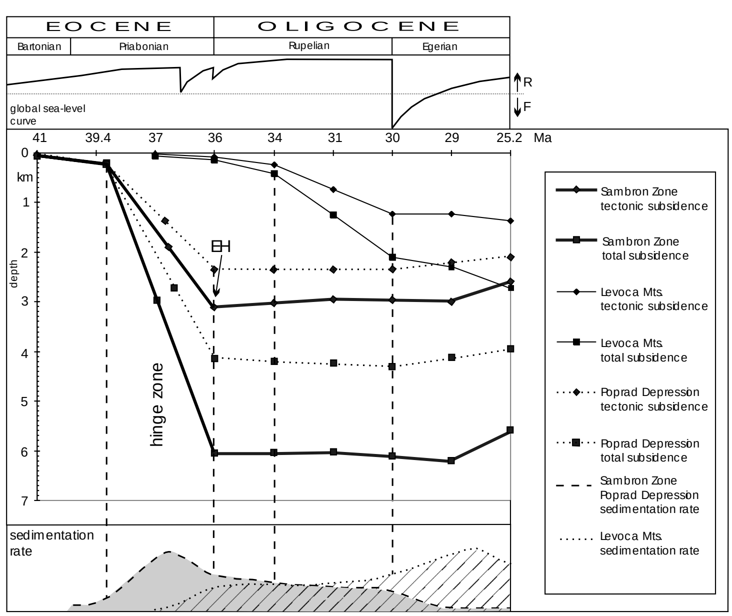

Fig. 12. Subsidence patterns derived from backstripping of the CCPB (Levoca Basin) compared with sea-level fluctuations and deposition rates. EH — indication of elevated heat.

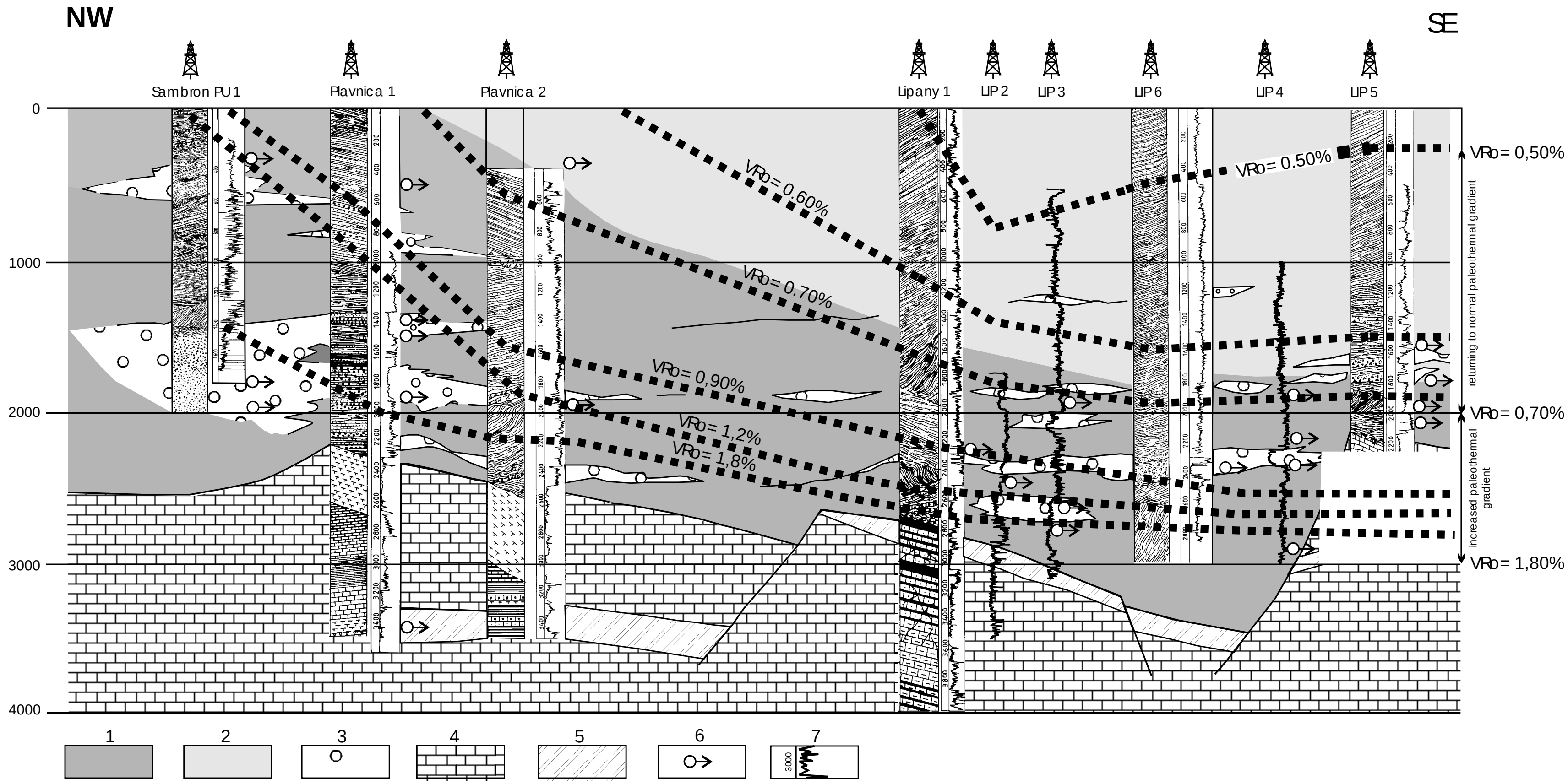

Fig. 13. Well-logs correlation showing the distribution of reservoir horizons with hydrocarbon indications in the Sambron Zone. Dashed curves show the vertical distribution of Ro values in the wells. Note the elevated Ro values in Lipany wells between 2 and 3 km (0.7–1.8%) pointing to increased paleothermal gradient in the Sambron Beds. Vitrinite reflectance data taken from Kotulova (1996); Masaryk et al. (1995). (1) Sambron Beds — shaly and fine-turbiditic sequence; (2) Lower Oligocene sediments (Huty Fm.); (3) intraformational conglomerates and breccias (reservoirs); (4) Mesozoic complexes in the basement; (5) correlative horizons of variegated Keuper sediments; (6) HC indications; (7) logging.

