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DUCTILE DEFORMATION AND REVISED LITHOSTRATIGRAPHY OF THE MARTONYI SUBUNIT (TORNA UNIT, RUDABÁNYA MTS.), NORTHEASTERN HUNGARY

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Abstract: New structural observations and mapping resulted in the reinterpretation of the Martonyi Subunit, part of the metamorphic Torna Unit, NE Hungary. This low-grade metamorphosed Triassic sequence contains lower Anisian Gutenstein Dolomite, a thin transitional pelagic sequence (Bódvarákó Formation?), Carnian Tornaszentandrás Slate, late Carnian-Norian Pötschen Limestone. This stratigraphy is closer to the Bódvarákó windows than to any other Torna subunits. The original sedimentation area could be located on thinned continental crust, relatively close to the oceanic crust of the Meliata branch of the Neotethys. The whole sequence suffered three phases of ductile deformation during Alpine (Cretaceous?) tectogenesis. First, layer-parallel foliation developed (D_1), most probably connected to first order nappe stacking. The second deformation phase (D_2) is marked by upright, chevron-type folding (D_{2a}). Detachment faults could form at the top of the Gutenstein Dolomite in order to accommodate space problems at fold hinges. The chevron folds were flattened later, during a progressive D_{2b} phase associated with the development of axial plane cleavage and steep reverse faults. The structural style varies depending on locations within folds and on lithology suggesting strain partitioning during the D_{2b} phase. Small kink folds with oblique axes can be related to reactivation of steep faults with oblique slip during the D_3 phase, at the transition of brittle-ductile deformation field. The whole unit was thrust upon non-metamorphic unit(s) (D_4 brittle phase) due to strike-slip displacement along the Darnó Zone sensu lato during the late Cretaceous and/or Tertiary.

Key words: Mesozoic, Inner Western Carpathians, NE Hungary, Torna Unit, ductile deformation, folds, foliation, strain partitioning.

Introduction

A metamorphic Triassic succession in the Rudabánya Mts. between Tornaszentandrás and Martonyi villages (Fig. 1) belongs to the Torna Unit sensu Less (1981, 2000) and Grill et al. (1984). Following this original definition, the metamorphic Torna sequence generally contains Anisian platform (ramp) carbonates (Gutenstein Dolomite, Steinalm Limestone), Upper Anisian-Ladinian basinal limestone (Szentjánoshegy Fm.), Carnian slate (Tornaszentandrás Fm.), upper Carnian-Norian cherty Pötschen Limestone (Fig. 2). These rocks suffered anchi to epizonal metamorphism indicated by metamorphic petrological data (Árkai & Kovács 1986).

The metamorphic sequence between Tornaszentandrás and Martonyi villages shows some peculiarities. Steinalm Limestone is definitely missing, and only the slate-cherty limestone couplet was considered to belong to the Torna Unit (Less et al. 1988; Grill 1989; Less 1998). Anisian Gutenstein Dolomite is closely associated in map view with metamorphic rocks. Mapping and boreholes demonstrated that the metamorphic cherty limestone-slate couplet is situated above the Gutenstein Dolomite. However, the above mentioned authors did not observe metamorphic foliation, internal ductile deformation of the dolomite, therefore they considered this rock to be non-metamorphic. They assigned the dolomite to the adjacent, non-metamorphic Bódva Unit which geographically surrounds the metamorphic Martonyi sequence (Figs. 2, 3). This opinion also suggests that the slate and cherty limestone would form a higher nappe unit. Because this upper “Martonyi nappe” is clearly metamorphic, this juxtaposition would only be possible after the metamorphism. Less et al. (1988) and Less (1998, 2000) suggested Miocene emplacement of this “neoallochthonous” metamorphic nappe. This thrusting would be connected to the left-lateral displacement of the Darnó Zone which bounds the whole area on both sides (Fig. 1).

In our paper we present a new structural map of the Martonyi Subunit derived from new mesoscale structural observations. They show that the Gutenstein Dolomite is the normal stratigraphic base of the slate-limestone couplet and underwent the same epizonal metamorphism and three phases of ductile deformation.

Geological settings

Lithostratigraphy

The Martonyi sequence is situated in the northeastern part of the Rudabánya Mts., in northeastern Hungary and forms a subunit of the metamorphic Torna Unit (Fig. 1). It consists of metamorphic Triassic rocks surrounded by non-metamorphic,

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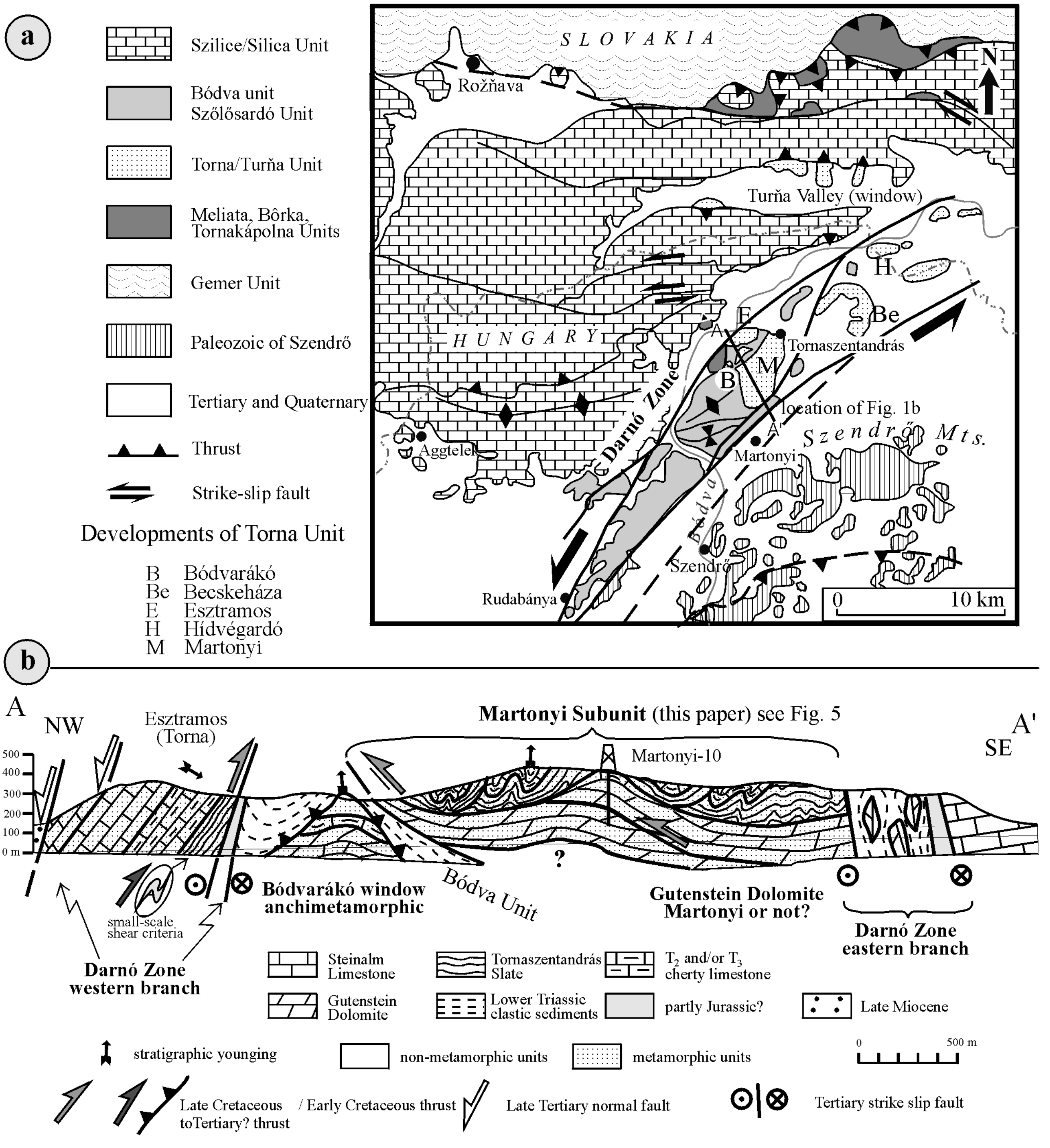

Fig. 1. Situation of the Martonyi Subunit in northeastern Hungary ***(a)*** and cross section ***(b)*** through the northern Rudabánya Mts., showing the main tectonic units (after Less et al. 1998; Mello 1997).

