AUSTRIAN JOURNAL OF EARTH SCIENCES | VOLUME 102 | 133 - 145 | VIENNA | 2009

UPPER CRETACEOUS GOSAU DEPOSITS OF THE APUSENI MOUNTAINS (ROMANIA) – SIMILARITIES AND DIFFERENCES TO THE EASTERN ALPS

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KEYWORDS

fission track dating
Apuseni Mountains
basin modeling
Eastern Alps
Gosau basin

ABSTRACT

The Apuseni Mountains were formed during Late Cretaceous convergence between the Tisia and the Dacia microplates as part of the Alpine orogen. The mountain range comprises a sedimentary succession similar to the Gosau Group of the Eastern Alps. This work focuses on the sedimentological and geodynamic evolution of the Gosau basin of the Apuseni Mts. and attempts a direct comparison to the relatively well studied Gosau Group deposits of the Eastern Alps.

By analyzing the Upper Cretaceous Gosau sediments and the surrounding geological units, we were able to add critical evidence for reconstructing the Late Mesozoic to Paleogene geodynamic evolution of the Apuseni Mountains. Nannoplankton investigations show that Gosau sedimentation started diachronously after Late Turonian times. The burial history indicates low subsidence rates during deposition of the terrestrial and shallow marine Lower Gosau Subgroup and increased subsidence rates during the period of deep marine Upper Gosau Subgroup sedimentation. The Gosau Group of the Apuseni Mountains was deposited in a forearc basin supplied with sedimentary material from an obducted forearc region and the crystalline hinterland, as reflected by heavy mineral and paleocurrent analysis. Zircon fission track age populations show no fluctuation of exhumation rates in the surrounding geological units, which served as source areas for the detrital material, whereas increased exhumation at the K/Pg boundary can be proven by thermal modeling on apatite fission track data. Synchronously to the Gosau sedimentation, deep marine turbidites were deposited in the deep-sea trench basin formed by the subduction of the Transylvanian Ocean.

The similarities to the Gosau occurrences of the Eastern Alps lead to direct correlation with the Alpine paleogeographic evolution and to the assumption that a continuous ocean basin (South Penninic - Transylvanian Ocean Basin) was consumed until Late Cretaceous times.

Das Apuseni Gebirge entstand infolge der oberkretazischen Konvergenz der beiden Mikroplatten Tisia und Dacia. Es lagerten sich hier Oberkreidesedimente ab, die Ähnlichkeiten zu der alpinen Gosau-Gruppe aufweisen. Im Mittelpunkt dieser Arbeit steht die sedimentologische und geodynamische Entwicklung der Gosau Becken des Apuseni Gebirges, sowie der Versuch eines Vergleiches mit den relativ gut untersuchten Gosau-Ablagerungen der Ostalpen.

Die Untersuchungen an den Gosausedimenten und den angrenzenden geologischen Einheiten erlaubten es einen Beitrag zum Verständnis der spätkretazischen bis paläogenen geodynamischen Entwicklung im Apuseni Gebirge zu leisten. Nannoplankton-Analysen zeigen, dass die Gosauablagerung diachron ab dem späten Turonium einsetzte. Die Beckenentwicklung ist gekennzeichnet von niedrigen Subsidenzraten während der terrestrischen und flachmarinen unteren Gosau-Ablagerung und erhöhten Subsidenzraten zur Zeit der tiefmarinen oberen Gosausedimentation. Schwermineralanalysen und Paläoströmungsrichtungen geben Hinweise darauf, dass die Gosausedimente des Apuseni Gebirges in ein Forearc-Becken abgelagert wurden, welches mit Erosionsmaterial von einem exhumierten Akkretionskeil und dem kristallinen Hinterland versorgt wurde. Populationen von Zirkon-Spaltspurenaltern zeigen weder ansteigende noch fallende Hebungsraten der angrenzenden geologischen Einheiten, die als Sedimentliefergebiete dienten. Erhöhte Hebungsraten an der Kreide-Paläogen-Grenze konnten mit Hilfe thermischer Modellierung an Apatit-Spaltspuren nachgewiesen werden. Während der Gosausedimentation wurden Turbidite in eine Tiefseerinne abgelagert, die sich bei der Subduktion des Transilvanischen Ozeans bildete.

Die Ähnlichkeiten zu den Gosauvorkommen der Ostalpen lassen eine direkte Korrelation mit der alpinen paläogeographischen Entwicklung zu und führen zu der Annahme, dass ein durchgehendes Ozeanbecken (Südpenninischer und Transilvanischer Ozean) bis zur späteren Kreide subduziert wurde.

1. INTRODUCTION

Although situated in an isolated position between the Pannonian and Transylvanian basins, the Apuseni Mountains are part of the Alpine-Carpathian mountain belt (Fig. 1). They were formed in Cretaceous times as a result of the closure of the

Transylvanian Ocean (East Vardar Ocean after Schmid et al., 2008), a branch of the Tethys Ocean (Săndulescu, 1975; Csontos et al., 1992). The collision of the two continental blocks, Tisia and Dacia, led to the formation of the Tisia-Dacia microplate (Csontos, 1995). A positive magnetic anomaly marks the suture of the Tisia and Dacia microplates beneath the Transylvanian Basin, and is interpreted to be related to an ophiolitic complex (Săndulescu, 1984).

The basement of the Apuseni Mts. is formed by the crystalline Bihor Unit, with metamorphic rocks and Variscan granites (Muntele Mare granite). It is partly overlain by a Permo-Mesozoic cover. The subduction of the Transylvanian Ocean resul-

