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Results, problems and future tasks of palaeostress and fault-slip analyses in the Pannonian Basin: the Hungarian contribution

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Feszültségmező- és vetőminta-elemzés eredményei, problémái és további feladatai a Pannon-medencében: a magyar kutatók hozzájárulása

Összefoglalás

A Pannon-medencében a modern paleofeszültség-meghatározás és töréses szerkezetelemzés Françoise Bergerat, Jacques Geyssant and Claude Lepvrier munkájával 1982–1984-ben kezdődött. Miután F. Bergerat néhány magyar kutatónak megtanította a módszer terepi és laboratóriumi eszköztárát, a modern töréses szerkezetelemzés kiterjedt a Pannon-medence magyarországi részére, néhány azzal határos területre, és máig is tart. Ez a munka az elmúlt 35 év eredményeit, a meghatározott kainozoos feszültségmezőket, határaikat és meghatározási bizonytalanságaikat veszi számba, egyfajta tudománytörténeti nézőpontból. A kutatás során felállított szerkezetfejlődési modell egyre összetettebb lett, és egyre több részletet ismertünk fel mind az Alcapa, mind a Tisza–Dacia tektonikai egységek deformáció-történetében. A paleomágneses és feszültségmező-adatok integrálásával igazoltuk, hogy a feszültségtengelyek és töréses elemek változása gyakran csak a kőzetblokkok függőleges tengely körüli forgásának köszönhető, és nem tükrözi a feszültségmező tényleges forgását. A billentésteszttel, a deformált kőzetek új radiometrikus kormeghatározásával és a felszíni és felszín alatti adatok együttes felhasználásával a feszültségmező-fejlődés nagyon finom tagolása és az irány szerint azonos mezők felújulásának kimutatása vált lehetségessé. A finomított fejlődéstörténeti modell segítségével néhány fázisra igazolni lehetett a heterogén feszültségmező fellépését. Az eredmények ellenére a töréses fázisok számát, egy adott fázis pontos időzítését és maximális feszültségtengelyének térbeli változásait a jövőben is vizsgálnunk kell. A deformált anyag reológiai viselkedésének és a töréses deformáció fizikai paramétereinek megértése szintén jövőbeni kutatási feladat, amelyet a deformációs szalagok, a folyadékzárványok és izotópok vizsgálatán keresztül végezhetünk el abból a célból, hogy jobban megértsük a deformáció, süllyedéstörténet, diagenezis és folyadékáramlás kapcsolatát.

Kulcsszavak: feszültségmező, vető, feszültségmeghatározás, forgás, kibillenés, Pannon-medence

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Abstract

In the Pannonian Basin fault-slip analysis and palaeostress determinations started in 1982–1984 by the work of Françoise Bergerat, Jacques Geyssant and Claude Lepvrier. After F. Bergerat introduced some Hungarian researchers to field and laboratory techniques, fault-slip analysis expanded into the Pannonian Basin in Hungary and in some adjacent areas, and is still going on. This paper reviews the results achieved during this ~35 year time span from a historical perspective, by the compilation of the determined Cenozoic stress fields, their temporal boundaries, and uncertainties. The model for the evolution of the stress field became more complicated, and more and more details in the deformation history were realised, both in the Alcapa and Tisza–Dacia units of the Pannonian Basin. The integration of palaeomagnetic and stress data indicated that some changes in stress axes (and in fault orientation) are due to vertical-axis block rotation, and are not real rotation of the external stress field itself. With the development of new approaches, like tilt test, combination of surface and subsurface fault data, radiometric age determination of deformed rocks, fine separation of fracture sets can be achieved and the multiple recurrences of stress fields with identical principal axes were demonstrated. The refined methods permitted the demonstration of basin-wide inhomogeneity of the stress field for some phases. However, the precise timing, the number of phases, separation of events with similar stress axes, and the variability of the maximal stress axes of a given stress field remain the major questions to be solved in the future. Rheological conditions of the deforming media and physical parameters of the fracturing will be the other future steps in research, to be achieved by studies of deformation bands, fluid inclusions, isotopes, in order to better understand the connection of deformation, subsidence, diagenesis, and fluid flow.

Keywords: stress field, fault, stress inversion, rotation, tilt, Pannonian Basin

Introduction – palaeostress and fault-slip analysis

Palaeostress and fault-slip analysis depict the geometry, kinematics, and dynamics of brittle structures (faults, joints, veins, etc.) observed in natural or artificial outcrops. In fact, this systematic method replaced earlier directional measurements which were unable to find genetic connections between the observed fracture systems (e.g. BALÁSHÁZY 1977 in Hungary). The key to understand the mechanics of brittle deformation comes from the early works of ANDERSON (1905, 1942) followed by WALLACE (1951) and BOTT (1959) which revealed the relationship of principal stress axes and faults, joints and dykes.

The field and analytical techniques were developed in the 1970s, mostly by French geologists. First, they solved the problem of the connection of the stress state of a point and the observed fault planes containing the striae by having established a simplified stress tensor which, as a second-order mathematical tensor, determines this functional relationship (CAREY & BRUNIER 1974, ANGELIER 1979a). Behind the model of this simple mathematical function, researchers supposed the unequivocal connection of the observed striae and the shear stress component resolved on the fault plane; this is why that this line of research refers to stress axes and faults, and not to kinematic axes. Although this presumption was proved not to be universal (MAERTEN 2000), but it is reliably acceptable for most cases. The computed stress axes are numerically well-defined although inherently have uncertainties. Nevertheless, numerical methods better characterise the stress state of deformation, rather than, for example, the graphical solutions for faults and stress; this latter method gives only wide spatial domains for possible locations of the axes and does not issue the ratio of axes (ANGELIER & MECHLER 1977, ALEXANDROWSKI 1985).

The first theoretical results were soon followed by the development of field measurement technique and computing methods (ANGELIER 1984, 1990), and the first interpretations of field studies (ANGELIER 1979b). This technique had later wide application in structural studies, while the determined stress regimes were extrapolated to large areas, sometimes to plates, and were used to characterise the structural evolution of plate boundaries and interiors (e.g. ANGELIER et al. 1986).

Several improvements and approaches were developed from these early years of research to recent times, and their complete list is beyond the scope of this contribution (NEMČOK & LISLE 1995, DELVAUX & SPERNER 2003, YAMAJI et al. 2003, ŽALOHAR & VRABEC 2008 and GERNER 1990, SIPOS 2013 in Hungary). Separation of fracture sets into phases still remains problematic. The easiest solution is the manual separation, supported by calculations of separated fracture sets. Later, computer-assisted methods were developed (ANGELIER & MANOUSSIS 1980), and recently included very sophisticated mathematic approaches (KERNSTOCKOVÁ & MELICHAR 2009, SIPOS et al. 2018).

Another school of fault-slip analysis elaborated a parallel, although not completely separated line of research, which is using kinematic axes instead of stress axes (MARRET & ALLMENDINGER 1990). The debate has not been closed (till some years ago) if the calculated axes can be named 'stress', 'kinematic' or 'strain' axes (MARRET & PEACOCK 1999).

The stress and fault-slip analysis was used in Hungary from its very early stage of methodological development, starting with pioneer works of Francoise BERGERAT, Jacques GEYSSANT and Claude LEPVRIER (BERGERAT et al. 1983b, 1984a, b). Subsequent visits of F. BERGERAT, and the PhD studies of some of us in France (L. CSONTOS, L. FODOR, L. BENKOVICS) helped to establish this method in Hungary, and later, in the whole Pannonian Basin. The goal of this contribution is to follow the evolution of knowledge on the palaeostress fields of the Pannonian Basin, which have implication on understanding of map-scale tectonic features. Although, this is a historical review, but sometimes I would try to draw modest conclusions on the results by formulating which seems to be (still) valid, where are the problems to be solved, and by giving estimations on future research directions. A secondary goal is to provide a fairly complete compilation of Hungarian publications dealing with palaeostress and fault-slip analysis; such list may help readers to use the appropriate works in their own research.

This summary is published in the memorial volume of Frank HORVÁTH because he realised the importance of knowledge on recent and palaeostress fields. In the ISES project of the early 1990s, he strongly encouraged us to conduct such research, he invited us to conferences, involved us in international cooperation, particularly with the Vrije Universiteit, Amsterdam, which resulted in common publications, PhD thesis (e.g. BADA 1999). Our second summary of stress field (FODOR et al. 1999) issued from this international cooperation, and was definitely catalysed by Frank.

Stress field data in time and by regions

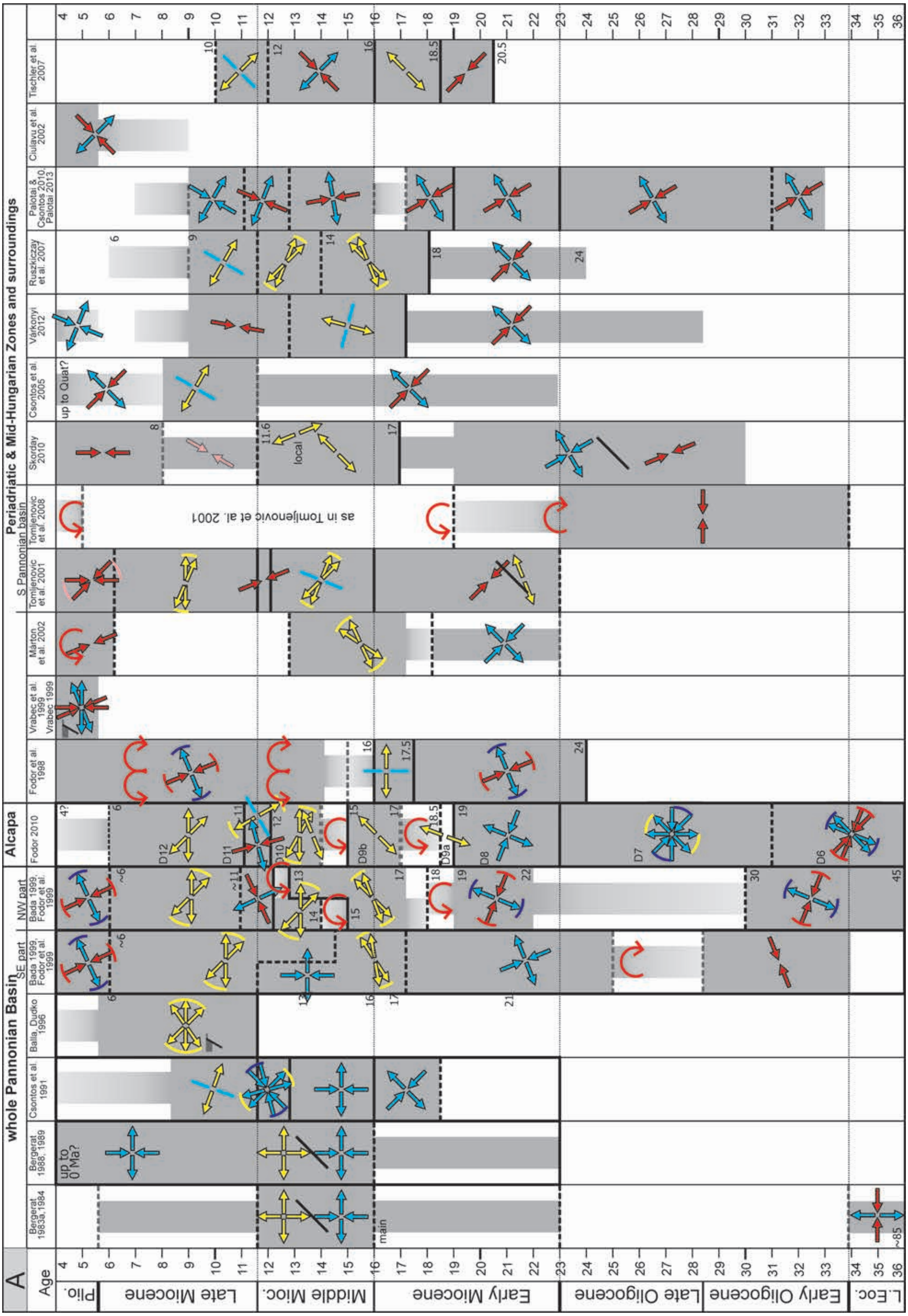
Presentation of stress field data

In this communication I compiled a table from most of works which presented palaeostress data (*Figure 1*).