Permian-Jurassic rocks of the Bódva Unit and by Late Miocene (Pannonian sensu lato) sediments (Fig. 3).

Less et al. (1988), Less (1998) attributed two main lithological members to the metamorphic Triassic suite of the Martonyi Subunit (Fig. 2). The Tornaszentandrás Formation contains brownish grey or black slate with well-developed foliation. This fine-grained, siliciclastic sediment contains a few limestone intercalations which prove a lower to middle Carnian age (Kovács et al. 1989). To the south, this slate becomes more sandy-silty and/or marly, but the transition toward the Rednekvölgy Beds (member of the Tornaszentandrás Fm.) seems to be continuous.

The upper Carnian-lower Norian Pötschen Formation is built up by cherty limestone and marlstone. The transition from the underlying slate is gradual, represented by a frequent alternation of slate, limestone beds and/or marlstone. The age

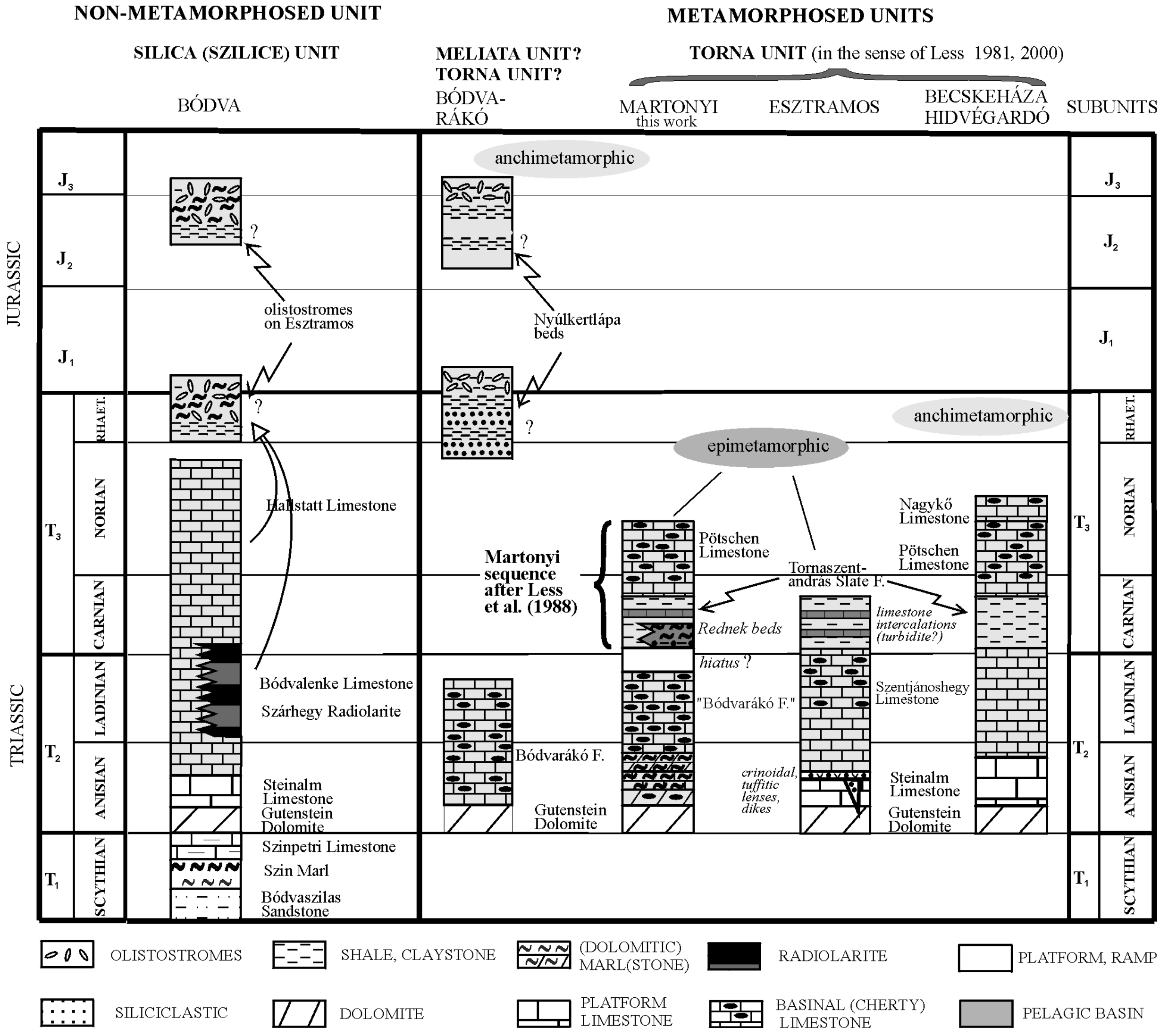

Fig. 2. Stratigraphic columns of the investigated area (NE Rudabánya Mts.), after Less (2000), Less et al. (1998) and Kovács et al. (1989) and our own observation for the Martonyi Subunit.

of this formation is defined by conodonts. Several locations yielded upper Carnian-lower Norian fauna (Kovács 1986; Kovács et al. 1989).

Anisian Gutenstein Dolomite is a dark grey, massive or thick-bedded dolomite rarely containing algal mats. We will try to demonstrate that — in contrast to Less et al. (1988) and Grill (1989) — the Gutenstein Dolomite forms the normal stratigraphic part of the metamorphic sequence.

The transition between the Gutenstein Dolomite and the overlying Tornaszentandrás Slate is generally badly exposed, but locally (often in scree) we have found specific rocks. These are dark grey (calcareous) dolomite with black chert nodules, brown dolomitic limestone, dark grey cherty limestone. In the Martonyi M-10 borehole, and on the surface in its surroundings, platy marlstone, dolomitic marlstone with extraclasts (olistoliths?) can be also observed. The thickness of this transitional formation is 20 m in the M-10 borehole and is underlain by the Gutenstein Dolomite. Several samples yielded middle Anisian (Pelsonian) conodonts (Kovács, pers. commun.). This age and the similar lithology permit a correlation with the middle Anisian-Ladinian black cherty limestone of the Bódvarákó Formation cropping out in the Bódvarákó tectonic window (Figs. 1–3; Kovács et al. 1989). In the following description we will use the term “transitional beds” or “Bódvarákó Formation” indicating the uncertain identity of these suites.

Boundaries of the Martonyi Subunit

The study area is connected to the Darnó Zone, a broad, major Cretaceous? to Miocene shear zone which separates the Rudabánya Mts. from the Aggtelek Mts. to the west and from the Szendrő Paleozoic to the southeast (Fig. 1). Sinistral strike-slip character of the zone was demonstrated by Zelenka et al. (1983) using regional data and by Szentpétery (1997) by the distribution of Oligocene-Lower Miocene formations. In our paper we adopted the definition that the zone includes the whole Rudabánya Mts. (for a review of the zone see Zelenka et al. 1983; Less 2000).

The Martonyi Subunit is situated within the Darnó Zone sensu lato. Its boundaries are always interpreted as tectonic (Less et al. 1988). At its northeastern part, a NNE trending fault is supposed to represent the boundary of the metamorphic rocks toward Pannonian sediments (Less et al. 1988) (Fig. 3). The fault certainly existed before the Pannonian, but its activity during or after the Pannonian is not clear; the contact may be stratigraphical (Pelikán P., pers. commun.). The (pre-Pannonian) fault may be a branch of the Darnó shear zone. At the southeastern side of the Martonyi Subunit, the eastern boundary fault juxtaposes non-metamorphic Mesozoic rocks against the metamorphic Torna sequence; several branches of the Darnó Zone cut through this eastern stripe of the non-metamorphic sequence (Balogh & Pantó 1952; Grill 1989).

At its southern tip the metamorphic Martonyi Subunit is interpreted to thrust over the non-metamorphic Bódva Unit (Less et al. 1988). The western boundary of the Martonyi Subunit is represented by a N-S trending fault. Its subvertical dip is supported by straight map view. Along the northwestern boundary of the Martonyi Subunit, a Middle to Upper Triassic metamorphic sequence is bounded by a steep fault, followed by a narrow stripe of Lower Triassic rocks supposedly also including the Permian evaporitic melange of the Bódva Unit (Fig. 3). This fault may also be a branch of the Darnó Zone and represent the thrust contact of the "neoallochthonous Martonyi nappe" sensu Grill (1989) and Less et al. (1988).