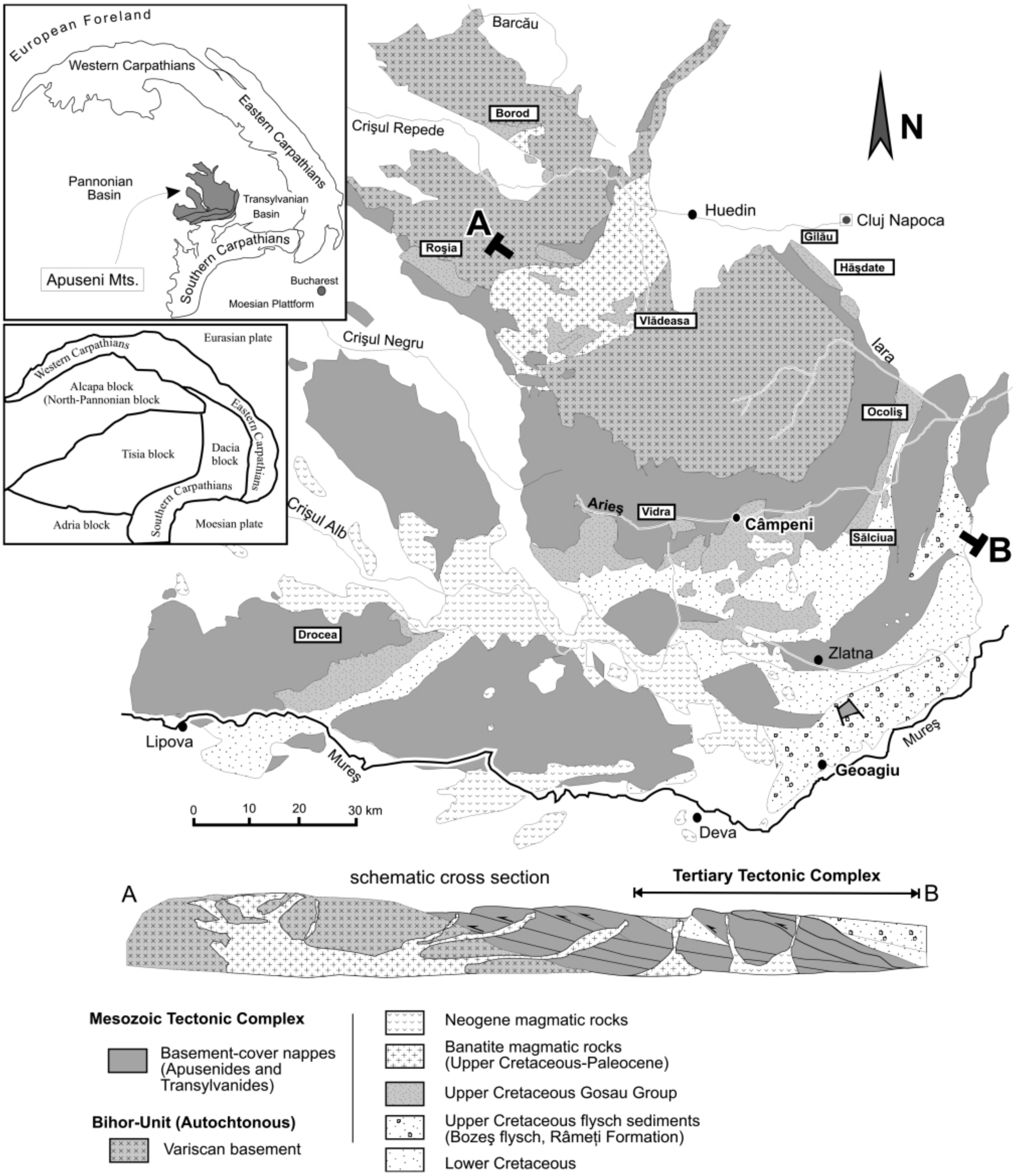

FIGURE 1: Regional geological setting of the Apuseni Mts. and boundaries of the continental blocks (small maps, upper left side). Structural map and main geological units of the Apuseni Mts. with a NW-SE striking schematic profile. Locations of the Upper Cretaceous Gosau occurrences are shown in white squares. Note the Gosau sediments of the Southern Apuseni Mts. actually belong to the Tertiary Tectonic Complex (after Ianovici et. al., 1976; Balintoni, 1994).

ted in mid-Cretaceous emplacement of basement-cover nappes, which in this paper are described as the Mesozoic Tectonic Complex (Fig. 1). This complex includes the Transylvanides (Balintoni, 1997), which occur in the Southern Apuseni Mts. as crystalline basement rocks covered by deep marine clastics, pelagic carbonates and ophiolite fragments, and the Apusenides (Balintoni, 1994, 1997; or Internal Dacides after Săndulescu, 1984), which are mainly built up by low- to medium-grade metamorphic rocks and remnants of a Permo-Mesozoic sedimentary cover. Mid-Cretaceous thrusting occurred over a limited time period before the Turonian. The following, mainly siliciclastic, marine Upper Cretaceous sedimentary successions were described as Gosau-type deposits, in correlation to the Gosau Group deposits of the Eastern Alps (Lupu, 1970; Lupu et al., 1993; Lupu and Zacher, 1996; Willingshofer, 1999; Schuller, 2004).

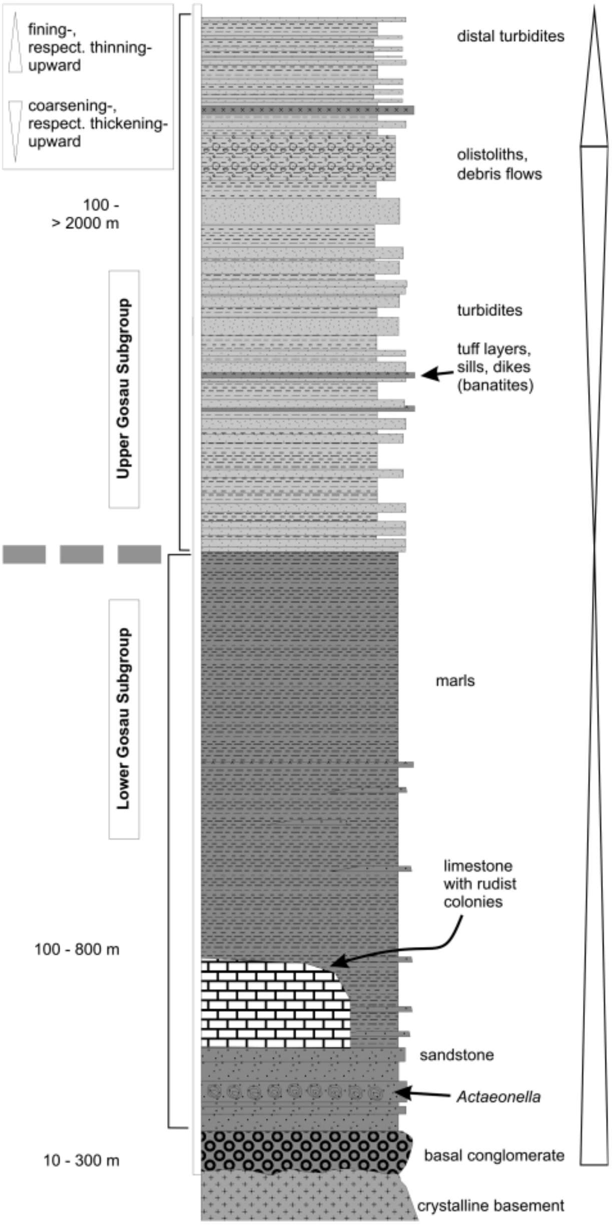

Figure 2: Schematic profile of the Upper Cretaceous Gosau Group of the Apuseni Mts., based on compiled outcrop data. The Lower Gosau Subgroup comprises terrestrial and shallow marine sediments, locally with thick limestones. The turbidites of the Upper Gosau Subgroup show a fining-upward trend. A horizon with debris flows and olistoliths can be traced through all occurrences. The banatite magmatism is responsible for subvolcanic intrusions (dikes, sills) and tuff layers (not illustrated in this figure). Note the thicknesses of each subgroup vary locally; the maximum thickness of the Upper Gosau Subgroup is unknown, due to post-sedimentary basin inversion and erosion.

Two Upper Cretaceous sedimentary successions are found in the Southern Apuseni Mts. (the Gosau Group and the Bozeş Formation, Fig. 1). Both successions comprise deep-water sediments (flysch) from Cenomanian to Maastrichtian times and are considered to be the post-tectonic cover of the Mesozoic Tectonic Unit (Săndulescu, 1984).

Subduction and closure of the Transylvanian Ocean resulted in volcanic activity, as evidenced by the emplacement of calc-alkaline volcanic rocks ("banatites"; von Cotta, 1864) during Late Cretaceous to Paleogene times (Ianovici et al., 1976).

A Paleogene tectonic event formed the so-called Laramian Transylvanides (Laramian tectogenesis after Balintoni 1997), which, in this work, are described as the Tertiary Tectonic Complex (Fig. 1). The structures of this tectonic event are restricted to the Southern and Eastern Apuseni Mts.. The units of the Tertiary Tectonic Complex incorporate parts of the Mesozoic Tectonic Complex (namely the Transylvanides) and post-tectonic sediments, including the Gosau deposits of the Southern and Eastern Apuseni Mts.. Besides the Variscan granites and the Upper Cretaceous to Paleogene calc-alkaline magmatic rocks ("banatites"), the mainly calc-alkaline Neogene magmatism forms magmatic suites in the Southern Apuseni Mts..

A 70-90° clockwise rotation from Early to Middle Miocene times, as evidenced by paleomagnetic data (Pătraşcu et al., 1994; Panaiotu et al., 1997), moved the Tisia-Dacia block into its present position. Eastward retreating Neogene subduction of the Eastern Carpathian Basin (Cheahlău Ocean: after Zweigel, 1997) resulted in eastward movement of the Tisia-Dacia block and induced back-arc extension in the Pannonian Basin (Royden and Báldi, 1988; Royden, 1993). The present tectonic positions of the Eastern and Southern Carpathians are the result of the Neogene collision of the Tisia-Dacia microplate with the European foreland and the Moesian platform.

