

A chronostratigraphy for the Dinaride Lake System deposits of the Livno-Tomislavgrad Basin: the rise and fall of a long-lived lacustrine environment

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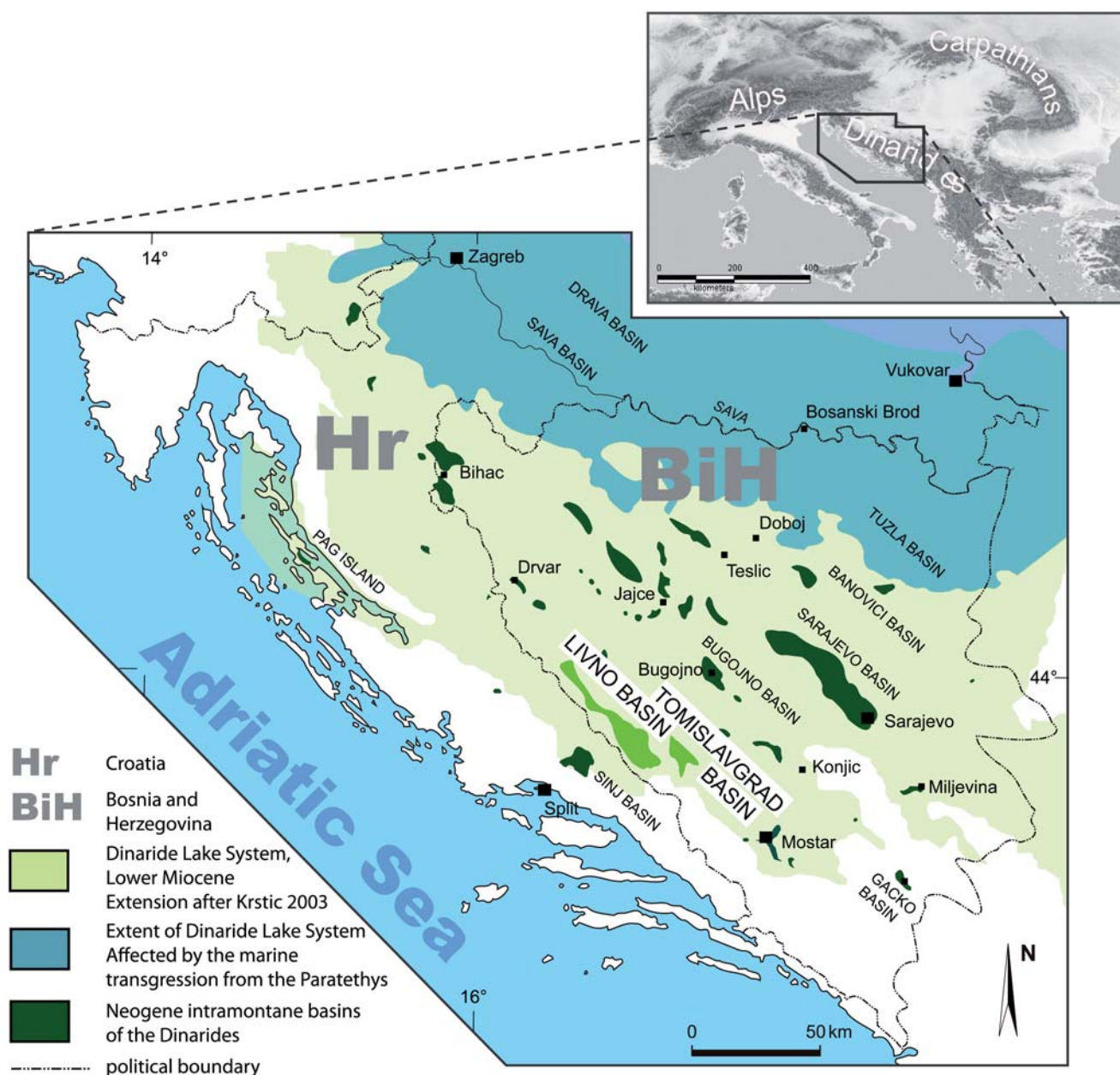
ABSTRACT: The Dinarides are an integral part of the Alpine orogenic belt and stretch over large parts of Slovenia, Croatia, Bosnia-Herzegovina, Monte Negro and Serbia. A great number of intra-montane basins formed in the interior of this Late Eocene to Early Oligocene orogen during the Miocene. These basins harbored a suite of long-lived lakes, collectively called the Dinaride Lake System (DLS). Lake Livno, with its 600km² of preserved surface, was the second largest of these Dinaride Lakes. At present, its deposits are divided between the Livno and Tomislavgrad basins, which were part of a single basin when Lake Livno first formed. High resolution age constraints for the over 2km basin infill have been lacking up to now, partly due to the endemic nature of its lacustrine fauna. This severely hampered geodynamic as well as paleoenvironmental reconstructions. Here, we present a chronostratigraphy based on radio-isotopic and magnetostratigraphic data. ⁴⁰Ar/³⁹Ar measurements reveal that the Tušnica volcanic ash, found in between the *Gomphoterium*-bearing coal seams at the base of the basin infill, is 17.00±0.17 Ma old. ⁴⁰Ar/³⁹Ar dating of the Mandek ash, correlative to the uppermost sedimentary unit, provides an age of 14.68±0.16 Ma. Correlation of the composite magnetostratigraphy for the main lacustrine depositional phase to the Astronomically Tuned Neogene Time Scale is straightforward and reveals that the majority of the deposits of Lake Livno accumulated between 17 Ma and approximately 13 Ma. The disappearance of Lake Livno is most likely attributable to a change in tectonic regime. Calcarenites and breccias, derived from the basin margins, first entered the lake around 14.8 Ma and subsequently coarsened and thickened upwards. The basin margins were apparently gradually uplifted before subsidence stalled. Comparison with chronostratigraphic data for other constituents of the DLS leads to the conclusion that their lifetimes largely coincide. Finally, we calibrate the most important marker fossils of the various Dinaride basins to the geological time scale and we present a new biochronological scheme for the DLS.

INTRODUCTION

In the Miocene, the Dinaride-Anatolian land separated the epicontinental Paratethys Sea from the Mediterranean and connected the Middle East with Central Europe. A great number of intra-montane basins developed within the Dinaride Mountain chain, in which a multitude of long-lived lakes settled (text-fig. 1). The longevity, thick sedimentary successions and large geographic extent of this so called Dinaride Lake System make it a key archive for the faunal and floral evolution of southeastern Europe (Krstić et al. 2003; Mandic et al. 2008; Jiménez-Moreno et al. 2008, 2009). Good age control on these sediments is lacking, since strong endemism characterizes the lacustrine fauna. The regional biostratigraphic scheme is furthermore far from complete and hardly time-indicative due to a lack of high resolution age data. This hampers regional geodynamic as well as paleobiogeographic reconstructions and several key questions remain unanswered. It is for example not clear if all basins

formed simultaneously or if they were generated in different phases. Their significance with regards to the geodynamic evolution of the orogen thus remains unclear.

To solve these questions, a large chronostratigraphic study with special emphasis on long continuous sections suitable for multi-disciplinary dating techniques was set up. This study resulted in high resolution age constraints on the Pag, Sinj, and Gacko basins of the DLS (Jiménez-Moreno et al. 2009; de Leeuw et al. 2010; Mandic et al. 2010, 2011). In this paper, we investigate the sedimentary succession of the Livno and Tomislavgrad basins in Bosnia and Herzegovina (text-fig. 1). These basins, with their almost 2km thick infill, harbored one of the main constituent lakes of the Dinaride Lake System. We use magnetostratigraphic and radio-isotopic dating techniques to construct a detailed (bio)-chronology for the evolution of Lake Livno.



