



Magnetostratigraphy and small mammals of the Late Oligocene Banovići basin in NE Bosnia and Herzegovina

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ABSTRACT

A combined magnetostratigraphic and small mammal investigation was carried out to acquire better age control on the sedimentary infill of the Banovići basin in Bosnia and Herzegovina. Although the Dinarides occupy a crucial paleogeographic position bridging Central Europe and Anatolia no detailed records of its small mammal fauna have been published until now. A rich small-mammal assemblage with over 500 molars was excavated from a section exposing marls and clays just underlying the basin's main coal layer. The fauna of this Turija small-mammal locality compares best with the uppermost Oligocene to lowermost Miocene localities from the European MP30/MN1 mammal zones and with Anatolian zone B from central Turkey. A 160 m thick series of lacustrine sediments, overlying the main coal layer in the nearby Grivice section, was sampled for paleomagnetic purposes. The magnetostratigraphic pattern of the Grivice section comprises a long reversed interval, a subsequent short normal interval, and another reversed interval. The most logical correlation of this pattern to the Late Oligocene part of the Geomagnetic Polarity Time Scale (GPTS) is to chrons C6Cr, C6Cn.3n and C6Cn.2r (24 to 23.2 Ma). This correlation implies a sedimentation rate of ~20 cm/kyr for the Banovići basin, and an age of approximately 24 Ma for the Turija mammal site. The proposed correlation fits well with other magnetostratigraphically calibrated mammal records in western and central Europe as well as Anatolia, and with the recalibrated ages of 24.95 ± 0.05 Ma and 24.72 ± 0.04 Ma for two basalt flows bracketing the Enspel MP28 site in Southern Germany. Our results indicate that a limited exchange of fauna from central Asia to western Europe existed in Late Oligocene and Miocene times.

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1. Introduction

A series of intra-montane basins formed within the Dinaride orogen after it emerged from the Tethys Sea in the Late Eocene to Early Oligocene. These basins were settled by lakes whose deposits potentially represent a rich source of information about the paleobiogeographic evolution of the Balkan region. Good age constraints are, however, often lacking due to the severely endemic character of the lacustrine fauna and the paucity of magnetostratigraphic and radio-isotopic data. In comparable continental settings small mammal biostratigraphic data often provide the necessary age constraints. The small mammal record of the Dinarides, however, is poorly known, especially compared to other areas in western Europe

(Barberá et al., 1994; Garcés et al., 1996; Krijgsman et al., 1996a; Agustí et al., 1997; Daams et al., 1999; Van Dam et al., 2001) and central Anatolia (Krijgsman et al., 1996b; Ünay et al., 2003b). This clearly hampers insight, not only in the biogeography, but also in the geodynamic evolution of the area.

The Dinarides occupy a paleogeographically very interesting position, being situated along the southern margin of the Paratethys and connecting Anatolia with the heart of Europe. Phases of strong endemism in the Paratethys marine record indicate that it was repeatedly disconnected from the Mediterranean by geodynamic or eustatic closure of gateways across the Dinarides–Hellenides and Pontides (Rögl, 1999). It is thus likely that terrestrial fauna was, at least periodically, able to migrate from Anatolia to Central Europe along the southern boundary of this epicontinental sea. Paucity of the small mammal record of former Yugoslavia (e.g. Maridet et al., 2007) currently prevents a detailed insight into the mammal exchange across the Dinaride Land during the Oligocene and Miocene.

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We conducted a magnetostratigraphic and small-mammal study on outcrops exposed in the open-pit coal mine of the Banovići basin, aiming to better constrain the age of the lacustrine deposits in Bosnia and Herzegovina. The rich small mammal assemblage of the Banovići basin thus represents a vital contribution to the European paleontological record and forms a new stepping stone bridging the Oligocene and Miocene records of Central Europe and Anatolia.

2. Geological setting

2.1. Regional stratigraphic and paleogeographic development

The Banovići basin is a ~12.5 km long and 6 km wide WNW–ESE directed elongated structure (Fig. 1). It belongs to a suite of largely isolated basins that were generated along the northeastern margin of the Dinarides after a Late Eocene–Early Oligocene tectonic phase (Tari and Pamić, 1998). Its basement rocks belong to the ophiolite massif of the Central Dinaridic Ophiolite Zone (Internal Dinarides) and consist of stratified massive peridotite, serpentinite, dolerites, amphibolite and amphibole schists (Sunarić-Pamić et al., 1971; Pamić et al., 1973a,b; Čičić et al., 1991a,b; Tomljenović et al., 2008). The western part of the basin exposes some middle Jurassic to lowermost Cretaceous limestones and siliciclastic rocks. The basin infill is of exclusively lacustrine origin and its basal part is marked as Oligocene to Miocene on the geological map. Although a detailed structural geological framework is still absent, the Banovići basin presumably initially formed in the Oligocene in response to dextral transpressional movements on the Sava, Drava, Busovača and Vrbas faults (Hrvatović, 2006). A second phase of basin formation befell the Dinarides in the Miocene, when the

Dinaride Lake System spread out across numerous intra-montane basins (De Leeuw et al., 2010, in press; Mandić et al., 2011).

2.2. Description of the basin infill

The infill of the Banovići basin consists of about 500 m of Oligocene to Miocene lacustrine deposits (Muftić and Luburić, 1963; Glišić et al., 1976) that currently extend over 37 km². It is partitioned into W–E elongated, generally southward tilted blocks (Fig. 1). The adjacent Seona (W) and Đurđevik basins (E) have a similar infill and might have originally been part of the same basin (Glišić et al., 1976). The basin infill is divided into two parts on the geological map (Fig. 1). The lower part of the basin infill (OI,M on Fig. 1) is about 80 m thick and starts with a fining upward series of conglomerates, sands and marls followed by a thin coal seam. This is overlain by sandy tufa limestone with lymneid snails in turn followed by an interval of greenish clay overlain by an alternation of coals and marls that grade upwards into the high quality, homogenous brown coal of the main coal seam (10–25 m). The top of the main coal layer is sharply defined and planar. The upper part of the basin infill (M1,2 on Fig. 1) comprises an up to 350 m thick series of lacustrine limestone, marl and marly sandstone that conformably overlies the main coal layer. Its lowermost 3 m contain abundant continental (Helicidae) as well as lacustrine (*Planorbis* sp., *Bythinella* sp., *Unio* sp., *Pisidium* sp.) mollusks. In the remaining part scarce fossil plant remains (*Glyptostrobus* sp.) as well as lacustrine mollusks (*Velutinopsis* sp., *Pisidium* sp.) and ostracods (*Candona* sp.) are preserved. Locally up to 80 m of conglomerates, sands and clays with lignite intercalations follow above an erosional hiatus. These are correlated to the upper Miocene of the neighboring