2. THE GOSAU SUCCESSION – SEDIMENTOLOGY AND STRATIGRAPHY

The results presented in this work are mainly based on data collected from the sediments of the Gosau deposits. Comparable to the well-studied Gosau Group in the Eastern Alps (Tollmann, 1976 and references therein; Faupl and Wagreich; 1992, Wagreich, 1995), this type of deposit is also described from other regions of the Alpine-Carpathian chain using regional terms (Western Carpathians: Salaj and Began, 1983; Salaj and Priechodská, 1987; Wagreich and Marschalko, 1995; Faupl et al., 1997; Transdanubian range: Haas, 1983; Siegl-Farkas and Wagreich, 1997). The Gosau deposits of the Apuseni Mts. were described using sedimentological and paleontological data (e.g., Lupu, 1970; Lupu and Lupu, 1983; Pitulea and Lupu, 1978; Lupu and Zacher, 1996) but those regional lithostratigraphic terms have generally not been utilized for our publication.

The Gosau succession was subdivided on the basis of its sedimentary facies into a Lower and an Upper Gosau Subgroup, as in the Eastern Alps (Wagreich and Faupl, 1994). According to this subdivision, the Lower Gosau Subgroup of the Apuseni Mts. contains terrestrial conglomerates and breccias, followed by shallow marine deposits (sandstones, siltstones, marls and patchy rudist limestones; Fig. 2) of Late Turonian to Late Campanian age (Fig. 3; Schuller and Frisch, 2003; Schuller, 2004). However, the onset of sedimentation occurred diachronously during Late Turonian to Santonian times, with earlier sedimentation in the west and eastward progradation. The Upper Gosau Subgroup is characterized by a deep marine turbiditic depositional environment. The age of the facies change from the Lower to the Upper Gosau Subgroup varies from Early Campanian to Late Campanian without a recognizable pattern. The mostly calcareous turbiditic sequence records a coarsening-upward trend followed by a fining-upward trend after an interval of debris flow deposits with olistoliths in some places (Fig. 2; Schuller, 2004). Partly non-calcareous, pelagic sediments indicate that the basin bottom reached depths below the calcite compensation depth (CCD).

General stratigraphic evolution and sedimentary records of the Gosau deposits of the Apuseni Mts. are similar to the Gosau Group of the Eastern Alps. However, the turbiditic Upper Gosau Subgroup is largely missing in the Northern Apuseni Mts., where only shallow marine sedimentation occurred until Late Campanian times. Near the extrusive center of the calc-alkaline Late Cretaceous to Paleogene banatite magmatism (Vlădeasa region, Fig. 1), a volcano-sedimentary succession is recorded, which overlies the shallow marine Lower Gosau Subgroup (Mantea et al., 1987) (Fig. 3). Deposition of the Gosau sediments of the Apuseni Mts. terminated around the Cretaceous/Paleogene boundary (Lupu and Zacher, 1996; Schuller and Frisch, 2003; Schuller, 2004). In contrast, the deposition in the Eastern Alps continued in some places until Eocene times.

2.1 BASIN MODELING

1D-basin modeling based on vitrinite reflection was performed on a Gosau succession near Câmpeni (Fig. 1) and along a profile of the Upper Cretaceous flysch succession (Bozeş flysch) of the Southern Apuseni Mts. near Geoagiu (Fig. 1). The latter profile was sampled in order to prove possible similarities to, or distinctions from the evolution of the Gosau basin. The geodynamic setting of the Bozeş flysch is a matter of discussion, since some authors consider this flysch to belong to the flysch succession of the Gosau deposits (Lupu and Lupu, 1983; Lupu et al., 1993; Balintoni, 1997).

The burial history and thermal evolution was reconstructed with the aid of numerical solutions of one-dimensional modeling by using the software module BasinMod-1D from Platte River Association. The input data are surface outcrops, which are projected as pseudowells, and vitrinite reflectance data. The vitrinite reflectance curve was calculated and adjusted to the measured vitrinite reflectance points by assuming different values for heat flow and erosion.

Basin modeling on the Gosau succession indicates a total sedimentary thickness of up to 3200 m, with 2100 m preserved and 1100 m of eroded sediments (Fig. 4). The burial history shows a short period of rapid subsidence (< 3.4 mm/a) during initial basin opening, low subsidence rates (< 0.33 mm/a) during the early Gosau period (Santonian to Maastrichtian) and higher subsidence rates (max. 2 mm/a) during the late Gosau

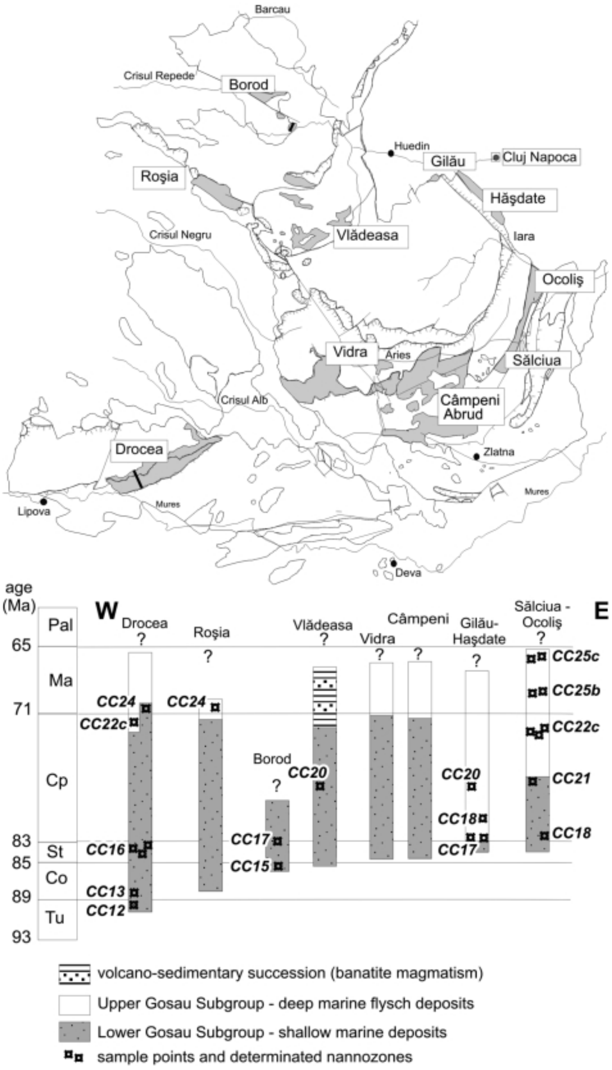

FIGURE 3: Compiled profiles with stratigraphic range and determined Nannozones (after zonations of Sissingh, 1977 and Perch-Nielsen, 1985) of the main Gosau deposits. First sediments were deposited in the Southwest (Drocea). The initial sedimentation successively moves to the Northeast (Sălciua-Ocoliş). In the Northern Apuseni Mts. no deep marine sediments are known. In the Vlădeasa region, a vulcano-sedimentary sequence overlies the shallow marine Lower Gosau Subgroup. Question marks at the top of each column indicate that erosion of the uppermost succession parts is presumed, due to postsedimentary basin inversion (Schuller, 2004); Pal: Paleocene; Ma: Maastrichtian; Cp: Campanian; St: Santonian; Co: Coniacian; Tu: Turonian.

period (Maastrichtian). The best fit curve (black line in Fig. 4b, 4c) to the measured vitrinite reflectance values was calculated assuming 1100 m eroded sediments and increased heat flow values (Fig. 4c) during the Late Cretaceous/Early Paleogene (due to banatite magmatism) and the Neogene (due to the Neogene magmatism). However, the heat flow during Neogene times did not reach the values of the Late Cretaceous/ Early Paleogene. Other scenarios with either lower heat flow and/or higher erosional thickness did not result in a better fit to the measured vitrinite values (Fig. 4b,c,d). The basin modeling indicates that the depositional area was influenced by the banatite magmatism.