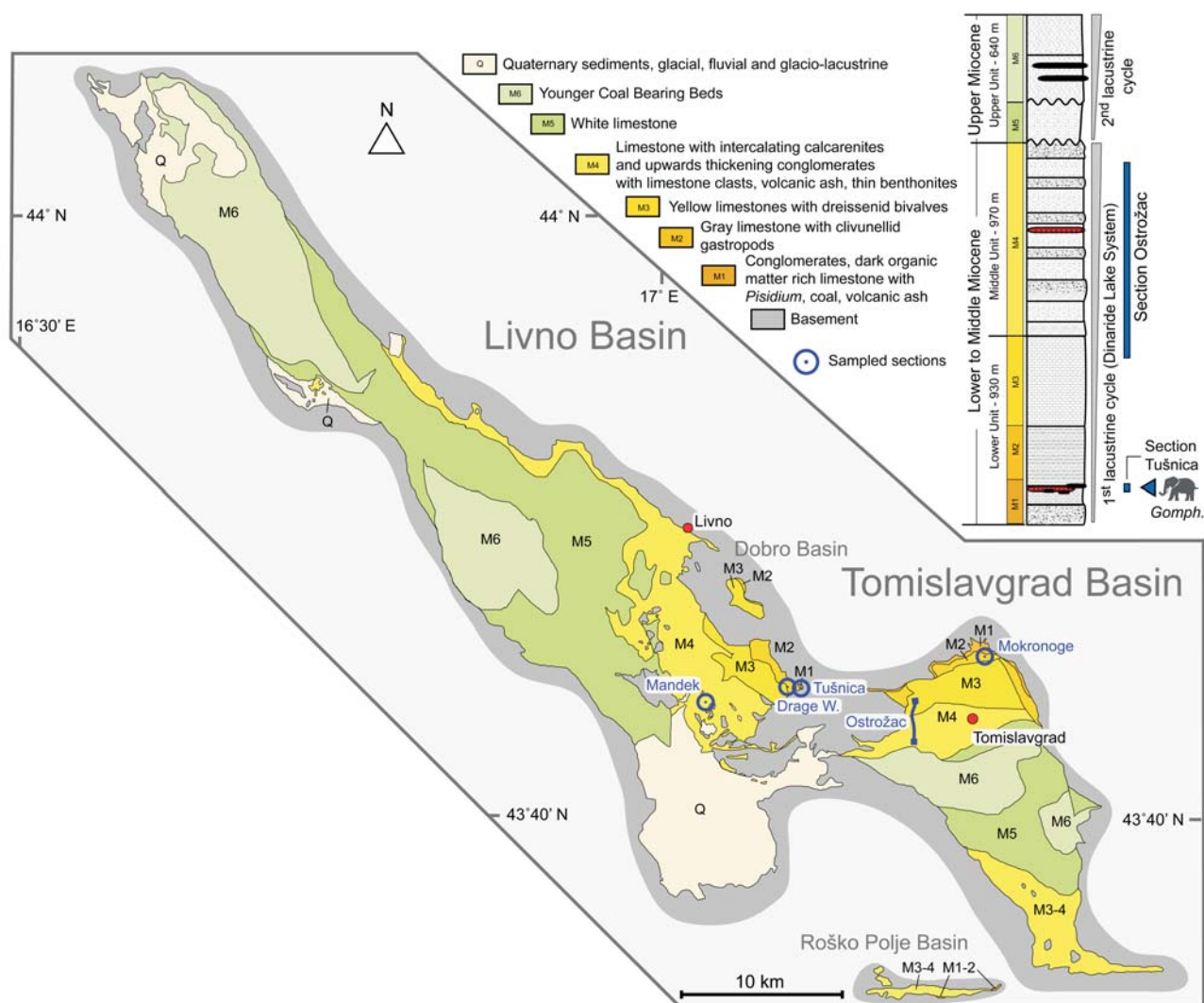
TEXT-FIGURE 1

Map indicating the location of the Livno and Tomislavgrad Basins in the interior of the Dinarides. Lake Livno was part of the Dinaride Lake System that stretched out from the island of Pag in the west to the Sava and Drava depressions in the north and the Gacko basin in the south.

GEOLOGICAL SETTING

The deposits of Lake Livno are at present distributed in four intra-montane basins situated in the High Karst area of the external Dinarides (text-fig. 2). This study concentrates on the two main basins; one surrounding the town of Livno, and the other the town of Tomislavgrad (formerly Duvno and Županjac). Although these basins are currently disunited and lie at different altitudes (700–710m and 860–890m), they were formerly part of a single basin. Their Miocene infill consists of up to 2.6km of lacustrine sediments, which represent two consecutive phases of lake formation.

The deposits of the first lacustrine phase (text-fig. 2) attain up to 2000m and consist for the larger part of limestone. The mollusk assemblages of this phase indicate that Lake Livno was part of the widespread Dinaride Lake System. At the very base of the sedimentary succession, there is an approximately 10m thick coal interval. In the main coal seam, remains of *Gomphoterium angustidens*, an ancient elephant, were found and Malez and Slišković (1976) therefore considered it to be of Middle Miocene age. The same level was, in contrast, correlated to the upper Lower Miocene based on its pollen content (Pantić 1961). The coal interval is overlain by a thick package of limestones. Calcarene layers, with carbonate grains, likely derived from



TEXT-FIGURE 2

Generalized stratigraphic column and geological map of the Livno, Tomislavgrad and Roško-Polje Basins with the location of the investigated sections and sites. The extent of the sampled sections is marked in the stratigraphic column by blue bars. The blue triangle indicates the approximate position of the Tušnica *Gomphotherium* site (Kochansky-Devidé and Slišković, 1972; Malez and Slišković, 1976). The geological map was compiled and adapted from the 1:100.000 geological maps of former Yugoslavia – sheets Livno, Sinj, Imotski and Glamoč (Papeš 1972; Papeš 1975; Ahac et al. 1976; Marinčić et al. 1976; Raić et al. 1976; Marinčić et al. 1977; Papeš and Ahac 1978; Raić and Papeš 1978; Papeš et al. 1982; Raić et al. 1984). Stratigraphic column was drawn according to Milojević and Sunarić (1964) and Papeš (1972, 1975).

basement rocks, intercalate in the middle part of the limestone succession. These layers coarsen and thicken upwards and eventually turn into carbonate clast breccias. These breccias also coarsen and thicken upwards. The uppermost part of the deposits of this first lake phase does not crop out, since it is covered by those of the second lake phase.

The deposits of the second lacustrine phase overlie those of the first phase discordantly and attain up to 640m (text-fig. 2). Based on its pollen (Pantić 1961; Pantić and Bešliagić 1964), mollusk (Jurišić-Polšak and Slišković 1988) and ostracod record (Milojević 1961; Milojević and Sunarić 1962), this second phase has been correlated with the Upper Miocene of Lake Pannon, which at that time covered large parts of adjacent Central and Eastern Europe. According to Milojević and Sunarić

(1964) and Papeš (1977), the Livno and Tomislavgrad basins had already been tectonically disconnected when the younger lake was established.

SECTIONS, LITHOLOGY AND DEPOSITIONAL HISTORY

The deposits of the first lake phase, on which we concentrate, are subdivided in four lithostratigraphical units, M1 to M4, on the Livno sheet of the geological map 1:100.000 of former Yugoslavia (Papeš 1972, 1975). Basal unit M1 reflects a period of coal deposition and is exposed in the Drage Quarry of the Tušnica mine, 10km SE of Livno (Saracevic et al. 2009). This outcrop also exposes the lowermost part of unit M2, which consists of gray limestone with clivunellid gastropods. The remain-

der of M2 is poorly exposed and available only in scattered outcrops, for example the Drage W. and Mokronoge sites. Unit M3 is composed of yellow limestones with dreissenid bivalves, and M4 of calcarenites and breccias intercalating with lacustrine limestones. Unit M3 and M4 together comprise a ~1400m thick succession, most of which is well exposed along the Ostrožac stream 3km west of Tomislavgrad.

The Tušnica Section

The 45m thick Tušnica section is located in the Drage opencast coalmine, situated at the foot of the Tušnica Mountain near the eastern boundary of the Livno Basin (text-fig. 2). It was logged and sampled along the SSE-NNW striking wall of the quarry. The base of the section is situated at N43°44'17.3'' E17°05'35.0'' (WGS84) and the top at N43°44'19.2'' E17°05'32.9''.

The lower 10.5m of the section are dominated by coal subdivided in three seams. The lower two seams are separated by a ~1m thick organic material rich sandy limestone interval with lymneid snails and plant remains. A volcanic ash bed separates the middle and upper coal seams (text-fig. 3a). The ash layer is ~20cm thick, laterally continuous, grayish-whitish in color, and consists of sandy and silty clay with dark mica flakes. The transition from coal to ash and vice versa is very sharp. It was sampled for ⁴⁰Ar/³⁹Ar dating at N43°44'25.8'' E017°05'28.2''. A transitional zone with clayey and coaly inter-layers starts above the upper coal seam. It is followed by dominantly dark brown and grayish, well-bedded limestones, rich in organic matter, that dominate the remaining 30m of the section (text-fig. 3b).

These beds belong to interval M2 (Milojević and Sunarić 1964) and contain scattered fish and plant remains.

The Ostrožac section

The 1700m thick Ostrožac section (text-fig. 3) is situated near the NW margin of the Tomislavgrad basin. It follows the Ostrožac brook, running down the eastern slope of the Tušnica Mountain, for about 2km. The brook strikes N-S, subnormal to the bedding that is ~150°/30° in the stratigraphically lower part of the section and ~170°/55° in the upper part of the section. The base (N43°43'40.5'' E17°10'59.6'') is located about 150m N of the place where the path to Eminovo Selo meets the road to the abandoned Vučipolje coal mine. The top (N43°43'40.5'' E17°10'59.6'') reaches the Jošanica village where a large megabreccia crops out just north of a large curve in the main road to Tomislavgrad.