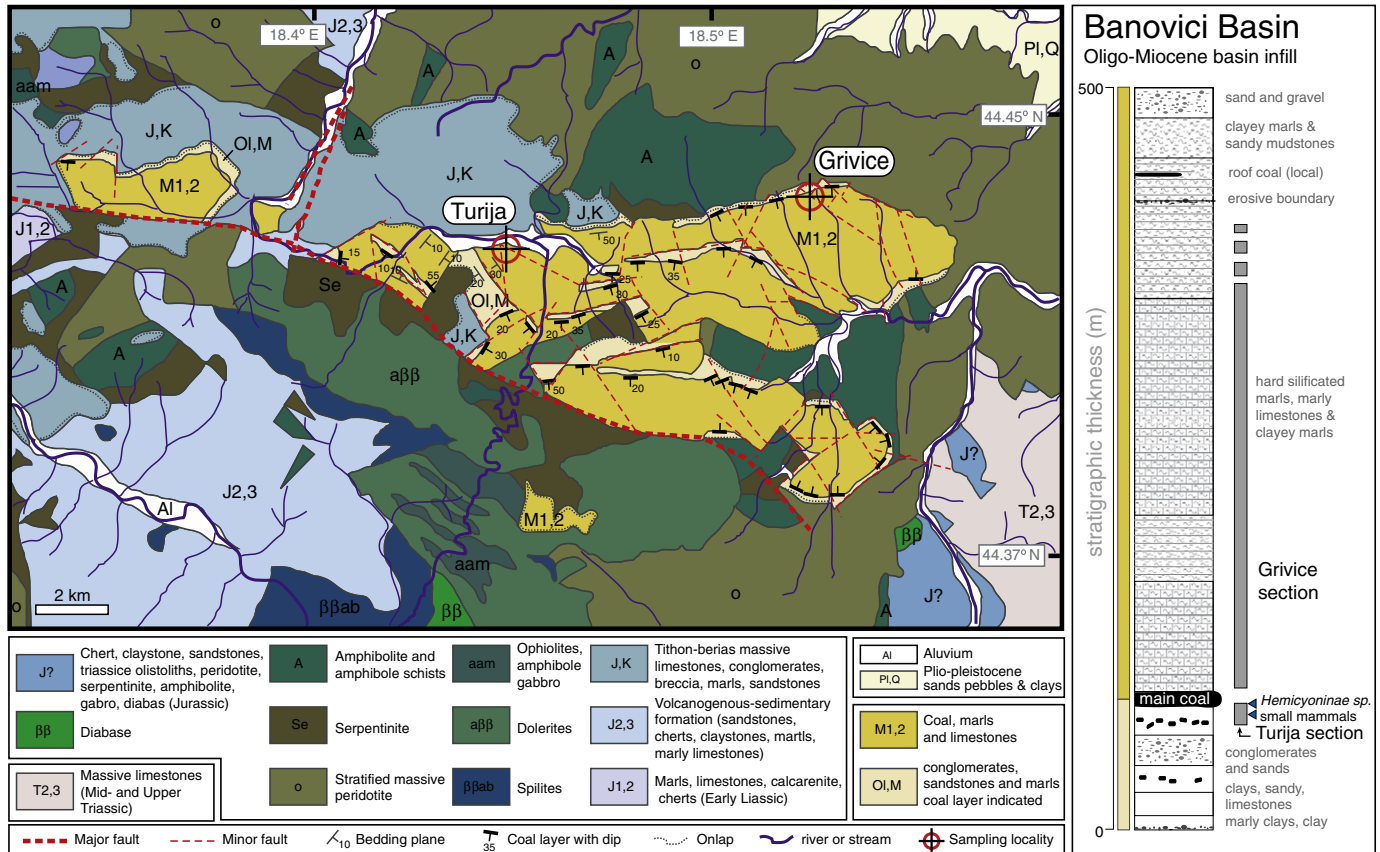


Fig. 1. Geological map (after Sunarić-Pamić et al., 1971; Pamić et al., 1973b; Čičić et al., 1991a, 1991b) and generalized stratigraphic column (modified after Muftić and Luburić, 1963) of the Banovići Basin.

Tuzla basin on the basis of their pollen spectra (Muftić and Luburić, 1963).

2.3. The Turija section

The Turija section (Fig. 2) is situated in the Turija open-pit mine located at the northern margin of the Banovići basin (GPS-WGS84: N44 25 32.7 E18 26 30.9). It exposes the very top of the strata underlying the main coal layer (Fig. 1). The outcrop reveals about 3 m of green clay with amphibolite lithoclasts in its lower part which are overlain by upward thickening coal seams alternating with greenish clay and grayish marls. A level with greenish clay 4 m above the base of the section was extensively sampled for small mammal fossils.

2.4. The Grivice section

The Grivice section was measured and sampled along the NNE–SSE striking wall of the quarry of the Grivice mine, situated along the basin margin 6 km east of the Turija section (Fig. 1). The base of the section is located at N44 26 04.8 E18 31 11.3 and the top at N44 25 58.6 E18 31 09.8. The section exposes the top part of the main coal layer (4 m) and a major part of the overlying lacustrine deposits (163 m, Fig. 3).

The approximately 100 m thick lower part is dominated by limestone and can be subdivided in five 15–22 m thick intervals with massive or thickly bedded limestones in their lower part grading into banded and thinly bedded limestones above (Fig. 3). The first of these intervals starts with 1.3 m of laminated dark brownish sandy limestone. The sand component diminishes upwards and sediment color changes to dark yellowish. Whitish limestones with dark intercalations follow and grade upwards into banded and bedded dark greenish limestone rich in organic material. The following two intervals have a similar built-up but lack the dark, organic rich interval characterizing the base of the first interval. The fourth interval bears clayey volcanic ash intercalations in its lower part. These are overlain by strongly laminated grayish limestones. The upper part is extensively banded and bears fossil leaves. Its topmost 4 m are dark in color which reflects a prominent increase in organic material. The

last limestone dominated interval is 23 m thick, has a similar architecture as the underlying intervals and contains plant remains and ostracods. The latter mainly occur in its upper part. A yellowish sediment color characterizes this interval.

The upper part (100–167 m) of the section is dominated by marl (Fig. 3). The grading from a more massive lower part to a well bedded and lightly banded upper part repeats itself once more between 100 and 126 m. The uppermost 41.5 m of the section lack well-expressed bedding. Three somewhat thinner intervals with a recurrent pattern can be distinguished here. These are respectively 16 m, 10.5 m, and 15 m thick. Their lower part consists of marly limestones and limy marls whereas their upper part is dominated by marls. Carbonate content thus decreases from the base to the top. The amount of preserved organic material and the density of ostracods, molluscs, fish and plant remains, in contrast, both increase upwards. A channel structure present at 140 m above the base of the measured section is filled in with reddish sand bearing mud clasts and a monotypic bivalve shell accumulation with *Pisidium* sp. (Fig. 3).

3. Small mammal taxonomy and biostratigraphy

3.1. Material and methods

The fossils of the Turija mammal site were collected from a 20 cm thick lignitic clay bed which contains limestone nodules and is located just below the main coal layer (Fig. 2). Two tons of sediment were washed and sieved over 0.5 mm sieves in the field. The residue was treated with chemicals in the laboratory, washed, sieved and subsequently sorted, mounted and measured. This fossiliferous layer produced a collection of 295 rodent molars (207 first and second molars). Beside the rodents, 181 insectivore teeth and molars, 7 marsupial molars and 30 lagomorph molars have been found (Table 2). All material is stored in Utrecht temporarily, but will eventually be housed in the Natural History Museum of Beograd. Detailed descriptions of the paleontological material will be published in separate papers.

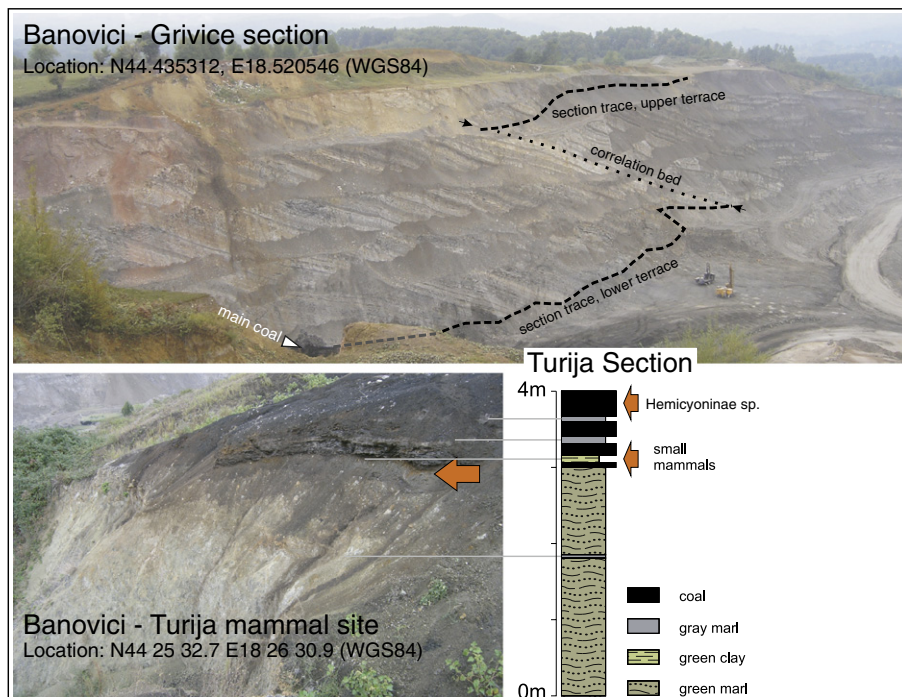


Fig. 2. Pictures of the Grivice and Turija sections and a stratigraphic column of the Turija section with the mammal site indicated.