Other metamorphic sequences in the surroundings

Further west from the stripe of the Bódva Unit, the anchimetamorphic Bódvarákó sequence occurs in two tectonic windows (Figs. 2, 3) (the Bódvarákó window sensu stricto and the Kőrös-völgy window). The windows contain Gutenstein Dolomite and black, cherty limestone (Bódvarákó Formation). Its age is middle Anisian-upper Ladinian (Kovács et al. 1989). This deep water limestone is overlain by the Nyúltkertlápa Beds, greenish grey slate, siltstone, occasionally with limestone olistoliths. Although no stratigraphic age is known, these beds are considered to be Upper Triassic (?)-Jurassic (?) (Kovács et al. 1989). Pelikán (pers. commun.) considers this rock to be the equivalent of the Lower Triassic of the Bódva Unit, thus the metamorphic suite would end with the Bódvarákó Formation. The rocks suffered anchizonal metamorphism (Árkai 1982). On the other hand, Kovács (pers. commun.) considers this olistostromal formation to be the equivalent of the Telekesoldal olistostromes of Late Jurassic age.

The Bódvarákó windows and the surrounding (overlying) Lower Triassic is bound by a narrow stripe of red marl and claystone containing non-metamorphic Triassic olistoliths of Ladinian–Norian age (Figs. 2, 3; Kovács 1986). On the basis of pelagic olistoliths, this uppermost Triassic-Jurassic (?) sediment is assigned to the Bódva Unit.

Further to the west, the metamorphic sequence of the Esztramos Hill built up by Anisian platform dolomites and limestones (Gutenstein and Steinalm Formations), with tuffitic (metarhyolite) intercalations (Turtegin 1997), crinoidal dykes at the top, Middle Anisian to Ladinian basinal carbonates and Carnian slate with limestone intercalations (turbidites?) (Figs. 2, 3). This classical Torna sequence forms an overturned limb of a large anticline with SE vergency (Fig. 1b; Kovács 1986; Less et al. 1998).

The steep NW boundary of the Esztramos Hill, the narrow stripe of upper Triassic-Jurassic(?) marlstone may represent strike-slip faults, namely the western branch of the Darnó Zone (Less et al. 1998). Although the Bódvarákó windows have locally steep strike-slip or normal fault boundaries, at other sites they are overlain by relatively flat lying thrust faults carrying the Bódva Unit.

Metamorphic sequences near Becskeháza and Hidvégardó-Nagykő (Figs. 1, 2) show stratigraphy similar to the Esztramos Hill (Kovács 1986). At the latter locality, Norian Nagykő limestone represents the youngest Torna sediment (Fig. 2). This Hidvégardó-Nagykő sequence is structurally above the Hidvégardó series (Grill et al. 1984), which has suffered only slight anchimetamorphic or only deep diagenetic transformation and does not belong to the Torna Unit. Supposed equivalents of all these metamorphic Torna sequences in Slovakia are described by Mello (1979) and belong to the "Turnaic nappe" sensu Mello (1997).

Methods

Structural observations and measurements were carried out in the majority of outcrops in the Martonyi Subunit. Measurements included bedding, several generations of foliation and fold hinges. Fold axes were constructed from bedding or foliation data using the Sswin software. Representative cross sections were constructed from outcrop-scale observations and mapping along sections.

We also carried out a detailed, but not complete mapping of the area. The main goals were to check formation boundaries and existing dip values, to control the bedding-foliation relationship. We also investigated the upper boundary of Gutenstein Dolomite because it has crucial importance in the evaluation of stratigraphic and tectonic problems.

Structural observations

Deformation features

The D_1 phase: S_{0-1} foliation (cleavage)

The observed deformation characteristics are grouped into several deformation phases that will be described below. The separation of these phases was essentially based on classical overprinting criteria (e.g. folded foliation, etc.). In some places this method could be applied very effectively (like at the Tornaszentandrás section), in other localities bad outcrop conditions generally allow us only to identify a certain part of the deformation history.

Carnian slate and the Pötschen Limestone also show a well-developed, smooth, closely spaced foliation which is

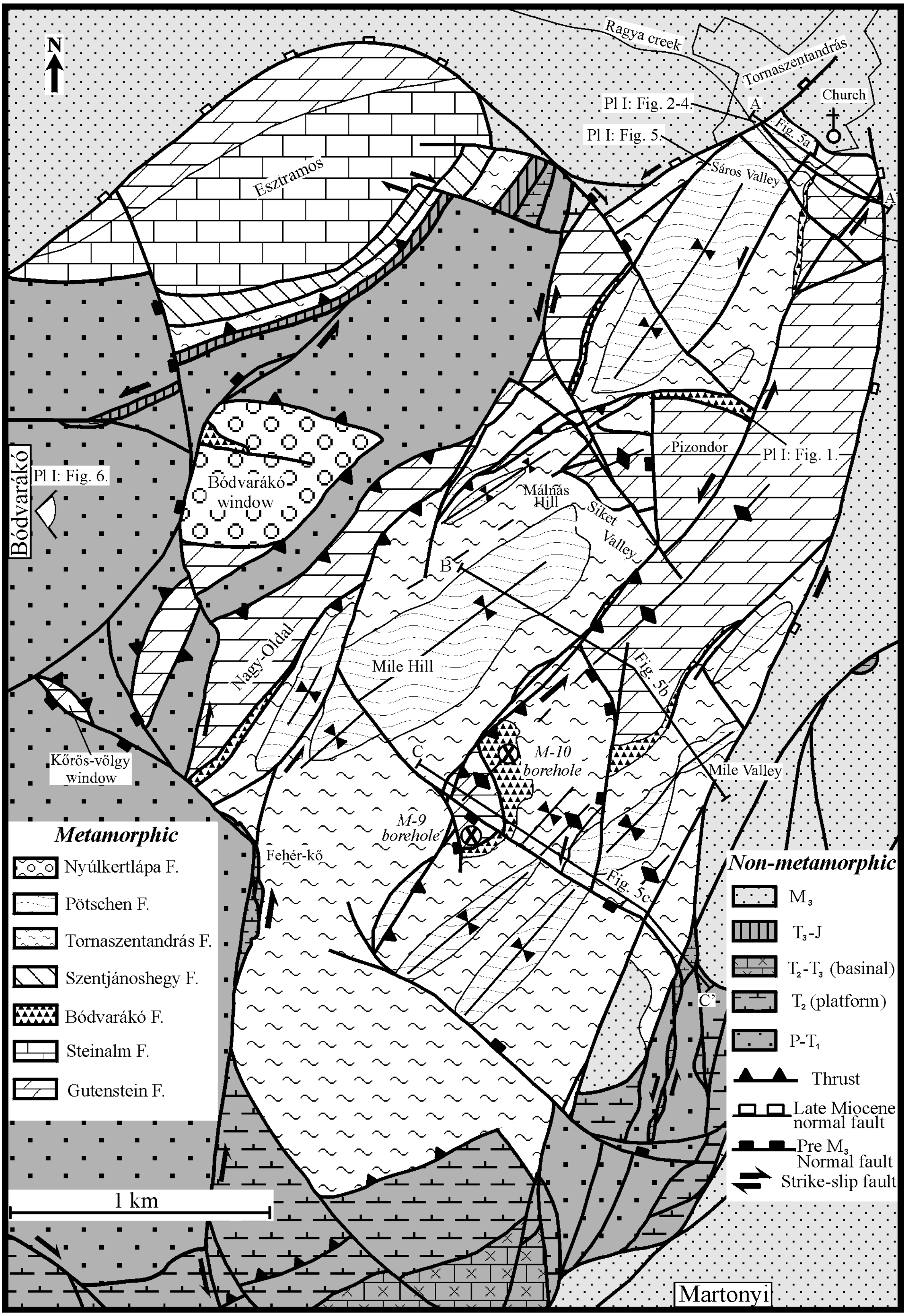

Fig. 3. Geological map of the Martonyi Subunit and its surroundings. Compilation from Less et al. (1988) and own data.