Milojević and Sunarić (1964) describe coal seams and limestone beds rich in organic material, with the same character and thickness as those in the Tušnica section, from the Vučipolje coal mine at a distance of 1km from the base of the Ostrožac section. They indicate that the overlying part of the M2 clivunellid limestone interval is about 300m thick. The stratigraphic distance between the Tušnica and Ostrožac section is estimated in accordance with this.

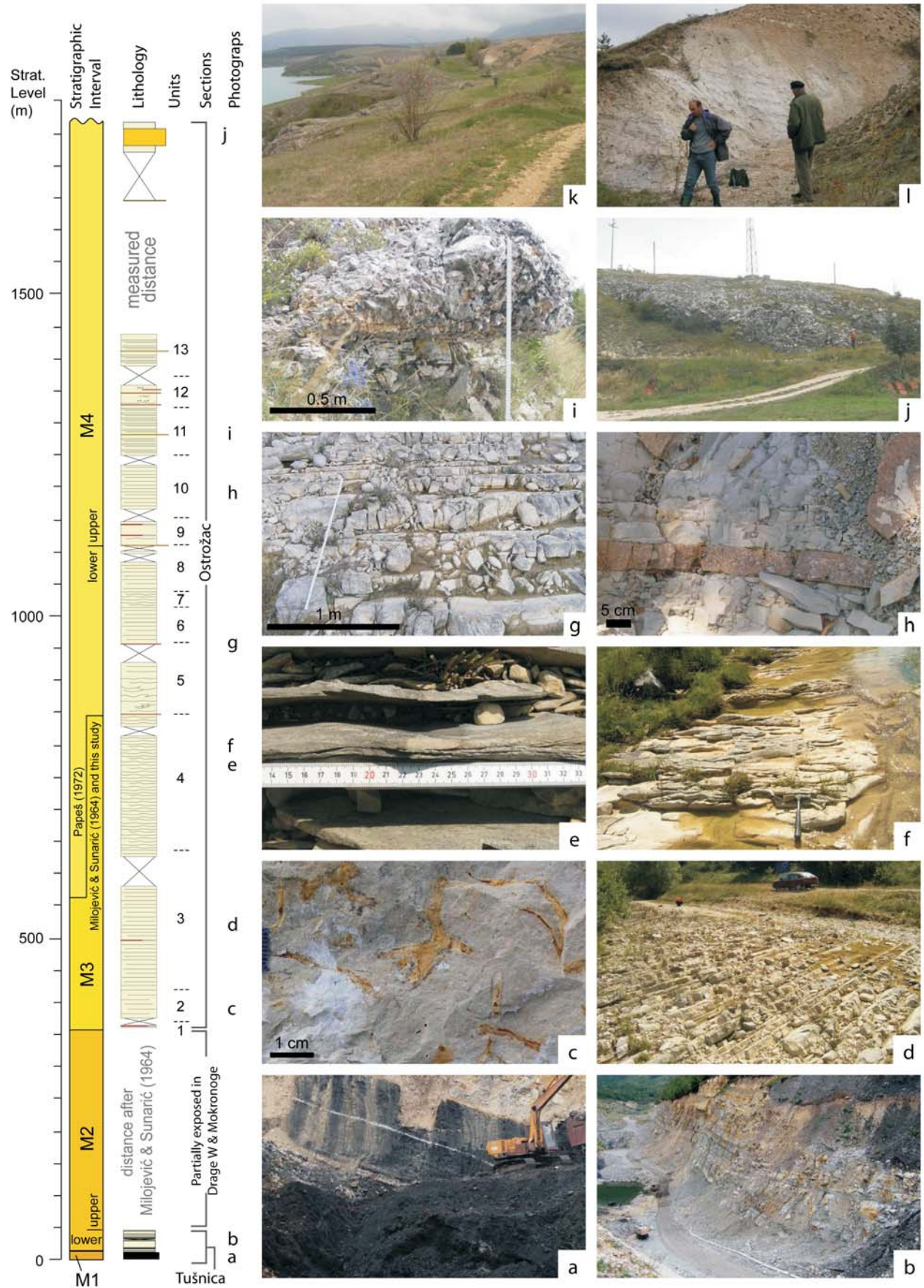
The Ostrožac section starts with pale-colored lacustrine limestones intercalated with clay layers and volcanic ash beds (Unit 1: 8.2m, text-fig. 3). These already belong to stratigraphic interval M3 (text-figs 2, 3). The well-bedded limestone, light beige, gray, yellowish or brownish in color, is dominantly

TEXT-FIGURE 3

Lithological column for the Dinaride Lake System sediments exposed along the Tušnica and Ostrožac sections of the Livno and Tomislavgrad Basins placed in a composite section for the main lacustrine cycle of the palaeo-lake (text-fig. 2). For a description of the pictures, marked a to l, we refer to the main text. Stratigraphic interval: correlation of the lithostratigraphic units from text-figure 2 to the studied section. Units M2 and M4 are subdivided according to lithostratigraphic scheme by Milojević and Sunarić (1964) differentiating lower M2 with dark, organic matter rich limestone with *Pisidium*, upper M2 with gray limestone and clivunellid gastropods, lower M4 with sandstone intercalations and upper M4 with upward thickening breccia intercalations. The M4 lower boundary was detected at the stratigraphic height indicated by Milojević and Sunarić (1964) that was distinctly higher than the position indicated on 1:100.000 geological map by Papeš (1972).

Units: numbered lithostratigraphic units identified by detailed logging in the field and indicated on the right of the lithostratigraphic column. Ostrožac section:

- 1 Limestone / clay / marl alternation with tephra intercalations.
- 2 Brownish limestone with plant remains.
- 3 Brownish well bedded limestone.
- 4 Brownish ripple bedded limestone.
- 5 Ripple through bedded limestone with channel and slump structures and sandstone intercalations.
- 6 Well bedded limestone.
- 7 Ripple bedded limestone.
- 8 Bedded limestones with thinning upwards sequences.
- 9 Partly cross bedded limestone with marl interbedding and a 2m thick breccia superposed by a 0.5m thick ash layer.
- 10 Thick bedded limestone.
- 11 Thin bedded limestone with 1m thick breccia.
- 12 Limestone intercalated by oolites and red sandstone lenses and beds.
- 13 Marly limestone with breccia intercalations. Tušnica section: Coal with clay and marl intercalations and a volcanic ash layer overlain by well bedded organic rich limestone bearing *Pisidium*, *Glyptostrobus* and fish bone remains.





TEXT-FIGURE 4

Dinaride Lake System endemic lacustrine mollusks from the W Drage (A) and Mokronoge (B and C) sites. A. *Clivunella katzeri*. B. *Mytilopsis drvarensis*. C. *Mytilopsis kucici*. The scale is the same in all three images.

fine-grained, although some coarser-grained intervals are present as well. The beds are ~10cm thick. The clay intercalations are at maximum 20cm thick and are predominantly found in the lower part of the unit. An interval of brownish limestone with roots of water plants follows (Unit 2: 49.6m; text-fig. 3c). The limestone is somewhat softer than those below. These are overlain by a thick interval of planar bedded limestones with a bed thickness of 5-20cm (Unit 3: 215.9m; text-fig. 3d). In this interval, plant remains disappear completely. A single bentonite layer is located in its middle part. In the next unit (Unit 4, 211.2m; text-figs 3e, 3f), ripple bedding dominates, although in some intervals plain beds return. The ripples are commonly about 1cm thick and there is about 10cm of distance between consecutive crests. Some intercalations of plant remains occur in association with horizons of coarser grained limestone. The next unit (Unit 5, 111.2m) starts with an about 5cm thick calcarenite layer situated within laminated limestones, with plant-stems preserved on its bedding planes. Ripple and trough cross beds characterize this unit. Slump and channel structures occur in combination with more calcarenite intercalations. These are red or brownish in color and consist of badly sorted, angular lithoclasts. Above follow intervals of well-bedded limestone (Unit 6, 54.0m; Fig. 3g) and ripple-bedded limestone (Unit 7, 24.4m) succeeded by a thinning upward succession of more well-bedded limestone (Unit 8, 72.2m). The first breccia recorded in the Ostrožac section occurs at the base of the following interval (Unit 9, 42.0m), which is dominantly composed of alternating cross-bedded and massive limestones. The breccia is about 2m thick and consists of angular, badly sorted carbonate lithoclasts. Two, up to 0.5m thick, volcanic ash layers occur in this unit as well. Both the tephra and breccia beds are laterally continuous and can be traced for at least several 100m. The breccia thickens westwards. Thickly bedded (Unit 10, 97.2m; Fig 3h) and thinly bedded limestones (Unit 11, 73.9m; Fig. 3i) with intercalated calcarenite layers and inversely graded breccia follow. Unit 12 displays a unique carbonate facies with frequent micro-breccia intercalations and ooid intervals (Unit 12, 48.3m). The topmost interval (Unit 13, 394.9m; Fig. 3j) is badly exposed and partly covered by an artificial