Of course, such a compilation cannot be complete, my

→ **Figure 1.** Stress axes and deformation phases in the Pannonian Basin. A) Results of the main summary studies, and data from parts of the Alcapa unit and from the Periadriatic and Mid-Hungarian Shear zones and their vicinity (southern Pannonian Basin in Croatia). B) Results of studies from the southwestern part of the Transdanubian Range. C) Results of studies from the NE part of the Transdanubian Range, northern Hungary and southernmost Slovakia. D) Results from studies in the Bükk Mts., Darnó zone, Aggtelek–Rudabánya Hills, and Tokaj Mts. E) Results of studies from the Tisza–Dacia unit. All data for Cenozoic deformation younger than Middle Eocene. Legend see Figure 1, E

→ ***1. ábra.*** *Feszültségtengelyek és töréses deformációs fázisok a Pannon-medencében, magyar kutatók munkái alapján. A) A fő összefoglaló tanulmányok és a Periadriai- és Közép-magyarországi-zónákról szóló munkák eredményei. B) A Dunántúli-középhegység DNy-i részéről szóló tanulmányok eredményei. C) A Dunántúli-középhegység ÉK-i részéről, Észak-Magyarországról és Dél-Szlovákiáról szóló tanulmányok eredményei. D) A Bükk, Darnó-zóna, Aggtelek–Rudabányai-hegység, a Tokaji-hegység feszültségadatai. E) A Tisza–Dacia-egység feszültségadatai. Csak a középső-eocénnél fiatalabb fázisok kerültek ábrázolásra. Jelkulcs az ábra E részén*


A
Age
Plio.
Late Miocene
Middle Mioc.
Early Miocene
Late Oligocene
Early Oligocene
L.Eoc.
whole Pannonian Basin
Alcapa
Periadriatic & Mid-Hungarian Zones and surroundings
S.Pannonian basin
SE part
NW part
Bergerat 1983a,1984
Bergerat 1988, 1989
Csontos et al. 1991
Balla, Dudko 1996
Bada 1999, Fodor et al. 1999
Bada 1999, Fodor et al. 1999
Fodor 2010
Fodor et al. 1998
Vrabec et al. 1999 Vrabec 1999
Márton et al. 2002
Tomljenovic et al. 2001
Tomljenovic et al. 2008
Skorday 2010
Csontos et al. 2005
Várkonyi 2012
Ruszkiczay et al. 2007
Palotai & Csontos 2010 Palotai 2013
Ciulavu et al. 2002
Tischler et al. 2007
main
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up to 0 Ma?
as in Tomljenovic et al. 2001
up to Quat?
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D9b
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D11
D12
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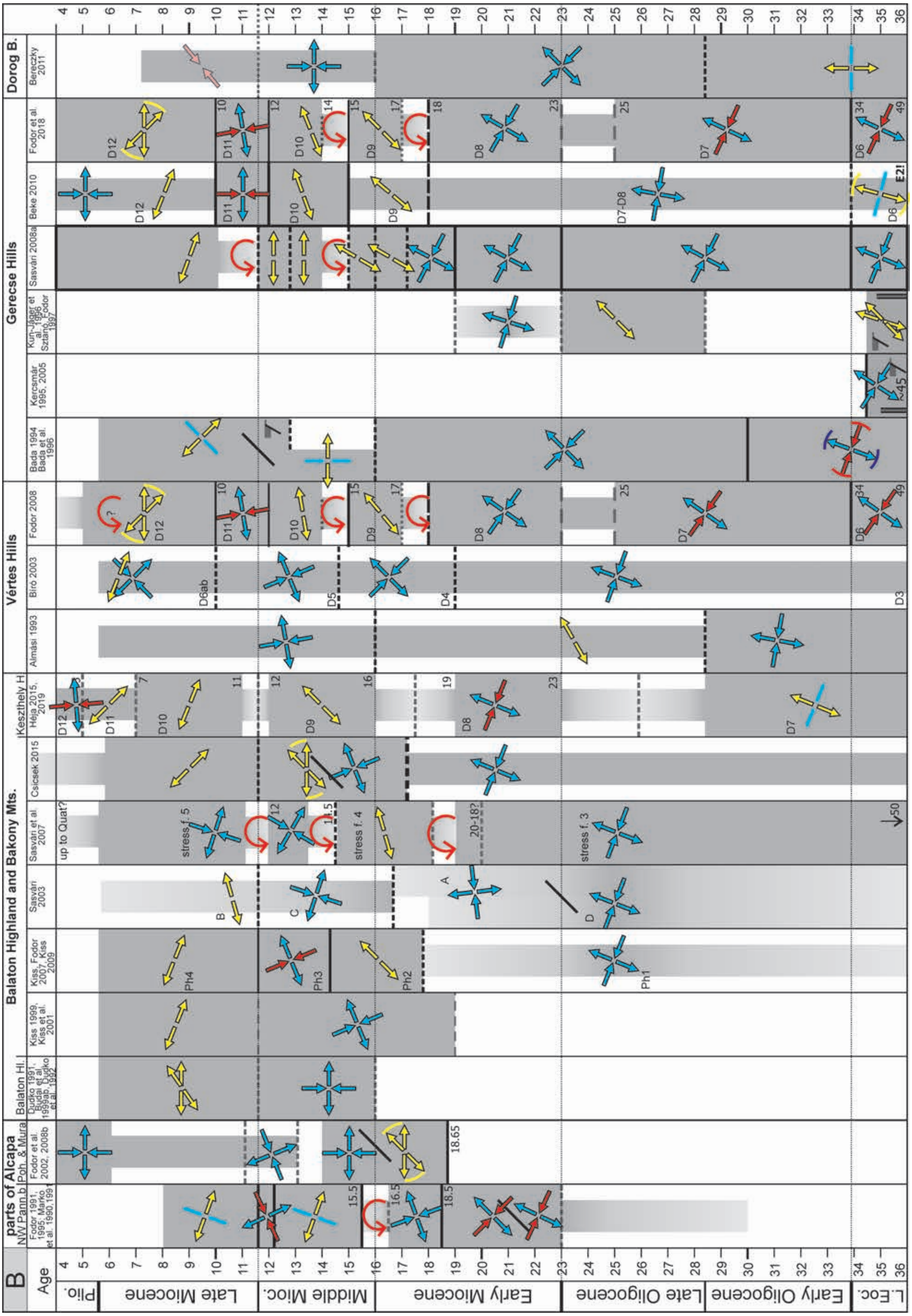
B
Age
Plio.
Late Miocene
Middle Mioc.
Early Miocene
Late Oligocene
Early Oligocene
L.Eoc.
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parts of Alcapa
NW Pann.b
Poh. & Mura
Fodor 1991, 1995; Markó et al. 1990,1991
Fodor et al. 2002, 2008b
Balaton Hl.
Dudko 1991, Budai et al. 1999ab, Dudko et al. 1992
Balaton Highland and Bakony Mts.
Kiss 1999, Kiss et al. 2001
Kiss, Fodor 2007, Kiss 2009
Sasvári 2003
Sasvári et al. 2007
Csicsek 2015
Keszthely H
Héja 2015, 2019
Vértes Hills
Almási 1993
Bíró 2003
Fodor 2008
Gerecse Hills
Bada 1994 Bada et al. 1996
Kercsmár 1995, 2005
Kun-Jáger et al. 1995 Sztanó, Fodor 1997
Sasvári 2008a
Beke 2010
Fodor et al. 2018
Dorog B.
Bereczky 2011
15.5
16.5
18.5
18.65
Ph4
Ph3
Ph2
Ph1
A
B
C
D
up to Quat?
stress f. 5
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14.5
stress f. 4
20-18?
stress f. 3
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D12
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D8
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E2!
D7-D8
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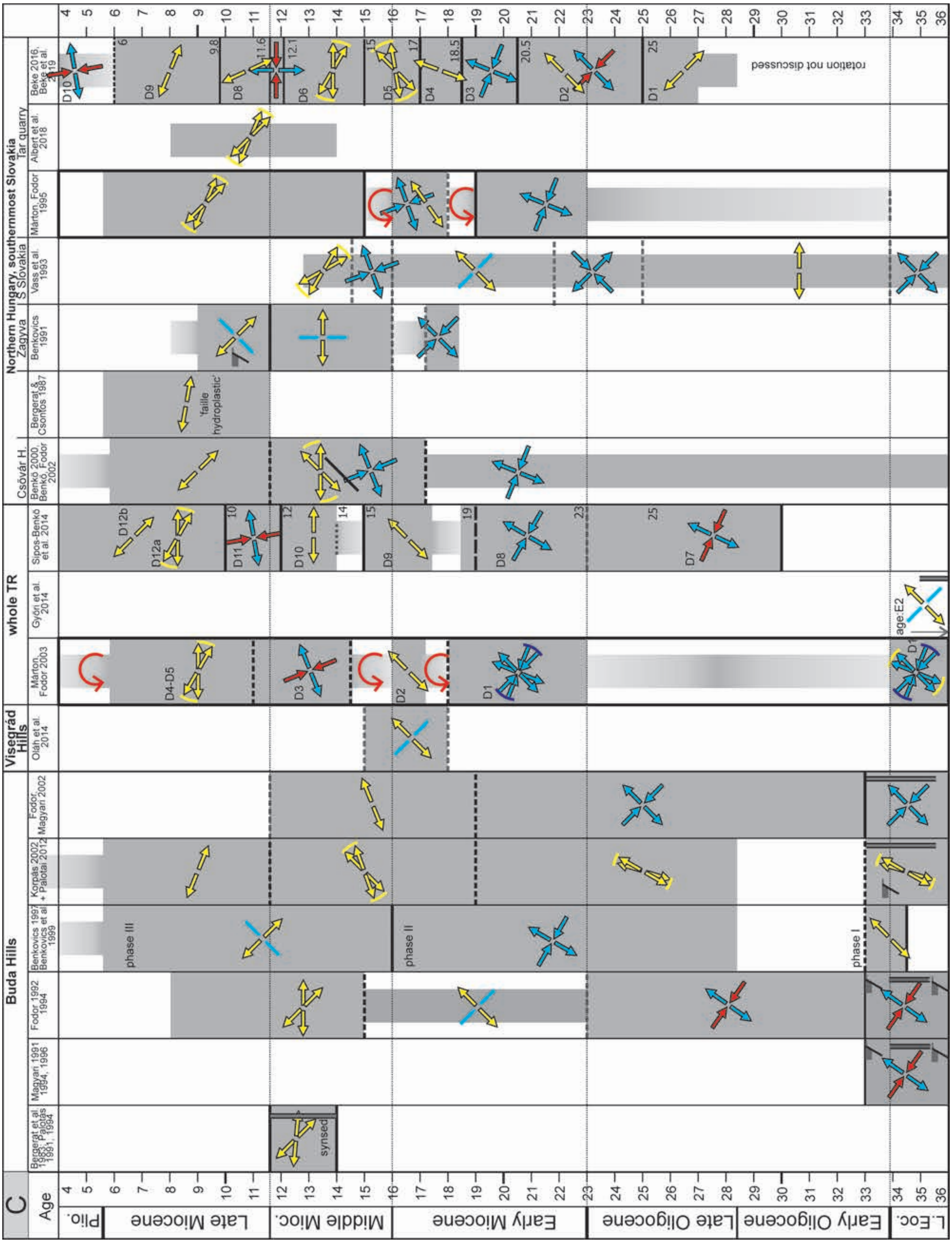
C
Age
Plio.
Late Miocene
Middle Mioc.
Early Miocene
Late Oligocene
Early Oligocene
L.Eoc.
Buda Hills
Bergerat et al. 1983; Pálotás 1991, 1994
Magyari 1991 1994, 1996
Fodor 1992 1994
Benkovics 1997 Benkovics et al 1999
Korpás 2002 + Palotai 2012
Fodor, Magyari 2002
Visegrád Hills
Oláh et al. 2014
whole TR
Márton, Fodor 2003
Győri et al. 2014
Sipos-Benkó et al. 2014
Csővár H.
Benkó 2000, Benkó, Fodor 2002
Northern Hungary, southernmost Slovakia
Bergerat & Csontos 1987
Zagyva
Benkovics 1991
S Slovakia
Vass et al. 1993
Márton, Fodor 1995
Tar quarry
Albert et al. 2018
Beke 2016, Beke et al. 2019
synsed
phase I
phase II
phase III
'faille hydroplastic'
D1
D2
D3
D4-D5
age:E2
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D12a
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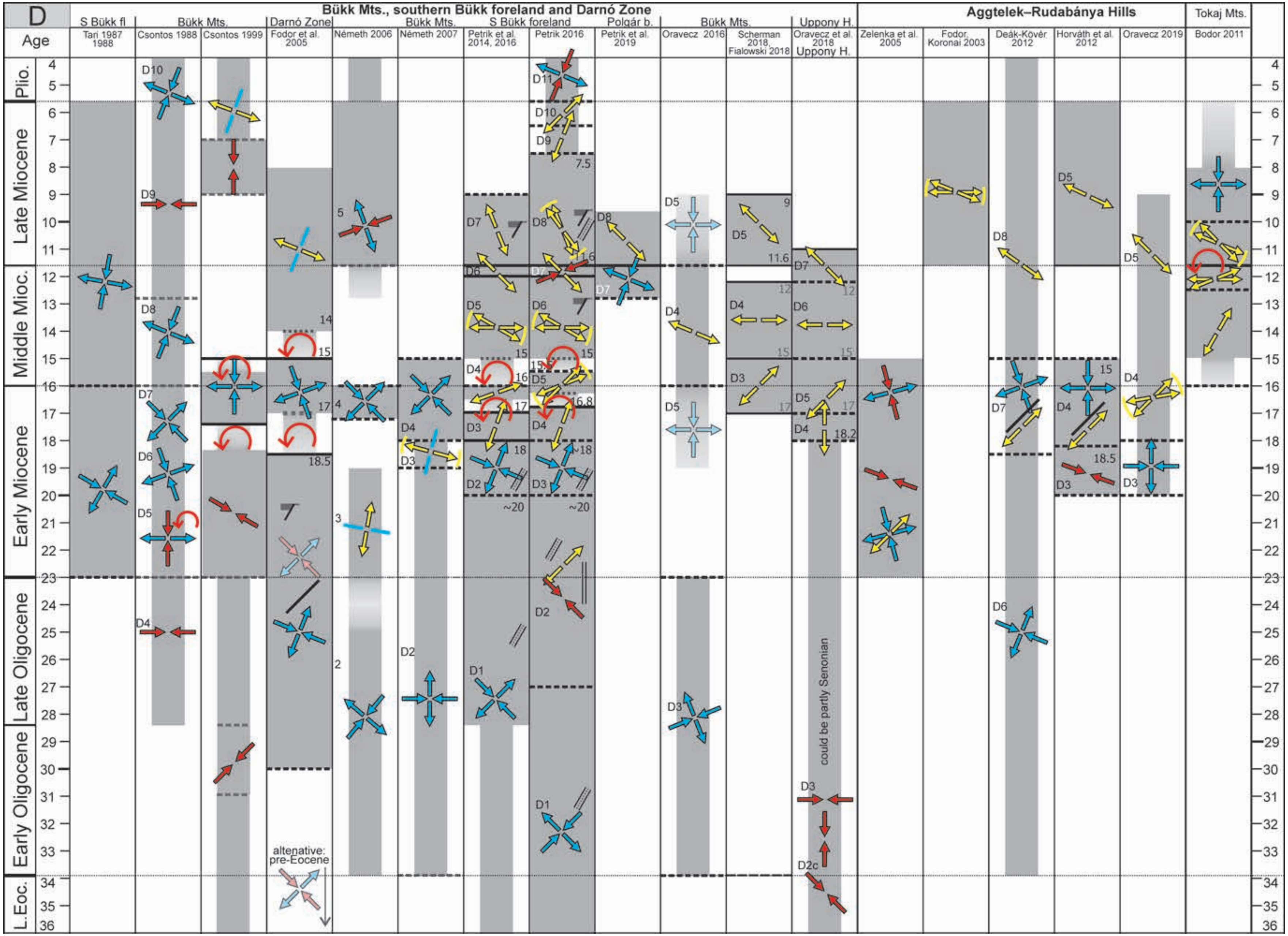
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Age
Plio.
Late Miocene
Middle Mioc.
Early Miocene
Late Oligocene
Early Oligocene
L.Eoc.
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Bükk Mts., southern Bükk foreland and Darnó Zone
S Bükk fl
Tari 1987 1988
Bükk Mts.
Csontos 1988
Csontos 1999
Darnó Zone
Fodor et al. 2005
Németh 2006
Bükk Mts.
Németh 2007
S Bükk foreland
Petrik et al. 2014, 2016
Petrik 2016
Polgár b.
Petrik et al. 2019
Bükk Mts.
Oravecz 2016
Scherman 2018, Fialowski 2018
Uppony H.
Oravecz et al. 2018 Uppony H.
Aggtelek–Rudabánya Hills
Zelenka et al. 2005
Fodor, Koronai 2003
Deák-Kövér 2012
Horváth et al. 2012
Oravecz 2019
Tokaj Mts.
Bodor 2011
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could be partly Senonian
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18.5
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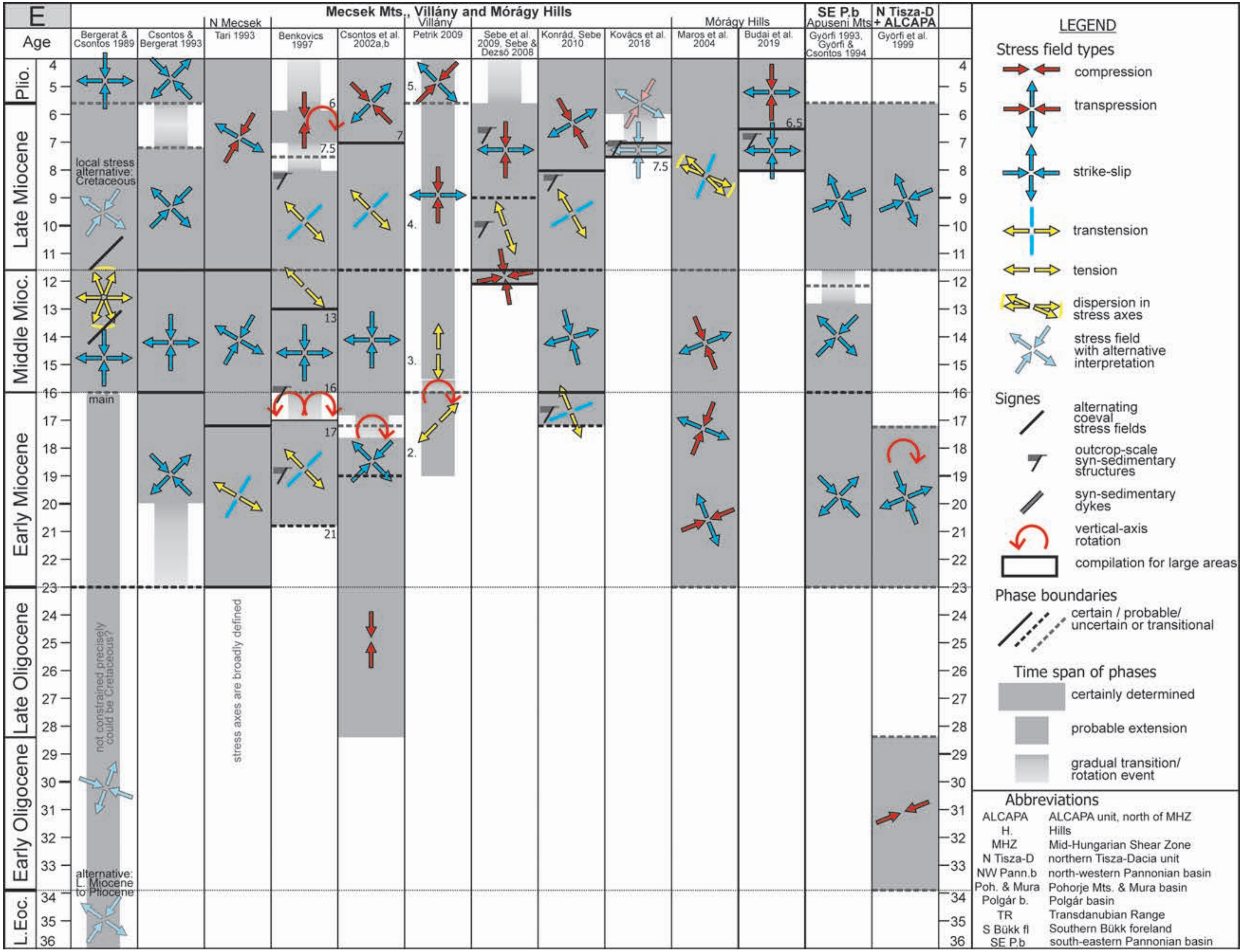
E
Age
Plio.
Late Miocene
Middle Mioc.
Early Miocene
Late Oligocene
Early Oligocene
L.Eoc.
Mecsek Mts., Villány and Mórágy Hills
N Mecsek
Villány
Mórágy Hills
SE P.b Apuseni Mts
N Tisza-D + ALCAPA
Bergerat & Csontos 1989
Csontos & Bergerat 1993
Tari 1993
Benkovics 1997
Csontos et al. 2002a,b
Petrik 2009
Sebe et al. 2009, Sebe & Dezső 2008
Konrád, Sebe 2010
Kovács et al. 2018
Maros et al. 2004
Budai et al. 2019
Győrfi 1993, Győrfi & Csontos 1994
Győrfi et al. 1999
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local stress alternative: Cretaceous
main
not constrained precisely could be Cretaceous?
alternative: L. Miocene to Pliocene
stress axes are broadly defined
6
7.5
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16
17
21
7
5.
4.
3.
2.
7.5
6.5
LEGEND
Stress field types
compression
transpression
strike-slip
transtension
tension
dispersion in stress axes
stress field with alternative interpretation
Signes
alternating coeval stress fields
outcrop-scale syn-sedimentary structures
syn-sedimentary dykes
vertical-axis rotation
compilation for large areas
Phase boundaries
certain / probable/ uncertain or transitional
Time span of phases
certainly determined
probable extension
gradual transition/ rotation event
Abbreviations
ALCAPA ALCAPA unit, north of MHZ
H. Hills
MHZ Mid-Hungarian Shear Zone
N Tisza-D northern Tisza-Dacia unit
NW Pann.b north-western Pannonian basin
Poh. & Mura Pohorje Mts. & Mura basin
Polgár b. Polgár basin
TR Transdanubian Range
S Bükk fl Southern Bükk foreland
SE P.b south-eastern Pannonian basin