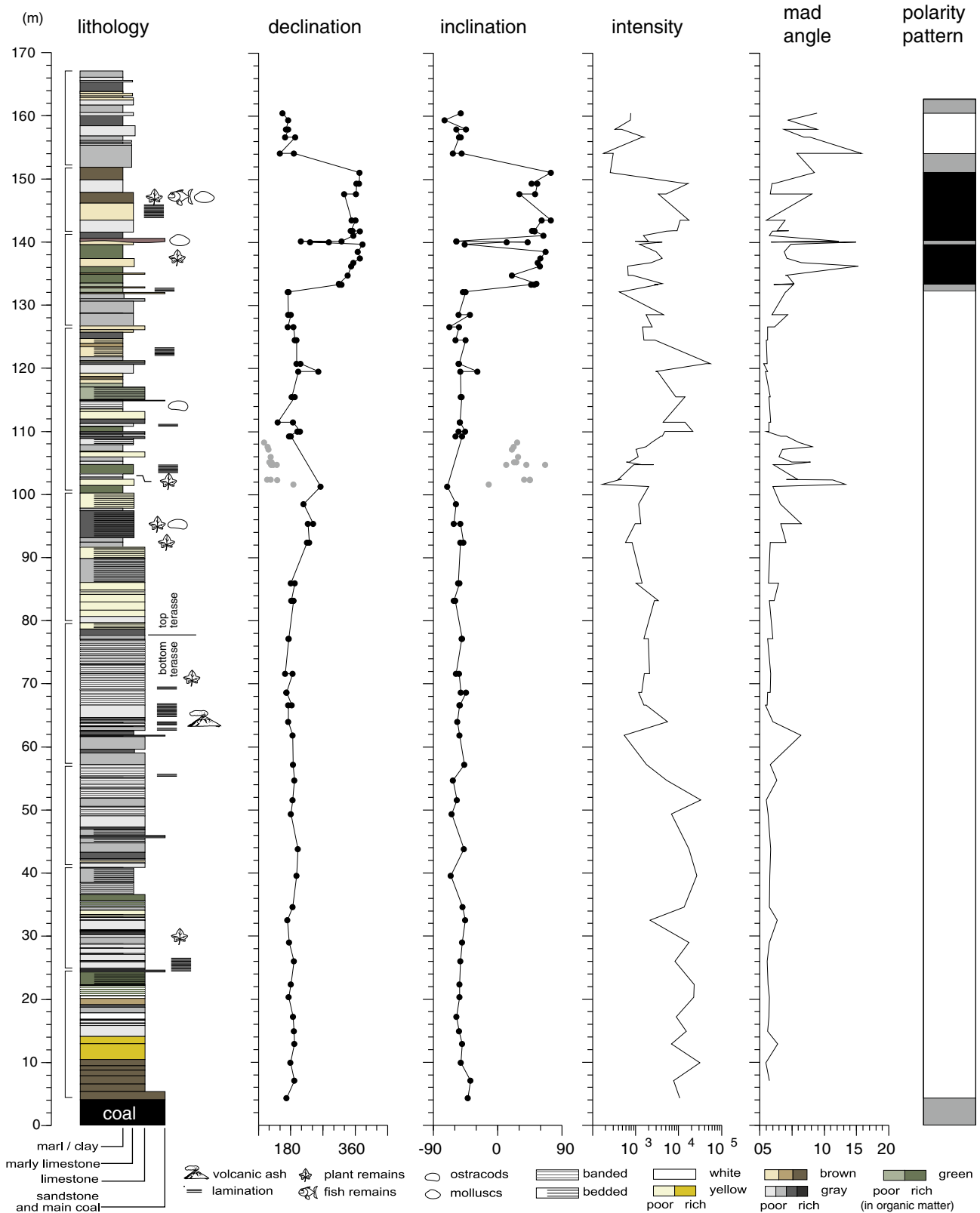


Fig. 3. Stratigraphic column and magnetic results for the Banovići Grivice section. The rightmost column shows the derived magnetostratigraphy. The intervals indicated to the left of the lithological column are described in detail in the main text.

3.2. Taxonomy

Ten rodent species belonging to eight genera are recognized (Fig. 4; new species are not included). Among these, the Muridae (extant hamsters, mice, and rats) are, with five species of four genera,

dominant in diversity as well as in the number of specimens (80%). The Gliridae (dormice) are with three species of two genera the second group (18%) and the Scuridae (squirrels) with two genera and two species are rare (2%). The Scuridae are represented by eight cheek teeth of *Palaeosciurus* (Fig. 4; 1–3) and two teeth of the

Table 1
Faunal list showing the complete small mammal record of the studied samples.

Order Rodentia
Family Sciuridae
<i>Palaeosciurus</i> aff. <i>P. feignouxi</i> Pomel, 1853
? <i>Ratufa obtusidens</i> Dehm, 1950
Family Gliridae
Subfamily Bransatoglirinae
<i>Bransatoglis</i> n. sp.
<i>Bransatoglis fugax</i> Hugueneu, 1967
Subfamily Dryomyinae
<i>Microdyromys</i> cf. <i>monspeliensis</i> Aguilar, 1977
Family Muridae
Subfamily incertae sedis
<i>Deperetomys</i> n. sp.
Subfamily Eumyarioninae Ünay-Bayraktar, 1989
<i>Mirrabella</i> aff. <i>anatolica</i> (de Bruijn and Saraç, 1992)
<i>Eumyarion</i> n. sp.
<i>Eumyarion microps</i> de Bruijn and Saraç, 1991
Subfamily Spalacinae Gray, 1821
Spalacinae n. gen. n. sp.
Order Insectivora
Family Soricidae
Subfamily Crocidosoricinae
2 Crocidosoricinae species
Family Heterosoricidae
sp. 1 (cf. <i>Quercysorex</i> Engesser, 1975)
sp. 2 (cf. <i>Heterosorex</i> Gaillard, 1915)
Family Talpidae
2 Talpidae species
Family Erinaceidae
sp. 1 (cf. <i>Amphelichinus</i> Aymard, 1850)
Family Dimylidae
1 Dimylidae species
Order Lagomorpha
Family Ochotonidae
cf. <i>Sinolagomys</i> Bohlin, 1937 (? <i>Bohlinotona</i> de Muizon, 1977)
Order Marsupialia
Family Herpotheriidae
? <i>Amphiperatherium</i> Filhol, 1879

enigmatic "*Ratufa*" *obtusidens* (Fig. 4; 4). The allocation of all the *Palaeosciurus* teeth to one species is questionable because of differences in size and morphology between the upper molars. The number of specimens is, on the other hand, too limited to allow the recognition of two species with confidence. We allocate these *Palaeosciurus* teeth to *P.* aff. *Feignouxi*, taking the morphological resemblance of the teeth of all the species of this genus and the paucity of the material from Turija into account.

The Gliridae are represented by two species of *Bransatoglis* (Fig. 4; 5–12) and a species of *Microdyromys* (Fig. 4; 13–20) that shows an unusually wide range of variation in dental pattern. The lower molars of *Bransatoglis* n. sp. (13 specimens) have three extra ridges between the mesolophid and the posterolophid. This clearly distinguishes the lower molars from those of *B. concavidens* and *B. spectabilis*. *Bransatoglis fugax* (14 specimens) resembles the material from the Late Oligocene type locality Coderet–Bransat (France MP30; Hugueneu, 1969; Schmidt-Kittler, 1987) better than the *B.* cf. *fugax* from the Early Miocene of southern Germany (Werner, 1994). *Microdyromys* cf. *monspeliensis* (28 specimens) has extra ridges in some teeth that do not occur in the type material of *M. monspeliensis*. The sample from Turija is in this respect very similar to *M. monspeliensis* from the Early Miocene of southern Germany (MN2; Werner, 1994). The

dental pattern of some teeth is reminiscent of those of *Glirulus diremptus* (Mayr, 1979), which suggests that the assemblages from Turija and southern Germany possibly document populations that are transitional between *Microdyromys* and *Glirulus*.

