Magyarhoni Földtani Társulat
Földtani Közlöny
Hungarian Geological Society
146/1, 3–10., Budapest, 2016

Folding and faulting of cherty dolostones at Ördög-orom, Buda Hills, Hungary

PALOTAI Márton[1, 2]

[1]Eötvös Loránd Tudományegyetem, Általános és Alkalmazott Földtani Tanszék — Department of General and Applied Geology,
1117 Budapest, Pázmány Péter sétány 1/c
[2]CASP, West Building, 181A Huntingdon Road, Cambridge CB3 0DH, United Kingdom; e-mail: marton.palotai@casp.cam.ac.uk

Redők és vetők az Ördög-orom tűzköves dolomitjában

Összefoglalás

A budai Ördög-orom felső-triász tűzköves dolomitból áll, amely breccsásodott és porlik. Jelen munka első részletes dokumentációja a sziklán kibukkanó intenzív töréses deformációs jelenségeknek és az enyhén aszimmetrikus redőknek. Ez utóbbiakat a tűzkőrétegek és a rétegzést követő tűzkőgumók lefutása jelzi. A redők rideg deformációs mechanizmussal keletkeztek, de a szerkezeti stílus átmenetet képez a folytonos deformáció felé. A rétegzésben lecsatoló rátolódások legalább részben a redőkhöz kapcsolódnak. A redőződés valószínűleg a kora-kréta során történt. A tektonikai transzportirányok NyDNy és ÉNy közt szórnak. A dolomitot több irányban jelentős töréses deformáció érte, amely részben felelős a breccsásodásért is.

Tárgyszavak: redő, vető, Dunántúli-középhegység, kréta, Budai-hegység, Ördög-orom

Abstract

The cliff of Ördög-orom in the Buda Hills, Hungary, comprises brecciated and powderised cherty dolostones of Late Triassic age. This aim of the present paper is to document the folds, faults and fractures of the cliff in detail for the first time. The chert layers and strings of chert nodules indicate that the style of the slightly asymmetric folding was transitional between brittle and ductile, although the deformation mechanism was brittle. Small scale thrusts, detached in bedding planes, are at least partly related to the folding. Tectonic transport directions scatter between WSW and NW. The age of this deformation phase is inferred to be Early Cretaceous. The dolostones were affected by intense fracturing and brecciation in multiple directions.

Keywords: fold, fault, Transdanubian Range, Cretaceous, Buda Hills, Ördög-orom

Introduction

Several, often contrasting theories have been proposed for the structural development and tectonic evolution of the Transdanubian Range and its easternmost part, the Buda Hills (e.g. WEIN 1977; FODOR et al. 1994, 1999; MÁRTON & FODOR 2003; SASVÁRI 2008a, b, 2009).

In order to provide data for regional tectonic interpretations, structural geological field work was undertaken at Ördög-orom, a well-exposed cliff in Budapest *(Figure 1)*. Although WEIN (1977) mentioned the folds of Ördög-orom, (*Figure 2*) no detailed geological investigations have been carried out on this cliff because of its inaccessibility due to the crumbly nature of the dolostone. Combining abseil techniques at five sections and the approach of the base and the top of the cliff elsewhere, it was possible to document the folds and brittle structures. The results of these efforts are presented in this contribution.

Geological background

The Transdanubian Range forms the uppermost tectonic unit in the Austroalpine nappe pile (TARI 1994, TARI & HORVÁTH 2010). Late Triassic formations of the Transdanubian Range are similar to those in the Southern Alps, and to a certain extent the Northern Calcareous Alps (HAAS et al. 1995). While the most common massive carbonates represent shallow marine conditions, cherty limestones in the Transdanubian Range were deposited in deeper marine