apologies for eventual deficiency. On the *Figure 1* only post-middle Eocene palaeostress data are presented, but in the text Mesozoic structural data are mentioned as well. I did not consider Quaternary data because their origin and timing can be debated and this topic in fact merits an independent publication. *Figure 1* shows the palaeostress evolution, using the stress field types and very simplified and averaged stress axes, sometimes with dispersion ranges of axial directions, sometimes with two main directions. Several works could be unified and reported by one set of signs.

I classified the structural phase boundaries (change between stress fields) given in publications as being certain, probable, or uncertain; the latter two cases are applied when the timing was not clearly formulated, when it remained poorly constrained by the original data, or simply when I did not get the message from the work. For clearly identifiable stratigraphic boundaries I used the presently accepted numerical ages (Geological Time Scale 2016 and for some Paratethys stages, SANT et al. 2017). When phase boundaries were not precisely formulated or there seems to be discrepancy between the text and figures an arbitrary boundary is presented.

Grey background shading indicates suggested temporal extension of a given phase, when I (subjectively) considered data less convincing, only narrow columns are used. Narrow columns with transitional grey shading indicate uncertainties due to lack of precise time constraints or when transition from one stress field to the other seems to be gradual. Time spans of rotations are also indicated in this way, mostly because registered stress axes should change continuously during such deformation, so a sharp boundary is difficult to set up. Specific signs for the types of structures (e.g. synsedimentary faults and dykes) are given. Spatially variable stress field is difficult to visualise, but I tried to indicate coeval stress axes.

Publications and Master or PhD theses are listed approximately chronologically. However, this rule has been changed in order to juxtapose spatially closely related results. This spatial distribution led to juxtaposition of works from different regions of the Alcapa unit (*Figure 1, B–D*); these are the Transdanubian Range (TR, subdivided into Bakony–Balaton Highland, Vértes, Gerecse, and Buda Hills), northern Hungary (between the Buda Hills and Darnó Zone) and NE Hungary (Darnó Zone, the Bükk Mts. and the Aggtelek–Rudabánya Hills and the Tokaj Mts.). Within these areas I try to present the data in one direction (generally from SW to NE). Some studies about the Periadriatic Fault and Mid-Hungarian Shear Zone are also shown where stress axes were determined or inferred (*Figure 1, A*). Because of the Miocene rotation history is different in the two main units of the country (Alcapa and Tisza–Dacia), data from the Mecsek–Villány area, and from the south-eastern Pannonian Basin are shown and described separately (*Figure 1, E*). I will mostly concentrate on data from Hungary, and marginal parts of the Pannonian Basin will only occasionally be mentioned.

I will not always refer to this figure in the text, it would lead to very frequent citation. In most cases, the text will not describe the complete stress field evolution of the cited author (the figure should do this), but I may subjectively emphasise the most important recognition(s).