Thermal maturity basin modeling on the Bozeş flysch indicates that this basin developed in a different geodynamic setting from the Gosau basin. The examined profile consists of a thin shallow marine sequence overlain by approx. 2500 m of siliciclastic turbidites. Upsection, a 200 m thick Neogene cover follows, which has no effect on the performed modeling. The burial history of the Bozeş flysch shows rapid subsidence (< 1.6 mm/a) during the Late Cretaceous, followed by an erosive phase in the Paleogene (Fig. 5-a). The best match to the vitrinite reflectance data (black line in Fig. 5-b, 5-c) is attained with very low heat flow (20-30 mW/m²) during Late Cretaceous, high heat flow during Neogene and an erosion of 4000 m during Paleogene times. The increased heat flow can be explained by the Neogene magmatic activity, which had stronger effects in the Southern Apuseni Mts. compared to the north. The best-fit curve to the measured vitrinite reflectance data indicates that the sediments were deposited in a basin with very low heat flow, as it is known from trenches at convergent plate margins or forearc regions with absence of an adjacent magmatic arc. In our case, a magmatic arc (banatite magmatism) is situated behind the forearc basin, thus higher heat flow values are expected (40-80 mW/m²). Consequently, the basin type would be that of an ocean trench. It has to be assumed that this basin was isolated from the Gosau depositional area and its evolution should be interpreted differently. The calculated total thickness of approx. 6600 m also indicates that the sediments were not deposited in a forearc basin, as is supposed for the Gosau sediments. The thick turbidite interval supports a trench scenario.

The results of basin modeling on the Bozeş Formation show that during the Late Cretaceous, apart from the Gosau depositional area, deep marine sediments were deposited in a trench outside of the active orogenic wedge, reflecting continuous subduction during Gosau sedimentation in the forearc region.

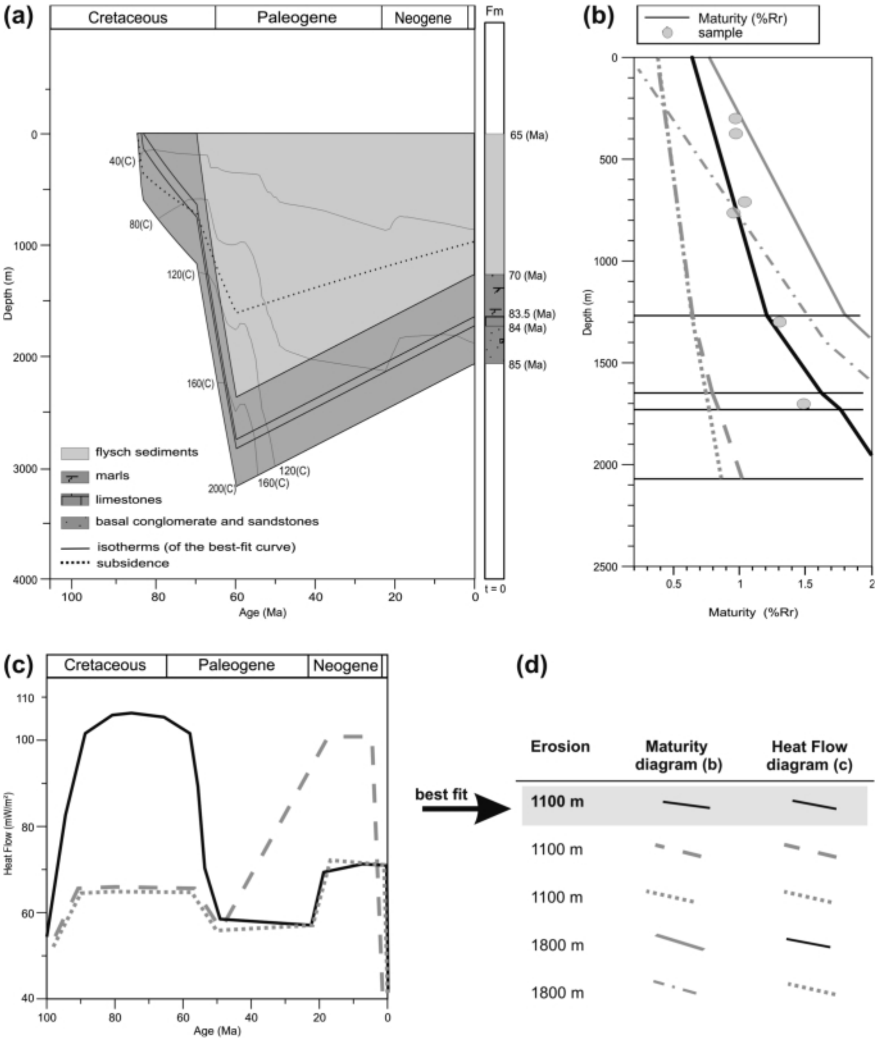

Figure 4: (a) Subsidence history of the Gosau Group (Câmpeni profile). (b) Vitrinite reflectance against depth: the dark line illustrates the calculated best-fit curve. (c) Heat flow diagram: heat flow values of the black line were used for the calculation of the best-fit curve. The grey lines of (b) and (c) show calculated curves with different assumptions of heat flow and erosional thicknesses, which did not result in an adequately fitting curve. (d): table illustrating assumptions and calculated results for different scenarios; e.g. best fit curve: a postsedimentary erosion of 1100 m and heatflow values of the black line in (c) were used to calculate the vitrinite maturity curve, shown as the black line in (b).

2.2 PROVENANCE ANALYSIS

The provenance of the detrital material of the Gosau deposits was constrained by means of heavy mineral assemblages and paleocurrent measurements. Our data indicate sedimentary transport from both sides of an elongated basin. According to Schuller and Frisch (2006), the basin was positioned in the forearc region above the Transylvanian subduction zone. It was supplied from the accretionary wedge on one side, and from the Bihor crystalline hinterland (Fig. 1) on the other side (Fig. 6). This scenario is supported by the provenance analysis of olistoliths (Bucur et al., 2004) and conglomerate pebbles within the Upper Gosau Subgroup (Schuller, 2004).

Some heavy mineral associations show increasing amounts of minerals (such as zircon and tourmaline) derived from magmatic rocks (cf. Schuller and Frisch, 2006). These minerals are interpreted to reflect the beginning of the subduction-related calc-alkaline magmatism in the Apuseni Mts. after the Early Campanian. Basin subsidence of the Upper Gosau Subgroup was accompanied by exhumation in the crystalline hinterland, previously demonstrated by Willingshofer (1999) on subsidence analysis and thermal cooling data. The change in all heavy mineral spectra reflects increasing regional exhumation of metamorphic units (Schuller and Frisch, 2006).

2.3 Fission track thermochronology

Fission track thermochronology on detrital zircons was used to define thermotectonic age populations, which can be correlated with characteristic zones in the source area and may in dicate changes in the exhumation processes in the surrounding hinterland. Fission track data on detrital apatites were used to detect potential thermal overprint of the Gosau succession. Thermal modeling on apatite fission track lengths of the crystalline basement reflects cooling paths and indicates exhumation of hinterland basement rocks.

Fission track data from detrital zircons record five age populations, which are older than sedimentation age of the sample, and are thus interpreted as cooling ages of five different source areas (Fig. 7; Tab.1). Consequently, five rock units, each with a different thermal history, have been eroded.