The Muridae are represented by one species of *Deperetomys*, one species of *Mirrabella* (Fig. 4; 21–23), one species of a new spalacid genus and two species of primitive *Eumyarion* (Fig. 4; 24–9). *Deperetomys* n. sp. (34 specimens) is the largest and probably oldest member of the genus. Although there remains uncertainty about the identification of primitive and derived dental characteristics in Muridae, because of parallel and convergent evolution in this very diverse family, we interpret the large, unreduced third molars of this *Deperetomys* species as primitive and the incipient development of the X-pattern formed by the protoconid/entoconid and hypoconid/metaconid connections in the first lower molar, that is characteristic for younger species of *Deperetomys*, as derived. *Mirrabella* aff. *anatolica* (13 specimens) is the second oldest record of the genus *Mirrabella*. The oldest is *M. hansoulii* from the Early Oligocene of Kyprinos (Thrace, Greece; Doukas and Theocharopoulos, 1997). The teeth from Turija differ from those of *M. anatolica* (from Harami 1 local zone C) in a number of details that do not leave any doubt that it documents a different species. The material from Turija shows a number of primitive murid characteristics that are modified in the species from Anatolia, yet these teeth are more robust and the upper third molar is more reduced. The material does therefore not fit the evolutionary trend reconstructed on the basis of the various species from Anatolia and Greece. We refrain from formally naming this species from Turija, because not all the tooth positions are represented in our collection and the variation in dental pattern is inadequately known.

The subfamily Eumyarioninae has the most diversified record among the murids from Turija. The Early Oligocene *Atavocricetodon* (Freudenthal, 1996) species from Spain have dentitions that are not essentially different from the *Eumyarion* from the earliest Miocene of Turkey (De Bruijn and Saraç, 1991) and Bosnia and Herzegovina. This suggests that the hiatus between *Eucricetodon* (*Atavocricetodon*) and the true *Eumyarion*, which is an immigrant into Europe (MN4) is filled in the eastern Mediterranean area. At the same time this raises the question of how to distinguish these two genera. We tentatively classify the two species from Turija in *Eumyarion* n. sp. and *E. microps* (55 and 96 specimens respectively). Among the primitive *Eumyarion* species, which have slender and "not inflated" cusps, the species from Turija are on average somewhat larger than *E. microps*, *E. carbonicus* and *E. montanus*, but there is overlap in size. The first upper and lower molars of *Eumyarion* n. sp. are shorter relative to the second upper and lower molars of the latter two species. The crescent-shaped anterocone, weak protoloph and usually strong paracone spur of the first upper molar makes this tooth readily distinguishable from this element of all other *Eumyarion* species. The second upper molar with its strong lingual branch of the anteroloph, often double protolophule and strong posterior spur of the paracone is quite characteristic also. The short posterior arm of the protoconid that is connected to the metaconid in the lower first molar is a characteristic that is shared with *E. carbonicus* and *E. montanus*, but these species have much stronger posterior arms of the hypoconid in all lower molars. *Eumyarion microps* from Turija has cheek teeth which are on average somewhat larger than the ones from the type locality (Harami 1, Turkey, De Bruijn and Saraç, 1991), but there is considerable overlap. There are some subtle differences in dental pattern between the two associations, but these are all a matter of degree and do not warrant the distinction of a different species.

Finally Spalacinae n. gen. n. sp. (33 specimens) is readily distinguishable from *Spalax*, *Pliospalax* and *Heramys* by its cusps that are not incorporated into the lophs in unworn molars. The dentition of this small new spalacid species also shows a mixture of original and derived characteristics. The small bifid, labially situated, anterocone of the upper first molar and the peculiar metaconid/anteroconid complex of the first lower molar are interpreted as primitive for Spalacinae and make these teeth very different. Other primitive

Table 2
Paleomagnetic results for the Grivice section.

Banovići Grivice	N	n	D	I	ΔDx	ΔIx	k	α95	K	A95
R directions	71	58	183.1	−52.9	3.1	2.7	77.9	2.1	53.3	2.6
N directions	19	19	349.2	55.6	10.4	8.2	22.6	7.2	16.9	8.4
R and N combined	77	70	2.8	53.5	2.8	2.4	79.8	1.9	54.7	2.3



Fig. 4. Biostratigraphically relevant rodent taxa recorded from Banovići Turija samples. 1–3: *Palaeosciurus* aff. *feignouxi*, 1: D4, 2: M1–2, 3: M3. 4: *Ratufa obtusidens*, M3. 5–12: *Bransatoglis fugax*, 5: P4, 6: M1, 7: M2, 8: M3, 9: p4, 10: m1, 11: m2, 12: m3. 13–20: *Microdyromys* cf. *monspeliensis*, 13: P4, 14: M1–2, 15: M1–2, 16: M3, 17: p4, 18: m1, 19: m2, 20: m3. 21–23: *Mirrabella* aff. *anatolica*, 21: m1, 22: m2, 23: M2. 24–29: *Eumyarion microps*, 24: M1, 25: M2, 26: M3, 27: m1, 28: m2, and 29: m3. All specimens on the plate are figured as left cheek teeth; an underlined number denotes that the original is from the right side.

characteristics that distinguish this new genus and species are that the first and third lower molars have the same length and that the lingual sinus of the third upper molar is open. In contrast, the posteriorly directed metalophs of the majority of the upper first and second molars and the development of an s-pattern in the second upper and lower molars through wear as in geologically younger members of the Spalacinae is probably much more complex than has been suggested so far. This new species is the smallest, and probably geologically oldest, member of the Spalacinae so far, but its phylogenetic position within the subfamily and the identity of the ancestor of the subfamily among the Paleogene Muridae remain unresolved.

3.3. Biostratigraphy

The biostratigraphic correlation of the rodent assemblage from Turija necessarily depends on comparison with faunas from other

areas such as central Europe and Anatolia, because our knowledge of the local succession is very limited. Comparison with areas along the east coast of the former Paratethys, such as Kazakhstan, where the Late Oligocene rodent fauna is well described (Bendukidze et al., 2009), is hampered by complete faunal dissimilarity.

Eomyidae species, which are important for precise correlation in the European biostratigraphy of the Oligocene/Miocene boundary interval, are, to our surprise, absent in the assemblage from Turija, which hampers a straightforward correlation with the European sequence. Six out of ten rodent species recognized in Turija are, nevertheless, similar to species known from Europe and/or Anatolia and they provide enough information for biostratigraphic correlation of the investigated succession. These are, as described in detail above, *Palaeosciurus* aff. *feignouxi*, *Ratufa obtusidens*, *Bransatoglis fugax*, *Microdyromys* cf. *monspeliensis*, *Mirrabella* aff. *anatolica*, and *Eumyarion microps* (Fig. 4). Fig. 5 provides the stratigraphic ranges of comparable species from central Europe and Anatolia in the European

MP/MN zones	Europe						Anatolia						
	P. feignouxi	Ratufa obtusidens	Bransatoglis fugax	Microdyromys monspeliensis	Mirabella anatolica	Eumyarion microps	P. feignouxi	Ratufa obtusidens	Bransatoglis fugax	Microdyromys monspeliensis	Mirabella anatolica	Eumyarion microps	Local zones
3				—	—	—		—	—	—			D
2	—	—	—	—	—	—	—	—	—	—	—	—	C
1	—	—	—	—	—	—	—	—	—	—	—	—	B
30	—	—	—	—	—	—	—	—	—	—	—	—	A

Fig. 5. The ranges of a number of small mammal species in the MP/MN mammal zones of Europe and local zones of Anatolia. Most data are from Werner (1994), Rössner and Heissig (1999), Freudenthal and Martín-Suárez (2007), Fortelius (2003), and Ünay et al. (2003a,b).

