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Late Aptian–Early Albian syn-tectonic facies-pattern of the Tata Limestone Formation (Transdanubian Range, Hungary)

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Abstract: The Upper Aptian to Lower Albian Tata Limestone Formation consisting of brown-grey bioclastic crinoidal limestone presumably represents the first unconformable formation, which recorded early deformation events of the Alpine cycle. The base of the Tata Limestone is affected by erosional features accompanied by significant breccia bodies. Reconstruction of the paleomorphology of the basin bottom supported by paleoecological (e.g. water depth) data shows (in the recent orientation) at least five northwest–southeast trending zones with significant erosional features and accompanied by coarse-grained graded breccia in a more clayey matrix (e.g. Cseh-1 borehole). These elevations were uplifted above deeper basins filled with crinoidal limestone. The geometry of the uplifted units is asymmetrical, anticline-like and the deeper depressions have a syncline-like structure. According to previous works to the anticline-like morphology of the uplifted zones and to the transport direction of the coarse breccia clasts, these uplifted units were possibly formed by thrusting, in a compressional regime. The differences in the thickness of the crinoidal limestone and the breccia interbeds show synsedimentary character of these movements. In the borehole Cseh-1, large limestone fragments appear already in the Sümeg Marl Formation and they are present throughout all the Tata Limestone sequence. This fact indicates that the tectonic movements started in the Barremian and continued during the whole Aptian.

Key words: Aptian–Albian, Carpathians, Transdanubian Range, tectonic model, syn-tectonic sedimentation, bioclastic limestone, scarp breccia.

Introduction

The Transdanubian Range is located in Hungary, in the heart of the Pannonian Basin and is made of gentle hills (600 m elevation; Fig. 1). It nevertheless provides nice exposures of Paleozoic to Miocene successions, which were traditionally related to the Austroalpine or South Alpine structural units (Kázmér & Kovács 1985; Császár et al. 1998). This unit is now regarded as an Upper Austroalpine nappe (Tari 1994; Fodor et al. 2003).

The Mesozoic successions are conformable until the mid-Late Albian. At the basis of a *Munieria*-bearing marl and rudistid limestone (Tés and Zirc Formations) angular unconformity is observed (Fig. 2a) (Császár 1986). However, a lower formation, named “Aptian crinoids limestone” or the Tata Formation (Fülöp 1976) also shows very gentle unconformity towards lower horizons (Császár et al. 1998). This is mainly manifested as hiatuses or dissolved surfaces and no pronounced angular unconformity was described so far. Our main goal was to investigate this unconformity and the overlying Tata Formation, in order to demonstrate pre- or syn-depositional tectonic activity and to better constraint the start of the Cretaceous structural events.

Main characters of the Tata Formation

The Tata Limestone Formation is one of the most easily recognized members of the Cretaceous sequence in the Transdanubian Range. The bulk of it consists of brown to grey, fine- to coarse-grained crinoidal limestones. In some places brachiopod or ammonite-rich coquina is found at its base; otherwise the formation is very poor in macrofossils. Based on paleontological investigations (Bodrogi 1994; Görög 1996; Fogarasi 2001; Szíves 2001; Bodrogi & Fogarasi 2002), the age of the Tata Limestone is Late Aptian to Early Albian (Fig. 2b). The base of the formation seems to be a time-transgressive surface: in western zones it could be Late Aptian, in eastern outcrops it is proven to be Early Albian (Szives 2001). In eastern areas (at Olaszfalu, Eperkés Hill and Tata Kálvária Hill) some small pockets at the unconformity may yield Middle Aptian fauna as well (Somody 1987; Szives 2001). In western zones (Sümeg and environs) the sedimentation was continuous from the underlying pelitic, glauconitic Sümeg Marl, the age of which is Barremian to Early Aptian (Haas et al. 1984). In the central area of the Transdanubian Range, the Tata Limestone conformably overlies a crinoidal limestone of Valanginian (Barremian?) age, which is a heteropic facies to the Sümeg Marl (Borzavár Formation). In the other areas the basis of the formation is erosional, at some places the erosion surface cuts down to Jurassic rocks or even deeper (Fig. 2b). In some places the biodetrital limestone overlies directly the Upper Triassic Dachstein Limestone. It is remarkable that there is a major hiatus even at places surrounded by Sümeg Marl exposures.

The top of the formation is either a marked unconformity, or a facies transition. The more unconformable

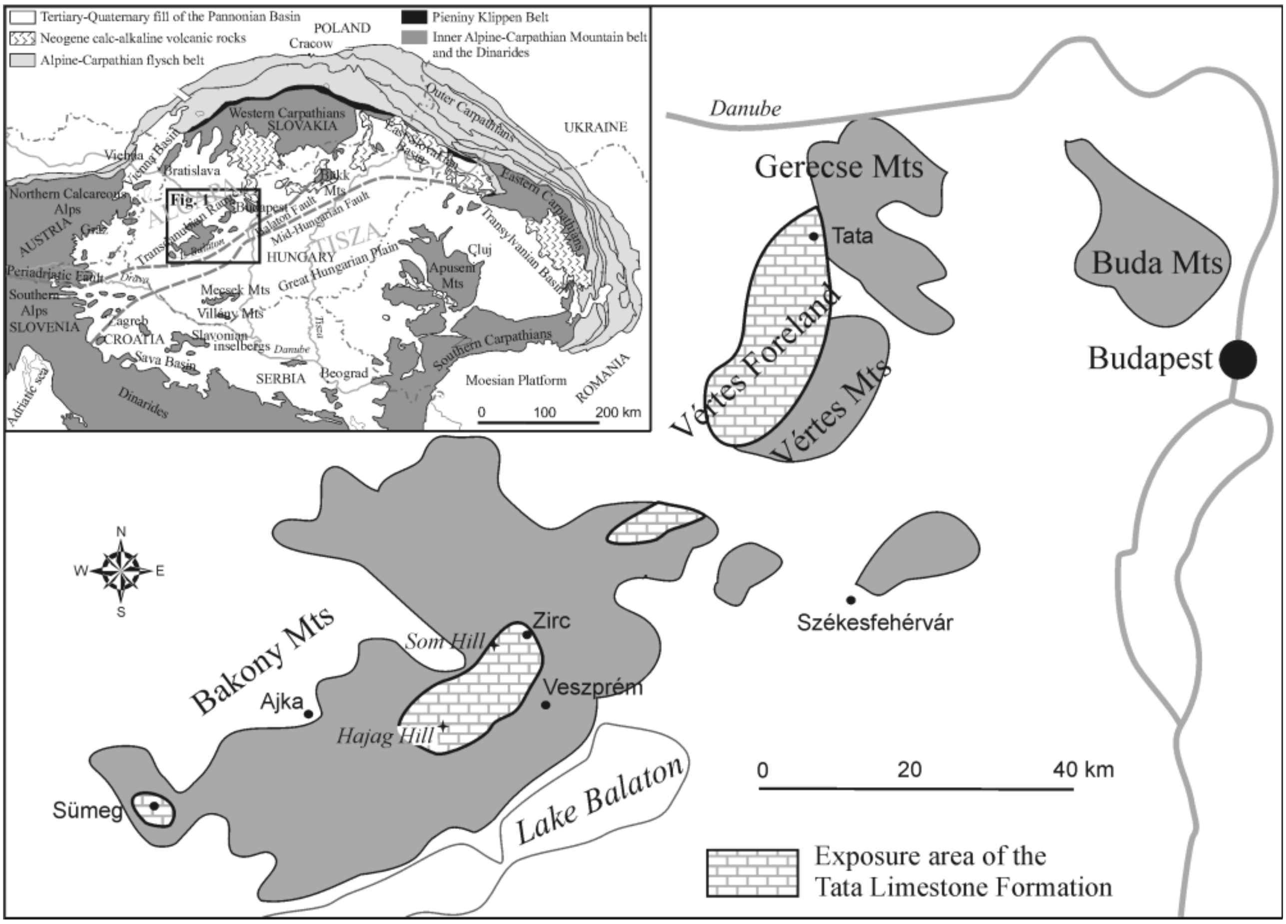

Fig. 1. Location of the Aptian-Albian Tata Limestone (Transdanubian Range, N Hungary).

parts are found in the west, while the facies transition is located in the east. Here the Tata Formation passes laterally to a rudistid patch reef (Környe Formation) and further to the east to dark basinal silt (Vértessomló Formation) (Császár 1986; Mindszenty et al. 2001). Both of these formations have an Early to Middle Albian age (Görög 1996; Bodrogi & Fogarasi 2002). In other places to the west (at the Bakony Mts, except Sümeg and environs) the Tata Limestone is covered by dark brackish, shallow marine marls (Tés Formation). Mindszenty et al. (2001) suggested that the facies belts moved to the west during Middle–Late Albian, due to a forebulge and fold-thrust propagation.