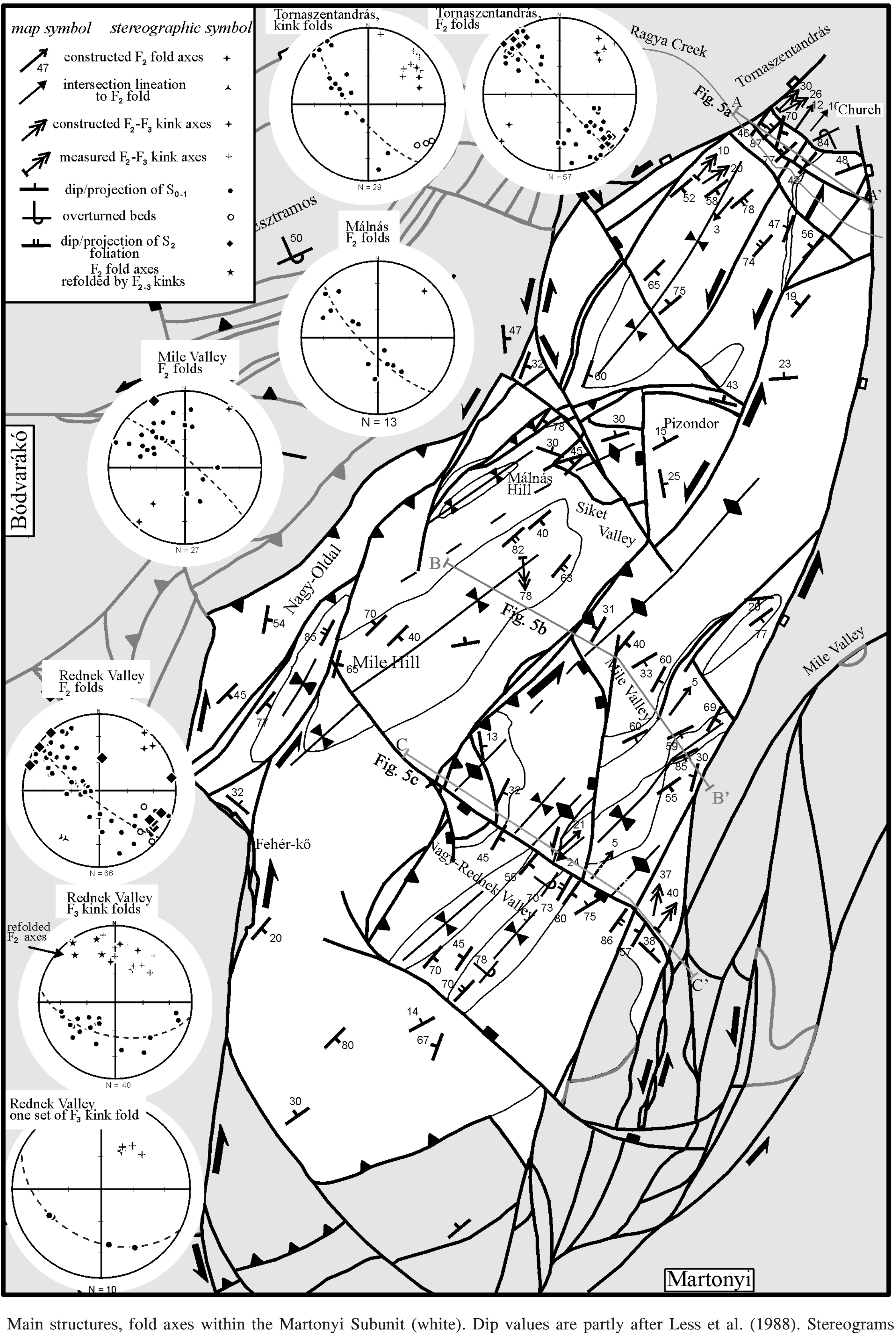

Fig. 4. Main structures, fold axes within the Martonyi Subunit (white). Dip values are partly after Less et al. (1988). Stereograms use lower hemisphere projection, Schmidt-net. Faults, formation boundaries as on Fig. 3.

parallel to bedding (S_{0-1}). The bedding-parallel nature of foliation can be demonstrated by thick chert layers and sandy limestone intercalations. In the Carnian slate this first S_{0-1} foliation is the dominant outcrop-scale structure and can be termed as slaty cleavage. In the cherty limestone, S_{0-1} dominates in the Rednek and Mile Valley section, but can hardly be observed/demonstrated in the central part of the Tornaszentandrás section (Fig. 3). The thick-bedded Gutenstein Dolomite does not seem to show observable S_{0-1} foliation. However, in the upper, cherty or calcareous dolomite beds and in the "transitional beds" widely spaced, bedding-parallel foliation occurs that can be regarded as weakly developed S_{0-1} cleavage (Pl. I: Fig. 1).

This cleavage is associated with strong flattening of the rocks which was formed with a subhorizontal position of the beds. No macroscopic or microscopic folding was observed to be associated with S_{0-1} foliation. In the Martonyi Subunit, S_{0-1} foliation represents the only structural feature of the D_1 deformation phase.

The D_2 phase: Outcrop-scale F_2 folds

Meter-size, close to almost isoclinal, upright folds (F_2) occur in outcrops of Pötschen Limestone and occasionally in slate (Pl. I: Figs. 2, 3). The axial plane is subvertical, and is parallel to the S_2 axial plane foliation. The axial plane, limbs and fold axes are trending NE-SW (Figs. 3, 4). The fold axes are generally subhorizontal attaining 10° plunge both to NE and SW. The geometry of these folds is of chevron type (Ramsay 1967, 1974). Limbs of folds are planar, while the hinge zone is narrow, sharp or subangular (classification of Twiss & Moore 1992). The hinge zone is thickened and the limbs are strongly boudinaged, particularly in chert beds. Chert layers often form decimetre-scale, third-order drag folds on limbs of larger folds (Pl. I: Fig. 3). Thinning of fold limbs can result in segmented fold hinge zones (rootless folds) in chert (Pl. I: Fig. 4).

The D_2 phase: S_2 axial surface foliation

The axial plane of chevron folds is parallel to closely spaced foliation S_2. These S_2 planes are always subvertical (dip > 80°), while the dip of bedding is about 40–80° (Pl. I: Figs. 2, 3, 4). The centimetre-scale, zig-zag-like appearance of the bedding planes is the consequence of the intersection of the well-developed S_2 foliation and bedding (S_{0-1}) (Pl. I: Fig. 2). Foliation is often refracted in the more competent chert layers. In the most deformed rocks, bedding cannot be determined, but was completely transposed parallel to the S_2 axial surface foliation. A prominent example of gradual transposition can be observed at the Tornaszentandrás section, where S_{0-1} can be seen on limbs of F_2 folds while only S_2 occurs in the most strongly deformed core (Pl. I: Figs. 2–4). This transposition, although not general, makes it difficult to separate the bedding parallel first foliation (S_{0-1}) and the axial plane foliation of F_2 folds (S_2) in many outcrops, from Tornaszentandrás up to the Mile Hill.

The F_2 folds together with the S_2 axial plane surfaces belong to the second (D_2) deformation phase. As described in the following chapter, structures of the D_2 phase dominate the map view of the study area. Generally, chert was deformed in a relatively more brittle way (e.g. boudinage), while limestones show absolutely ductile rheology during deformation. The ductile nature of the F_2 folds together with the S_2 foliation argue for anchi to epizonal metamorphic conditions.

The D_2 –D_3 phase: Kink folds (F_2–F_3)

The S_{0-1} foliation planes were frequently folded by small folds with kink geometry. Such folds occur mainly in the Tornaszentandrás Slate or locally in marly Pötschen Limestone beds. The hinge zone is sharp to subangular, limbs are planar. Each pair of folds is composed of one shorter and two longer limbs. Fold shape varies along axial planes and folds die out within a few half-wavelength (Pl. I: Fig. 5). Fold axes generally plunge subhorizontal or moderately to the NE or N, but locally are close to vertical (Fig. 4). The number of kink folds varies in the different sections. They are lacking in the Mile Valley, less frequent at Tornaszentandrás, and abundant in the Nagy-Rednek Valley, where they often form larger, outcrop-scale structures (Fig. 5c).

Although they seem to be geometrically rather similar, the interpretation of these kink folds might be complex. Difficulties arise mainly because of the variable plunge of axes and dip of axial planes. The folds with subhorizontal axes may simply represent disharmonic drag folds on limbs of larger F_2 folds. The shear sense deduced from the kink asymmetry is always in accordance with their position on the given fold limb. The attribution of the kinks to the D_2 phase is also supported by the parallelism of outcrop- to map-scale F_2 fold axes and kink axes.

Folds with moderate to steep axes could belong to a slightly younger deformation phase (D_3). Oblique plunge may indicate a strike-slip component of shortening, and thus the transpressional character of the deformation. The separation of D_2 and D_3 folds is, however difficult since fold axes do not form well-separated classes but a continuous spectrum of dip and orientation (Fig. 4).