Fault mapping and kinematics without the palaeostress approach

Before going into details of palaeostress analyses, I mention the older approach which dealt with mapping of faults and sometimes also with the determination of their kinematics. In fact, most maps showing fault systems could be mentioned here although the often rectilinear geometry, orthogonal fault orientation, and other aspects of fault presentation can strongly be criticised. Among the researchers who influenced positively the fault analysis of Hungary, J. MÉSZÁROS is to be mentioned first, who described systematically dextral strike-slip fault system in the Bakony Mts. which is still basically valid (MÉSZÁROS 1982, 1983). The works of BALLA (1984, 1988a, b) and BALLA & DUDKO (1989) gave a coherent evolutionary scheme for the Pannonian Basin structures, and are of very large importance; in fact, these works influenced our thinking since the time of publications. Although they did formulate their results in fault geometry, kinematics, and timing, it would be possible to convert the conclusion into stress data. A great number of publications have significant data on the brittle structural evolution of the Pannonian Basin, both from subsurface data sets, and from maps (BREZSNYÁNYSZKY & HAAS 1990, BREZSNYÁNYSZKY & SÍKHEGYI 1987; FÜLÖP 1990; JASKÓ 1988, 1989; HORVÁTH 1990, 1995; HORVÁTH & RUMPLER 1984; ROYDEN & HORVÁTH 1988; HORVÁTH & TARI 1999; TARI et al. 1992, 1999; CSONTOS 1995; DETZKY-LŐRINCZ et al. 2002; HAAS et al. 2010; TARI & HORVÁTH 2010; HORVÁTH et al. 2015) but this work will concentrates only on those ones which have an approach of palaeostress and fault-slip analysis. All works dealing with the origin, evolution, and geometry of the faults in the Pannonian Basin will not be referred, despite their tremendous contributions to the topic of faults.

Early structural observations – close to the palaeostress conception

An interesting precursor work was published by BOKOR (1939). He was aware of the relation of Mohr fractures, shear stress, stress ellipsoid and “deformation axes”. He measured joints in the Buda Hills, and suggested N–S compression. However, he considered all fractures with strike-slip character, an error which led him in a dubious estimation of stress axes.

Another approach tried to find the “pair of compressional forces”, which can be considered as a precursor of compression in modern palaeostress terminology, although the physical basis was not clearly presented (and maybe not understood). In this line, BALKAY (1960) estimated NW–SE directed such “forces” in the northern Bükk Mts. This work, and, among many others, one of TOMOR-THIRRING (1936) and ZELENKA (1975) represent examples of outcrop-scale structural observations, although still far from modern fault-slip analysis.

In the *Transdanubian Range* MAROS (1986, 1988) carried out modern fault mapping and outcrop-scale kinematic observations without using sophisticated computer techniques; his kinematic observations were valuable (e.g. strike-slip character of the Vértessomló Line), but comparison with modern stress data is not easy due to lack of timing of the phases (this is the reason it is not shown on *Figure 1, A–E*). TARI (1991) also used the information on kinematics of some dextral faults, and established his model on the rotation of these faults, although stress axes were not deduced from his analyses.

Results of early palaeostress studies (1982–1991)

The first modern fault-slip measurements of BERGERAT, GEYSSANT and LEPVRIER and the subsequent palaeostress calculations were completed in 1982–1984 and were mainly done on Mesozoic rocks, where fault-slip observations are much easier than on Cenozoic rocks. The first results suggested multidirectional extension, connected to, or alternating with, strike-slip regime (BERGERAT et al. 1983b, 1984a, b) (*Figure 1, A*). Pre-Miocene E–W compression was also recognised but with poor time constraints. Syn-sedimentary late Badenian to Sarmatian extension was also documented in *the Buda Hills* (*Figure 1, C*) (BERGERAT et al. 1983a).

In the *first basin-wide summary* of fault-slip data BERGERAT (1988, 1989) suggested the alternation of strike-slip regime with E–W tension and locally developed N–S (graphically NNW–SSE and NNE–SSW) tension through the whole Miocene and Pliocene. In her model extensional deformation developed between important strike-slip zones. This model was partly based on field works in the *Mecsek–Villány* area (BERGERAT & CSONTOS 1988).

The effect of this methodological know-how is clearly visible on the parallel structural analysis and mapping of the *Bükk Mts*. which, in addition to valuable fault kinematic data within the mountains, led to the first sketchy fault-slip analysis of the *Bükk Mts. and their southern foreland* (*Figure 1, D*). CSONTOS (1988) in his first work separated six Cenozoic deformation phases and attributed a number of ductile structures to these events. Later he revised the timing of phases (CSONTOS 1999) and he incorporated the vertical-axis rotations to explain changes in the stress axes. At the same time of the early analysis in the Bükk, TARI (1987, 1988) conducted a pioneer work in the *southern foreland* (Vatta–Maklár trough) analysing seismic reflection profiles, and comparing the derived fault pattern to surface fault-slip data. He established the strike-slip origin of this basin. A small study of few outcrops of Miocene coal and lignite documented roughly E–W tension governing "hydroplastic faults" (*Figure 1, D*) (BERGERAT & CSONTOS 1987).

In the meantime, the author of this contribution completed his PhD work on the Vienna and satellite basins in the *north-western part of the Pannonian Basin system*, and it was one of the first detailed studies of a small region (*Figure 1, A*), (FODOR 1991, 1995; FODOR et al. 1990; MARKO et al. 1990, 1991). In these works, clear clockwise change in stress field appeared, from Oligocene to end-Sarmatian, and a counter-clockwise change, back to ESE–WNW extension, after the Sarmatian. As a local synthesis, MARKO et al. (1995) summarised fault-slip and stress field data for the Slovakian part of the Vienna and surrounding Miocene basins.

All these works led to the *second synthesis* of observations and analyses on palaeostress fields of the *entire Pannonian Basin* (CSONTOS et al. 1991) (*Figure 1, A*). This work emphasised the clockwise change in the palaeostress axes through the Miocene, and connected this change to the temporally varying deformations in the external flysch belt of the Carpathians. Although we mainly referred to the 'orogenic vectors' of JIŘÍČEK (1979), a term uncertain in nature, our main result probably was to establish the connection of deformation events at the front of the Carpathian orogen and inside the hinterland (Pannonian back-arc basin). In several of our works published in those years we clearly recognised the close temporal connections of the changing palaeostress axes and gradual shift of the main external thrusting along the Carpathian front (FODOR et al. 1990, CSONTOS et al. 1991, FODOR 1995, FODOR & CSONTOS 1998).

Results of palaeostress studies from 1991 to 1999

Following these early years, during the 1990s several works concentrated in small areas, and have issued precisions for the general stress field evolution or found local features. They were mostly MSc theses, but their conclusions seem to be well-based on the newly learnt technique.

In the *Balaton Highland* and *southern Bakony Mts.,* during the geological mapping work DUDKO (1991), DUDKO et al. (1992) and BUDAI et al. (1999a, b) described the observed brittle structures, comprising Cretaceous thrusts and folds, and Miocene strike-slip versus extensional basin formation phases (*Figure 1, B*).

In the Gánt quarries of the *Vértes Hills* ALMÁSI (1993) confirmed the same Eocene to Oligocene stress field as has been documented in the Buda Hills. He was the first to realise the very local stress field inhomogeneity around fault oversteps; an idea explored later in detail by FODOR (2007). The recognised E–W trending strike-slip faults are similar to those ones found by GYALOG (1992) in the close vicinity.

In the Gerecse Hills, BADA (1994) collected a great number of data and separated 7 phases, three of them being Mesozoic in age (BADA et al. 1996). Although recent summary (FODOR et al. 2018) seems to refine the stress field evolution, and may change the age of some measured faults from Miocene to Mesozoic, the recognised stress fields are valid. KUN-JÁGER et al. (1996) recognised not only the tensional stress fields but also the geometry of syn-rift faults within the central Gerecse, most of their remarks became verified during later works (MURÁTI 1997, ÁDÁM et al. 2001, compare also with FODOR et al. 2018). LANTOS (1995, 1997) and KERCSMÁR (1995) estimated Jurassic and Eocene stress fields from sedimentary dykes and other syn-sedimentary structures; these results were extended later (LANTOS 2004 and KERCSMÁR 2005, KERCSMÁR & FODOR 2005). SZTANÓ & FODOR (1997) demonstrated Late Eocene extensional stress field and a younger (Eggenburgian?) strike-slip type field with similar ρ_3 axis, in a later disappeared northern Gerecse road cut (Nyergesújfalu).

In the Buda Hills MAGYARI (1991, 1994, 1996, 1998) extended our knowledge on the Eocene deformation, determining (E)SE–(W)NW compression and perpendicular tension and placed the deformation in the context of the overview work of FODOR et al. (1992, 1994) (*Figure 1, C*). These latter ones extended the Eocene stress field into the Oligocene and early Miocene based on deformed Eocene rocks, and also on the palaeogeographic evolution of the Buda Hills. BALLA & DUDKO (1990) observed SSE vergent folds in the Oligocene, what they dated as Miocene; this could fit into the stress history described above. The compressional–transpressional origin of the Buda Hills is in agreement with the model of TARI et al. (1993) based on large-scale geodynamic interpretation and subsidence data. PALOTÁS (1991, 1994) completed the knowledge on the Sarmatian syn-sedimentary deformation of the Tétény plateau already observed by BERGERAT et al. (1983a). BENKOVICS (1997) and BENKOVICS et al. (1999) recognised E–W trending dextral shear zones, similar to those observed by FODOR et al. (1994) and MAGYARI (1996).

In *NE Hungary*, BENKOVICS (1991) characterised the *Zagyva graben* as marked by ESE–WNW extension, and he realised several deformation episodes with similar or slightly changing stress axes (*Figure 1, C*). He also found a still enigmatic stress field with E–W horizontal σ_1 axis, similar to the findings of NEMČOK et al. (1989) and FODOR et al. (1990) in the Vienna Basin. Just north from this graben system, in southernmost Slovakia, palaeostress determinations resulted in six pre-Pliocene phases with strike-slip, transtensional or extensional character (VASS et al. 1993). An alternative interpretation of phase boundaries were later presented in the work of FODOR et al. (1999), mostly based on data of a common field trip with Slovak colleagues.

Methodological advance — palaeomagnetism and palaeostress

Palaeomagnetic data revealing vertical-axis rotations were soon compared to stress data; probably the idea first occurred in CSONTOS (1988), FODOR & MARKO (1990), and FODOR et al. (1990) while TARI (1991) used kinematic data to infer rotations. In the preliminary work of FODOR (1991, 1995), and in the first study directly comparing stress and palaeomagnetic sites, MÁRTON & FODOR (1995) concluded that the (1) two phases of vertical-axis rotations and two changes in the maximal horizontal stress axis occurred during the Miocene, (2) the block rotation happened in opposite direction with respect to changes of the stress axes (counterclockwise and clockwise, respectively), and (3) the two phenomena were coeval within the precision of time constraints. This correlation strongly suggests that most of the changes in the direction of the stress axes were apparent and only due to the physical rotation of rocks. This conclusion inspired most subsequent works, and was later extended to the Transdanubian Range (MÁRTON & FODOR 2003), to the Mecsek Mts. (BENKOVICS 1997; CSONTOS et al. 2002a, b, MAROS et al. 2004), to Medvednica Mts. (TOMLJENOVIĆ et al. 2008), and embedded in syntheses about the whole Pannonian Basin (FODOR et al. 1999).

Large summaries

BALLA & DUDKO (1996) collected a great number of data (mostly from other authors) on the fracture sets displacing Pannonian strata. They accepted the stress estimations or calculations of the original authors, and compiled the first detailed map representing stress data from the *Hungarian part of the Pannonian Basin* (*Figure 1, A*). The data set reflects heterogeneous tensional axes, ranging from NE–SW to SE–NW, with mean and frequent E–W direction. However, it is not a complete presentation of Late Miocene stress field because most fractures of that age are present in older rocks.

All these early works led to *the third basin-wide summary* of palaeostress data (FODOR et al. 1999). In this work, we confirmed for the Alcapa unit the clockwise rotation of palaeostress axes from the early Miocene to the end of Sarmatian, and afterward a change of stress axes in counterclockwise direction. This summary already integrated the conclusions of coordinated palaeomagnetic and fault-slip studies, and demonstrated that the change in palaeostress axes are apparent and are mostly (but not totally) due to vertical-axis rotations. This is the reason that apparent change in stress axes were opposite in the northern versus the southern Pannonian units (Alcapa versus Tisza–Dacia). The palaeostress data were used in a semi-quantitative tectonic reconstruction of the entire Pannonian–Carpathian region depicting the geometry of fault patterns and the dynamic background of deformations. The stress trajectories were restored by averaged palaeomagnetic data, and they were projected on a qualitative reconstruction which took into account earlier tectonic reconstructions, like those of BALLA (1984, 1988a, b), TARI (1994) and TARI et al. (1995). The work of BADA (1999) largely contributed to this synthesis, in fact he compiled the database in digital format and solved the presentation of the stress axes. He also prepared finite element computer models for the stress field evolution and emphasised the role of slab rollback, topography, and Adria push which altogether led to the rifting of the Pannonian Basin.