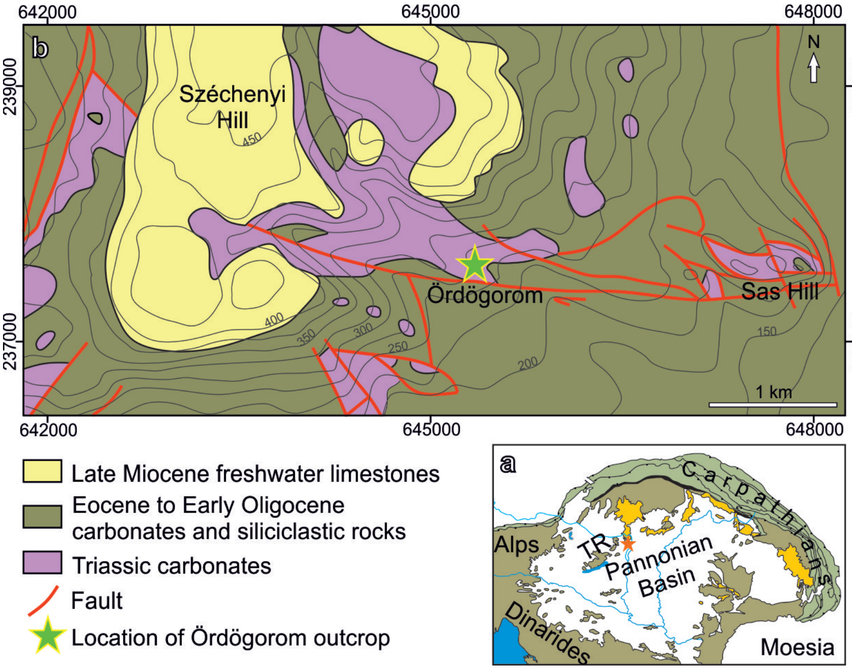


Figure 1. a, Location of the Buda Hills within the Pannonian Basin (indicated by an asterisk). TR – Transdanubian Range. **b,** Geological map of the southern Buda Hills (modified after FODOR [unpublished] in POROS et al. [2013] and in MINDSZENTY [2014]). Coordinates are in EOV (Hungarian national reference system)

1. ábra. *a, A Budai-hegység helyzete a Pannon-medencében (csillaggal jelölve); b, A Budai-hegység déli részének földtani térképe (FODOR in POROS et al. [2013] és in MINDSZENTY [2014] után módosítva)*

slope and basin settings, mainly in intraplatform basins (HAAS 2002). *Figure 1, b* shows the geological map of the southern part of the Buda Hills, without distinguishing between various Triassic formations (given that no relevant modern mapping is available).

One of the deeper marine formations — the Norian–Rhaetian Mátyáshegy Formation (KOZUR & MOCK 1991, HAAS 2002, HAAS & BUDAI 2014) — is made up of thinly-bedded or laminated cherty dolostones and limestones. Chert occurs as layers and lenses within the carbonates. The dolostones in this formation are the result of late dolomitisation of the limestones (HAAS & BUDAI 2014). In other parts of the Buda Hills, however, Middle Triassic dolostones are characterised by a higher temperature dolomitisation overprint of synsedimentary dolomites (HIPS et al. 2015).

The brecciation and powderisation of Triassic dolostones in the Transdanubian Range, especially in the Buda Hills, is a widespread phenomenon. According to POROS et al. (2013), it was caused by repeated freeze-thaw cycles during the Pleistocene. FODOR et al. (1994) described brecciation related to the Cretaceous folding in the Buda Hills.

Triassic carbonates were involved in the Alpine orogeny and subsequent deformation events, and generally acted as competent units prone to brittle failure. In some cases,