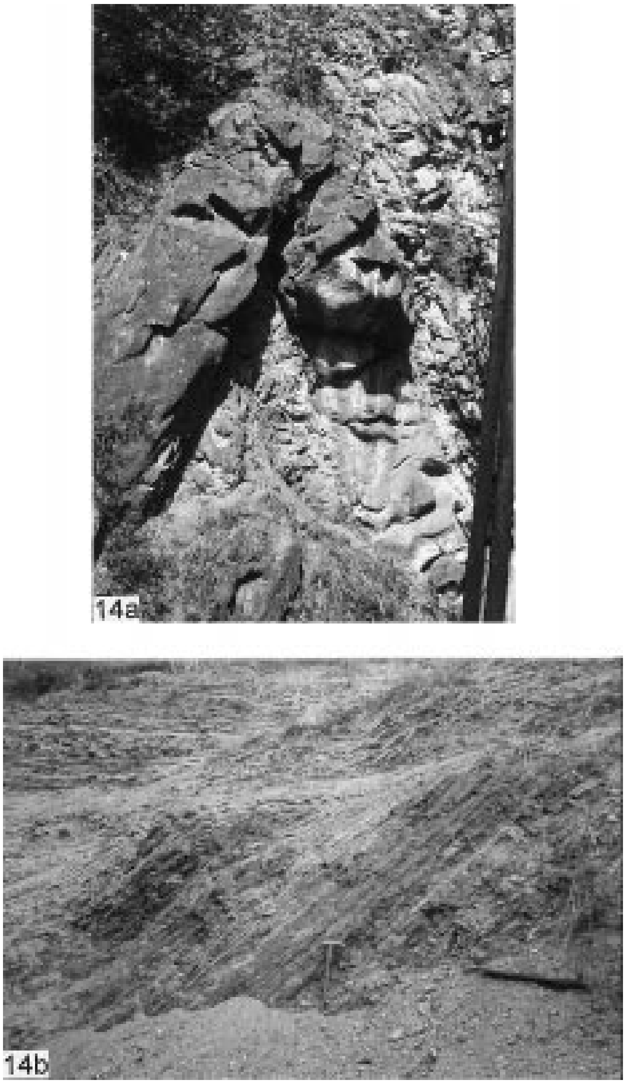

Fig. 14. (a) Upright symmetric chevron-type macrofold in the Sambron Zone (for scale use the pylon on the right). (b) Fault-propagation macrofold in the Sambron Zone. Folded sequence consists of serpentinite-rich sediments, like Zebra-type turbidites.

thrust loading, the retroarc foreland of the CCPB underwent the additional subsidence and landward migration of depocentres (Fig. 21). The Late Oligocene subsidence was controlled mainly by flexural loading and high accumulation rate of sand-rich deposits, which resulted in the overfilled basin. It is possible that the flexural loading was able to regenerate a higher heat flow for Late Oligocene sediments in the Levoca Mts. The load effect in the CCPB brought the increase of total subsidence after 30 Ma (Fig. 12). The Sambron Zone lacks the sedimentary record for adequate loading after 30 Ma. On the contrary, its concave-upward subsidence pattern shows a slow tendency to uplift during this time. Thus, the distribution of the vitrinite reflectance data within the CCPB is not entirely consistent with stratigraphy and depth. For instance, reflectance values of 0.7% R_o obtained from near-surface sediments of Upper Oligocene formations in the Levoca Mts. (Tichy Potok wells) are approximately the same as those determined from Lower Oligocene sediments of the Sambron Zone at a depth of 2000 m (Lipany wells). According to K–Ar dating of tuffs in the Levoca Mts., Upper Oligocene sediments reached the maximal burial temperature of 120–140°C at 22.5 Ma (Uhlik, 1999). It implies that Upper Oligocene sediments of the Levoca Mts. had to be buried during the Early Miocene. During that time, the deformed sediments of the Sambron Zone were unconformably overlapped by the Eggenburgian sediments of the Celovce Formation. There is a distinct thermal gap between these formations, which resulted from the erosion of the Sambron Zone before the deposition of the Celovce Fm., which provides the lowest grade of the thermal alteration. Vitrinite reflectance data from the Lower Oligocene sediments (Masaryk et al., 1995) indicate that the Sambron Zone lost a sedimentary sequence as much as 2 km thick. This missing sequence of the Oligocene sediments had to be eroded off during the Late Oligocene/Early Miocene. At the same time, the subsidence and sedimentation in the central part of the CCPB continued. The youngest sediments of the Levoca Mts., that correspond to NP 25–NN1(?) Biozones, yield vitrinite reflectance values adequate for 2.5 km of burial depth (Kotulova, Biron, & Sotak, 1998). These vitrinite reflectance values from near-surface locations are equal to those occurring in the Presov-1 well at the depth of 2500 m, where coeval Upper Oligocene sediments of the CCPB are conformably overlapped by Eggenburgian-Karpatian sediments of the East Slovakian Basin. Similarly, Upper Oligocene–Lower Miocene? sediments of the Levoca Mts. indicate that they have been overlain by a 2–3-km-thick missing sedimentary sequence (Kotulova, 1996). The estimated thickness of the unknown sequence appears to be eroded off above the inverted normal faults (Fig. 21), indicated as backthrusts in the southern part of Levoca Mts. (Vozarova, 1995), Branisko Mts. and Vysoke Tatry Mts. (Sperner, 1996).