There is always a significant extraclast content in the formation. This is eventually manifested as spectacular breccias near the base of the formation. The extraclasts originated from older members of the Mesozoic sequence. The average size of these detrital limestone fragments is different in each outcrop: at some places they are coarse-grained (with boulder sized limestone fragments), making up thick breccia bodies. At other places the extraclasts are represented by only some well sorted and well rounded, sand-grain sized limestone fragments in the crinoidal matrix. The coarser members were interpreted so far as shallow marine transgressive basal breccias (Fülöp 1976).

Lelkes (1981, 1983) made a detailed microfacies study of the formation. He described three main microfacies types. According to him the deepest environment (100 m) produced a sponge-bearing, micritic limestone ("A"-type). This was observed at two distal places. The bulk of the formation was ranged to a medium-grained, well sorted, cross-bedded, hummocky bedded bioclastic grainstone with extraclasts ("B"-type) deposited in shallow and medium depth (30–100 m). The shallowest (10–30 m), coarse-grained heavily recrystallized grainstone with minor extraclasts ("C"-type) was also described from a couple of exposures.

Methodology

Our main interests were to map the erosional features at the base of the Tata Limestone, to locate the significant breccia bodies at the base of the formation and to try to collect some paleoecological data to reconstruct the paleomorphology and paleo-water depth of the sedimentary basin. Conventional methods were used to reach this goal: macroscopic, and microscopic description was made from the chosen sections. Thin section study was done to describe the microfacies and the foraminiferal communities of the crinoid limestone.

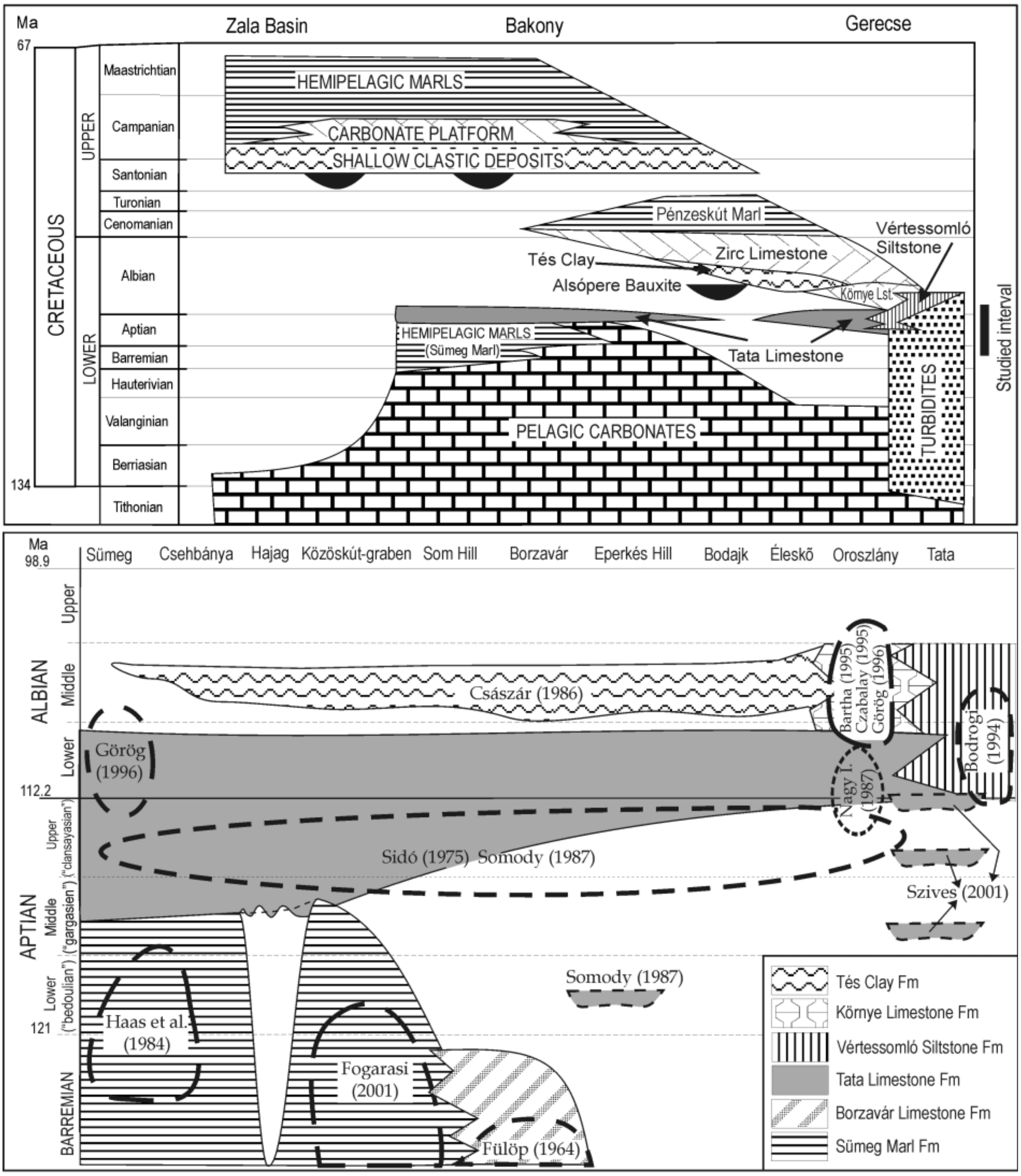

Fig. 2. Stratigraphic tables for **(a)** the Cretaceous (after Császár 1998) and **(b)** for the Tata Limestone. The latter table is compiled after Fülöp (1964), Sido (1975), Haas et al. (1984), Császár (1986), Somody (1987), Bodrogi (1994), Bartha (1995), Czabalay (1995), Görög (1996), Fogarasi (2001).

The collected data were plotted on a map (Appendix, modified after Császár & Cserekle i 1982). In addition, borehole and other mapping data were used to construct a geological map of the formations directly underlying the Tata Limestone. This map was then combined with facies data to construct a set of cross-sections. Other structural data (Albert 2000) were also used to make an interpretation of this geological map.

Basal layers and breccias

Five sections will be described in more detail. These are the succession of Csehbánya-1 (Cseh-1) well, the exposures of Hajag, Som-hegy, Borzavár and Vértessomló.

The ***Csehbánya-1 well*** is located (Appendix) in a Miocene basin. The Neogene and Paleogene strata are underlain by Cretaceous and Jurassic rocks. The Upper

Jurassic–Lower Cretaceous white micrites (Biancone) are conformably covered by grey, glauconitic sandy marl and silt with coalified plant remains: the Sümeg Marl (Fig. 3). This formation of Barremian–Early Aptian age (Haas et al. 1984) contains variable size clasts derived from the Upper Jurassic–Lower Cretaceous succession. In some intervals breccia layers are observed. These are grain supported, fining upwards and have a pelitic matrix (Fig. 4). High in the well Middle Jurassic radiolarite is also present among the clasts. At 441 m the first crinoidal limestone interlayer occurs within the extraclast-bearing grey, micro-bedded marl. Further upwards more and more crinoid-bearing marl follows. Several other breccia horizons with glauconitic clasts and crinoid-rich glauconitic matrix are found in this part of the well. These are normally graded, grain-supported breccias with the crinoid content increasing upward in each breccia horizon. The extraclasts are dominated by whitish limestones and cherts. The lower limit of the Tata Formation is interpreted at the first occurrence of the crinoidal limestone. Both the Sümeg Marl and the Tata Formation are deeper basinal sediments with several grain-supported, normally graded, resedimented breccia horizons. It seems the extraclastic input decreases upwards and leaves the place to increasing crinoid-input.

The ***Hajag exposure (Gombás puszta)*** is located 3 km from the former well (Appendix). This exposure on a steep hill-side covers a 5 m thin and condensed Jurassic succession (Fig. 5) (Fülöp 1964). The basal Tata Beds lie on Upper Jurassic, or Lower Jurassic strata. Although the transition is within a short distance, no visible angular unconformity is

Fig. 4. Graded breccia sample from the Csehbánya-1 well, 396–398 m interval, with a chert fragment of 2 cm in diameter in the middle of the core.

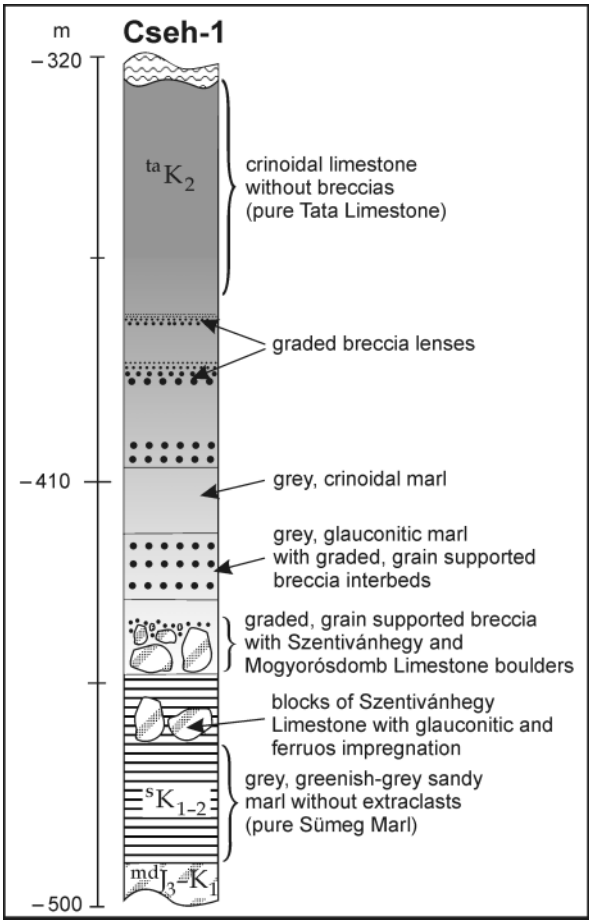

Fig. 3. Stratigraphic section of the well Csehbánya-1, only the Lower Cretaceous succession is shown.