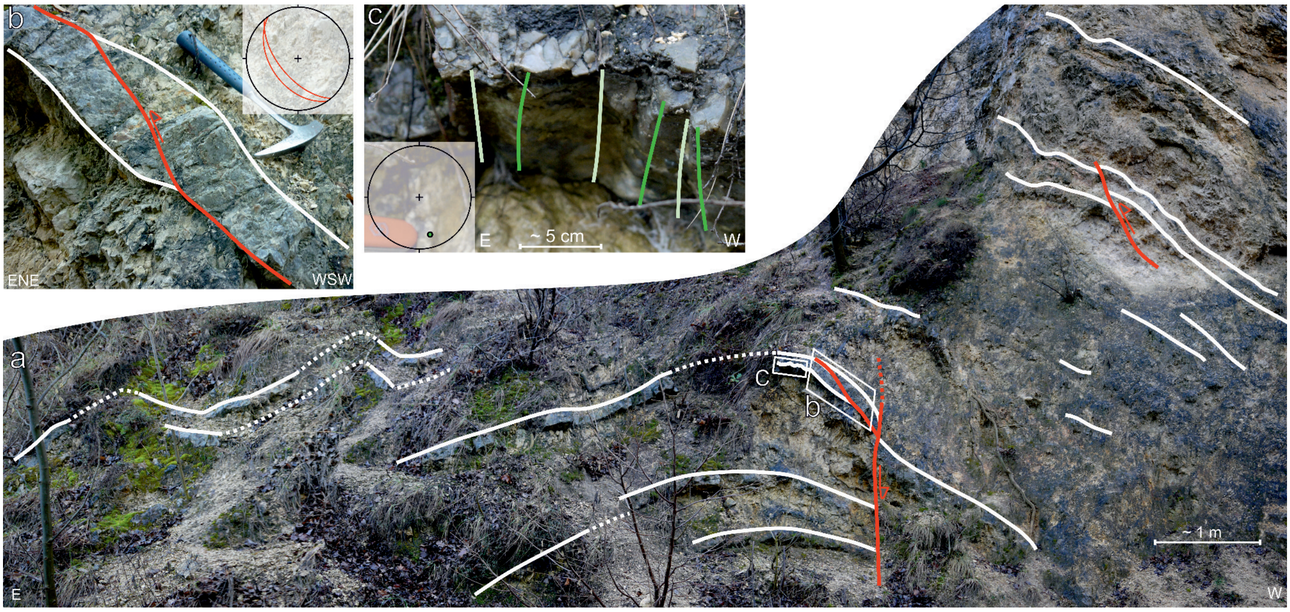


Figure 2. a, Slightly asymmetric fold train exposed at the roadside part of the outcrop. The antiform in the centre is thickened in the hinge. Thrusts detached in the dolostone offset chert beds. A small-scale subvertical fault offsets various beds. Insets show the locations of 'b' and 'c'. **b,** Duplexing of a single chert bed on the limb of the antiform and the stereographic image of the fault. **c,** M-shaped parasitic folds at the dolostone-chert interface in the fold hinge, and their stereographic image

2. ábra. a, *Enyhén aszimmetrikus redők a feltárás útmenti részén. A középen látható antiform a csuklóban kivastagszik. A dolomitban lecsatoló áttolódások elvetik a tűzkőrétegeket. Egy közel függőleges vető kismértékű elvetést okoz. A b és c ábra helyét négyszögek jelzik. **b,** Egy tűzkőrétegben kialakult duplex az antiform szárnyán, és az áttolódás sztereogramja. **c,** Dolomit-tűzkő réteghatáron kialakult szimmetrikus parazitaredők a redőcsuklóban, valamint a parazitaredő sztereogramja* however, they were folded as well (Wein 1977, Fodor et al. 1994, Pelikán 2013). Folding of Triassic carbonates in the Transdanubian Range occurred in the Early Cretaceous (Sasvári 2008b, Tari & Horváth 2010) and the Palaeogene (Fodor et al. 1994), although even later times have been suggested (Pelikán 2013).

The Barremian to Early Albian in the Transdanubian Range was dominated by NE–SW to N–S compression (Fodor et al. 1994, 2013; Pocsai & Csontos 2006; Palotai et al. 2006). This event represents a far-field echo of the subduction of the Vardar–Meliata Ocean (D1 phase) (cf. Fodor et al. 2013). The D1 phase was followed by a gradual rotation of the shortening directions into the NW–SE direction characteristic for the Albian orogeny in the Transdanubian Range (D2 phase) (Tari 1994, Fodor 2008, Tari & Horváth 2010) as a result of Alpine nappe stacking. The D1 phase was thought to account for all thrusts and large scale folds of Cretaceous age in the Buda Hills by Fodor et al. (1994). The Palaeogene – Early Miocene was characterised by transpression with WNW–ESE to NW–SE compression and perpendicular extension directions (D3 phase) (Fodor et al. 1994).

The Ördög-orom forms a ca. 150 m long, ca. 40 m high, north facing cliff in the southern part of the Buda Hills (47°28’55”N, 18°59’12”E) *(Figure 1)*. The steep cliff is entirely made up of the Mátyáshegy Formation. On top of the cliff, outside the current area of interest, the Triassic is unconformably overlain by a transgressive Eocene succession (Wein 1977, Fodor et al. 1994, Magyari, 1996). On the western side of the cliff, Late Miocene sedimentary dykes are known within the dolostone (Fodor & Kázmér 1989, Magyari 1996).