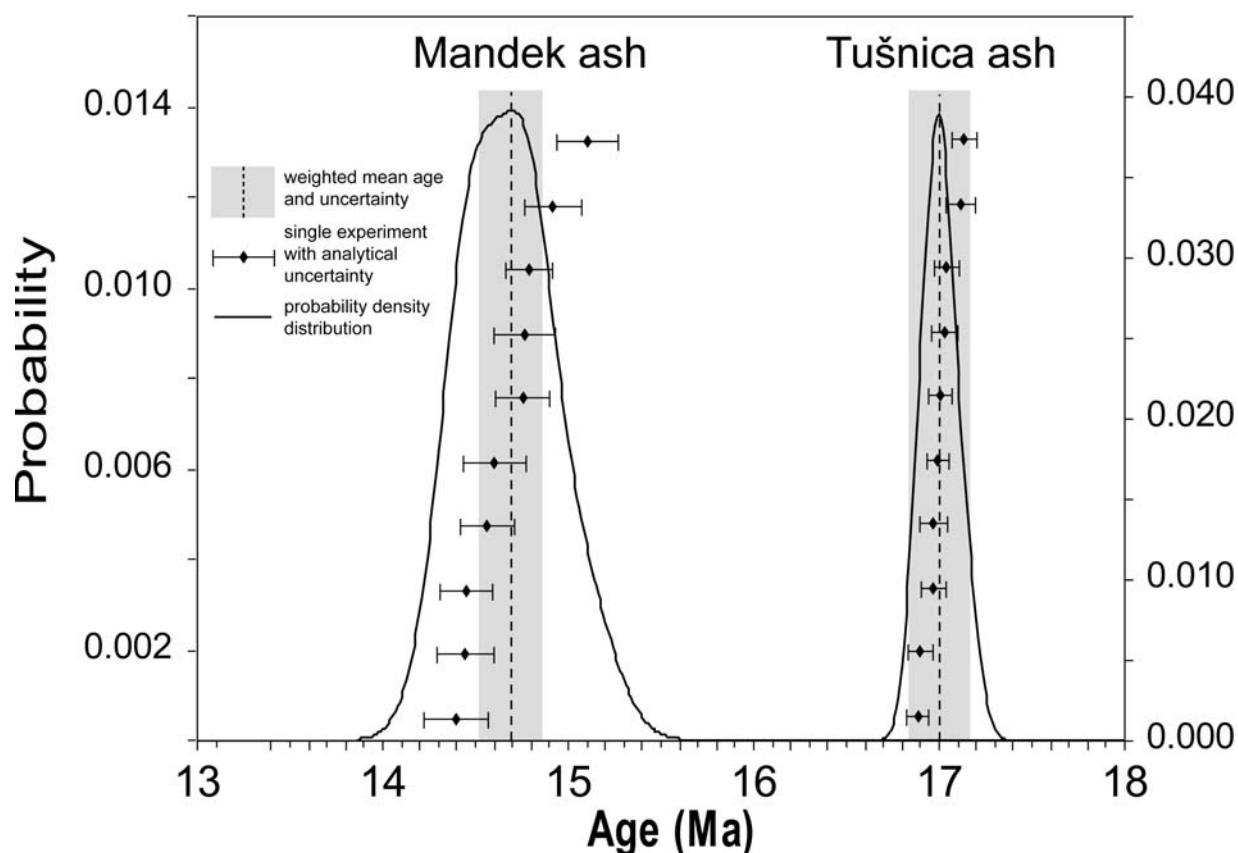
lake. It consists of marly limestones with recurrent breccia intercalations. The topmost breccia is a 26.3m thick megabed with limestone blocks of up to 2m in diameter. More marly limestones follow until the discordant contact (Milojević and Sunarić 1964; Papeš 1975) with the deposits of the younger lacustrine cycle is reached (text-fig. 2). The measured thicknesses and the succession of lithologic units correspond very well with data presented by Milojević and Sunarić (1964).

The Mandek section

The Mandek section (text-fig. 3l) is located 10km south of Livno, just E of the town of Mandek on the shore of artificial Lake Mandek (text-fig. 3k) and belongs to stratigraphic unit M4. The section was logged from North to South along the gully of the Vojvodinac brook, which runs normal to the bedding. The outcrop was mentioned by Luburić (1963). It exposes a volcanic ash, weakly lithified and whitish in color. At its top, it grades into lacustrine carbonates, dominated by fine-bedded limestone. The ash layer is about 6m thick in this exposure. A prominent 8m thick breccia horizon crops out 14m stratigraphically below the ash. The separating interval is completely covered by vegetation. Below the breccia, there is an additional 15m of lacustrine limestone in which a second 30cm thick bentonitic tephra occurs. Both ash horizons are also indicated on the geological map of Papeš (1972). A sample of the upper ash layer was collected in a small pit about 100m E of the gully at N43°43'49.9'' E017°01'21.6''.

The Drage West and Mokronoge sites

Although the clivunellid-bearing interval, M2, is in general poorly exposed in the Livno Basin as well as the Tomislavgrad Basin, small exposures crop out at the Drage West and Mokronoge sites (text-fig. 2). Drage West (N43°44'29.0'' E17°04'55.6'') is located about 300m W of the main entrance to the Tušnica coalmine. The narrow gully displays light and dark brownish bedded limestones with *Clivunella katzeri* (text-fig. 4A), small dreissenid bivalves and plant remains such as *Taxodium*-related *Glyptostrobus europaeus*, and belongs to the upper part of interval M2. The Mokronoge site (N43°45'20.5''



TEXT-FIGURE 5

Probability density diagrams for the multiple total fusion experiments for the Mandek, Tušnica tuffs.

E17°13'58.2'') is located near an Islamic graveyard just S of the town of Mokronoge, alongside the road to Tomislavgrad (Kochansky-Devidé and Slišković 1978). It exposes well-bedded, light beige limestones with abundant dreissenid bivalves and plants remains. The bivalves include rather small specimens of *Mytilopsis drvarensis*, about 30mm in diameter (text-fig. 4B), and remarkably large specimens of *M. kucici* (text-fig. 4C), about 50mm in length.

Depositional history

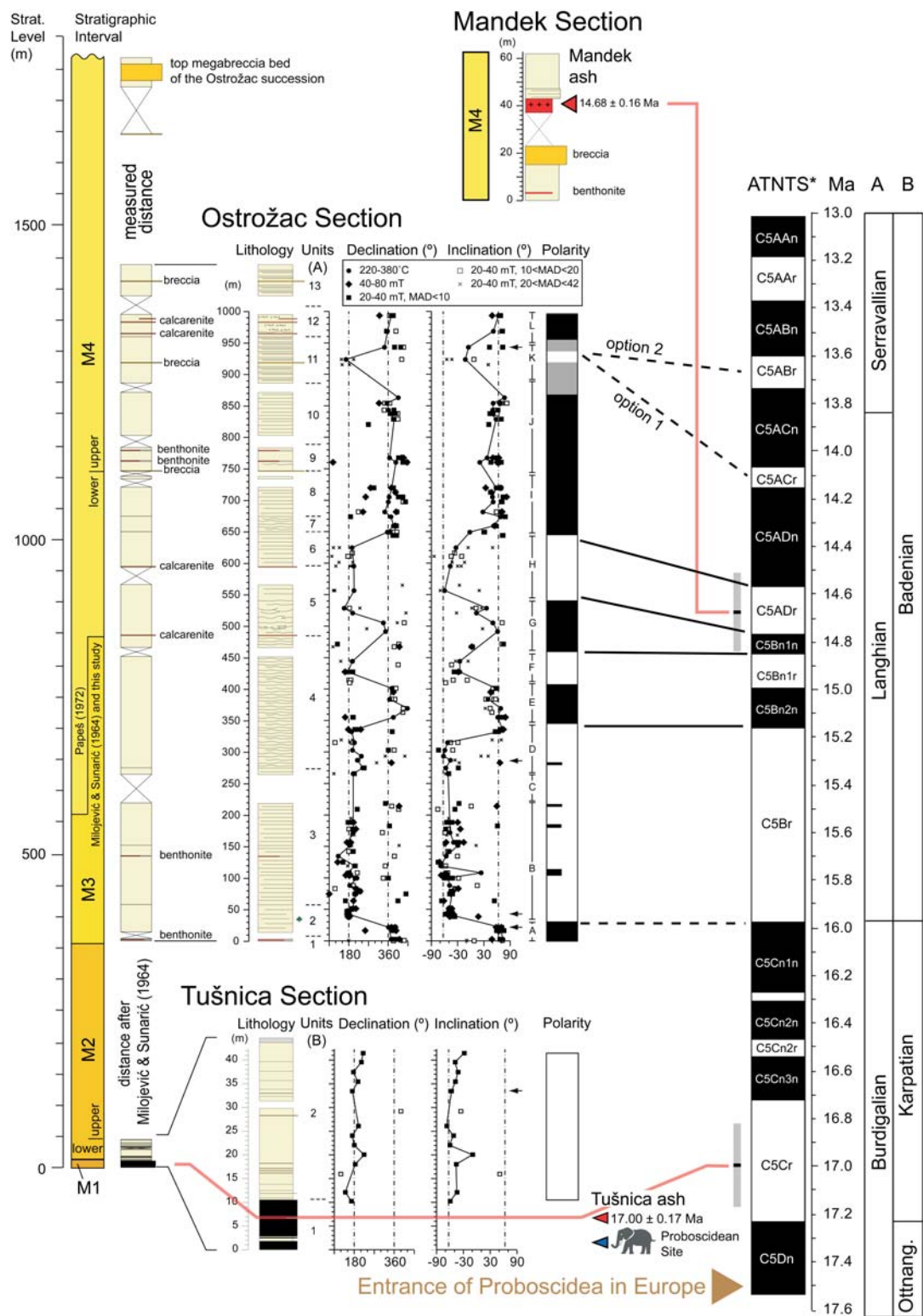
The coals exposed in the Tušnica and Vučipolje mines testify to swamp conditions during the initial phase of basin formation. Coal formation was terminated when the basin flooded and a long-lived lake was established. As the lake deepened suboxic bottom conditions developed, as indicated by the organic-rich limestones of the Tušnica mine and the overlying clivunellid limestones (Unit M2, text-fig. 3). The strata exposed in the lower part of the Ostrožac section are indicative of predominantly shallow water conditions. The rippled structure of these limestone beds shows that they accumulated by traction currents in the shallow littoral zone. The calcarenites and breccias that characterize interval M4 are badly sorted, which implies short transport. We interpret them as debris-flows indicative of local seismic activity in conjunction with uplift of the basin margins from which the material originates. The coarsening upwards sequence, which these calcarenites and breccias that filled in the basin built, preluded the end of the first lacustrine phase. The angular discordance between the first and second

