Abstract
During last decades, the geodynamics of the Pannonian-Carpathian region have been object of an heated scientific debate. As a contribution to this research, in this study low temperature thermochronology is used to investigate the behaviour of the chain at shallow crustal levels and to provide temporal and spatial constraints to its evolution. Apatite and zircon (U-Th)/He dating and apatite fission track analysis are used in order to reconstruct the burial and exhumation history of the Polish and Ukrainian Carpathians, so far the less studied region of the chain. Results indicate an eastward increasing in burial and point to the relevance of post-thrusting extensional tectonics as an exhumation-driving process.

Introduction
The Carpathian-Pannonian region’s geodynamic evolution has been, for the last decades, object of debate for the scientific community. The aim of this study is to provide a further contribution to the understanding of this territory. Low temperature thermochronometry and paleotemperature studies allow to define thermal histories, which can be used, in turn, to infer the occurrence of thermal perturbations and of their extent, as well as the timing and spatial pattern of burial and exhumation. Three low temperature thermochronometers were used to date rocks belonging to the Polish and Ukrainian Outer Carpathians, and the results were inverted to model time-temperature histories. Thermal histories were then integrated with paleotemperature data and observations on the structural, stratigraphic and topographic setting of the region, in order to extrapolate constrains on burial and exhumation.

Geological setting
The Carpathians are a 1500 Km long arc shaped mountain belt, representing the eastern prolongation of the Alps to which they are linked by the strike-slip Vienna Basin. To the south they are in continuity with the Dinarides, and in back arc position they enclose the Pannonian Basin. The chain formed during the Alpine orogenesis by N to SE-ward collision between the ALCAPA (of African origin) and Tisza-Dacia (of European origin) microplates and the European plate (e.g. Sperner et al., 2002). A narrow zone of intensely deformed and sheared Mesozoic to Paleogene rocks, traditionally named “Pieniny Klippen Belt” (PKB, e.g. Birkenmajer, 2001), divides the Mesozoic thrust belt, namely the Inner Carpathians (IC) from the its accretionary wedge, the Outer Carpathians (OC; e.g. Tasarova et al., 2009 and reference therein). The OC basin, built on thinned European continental crust, was filled with an Upper Jurassic to Miocene sedimentary succession, which was deformed and accreted to the wedge between Paleocene and Pliocene (e.g. Golonka et al., 2006). The final orogenic stage was characterized by back-arc extension, which was responsible for the origin of the Pannonian Basin and shaped the Carpathian-Pannonian region to its present form (e.g. Huismans et al., 2001; Fodor et al.,
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Volcanism related to extension (e.g. Harangi and Lenkey., 2007) also occurred in association to back arc dynamics. This study focused on the portion of the chain originated by the collision between the ALCAPA and the European Plates, and, in particular on the Polish and Ukrainian Outer Carpathians.

Methods
Thermochronometry plays on the sensitivity to a low temperature range (between ca. 30°C and 550°C) of some radioactive systems to understand thermal histories of rocks and minerals in that temperature range. An estimate of the thermal sensitivity of a thermochronometer is given by its closure temperature $T_c$. In this study, three thermochronological methods have been used:

- apatite (U-Th-Sm)/He dating (AHe), which standard closure temperature is $T_c=60°C$;
- apatite fission track dating (AFT), with $T_c=110°C$;
- zircon (U-Th-Sm)/He analysis (ZHe), which has $T_c=175°C$.

Thermochronometric data are related to thermal history, which is in turn related, in most cases, to burial and exhumation history. There are, however several complications in the relationships between the three, since exhumation rates influence both the crustal thermal field and the thermal sensitivities of the thermochronometers. Thus, given a certain crustal thermal model, thermochronometric ages can be uniquely related to exhumation rate only assuming it having been steady prior as well as after the closure of the system. Under the assumption of a certain thermal field and of steady state exhumation rate, closure temperature and closure depth can be estimated, and the range of possible exhumation rates can be defined. Changes in exhumation rates with time can be estimated from measurements of multiple cooling ages from the same rock, taking care in considering transient thermal effects.

Results and discussion
In the third year of PhD 18 new AHe and 10 new ZHe samples have been analyzed. A total of 20 AFT samples, 58 AHe and 28 ZHe samples were analyzed during the PhD. Here the main results are briefly presented and discussed.

Paleothermal structure
The paleothermal structure of the wedge inferred from thermochronology and confirmed by paleotemperature data is rather complex, and it appears related to tectonic structure of the chain, being instead unrelated to the distance from heating sources (Neogene volcanic fields, Pannonian mantle plume). Major thermal perturbations in the accretionary wedge during its formation and thrusting can therefore be excluded. Heating and cooling of the wedge were then principally due to burial and exhumation. Furthermore several samples belonging to rocks originally buried by thick sedimentary piles show a low heating degree. A low (ca. 18°C/Km) paleo-geothermal gradient, constant during the Cenozoic is therefore assumed.