The stereograms *(Figure 3, f–i)* were created with SG2PS software (Sasvári & Baharev 2014).

General observations

The dolostone is heavily brecciated throughout the Ördög-orom. The powderisation of the dolostone resulted in mosaic breccias *sensu* Poros et al. (2013), but mosaic breccia blocks floating in dolostone powder, and crackle breccias also occur. This indicates an intermediate stage of cryogenic dolostone disintegration (cf. Poros et al. 2013). Except for a few well defined fault zones *(Figure 3, b, e)*, no distinction could be made between tectonic and cryogenic brecciation.

Bedding planes within the carbonate are completely obliterated by the advanced powderisation. Bedding can only be determined where continuous chert layers occur (unaffected by brecciation), or inferred where chert lenses are aligned in a string *(Figures 2, a; 3, a, d)*.

Folds

Chevron folds are common, indicating the brittle rheology of the cherts *(Figure 3, c)*. In some cases, however, rounded folds were also observed *(Figure 3, d)*. The wavelength of folds is estimated between 3–10 m, while the fold amplitude is less than 2–3 m.

A fold train is delineated by several continuous chert layers in an easily accessible part of the outcrop next to the road at the bottom of the cliff *(Figure 2, a)*. The folds are slightly asymmetric, with generally shorter western limbs. This may indicate a process of generally western tectonic transport.

In the hinge of the antiform in the centre of *Figure 2, a*, the top of a chert layer is smooth, while the base of it forms small scale M-shaped folds (initial cuspate-lobate structures?) at the contact with incompetent dolostone *(Figure 2, c)*. The hinge directions of these folds align well with fold hinges measured elsewhere *(Figure 3, h)*.

The dolostone layers thicken towards the fold hinge of the same antiform. This may suggest the weak rheology of the dolostones relative to the cherts. A duplex within the chert — in its hinge zone — is most likely detached in the dolostone immediately below and above the chert layer *(Figure 2, b)*. This structure resulted in the thickening of the chert layers. Thrusting in the inner arc of the fold is therefore thought to account for the observed fold geometry.

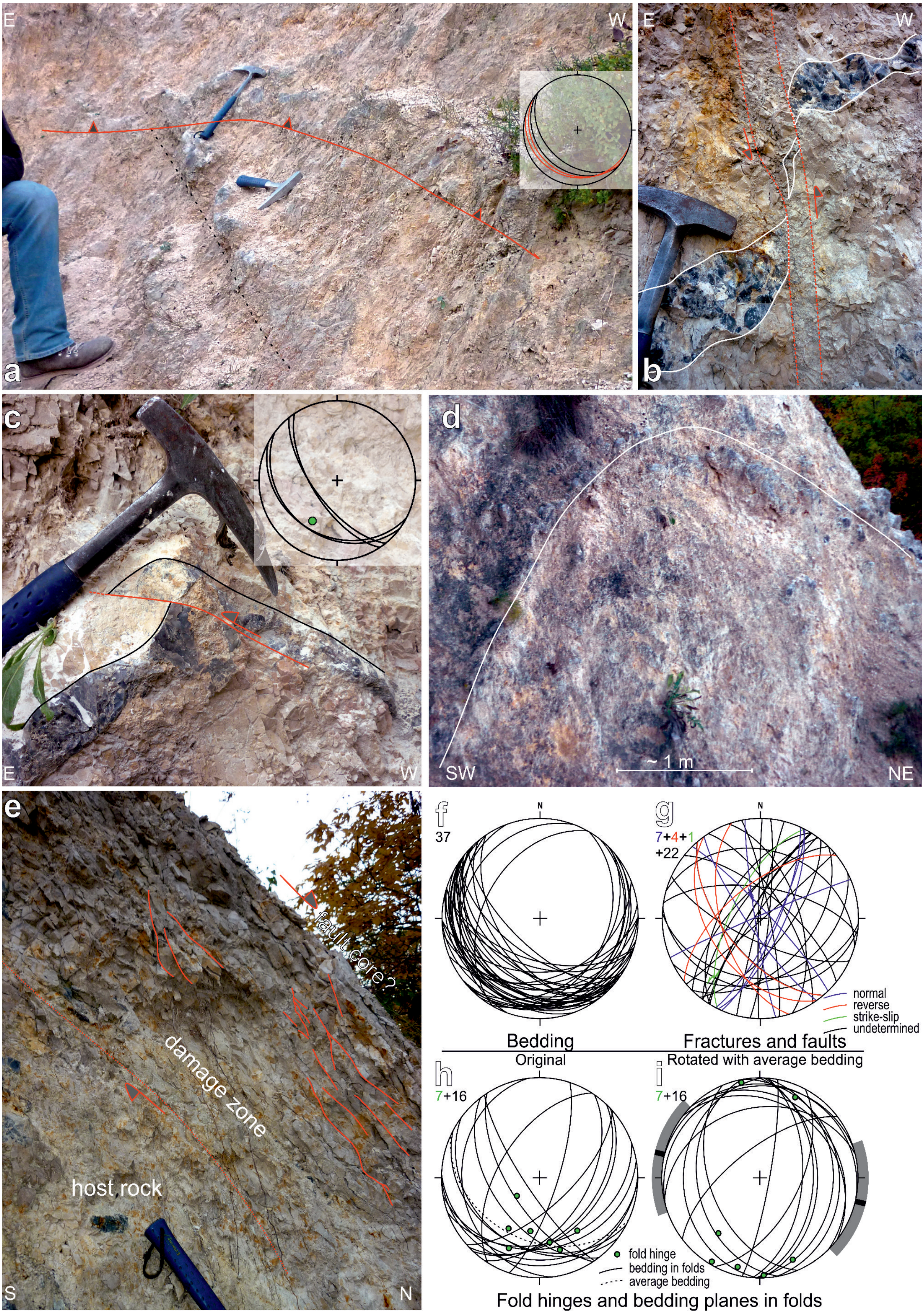
The measured fold hinges dip to the south at low angles *(Figure 3, h)*. The intersection lines of bedding planes that were measured close to changes in dip (i.e. around fold hinges) also scatter around S–SSW *(Figure 3, h)*.