Correlating the isolated age populations with their inferred source rock units is difficult due to the lack of zircon fission track data from the Apuseni Mts.. At least the correlation of the 1st age population with the crystalline rocks of the Bihor-Unit (Fig. 1) can be made by using our own measurements (sample VS 105, VS106, VS107, VS109 in Appendix Table 1). The correlation of zircon fission track data with other geochronologic data can only be approximated. Ar/Ar cooling ages of hornblende and muscovite should generally show higher ages, since these minerals have higher closing temperatures. Ar/Ar data (Dallmeyer et al., 1999), which scatter from 100 to 120 Ma, have mainly been measured on rocks of the Baia de Arieş Unit (Ianovic et al. 1976), a sub-unit of the Mesozoic Tectonic Complex, and on mylonites of the Bihor Autochthonous Unit. These ages can be correlated with the 1st population (90 – 100 Ma) of the zircon fission track ages. Ar/Ar ages that scatter from 120 to 216 Ma have been determined by Dallmeyer et al. (1999) on rocks of the Biharia Unit (a subunit of the Mesozoic Tectonic Complex) and the Someş Unit (a metamorphic sub-unit of the Bihor Autochthonous Unit). These rocks can roughly be assigned to the 2nd and 3rd population. A distinct correlation cannot be made, since both units record ages that scatter from 120 to 216 Ma. The Codru Unit – the lowermost nappe complex of the Apusenides (Fig. 1; Săndulescu, 1984; Balintoni, 1997) - generally records Ar/Ar ages above 330 Ma. Parts of the Bihor-Unit also record this time range. These ages can be correlated with the 4th and 5th age population of the detrital zircons. Consequently, the Codru nappe-complex and at least parts of the Bihor Autochthonous Unit were exhumed above the PAZ (par-

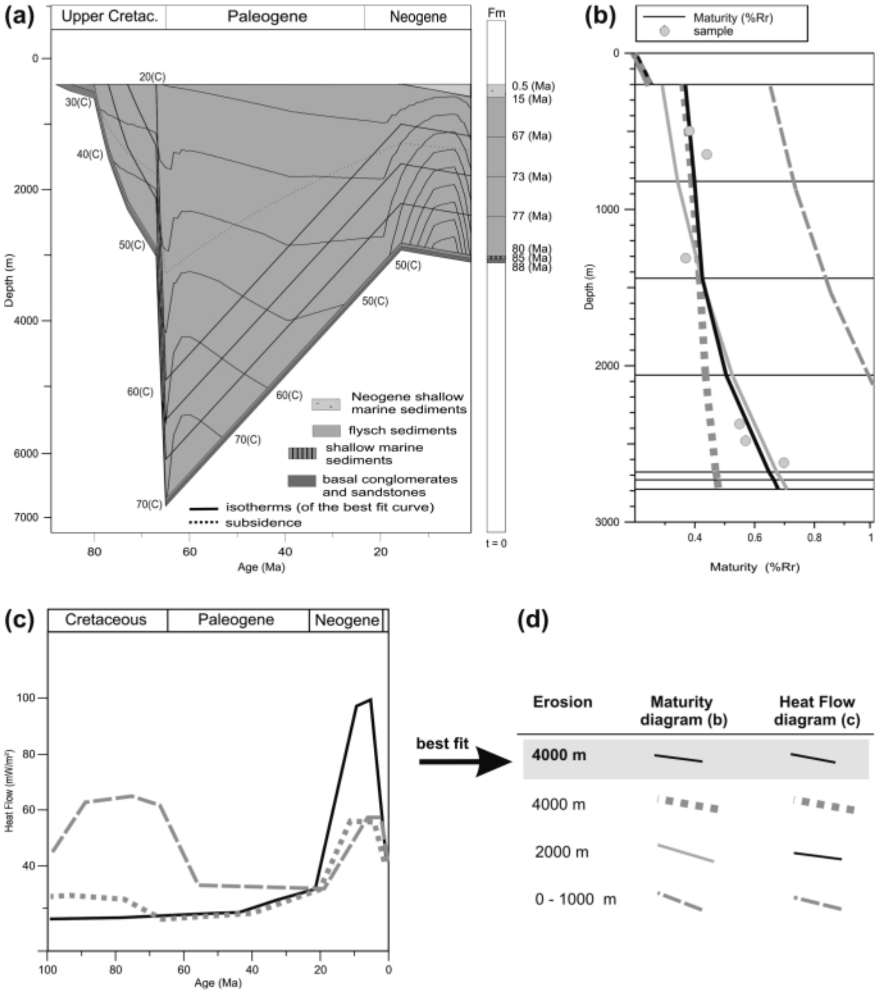

Figure 5: (a) Subsidence history of the Late Cretaceous sediments of the Geoagiu Formation and Bozeş flysch. (b) The dark line illustrates the calculated best-fit curve with high heat flow values in the Late Cretaceous. (c) The grey lines show calculated curves with different assumptions of heat flow and erosional thicknesses. (d) Table illustrating assumptions and calculated results for different scenarios (cf. Fig. 5).

tial annealing zone). However, it was not until the Late Cretaceous that these units were exposed to surface and eroded, since none of the older samples from the sedimentary succession contain zircons of the 4th (250 to 300 Ma) and 5th (~ 400 Ma) age populations.

The zircon fission track age populations 1 to 3 (Fig. 7) are found in the entire Gosau succession, indicating continuous erosion of corresponding source terrains throughout the entire Gosau period. Decreasing or increasing lag-time (i.e. difference between fission track age and sedimentation age; e.g. Garver and Brandin, 1994) within an age population would indicate higher or lower exhumation rates of distinct source terrains. However, fission track ages of each age population scatter within a broad range. A successive decrease or increase of lag-time is not detectable. This indicates that the source terrains are independent tectonic units with different exhumation rates. For instance, the 1st age population was interpreted to derive from the Bihor Autochthonous Unit and from the Baia de Arieş Unit. It can be assumed that the Bihor Autochthonous Unit experienced different exhumation rates from the crystalline rocks of the Baia de Arieş Unit. The latter is incorporated in thrust sheets of the Mesozoic Tectonic Complex which is tectonically active during Late Cretaceous times.

The uppermost part of the Gosau succession (uppermost Maastrichtian) was supplied with material from two additional sources: rock units with zircon fission track ages of 250-300 Ma and perhaps even 400 Ma (populations 4 and 5 in Fig. 7).

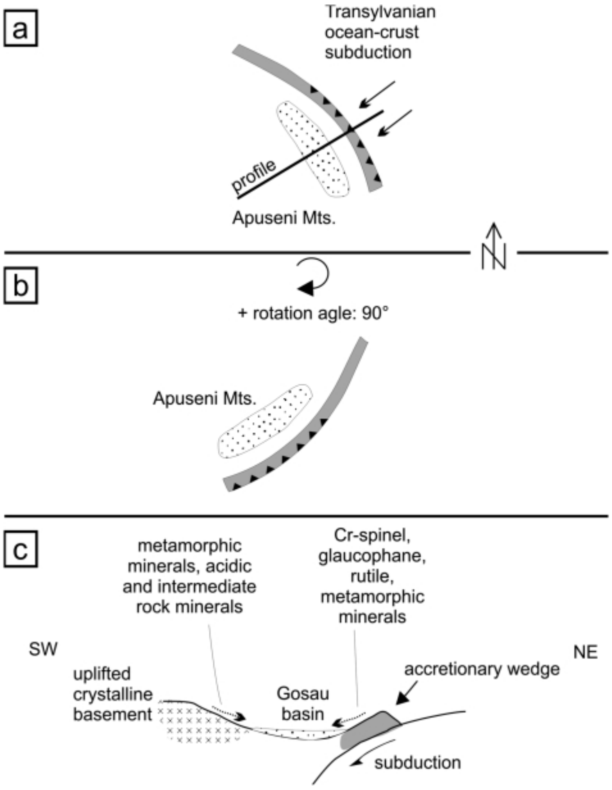

Figure 6: Regional geodynamic position of the Gosau basin during the sedimentation period (a), and in present-day coordinates after the Miocene 90° clockwise rotation of the Apuseni Mts. (b). The profile (c) illustrates the transport directions and mineral spectra during basin formation and sediment accumulation (Schuller and Frisch, 2005).