6. Reservoir rocks and fluid/pressure regime

The CCPB has fair- to pure-quality reservoirs. Flysch sandstones are mostly siliciclastic turbidites not having sufficient porosity for good reservoir properties. Their measured porosity and permeability ranges between 0.3 and 6% and between 12 and 76 $\mu m^2 \times 10^3$, respectively (Ondra & Hanak, 1989; Rudinec, 1989). Their pore systems are filled up by a depositional matrix and significantly reduced by mechanic compaction and carbonate, phyllosilicate and silica cementation. As shown by the blue-resin technique (Bebej, 1996), the total porosity of these quartzolithic sandstones was not enlarged by secondary effects, which include only a dissolution of some volcanolithic and feldspar grains. Exceptions exist in the Sambron Zone where flysch sandstones contain a high amount of unstable components like basalts, ultramafics and glass clasts. This type of arenites

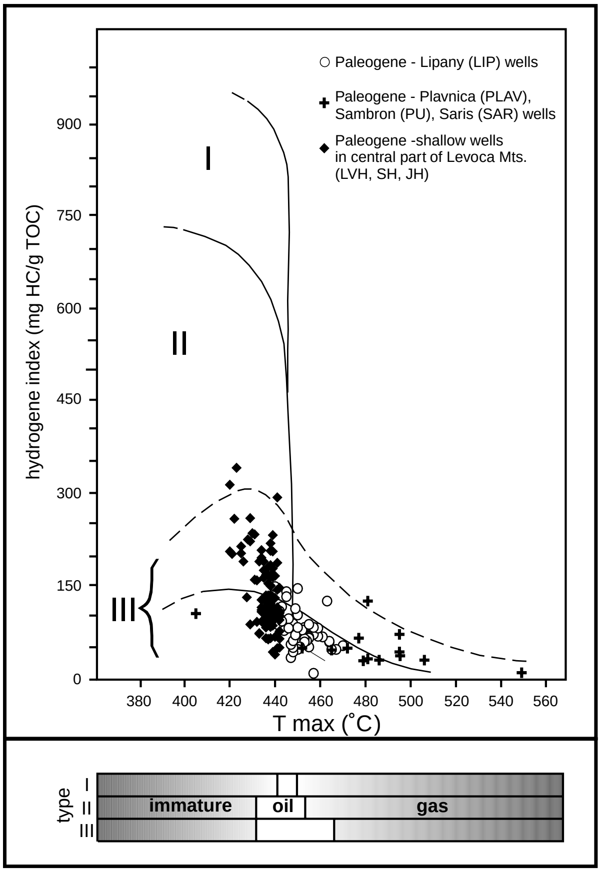

Fig. 15. Kerogen type of Paleogene sediments based on HI–T_{max} diagram (Espitalié, 1986).

also occurs in the matrix of intraformational breccias and conglomerates, which form regional reservoir horizons with hydrocarbon shows in the Sambron Zone found in all deep boreholes (Fig. 13). These scarp sediments contain mostly carbonate clasts and green-colored arenaceous matrix, cemented by smectite (saponite) and mixed-layer chlorite/smectite. Precipitation of these clays reflects high Mg and/or Fe concentrations determined from mafic detritic material (Biron, Sotak, & Bebej, 1999). The presence of smectite and corrensite appears to be important for the fluid pressure control in intraformational bodies. These minerals occur as oriented slickenfibre aggregates intergrowing the matrix and filling pressure shadows and en-echelon veins (Fig. 6e). Intraformational breccias occur in claystone formations with a high degree of post-sedimentary alteration. Ordered R3 mixed-layer illite/smectite yields the estimated temperature of about 170°C (Pollastro, 1993). However, a persistence of highly expandable clay minerals in intraformational breccias indicates considerably lower temperatures of post-sedimentary alteration, which are below 100°C. The slow-down of diagenetic processes is characteristic of a rock environment with fluid overpressure (Jaboyedoff & Jeanbourquin, 1995). This evidence allows us to interpret that the diagenetic system of intraformational breccia bodies, which are the best reservoir rocks in the CCPB (Rudinec, 1992), was originally overpressured. It seems that the fluid overpressuring of the Sambron Zone was not only driven by overburden but by combination of overburden and tectonic stress. The Sambron Zone is considered to be the zone of retreat accretion and backthrusting. Based on analogy with overpressure pulses known from modern accretionary prisms (e.g. Brown, Bekins, Clennell, Dewhurst, & Westbrook, 1994; Maltman, Byrne, Karig, & Lallemant, 1993; Moore et al., 1982), the evidence for overpressure is also acceptable for the Sambron Zone. Permeable horizons, like the breccias in the Sambron Beds, served as a fluid channels during accretionary deformation (Valenta, Cartwright, & Oliver, 1994). Apart from breccia horizons, the structural permeability of the Sambron Zone has been used for expulsion of overpressured hydrothermal and hydrocarbon fluids. Extensional veins along meso-scale strike–slip faults filled by bitumens and Marmarosh Diamonds indicate that yet other fluid channels were formed by fault zones, which is also in accordance with observations from modern accretionary prisms (e.g. Knipe, 1993; Moore, Orange, & Kulm, 1990).

The CCPB is currently a cold region with very low formation pressures (Rudinec & Magyar, 1996). The hydrostatic pressure gradient varies from 9.86 to 10.36 kPa m^{-1}. These subhydrostatic pressures probably resulted from uplift and compressional tectonics in the Pieniny Klippen Belt area. The geothermal gradient of the CCPB region ranges between 24 and 27°C. Recent pressure and temperature data are substantially lower than paleopressures and paleotemperatures. Extremely high pressure values of 110–150 MPa in the Sambron Zone, reaching lithostatic values, and crystallization temperatures of 130–150°C have been obtained from hydrocarbon-rich fluid inclusions trapped in the quartz/calcite veins (Hurai, Siranova, Marko, & Sotak, 1995). This internal overpressuring of veins can be attributed to the thermal degradation of higher hydrocarbons accompanied by liberation of large methane volumes. The overpressuring in the central part of the CCPB is also inferred from occurrences of solid bitumens and exudatinite in Tichy Potok wells in the Levoca Mts (see Parnell, 1994). According to Kotulova (1996), the mentioned protopetroleum products here were generated by early expulsion from source rocks, which contain terrestric and marine OM, enriched in resinite particles, like macerals derived from plant resins. Considering the mean vitrinite reflectance of 0.6% and illite/smectite diagenesis, indicated by R1 I/S with 30% of smectite layers (Biron, 1996), these sediments reached the maximum temperature of about 110°C at a burial depth of about 2.5–3 km (see Pollastro, 1993). Oil and gas-condensates in described conditions can be generated from the resinite-rich terrestrial OM earlier than from other OM types (Powell & Snowdon, 1983). Transformation of the kerogen to liquid and gas hydrocarbons in the Levoca Mts. led to overpressuring of near-source rock mainly because of the accompanying volume expansion (see