The dataset (containing the measured fold hinges and the bedding planes) recorded on outcrop scale folds was rotated with the average of bedding planes that were measured away from outcrops scale folds; the aim of this was to achieve a pre-tilt geometry *(Figure 3, i)*. In this case, both the measured fold hinges and constructed fold axes scatter between 340° and 45° around north, and between 170° and 200° around south at low angles. Assuming subsimple shear, the direction of maximum shortening can therefore be estimated between WSW–ENE and NW–SE.

Faults and fractures

The dolostone is intensely fractured and brecciated where powderisation has not completely destroyed earlier structures *(Figure 3, a–e)*. In some cases, the sense and amount of dip-slip offset along faults could be determined by offset chert layers *(Figure 3, b, g)*, but often no markers were found. Steep NE–SW oriented fractures prevail (often with minor normal offset), but there is a wide scatter of directions *(Figure 3, g)*. The handful of measured and proven reverse faults (identified by offset chert beds) dip to the SW or the NW *(Figure 3, g)*. Only two small scale striated fault surfaces *(Figure 3, g)* were identified on faulted chert nodules.

At some cliff sections, a dense set of steep, slope-parallel fractures was observed close to the envelope of the cliff *(Figure 3, e)*. This systematic fracture set fades away towards the interior of the brecciated/powderised rock volume. Two interpretation alternatives can be put forward.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Fractures and faults
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Rotated with average bedding
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fold hinge
bedding in folds
average bedding
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Fold hinges and bedding planes in folds

← **Figure 3. a,** Bedding outlined by chert string (dashed line) is cut off by a suspected low angle thrust. b, Small-scale fault with dip-slip offset outlined by the oriented brecciation of the dolostone and the drag of a chert bed. c, Chevron antiform in chert, and its stereographic image. The discrepancy between the measured fold hinge and the intersection of bedding planes is due to errors in measurement. A shallow angle fold axis dipping approximately to the south is inferred. The chert bed is displaced by a small scale thrust detached in the bedding of the west-dipping fold limb. Note the fractures in the dolostone. d, Rounded antiform outlined by a chert layer. This structure could not be accessed directly. e, Damage zone of the normal fault at least partly responsible for the topography of the cliff. f-g, Stereograms (lower hemisphere stereographic projection, Schmidt net) of structural elements at Ördögorom. Data numbers are indicated in the top left corner of each diagram. f, Bedding planes, with generally shallow dip to the south and southwest. Bedding planes on limbs of observed folds are not shown. g, Fractures and faults. Note that some faults without striae classified as normal or reverse might actually be strike-slip faults with some dip-slip component. h-i, Fold hinges and bedding planes measured in their immediate vicinity. The average of bedding planes measured away from outcrop scale folds is shown as dashed line. h, Present day geometry. Fold hinges and bedding plane intersections scatter widely around south. i, Corrected by average bedding to reconstruct pre-tilt geometry. The range of inferred shortening directions is shown in grey, average direction in black