In the Nagy-Rednek Valley, some small (dm-scale) folds have (N)NW trending axes (Fig. 4, stereogram above bottom left corner). These folds occur on NW trending beds of F_3 kink folds. We interpret that the F_3 kink folds refolded earlier, small F_2 folds; their original NE trending axes became NW trending ones.

Map-scale structures (F_2 folds, faults) and cross sections

The most characteristic structure of the study area is the relatively constant NE strike of beds (and parallel S_{0-1}) and the presence of NE trending stripes of different rock units. The Pötschen Limestone is bordered by Carnian slate on both sides forming a continuous belt from Tornaszentandrás to Málnás Hill, while several belts of limestone and slate are present east and southeast from the M-10 borehole (Fig. 3).

Dip values, cross sections and small-scale structures prove that parallel distribution of formations reflect strong folding on

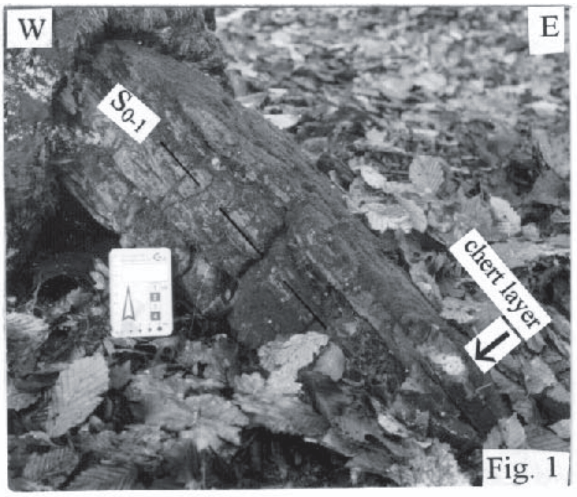

Fig. 1

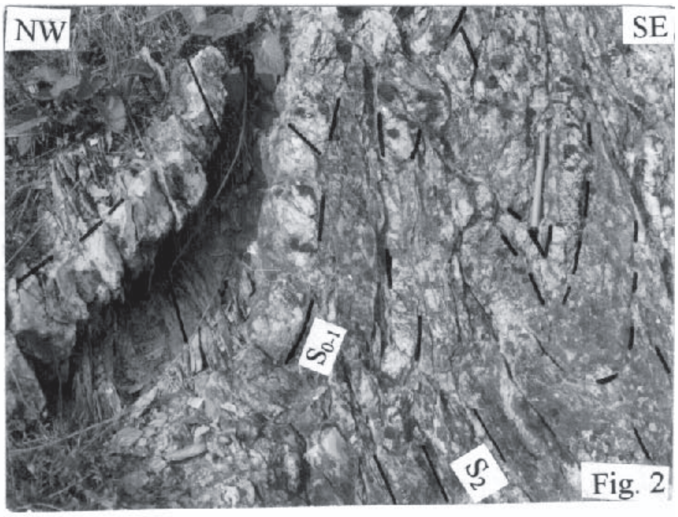

Fig. 2

Fig. 5

Fig. 3

Fig. 6a

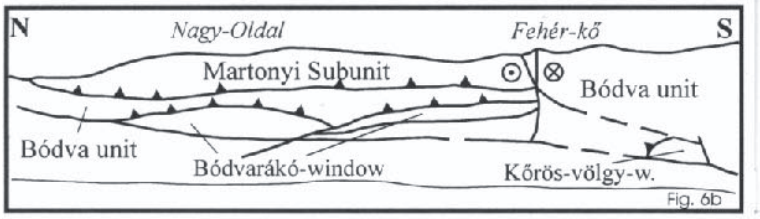

Fig. 6b

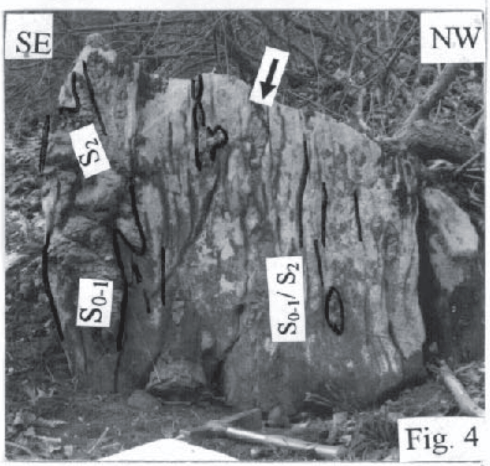

Fig. 4

map-scale. Except for few locations, the dolomite always dips under the overlying Carnian slate or "Bódvarákó Formation". Dip direction is always similar in closely located dolomite/slate outcrops, but dip degree is frequently smaller in dolomite. This different dip degree may simply reflect different position within the fold (e.g. approaching fold hinge in the dolomite) or can be explained by other reasons (discussed later).

Tornaszentandrás section

In the northeastern part of the area, two belts of dolomite surround the slate and cherty limestone belts. This arrangement is considered to be a syncline. Two sections at Tornaszentandrás show details of this structure (Fig. 5a). The Ragya Creek crosses the village, and its northern side represents the type locality of the Carnian Tornaszentandrás Slate (Less 1987). From the southeast, the section begins with Anisian Gutenstein Dolomite outcropping both below the church and on the southern side of the Ragya Creek. Bedding can occasionally be determined using sedimentary lamination.

On the southwestern side of the Ragya Creek, black chert, cherty or platy dolomite, thin-bedded limestone occur (in scree) above the dolomite. This 10–15 m thick sequence is followed by the Tornaszentandrás Slate. The upper part of this slate contains black limestone intercalations, overlain by the alternation of limestone and marlstone. The slate gradually changes to limestone, cherty limestone of the Pötschen Formation which form the central and northern part of the section. In the "Sáros" Valley, the section can be continued more to the NW. This part exposes the slate-limestone transition while more to the northwest, scree of the slate occurs (Fig. 3).

In the dolomite, we did not observe any microscale structures which can be related to ductile deformation, only brittle fractures occurred. Thin sections already showed that internal deformation of dolomite beds did not modify the shape of ooids (Less Gy., pers. commun.).

At the northwestern end of the section (near to the pub and in the "Sáros" Valley) the transition between the slate and cherty limestone dips to the SE at 45–60° (Figs. 4, 5a). The southeastern part exposes dolomite, the overlying slate and the transition to cherty limestone dipping 45–60° to the NW or WNW. In that way the slate and its upper transition clearly forms a syncline (F_2), that was already described by Vitális (1909). Because the dolomite dips concordantly under the slate, they seem to be folded together. The youngest member, the cherty limestone occurs in the core of this syncline. The bedding versus S_2 relationship indicate two northwest-ward and two southeast-ward younging parts of the Ragya section at Tornaszentandrás. This pattern suggests two decametric, close synclines and one anticline, while F_2 folds of a smaller order also occur (Fig. 5a).

We could follow this F_2 syncline up to the Siket Valley to the SW (Figs. 3, 4). Here the SE limb is truncated by a steep fault which puts steeply southeast-dipping dolomite against Carnian slate. The thickness of the dolomite belt decreases southwestward, indicating its tectonic truncation. This contact is interpreted as a reverse fault. The dip values of the following slate suggest the presence of two synclines and one anticline in the Siket Valley. The dolomite core of the anticlines can be followed to the western slope of the Pizondor, where a N-S trending fault truncates the folded structure. This fault can be traced southward, across the Mile and Nagy-Rednek sections (Figs. 3, 5).

Mile Valley section

The Mile section is running NW-SE along the upper part of the Mile Valley (Fig. 5b). The importance of this section that it shows the best outcropped cross-section through the dolomite. Due to easily observable bedding, a large open anticline can be demonstrated. Its NW limb is tectonically reduced and is in contact with Carnian slates. The fold axis is parallel to folds near Tornaszentandrás and represents the same F_2 folding phase (Fig. 4). The only difference is that the interlimb angle is larger (~100°), the hinge zone is subrounded, thus the fold style is far from a chevron fold.

On the southeastern side the dolomite is followed by the slate. The transition is represented by 5 m thick cherty limestone which was interpreted by Less et al. (1988) as Pötschen Limestone. The close geometric situation to dolomite makes it probable that this rock is the previously described "transitional beds". Further to the southeast, the Carnian slate is overlain by Norian cherty limestone which forms a syncline (Fig. 5b).

The anticline in dolomite is cut by a fault which is sub-parallel to the valley. However, the fold axis can be projected toward another occurrence of dolomite, near the boreholes Martonyi M-9, -10.