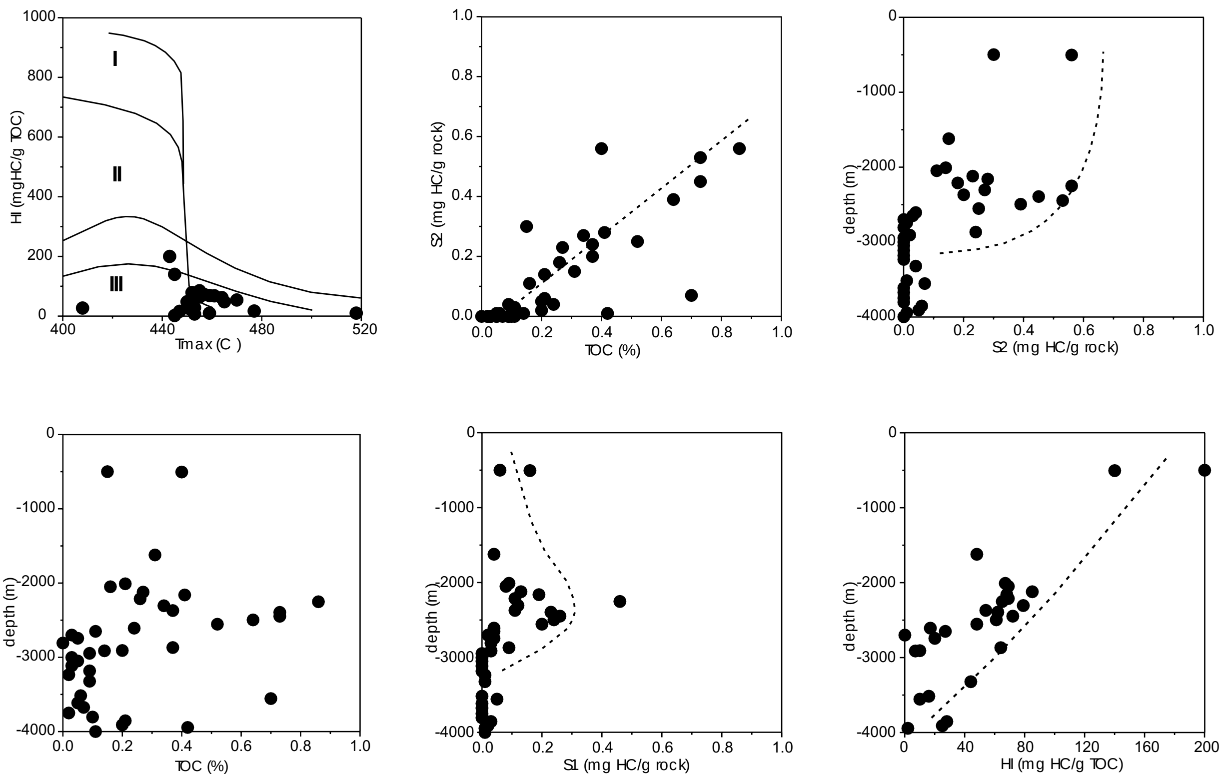

Fig. 16. Geochemical characteristics of organic matter in Lipany 1 well.

Osborne & Swarbrick, 1997). After a short outward migration away from the source rock and higher pressure conditions, hydrocarbon fluids were accumulated in discontinuity sets of sedimentary rocks. The solidification of these hydrocarbons occurred either during continuous burial diagenesis by polymerization or during uplift and cooling of basin formations because of fluid pressure drop or gas exsolution from liquid and semi-solid bitumens (Kotulova, 1996).

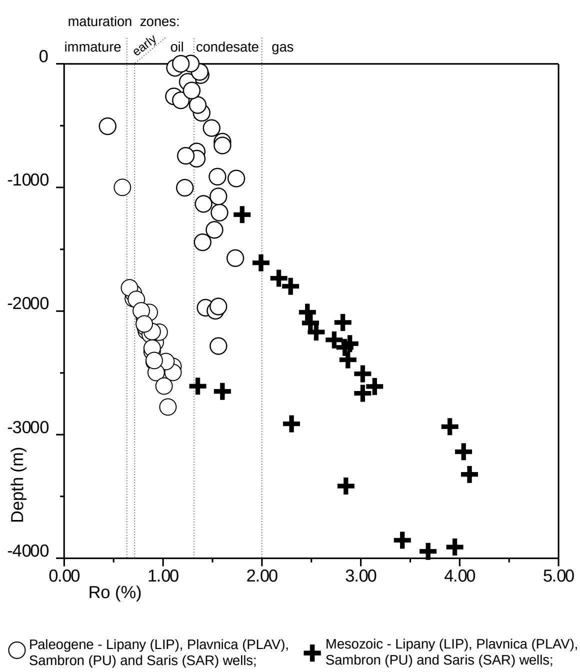

Fig. 17. Vitrinite reflectance in relation to depth in Paleogene and Mesozoic sediments.

7. Organic geochemistry and kerogen maturation zonality

Paleogene rocks and some pre-Tertiary rocks from well cores reaching up to 3000 m have been characterized using routine organic geochemical methods. Sample lithologies comprise mostly shales, partly sandy shales and carbonates.