MP/MN scheme and the preliminary Anatolian zonation (Ünay et al., 2003a). It suggests that the assemblage from Turija ranges between the European MP30 and MN3 zones, approximately equivalent to the range of zones A–D in Anatolia. More specific correlation to the European MP30 zone and zone B in Anatolia is supported by the detailed faunal comparison provided above. Particularly important for a correlation to the older end of the spectrum are the presence of *Bransatoglis fugax* (which resembles material from MP30; France), the new *Deperetomys* species that is more primitive than *D. intermedius* from zone C in Anatolia, *Eumyarion* n.sp., which differs from *E. carbonicus* from zone C in Anatolia, and the new spalacid that is in many respects more primitive than the hitherto oldest spalacid *Debruijnina arpati* from zone D in Anatolia (~MN3). We conclude that the Turija locality is older than locality Harami 1, which is located in Central Anatolia and pertains to Anatolian zone C. The rodent assemblage from Turija might be time-equivalent to the assemblages from Coderet–Bransat (France) that belong to the Late Oligocene MP30 zone. We thus interpret the Turija assemblage as top MP30/base MN1. The absence of Eomyidae from the Turija assemblage, and the presence of species that are not known from elsewhere, hamper a more precise correlation.

4. Magnetostratigraphy of the Grivice section

4.1. Sampling and laboratory methods

The Banovići–Grivice section, was sampled for paleomagnetic measurements in order to acquire a magnetostratigraphy (Fig. 3).

Samples were collected with a hand-held gasoline-powered drill. In the field, the orientation of all samples and bedding planes was measured by means of a magnetic compass and corrected for the local magnetic declination (3°). The gross sampling resolution achieved was approximately one site every 3 m. At each site 2 samples were taken. After the first demagnetization results were available a second sampling series covered the intervals 100–110 m and 134–142 m in more detail.

In the laboratory, the obtained cores were cut into several specimens that were subsequently stepwise demagnetized. The natural remanent magnetization (NRM) of the samples was measured after each demagnetization step on a 2G Enterprises DC Squid cryogenic magnetometer (noise level $3 \cdot 10^{-12}$ Am²). Demagnetization was accomplished by a laboratory-built automated measuring device applying 16 5–20 mT increments up to 100 mT by means of an AF-coil interfaced with the magnetometer. The presence of iron sulfides in the studied samples was anticipated. In order to overcome the problem of gyroremanence during alternating field demagnetization the specifically designed per component demagnetization scheme of Dankers and Zijdeveld (1981) was applied. In addition, small (2–5 mT) field steps were taken in the 20–40 mT range. The characteristic remanent magnetisation (ChRM) was identified through assessment of decay-curves and vector end-point diagrams (Zijdeveld, 1967). ChRM directions were calculated by principal component analysis (Kirschvink, 1980).

To identify the magnetic carrier(s), high temperature thermomagnetic experiments were performed on a modified horizontal-translation type Curie Balance (Mullender et al., 1993). Bulk sediment samples of BA06 and BA50 were heated up to 700 °C in air. At 200,

300, 350, 450, 500 and 600 °C samples were cooled a 100 °C in order to distinguish thermal behavior from chemical alterations. Heating and cooling occurred at a rate of 10 °C/min. The cycling field varied between 150 and 300 mT.

4.2. Rock magnetism

Curie Balance measurements for sample BA06.1, BA50.1, BA08-04.1, and BA08-09.1 are displayed in Fig. 7g, h, o, and p respectively. For sample BA06 heating and cooling segments are virtually reversible up to 300 °C. Between 300 and 350 °C the magnetization decreases and upon cooling it is not restored. This indicates the presence of greigite, which is remarkably stable and does not break down completely into a non-magnetic phase up to 400 °C where a local minimum in magnetization is observed. Note that often this minimum is observed at ~350 °C, i.e. 50 °C lower. The rise in intensity upon heating above 400 °C is characteristic for the transformation of pyrite (and of greigite that, however, is marginally present in comparison to pyrite) into magnetite. The creation of magnetite slows down considerably on cooling or is even halted entirely when the sample is cooled below 400 °C. The magnetization increases on cooling because the spontaneous magnetization of magnetite increases with decreasing temperature. The formation of magnetite resumes again upon heating as indicated by a steady rise in magnetization between ~420 and 500 °C. The increase in magnetization is much steeper on the 500–400 °C cooling segment than on the 450–350 °C segment which confirms an increased amount of magnetite. The small change in slope in the heating curve at ~580 °C, coincides with the ordering temperature of magnetite. The distinctly lower magnetization along the 600–500 °C cooling segment with respect to the 500–600 °C heating segment indicates that some magnetite oxidized to haematite, which is much less magnetic. After heating up to 700 °C, the final cooling curve is located even lower than the 600–500 °C cooling segment, which indicates that even more magnetite was oxidized to haematite. However, some magnetite remained present, since the magnetization increases sharply between 570 °C and 550 °C. The next break in slope in the cooling curve slightly above 300 °C is close to the ordering temperature of pyrrhotite and the strong increase in magnetization between 300 and 20 °C should thus be attributed to the pyrrhotite created during the experiment. These results indicate the original presence of greigite and pyrite in sample BA06.1, in line with its lacustrine origin.

Greigite is also present in sample BA50.1 since the cooling segments of 300–200 °C and 350–250 °C are located below the corresponding heating curves, again indicative of the transformation of greigite into a non-magnetic (or less magnetic) phase. The increase in magnetization along the cooling segments of 450–350 °C and 500–400 °C is less steep than for BA06.1 indicating a lower amount of pyrite. In analogy with BA06.1, magnetite eventually oxidizes to haematite. The final cooling curve is located below the preceding heating and cooling curves since all thermally created magnetite and presumably most (if not all) of the original magnetite is oxidized to haematite. The lack of a clear rise in magnetization upon cooling below 300 °C excludes the presence of a significant amount of pyrrhotite which concurs with a more complete oxidation to haematite. Curie Balance diagrams for sample BA08-04.1 and BA08-09.1 are very similar. Hardly any greigite is present. Significant amounts of magnetite are created from pyrite above 400 °C and eventually a reasonably significant fraction of the magnetite oxidizes to haematite. No significant amounts of pyrrhotite are being formed during the thermal cycles.

4.3. Demagnetization and magnetostratigraphy

For all sites at least one, and for the upper two thirds of the section both of the two samples were demagnetized. Overall, demagnetiza-

tion diagrams are of good quality. The NRM of the Banovići marls generally consists of two components. A low field overprint is typically demagnetized from 5 to 32 mT (e.g. Fig. 6b, e) and a well-defined high field component that is removed between 32 and 80 mT is interpreted to be the ChRM (e.g. Fig. 6a and d). NRM intensities typically range between 2 and 50 m Am⁻¹. The low field component decays slightly quicker than the high field component. At 32 mT mostly 50% of the NRM had been removed. At 100 mT often c. 90% of the NRM had been removed. No gyroremanence is observed.

The steep bedding tilt of the investigated strata facilitates isolation of the ChRM. The low field component that appears in demagnetization diagrams typically carries directions that trend to the present day field direction in geographical coordinates and most likely represents a badly expressed recent overprint. The high field ChRM component is very clear and has a reversed polarity in the main part of the section (Fig. 3). It bears a normal signature between 132 and 152 m. The directions between 102 and 108 m do neither fit a normal nor reversed polarity. Curie balance measurements indicate these samples have a deviating mineralogy and do not contain the stable greigite present in the rest of the section. After the first demagnetization results were available, the interval was re-sampled and carefully inspected. However, the newly acquired results confirmed the original measurements and no signs of profound alteration or disturbance were encountered in the field. We regard the directions from this interval as unreliable and not representative of the paleomagnetic field at the time of deposition. The section thus contains two reversed and one normal polarity intervals.