*← **3. ábra. a,** A tűzkőgumók által kirajzolt rétegzést (szaggatott vonal) átvágja egy laposabb felület, amely valószínűleg egy áttolódás. b, A dolomit irányított breccsásodása és a tűzkőréteg elvonszolódása által jelzett kisméretű vető. c, Tűzkőrétegben kialakult chevron antiform és sztereogramja. A redőcsukló és a szárnyakon mért dőlések metszésvonala közti különbség a mérés bizonytalanságából ered; egy laposan délre dőlő redőtengely valószínűsíthető. A tűzkőréteget kis mértékben elveti egy áttolódás, amely lecsatol a nyugatra (W) dőlő redőszárny rétegzésében. A dolomit töredezett. d, Tűzkőréteg által kirajzolt lekerekített antiform. Ezt a redőt nem sikerült megközelíteni. e, Az Ördögorom letöréséért legalább részben felelős normálvető zúzott zónája. f-g, Sztereogramok alsó félgömb vetületben, Schmidt-hálón. Az adatok száma a bal felső sarokban van feltüntetve. f, Többnyire lapos déli és délnyugati rétegdőlések (a redőcsuklók közelében mért dőlések kivételével). g, Törések és vetők. A normálvetőként (normal) vagy feltolódásként (reverse) jelzett karc nélküli vetők egy része lehetséges, hogy valójában eltolódás (strike-slip) némi dőlésirányú elmozdulással. h-i, Redőcsuklók és az észlelt redőkön mért rétegdőlések. h, Jelenlegi helyzetükben a redőcsuklók és a rétegdőlések metszésvonalai egy tág tartományban dél körül szórnak. Az észlelt redőkön mért adatok kizárásával számolt átlagos rétegdőlést szaggatott vonal jelzi. i, Az átlagos rétegdőléssel korrigált, billenés előtti helyzetben a lehetséges rövidülési irányok tartományát szürke, az átlagos rövidülési irányt fekete sáv jelzi*

(1) The fracture set is related to the late exfoliation of the dolostone in the vicinity of the topographic break-off of the cliff. (2) The fracture set forms the 0.5–1 metre wide damage zone of the fault that created the cliff, or of an auxiliary fault parallel to that. The majority of these fractures are oriented sub-parallel to the slope, and might be interpreted as being related to exfoliation. There are, however, steeper fractures as well, and the composite pattern *(Figure 3, e)* resembles the Riedel shear geometry in normal fault zones. Therefore, the second alternative is preferred. Additional support for this interpretation is given by map-scale faults near Ördög-orom *(Figure 1, b)*. An east–west striking fault runs south of Ördög-orom. Although this fault is shown to have dextral kinematics, its map view pattern supports a dip-slip component of offset. The ESE–WNW striking fault that runs north of Ördög-orom is clearly a dip-slip fault.

Several steep fault zones were identified by offset, and occasionally dragged, chert layers *(Figures 2, a; 3, c)*. The dip-slip offset on these faults is generally 10–20 cm. They often involve a narrow (i.e. a few cm wide) damage zone in the dolostone, showing more pronounced brecciation than in the host rock.

A peculiar feature was identified next to a bunker entrance that is accessible from the road at the base of the cliff (47°28’56.02”N, 18°59’13.42”E) *(Figure 3, a)*. Strings of gently southwest-dipping chert nodules (indicative of bedding) are truncated by another chert nodule string that dips in the same direction, but at a lower angle. It was not possible to trace this relationship far beyond than shown in *Figure 3, a.* Consequently, it is difficult to determine whether this represents part of the internal geometry of a sedimentary bed form (which would provide evidence for syn-sedimentary deformation of strata) or an overthrust. Given the slope and basin setting of these sediments (HAAS 2002), erosional truncation at this scale is thought to be unlikely, and a tectonic overthrust is preferred.