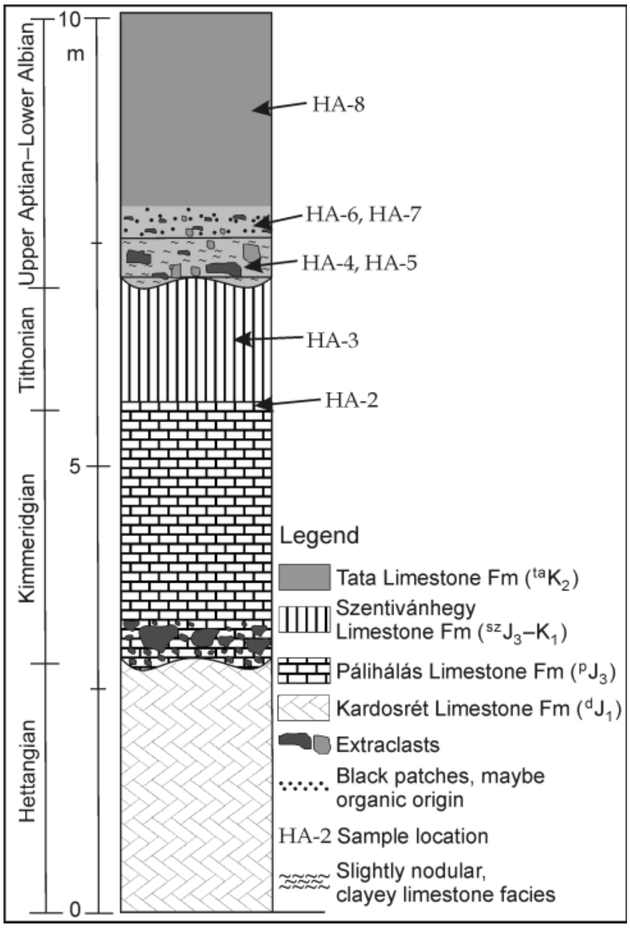

Fig. 5. Section at Gombás puszta.

seen between Jurassic and Upper Aptian beds. The base of the Tata Formation is made of a 0.5 m thick breccia layer of nodular appearance. The clasts are derived from older formations and from the Tata Formation itself. This horizon is covered by well-layered crinoidal limestone with extraclasts of 2–3 mm in size. Centres of crinoid fragments are frequently coloured in black. This might indicate an organic-rich or reductive environment. These layers quickly pass to the typical, coarse-grained crinoidal limestone with cross-stratification without recognizable extraclasts. In thin sections a lot of bioclasts other than crinoid-ossicles are recognized. There are frequent and relatively big (0.5–1 cm) fragments of corals, brachiopods and these are bio-eroded (Fig. 6). The coarse-grained crinoidal grainstone frequently contains dissolved grains, filled by coarse sparitic cement. This latter was produced at two time intervals: first a thin, radial, submarine cement was formed, then a coarse-grained shallow burial cement filled the voids. All clasts are well rounded and sorted. The absence of micrite suggests a well-agitated environment. The high percentage of shallow water fauna as well as bio-erosion suggests the upper part of the photic zone with a maximum of 15 m water depth. It is interesting to note that further to the east 2 km from this shallow facies exposure another well (Hárskút-2) found the Barremian–Aptian Sümeg Marl, and then the Tata Formation as a sponge spicule bearing micrite (Appendix). Neither the marl, nor the Tata Limestone contains extraclasts or breccias. The transition between the marl and limestone appears gradual. Lelkes (1983) described his deepest microfacies in the Hárskút-2 well. Higher in the well the Tata Limestone becomes progressively more crinoidal and has shallower marine facies.

The ***exposure on the top of the Som-hegy*** (Appendix) shows the contact of the Upper Jurassic–Lower Cretaceous and the Tata Limestone. In a trench (Fülöp 1964) the pinkish white, marly micrite (Biancone, possibly of a Valanginian age) is encrusted by an undulated and ferruginous-manganiferous surface (Fig. 7). This typical hard-ground is covered by apparently conformable beds of the Tata Limestone. The basal beds are made of a weakly lithified clastic layer with red clay matrix. Several types of fragments encrusted by fer-

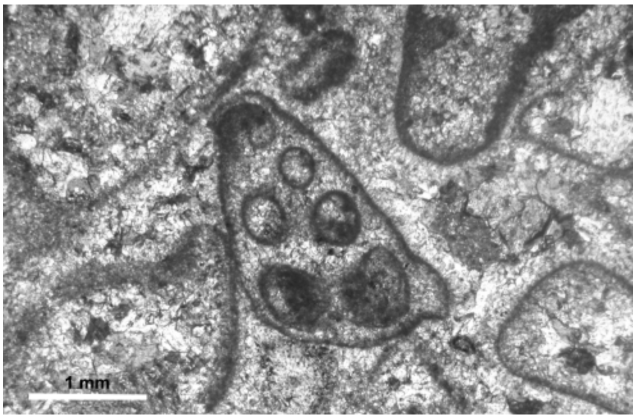

Fig. 6. Gastropod fragment with micritic encrustation in early diagenetic cement. (Hajag Mountain, Gombás-Puszta exposure).

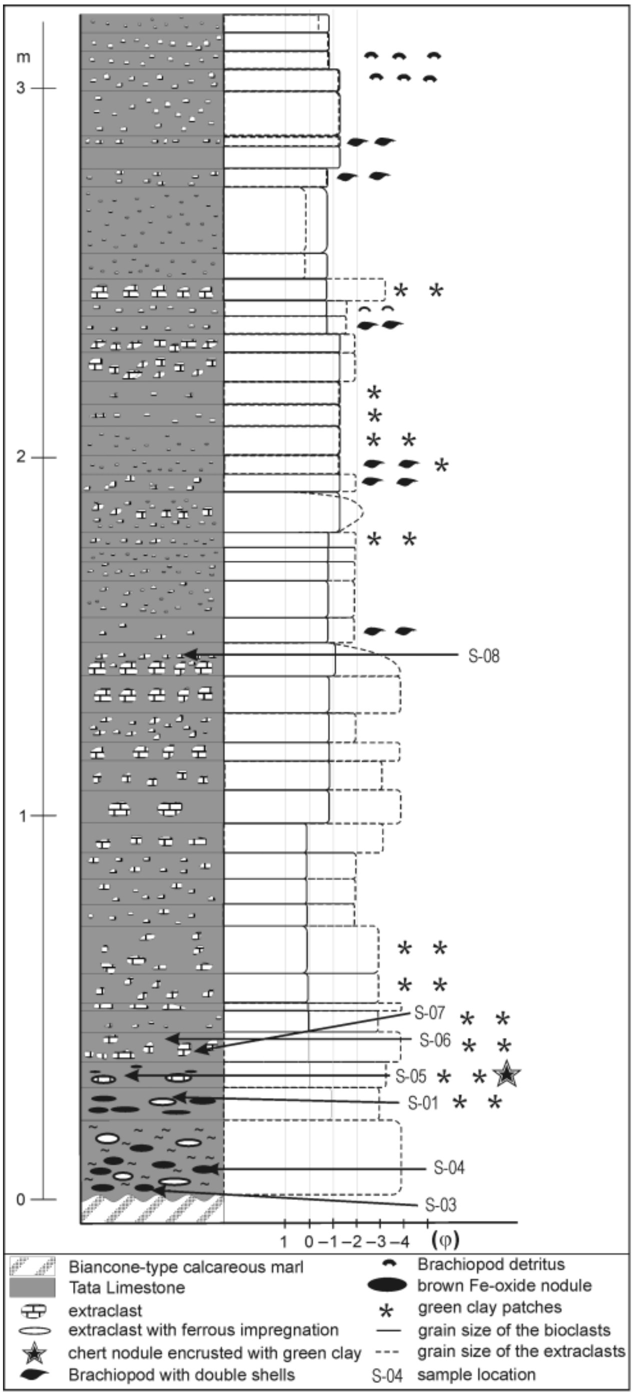

Fig. 7. Section at Som-hegy.

ruginous surface and fossils (mainly shark teeth) were found floating in the matrix. The carbonate content increases in the next 10 cm bed, with pinkish micritic matrix. This bed also contains encrusted red and green pebbles and glauconite grains. The higher beds are lacking in encrusted ferruginous clasts, but contain greenish clay pebbles, carbonate and radiolarite clasts with greenish clay coating. The next laminated clay layer is covered by crinoidal limestone with very frequent extraclast pebbles. These extraclasts of variable size are persistent higher upwards (Fig. 8). At about 75 m horizontal distance from the base, a huge (20×30 m) Lower Jurassic thick bedded limestone block occurs within the formation. This block, formerly interpreted as a horst, has no root and is not exposed in a very near undercutting cave (Fig. 9). Therefore it is interpreted as an olistolith. There was no grain size change neither in eastern, nor in western directions. 500 m further to the NE the Tata Limestone is a crinoidal, well bedded limestone with practically no extraclast (only mm size clasts occur). Unfortunately, the transition between the thick breccia and the extraclast-free outcrops is not exposed properly.