ChRM directions without tilt correction clearly do not cluster near the present day field (PDF) direction (Fig. 7a). This indicates they do not reflect a PDF overprint. Upon tectonic tilt corrections the directions from the combined reversed intervals cluster around $\text{dec} = 183.1^\circ$ and $\text{inc} = -52.9^\circ$ using the Vandamme cutoff (Vandamme, 1994) to discard outliers (Fig. 7b, Table 1). The directions from the normal interval have an average declination of 349.2° and an average inclination of 55.6° (Fig. 7c, Table 1). When we combine the normal and reversed directions (Fig. 7d), we arrive at an average declination of 2.8° , and an inclination of 53.5° (Table 1).

5. Chronology for the Banovići basin

The MP30/MN1 small mammal assemblage encountered in the lowermost part of the main coal sequence indicates a Late Oligocene to Early Miocene age. This contrasts former late Early Miocene age inferences based on pollen spectra and lithostratigraphic correlations with the Sarajevo and Livno basins (Muftić and Luburić, 1963; Glišić et al., 1976). The fauna encountered in the Turija section is older than that of the Harami 1 locality in Anatolia that has been correlated to chron C6Bn.2n of the magnetic polarity time scale by Krijgsman et al. (1996b). This provides a numerical minimum age of approximately 22.2 Ma according to the timescale of Lourens et al. (2004). The acquired magnetic polarity pattern for the Grivice section, with a long reversed interval, a subsequent short normal interval, and another reversed interval, can best be correlated to the Late Oligocene interval of chrons C6Cr, C6Cn.3n, and C6Cn.2r of the GPTS (24–23.2 Ma) (Fig. 8). According to this correlation, the Turija mammal locality is around 24 Ma old.

The main lacustrine phase of Lake Banovići thus started around 24 Ma. Whereas in more central parts of the basin over 300 m of lacustrine deposits accumulated above the main coal horizon, their thickness decreases to about 200 m or less towards the basin margin (Glišić et al., 1976). Our correlation of the magnetostratigraphic pattern of the ~160 m long Grivice section to the 24–23.2 Ma interval of the GPTS implies a sedimentation rate of approximately 0.2 m/kyr. Extrapolation of this sedimentation rate to the remaining 40 m of sediments results in a 23 Ma age for the topmost lacustrine sediments.

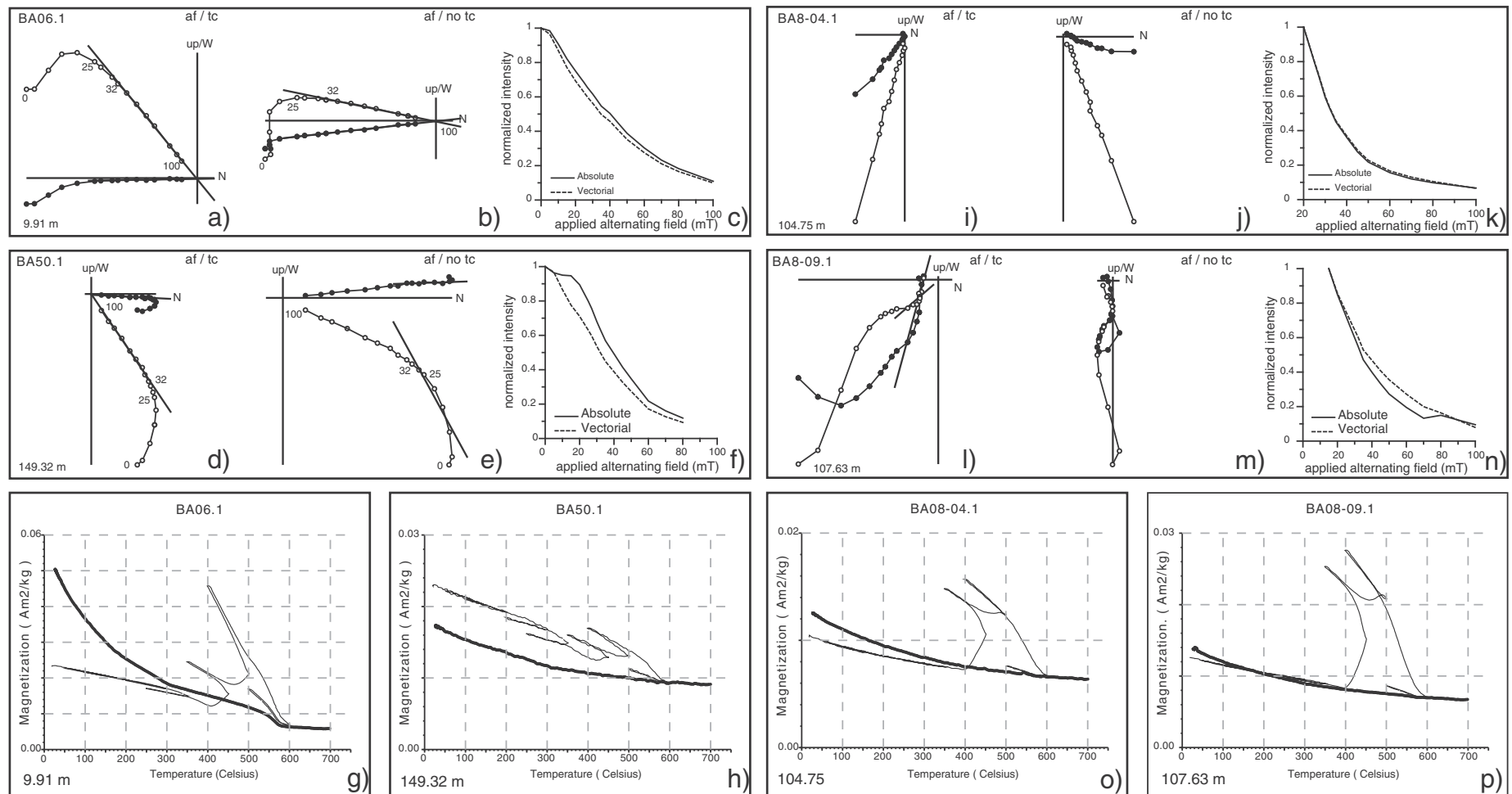


Fig. 6. Demagnetization, decay and Curie Balance results for four samples from the investigated Banoviči section. Diagrams marked 'no tc' are not corrected for the tilt of the strata. In diagram a, b and d the ChRM direction is indicated. In diagram e the direction of the overprint is indicated. The number in the lower left corner of each diagram identifies the stratigraphic position (m) of the demagnetized sample in the section. Field strengths indicated along the diagrams are in mT. On the decay diagrams 'absolute' indicates the measured intensity plotted as function of AF level. 'Per division' indicates the normalized vectorial decay between subsequent steps.