Palaeostress studies between 2000 and 2010

Methodological advances — seismic profiles, maps

Already from the 1990s but mainly during the 2000s seismic reflection data were improved considerably. This development has facilitated a more detailed imaging and thus deeper understanding of the fault pattern, not only along 2D sections but now in 3D data sets. This technique provides unprecedented tools to image fault patterns, but the question arises if fault kinematics could also be determined. The answer depends on the case. Some aspects of fault kinematics can be deduced from seismic data but not (or rarely) the complete slip vector. The complete fault pattern permits the deduction of the principal stress directions a generalised to the entire study area but stress determination in individual points are not possible. The early studies in this line mostly depicted fault kinematics and fault patterns in sub-basins (e.g. POGÁCSÁS et al. 1989, 1994). For the point of view of palaeostresses a combination of data sets, namely surface fault-slip data and seismic profiles can give good results. The work of TARI (1987, 1988) and of BENKOVICS (1991) already benefitted from this combined approach. Other works, namely WÓRUM (1999) and CSONTOS et al. (2002a, b), also used this combination in the Mecsek area. CSONTOS et al. (2005) suggested fault kinematics from fault patterns derived from seismic data sets. Limited amount of seismic data was also used for the Darnó Line (FODOR et al. 2005). Probably the largest quantitatively balanced subsurface and surface datasets were provided by PETRIK (2016).

The combination of data on the outcrop- and map-scale fault patterns improved the geological maps considerably but, as a reaction, also contributed to the understanding of the stress field evolution. The first of such works were the maps of the Bükk Mts. (CSONTOS 1988) and of the northern Vértes (MAROS 1986, 1988) as I mentioned earlier. The first of such printed map was that of the *Balaton Highland* (BUDAI et al. 1999b) but the large fault-slip dataset of DUDKO (1991) was not presented in detail and only partially embedded in the explanatory booklet (BUDAI et al. 1999a). This slight deficiency was completed in the *northern TR* (DUDKO et al. 2000) and *in the Vértes Hills*, where fully presented fault-slip data were completely taken into account during the compilation of the map itself (FODOR et al. 2008a). The other advancement of these two last maps that they showed with different symbols both the age and kinematics of the faults.

In addition to Cretaceous elements, the map of DUDKO et al. (2000) separated Palaeogene, late Eggenburgian–Sarmatian and late Miocene–Pliocene phases, while the map of FODOR et al. (2008) shows the faults of the same number of Cenozoic phases with slightly different temporal boundaries. DUDKO et al. (2000) defined a great number of faults mostly matching more detailed maps (e.g. BUDAI et al. 2018) although the rectilinear fault traces seem to be a simplification. The dextral character of the Vértessomló–Nagykovácsi and normal slip on NW–SE striking faults are still held valid.

Palaeostress studies in the Alcapa unit

Case studies continued from 1999 to recent years increasing considerably our knowledge on fault pattern and deduced stress fields. In the western–south-western margin of the Pannonian Basin in northern Slovenia FODOR et al. (2002, 2008b) demonstrated E–W to NE–SW extension, both in ductile and brittle deformation styles; these structures formed during the syn-rift phase of the Pannonian Basin (*Figure 1, A*). This phase was overprinted by NE–SW compression and transpression with N–S compression, this latter being the neotectonic deformation.

In the *Bakony Hills* ALBERT (2000) analysed two sets of Mesozoic folds and these data could be transformed to sub-perpendicular contractional directions. KISS (1999, 2009) and KISS et al. (2001) described Miocene extension in the Bakony Mts. and demonstrated the presence of transpressional fault zones around Csesznek and in the northern Bakony as well (KISS & FODOR 2007). SASVÁRI (2003) established 4–6 stress fields in the surroundings of the Telegdi Roth line, although Miocene sinistral character of the fault does not match the view of KISS (1999, 2009). In a revised work SASVÁRI et al. (2007) emphasised Eocene to early Miocene dextral slip of the fault, while the subsequent evolution was similar to other's results. At the same time, PALOTAI et al. (2006a, b) investigated fault pattern and potential kinematics of two important outcrops in the TR, on the Eperkés Hill, the other in the *Pilis Hills*. In both cases they confirmed redeposited blocks of older rocks into Late Jurassic matrix; the triggering faults would be extensional or thrust faults with their preference for the latter solution.

In the Vértes Hills FODOR (2008) prepared an extensive work where 13 Mesozoic to Quaternary brittle deformation phases were presented. The elaborated evolutionary scheme was later used in several works (e.g. FODOR 2010, FODOR et al. 2018), the Cenozoic phases being named D6–D13. The compilation of structural data was based on earlier results (BÍRÓ 2003, FODOR & BÍRÓ 2004, BUDAI et al. 2005, BENKŐ 2005, etc.) and on an early version of digital map with real tectonic data base behind (KÓTA 2001) and embedded in a detailed mapping program (BUDAI et al. 2008, FODOR et al. 2008a).

Parallel to the mapping work in the Vértes Hills, in the neighbouring *Gerecse Hills* the works of SASVÁRI (2008b, 2009a, b) demonstrated a number of brittle structures and also folds, mostly considered as Mesozoic in age. He made a summary of the then available stress data, and this was the first of such detailed compilation for the entire TR (SASVÁRI 2008a). In this work, he reviewed the stress fields stage by stage, thus easy recognition of deformation phases is somewhat hampered by this approach. .

Still in the *Gerecse Hills* BEKE (2010) found several dykes, faults of Middle Eocene age with NNE–SSW to NE–SW tension. The new data, together with revision of earlier measurements, extended some phases of FODOR (2008), particularly D11 transpressional deformation, into the Gerecse. HORÁNYI et al. (2010) determined ESE–WNW Jurassic extension having created small dykes and syn-sedimentary grabens, followed by early Cretaceous tilt in the same direction.

In the *Buda Hills* KORPÁS et al. (2002) and FODOR & MAGYARI (2002) provided additional arguments for syn-sedimentary Eocene and post-sedimentary younger deformations (*Figure 1, C*). Interestingly, Korpás et al. (2002) did not find the otherwise ubiquitous strike-slip deformation of (late) Oligocene to Eggenburgian age. They suggested that the eastern boundary fault zone of the Gellért Hill was probably active already in the Palaeogene but certainly during several Miocene phases; also supported by observations of Palotai et al. (2012) from below the Danube. Gál et al. (2008) studied WNW-trending chalcedony and NNW-trending barite veins and connected their formation to the late Early Oligocene and to the Middle Miocene stress fields, respectively. In the easternmost outcrop of the TR, in the *Csővár Hills* Benkő (2000) and Benkő & Fodor (2002) demonstrated N–S Cretaceous contraction (*Figure 1, C*), and several Cenozoic deformation phases, in agreement with earlier measurements of F. Bergerat and L. Csontos (unpublished, incorporated in Fodor et al. 1999).

In the comparative study of palaeomagnetic and stress data carried out in the entire TR Márton & Fodor (2003) defined 4 stress fields, strike-slip faulting before rifting, the main rifting event, and late Badenian to earliest Late Miocene transpression, followed by post-rift extension (*Figure 1, B*). Two of the rotation phases were correlated to the changes between the principal stress axes, like it was suggested in northern Hungary. However, changes in stress axes and correlative rotations were smaller than in north-eastern Hungary.

In north-eastern Hungary, several works concentrated on deformations of Mesozoic rocks. Because the deformation style is mostly ductile, and the deformation mechanism is partly crystalplastic, these studies often dealt with shortening rather than compressional directions. However, because brittle and crystalplastic structures are sometimes mixed and brittle deformation phases were also presented, these works are also mentioned in this compilation (*Figure 1, D*). In the *Bükk Mts.* Forián-Szabó (2001) and Forián-Szabó & Csontos (2002) assumed the south-eastern vergency of the Kis-fennsík nappe due to NW–SE compression. This major phase, and several previous and successive folding phases could happen in the Cretaceous. Koroknai (2004) dealt with the Cretaceous ductile structures of the Uppony and Szendrő Hills and could determine shortening directions and northern vergency. Németh & Mádai (2003, 2004) and Németh (2005) also focused on ductile (mostly crystalplastic) deformation of the *Bükk Mts*. and determined the temperature condition of folding. However, Németh (2005) reported brittle faults belonging to several Cenozoic phases. In the eastern part of the Bükk Mts., and in a small southern Bükk area Németh (2006, 2007, respectively) described one pre-Late Eocene N–S shortening, and three to four younger stress fields. While two of these stress fields correlate with those reported by Márton & Fodor (1995), the latest field, related to the uplift of the mountains, differs significantly from those reported from the surrounding basin area with its compressional or strike-slip type.

In the *Aggtelek Hills* Hips (2001) followed the earlier work of Csontos & Hips (1997), analysed the considerably folded Lower Triassic rocks and suggested three shortening phases with NW–SE, N–S and NE–SW shortening directions (*Figure 1, D*).

Based on previously unpublished data of Bergerat, Csontos and Fodor (1988–1991), Fodor et al. (2005) reconstructed the stress field evolution of *the Darnó Zone*. The established 3 phases, and the intervening two rotations are similar to those having been suggested by Márton & Fodor (1995). Fodor et al. (2005) was not able to decide if a forth stress field, a NW–SE compression was a Cenozoic or older phase; this problem has been clarified by Oravecz et al. (2018).

More to the north, in the *Rudabánya Hills* few works led to similar results within or in the vicinity of the *northern segment of the Darnó Zone* (*Figure 1, D*). Zelenka et al. (2005) connected the formation of an anhydrite dome to strike-slip opening, compression and then transpression during the Early Miocene; although the time constraints for the suggested phases are not the best. The last event, the post-early Badenian ESE–WNW extension was confirmed by Fodor & Koroknai (2003) in few outcrops of the northernmost tip of the zone, partly based on displaced Pannonian sediments.

In the *Aggtelek Hills* Hips (2001), following the earlier work of Csontos & Hips (1997), analysed the considerably folded Lower Triassic rocks and suggested three shortening phases with NW–SE, N–S and NE–SW shortening directions (*Figure 1, D*).

In the Tokaj Mts. Bodor (2011) documented detailed stress field evolution within the middle Miocene and early Late Miocene. The established clockwise change in the stress axes is at odds with the already stable stress directions in other parts of the Pannonian Basin. A local young block rotation near the middle to Late Miocene boundary explains one of the CW changes in principal stress directions. In fact, such young block rotation has been documented both in the Hungarian and Slovak side of the area (Márton & Pécskay 1995, Orlicky 1995). These results followed older measurements of Bergerat & Fodor (1988) and Györfi (1994–1995) with preliminary interpretation of Bada (1995) which remained unpublished but incorporated in Fodor et al. (1999). The established phases can be reconciled with numerous earlier studies of the Tokaj Mts., which mostly observed the direction of magmatic dykes, volcanotectonic lines, and faults, all in roughly NW–SE, N–S and NE–SW orientation (Molnár & Zelenka 1995; Zelenka & Horváth 2009). Sasvári & Kondela (2009) observed a number of striated faults along mineralised veins and reconstructed at least two stress fields, an ENE–WSW extension and a transtensional field with SE–NW extension. Extensive K–Ar data sets constraint the volcanism and mineralisation between ca. 15 and 9.5 Ma (Pécskay & Molnár 2002), but the combined interpretation of dyke orientation, volcano-tectonic features and fault-slip data is still to be done in the future.

Summary for the Alcapa unit

Most of these works contributed to the *fourth summary* of palaeostress data although this summary was not complete and not extended to areas located south of the Mid-Hungarian Zone (*Figure 1, A*). In my unpublished theses

(Fodor 2010) I described the thirteen post-Triassic phases, already shown in Fodor (2008), using an approach which combined most of the mentioned methods. I strengthened the idea of Miocene clockwise change of maximal horizontal stress axes, and the vertical-axis rotation as the cause of such apparent change. I also elaborated more detailed chronology of the phases (8 of Cenozoic) using tilt test, seismic and other geophysical data, preliminary information from deformation bands, etc. It turned out that during some phases (e.g. D10–D11) the stress field was markedly different in the western and north-eastern part of the Pannonian Basin, north-west from the MHZ.

Studies after 2010

Methodological advances — mineral veins, tilt test, AMS, deformation bands

The complexity of the fault-slip and palaeostress analysis as a method expanded during the last decade. Mapping, tilt test, usage of seismic data, study of deformation bands, precise dating of deformed magmatic rocks, all contributed to elaborate a more detailed brittle structural evolution than achieved by previous works.