lacustrine units provides additional evidence for tectonic activity at the end of the first phase. This interpretation is in line with that of Milojević and Sunarić (1964) and Papeš (1975), who suggested that uplift of the Tušnica Mountain began during deposition of Unit M4. They postulate that this divided the Livno-Tomislavgrad basin into two independent lakes during the second lacustrine phase.

RADIO ISOTOPIC DATING

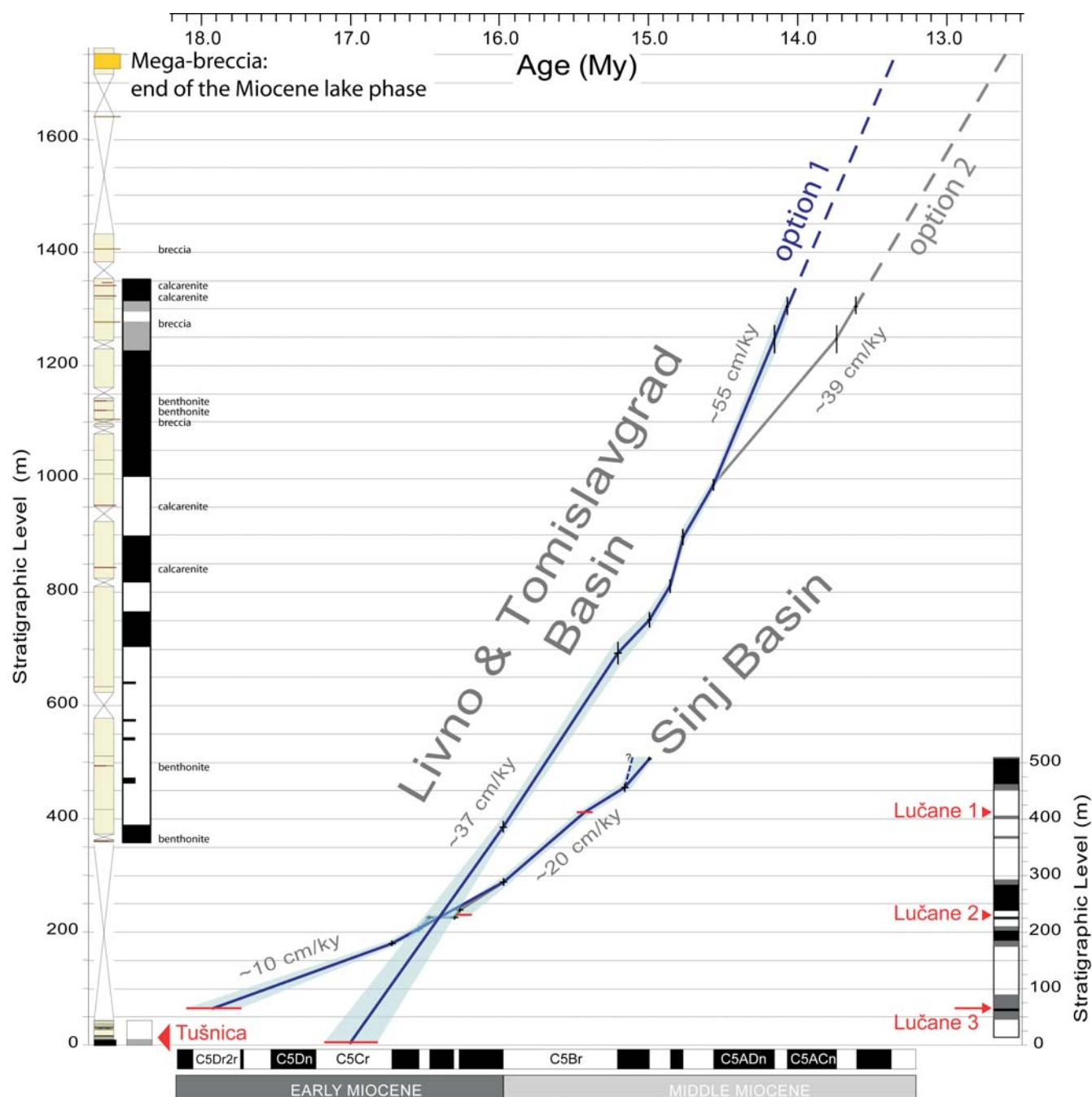
Sampling and methods

Two major volcanic ash deposits are intercalated in the basin infill (text-fig. 2). These are the tuff intercalated into the main coal of the Tušnica section and the thick tephra layer of the Mandek section. Both ashes were sampled and subsequently processed at the Department of Isotope Geochemistry (VU Amsterdam). The bulk samples were crushed, disintegrated in a calgon solution, washed and sieved over a set of sieves between 63 and 250µm. The residue was subjected to standard heavy liquid as well as magnetic mineral separation techniques. The fraction of grains larger than 150µm from both samples contained ample feldspar crystals. These were handpicked and leached with a 1:5 HF solution in an ultrasonic bath for 5 minutes. The mineral separates were then loaded in a 6mm ID quartz vial together with Fish Canyon Tuff (FC-2) and Drachenfels (Dra-1, f250-500) sanidine. The vial was irradiated at the Oregon State University TRIGA reactor in the cadmium shielded CLICIT facility for 10 hours.



TEXT-FIGURE 6

Lithological columns, obtained magnetic data and resulting polarity pattern for the Tušnica and Ostrožac sections in the Livno and Tomislavgrad basins, placed in a composite section for the main lacustrine cycle of the palaeo-lake (Fig. 2). Stratigraphic interval: Correlation of lithostratigraphic units from Figure 2 to the studied section. Units: Lithostratigraphic units identified by sedimentological logging. For a detailed explanation of the stratigraphic intervals and sedimentary units see Figure 3. Polarity column: In the polarity column, black indicates normal polarity, white reversed polarity and grey intervals for which no reliable polarity could be established. Black arrows: Samples for which demagnetization and decay diagrams are shown in Figure 6. Letters A – L: Polarity intervals discussed in the text. ATNTS (Astronomically Tuned Neogene Time Scale) after Lourens et al. (2004). Column A: Mediterranean stages, Column B: Central Paratethys stages.



TEXT-FIGURE 7

Reconstruction of the sedimentation rate for the Livno and Tomislavgrad Basin and comparison with the rate of sedimentation in the Sinj Basin (de Leeuw et al. 2010).