Heating and burial
All the ZHe ages are older than the depositional age, indicating that none of the analyzed samples was heated over 175°C after deposition. On the other hand the AFT and AHe dates are in most cases younger than the depositional ages, indicating an heating of the accretionary wedge higher than 60-110°C. AFT and AHe data also clearly point to an eastward increasing heating of the accretionary wedge. Burial of the innermost units of the accretionary wedge varied in the range 3.6-8.6 Km, with the maximum values reached in the Ukrainian sector: a major component of tectonic burial is necessary to justify such burial depths. The outer thrust sheets were buried at temperatures lower than 60°C.

Thermal modeling
The software HeFTy (Ketcham, 2005) was used for thermal modeling, in order to identify the thermal histories compatible with thermochronological data. The results confirm the estimated heating for the single sample, an point to variability in cooling ages and rates along the chain.
Cooling
In the westernmost sector the wedge cooled earlier (between 23 and 12 Ma) and at relatively low rates (0.8°C/Ma). In the Easternmost sector the cooling ages are very uniform (ca. 7-10 Ma) and rates are higher than in the western sector. Finally the youngest (ca. 5-7 Ma) and fastest (11-20°C/Ma) cooling episodes occurred in the central sector of the study area.

Exhumation rates and triggering processes
As in the case of heating and burial, cooling of the wedge mostly depends on its exhumation. Thermal models indicate in most cases steady cooling rates through the AFT and AHe closure temperatures: exhumation rates can be therefore estimated based on crustal thermal structure and cooling rates. Average exhumation rates are 0.4 mm/yr in the westernmost sector; 1.1mm/yr in the central sector, 0.7 mm/yr in the easternmost sector. The three sectors which differ by timing and rates of exhumation also have different topography and structural setting. In the easternmost sector shortening and relief are the highest and exhumation ages and rates are very uniform, suggesting that exhumation occurred during post-thrusting uplift. In the central sector, where the exhumation ages are the youngest and rates are the fastest, shortening and relief are the lowest and several post thrusting normal faults are present, suggesting a major role of extensional denudation in exhumation. The westernmost sector appears as an alternation of heights and lows and exhumation ages are very inhomogeneous: we suggest that the main exhumation phase occurred by erosion during thrusting.

Cooling ages of the source terrains
Since the wedge was buried at temperatures lower than the ZHe Tc, it was also possible to use ZHe dates to constrain the cooling ages of the source terrains of the sediments. The two most numerous ZHe age populations are respectively Alpine and Variscan in age. Sedimentary provenance from the southern margin and basement heights within the Outer Carpathian basin is compatible with such ZHe age distribution.

Conclusions
- Burial of the innermost portions of the accretionary wedge, comprised between 3.6 and 8.6 Km, increases toward the East and it is mainly due to tectonic load. This implies a thickening of the accretionary wedge toward the East.
- Exhumation of the accretionary wedge occurred between the Early and Late Miocene. Three different sectors, characterized by different exhumation timings and rates can be identified. In the
western sector exhumation occurred by erosion of the accretionary wedge during its formation, in
the central sector it mainly occurred by denudation operated by normal faults and in the eastern
sector it was induced by post-thrusting uplift.

- The western and central sector of the study area underwent lower shortening and nonetheless
widespread post thrusting extension, whereas the eastern sector underwent higher shortening and
no post-thrusting extension. We suggest therefore that post thrusting extension is rather related to
plate dynamics rather than to gravitational collapse.

References


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of the Western Carpathian–Pannonian Basin region based on the CELEBRATION 2000 seismic
experiment and gravity modeling. *Tectonophysics*. 475, 454–469
SUMMARY OF ACTIVITY IN THIS YEAR

Courses:

HELLAND-HANSEN W. “Sequence stratigraphy: principles and applications”, Dipartimento di Geoscienze, Università degli Studi di Padova.


ROURE F. short course –“ Formation and deformation of sedimentary basins”; University of Roma Tre.


Posters:


ANDREUCCI, B., ZATTIN, M., MAZZOLI, S., SZANIAWSKI, R., JANKOWSKI, L. Variable thermal histories along the northern Outer Carpathians: new thermochronological and thermal maturity data from Ukraine. EGU General Assembly 2012, Vienna (Austria).

CASTELLUCCIO, A., ANDREUCCI, B., ZATTIN, M., MAZZOLI, S., SZANIAWSKI, R., JANKOWSKI, L. Tectono-thermal evolution of the Polish and Ukrainian Outer Carpathians: interplay between erosion and extensional tectonics within exhumation.

Publications:


Teaching activities:


Field work:

Sampling and structural survey in the Ukrainian Carpathians, 20-27 June 2012.