One of the possible expansion of the fault-slip analyses could involve the study of mineral veins and their fluid inclusions. In the *central TR (Velence Hills)* Benkó et al. (2008, 2014a, b) used fluid inclusion planes to derive the direction of fault acting during inclusion formation; fluctuating extension in NW–SE to NE–SW were deciphered from such data (*Figure 1, B*) and Triassic age was suggested from K–Ar geochronological data. Győri et al. (2014) combined petrographic, isotope and fault-slip data to determine Campanian(?) and Eocene ages of red calcite veins of NNE–SSW and NW–SE striking sets occurring across the *entire TR (Figure 1, B)*. The first group of calcites was already interpreted as reflecting a local tensional stress field during Senonian compression by Kercsmár (2004).

Tilt test was progressively recognized as an important tool in the relative and absolute chronological determinations of fault sets. One of the pioneer works in the Pannonian Basin was that of Kiss et al. (2001), and later this became part of the routine analysis. Probably the most detailed elaboration was by Fodor (2008) in the Vértes, Fodor et al. (2005) in the Darnó zone, Petrik et al. (2014, 2016) and Petrik (2016) in the southern Bükk foreland. Fracture sets formed before the tilt of a given formation should form in an early phase of deformation. When the tilting is Cretaceous, like in the TR, the pre-tilt fractures are older than the main folding phase of the range (latest Aptian to early Albian). In this way, Triassic faults were recognised in the Keszthely Hills (Héja 2015, Héja et al. 2018).

The combination of fault-slip and palaeomagnetic data made also a progress integrating anisotropy of magnetic susceptibility (AMS) data. Sipos-Benkő et al. (2014) used AMS data to infer early stage deformation and compare AMS and stress axes *within the TR*. AMS axes shows good correlation with one of the earliest stress axes, thus it has been proved to be successful measure for deformation in sediments. This Pannonian results confirm the validity of this application described in other Mediterranean areas (Cifelli et al. 2005). Sipos et al. (2018) went further and, with the help of a new approach (Sipos 2013), established the connection of Miocene AMS and stress axes in the western–south-western margin of the Pannonian Basin in northern Slovenia. In this study the tilt test was routinely applied for both the AMS and fault-slip data and only pre-tilt data were compared.

During the last decade the importance of deformation bands (DBs) were progressively recognised in the brittle structural analysis (Fossen et al. 2007) and the same happened also in Hungary (Beke & Fodor 2014, Apró et al. 2014). These strain-localisation structures are important, because they register, with unprecedented details, the evolution of the fracture system. It is mainly due to the fact that, although macroscopically similar, different DBs can be separated using thin sections because their formation mechanism changes irreversibly during the burial of host sediments.

Palaeostress studies in the Alcapa unit

Within the TR, examples of complex fault-slip analysis, combined with subsurface or surface mapping are from the *Bakony and Keszthely Hills* (Csicsek 2015, Csicsek & Fodor 2016; Héja 2015, 2019). These works demonstrated the heterogeneous compressional directions during the Cretaceous orogeny, but also revealed multistage shortening and few Cenozoic stress fields (*Figure 1, B*). Data on Cretaceous deformation slightly modified the pioneer work of Tari (1994) and Tari & Horváth (2010) who described in detail the Cretaceous deformation of the TR.

In the Gerecse Hills, Fodor et al. (2018) summarised available structural data for the area and gave detailed structural evolution; separating spatially and temporally changing stress fields in the Cretaceous (mostly in accordance with Sasvári 2008b, 2009b); such variable Cretaceous deformation is unique for the TR. The data of Szives et al. (2018) presented only briefly these Cretaceous phases but clarified by biostratigraphy the temporal extent of the first and second ones. On the other hand, Cenozoic evolution of the Gerecse outlined by Fodor et al. (2018) is broadly similar to that of the Vértes Hills (Fodor 2008) (*Figure 1, B*). Based on the combination of mapping and fault-slip data they changed the age classification of certain faults from Cenozoic to Mesozoic (compare Fodor et al. 2018 and Bada et al. 1996).

In the Dorog Basin Bereczky (2011) determined 7 stress fields, two of them were Cretaceous in age and fit to the evolution of the nearby Gerecse Hills (*Figure 1, B*). The two Palaeogene stress fields show similarities to those of the Gerecse and Buda Hills, while the mid-Miocene is interpreted as strike-slip deformation, which is at odds to results from the surroundings.

In the Visegrád Hills the combination of Danube river seismic data, geological and geophysical maps revealed important tensional, locally transtensional deformation

(Oláh et al. 2014); σ_3 was in roughly in NE–SW direction (*Figure 1, C*). Normal faults could be connected to E–W dextral faults, one having been exposed temporally below the Danube (Bencze et al. 1991).

The stress fields of Sipos-Benkő et al. (2014), derived from the *entire TR*, were basically similar to those found by earlier studies (Márton & Fodor 2003, Fodor 2008). The notable exceptions were the Late Miocene stress fields they assumed a change in minimal stress direction from E–W to NW–SE being coeval with a counterclockwise rotation event (*Figure 1, C*). This model needs additional data.

In *northern Hungary*, several works described in detail the evolution of stress fields and map-scale fault patterns. These works were not independent from each other, and mutually used common time constraints or stress directions. Petrik et al. (2014, 2016) refined the stress evolution in the *southern Bükk foreland and southern Darnó Zone (Figure 1, D)*. Stress axes are close to the ones of Fodor (2010) but, with the help of new radiometric ages of volcanoclastic rocks (Lukács et al. 2015, 2018), the age of rotations, and the boundaries of correlative phases have been shifted toward younger ages. Petrik (2016) went even further in separating 11 phases from the Eocene to present. Although the number of phases, their separation can be discussed, this is the most detailed stress field evolution suggested in the Pannonian Basin. In this work, the time spans of rotations were slightly shifted again toward younger ages. More to the south, in the Polgár Basin Petrik et al. (2019) found evidence for a change in the stress field, from strike-slip to extensional character, based on structures and magmatic features analysed on seismic 3D data sets.

Concerning the deformation bands, in recent works conducted in *north-eastern Hungary* Beke (2016) and Beke et al. (2019) were able to demonstrate that only 100–200 m of burial leads to change in mechanism, and 500 to 1000 m of burial corresponds to another change in mechanism. While the former burial depth could occur during only several ka to maximum 2–3 Ma, the study of DBs permits a temporal resolution previously unobtainable. In the latest work Beke et al. (2019) suggested 10 phases from 27 Ma to present based on a combination of observations (*Figure 1, C*). The separation of D2 from D5 phase was possible by tilt test, the repetition of ESE–WNW tension, both characterising D6 and D9 phases, needed relative chronological criteria, and the separation of phases D4 and D5 is necessary if rotation event is incorporated in the story *(Figure 1, D*). With a new technique Albert et al. (2018) analysed in detail the complete fracture system of the Tar quarry and found the same extensional deformation like other studies in the region (Benkovics 1991, Beke et al. 2019).

The last palaeostress analyses in *north-eastern Hungary* were concentrated on Mesozoic deformations, thus their contribution was more significant to Mesozoic than to Cenozoic stress field evolution. In the *southern Bükk Mts*., in the quarry of Bükkzsérc Oravecz (2016) recognised Jurassic normal faults and associated slump folds having formed by SE–NW extension (*Figure 1, D*). After correction of the block rotations, this deformation can be reconciled with the Jurassic palaeogeographic position of the Bükk in the Neotethyan framework (Oravecz et al. 2017). The established post-Jurassic stress fields show similarities to those observed by Németh (2006, 2007) partly in the same quarry; these are the N–S compression, ENE–WSW (or E–W) compression. In the *south-western Bükk Mts*. Scherman (2018) and Fialowski (2018) used the tilt test to verify pre-tilt WNW–ESE to NW–SE shortening. This direction should be close to the regional compression, which could characterise the nappe emplacement (Scherman et al. 2018). Oravecz et al. (2018) concentrated to the Nekézseny fault *at the boundary of the Bükk and Uppony Mts*. The authors verified the NW–SE compression which resulted in folding and even overturning of the Senonian strata; the arguments favour latest Cretaceous timing of deformation. In fact, this is the fourth stress field of Fodor et al. (2005) which was poorly constrained at that time. The subsequent Cenozoic events follow the general stress field evolution of the northern Pannonian Basin.

In the Rudabánya Hills, post-early Badenian ESE–WNW extension was confirmed by several studies, partly based on deformed Pannonian strata located in very small grabens (Deák-Kövér 2012, Horváth et al. 2012). These studies also suggested the compressional–transpressional stress regime for the Early Miocene phase of the Darnó Zone.

Finally, in the latest work Oravecz (2019) demonstrated Triassic salt structures *in the Aggtelek Hills* which were reactivated by ~NW–SE compression during the Cretaceous orogeny and were affected by few poorly dated Cenozoic phases (*Figure 1, D*). This result changes the interpretation of folds, having been considered only as contractional features (Grill 1989, Csontos & Hips 1997). Also the demonstration of salt structures and their reactivation seem to explain the long-time observed "young-on-older type" fault contacts previously interpreted simply as thrusts (Hips 2001, Fodor et al. 2006).

Palaeostress studies within or near the Periadriatic and Mid-Hungarian Fault Zones

South from the rigid part of the Alcapa unit, the wide, strongly deformed Mid-Hungarian Shear Zone (MHZ) has no outcrop within Hungary. However, the Periadriatic Fault zone, equivalent to the northern branch of the MHZ is exposed in northern Slovenia. Fodor et al. (1998) verified the recurring dextral slip along and near the Slovenian Periadriatic Fault zone; the compressional or strike-slip regime was only interrupted with a short period of E–W transtension during the Karpatian (17.5–16 Ma) (*Figure 1, A*). The deformation comprised clockwise and counterclockwise block rotations, probably during two time slices. The post-Miocene dextral slip of the Šoštanj Fault (southern branch of the Periadriatic Fault zone) was verified by Vrabec (1999) and Vrabec et al. (1999); syn-tectonic fill of the Pliocene Velenje Basin provided a good time constraint.

Further to the east, along the transition of the Periadriatic and Balaton faults in Slovenia Márton et al. (2002) demonstrated the post-Miocene (neotectonic) compression and CCW rotation; these events are similar to ones observed west and east of this area (FODOR et al. 1998, TOMLJENOVIĆ et al. 2001). The neotectonic compression was preceded by NNE–SSW tension related to the Miocene opening of this part of the Pannonian Basin (*Figure 1, A*).

The southern–south-western part of the Pannonian Basin around the Medvednica and Ivanščica Mts. is one of the most complex area where the structural evolution shows connections to all the Periadriatic Fault, the Mid-Hungarian Shear Zone, the Dinarides and to the Tisza–Dacia unit. In this area TOMLJENOVIĆ & CSONTOS (2001) demonstrated a complex Neogene structural evolution using stress field data and seismic reflection profiles (*Figure 1, E*). This evolution was marked by alteration of compressive and extensive phases and terminated by latest Miocene to recent folding (inversion of this part of the Pannonian Basin). In their later work TOMLJENOVIĆ et al. (2008) characterised the Oligocene–Early Miocene stress field and demonstrated a 130° clockwise rotation, which distorted pre-Oligocene structures from their original Dinaridic orientation. Two post-Oligocene counterclockwise rotations complicate the stress field evolution.

The Hungarian part of the MHZ was analysed by seismic reflection profiles; in such an approach, the stress axes were only approximatively inferred from the map pattern of faults. In this line, SKORADY (2010) verified the dextral, Olgiocene to early Miocene (pre-Karpatian) kinematics of the northern fault branch of the MHZ, associated to thrusts and folds more to the north. She also observed the syn-rift extension and neotectonic compression.

More to the north-east, CSONTOS et al. (2005) estimated Early to Mid-Miocene NW–SE compression and late Miocene to Quaternary(?) transtension along the middle part of the Mid-Hungarian Shear Zone, south of the Lake Balaton. This study completed earlier works of BALLA et al. (1987) and CSONTOS & NAGYMAROSY (1998) about the shear zone but added map representation of fault kinematics and estimated stress axes.

In a small area south from the Lake Balaton VÁRKONYI (2012) found 4 phases and he estimated the stress axes from the fault patterns. Pre-Karpatian dextral slip, Sarmatian–early Pannonian compression and reactivated neotectonic strike-slip faulting are similar to other studies. The direction of roughly N–S Karpatian–Badenian transtension seems to be a new feature but supported by the seismic data. The neotectonic strike-slip faulting was confirmed by VISNOVITZ et al. (2015) and extended below the Lake Balaton. TÖRŐ et al. (2012) extended the observation of pre-rift dextral strike-slip faulting, and the early Late Miocene strike-slip type deformation, but they did not provide map or stress axes.