All age calculations use the decay constants of Steiger and Jäger (1977). The age for the Fish Canyon Tuff sanidine flux monitor used in age calculations is 28.201 ± 0.03 My (Kuiper et al. 2008). The age for the Drachenfels sanidine flux monitor is 25.42 ± 0.03 My (Kuiper et al. in prep). Correction factors for neutron interference reactions are $2.64 \pm 0.017 \times 10^{-4}$ for $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$, $6.73 \pm 0.037 \times 10^{-4}$ for $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$, $1.211 \pm 0.003 \times 10^{-2}$ for $(^{38}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ and $8.6 \pm 0.7 \times 10^{-4}$ for $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$. Errors are quoted at the 1σ level and include the analytical error and the error in the irradiation parameter J . All

relevant analytical data as well as error determination can be found in the online supplementary material.

$^{40}\text{Ar}/^{39}\text{Ar}$ ages

Ten multiple grain fusion experiments have been analyzed for the Mandek and Tušnica tuffs in order to determine the $^{40}\text{Ar}/^{39}\text{Ar}$ age. These provided two, almost homogenous age populations (text-fig. 5). The full analytical data are given in the supplementary material. For the Tušnica tuff, the average percentage of radiogenic $^{40}\text{Ar}^*$ is 89.5% and its K/Ca ratio is on av-

erage 3.3. The isochron ages are concordant with the weighted mean age and the trapped $^{40}\text{Ar}/^{36}\text{Ar}$ component is atmospheric. This provides an age of 17.00 ± 0.17 Ma for the Tušnica tuff, in exact agreement with the age indicated by the probability density distribution calculated for the 10 duplicate experiments (text-fig. 5). This age is thus assumed to reflect the crystallization age of the tuff. For the Mandek tuff, the average percentage of radiogenic $^{40}\text{Ar}^*$ is 59.5% and its K/Ca ratio is on average 1.51. Also for this tuff, the isochron ages are concordant with the weighted mean age and the trapped $^{40}\text{Ar}/^{36}\text{Ar}$ component is atmospheric. This provides an age of 14.68 ± 0.16 Ma for the Mandek tuff. This age is in good agreement with the age indicated by the probability density distribution (text-fig. 5) and reflects its crystallization age. For both ash samples, the MSWD of the calculated weighted mean ages is smaller than the T-student distribution at the 95% confidence level (supplementary material).

Beside the Mandek and Tušnica tuffs, several volcanic ash layers in the Ostrožac section were sampled and subjected to mineral separation techniques. However, all except one were bentonized and too fine grained to provide suitable grains for $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Results for sample VU1, taken from the only coarser grained ash, situated at the base of the Ostrožac section, were disturbed by a large reworked component. Thus its crystallization age could not be determined.

MAGNETOSTRATIGRAPHY

Sampling and methods

Hand samples were gathered from the Tušnica and Ostrožac sections in order to construct a magnetostratigraphy. The orientation of all samples and bedding planes was measured by means of a magnetic compass, and corrected for the local magnetic declination. In the laboratory, standard paleomagnetic cores were drilled and subsequently divided into several specimens. Thermal as well as alternating field demagnetization techniques were applied in order to isolate the characteristic remanent magnetization (ChRM). The natural remanent magnetization (NRM) of the samples was measured after each demagnetization step on a 2G Enterprises DC Squid cryogenic magnetometer (noise level $3 \cdot 10^{-12} \text{Am}^2$). Heating occurred in a laboratory-built, magnetically shielded furnace employing 10–30°C temperature increments up to 280–350°C. AF demagnetization was accomplished by a laboratory-built automated measuring device applying 5–20mT increments up to 100mT by means of an AF coil interfaced with the magnetometer. The ChRM was identified through assessment of decay-curves and vector end-point diagrams (Zijderveld 1967). ChRM directions were calculated by principal component analysis (Kirschvink 1980) without forcing through the origin, and are always based on at least four consecutive temperature or field steps.

Demagnetization results

The samples of the clayey limestones of the Tušnica section were subjected to stepwise AF demagnetization. Their NRM generally consists of two components. A normal overprint, especially observable in non-tilt corrected diagrams (supplementary text-figure 9), is removed in fields up to 25mT. Subsequently, between 25 and 60mT, approximately 95% of the NRM disappears. This second component decays straight to the origin and we interpret it as the ChRM. ChRM intensities range between $1 \cdot 10^{-4}$ and $12 \cdot 10^{-4} \text{A/m}$. We do not observe any gyroremanence. All ChRM directions have a $\text{MAD} < 15$. Since

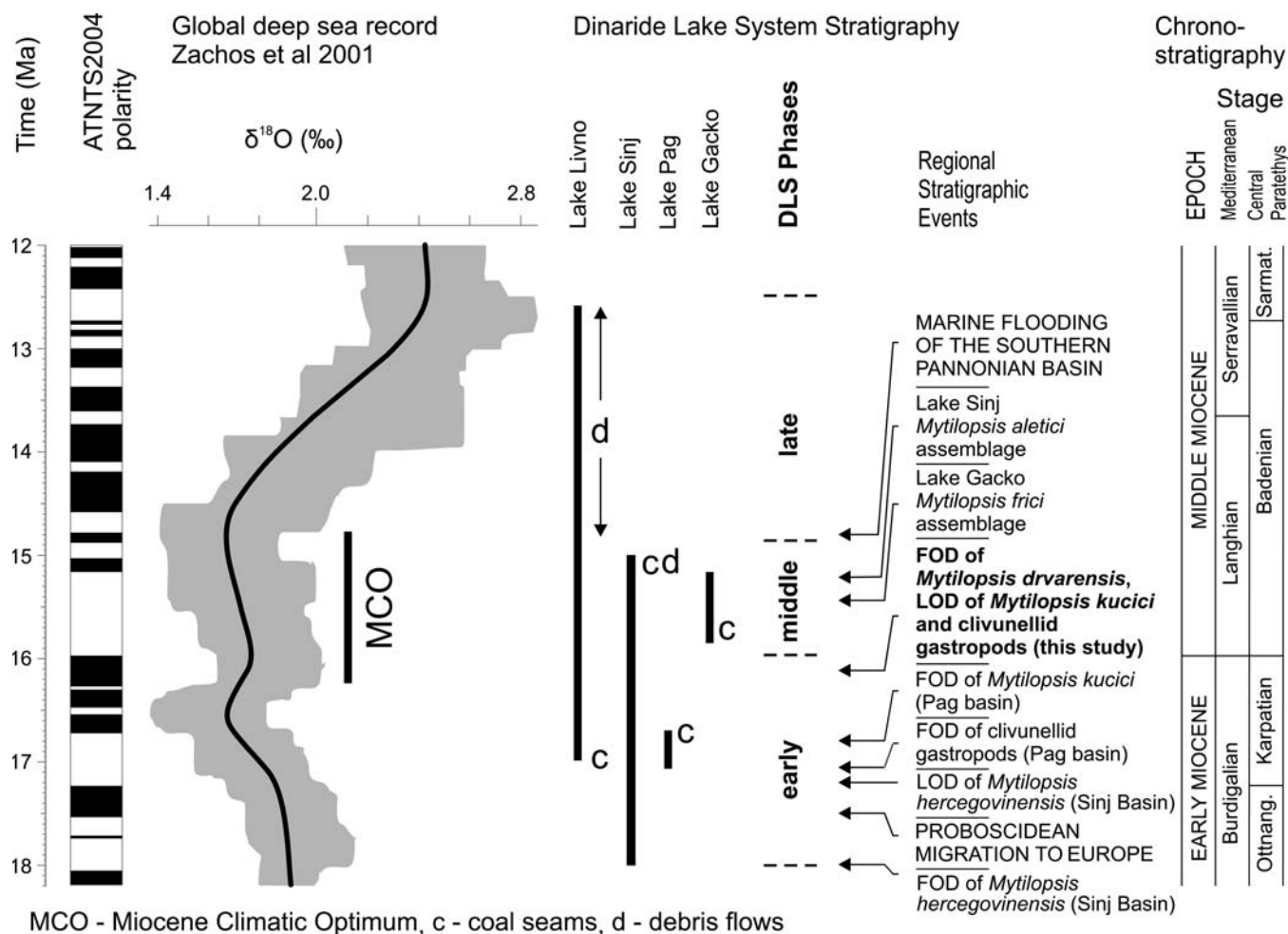
all reliable samples show reversed directions, we interpret the whole Tušnica section to be of reversed polarity (text-fig. 6).

Thermal demagnetization diagrams (supplementary text-figure 9) of the limestones of the Ostrožac section indicate that their NRM is generally composed of two components. A low temperature component, mostly removed below 220°C, displays only normal polarities and is interpreted to be a recent overprint. The high temperature component is demagnetized above 220°C and displays normal and reversed directions. At 400°C, typically 80–95% of the NRM had been removed. Taking into account the very low intensity signal, thermal demagnetization diagrams are of surprisingly good quality, and mean angular deviation remained below 20° for 90% of the derived directions. For only five samples, Zijderveld diagrams were regarded as non-interpretable due to high scatter in the vector endpoints. For the other 54 samples, directions and polarities were established.