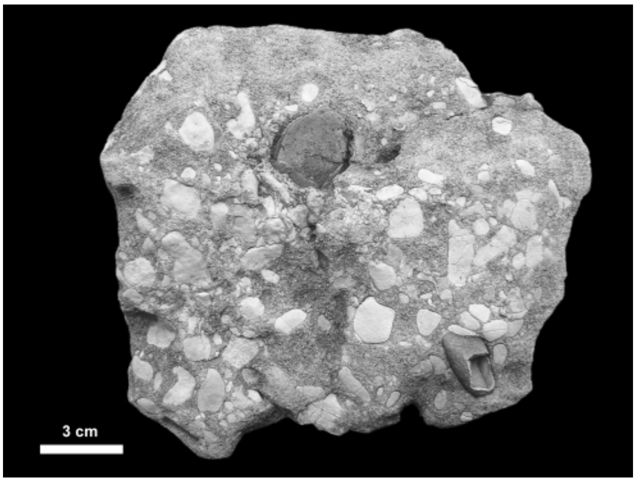

Fig. 8. Breccia at Som-hegy.

In thin section, the basal grainstone beds contain a great amount of bio- and extraclasts. Beside crinoid ossicles, agglutinated benthic foraminifers (*Verneuillinoides*) are present in a great number. These fossils are characteristic for the inner shelf to shallow bathyal environments and are not present in littoral or lagoonal environments (Van den Akker 2000). The clasts are strongly bio-eroded with bacterial dissolution marks. They are frequently impregnated by ferrous solutions. In some cases silicification also occurs. The clasts are dominantly Lower Cretaceous–Upper Jurassic whitish, pinkish micrites, but cherts, radiolarite clasts also occur. Less frequently weakly rounded and angular quartz forms the core of ferruginous nodules. These quartz clasts show an undulating extinction and are probably of metamorphic origin. The crinoids are reworked, transported and sorted. Higher in the section (0.5 m from the unconformity) a biomicrite packstone–

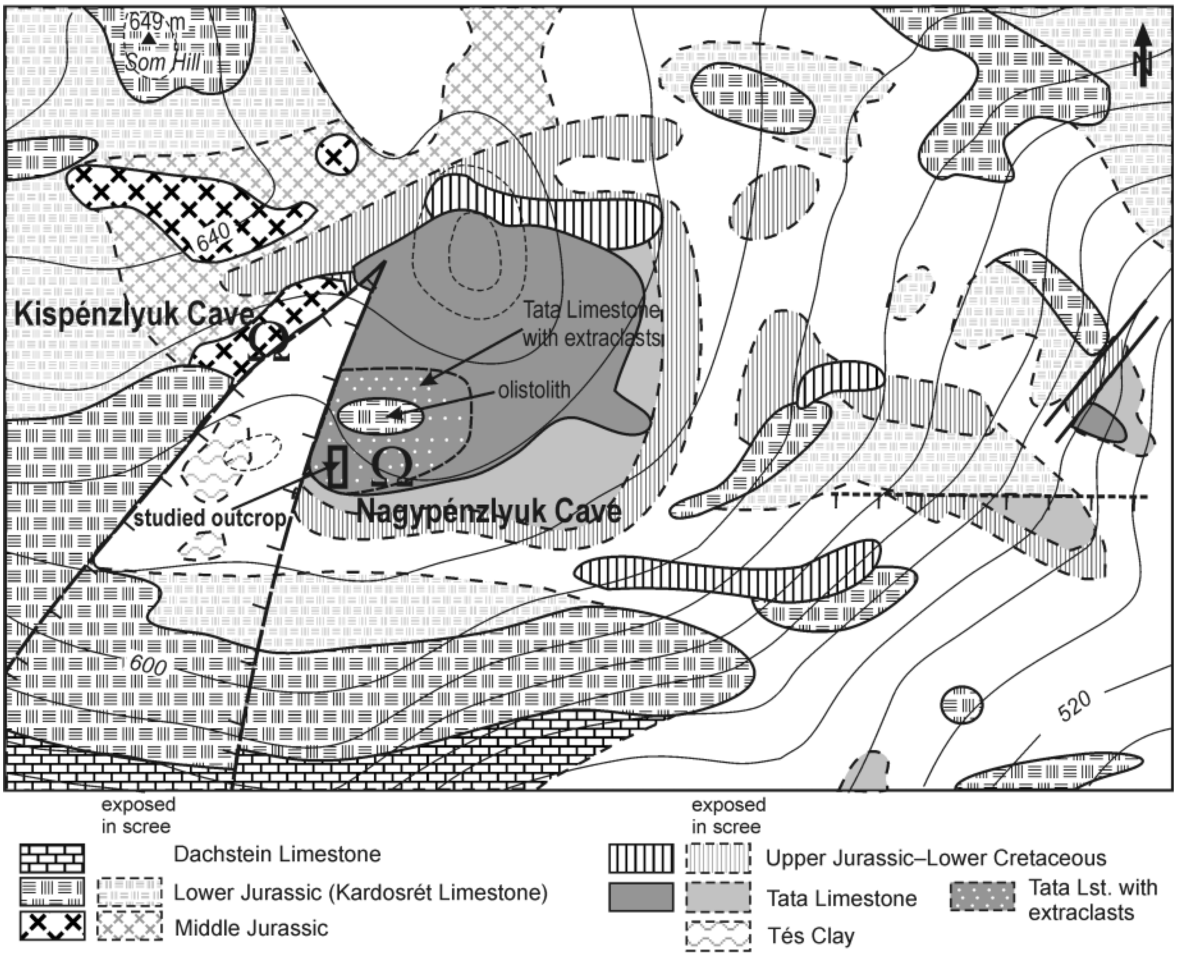

Fig. 9. Map of Som-hegy, after Császár (1982), modified.

grainstone is found. The sparitic cement suggests early diagenetic cementation and rapid sedimentation (Mindszenty, pers. comm.). This pinkish layer contains extraclasts without bio-erosional marks and with glauconite coatings on them. Their material is derived from the Lower Cretaceous Biancone and underlying Upper and Middle Jurassic ammonitico rosso type micritic limestones. The foraminiferal assemblage is characterized by both planktonic and benthic forms (Fig. 10).

In the basal beds the plankton-benthos content is 40–50 % versus 60–50 %. Higher up in the section (0.5 m from the basis) it raises to 60–70 % versus 40–30 %. On the basis of the plankton-benthos content, the depositional depth in the basal bed (van Marle et al. 1987) would correspond to 150–250 m. (The recent ratio and depth relation may not be directly applicable to Cretaceous assemblages.) Higher up the water depth should dramatically increase to a minimum of 200, but possibly 400 m. Such a dramatic increase is unlikely; therefore we suppose that the basal beds (like the others) were redeposited from a shallower area. In fact the sedimentology would correspond much more to a slope and deeper basin, than a shallower shelf environment. It is interesting to note that 300 m SE from this exposure, on the hillside, Tata Limestone overlies directly the Lower Jurassic massive, thick bedded formations. Therefore the source of the redeposited extraclasts may be in this southeastern region. The area is affected by younger strike slip tectonics (Sasvári 2003), therefore this conclusion should be taken with care.