The total organic carbon (TOC) content of Paleogene source rocks with disseminated organic matter in the Lipany wells area is up to 2%. Source rocks with coaly organic matter in LVH wells have TOC of up to 10%. Primary geochemical features of the oil-bearing Lipany area based on Rock-Eval pyrolysis are shown in Fig. 16. The kerogen is predominantly terrestrial (Type III in Fig. 15). However, the hydrocarbon generation potential in Lipany and mainly Plavnica wells is exhausted to a considerable extent.

The kerogen maturation zonality, estimated by microphotometry, is shown in Fig. 17, maximum pyrolysis T_{max} temperature values and kinetic modelling of hydrocarbon generation in Figs. 18–20. The highest maturation level within Paleogene sediments was reached in the northwestern part of the Levoca Mts. in Plavnica 1, 2 and

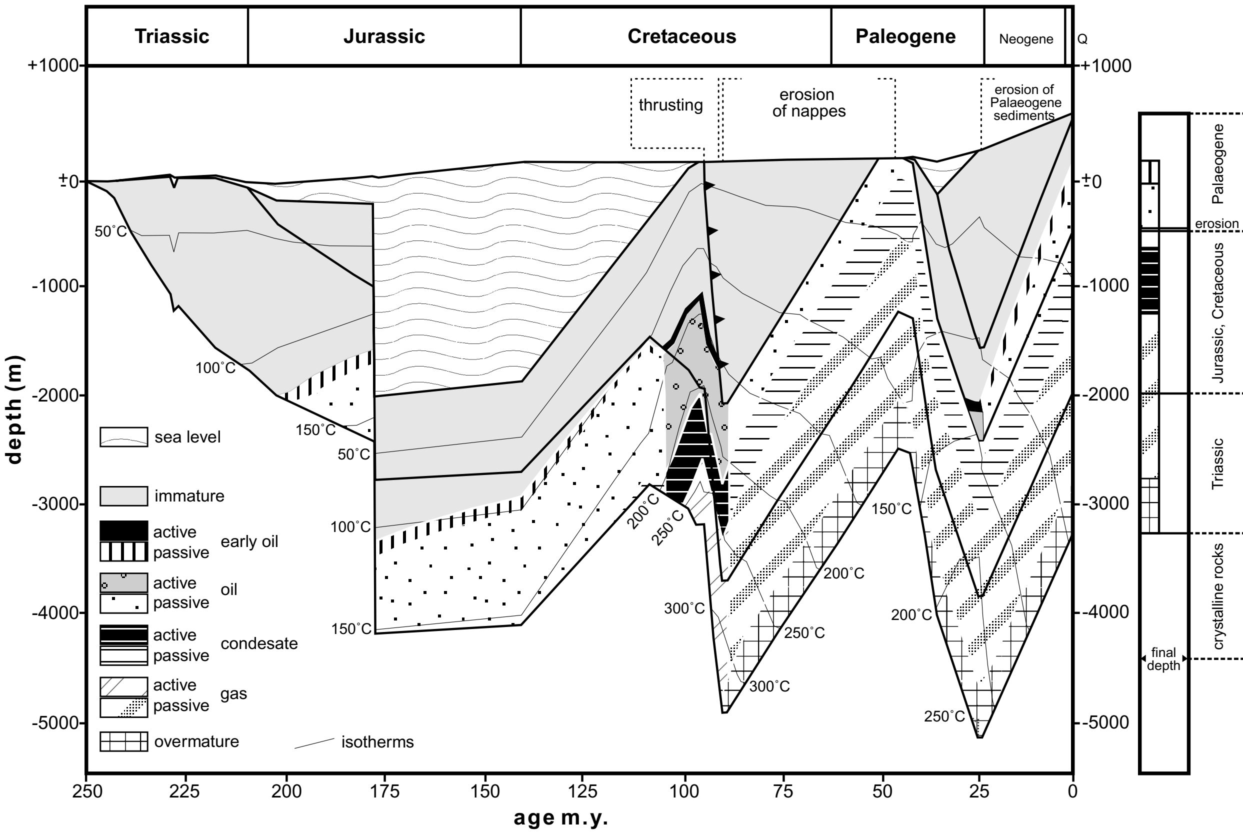

Fig. 18. Saris 1 well burial history plot and hydrocarbon generation windows.