Two and sometimes three components appear during AF demagnetization. A low field component, demagnetized between 0 and 15mT, displays only normal directions and is assumed to be a present day field overprint. The second component, demagnetized between 20 and 40mT, displays normal as well as reversed directions. At 40mT, mostly over 90% of the NRM had been removed. For a minority of the samples, an even higher field component appears. It is typically demagnetized between 40 and 80mT. The established AF directions were subdivided, based on their respective field interval and MAD. In text-figure 6, we thus distinguish directions of the high-field (40–80mT) component, and directions of the intermediate component (20–40mT). The latter are subdivided into three groups with $\text{MAD} < 10$, $10 < \text{MAD} < 20$, and $20 < \text{MAD} < 42$ respectively. All directions were established without forcing the resultant vector through the origin, except when vector endpoints between 40 and 80mT clustered. Directions of the intermediate and high field component are generally very similar and are interpreted to reflect the geomagnetic field at the time of deposition.

Text-figure 6 displays the declination and inclination of the established thermal as well as AF directions versus stratigraphic level. Directions resulting from thermal demagnetization were regarded as most reliable for construction of the magnetostratigraphy and thus taken into account first. Subsequently, the directions resulting from AF demagnetization were considered. The 40–80mT component was regarded as most reliable, followed by the 20–40mT components ordered from low to high MAD. The resulting polarity pattern has been subdivided into parts A–L, indicated on the left hand side of the Ostrožac section polarity column in text-figure 6, which will each be discussed in detail.

In interval A, thermal as well as AF demagnetization diagrams indicate a normal polarity. Zijderveld diagrams of interval B are of high quality and thermal and AF directions clearly indicate a reversed polarity. Interval C is covered with alluvium and therefore no polarity can be established. Interval D is again characterized by a reversed polarity, as indicated by the thermally derived directions. Alternating field demagnetization diagrams are of a very low quality for this interval and often provide ambiguous directions. At the boundary of intervals D and E, we observe down-working of the normal polarity magnetic field of interval E into the sediment column. We thus interpret Interval E to start where only normal components are observed. A reversed polarity characterizes interval F. It is striking that heat-



TEXT-FIGURE 8

Chronology for key biostratigraphic and depositional events of the Dinaride Lake System.

ing samples from this interval above 200°C results in a sharp increase in intensity. The generated components have random directions, and thermal demagnetization diagrams are severely disturbed. Apparently, new magnetic minerals are being created. Thermal demagnetization diagrams of interval G demonstrate normal polarities. AF results of G are generally of very low quality and cannot be reliably interpreted. Interval H carries a reversed polarity, as demonstrated by thermal demagnetization diagrams. Some signs of alteration appear above 200°C. AF results are of low quality but generally corroborate the reversed polarity. Both AF and thermal results are of high quality in intervals I, J, and L, and they are clearly of normal polarity. In intervals J and M, intensities often sharply increase when samples are heated above 250–330°C. This temperature interval indicates that the rise in intensity might be attributable to the alteration of iron sulfides. The directions of the ChRM component have been determined by forcing a vector from the 220–280°C temperature steps through the origin. Interval K is relatively short and bears a reversed polarity as indicated by both thermal and alternating field demagnetization diagrams.

CHRONOSTRATIGRAPHIC FRAMEWORK

Correlation of the magnetostratigraphy for the Livno Basin to the geological timescale is facilitated by the acquired $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the Tušnica and Mandek tuffs. Since the former has an age of 17.00 ± 0.17 Ma, the reversed polarity interval retrieved in the Tušnica - Drage Quarry must correlate to chron C5Cr (text-fig. 6). The large reversed interval in the lower part of the Ostrožac section most likely represents chron C5Br. This implies that the unexposed interval between these two sections, comprising approximately 350m (Milojević and Sunarić 1964), covers the time span of C5Cn. The topmost part of this chron straddles the very base of the Ostrožac section (text-fig. 6). Interval E most likely corresponds to C5Bn.2n, interval F to C5Bn.1r, interval G to C5Bn.1n, and interval H to C5ADr. Intervals I and J together correlate to chron C5ADn. We cannot exclude, however, a short reversed interval in the top of interval I or the base of interval J. Reversed interval K might thus represent either C5ACr or C5ABr. This results in a correlation of interval L to either C5ACn or C5ABn. This correlation suggests an age of approximately 16 Ma for the base, and an age of either

14 Ma or 13.5 Ma for the top of the Ostrožac section. The first option (option 1) implies that the sedimentation rate strongly increases in the breccia-bearing part of the section (text-fig. 7). Adoption of the second option (option 2) means sedimentation rates increase only slightly. The 14.68 ± 0.16 Ma Mandek ash correlates to stratigraphic interval M4 of the 1:100,000 geological map of the Livno Basin. The age of the Mandek ash suggests that it is time-equivalent to part of interval H of the Ostrožac section. An 8m thick breccia crops out 14m below the Mandek ash. Since the first breccia enters the Ostrožac section in the top part of interval I, we conclude that breccias apparently start to accumulate asynchronously in different parts of the basin.

Since the Tušnica section is located at the very base of the basin infill, sedimentation in the Livno Basin started around 17 Ma. In order to estimate when deposition ended, an additional 300m of poorly exposed sediments that overlie the section sampled along the Ostrožac stream have to be taken into account (text-fig. 6). Extrapolating the calculated sedimentation rates for the topmost sampled interval, we estimate a minimum age of between 12.6 and 13.2 Ma for the mega-breccia at the top of the Ostrožac section (text-fig. 7). Since the breccias coarsen and thicken upwards, the amount of clastic input gradually increases along the sampled section. In the interval above, this effect is more strongly pronounced and the sedimentation rate might thus increase significantly. Most of the infill of the Livno Basin, attributed to the first lacustrine cycle, thus accumulated between 17 and approximately 13 Ma.

DISCUSSION

Comparison with the other lakes of the Dinaride Lake System

For a long time, accurate age control on the lacustrine deposits of the intra-montane Dinaride basins remained an outstanding problem. Recently, however, new chronostratigraphic data have become available. The DLS sediments in the Sinj basin accumulated between 18 and 15 Ma (de Leeuw et al. 2010), while deposition in the Gacko basin lasted from 15.8 to approximately 15.0 Ma (Mandic et al. 2010). The sediments exposed along the shores of the island of Pag are between 17.1 and 16.7 Ma (Jiménez-Moreno et al. 2008). The lacustrine phase of the Sava and Drava depressions, situated along the northern rim of the Dinarides, and collectively called the North Croatian Basin, lasted from 18 Ma to at least 16 Ma (Mandic et al. 2011). The DLS sediments in the Livno basin have now been shown to have accumulated between 17 and approximately 13 Ma. We conclude that deposition in all these Dinaride Lakes concentrates in a period stretching from the Early to Middle Miocene (18–13 Ma), which correlates to the Burdigalian and Langhian stages of the Geological Time Scale and to the regional Ottnangian, Karpatian and Badenian stages of the Paratethys.

A profound phase of basin formation thus struck the Dinarides in the Early to Middle Miocene. At that time, the DLS, which occupied the resulting depressions, stretched out from the Island of Pag in the west, to the Gacko Basin in the south, and the Sava and Drava basins in the north. Subsidence in the Livno Basin was fairly rapid compared to the Sinj, Gacko and Pag basins. The sedimentation rate in the Sinj Basin on average amounted 17cm/kyr (de Leeuw et al. 2010), similar to the sedimentation rate of 22–30cm/kyr on the Island of Pag (Jiménez-Moreno et al. 2008). In Gacko, the average rate of deposition was estimated to be between 10–30cm/kyr, based on

assumed astronomical forcing of sedimentary cycles (Mandic et al. 2010). In the Livno basin the sedimentation rate was significantly higher, around 37–55cm/kyr. Since all of the investigated sediments accumulated in or close to the photic zone, the accumulation rate directly reflects basin subsidence.