The ***Borzavár exposure*** (Appendix) shows a Valanginian–Lower Barremian crinoidal limestone and the Tata Limestone, with no apparent unconformity. The lower crinoidal limestone is covered by a thin clay horizon and the cross-bedded, crinoidal Tata Limestone. The foresets of the cross-beds were measured in this latter and a dominant NE–SW transport was found. A secondary NW–SE transport was also recorded (Fig. 11). With the naked eye the medium-grained crinoid sand apparently contains no extraclasts. In thin sections the clasts are dominated by

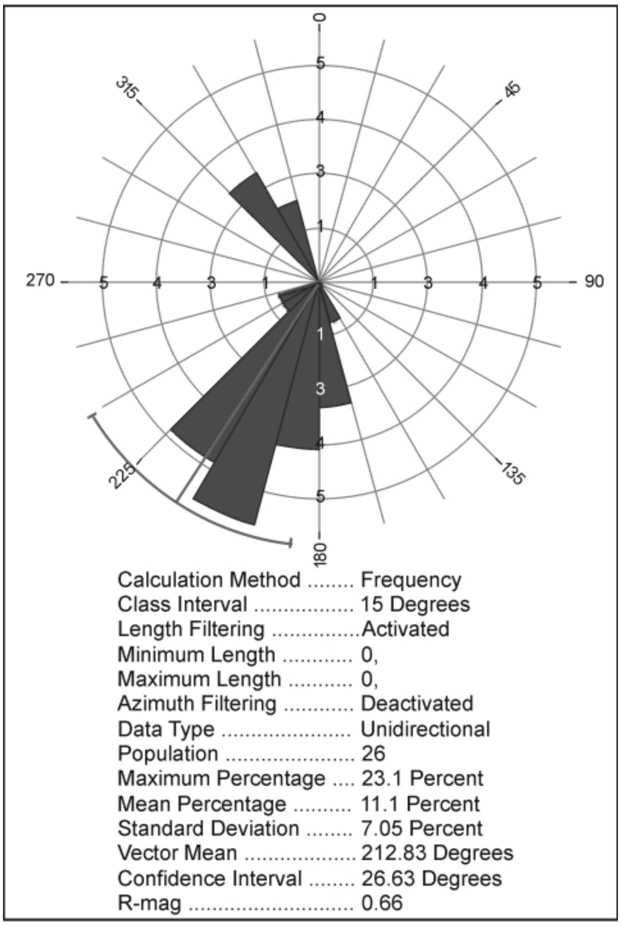

Fig. 11. Rose diagram of measured cross-bedding foreset lamellae. Dark signs indicate direction of sediment transport.

crinoid ossicles, which are reworked. The grainstone cement is syntaxial. Bryozoan and brachiopod fragments also occur. The foraminiferal assemblage is dominated by reworked, thick-shelled lenticulinas and by some agglutinated forms. No planktonic form was found. Sometimes sponge spicules are dissolved to form chert nodules. In thin sections a lot of sand grains proved to be extraclasts (30 %). Most of these are undeterminable micritic grains, but some are certainly derived from Lower Jurassic oncoidic limestone and Middle Jurassic pelagic Bositra limestone. The clasts were sorted and deposited parallel to the cross-bedding laminae. The above described sedimentological features speak in favour of a shallow, well agitated marine environment. The oxygenation of the environment was good (as indicated by the presence of *Lenticulina*), the sedimentary rate being relatively high. The extraclasts are probably rounded by wave activity.

The ***Vértessomló exposure*** is a small trench along a forest road (Appendix, Fig. 12). The Tata Limestone covers a Tithonian–Berriasian pinkish limestone. The basal bed contains a 60 cm thick coarse breccia with 6–8 cm clasts in pelitic-sandy matrix. The clasts are mostly composed of the uppermost Jurassic and lowermost Cretaceous carbonates. This bed is overlain by weakly cemented sandy-calcareous silt with calcareous nodules. Then a stronger cemented

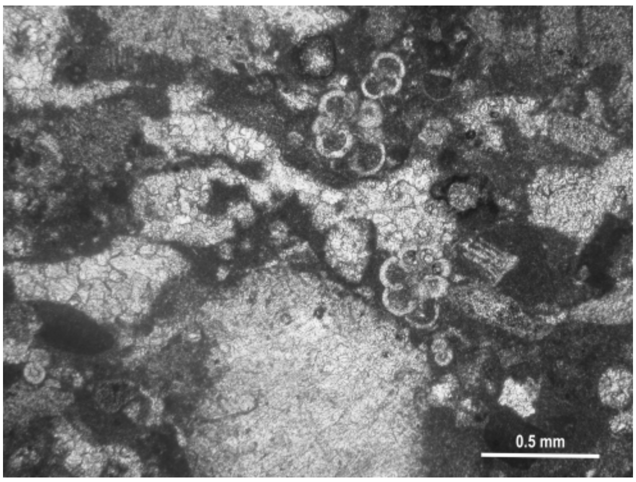

Fig. 10. Thin section with crinoid fragments and planktonic foraminifera, Som-hegy.

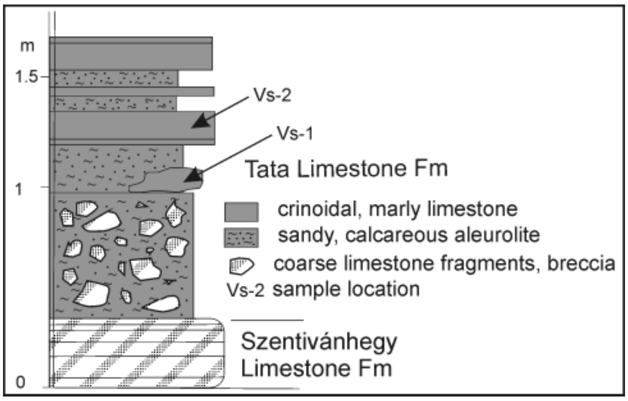

Fig. 12. Section of the Vértessomló road cut.

marly limestone comes with frequent crinoids. Higher the succession continues as an alternation of sandy siltstone and crinoidal limestone layers. In thin section, the poorly cemented nodular layer was biomicritic wackestone. The bioclasts are mostly echinoderm fragments, but foraminifers and mollusc shell fragments are also frequent. The foraminiferal fauna is dominated by *Lenticulina* (30–40 %), while the rest contained mono-, bi-, triserial forms. There were no planktonic elements observed. The mollusc shells are oriented parallel to layering and show a weak grading. Some of the clastic quartz grains show undulating extinction in crossed nicols. The sample immediately above this layer shows the presence of glauconite as individual grains or as infill in foraminifers (Fig. 13). The rock is a packstone with mainly echinoderms as clasts. Contrasting the former layer, this one has a very high (70 %) planktonic foraminiferal proportion. This content indicates several 100 m water depth. The apparent contradiction between shallow and deep water may be resolved by considering the signs of redeposition in the lower bed. The breccia elements may have been derived from shallow water environment, but were redeposited in deeper water basin facies. The rest of the formation is also a deep basin deposit.

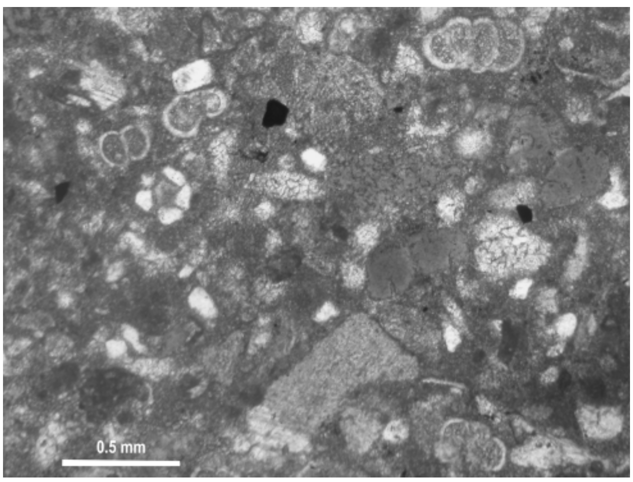

Fig. 13. Thin section with crinoid fragments and planktonic foraminifers. Dark grains are glauconite infills, Vértessomló.

Discussion

The map constructed for the basal horizon of the Tata Limestone (Appendix a,b,) was produced using available well data, taking into account Császár & Csereklei (1982). The nature of the basal beds is indicated as coloured squares (exposures) and circles (wells). The prominent breccia locations are marked as red circles, or quadrangles. Younger structural elements were simplified. Since the present day topography is not relevant for the mid-Cretaceous situation, it is not marked; only some key hills or settlements are indicated for orientation. The two maps show the two main exposure areas in the Bakony and Vértes Foreland.

Both maps show northwest–southeast trending (recent orientation) uplifted zones with significant differential erosion at the base of the Tata Limestone. There are indications of slight folding of the Tata Formation basement. These folds are best seen near Zirc and southeast of Tata. In both regions small wavelength folds can be constructed based on well and exposure data. These folds have a NW-SE axis, very similar to one of the fold sets observed in the Zirc region. The longer wavelength anticlines have a longer NE limb and a shorter SW one. This is especially well seen in the Hajag region and in the Vértes Mountain, which is interpreted as a major anticline.

It is remarkable that most breccia localities are found in more complete Upper Jurassic–Lower Cretaceous successions, while Tata Limestone without breccias may cut down deep into the Mesozoic succession. The deep marine breccia bodies appear to be localized along quick changes in the basement lithology, in other words along the limits of main pre-Tata structures. They are always on the lower, synclinal part and never on the anticlinal part.