Population 4 was also detected in the Paleogene terrestrial sandstones, which unconformably overlie the Gosau deposits. Populations 4 and 5 show that after the Late Maastrichtian the corresponding source rock units were exposed to erosion, probably due to the tectonic activity beginning at the Cretaceous/Paleogene boundary. This interpretation is supported by thermal modeling on crystalline rocks of the Bihor Autochthonous Unit (Fig. 8; Tab. 2). The thermal history revealed a cooling event at the Cretaceous/Paleogene boundary followed by a relaxation during Eocene times. This result is supported by Sanders (1998) who performed thermal modeling on the crystalline rocks of the Bihor Autochthonous Unit and the Apusenides.

Outcrop data suggest syn-sedimentary compressive tectonics, which reached its climax at the Cretaceous/Paleogene boundary and terminated sedimentation in the Gosau basin. However, the compressive structures are restricted to the area of the Southern and Southeastern Apuseni Mts.. Apatite fission track ages from the Gosau sediments show that this tectonic event had no detectable thermal effects on the apatite fission track thermochronometer. None of the examined samples shows ages younger than the sedimentation ages (Tab. 2). Although compressive structures can be found in all Gosau sediments of the Southern and Eastern Apuseni Mts., these tectonics did not cause large-scale thrusting. Since the closure temperature of apatite lies around 100°C, even thin-skinned thrusting would cause at least partial annealing of the fission tracks and thus rejuvenation of their cooling ages. It can be concluded that the Late Cretaceous to Early Paleogene tectonics in fact led to intensive shortening, folding and reverse faulting. However, regional thrusting and nappe stacking can be excluded from field evidence.

3. Discussion

Several models have been proposed to explain the Mesozoic geodynamic evolution of the Gosau basins of both the Apuseni Mts. and the Eastern Alps. A comparative discussion should help to support some ideas proposed in this study.

Prior to the Gosau Group deposition, considerable tectonic activity in both areas is indicated by a distinct angular unconformity of Turonian age and younger. A striking similarity of the Gosau Group in both orogens is the facies evolution: terrestrial, coarse grained to shallow marine deposits (including similar fossil assemblages) followed by an abrupt change to deep-water turbidites. Some similarities to the Eastern Alps were shown by provenance studies on the Gosau Group of the Apuseni Mts. (Schuller and Frisch, 2006). Heavy mineral assemblages and paleocurrent data indicate continuous erosion of a forearc ridge on the one side of the basin and a crystalline basement on the other during deposition of the entire Gosau Group of the Apuseni Mts.. Comparable to this, in the Eastern Alps an increased amount of heavy minerals derived from rocks related to an obducted forearc ridge are characteristic for the Lower Gosau Subgroup, whereas the

sample nr.	location	geological unit	age of sedi-mentation	central age	sd	Population 1	sd	Population 2	sd	Population 3	sd	Population 4	sd	Population 5	sd
			(Ma)	(Ma)	(Ma)	(Ma)	(Ma)	(Ma)	(Ma)	(Ma)	(Ma)	(Ma)	(Ma)	(Ma)	(Ma)
159	Băisoara	banatites		70.0	2.7										
163	Vlădeasa			70.4	2.9										
M11	Ocoliş			64.4	2.7										
130	Linteni	Paleogene (fluvial sediments)	54	107.8	5.9	115.5	5.5	154	85.4			295.7	17.3		
M64	Muşca	Upper Gosau	66	274.2	14					216.9	34.5	290.2	23.5	398.7	34.6
M24	Abrud-Zlatna	Upper Gosau	67	148.3	10.8	96.2	37.6			180.5	29.6	255.4	9.8		
M27	Drocea	Upper Gosau	69	112.6	4.4	109.5	21.1	150.8	2.4						
M52	Drocea	Upper Gosau	70	149.5	8.0			139.4	27.9	171.6	86.7				
M15	Sălciua	Upper Gosau	72	110.9	7.1	79.4	9.9	134.7	52.2						
VS 127	Hăşdate	Upper Gosau	78	107.7	5.3	108.2	28.4	140.8	49.5						
M26	Vlădeasa	Lower Gosau	78	144.2	7.8	110.5	16.0	143.0	1.9	172.6	63.0				
Mai 82	Hăşdate	Upper Gosau	79	94.8	3.8	85.7	17.2	127.8	7.4						
247	Roşia	Lower Gosau	80	111.4	11.7	98.0	41.5			201.0	37.5				
Mai 8	Vidra	Lower Gosau	82	99.1	4.1	93.0	17.9	133.0	19.8						
Mai89	Hăşdate	Upper Gosau	83	104.6	5.1	102.1	24.0			178.0	13.0				
M61	Gilau	Upper Gosau	83	128.9	7.3	85.9	5.7	122.4	9.7	170.0	69.8				
VS 44	Vidra	Lower Gosau	83	102.5	5.0	97.9	22.7	152.8	11.5						
M 49	Drocea	Lower Gosau	84	166.9	10.4	89.2	1.9	128.3	7.7	216	65.8				
Mai 92	Hăşdate	Lower Gosau	84	106.9	5.0	85.0	10.7	129.0	14.4						
M16	Sălciua	Lower Gosau	84	108.5	5.3	104.0	25.6			166.9	47.9				
165	Vlădeasa	Lower Gosau	85	91.4	3.7	91.4	3.7								
204	Drocea	Lower Gosau	89	121.4	7.0	95.7	28.2	145.6	15.8	205.8	21.1				
VS 107	Muntele Mare			94.9	4.7										
VS109	Băişoara Mt.	crystalline units		85.5	3.8										
VS105	Iara valley			94.5	4.5										
VS106	Iara valley			86.2	6.2										

Table 1: Zircon fission track ages including the calculated age populations for the sediments (Gosau and Paleogene). Note the euhedral crystals of the detrital zircon data sets have been deselected in the upper part of the succession (samples younger 80 Ma) to avoid rejuvenation of the populations due to banatite magmatism (Schuller, 2004).

Upper Gosau Subgroup is dominated by metamorphic heavy minerals derived from an uplifted crystalline hinterland (e.g. Woletz, 1967; Gruber et al., 1991; Faupl and Wagreich, 1992).

Another common feature of the Gosau basins of both orogens is the rapid subsidence, marked by the onset of the deep-water sedimentation phase, which did not cease until the final closure of the basin. Wagreich and Faupl (1994) and Wagreich (1993, 1995) propose subduction of an oceanic high (e.g. a mid-ocean ridge), which caused subduction erosion. The oblique convergence of the two plates resulted in diachronous subduction of the oceanic high. Thus, the change from shallow marine (Lower Gosau Subgroup) to deep marine sedimentation (Upper Gosau Subgroup) shifted from west to east in the Eastern Alps. In the Apuseni Mts., no clear shift of this facies change can be identified. Although diachronous onset for the initial (Lower Gosau) sedimentation is recorded (Fig. 3), the change from shallow to deep marine sedimentation does not show any systematic shift. In the Apuseni Mts., the abrupt subsidence into a deep-water environment occurred earlier than in the southeastern part of the Eastern Alps: in the easternmost Eastern Alps in Late Maastrichtian (Grünbach Gosau: Wagreich, 1993), but already in Campanian to Early Maastrichtian time in the Apuseni Mts.. This, however, can be explained by the offset of an inferred mid-oceanic ridge along a transform fault (the eastern segment being shifted to the south). On the other hand, Schuller (2004) proposed subduction rollback as the cause for strong dilatation and thus rapid subsidence in the forearc Gosau basins at the margin of the upper plate. Subduction rollback was proposed by Froitzheim (1997) as the driving mechanism for the entire Late Cretaceous extension in the Eastern Alps. Conversly, Schuller (2004) assumes that the change from advancing to retreating subduction with corresponding slab rollback was responsible for the rapid change from shallow marine (Lower Gosau Subgroup) to deep marine (Upper Gosau Subgroup) sedimentation in the Apuseni Mts..