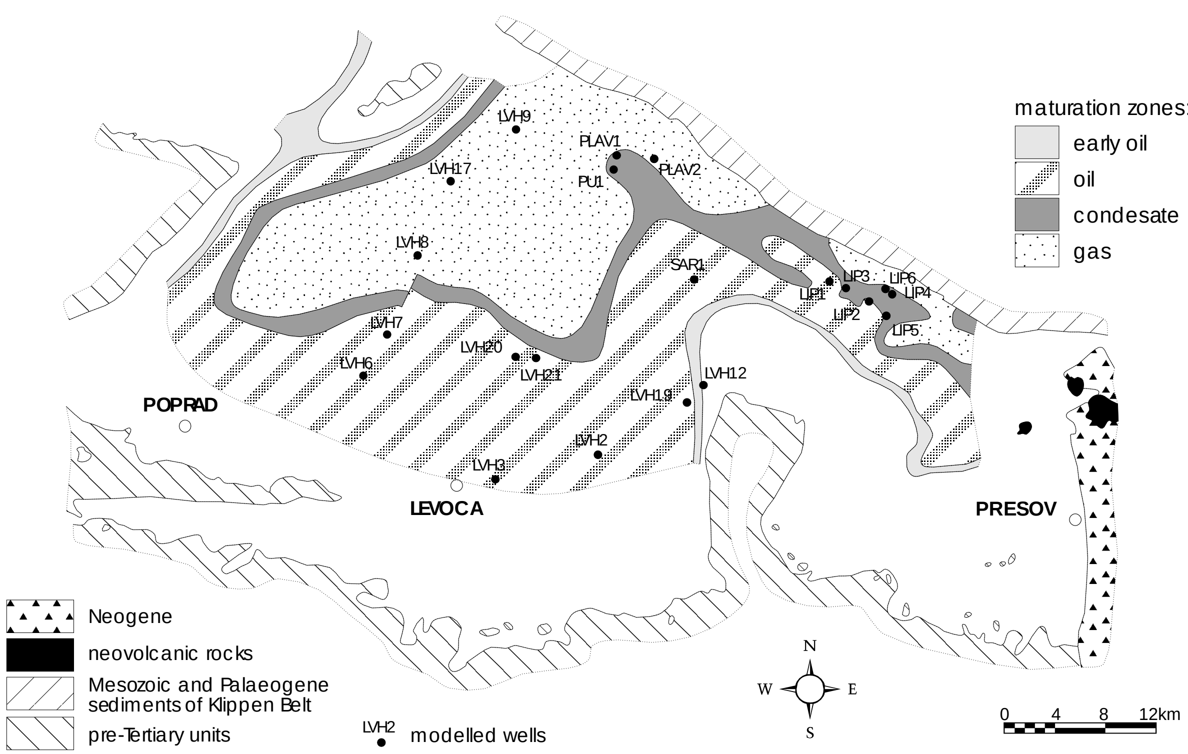

Fig. 19. Maturation zones at the Paleogene base of the Levoca Basin.

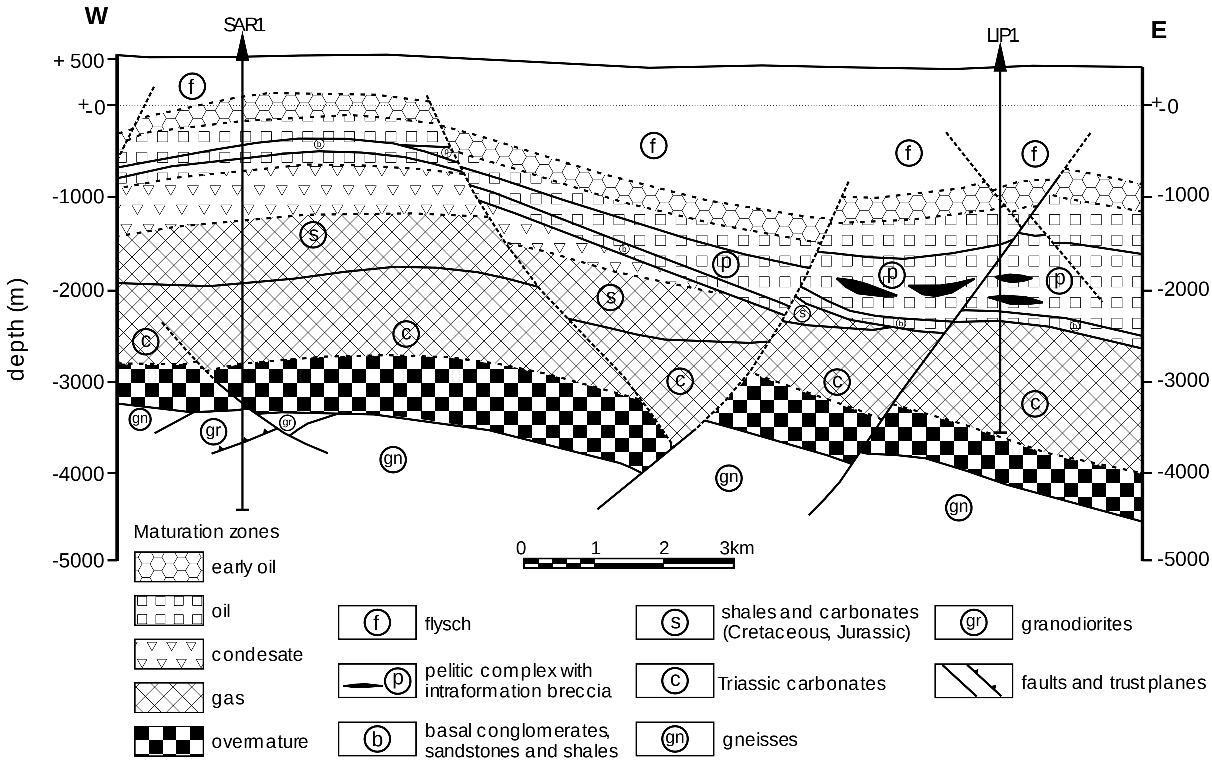

Fig. 20. Maturation zones in generalized geological cross-section between SAR-1 and LIP-1 wells.

Sambron PU1 wells, where it is in the final stage of the oil to dry gas generation (Fig. 17). The present residual hydrocarbon potential is of about 0.19 kg HC per ton and represents only a relict of the original hydrocarbon potential. This maturation stage was reached in the geological past at considerably greater depth. The organic matter in Lipany wells in the northeastern part of the basin is less mature. Maturity ranges from the early hydrocarbon to beginning of gas production (Fig. 17). The total hydrocarbon potential is about 0.3–0.8 kg HC per ton. It represents, like in the NW part of the CCPB, a relict of the original hydrocarbon potential. A portion of this potential represents small oil accumulations discovered by Lipany wells. The area with relatively less mature organic matter lies in the centre of the Levoca Mts., in the LHV and Tichy Potok wells area. The maturation stage here corresponds to the early oil production stage with a total hydrocarbon potential of about 0.8–5.5 kg HC per ton. The hydrocarbon potential in coaly sediments of this area reaches values of tenths of kg HC per ton and it is most comparable with the original potential. Maximum values in LVH 6 well are 200 kg HC per ton.

Metamorphic discordance between Paleogene sediments and underlying Mesozoic formations is indicated by vitrinite reflectance in both NW and NE parts of the basin (Fig. 20). Present depth and temperature conditions exclude Mesozoic sediments from being potential active producing source rocks. Geological reconstruction indicates that the present maturation stage of Mesozoic sediments was reached within the period of Middle to Late Cretaceous (Fig. 18) and was not significantly influenced by sedimentation of the overlying Paleogene strata.