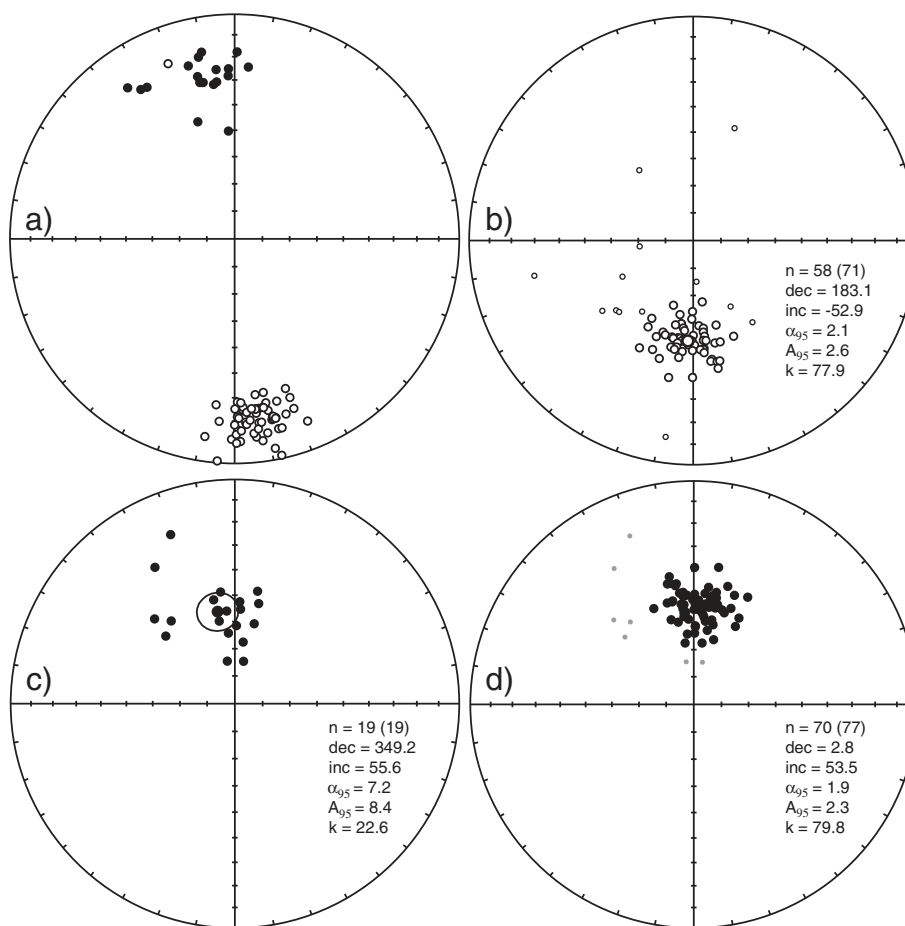


Fig. 7. Paleomagnetic directions for the Grivice section in equal area diagrams. For a detailed description see text.

The strong affinities of the Turija fauna with assemblages from both Anatolia and Central Europe indicate that the intra-montane basins of the Dinarides comprised an important paleogeographic position for Asia–Europe mammal migration during the Oligocene and Miocene (Fig. 9). This is in good agreement with earlier paleogeographical reconstructions that indicate the presence of a land-bridge along the southern margin of the Paratethys Sea in Late Oligocene times (e.g. Rögl, 1999).

6. Discussion

6.1. The Turija *Hemicyoninae* (bear-dog) fossils

In the upper part of the Turija section, 1 m above the small mammal bearing layer, a lower jaw of a bear-like animal, identified as *Hemicyon* cf. *stehlini* (Vrabac et al., 2005), was found by mine-workers. *Hemicyon* is known from many European MN3–MN7/8 localities (Agustí et al., 2001). This identification thus suggests a Burdigalian–Langhian age for this level. If the determination of these bear-like remains is correct, a hiatus of over 4 Myr in the upper meter of the Turija section must be present. The magnetostratigraphic pattern of C6Cr–C6Cn.2r is not unique and the Grivice pattern can for instance also be correlated to younger intervals of chrons C5Dr2r, C5Dr1n, and C5Dr1r (17.9–17.7 Ma), or C5Br, C5Bn2n, and C5Bn1r (16.0–14.9 Ma). There are, however, no indications for such a profound hiatus in the coal deposits in the Turija section. In combination with the stratigraphically lower small mammal fauna, we thus conclude that either *Hemicyon* has a

larger biostatigraphical range or that this lower jaw belongs to a different taxon.

6.2. Implications for mammal chronology

Our correlation of the Turija MP30/MN1 site with the base of C6Cr (Fig. 8) follows the magnetostratigraphic correlation of the Anatolian Inkonak and Harami 1 sites (Krijgsman et al., 1996b). These fall in local zones A and C which correlate to MP30 and MN2 respectively. The Turija fauna is most similar to the Kargi 1 and Kilcak 0–3b of upper zone A, lower zone B and its age is thus in close correspondence with the age of similar fauna in Anatolia. In the Ebro basin, several mammal sites are magnetostratigraphically calibrated (Gomis Coll et al., 1999; Agustí et al., 2001). Correlation of the two MP30 sites in the Torrente de Cinca section in the Ebro basin by Agustí et al. (2001) to C6Cr is in good agreement with our age for the Turija site.

We are hesitant to adopt the age intervals listed by Mertz et al. (2007) for the MP29 and MP30 reference levels because they are based on interpolation of equal time-intervals between the top of MP28 and a disputed 24.0 ± 0.1 Ma absolute age for the Oligocene–Miocene boundary by Wilson et al. (2002). The astronomically tuned age of this boundary in the Gradstein et al. (2004) timescale is 23.03 Ma. In addition, the MP30/MN0 zone is often mentioned to straddle the Oligocene–Miocene boundary which also excludes the age of this boundary as a good upper limit on the age of the MP30/MN0 zone.

The only absolute ($^{40}\text{Ar}/^{39}\text{Ar}$) ages, currently available for upper Oligocene mammal localities, come from the two basaltic flows that intercalate with the MP28 fauna of the Enspel fossil deposits in