Collision of the Tisia and Dacia plates during closure of the Transylvanian Ocean is proposed by several authors to have occurred during mid-Cretaceous (Săndulescu, 1984; Balintoni, 1997; Neubauer, 2002, Iancu et al., 2005). Following their model, the Gosau deposits and the thick Upper Cretaceous sediments on the outer side of the orogenic wedge (e.g.

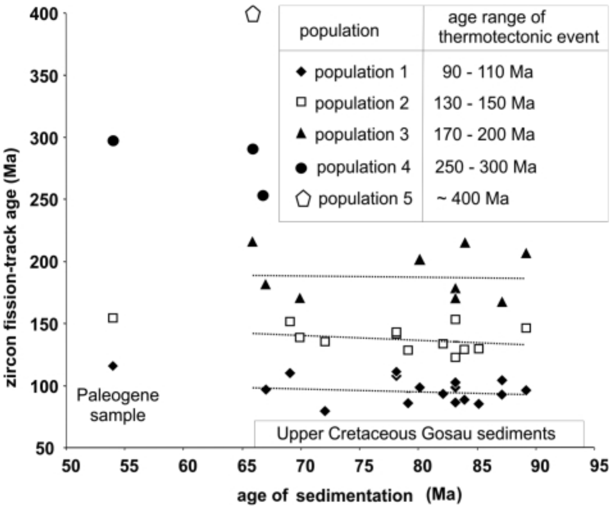

Figure 7: Separated age populations of detrital zircon fission track ages with correlation to thermotectonic events. Note the Paleogene sample does not belong to the Gosau Group (dotted lines: best fit of populations 1 to 3).

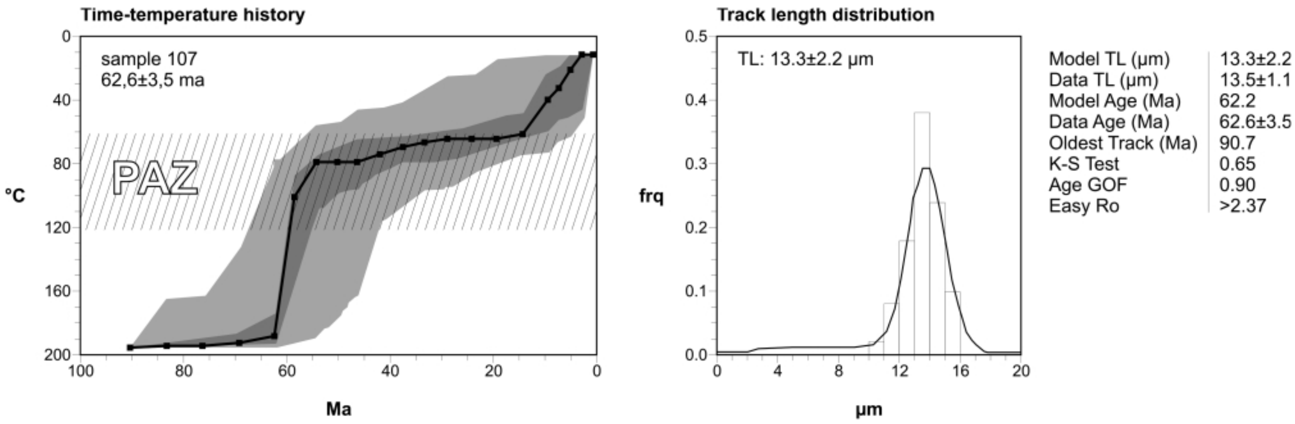

Figure 8: Modelled thermal history from apatite fission track lengths of the Bihor Autochthonous Unit. The modeling was performed with AFTSolve® (Ketcham et al., 2000) by using the "unsupervised search style". The left diagram displays the time/temperature path, the right one shows the frequency distribution of the measured confined track lengths. The light gray envelope (left diagram) comprises acceptable thermal paths, dark gray includes paths with good fit and the black line represents the best fit (Ketcham et al., 2000; PAZ=Partial Annealing Zone).

Bozeş flysch) can only be explained as parts of intramontane basins, which were deposited after the collision of the two continental plates. However, if one considers that boreholes through the Transylvanian basin record thick Late Cretaceous successions (Ciupagea et al., 1970; Stefănescu, 1985; Ciulavu and Bertotti, 1994) and that Late Cretaceous deposits are also known from some outcrops in the Outer Transylvanides (Median Dacides after Săndulescu, 1984) in the Eastern Carpathians, this would result in a Late Cretaceous sedimentation area of approx. 350 km in diameter (shortening at the K/Pg boundary is not considered). This is not realistic for an intramontaneous basin. Therefore, we suggest the Upper Cretaceous deep marine sediments of the Bozeş flysch, the Transylvanian basin and the Eastern Carpathians were deposited in a trench system connected to the subduction of the Transylvanian Ocean. Basin modeling on the deposits of the Bozeş flysch suggests the existence of an oceanic trench until Late Maastrichtian time.

According to Neubauer (2002), the mid-Cretaceous continental collision was followed by slab breakoff in the Late Cretaceous, which was responsible for the generation of the banatite magmatism. Because our data suggest ongoing subduction until the Creatceous/Paleogene boundary, the banatite magmatism can be better explained by the retreating subduction scenario. Schuller (2004) proposed a model which describes this process as a consequence of retreating subduction, subsequently followed by mantle wedge corner flow, which caused the magma generation.

sample nr.	location	geological unit	age of sedimentation	central age	error
			(Ma)	(Ma)	(Ma)
M24	Abrud-Zlatna	Upper Gosau	67	71.2	4
M27	Drocea	Upper Gosau	69	81	3.9
M15	Sălciua	Upper Gosau	72	75.8	3.8
VS 107	Bihor unit	Variscan granite		62.6	3.5
VS109	Bihor unit	Someş unit		77.3	4.3

Table 2: Results of apatite fission track dating. Note the samples belonging to the Gosau sediments did not experience thermal overprint after sedimentation.

Although fission track data from the Gosau Group of the Eastern Alps are missing, a comparison with the Apuseni Mts. in this respect is possible since thermotectonic events within the Eastern Alps are well defined. Three Mesozoic thermotectonic events of similar age are also known from the Eastern Alps. The mid-Cretaceous tectonics of the Eastern Alps led to nappe emplacement in the external parts of the Northern Calcareous Alps (NCA). This would coincide with the 1st age population, respectively thermotectonic event. The 2nd age population would correlate with the Late Jurassic nappe emplacement in the internal parts of the NCA (e.g. Hallstatt Unit) at the southern border of the Austroalpine mega-unit (Frisch and Gawlick, 2003). A thermal heating period during crustal thinning and rifting processes (due to the opening of the Penninic Ocean) is proposed to have occurred in the Austroalpine realm during Late Triassic to Early Jurassic times (Dunkl et al., 1999; Kuhlemann et al., 2006). The 3rd age population from the Gosau sediments of the Apuseni Mts. is proposed to be derived from rocks which underwent a similar tectonothermal evolution in an equivalent geodynamic frame. The oldest age populations are related to Variscan orogeny which is known in both the Eastern Alps and the Apuseni Mts..

4. Conclusions

The sedimentation of the Upper Cretaceous Gosau succession of the Apuseni Mts. evolved in the same geotectonic frame as that of the Eastern Alps. The similarities, but also differences elaborated in this study, are evident.