Paleogene sediments in different parts of the Levoca Mts. are not equivalently mature (Fig. 19). The maximum hydrocarbon production was reached in Late Oligocene. Since this period these sediments have remained in the relict maturation stage (Figs. 18 and 20), which was originally reached at considerably greater depth. Case examples of Plavnica and Sambron PU1 wells indicate depths 2000 m deeper than present depths.

Based on mentioned results we present the following katagenetic zonality for kerogen Type III:

- The top of the early hydrocarbon generation zone lies at −600 to −1200 m altitude in the Lipany wells in the northeastern part of the CCPB, at 0 to +800 m altitude in Plavnica and Sambron PU1 wells in the central and northwestern parts of the CCPB and partly on the surface in the northwestern portion of the basin.
- The top of the oil generation zone lies at −800 to −1400 m altitude in the NE part of the CCPB, −200 to +800 m altitude in the central part of the basin and partly on the surface in Plavnica 1, LVH 2 and 3 wells.
- The top of the condensate zone lies at −2400 to 3000 m altitude in the NE part of the CCPB and −400 to −1800 m altitude in Plavnica 2 well, central and NW parts of the basin.

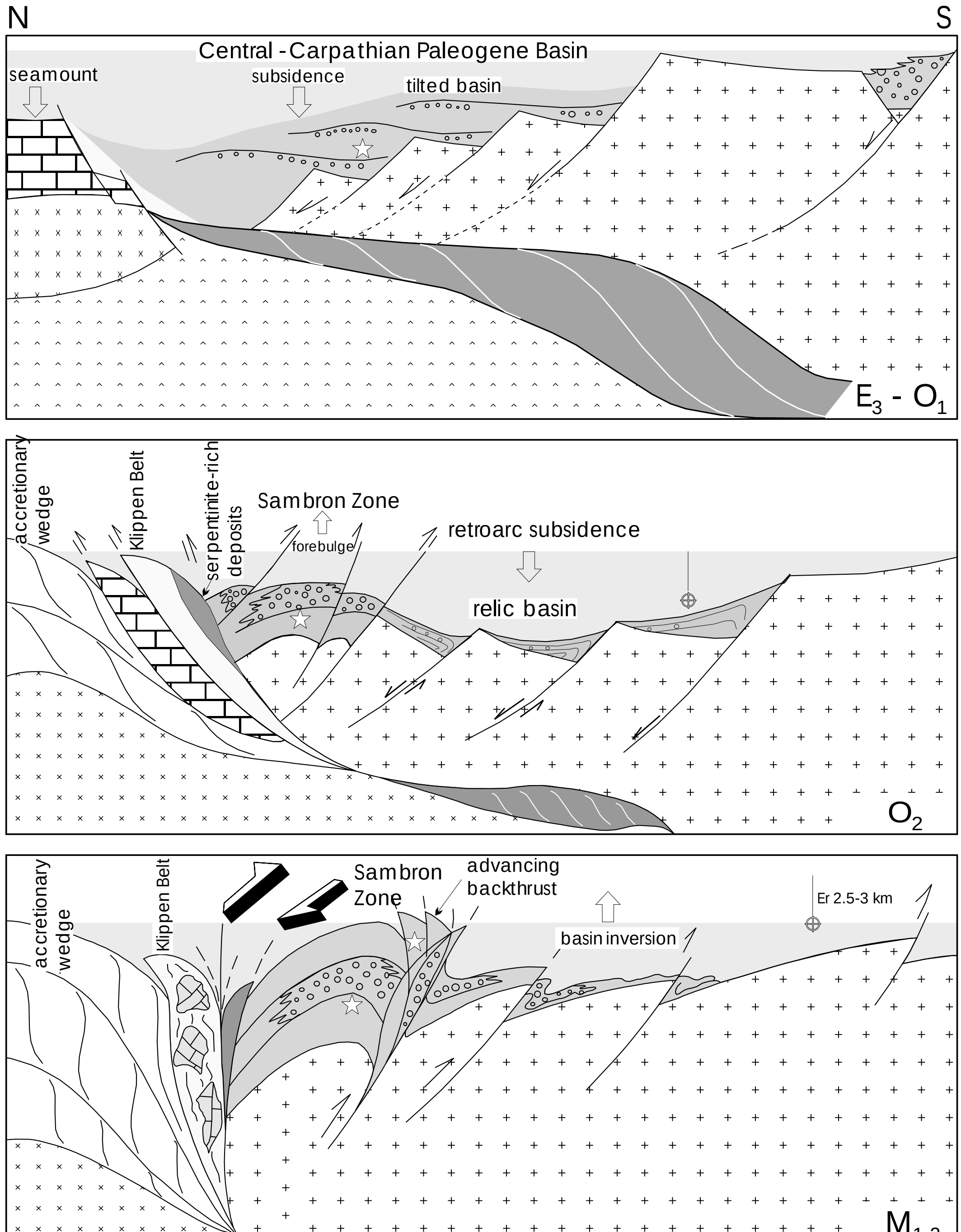

Fig. 21. Evolutionary scheme of the CCPB. Interpretation shows initially (E_3–O_1) trenchward tilting of continental margin above a zone of subduction and subcrustal erosion, subsequently (O_2) forebulge collision producing the thrust load for retroarc basin subsidence, and finally (M_{1-2}) backthrusting and antiformal stacking of the Sambron Zone and basin inversion. Symbols indicate depth/reflectance changes in R_o values in burial and uplift periods of basin evolution (asterisks $R_o \approx 1.5\%$, circles $R_o \approx 0.7\%$, reflectance data taken from Kotulova, 1996; Masaryk et al., 1995). Abbreviations: E_3 — Late Eocene, O_1 — Early Miocene, O_2 — Late Oligocene, M_{1-2} — Late and Middle Miocene, Er — estimated erosion.