Nagy-Rednek section

This section runs parallel to the Mile section, further to the SW in the Nagy-Rednek Valley. At the northwestern end of the section, the Carnian slate is in tectonic contact with east-dipping Gutenstein Dolomite (Fig. 5c). The dip of the dolomite is gentle but becomes steeper at the southeastern end of the 300 m long exposure. The slight change in dip degree and orientation is related to folding. Like in the Mile section, this fold can be attributed to F_2 folds, although the shape is open and the hinge is subrounded. The Martonyi M-9 borehole penetrated 150 m of dolomite from the bottom of the valley and reached the deepest stratigraphic level within the Martonyi Subunit. The borehole Martonyi M-10 has reached the Gutenstein Dolomite which is covered by the 20 m thick "transition-

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Plate I: Structural elements in the Martonyi Subunit. See Fig. 3 for locations and Fig. 5 for position on sections. **Fig. 1.** Bedding-parallel $S_{0\text{-}1}$ cleavage in cherty dolomite, north of Pizondor. **Fig. 2.** Close, meter-size F_2 fold at Tornaszentandrás, church hill. **Fig. 3.** S_2 axial plane foliation, isoclinal F_2 folds (Tornaszentandrás, church hill). **Fig. 4**. Transposition of bedding ($S_{0\text{-}1}$) into S_2 foliation, and related rootless folds in cherts (arrow), south of Tornaszentandrás. **Fig. 5.** Kink folds in marlstone, south of Tornaszentandrás, in the "Sáros" valley. **Fig. 6. a**—Panoramic view of the main tectonic units in the NE Rudabánya Mts. Note higher topographic (and tectonic?) position of Martonyi Subunit over the Bódva and Bódvarákó Units. View from west, from the road Perkupa-Bódvaszilas; **b**—Interpretative drawing for Fig. 6a.

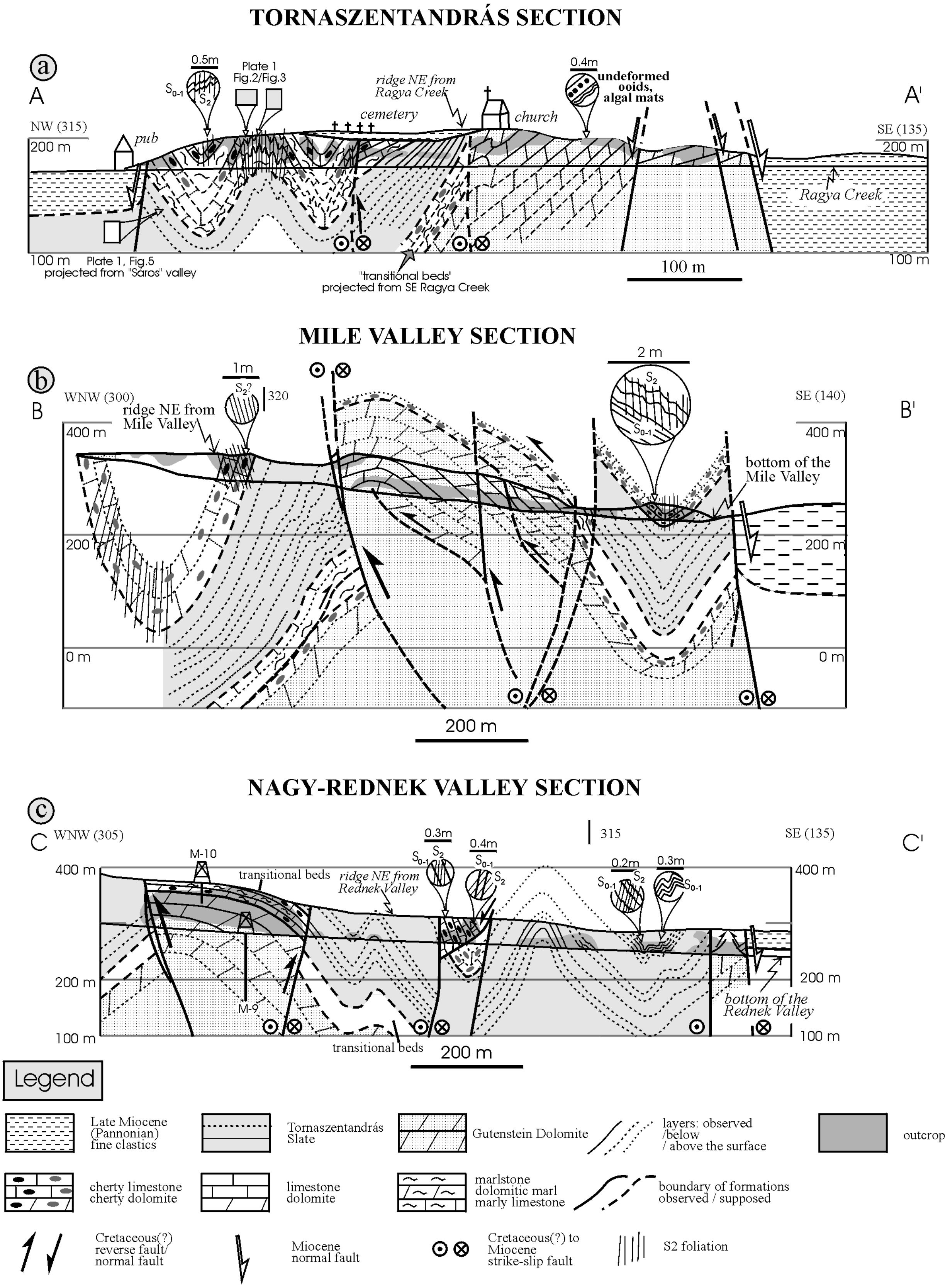

Fig. 5. Cross sections in the Martonyi Subunit, locations on Fig. 3. Note different scale at section *(a)*. No vertical exaggeration.

al beds". This is covered by folded Carnian slate, then grey cherty limestone follows. 80 m southward the slate dips below the younger cherty limestone. Slate-marlstone-sandstone constitute the remaining 250 m.

Both the slate and limestone form close to tight folds with subvertical axial plane (Fig. 5c). Two anticlines and two synclines can be detected in the slate while one syncline is supposed in the limestone. Here, SE-vergent overturned beds also occur along a 20 m long part. However, this local feature is not convincing to attribute vergency for the folding (in contrast to Less et al. 1998). The limestone mainly shows layer-parallel cleavage ($S_{0\text{-}1}$), subvertical S_2 is only rarely seen. On the other hand, S_2 and not only $S_{0\text{-}1}$ foliation occurs in the slate. The slate is frequently deformed by cm to meter-scale, asymmetric, disharmonic kink folds. The axes of kinks are dipping N to NE with moderate plunge (Fig. 4).

Discussion

Structural evolution

The D_1 deformation phase

The first $S_{0\text{-}1}$ foliation was most probably formed due to deep tectonic burial (e.g. thrusting) representing the first D_1 event in the study area (Fig. 6a). The K-white mica b_0 values suggest transitional medium/high pressure conditions (Árkai & Kovács 1986). Corresponding loading was produced by higher nappes of undiscussed origin. This first order nappe stacking probably occurred during the subduction of the Meliata oceanic branch of the Neotethys. During subduction, the Martonyi Subunit was incorporated into the nappe pile from the thinned continental crust, while the Bódvarákó sequence might represent the close vicinity of the oceanic crust.

In accordance with Grill (1989), we did not observe any shear criteria giving a well-defined direction of tectonic transport of first order nappe stacking within the Martonyi Subunit. The only indication comes from an outcrop from the nearby Esztramos Hill showing S-vergent small intrafoliational folds (Csontos & Hips 1997; Less et al. 1998). In spite of this weak indication, we have no conclusion up to now on the direction of primary nappe stacking and subduction from outcrops in the Rudabánya Mts. Clear indication of vergency cannot be deduced from D_2 either, because the F_2 folds are upright without any prominent asymmetry. NW dipping, steep foliation (S_2) described by Less et al. (1998) represent, in fact, exceptions and cannot be used for vergency determination. The southeastern vergency at Tornaszentandrás, reported by Hók et al. (1995) also lacks convincing field evidence.

Because of the lack of characteristic synkinematic minerals, we cannot unambiguously decide whether D_1 or D_2 is associated with higher P and/or T values of metamorphism.