A series of cross-sections along relevant exposures was constructed (Figs. 14, 15). These sections were levelled at two horizons: at the base of Tata and at the top of Tata. The first construction stems from the assumption that the pre-Tata erosion created a peneplain. This might not be a valid assumption, since in several key locations, hardgrounds were found at the base of Tata and deep water peneplanation is not possible. The second construction stems from the assumption that there was a pre-Tata paleotopography, which was subsequently filled up. We observe in fact a shallowing upwards tendency in all sections, although there is no direct sign for the total filling up of the basin. Strong facies differences suggest the existence of a paleo-topography. However, it is quite obvious, that the thickness of the Tata Formation could have been affected by later erosion, but the sedimentary gap between this formation and the overlying mid-Upper Albian marls is generally small. In eastern areas there is no gap between top Tata and overlying reefal limestones and interfingering shales. Therefore we consider the up-to-now

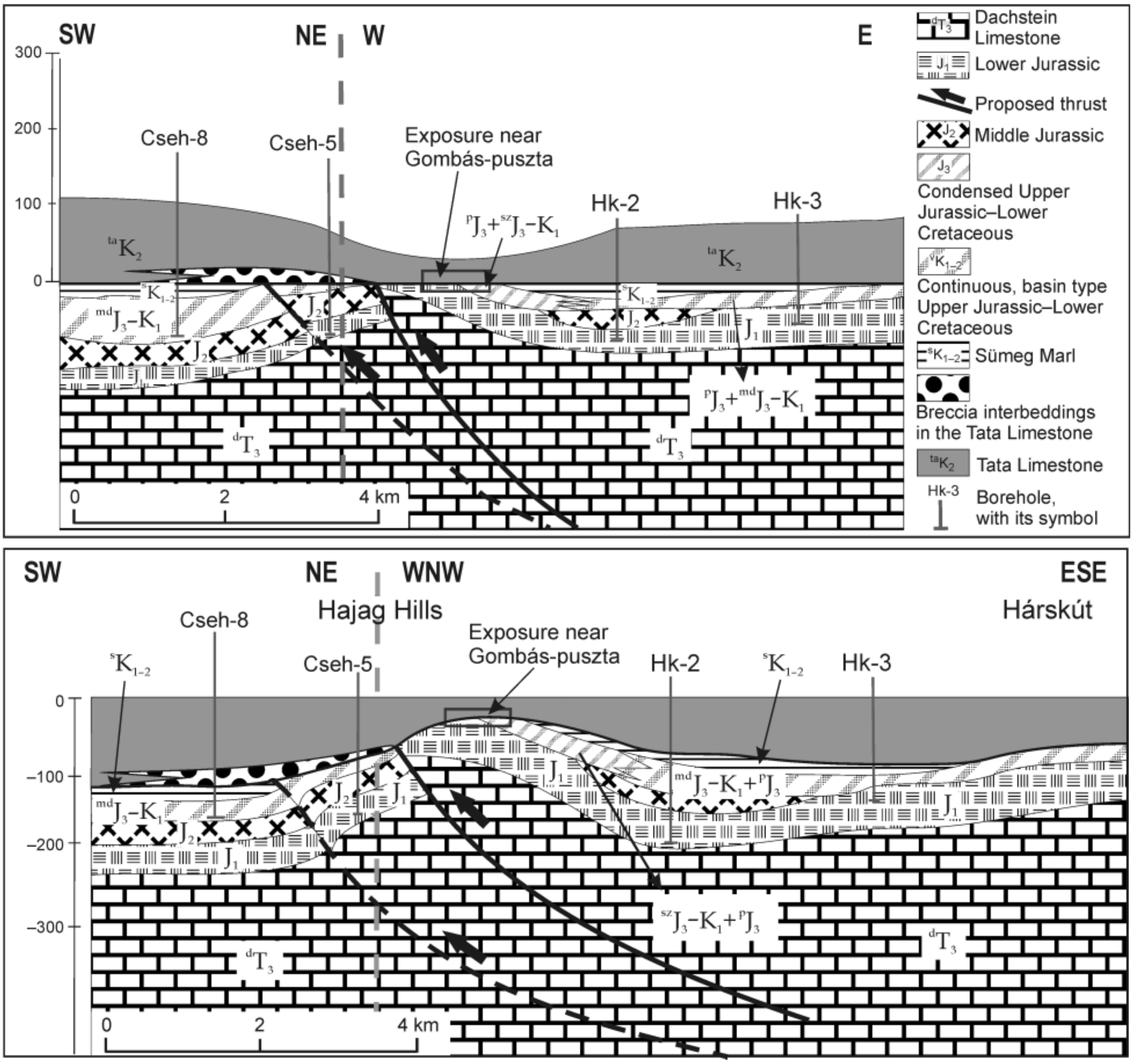

Fig. 14. Sections constructed across the Hajag area (Central Bakony Mts). **a** — levelled to the basal horizon of the Tata Limestone, **b** — levelled to the top of the Tata limestone. Location of section marked in Appendix.

preserved thicknesses of Tata Limestone to reflect in a way the original thicknesses.

On the maps (Appendix a,b,), as in both section types (Figs. 14, 15) the pre-Tata rock units form a folded structure beneath the unconformity. The sections levelled to the base horizon of the Tata Limestone do not explain, however, the occurrence of breccia bodies and the observed facies and thickness changes. In the sections levelled for the top of Tata Formation, the folded structures remain the same beneath the unconformity, though they are a bit accentuated. In these sections the anticlines become (paleo-) topographic highs, while the synclines become lows.

The Tata Limestone is generally thinner, where it overlies older Jurassic and Triassic formations above anticlines. Facies are shallow water type with frequent cross-bedding. Extraclasts are present only as very small, rounded fragments. In the Vértes area the thin Tata Formation passes into a reef limestone above the highs. Sediment transport direction measured at shallow water facies cross-bedded carbonate sands near Borzavár indicates a transport from NE to SW, from a background without Tata but with exposed Triassic.

The thicker sequences cover an Upper Jurassic–Lower Cretaceous succession with less or no hiatus in the cores of synclines. These areas with less erosion are interpreted as of deeper basinal facies, filled with thicker crinoidal limestone and marl. At the margins of these basins there are often coarse-grained, graded breccia interbeds in a more clayey matrix (e.g. Cseh-1 borehole). According to detailed sedimentological studies, the breccias are all submarine, slope sediments. These breccia bodies originated

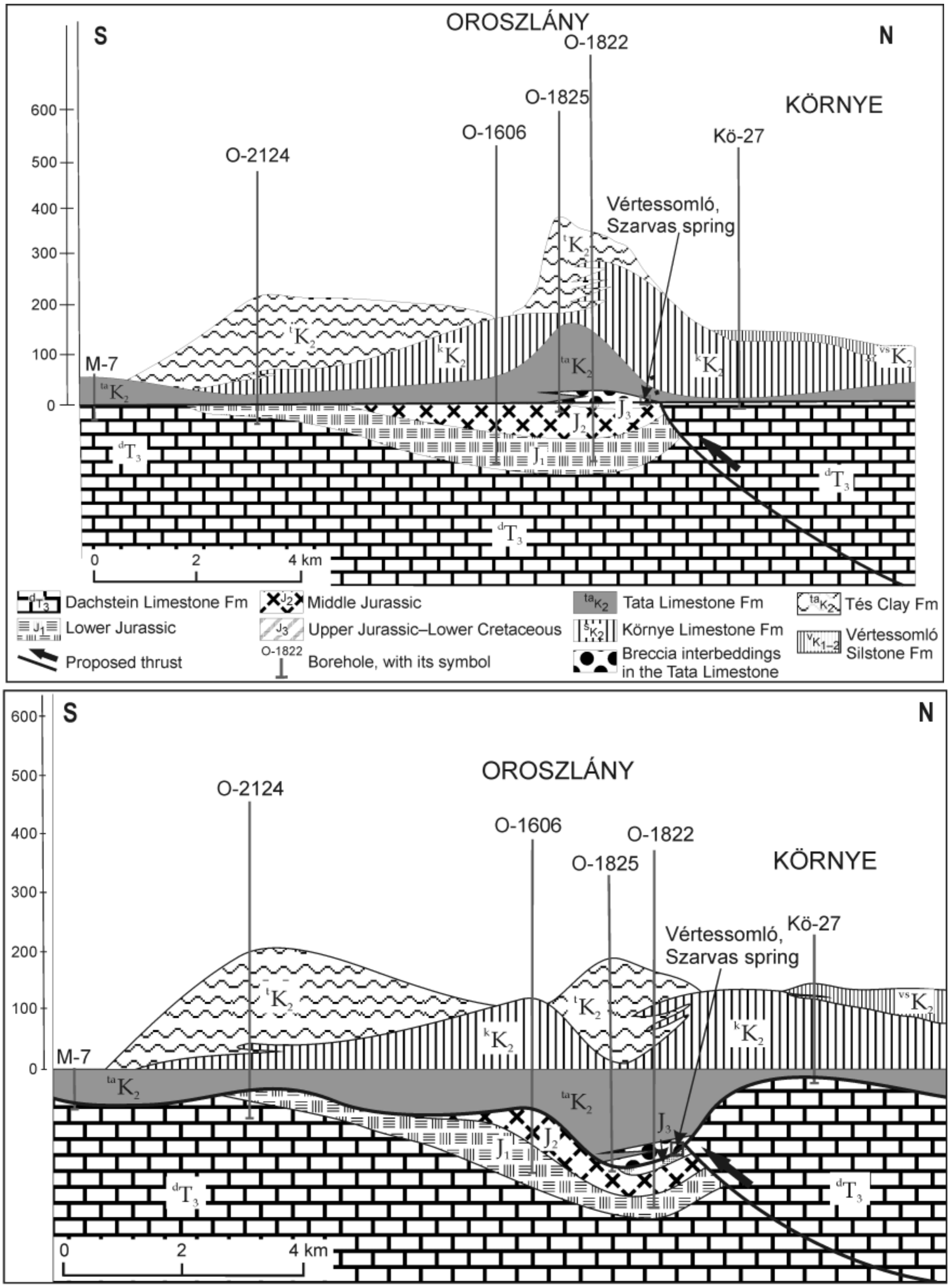

Fig. 15. Sections constructed across the Vértes area. **a** — levelled to the basal horizon of the Tata Limestone, **b** — levelled to the top of the Tata Limestone. Location of section marked in Appendix.

from the adjacent uplifted zones and are interpreted as scarp breccias. Their composition roughly reflects an inverted stratigraphy, as is expected of a gradually emerging source. At the centre of these deep areas a pelitic, psammitic basin-type facies of the Tata Limestone was recognized. In the eastern Vértes area the Tata Limestone passes laterally towards the basinal Vértessomló Siltstone (see also Mindszenty et al. 2001; Császár 2002).