- The top of the dry gas zone lies at −3000 to 3200 m altitude in the NE part of the CCPB in the vicinity of the Klippen Belt and at 1000 to −2200 m altitude in both N and NW parts of the basin. The residual hydrocarbon potential is practically completely exhausted.

8. Geotectonic setting and basin evolution

The CCPB was formed as a marginal sea of Peri-Tethyan basins. It shows a fore-arc basin position developed in the proximal zone of the Outer Carpathian accretionary prism.

The CCPB began to subside probably due to the extensional collapse and basal erosion (attrition) of the overriding plate above the zone of subduction (see Moberly, Shepard, & Coulbourn, 1982; Wagreich, 1995). Despite the regional tectonic control, the basin evolution reflects an important role of global sea-level changes (Bartholdy et al., 1999; Sotak, 1998a; Sotak & Starek, 1999). The CCPB reveals a polystage development: (1) initial faulting and alluvial fan deposition in a halfgraben-type basin, (2) carbonate factory in a shelf-margin basin, (3) glacio-eustatic regression and semi-isolation in a restricted basin, (4) progressive faulting and fault-controlled accumulation of radial fans in a tilted basin, (5) highstand aggradation in a starved basin, (6) Mid-Oligocene sea-level lowering and retroarc backstepping of depocentres in a relic basin, and (7) wedging of sand-rich fans and suprafans in an over-supplied basin (Fig. 21). The CCPB lacks sediments of the younger depositional cycle, which is indicated by burial temperature of Upper Oligocene formations. This missing sequence was inferred to have been formed by the Lower Miocene sediments.

Upper Oligocene fan systems of the CCPB show an organization responsive to geodynamic setting of active margin-fans, as indicated by elongated shape, development of attached lobes and suprafan lobes (Shanmugam & Moiola, 1988). The CCPB sedimentation ceased because of subduction-related shortening and gradual uplift. The youngest oceanic crust indications include detrital serpentinites in the Upper Oligocene sediments of the perisutural basin (Sotak & Bebej, 1996). The basin inversion progressed from the north, where the flysch sediments of the Sambron Zone were folded and eroded already before the Eggenburgian, as is indicated by unconformity below the Celovce Fm. The related regional maximum principal compressional stress σ_1 in the CCPB had N–S and NE–SW direction (Marko, 1996; Nemcok, 1993; Nemcok & Nemcok, 1994; Sperner, 1996). It coincided with northward and northeastward out-of-sequence thrusting of the Outer Carpathian accretionary wedge above the southwestward subducting slab. The Sambron Zone became the rear part of the accretionary wedge, affected by detachment faulting, antiformal stacking and backthrusting. The maximum amount of the perpendicular shortening in the Sambron Zone has been calculated as about 70% (Nemcok et al., 1996). The change of compressive stress to NW-directed σ_1 reflects the oblique plate convergence characterized by transpression and dextral wrenching (Bada, 1999; Ratschbacher et al., 1993; Roca, Bessereau, Jawor, Kotarba, & Roure, 1995). The northern side of the basin was bounded and amputated by a first-order transform fault related to oblique-plate boundary (Pieniny Klippen Belt). It accommodated the extreme deformation resulting from horizontal shortening, vertical lengthening and noncoaxial dextral shearing (Ratschbacher et al., 1993). The boundary between the Sambron Zone and the Pieniny Klippen Belt is supposed to be a crustal-scale wrench fault juxtaposing units of orginally distant provenances. As a consequence, the CCPB lacks at least one-third of its Periklippen part (cf. Marschalko, 1975). Later disintegration of the Central Carpathian fore-arc basin led to the opening of wrench furrow basins along the Pieniny Klippen Belt (Kovac et al., 1998).

The geotectonic origin of the CCPB was closely related to the Tertiary dynamics of the ALCAPA plate (sensu Csontos, 1995). The Tertiary collision in the Alps initiated the eastward extrusion of the ALCAPA lithospheric fragments (Ratschbacher, Merle, Davy, & Cobbold, 1991), which orogenic front above the southwestward subducting slab created a catchment area for the CCPB in the fore-arc position. Progressive indentation of the ALCAPA plate (Tari, Baldi, & Baldi-Beke, 1993) advancing above the subducted slab led to form a highly asymmetric doubly vergent accretionary wedge of the Outer Carpathian flysch prism. During the Early Miocene, the ALCAPA came into continental collision with strong embayment of the European foreland (Bada, 1999; Sperner, 1996), which enabled its counter clockwise rotational movement (Kovac & Tunyi, 1995; Marton & Marton, 1996). This rotation was compensated by dextral shearing in the transpressional zone of the Pieniny Klippen Belt (Ratschbacher et al., 1993), and resulted in oroclinal bending of the Carpathian arc.

Acknowledgements

The work has been carried out under the financial support of the Scientific Grant Agency of the Slovak Academy of Sciences (2/7068/20), Slovak Ministry of Environmental Affairs (project — “Flysch regions of the Eastern Slovakia — geophysics”), internal projects of Research Oil Company for Exploration and Production (VVNP) and NAFTA a.s. Gbely. A friendly review by Michal Nemcok contributed substantially to improvement of the paper. Special thanks go to Julia Kotulova for providing the reflectance data and additional OM characteristics. The authors wish to thank A.S. Andreyeva-Grigorovich, I. Barath, J. Bebej, A. Biron, T. Durkovic, J. Francu, P. Gross, B. Hamrsmid, N. Hudackova, V. Hurai, J. Jablonsky, J. Janocko, S. Karoli, M. Kovac, J. Magyar, F. Marko, E. Marton, J. Michalik, M. Misik, A. Nagymarosy, P. Ostrolucky, D. Plasienka, R. Rudinec, J. Salaj, J. Spisiak, L. Svabenicka and P. Uhlik for fruitful discussions and provision of some unpublished data. Helpful comments on the manuscript were provided by reviewers George Postma and Blanka Sperner. R. Vitalos and N. Halasiova are thanked for their help with figure drafting.

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