The role of tectonics and climate in the development and disappearance of Lake Livno

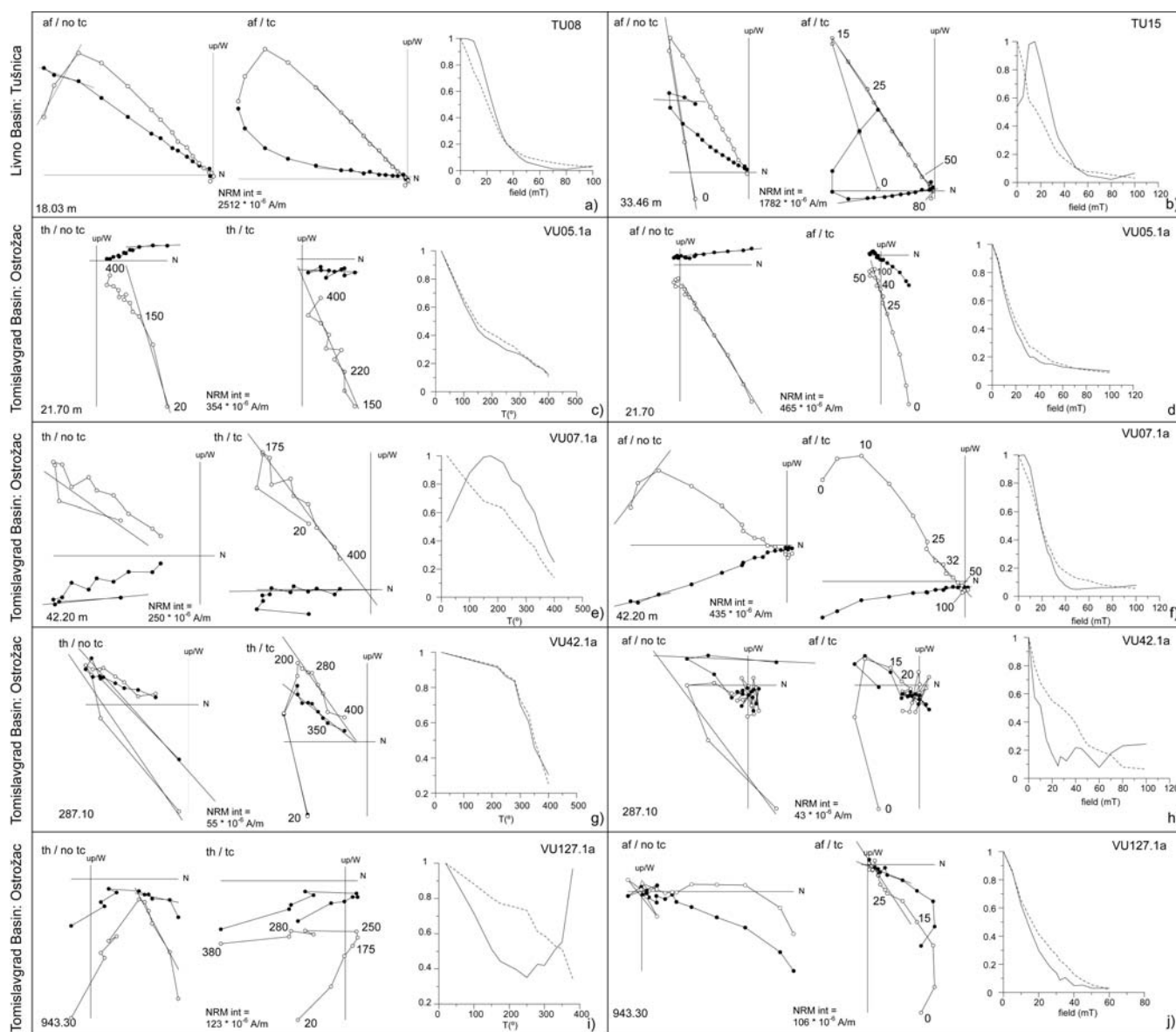
The life-time of Lake Livno and the other lakes of the Dinaride Lake System coincided with a phase of profound syn-rift extension in the neighbouring Pannonian Basin (Horváth 1995). This suggests extension may have penetrated into the orogen triggering the formation of the Dinaride intra-montane basins, in line with paleostress data of Ilić and Neubauer (2005) and the tectonostratigraphic model for formation of the North Croatian Basin of Pavelić (2001). Both persistent basin subsidence and a long-term appropriate climate are necessary to guarantee accumulation of a 1.7km thick pile of lacustrine sediments. It is thus evident that Early to Middle Miocene climatic conditions were suitable for lake formation in the Dinarides. Detailed facies and pollen analysis suggests Lake Sinj and Lake Gacko were sensitive to cyclic changes in climate (Mandic et al. 2010; Jiménez-Moreno et al. 2008, 2009). Whether these are reflected in the thick sedimentary record of the Livno Basin remains to be explored.

At 14.8 Ma, shortly after deposition in the Sinj and Gacko basins ended, the first calcarenites were deposited in the Livno Basin. Between 14.4 and 14.2 Ma, the first breccia was deposited in the Ostrožac section. In other locations in the basin, breccias started to accumulate even earlier, as becomes clear from the Mandek section where a breccia underlies the 14.68 ± 0.16 Ma volcanic ash. From this moment onwards, breccias thicken and coarsen until deposition of a mega-breccia eventually concluded the Miocene lacustrine phase. These breccias contain clasts of Mesozoic age derived from the basin margins and reveal that these were prone to erosion. This suggests the margins became uplifted in response to enhanced tectonic activity. Subsidence apparently stalled or was outpaced by the enhanced input of erosional material. A change in tectonic regime is thus the most likely cause for the disappearance of Lake Livno which slightly postdates 13 Ma. During the second lake phase, separate lakes develop in the then disunited Livno and Tomislav basins. An angular unconformity separates the deposits of the first and second lake phase. This supports a tectonic cause for the end of the first lake phase.

Towards a time-indicative endemic mollusk biostratigraphy

Our new chronostratigraphy for the Dinaride basins pinpoints the age of a number of mollusk occurrences (text-fig. 8), important for the regional biostratigraphic scheme (Kochansky-Devidé and Slišković 1972, 1978, 1980). The first is the occurrence of the primitive dreissenid bivalve *Mytilopsis hercegovinensis* (18–17.2 Ma), documented in the lower part of the Sinj section. This type of *Mytilopsis* is morphologically related to the larger sized *Mytilopsis kucici*, which occurs above a horizon with clivunellid gastropods (~17 Ma) in the upper part (~16.7 Ma) of the section on Pag (Bulić and Jurišić-Polšak 2009, Jiménez-Moreno et al. 2009).

In the Livno and Tomislavgrad basins, clivunellids are restricted to stratigraphic unit M2 with an approximate age range of 16.1–16.9 Ma (text-fig. 6). It contains fossils of *Clivunella katzeri*, a primitive morphotype of *Mytilopsis drvarensis*, and a



TEXT-FIGURE 9
Supplemental data.

progressive morphotype of *M. kucici* (text-fig. 4). This is the oldest recorded occurrence of *M. drvarensis* and its presence in unit M2 demonstrates that it had already appeared in the Early Miocene. The specimens of *M. kucici* and *Clivunella katzeri* recorded, on the other hand, are the youngest ones known and these species might have become extinct at the Early to Middle Miocene boundary. The occurrence of either clivunellids or *M. kucici* in combination with *M. drvarensis* is thus an important marker for the uppermost Lower Miocene in the DLS. In contrast to *M. kucici* and *C. katzeri*, the stratigraphic range of *Mytilopsis drvarensis* extends into the Middle Miocene and a striking radiation of the species occurs in chron C5Br (16-15.2 Ma) (de Leeuw et al. 2010).

Two more first occurrences complete our current knowledge of the DLS biochronostratigraphic scheme. These are the

Mytilopsis frici FO at 15.6-15.4 Ma in the Gacko Basin (Mandic et al. 2010), and the *Mytilopsis aletici* FO at 15.4 Ma in the Sinj Basin (de Leeuw et al. 2010). The establishment of age ranges for these endemic mollusks allows their use as time indicators and might enable future dating of fossil-bearing successions that are not suitable for paleomagnetic and radio-isotopic techniques.

CONCLUSIONS

A detailed chronostratigraphic framework based on integrated magnetostratigraphic and radio-isotopic data demonstrates that the majority of the DLS sediments in the intra-montane Livno and Tomislavgrad basins accumulated between 17 and approximately 13 Ma. The very top of the DLS sediments is overlain discordantly by deposits of a younger lake phase and do not

crop out. The end of the first lake phase is therefore poorly constrained.

When subsidence initially set in, swamp conditions prevailed and several coal seams formed. Subsequently, the basin, then still undivided, was flooded and a long-lived lake established. Around 1700m of lacustrine limestones with several intercalating volcanic ash layers accumulated. Around 14.8 Ma, calcarenites and breccias, derived from the basin margin started to enter Lake Livno. They coarsened and thickened over time. This suggests an inversion of the tectonic regime with gradual uplift of the basin margins that eventually caused Lake Livno to disappear. During the second lake phase, two separate lakes formed in the then separated Livno and Tomislavgrad basins.

Comparison with other recently dated Dinaride lakes demonstrates that their life-times coincide and shows that a profound phase of basin formation struck the orogen in the Early to Middle Miocene. The concomitant climatic conditions were apparently beneficial for lake formation. The occurrence of either clivunellids or *M. kucici* in combination with *M. drvarensis* is shown to be time-indicative of the uppermost Early Miocene and is thus considered an important chronological marker in the DLS. Integrated radio-isotopic and magnetostratigraphic dating techniques once more prove to be a powerful chronostratigraphic tool in settings subject to endemism.

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