In our view the assumption of a syn-sedimentary topography during the deposition of the Tata Formation ex-

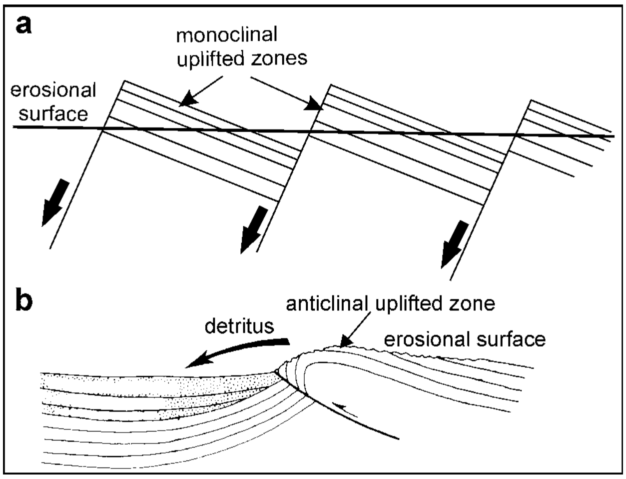

Fig. 16. Normal fault and thrust fault solutions to explain the syn-depositional topography and facies variations. **a** — SW dipping and rotated normal fault blocks, **b** — NE dipping thrust faults and ramp anticlines.

plains the observations on the facies, paleo-transport and breccia occurrence. This in turn supposes a driving force to create such a syn-sedimentary topography. The localized deep water/slope breccias suggest that there were sudden breaks, or steeper slopes in topography. Two hypotheses can be put forward to explain the topographic differences. The first suggests NW–SE trending, SW-dipping normal faults, the second suggests NW–SE trending, mainly NE-dipping thrust faults (Fig. 16). The presence of folds of NW–SE axial trend strongly supports the second possibility. In fact the thrust faults in question could have created ramp antiformal and foreland-hinterland-synformal structures; the thrust load could have contributed to basin formation. Asymmetric erosion and facies differences could be explained by tilted normal fault blocks, but then the folds remain unexplained. The frontal parts of the tilted blocks, where younger formations are again preserved, are not impossible, but hard to explain by normal fault mechanism.

Borehole and outcrop data are spaced enough to enable construction of a variety of thrust fault directions. Logically, these constructed thrusts should be parallel to one of the potential deformation directions: either NW–SE or NE–SW, as also seen on the maps of the Appendix. It is suggested that the thrust faults active before/during Aptian were striking NW–SE and not in a perpendicular direction. Besides fold data (see below, Appendix), there is an additional argument in the Hajag region which merits attention. The northeastern limb of the Hajag anticline is occupied by the Sümeg Marl, the youngest formation before the Tata Formation. However, the visible NW-SE strike of the proven extent of this Sümeg Marl exposure is interrupted by a NE–SW tilted structure. There, Aptian is also eroded away, so this must be a post-Aptian structure. The NW–SE trend of the Sümeg Marl occurrences would be much better explained by a NW-SE striking thrust fault, than by a perpendicular (here post-Aptian) structure.

Detailed tectonic studies in the neighbouring units of the Transdanubian Range show that in the Barremian–Early Albian time interval possibly two almost orthogonal folding events (Albert 2000) occurred. One of the folding phases had a NW-SE to NNW-SSE axial direction and the other had NE–SW axial direction. Both seem to be covered by the Middle–Late Albian unconformity and shallow water marls. The second event was possibly coupled with strike slip motions (Mészáros 1983; Kiss et al. 2001) and thrusts (Sasvári 2003). It produced long wavelength folds dominating the structure of the Transdanubian Range. The first event produced much smaller folds and coeval thrusts (Albert 2000).

The Transdanubian Range is traditionally linked to the Eastern and to the Southern Alps (Upper Austroalpine nappes). Strong genetic links exist towards the Dinaric platform as well. Except the Southern Alps, all of these regions are characterized by widespread shear and nappe formation, compressional movements in the pre-Middle Albian period. WNW–ESE trending shortening was proven in the Graz Paleozoic, in the Gurktal Paleozoic, the Greywacke-zone of the Eastern Alps (e.g. Ratschbacher 1986; Neubauer 1987). The Dinaric margin underwent NE-vergent shear followed by SW-vergent shear and folding prior to Albian (Csontos et al. 2004). In both places 120 to 100 Myr metamorphism indicates an Early Cretaceous nappe stacking episode (Milovanović 1984; Kralik et al. 1987; Fritz 1988; Belák et al. 1995). The different shear directions all parallelize after the subsequent, paleomagnetically indicated rotations are taken into account (Márton & Fodor 1995; Márton et al. 1999, 2002; Csontos et al. 2004). In other words, the whole broader region is characterized by compression during the Early Cretaceous, therefore the presence of normal faults or extensional systems seems unlikely.

Conclusions

The facies pattern, thickness changes, differential erosion and the scarp breccias suggest a syn-depositional compressional activity through the whole Tata Limestone depositional area. The anticline-like morphology of the uplifted zones suggests that the uplifted units were created by thrusting, in a compressional regime (Appendix c). The differences in the thickness of the crinoidal limestone and the breccia interbeds show that these movements were synsedimentary. In the borehole Cseh-1 the coarse limestone fragments appear already in the Sümeg Marl Formation and they are present in the whole drilled Tata Limestone sequence. Thus, the tectonic movements must have started in the Barremian–Early Aptian and continued through the Aptian, or Early Albian. The Early Albian facies transitions in the eastern Vértes Mountains also suggest that the same facies pattern and depositional logic is still preserved. Therefore we propose a longer, Barremian-Early Albian compressional activity, dominated by NE-SW shortening. Eventually, at the end of the Early Albian, another shortening at a high angle may have occurred. The maximum of these shortenings could be located in the Dinarides. In the Late Jurassic–Early Cretaceous widespread ophiolite obduction occurred there. An obducted ophiolite nappe reached the northern premises of the Transdanubian Range by the Early Cretaceous (Császár & Bagoly-Árgyelán 1994; Tari 1994, 1995; Mindszenty et al. 2001). The advancing nappe could have created the stress field necessary to initiate a foreland-ward propagating thrust system. From our data it seems that this system is as early as Barremian (if not earlier) in the Transdanubian Range. Thrusting might have occurred in distinct episodes, but the age resolution in the given period is too low to give the exact time periods of thrusting.