The sedimentary facies successions are similar. The stratigraphic range covers nearly the same time interval. Deposition thickness is approximately equal. The provenance studies and fission track analysis in both mountain ranges lead to geotectonic interpretations which prove the erosion and Late Cretaceous exhumation history in the basin hinterland. A diachronous time shift for the second subsidence phase (Lower Gosau to Upper Gosau facies change) has not been detected within the Apuseni Mts., although such a shift is well documented for the Eastern Alps. In the Apuseni Mts. the facies change scatters without a regional pattern between Campanian and Early Masstrichtian times. Burial history and thermal basin modeling suggest a similar geotectonic basin setting for both orogens.

The subduction of the Transylvanian Ocean - probably the prolongation of the South Penninic Ocean of the Eastern Alps - was responsible for the generation of the Gosau basins of the Apuseni Mts.. The process leading to rapid basin subsidence (the change from Lower Gosau Subgroup to Upper Gosau Subgroup) occurred in both orogens but the systematic migration of collision of the subducted ridge with the upper plate and subduction erosion as it has been inferred for the Eastern Alps (Wagreich, 1993) did not systematically continue into the Apuseni Mts.. The explanation for this "out-of-sequence" subsidence may be an offset of the ridge along a transform fault between the Eastern Alps and Apuseni Mts. or, alternatively, subduction rollback in the Apuseni Mts. as a different mechanism from that operating in the Eastern Alps.

ACKNOWLEDGMENTS

Many thanks are addressed to the reviewers Michael Wagreich and Ernst Willingshofer who helped to improve the quality of the manuscript with important remarks and beneficial comments. Special thanks are sent to the numerous collaborating colleagues from the Babeş-Bolyai University/Cluj-Napoca (Romania) and several other Romanian geologists. We also want to thank Eliza Larratt who improved the spelling of the manuscript. We acknowledge the support of Platte River Assoc., who provided us with a free loan version of their software package. This work is part of a project financed by the DFG (Deutsche Forschungsgemeinschaft; Proj.Nr: Fr 610/18-1).

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Received: 27. February 2009
Accepted: 20. May 2009

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APPENDIX: FISSION TRACK METHODOLOGY

Apatite and zircon crystals were recovered from whole rock samples using standard magnetic and heavy liquid separation techniques. Apatites were embedded in epoxy, zircons in PFA Teflon™. Prepared mounts with grains were polished to 4π geometry. Spontaneous tracks in apatites were revealed by etching with 5.5 M HNO_3 solution for 20 seconds at 21°C (Donelick et al., 1999). Zircons were etched in an eutectic mixture of KOH and NaOH at 215°C for 20 to 80 hours (Zaun and Wagner, 1985). The zeta calibration approach (Hurford and Green, 1983) was adopted to determine the age.

Appendix Tables: fission track counting statistics. Cryst: number of dated crystals. Track densities (ρ) are as measured (x105 tr/cm²); N: number of tracks counted. Zircon ages were calculated using dosimeter glass: CN-2 with ζ = 345.95 ± 10.78 . P(χ²): probability obtaining Chi-square value (χ2) for n degree of freedom (where n = no. of crystals - 1). FT age: central age ± 1 standard deviation.

Code	Locality	Lithology	Cryst.	Spontaneous		Induced		Dosimeter	$P(\chi^2)$		FT age		
				ρ_s	N_s	ρ_i	N_i	ρ_d	N_d	(%)	(Ma ± 1σ)		
159	Băisoara	banatite	25	159.68	2433	122.93	1873	8.11	5182	54.2	70.0	±	2.7
163	Vlădeasa	banatite	23	172.94	1972	131.72	1502	8.07	5182	96.1	70.4	±	2.9
M11	Ocoliş	banatite	25	124.80	1926	102.38	1580	7.96	5182	81.6	64.4	±	2.7
130	Linteni	sandstone	50	96.69	3764	45.21	1760	7.40	5802	0.0	107.8	±	5.9
M64	Muşca	sandstone	44	157.28	4499	33.35	954	9.00	6612	0.5	274.2	±	14.0
M24	Abrud-Zlatna	sandstone	49	123.60	3402	41.60	1145	7.80	5182	0.0	148.3	±	10.8
M27	Drocea	sandstone	48	114.40	4847	50.37	2134	7.42	5182	5.2	112.6	±	4.4
M52	Drocea	sandstone	49	113.05	4734	42.79	1792	8.67	6612	0.0	149.3	±	8.0
M15	Sălciua	sandstone	47	126.31	4321	57.94	1982	7.69	5182	0.0	110.9	±	7.1
VS 127	Hăşdate	sandstone	50	98.15	3126	42.95	1368	7.07	5182	0.1	107.7	±	5.3
M26	Vlădeasa	sandstone	50	107.63	4867	36.07	1631	7.34	5802	0.0	144.2	±	7.8
Mai 82	Hăşdate	sandstone	50	89.35	4787	46.12	2471	7.34	5182	0.1	94.3	±	3.8
247	Roşia	sandstone	24	169.71	1368	83.49	673	8.79	6612	0.0	111.4	±	11.7
Mai 8-	Vidra	sandstone	49	95.27	4280	48.51	2179	7.57	5182	0.5	99.1	±	4.1
Mai 89	Hăşdate	sandstone	50	99.78	4610	45.61	2107	7.35	5802	0.0	104.6	±	5.1
M61	Gilau	sandstone	50	103.29	4498	46.39	2020	8.88	6612	0.0	128.9	±	7.3
VS 44	Vidra	sandstone	49	105.24	3238	52.78	1624	7.88	5182	0.0	102.5	±	5.0
M49-	Drocea	sandstone	50	133.34	4417	47.73	1581	9.06	6612	0.0	166.9	±	10.4
Mai92b-	Hăşdate	sandstone	49	80.47	3971	37.02	1827	7.49	5182	0.0	106.9	±	5.0
M16	Sălciua	sandstone	49	118.26	3406	56.66	1632	7.76	5182	0.0	108.5	±	5.3
165	Vlădeasa	sandstone	50	73.71	3543	38.74	1862	7.22	5182	8.7	91.4	±	3.7
204	Drocea	sandstone	48	119.40	3791	46.36	1472	7.15	5182	0.0	121.4	±	7.0
107	Valea Şoimului	Variscan granite (Granit de Mt. Mare)	25	48.44	1457	27.19	818	8.03	5182	64.4	94.8	±	4.7
109	Băişoara Mt.	micaschist (Someş Unit)	26	148.97	1889	92.35	1171	8.00	5182	68.7	85.5	±	3.8
105	Iara valley	micaschist	25	180.36	1702	93.46	882	7.38	5802	69.1	94.4	±	4.5
106	Iara valley	micaschist	15	110.12	1050	64.71	617	7.6093	5182	3.9	85.9	±	4.8

TABLE 1: Zircon fission track counting statistics (weighted mean, ζ = 133.54 ± 2.5).

Code	Locality	Lithology	Sedimentat. age ma		Cryst.	Spontaneous		Induced		Dosimeter		$P(\chi^2)$	FT age		
						ρ_s	N_s	ρ_i	N_i	ρ_d	N_d	(%)	(Ma ± 1σ)		
107	Valea Şoimului	Variscan granite (Granit de Mt. Mare)	-		20	6.39	615	11.83	1139	6.66	4291	64.91	62.6	±	3.5
109	Baişoara Mt.	micaschist (Someş Unit)	-		20	7.58	793	12.07	1263	7.08	4291	20.18	77.3	±	4.3
M15	Sălciua	sandstone	72		20	9.49	862	14.90	1354	6.84	4291	58.76	75.8	±	3.8
M24	Abrud/Zaltna	sandstone	67		20	6.68	616	11.37	1049	6.96	4291	57.28	71.2	±	4
M27	Drocea	sandstone	69		20	10.00	958	14.56	1394	6.78	4291	57.19	81	±	3.9

TABLE 2: Apatite fission track counting statistics (weighted mean, ζ = 349.8 ± 6.3).