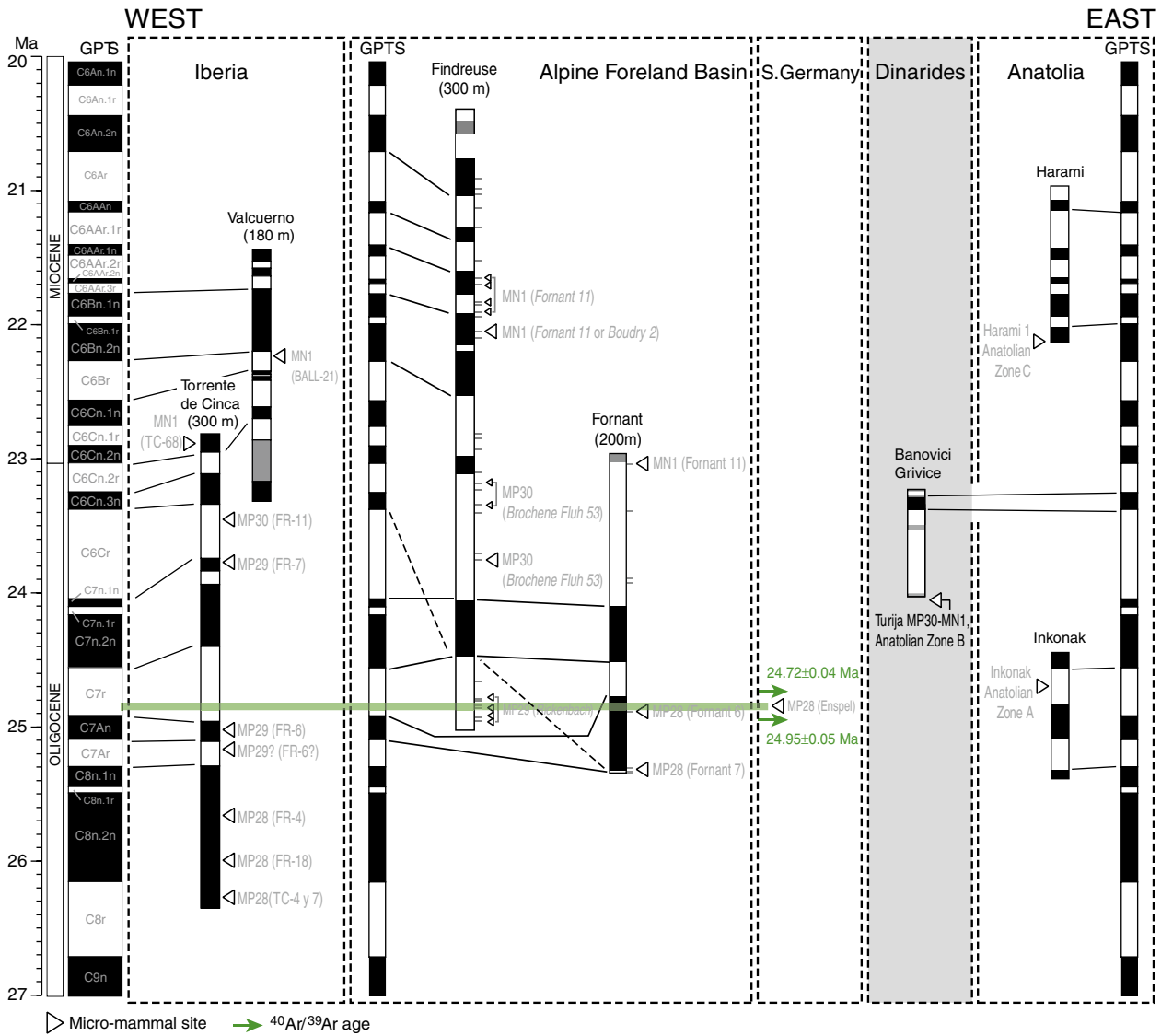


Fig. 8. Correlation of the Grivice magnetostratigraphic pattern to the GPTS 2004 and comparison with some other magnetostratigraphically calibrated mammal localities in Europe and Anatolia. Correlation of the Torrente de Cinca and Valcuerno sections after Agustí et al. (2001) and Gomis Coll et al. (1999). Correlation of the Fornant and Findreuse sections after Agustí et al. (2001). Alternative correlation by Schlunegger et al. (1996) indicated by dashed lines. Absolute ages for the Enspel MP28 (Mertz et al., 2007) are recalibrated according to Kuiper et al. (2008). Correlation of the Inkonak and Harami sites according to Krigsman et al. (1996b).

southern Germany (Mertz et al., 2007). We recalibrated the 24.79 ± 0.05 Ma and 24.56 ± 0.04 Ma ages for the Enspel Lower and Upper flow, according to the recently calculated astronomically tuned age of the Fish Canyon Tuff (Kuiper et al., 2008), and arrive at 24.95 ± 0.05 Ma and 24.72 ± 0.04 Ma, respectively. The flows that are interpreted to bracket the lacustrine sediments at the Enspel site that contain the eomyids relevant for the MP28 correlation are thus 0.16 Ma older than previously thought. The Enspel MP28 site is consequently between 24.95 ± 0.05 Ma and 24.72 ± 0.04 Ma old (Fig. 8).

The absolute ages for the Enspel basalts and our correlation of the Turija site indicate that, as earlier suggested by Agustí et al. (2001), the correlation of magnetostratigraphically investigated sections in the Swiss Foreland Basin (e.g. Schlunegger et al., 1996, 1997a,b, 2007; Kempf et al., 1997, 1999; Schlunegger, 1999; Strunck and Matter, 2002; Kempf and Pross, 2005) has to be revised. These authors placed MP28 fauna in C7n and the lower half of C6Cr, and MP29 exclusively in C6Cr. This correlation introduces a large diachrony in the record, with ages that are about 1 Ma younger than Enspel radio-isotopic ages suggest. The 24 Ma age for the Turija fauna fits very well with the age of sites with a comparable faunal assemblage in the Fornant–

Findreuse section in the Alpine Foreland Basin in the Haute Savoie following the alternative magnetostratigraphic correlations by Sen (1997) and Agustí et al. (2001) (Fig. 8).

6.3. Regional implications

Precise age determination has long been the biggest outstanding problem for most intra-montane basins in the Dinarides (Pavelić, 2001). The here established 24–23 Ma age for the infill of the Banovčić basin represents a major step forward for the regional stratigraphic scheme.

Paleo-vegetation data indicate that European continental climate in the Late Oligocene is marked by a distinct temperature peak (Mosbrugger et al., 2005). This Late Oligocene Climatic Optimum is registered in marine isotopic records as well (Zachos et al., 2001; Villa et al., 2008). Correlation of the Grivice section to upper Oligocene chrons C6Cr, C6Cn.3n, and C6Cn.2r implies that the lifetime of Lake Banovčić coincided with optimum climatic conditions and an elevated global temperature. Our new fossil findings in the Banovčić basin furthermore indicate that an at least limited exchange of fauna

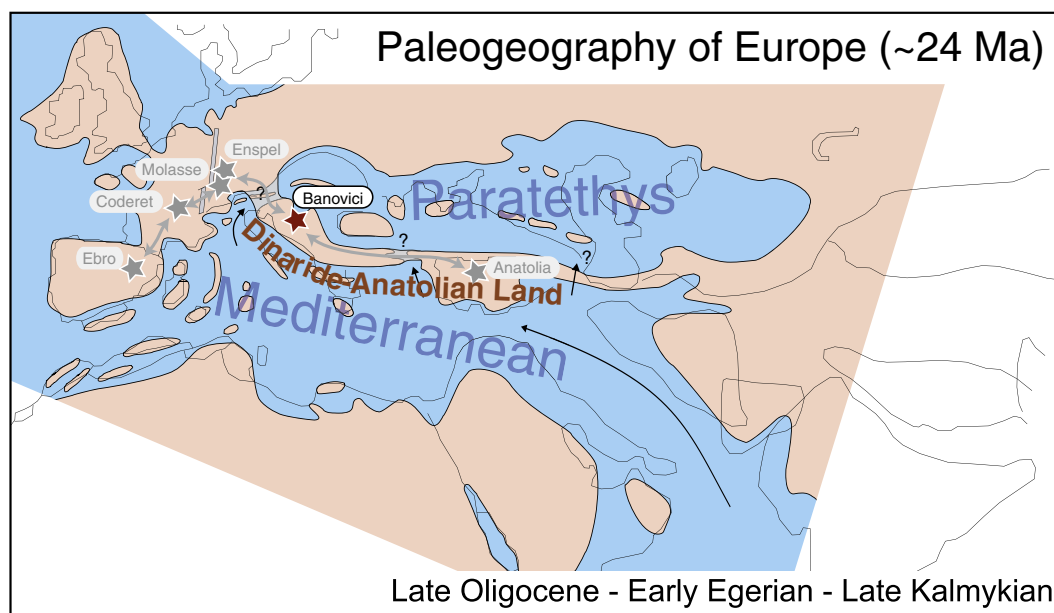


Fig. 9. Paleogeographic setting of Banovici and other mentioned mammal sites in the Late Oligocene (modified after Rögl, 1999).

between Central Anatolia and Europe took place around 24 Ma. Unfortunately, there is still a big gap in the mammal record of former Yugoslavia, which hampers a thorough understanding of mammal migration patterns between Asia and western Europe during the Oligo-Miocene. The excavation, description, and dating of more sites like Banovici is thus highly essential in order to understand the terrestrial paleobiogeographical relations of this crucial area.

Our results also contribute to a better understanding of the geodynamic history of the Dinarides. Although in the larger part of the Banovici basin sediments are heavily tectonized, our paleomagnetic results indicate that the basin did barely rotate since then. Comparison of the observed declination ($2.8 \pm 2.8^\circ$) to the declination ($5.9 \pm 4^\circ$) expected on the basis of the 20 Ma reference pole for Europe (Torsvik et al., 2008) shows these are statistically indistinguishable when the respective uncertainties are taken into account. The difference between the observed and expected inclination, 53.5° vs. 60.8° , most likely results from a flattening effect due to compaction of the sediments (e.g. Krijgsman and Tauxe, 2004).

7. Conclusions

The Banovici basin infill was dated to be of latest Oligocene age on the basis of small mammal biostratigraphic and magnetostratigraphic results. The assemblage of the Turija mammal site at the base of the basins main coal layer best compares with localities attributed to European MP30–MN1 small mammal zones and Anatolian zone B. The magnetostratigraphic pattern of the Grivice section, exposing 167 m of lacustrine marls and limestones overlying the main coal layer, consists of a long reversed interval at the base, a short normal in the upper part, and another reversed interval at the very top of the section. Using the small mammal assemblage as a rough age indicator, correlation of the magnetostratigraphic pattern to the C6Cr to C6Cn.2n interval of the GPTS is preferred. This correlation indicates the main lacustrine phase of the Banovici basin started shortly after 24 Ma and lasted till ~23 Ma and implies deposition took place at a rate of 0.2 m/kyr. The presented results contribute to a better understanding of the mammal biostratigraphy and the paleogeographic development of the north-eastern margin of the Dinarides.

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