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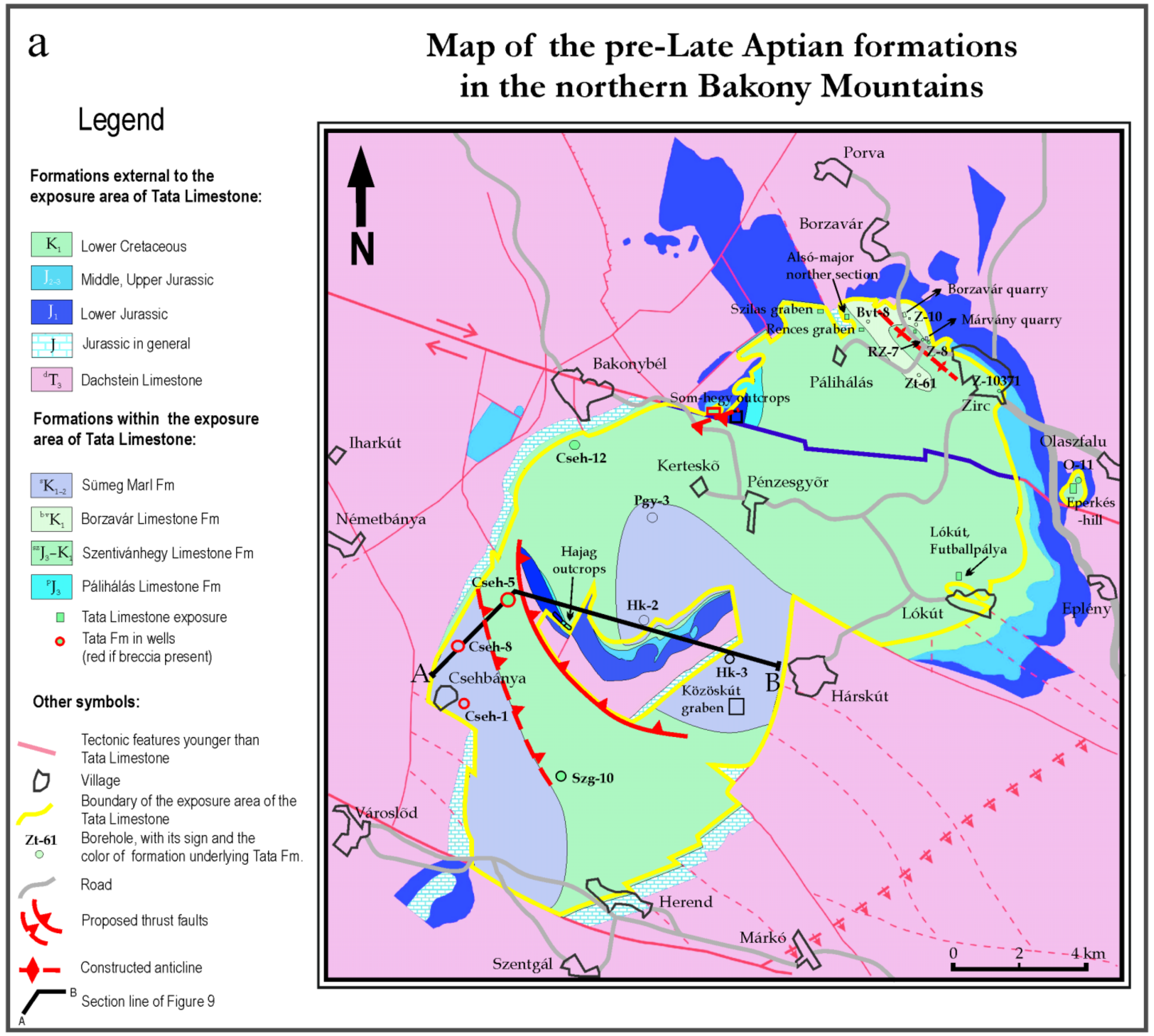

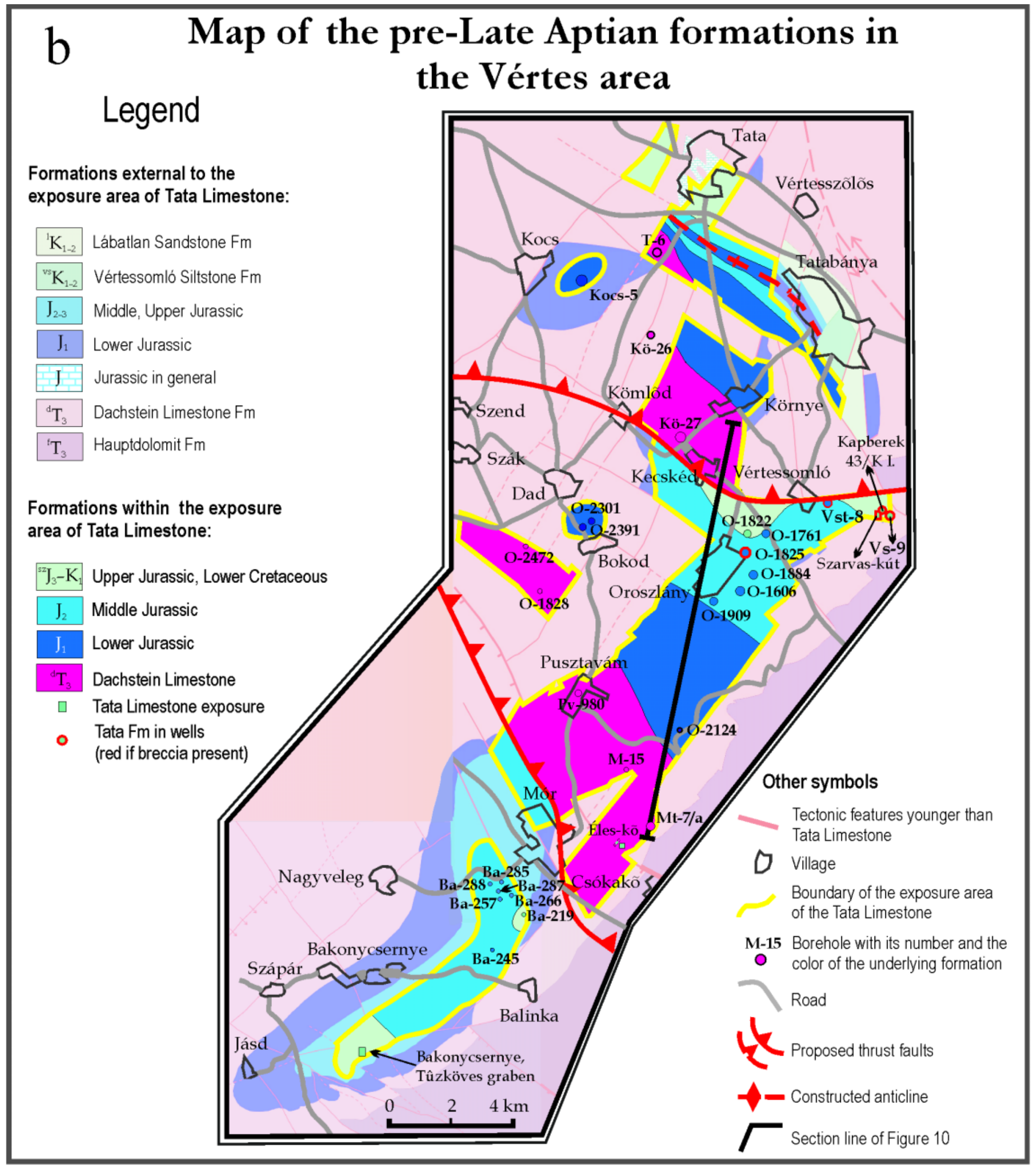

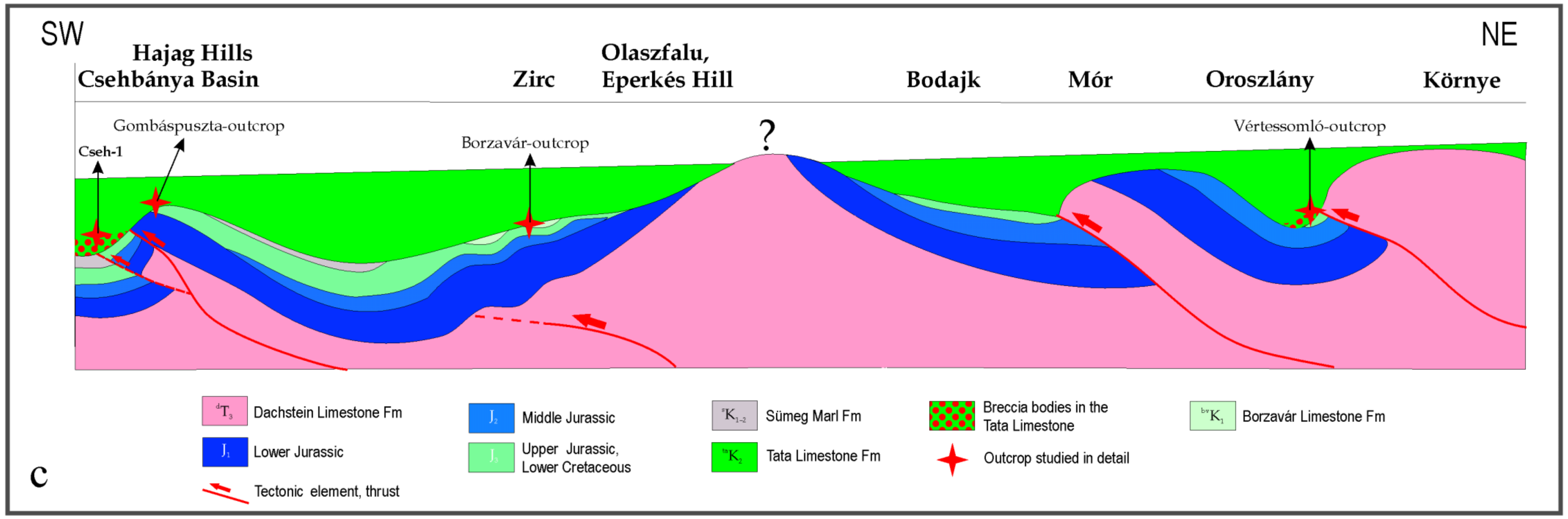

Appendix

Maps of the pre-Tata limestone formations in the two development areas (after Császár & Csereklei 1982). **a** — Bakony Mts; **b** — Vértes Foreland; **c** — NE-SW conceptual section along the Transdanubian Range.

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