Although RUSZKICZAY-RÜDIGER (2007) and RUSZKICZAY-RÜDIGER et al. (2007) mostly studied the neotectonic, post-4 Ma deformation of the Tóalmás segment of the MHZ, they recognised pre-rift compression, the early and late syn-rift phases (18–14 and 14–11.6 Ma) and the early Late Miocene sinistral slip of the fault zone. The study of seismic sections demonstrated NNW–SSE compression *within a larger area near the Tóalmás Fault* (PALOTAI & CSONTOS 2010, PALOTAI 2013). The fold-and-thrust belt started to form during the Kiscellian and lasted to the end of Early Miocene (*Figure 1, A*). Inversion of late Sarmatian to earliest Pannonian in age, and sinistral transtension of early Pannonian age were also demonstrated along the Tóalmás Fault.

In the north-eastern end of the MHZ, at the Alcapa–Tisza junction, below the north-easternmost corner of the Pannonian Basin, CIULAVU et al. (2002) demonstrated positive flower structures along the major boundary fault zones of the two units. They suggested post-Miocene deformation and NE–SW compression. Slightly to the east, in the Maramures area TISCHLER et al. (2007) extended the data base of GYÖRFI et al. (1999, see below). They confirmed the importance of NW–SE and NE–SW compression and transpression, already found by GYÖRFI et al. (1999), which were responsible for the Alcapa thrusting onto Dacia and sinistral displacement of the Bogdan Voda–Dragos Voda fault system, respectively (compare *Figure 1, A* and *E*). Their precise timing was supported by fission track and sedimentological data.

Palaeostress studies in the Tisza–Dacia unit

South from the Mid-Hungarian Shear Zone, in the *Tisza–Dacia unit* the outcrops are not very extended in the Hungarian part. However, fault-slip and palaeostress studies were intensive in this unit, partly along the south-eastern margin of the Pannonian Basin and partly in the Mecsek–Villány area (*Figure 1, E*).

The first data in the Mecsek–Villány Mts. (BERGERAT & CSONTOS 1988) and the re-evaluation of field data (CSONTOS & BERGERAT 1993) emphasised the importance of strike-slip faults, and suggested 3 strike-slip phases and the reoccurrence of one of them during the Pliocene. TARI (1993) also contributed to the fault kinematic analysis recognising left-lateral transtensional to transpressional deformation through Early to Late Miocene in the *northern imbricate zone of the Mecsek*.

GYÖRFI (1993) and GYÖRFI & CSONTOS (1994) established NE–SW tension in the grabens of the *Apuseni Mts*., *at the south-eastern margin of the Pannonian Basin*. Later GYÖRFI et al. (1999) described one compressional and two strike-slip type deformation phases in the boundary zone of the Tisza–Dacia and Alcapa units, the second phase was attributed to the thrusting of Alcapa onto the Tisza–Dacia unit.

In the Mecsek and Villány Mts. BENKOVICS (1997) elaborated in detail the structural evolution. He found three Permo–Mesozoic phases, including late Cretaceous NW–SE compression (BENKOVICS et al. 1997). For the Cenozoic, he documented six phases, partly transtensional with NW–SE σ_3, partly strike-slip (N–S σ_1, during 16–13 Ma) and established the latest Miocene to Quaternary shortening and inversion of both the Mecsek and Villány Mts. from ca. 7.5 Ma. He also incorporated the clockwise block rotation at the end of Early Miocene and also a differential rotation between the Northern Imbricate Zone and other units.

All these studies were incorporated in the third palaeostress summary, which already taken account the different rotation pattern of the Tisza–Dacia with respect to the Alcapa unit (*Figure 1, A*).

After this synthesis CSONTOS et al. (2002a, b) improved the understanding of the evolution of the stress field, by describing varying transpressional, strike-slip phases, interrupted by clockwise rotation, late Miocene tension to transtension, and latest Miocene to recent (neotectonic) transpression in the entire *Mecsek–Villány area* (*Figure 1, E*).

In the *Villány Hills* PETRIK (2009) determined 6 stress fields. While data were registered on Mesozoic rocks, timing seems to be questionable and the stress axes are different from the results of others. Along the southern margin of the *Mecsek Mts*. SEBE & DEZSŐ (2008) and SEBE & KONRÁD (2009) documented stress data from few sites, indicating thrusting during latest Sarmatian and the late(?) Pannonian. KONRÁD & SEBE (2010) extended the stress database and demonstrated dozens of outcrops with small-scale structures. Using this dataset they characterised the young deformations along the main fault zones of the Mecsek Mts.

Extensive data set has been accumulated during the research of the potential nuclear waste depository site south of the Mecsek Mts., *in the Mórágy Hills*. Despite the extremely large dataset and detailed interpretation (see summary of BALLA et al. 2009), conclusions regarding the palaeostress fields are less abundant. As part of this extensive study MAROS et al. (2004) documented two Palaeozoic, three Mesozoic and five Cenozoic stress fields. After late Cretaceous NW–SE tension, the Early and Middle Miocene were characterised by transpressional stress fields, while their connected faults were passively rotated in clockwise direction.

In the *Mecsek Mts.* few additional stress data were published after 2010. KOVÁCS et al. (2018) determined Pannonian syn-sedimentary strike-slip deformation and post-sedimentary transpression (*Figure 1, E*). In the Mórágy area, combination of structural and sedimentological data suggest that syn-sedimentary faulting by ~N–S compression and perpendicular tension controlled the sedimentation between 8–6.5 Ma, and this phase was followed by folding in the same stress field (BUDAI et al. 2019).

Discussion

Some concluding remarks on the stress field evolution

This summary demonstrates that our idea on the stress field evolution comprises more and more deformation phases. I think that this is real, the Cenozoic stress field evolution in NE Hungary was at least as complex as the models of FODOR (2010), PETRIK et al. (2014), PETRIK (2016) and BEKE et al. (2019) (see on *Figure 1*), although new data may modify the number of phases and their timing. The presently suggested structural evolution means a temporally frequently changing fault pattern, particularly in the Miocene, during the formation (rifting) of the Pannonian Basin. It is also clear that spatial differences in the maximal horizontal stress axes were fundamental during certain phases within the Pannonian Basin; such regionally varying stress fields imply coherently varying fault patterns and eventually fault kinematics, too. A simple, idealistic fault pattern with identical orientations and kinematics across the entire basin was certainly not the case during most of the rifting events. This complexity in the stress field and fault pattern evolution was suggested earlier (e.g. FODOR et al. 1999) and has supported by more recent studies.

Problems and possible solutions

At the end of this overview I mention some of the problems of palaeostress determination and fault-slip analysis in general. These concerns raised during the research in the Pannonian Basin, but the international publications contain even wider spectrum of problems (e.g. SPERNER & ZWEIGEL 2010).

A) During fault-slip analysis most of us do not like to “loose” even a single fracture. Thus we may “over-interpret” the few fractures remaining after phase separation and they seems to form a “new” stress field. It is equally true for striated faults, the last 4–5 faults which do not fit to any formerly separated phases may fit to a new stress field, albeit with large misfit values. Sophisticated phase separation can also lead to “apparent phases” when only the mathematical misfit criteria are taken into account, and the geometrical connection of fractures is not considered. Joints are difficult to interpret and needs care, because their origin is not necessarily due to crustal stress (but to cooling, slope failure, dewatering etc.). Orthogonal sets of joints could also form at the same time, and not subsequently; at least such solution was suggested for cases when σ_3 and σ_2 are very close to each other and permutation of axes was possible (ANGELIER & BERGERAT 1983, TIBALDI 1992, ACOCELLA & FUNICIELLO 2006). All these pitfalls may lead to overestimate the number of stress fields (phases) in a given area.

B) During the last decade we demonstrated that very similar or even identical stress axes and related fault pattern did occur in two or more temporally separated phases during the Mesozoic–Cenozoic structural evolution. When tilt test can be applied (dip is larger than ca. 10–15°) the separation of the two temporally separated, but similarly oriented phases is possible. *Figure 2* shows 4 examples of such cases. NW–SE compression characterised both the *Bakony and Vértes Hills* during the Cretaceous (early Albian) contraction (D3a phase of FODOR 2008, 2010), while a very similar compression reoccurred during the late Oligocene to early Miocene (D7 and D8 phases of the same works). NE–SW tensional stress field was characteristic during several phases, namely during Triassic (HÉJA et al. 2018) and Jurassic extension, late Cretaceous (Senonian) extension (KISS 2009), and during the main syn-rift phase of the Pannonian Basin (FODOR et al. 1999). *Figure 2* shows that similar stress fields occurred during the late Oligocene to earliest Miocene in the Bükk foreland (Petrik et al. 2014, 2016; Petrik 2016) prior to or during the first tilting event which pre-dated the main syn-rift phase. This means that a NW–SE striking fault in Triassic rock could be active in 4 or 5 phases with normal kinematics providing that it was not tilted much during any of the deformation phases. N–S compression could also be active during several phases, starting from the Cretaceous (Bada et al. 1996), during the syn-rift phase and also during the neotectonic deformation. In the Miocene (Karpatian) sediments of the Pohorje Mts., tilt test demonstrated the reoccurrence of this stress field during and after the Miocene (*Figure 2*) (Fodor et al. 2008b).

C) We would need independent time constraints to classify the fracture sets of each studied outcrops; a requirement generally not fulfilled. The "general solution" is the classification of separately determined stress states with similarly oriented axes into a common phase. Such "directional classification" will inevitably lead to a stress field with parallel principal axes in each observations points ("homogenous stress field" in a slightly unprecise jargon), and a stress determination, whose axial direction is different from the dominant one will be separated into a different phase. In this simple way, any directional variability of the stress field across a basin can hardly be demonstrated.

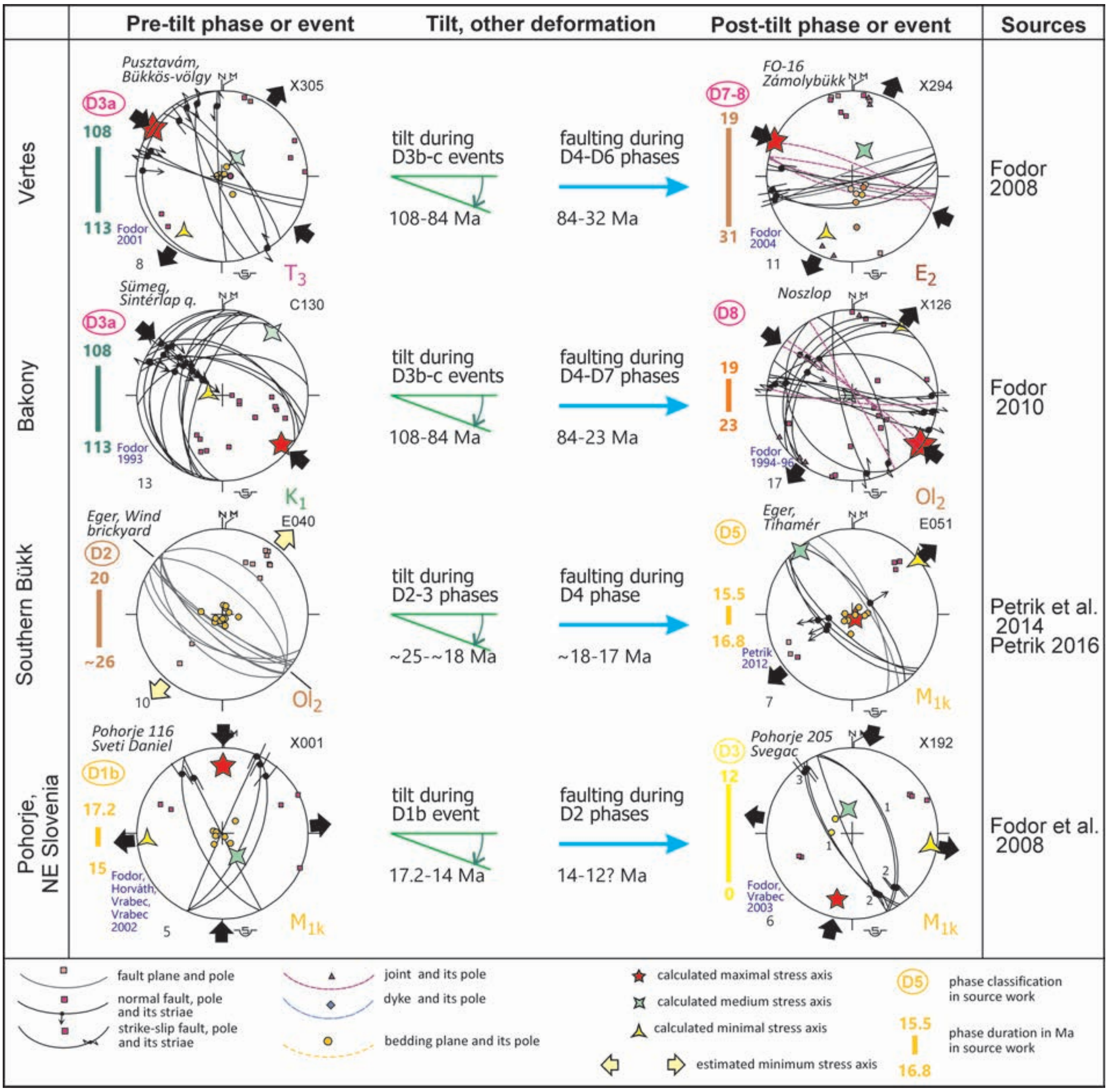

Figure 2. Demonstration of repetition of the same stress regime during the tectonic evolution. Tilt test clearly shows the reoccurrence of the principal stress axes of a pre-tilt phase during a younger post-tilt phase. Note time spans of pre- and post-tilt phases and the tilt itself; they vary in each cases C, X, E in upper right hand corner indicate compressional, strike-slip and tensional stress regime