Spatial and temporal model for D_2–D_3 ductile deformation

Cross sections and dip data show that map-scale folds have smaller tightness and larger bluntness in dolomite than in the slate-cherty limestone couplet. One consequence of different fold shape through the stratigraphic section is the detachment of Pötschen Limestone and probably the slate from the dolomite base. This detachment surface can be located close to the upper boundary of the dolomite, in the marly "Bódvarákó Formation". Marly layers of these beds could form duplexes at or ductily flow into hinge zones of F_2 folds (stage D_{2a}, Fig. 6b). Such thickening can be suspected at the anticline hinge near the Martonyi M-10 borehole, (the only well-preserved hinge zone in "Bódvarákó Fm.") where the thickness of these beds seems to be larger than usual.

De Sitter (1958) showed that chevron type folds lock up when folds attain a 60° interlimb angle. This value can be somewhat different, if frictional properties between layers change (Ramsay 1974). In upright folds, this limit may represent 50°–60° of fold limb dip. Additional shortening (if it occurs) should be accommodated by other type of structures. Gray & Willman (1991) observed, that further steepening of fold limbs is due to penetrative horizontal flattening and vertical lengthening of folds which can be observed in any scale and reflected by diverse strain markers. Development of foliation along the axial plane of such flattened chevron folds started only at this flattening stage and not earlier.

This observation can be applied in the interpretation of structures near Martonyi. In the dolomite, dip values rarely exceed 45–50° which is close to the natural limit of fold limb dip. Up to this stage, folding is accommodated by flexural folding, which is possible even in the rigid dolomite. Further shortening by fold-flattening resulted in steepening of fold limbs only in the slate and particularly in the Pötschen Limestone which are suitable to suffer such a pervasive ductile deformation at this low-grade metamorphic stage. The Pötschen Limestone in cores of synclines suffered the highest deformation, and shows the steepest fold limbs and the appearance of axial plane foliation (as was demonstrated at the Tornaszentandrás section, Fig. 5a). Horizontal flattening locally resulted in complete parallelism of $S_{0\text{-}1}$ and S_2.

The lack of S_2 foliation, the relatively moderate dip of fold limbs in the dolomite suggest that fold flattening (D_{2b} phase) did not occur in this rigid lithology. The additional shortening of D_{2b} can be accommodated by brittle faulting of the dolomite. Relatively steep reverse or reverse-strike-slip faults could break through fold limbs in dolomite (Fig. 6c). These faults can bend to a subvertical, layer-parallel position in the Pötschen Limestone. Such steep faults were observed at some locations (particularly in the NW part of Mile and Rednek sections and at the Nagy-Oldal) and are supposed at other localities. Their steep dip is supported by straight map view (intersection of faults and topography). Different deformational mechanism across the folds may account for certain strain partitioning (horizontally and vertically) during the D_{2b} phase.

The presence of kinks with moderate to vertical axes (D_3 phase) may suggest oblique shortening with respect to the F_2 fold axes (Fig. 6c). This oblique shortening could also be associated with oblique-slip reactivation of steep faults cutting through the F_2 folds. This transpressional deformation could occur at shallower crustal depth, at the transition of the brittle-ductile field.

It is difficult to determine the age of the ductile deformation phases. From regional geodynamic models (e.g. Grill et al.

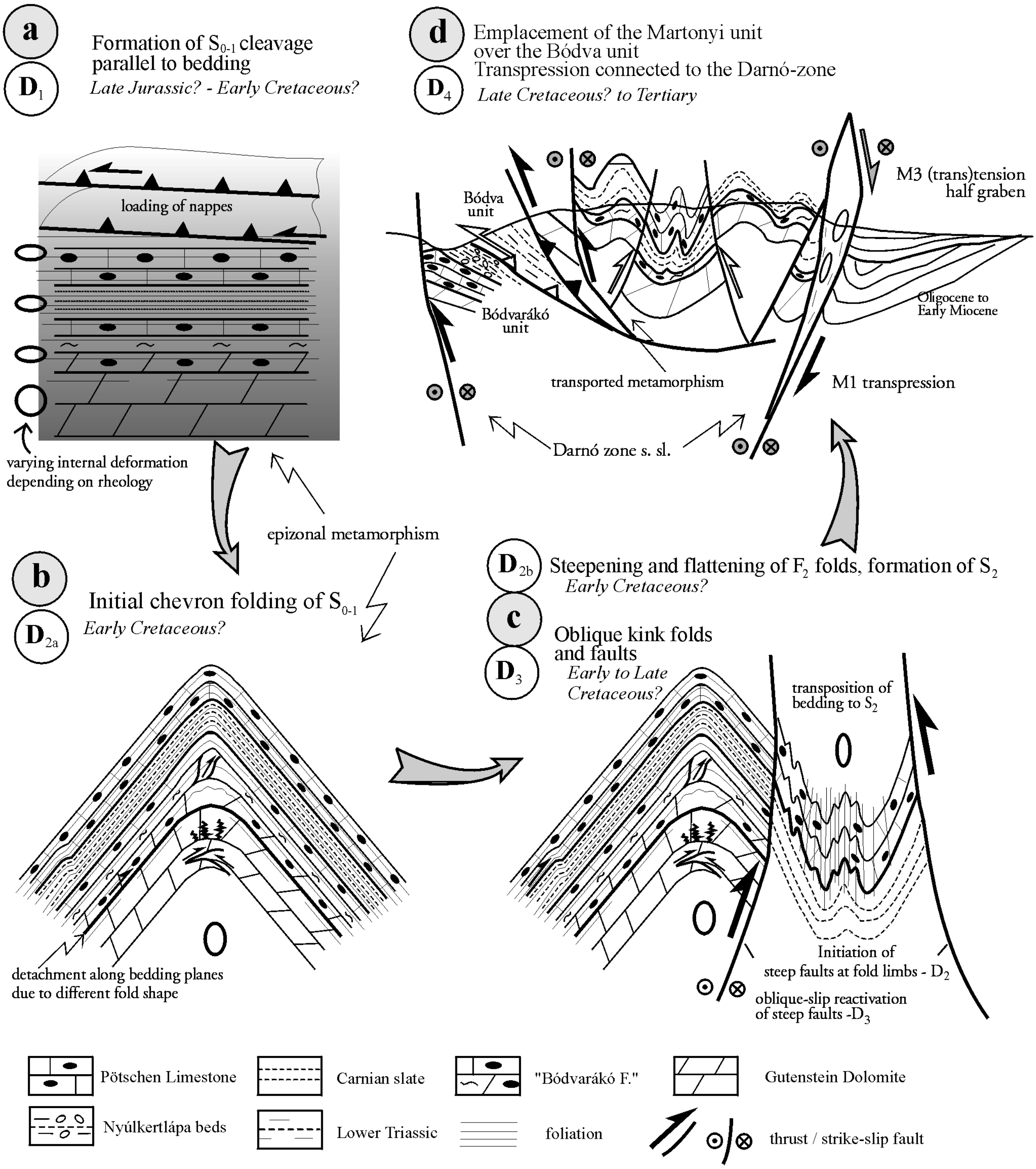

Fig. 6. Schematic structural evolution of the Martonyi Subunit. See discussion in the text.

1984) one can speculate late Early Cretaceous age for D_2 phase, while older D_1 (nappe stacking) may be of Late Jurassic? to Early Cretaceous age.

Position of the metamorphic units with respect to non-metamorphic suites

The northwestern contact of the metamorphic Martonyi Subunit toward the Bódva Unit is represented by a well-constrained, moderately steep fault dipping to the southeast, beneath the metamorphic unit. Because the metamorphic rocks are at higher topographical position (Pl. I: Fig. 6), they were probably thrust (obliquely?) onto the Bódva Unit (Less 1998). The similar topographical position of the Torna versus the Bódva units occurs at the southern tip, but the dip of the boundary fault is not clear.

Along the western boundary fault, near the Fehér-kő, small, isolated lenses of Middle Triassic carbonates occur between metamorphic upper Triassic (Martonyi) and non-metamorphic Lower Triassic (Bódva) rocks (Less et al. 1988) (Fig. 3; Pl. I:

Fig. 6). These lenses can be regarded as strike-slip duplexes. Displaced structures (folds, faults) within the Bódva Unit indicate its sinistral slip (Fig. 3).