Small-scale low angle thrusts, offsetting chert layers, were observed at a few locations *(Figure 2, a)*. They seem to detach in the bedding planes of the dolostone, although this is hard to prove in all cases. These thrusts are at least partly *(Figure 2, b)* related to folds by accommodating shortening on fold limbs.

Discussion

The slope and basin deposits of the Mátyáshegy Formation were commonly affected by synsedimentary deformation (HAAS 2002). It is therefore possible that the observed folds are at least partly slump folds. The reason to prefer their tectonic origin is as follows. Brittle thrusts that offset chert beds are detached on the fold limbs and accommodate fold-related shortening *(Figure 2, b)*. This geometry is uncommon in synsedimentary folds. Although fold trains could usually not be traced for longer distances due to outcrop conditions, the folds are not highly dysharmonic *(Figure 2, a)*. This also suggests their tectonic origin, although synsedimentary deformation cannot totally be ruled out either.

Accepting their tectonic origin, the style of folding at Ördög-orom is in the brittle-ductile transition zone. The deformation mechanism, however, is brittle as indicated by chevron folds in the chert layers and small-scale fold-related thrusts. The observed fold geometries suggest the contractional origin of these structures. Based on fold asymmetry, tectonic transport was generally top-to-the-west.

The scatter of ENE–WSW to NW–SE oriented shortening directions — derived from the measured folds (*Figure 3, i*) — does not clearly align to the previously known shortening phases in the Transdanubian Range (D1: NE–SW, D2: NW–SE), but is in between. This can be explained in three ways.

(1) The accuracy of fold direction measurements in the cherty dolostones on Ördög-orom was insufficient. Indeed, directions of measured fold hinges, as well as the intersection lines of folded beds as constructed fold axes, scatter

between ENE–WSW and NW–SE, inhibiting a differentiation between the two main phases known in the region.

(2) The folds on Ördög-orom formed during the transition from D1 to D2, i.e. during the Early Albian. A similar transitional phase was proposed by SASVÁRI (2009) for the Gerecse Hills (further west within the Transdanubian Range). This model would imply an extremely rapid phase of folding which, based on the available data, cannot be ascertained.

(3) The Buda Hills underwent differential rotation relative to more western parts of the Transdanubian Range after the formation of folds. The differential rotation of the western and eastern parts of the Transdanubian Range (the latter including the Buda Hills) was proposed by MÁRTON (1998). As the folding direction at Ördög-orom could only be determined within a wide range, again no clear conclusion can be drawn.

Five of the few proven reverse faults indicate NE–SW shortening (in accordance with the D1 phase), while there is a single reverse fault which suggests NW–SE shortening (in accordance with the D2 phase) *(Figure 3, g)*.

The Palaeogene – Early Miocene of the Buda Hills was characterised by transpressional deformation (D3 phase) (FODOR et al. 1994). Some folds with NE–SW oriented axes in other parts of the Buda Hills were assigned to this phase (FODOR et al. 1994). Despite the relatively poor 3D exposure, the observed folds at Ördög-orom do not appear to be arranged in *en échelon* manner, but seem purely contractional. Therefore, they are unlikely to have been formed during the D3 phase.

Strain perturbations might have played an additional role in the scatter of folding and thrusting directions in structures that were most likely formed during a single deformation phase.

The normal faults and the majority of undetermined steep joints are most likely related to Miocene and Quaternary tectonics (cf. FODOR et al. 1999).

Conclusions

The chert layers and strings of chert nodules in the Triassic dolostones at Ördög-orom indicate slightly asymmetric folding. Small-scale thrusts, being detached in bedding planes, are related to folding. These structures indicate a brittle deformation mechanism. Tectonic transport directions scatter between WSW and NW. The age of this phase is inferred to be Early Cretaceous. The dolostones were affected by intense fracturing and brecciation in multiple directions.

Acknowledgements

The field support of Dávid BAJNAI and László SKUBLICS, the technical help of Mihály PALOTAI, and the permission of the Mayor's Office of Budapest Council to carry out this study, are highly appreciated. This study benefited from the thorough reviews of Norbert NÉMETH and Jozef HÓK, and the helpful comments of the handling editor, László FODOR. This is Cambridge Earth Sciences contribution ESC.3578.

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Kézirat beérkezett: 2015. 9. 29.