***2. ábra.** A szerkezetfejlődés során ismétlődő feszültségmezők kimutatása. A billentésteszt egyértelműen kimutatja a kibillenés előtti idősebb feszültségtengelyeknek egy fiatalabb, kibillenés utáni fázisban való újbóli megjelenését. A jobb felső sarokban a C, X, E jelek a kompressziós, eltolódásos és tenziós feszültségrezsimet jelzik*

To illustrate the problem of "homogenous" versus "heterogeneous" stress field (with parallel or variable principal stress directions, respectively), *Figure 3* shows a case study from the *southern TR*. In his early work, HÉJA (2015) determined three compressional stress states, with maximal stress axes at ~E–W, NW–SE and NE–SW, and classified them into two or three different deformation phases from Cretaceous to early Cenozoic (D3, D4, and D3 or D6, respectively). In his revised version (HÉJA 2019), all different stress states belong to the same Cretaceous deformation phase which had a strongly variable maximal stress direction. The variability of the principal stress directions is due to inherited Triassic structures which buttressed the deformation and resulted in contractional–compressional structures, expressed both by folds and faults, whose orientation changed from place to place. This interpretation seems to be more realistic because takes into account the effect of older structures inherited for the Cretaceous shortening phase.

The problem of stress axes classification cannot overcome easily, only if we can improve the time constraints by different methods. Most commonly, one can search for relative chronological data of different fracture sets (and derived stress states), carry out tilt test, which establish relative chronology with respect to a temporally constrained tilting event, execute mineral vein investigation, and check the relationship of fractures to deformation bands and/or to burial and diagenetic history. Absolute dating of calcite fibres or dominoes related to fault slip would be the ultimate solution but this method is still not easily accessible although several works validated the method (e.g. NURIEL et al. 2012, ROBERTS & WALKER 2016).

D) *Figure 1, A–D* shows a frequent and important changes in stress axes; however, the fault pattern of outcrop-scale does not seem to be reflected in the pattern of major faults figured on available basin-scale maps. The solution for this problem is equivocal; (1) we over-interpreted the outcrop-scale fracture pattern, and some of the suggested phases have very localised extension and are just due to local effects (stress perturbation, more complex relationship between stress and fractures including non-independent slip on connected faults, etc.), (2) reactivation by oblique-slip or strike-slip of pre-existing major faults; the number of map-scale faults will not increase, but on outcrop-scale small new faults favourably oriented to new stress axes could form.

E) For long time, the problem of rotation and changes in stress field seemed to be solved (MÁRTON & FODOR 1995, 2003) while suggesting coeval rotations and changes of stress axes mostly due to rotations. However, as more data have been collected by both palaeomagnetic and fault-slip techniques, new problems emerged. These are the post-Middle Miocene rotations within the Transdanubian Range, indicated by palaeomagnetic data (MÁRTON et al. 2006). Such a rotation could be reflected in stress data, but for Late Miocene, they have poor temporal constraints (SIPOS-BENKŐ et al. 2014) and it is not clear if differences in stress axes are due to local variations or to the rotation. In addition, map-scale structures do not reflect any Late Miocene deformation which would be suitable to accommodate larger than 20° rotations; thus these rotations should be local but even such map-scale structures are still missing. The other problem is that new palaeomagnetic data and precise absolute ages of the Bükkalja Miocene volcanic levels clearly show mismatch; rotation seems to be present even in the Harsány horizon (MÁRTON et al. 2007) which was dated as the youngest one on surface (14.358±0.015 Ma, LUKÁCS et al. 2018), while other sites showing no rotation seem to be older (14.88±0.014 Ma, Demjén ignimbrite). Complex and comparative studies, surface and subsurface mapping, and deeper understanding of the processes (magnetisation, deformation, crystallisation versus eruption) will be necessary in the future.

F) One of the ultimate goals for outcrop-scale fault-slip analyses was the understanding of fault kinematics of large structures, like the Darnó, Mecsekalja, Balaton or Mid-Hungarian Shear Zones. Because most of these fault zones are covered by young sediments, kinematic determination would only be possible if we could project surface kinematic or stress data to the faults, which needs the supposition of a homogenous stress field, and a mechanically uniform Pannonian Basin. We know that this is not the case, and the structural evolution of the basin has been governed by the inheritance of major discontinuities, like the mentioned fault zones. Near these structures specific stress conditions should be present, like, for example, the closely perpendicular compression along the strike-slip San Andreas Fault (ZOBACK et al. 1987). The kinematics of these major faults are governed by large-scale plate tectonic processes, and the fault zones could play the role of transfer faults accommodating differential extension or contraction; such scenario was postulated by TARI et al. (1992), CSONTOS & NAGYMAROSY (1998) for the Miocene. The solution is easy to be outlined but more difficult to provide; we need detailed kinematic analyses of the major fault zones by all available data, mostly by modern 3D seismic data (like the works of PALOTAI & CSONTOS 2010, PETRIK et al. 2019), analogue and computer modelling of the role of fault inheritance on kinematics, stress, and rotation (like the work of BALÁZS et al. 2017).

Future perspectives

We can put the question if the era of fault-slip and palaeostress analysis has been terminated or not? Looking to the poor structural geological imaging of our country, the answer is definitely no. Every new observation contributed to imaging the fault network, and will continue to do so. Such studies will describe fault kinematics, stress fields and their evolution; still a large part of the country (both in outcropping and covered areas) has not been surveyed yet in detail. However, isolated fault-slip analysis will not be enough. Integration of surface structural data with seismic profiles, particularly with modern 3D data sets, boreholes

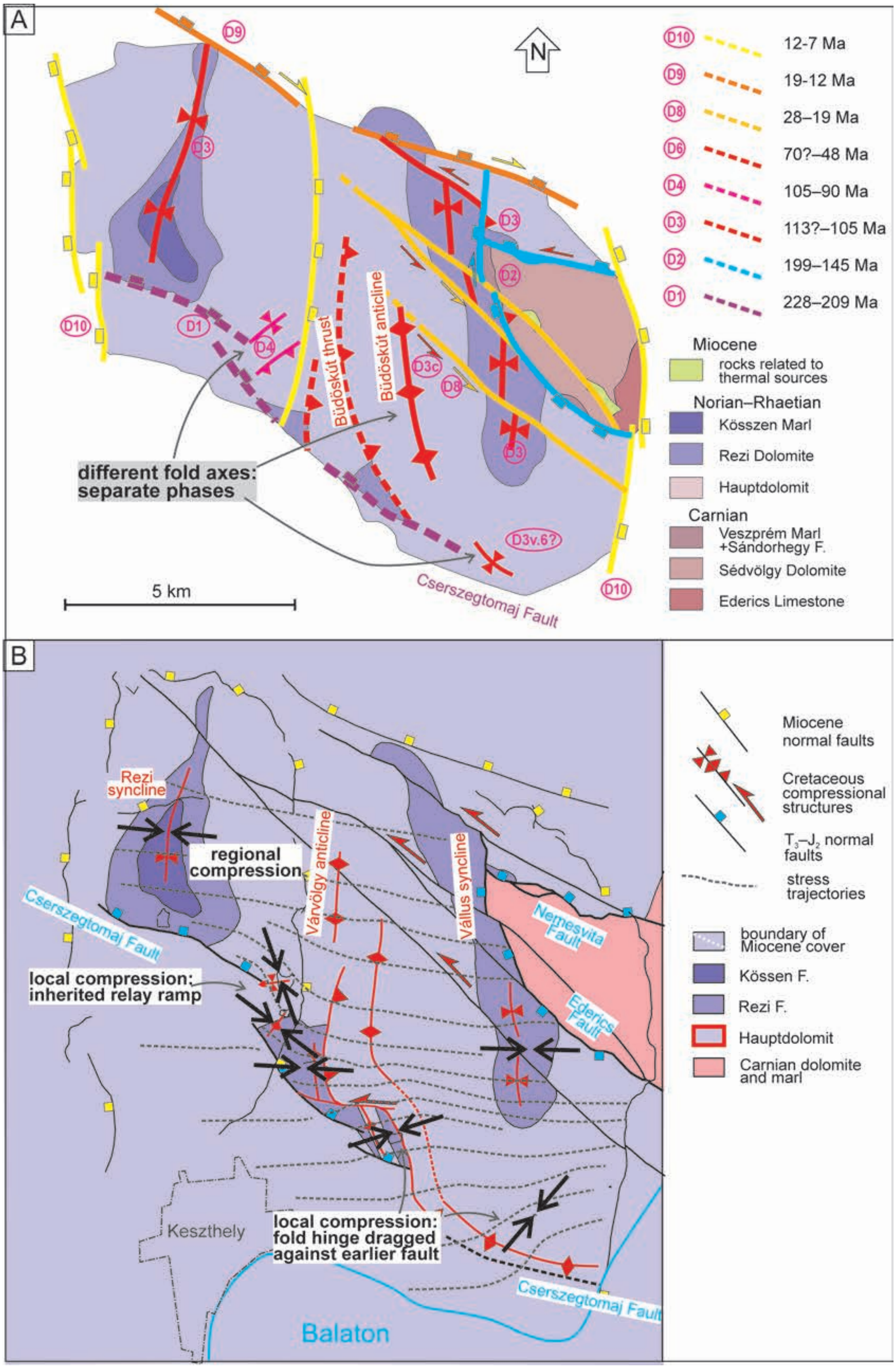

Figure 3. Comparison of classification of individual stress determinations. A) Separation into directionally homogenous stress fields (Héja 2015, modified). B) All contractional deformation are grouped within one phase with highly heterogeneous stress fields (after Héja 2019, modified). Note curved stress trajectories near buttressing inherited normal faults

3. ábra. *Az egyedi feszültség-meghatározások csoportosításainak összehasonlítása. A) Az irány szerint homogén feszültségmezőbe való sorolás Héja (2015) munkája alapján, módosítva. B) Minden rövidüléses-kompressziós deformáció egy fázisba való sorolása igen heterogén feszültségmezőhöz vezet (Héja 2019, módosítva). A feszültség-trajektóriák az átöröklött normálvetők hatása miatt ívelődnek* and diverse geophysical data should be the basis of future analyses. All this should lead to map or 3D visualisation of the brittle structural framework. In this line, new techniques, like the usage of Remotely Piloted Aircraft combined with 3D photogrammetric model, will help understanding the 3D fracture geometry (Török et al. 2018, Albert et al. 2018). If combined with kinematic analysis these methods will help palaeostress estimations, too.

The analysis of deformation bands will serve further detailed understanding of fracture evolution because we will be able to date such fractures with good precision. In addition, rheological evolution of the deforming media will be followed, and, as probably most importantly, fluid flow evolution along these fractures will be described. The presently ongoing structural diagenetic research will connect deformation, burial, diagenesis, and fluid flow (Szőcs et al. 2018). This topic leads already to a major challenge, to understanding the role of fractures in fluid flow, basin-wide and locally. From the "fluid side" several results are embedded in publications (Havril et al. 2016, 2018) and in divers applied researches like those conducted at geothermal fields and reconstruction of fracture network; its connection to fluid flow and mineralisation is under way in several parts of the Pannonian Basin (Dabi et al. 2013, Bauer & M. Tóth 2017, M. Tóth 2018). Although this is not strictly the topic of fault-slip analysis, but potentially, this will be the field where hydrogeology, hydrocarbon geology and brittle structural geology would (should) meet. Studies in this respect have been published (e.g., Szabó et al. 2016, Garaguly et al. 2018) and future efforts will follow.

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