The southeastern boundary fault can be detected on the Nagy-Rednek section which terminates in non-metamorphosed rocks belonging to the "Rudabánya ore belt" (Pantó 1956). Although Balogh & Pantó (1952) interpeted this belt as a thrust zone, more recent data suggest strike-slip motion (Grill 1989). The zone consists of Middle Triassic limestone and ankeritic dolomite lenses embedded in Permian-Lower Triassic siltstone-evaporite matrix (Figs. 1b, 3). The lens-like map view of Anisian carbonates suggests a strike-slip origin for the anastomosing fault branches within the Darnó Zone. Further to the south, near Rudabánya, other evidence support this interpretation. Among others, Pantó (1956) observed horizontal slickenlines on parallel fault planes in the Rudabánya ore body. Szentpétery (1997) indicated strongly tilted, sinistrally displaced Oligocene-Eggenburgian sediments.

In summary, our observations show that the Martonyi Subunit is bounded by steeply or moderately dipping faults from each side. These tectonic contacts represent sinistral strike-slip or oblique-reverse faults (Figs. 3, 6d). We agree with Less (2000) that the recent position of the metamorphic unit is the result of strike-slip motion along the Darnó Zone and, at least a slight allochthonity over the non-metamorphic Bódva Unit. However, we cannot unambiguously decide if the metamorphic unit represents a thin, flat lying nappe over the Bódva (or other ?) Unit (like e.g. in the Hidvégardó-3 borehole, Kovács 1986) or just a transpressional, steep-sided pop-up structure arising from below the Bódva Unit (Fig. 6d). The age of this brittle transpression may start in the latest Cretaceous. The strongly deformed Eggenburgian and only slightly fractured Pannonian indicate Early to Middle? Miocene transpression. Several branches of the Darnó Zone could be reactivated as a normal (or normal-oblique) fault after the Pannonian, during Late Miocene–Pliocene (trans)tension (Fig. 6d).

Stratigraphic and paleogeographic consequences

Tectonic/stratigraphic position of the Gutenstein Dolomite

Our observations show that the dolomite is generally in contact with the Tornaszentandrás Slate. More precisely, the thin suite of "the Bódvarákó Formation" can be demonstrated at a number of places. This sequence may represent the sudden transition from platform to basinal depositional setting and the whole dolomite-slate sequence could be interpreted as continuous.

This sedimentological-lithostratigraphical observation is also supported by structural data. When the dip of the dolomite can be established, it always dips below (toward) the slate. The dip degree of both dolomite and slate are similar at the Tornaszentandrás section (Fig. 5a). However, at several localities the slate dips more steeply than the dolomite but in the same direction. Such a place can be found SE from the Mile Hill, on the Nagy-Oldal and along the Nagy-Rednek and Mile Valley sections. This sudden change in dip degree is the consequence of faulting which is related to shortening during the late stage of D_2 (see previous chapter). This faulting, however, did not essentially disturb the stratigraphy.

Metamorphism of the dolomite

Subvertical S_2 foliation of the cherty limestone represents the axial plane of the map-scale synclines. This geometry suggests that the map-scale syncline and outcrop-scale F_2 folding represent the same D_2 deformation phase. The ductile behaviour of the F_2 folds in the core and the total transposition of the bedding demonstrate that the folding and S_2 foliation were formed at least in anchizonal metamorphic conditions. The exact physical conditions cannot be determined but such ductile flow of limestone indicate temperatures over 200 °C.

Map analysis and cross sections clearly suggest that the Gutenstein Dolomite underwent F_2 folding. Consequently, it suffered the same metamorphism during folding. This tectonometamorphic evolution contradicts the previous interpretation of Less et al. (1988), Grill et al. (1984), Grill (1989) that consider the Gutenstein Dolomite as a non-metamorphic rock belonging to the Bódva Unit.

This idea was partly based on the observation that original sedimentological features of the dolomite were not significantly affected by any ductile deformation processes. We agree with this observation, but the lack of ductile deformation does not exclude metamorphism of the rock. Considering the rheological properties of dolomite in anchi-epizonal conditions, ductile (internal) deformation (e.g. foliation) will not appear in contrast to limestones (Fig. 6a). Rheological differences can also explain the lack of both S_{0-1} and S_2 cleavages in dolomite. It is also supported by the observation that a small lithological change (larger marl content) permits the development of incipient foliation at the top of the dolomite or in the "transitional" cherty limestone.

On the other hand, the suggested evolution of F_2 folding gives an explanation for the lack of S_2 foliation. The formation of S_2 axial plane foliation is expected only at the final stage of the F_2 folding (D_{2b} phase). This shortening was transferred to faulting in the dolomite (Fig. 6c).

Consequences for lithostratigraphy of Torna units

Less (1981, 2000) defined the metamorphic Torna sequence as containing the Anisian platform limestone (Steinalm Fm.). The lack of the Steinalm Limestone in the Martonyi Subunit seems to contradict its classification to the Torna Unit. However, the Bódvarákó sequence shows that platform limestone could be replaced by pelagic sedimentation already in the middle Anisian (Kovács et al. 1989). If our structural interpretation is correct, the stratigraphy of the Martonyi Subunit is closer to the Bódvarákó than to the "classical" Torna sequence (e.g. Esztramos Hill). The middle Anisian platform and late Anisian-Ladinian basinal carbonates are replaced by a very thin suite of (dolomitic) marlstone and cherty limestone which may be the equivalent of the deep water cherty limestone of the Bódvarákó Formation. Both formations can indicate fast subsidence at the margin of the carbonate platform, probably close to the rift axis.

However, the clear identity of the Martonyi and Bódvarákó sequences cannot be declared. The middle Anisian-Ladinian Bódvarákó Fm. is covered by the upper Triassic-Jurassic (?) Nyúlkertlápa Beds or, by an alternative interpretation, directly cut by a thrust plane (Pelikán P., pers. commun.).

On the other hand, the metamorphic degree of the two sequences is different (Árkai 1982). The Martonyi sequence suffered lower epizonal metamorphism, while the Bódvarákó window shows only anchizonal metamorphism. The deformation style of the two units seem to be different since the F_2 folds and S_2 foliation are missing from the Bódvarákó windows. In any case, direct identification of the Bódvarákó with the Martonyi sequence does not work.

The assignment of the Bódvarákó Unit to any first order tectonic unit is not clear. The early subsidence, anchimetamorphic character led Kovács et al. (1989) and Less (2000) to assign it to the Meliata Unit (sensu lato) (Fig. 2). In our paper we suggest that this window has similar stratigraphy to the Martonyi Subunit, so it may belong to the Torna Unit, too.

Our observations strengthen the conclusion of Less et al. (1998, 2000) that the Torna Unit (and the metamorphic units in general) incorporates diverse Triassic successions, which were formed in different paleogeographical positions on the attenuated continental crust. The Bódvarákó and the Martonyi sequences were probably closer to the rift axes, and their fast subsidence may directly reflect the onset of rifting during the earlier part of the Middle Anisian. The Esztramos, Szent-János-hegy (Becskeháza) indicate later subsidence of the carbonate platform (late Middle and Late Anisian, respectively), due to minor thinning of the continental crust, located far from the rift axes.

Conclusions

Structural observations and mapping showed that the metamorphic sequence near Martonyi consists of Gutenstein Dolomite, thin transitional beds ("Bódvarákó Formation") to Carnian slate and cherty Pötschen Limestone. The whole sequence suffered intense ductile deformation with two phases of folding, associated with anchi- to epizonal metamorphism. First, the layer-parallel S_{0-1} cleavage developed due to tectonic overburden of higher nappes. Second, upright chevron-type folds deformed the complete sequence. Detachment along the upper boundary of rigid dolomite probably occurred. During the final stage of this shortening, fold limbs flattened in the core of synclines where an axial plane foliation (S_2) was formed. This final horizontal flattening was accommodated by steep faulting in the dolomite. In this way, strain partitioning is demonstrated within the sequence with different rheological properties: shortening is accommodated by intense folding and axial plane foliation in incompetent lithologies, and by brittle faulting in competent lithologies. Structural style depends also on position across the F_2 folds. The D_3 phase is marked by kink folds with oblique axes, probably formed during transpression, at the transition of brittle-ductile field. The metamorphic unit was slightly or largely emplaced over nonmetamophic units (Bódva) after metamorphism, connected to transpression along the Darnó Zone.

Because Gutenstein Dolomite suffered D_2 folding, it is also a metamorphic rock, forming the normal stratigraphic base of the sequence. The lack of Steinalm Limestone is similar to the Bódvarákó sequence. These two units show that the Torna Unit incorporated different Triassic sequences: all were formed on thinned continental crust but in different paleogeographical positions across the passive margin(s) of the Neotethyan Meliata oceanic branch.

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