TECTONOTHERMAL EVOLUTION OF THE CENTRAL-WESTERN CARPATHIANS AND THEIR FORELAND

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Abstract

The Carpathians are one of the main East European targets in oil and gas exploration. Understanding the tectonic evolution and the variation of the thermal regime is crucial for this purpose. Cross-section balancing and sequential restoration integrated with low-temperature thermochronometry (apatite fission track and apatite (U-Th-Sm)/He analysis) can better constrain the burial and exhumation history of this area. Our structural and thermal modelling highlight different timings, exhumation processes and amounts of shortening for the Polish and Ukrainian Carpathians. In the western Polish Carpathians exhumation is coeval with thrusting, starting from the Late Oligocene. The shortening is around 50%, increasing eastwards where post-thrusting exhumation ages, low-angle normal faults and high erosion rates suggest the occurrence of a post-thrusting unroofing phase. On the other hand the Ukrainian Carpathians are characterized by constant amount of shortening (51%) and exhumation controlled by erosion during post-collisional regional uplift.

Introduction

Several open issues about the geodynamic evolution of the Central-Western Carpathians and the increasing interest of some oil companies in the exploration of unconventional resources make the geologic study of this chain very interesting. The Silurian black shales, buried under thousands of meters thick Mesozoic cover and Miocene foreland deposits, are one of the main targets in gas exploration. Cross-section balancing and sequential restoration integrated with low-temperature thermochronometry allow us to constrain the tectonic and thermal evolution of the Central-Western Carpathian thrust and fold belt and their foreland. The sequential restoration provides us all stages of the Carpathian tectonic evolution back to the Upper Cretaceous and the width of the undeformed sedimentary basin. Post-depositional evolution has been constrained by low-T thermochronometry in order to trace the exhumation history. In particular, new data from (U-Th-Sm)/He (AHe) analysis allows us to constrain the timing of the exhumation through the temperatures ranging between 35°-60° (so called Partial Retention Zone). Other thermal indicators from companion projects, such as Apatite Fission Track (AFT) and vitrinite reflectance (R_o) analysis, have been used to constrain respectively the age of cooling through the 60°-120° isotherms (Partial Annealing Zone) and the maximum burial.

Geological setting

The Central-Western Carpathian region includes the Southern Poland, Slovakia and Western Ukraine. This oocline is part of the Alpine orogenic system forming after the collisional event involving the Euro-Asiatic Plate, and the ALCAPA and TIZA-DACIA Microplates. The Permo-Triassic to Jurassic extension is followed by a Late Cretaceous to Upper Miocene compressional phase (i.e, Sandulescu, 1988). The tectonic setting can be subdivided into three different tectonic domains (i.e.,Książkiewicz et al., 1977):

- the Inner Carpathians (IC) made up of allochthonous crystalline pre-Cambrian basement with its Palaeozoic to Mesozoic cover;
- the Pieniny Klippen Belt (PKB), a wildflysch with olistoliths and olistostromes in Upper Cretaceous shaly-sandy matrix, intensely deformed and overlaid by undeformed Paleogene cover;
- the Outer Carpathians (OC) formed by detached Cretaceous to Miocene terrigenous deposits stacked in several thrust sheets.

The pre-Tertiary substratum of the foreland is characterized by the development of elongated NW trending horsts and grabens, filled by thick terrigenous and carbonate Mesozoic deposits on the Variscan basement (Hakenberg, 1980). The Neogene molassic deposits rest on top of the Mesozoic sedimentary cover or directly on the crystalline pre-Cambrian basement.
Methods

Seven balanced cross-sections have been constructed across the Polish and Ukrainian Carpathians during a five months internship at Midland Valley Exploration. All transects have been traced to be parallel to the tectonic transport. Four of them have been sequentially restored by means of the Move 2013.1 software, dedicated to the structural modelling, in order to reconstruct the paleogeographic scenario before the Upper Cretaceous compressional event involving the Inner Carpathians. The algorithms applied to the 2D structural restoration are: flexural slip (that works by unfolding a template and its template-parallel slip system to a horizontal datum), vertical simple shear (applied to listric normal faults), fault parallel flow (used to restore imbricate fan structures). The other cross-sections have been restored applying flexural slip algorithm in order to measure the amount of shortening. Two sequentially restored sections have been then processed with FETKIN at the University of Texas in Austin. FETKIN is a program for forward modelling thermochronological ages on geological cross-sections (Almendral et al., submitted). For a given tectonic scenario, FETKIN calculates the AFT and AHe ages for samples located along the section. Modelled ages are computed from time-temperature histories that result from coupling the modelled kinematics of deformation obtained from Move and Finite Element computation of temperatures. The predicted ages have been compared with new measured AHe ages and low-temperature thermochronometric ages coming from previous studies (Anckiewicz et al., 2012, Andreucci et al., 2013, Mazzoli et al., 2010, Zattin et al., 2011) with good results. A first attempt to join all the cross-sections in a 3D model has been done but it is still a work in progress.

Result

Balanced cross-sections have been constructed along the Western Carpathians arc. The restoration shows a Permo-Triassic to Jurassic intracontinental rifted basin covered by Lower and Upper Cretaceous deposits. The thickness of the post-thrusting deposits increases southwards, in the N-S oriented cross-sections, and south-westwards in the NE-SW oriented ones. The compression starts during the Late Cretaceous in the IC with the reverse activation of normal faults cutting through the basement. The emplacement of these thrust units leads the underplate to flexure and the creation of accommodation space in the frontal part of the IC arc. This space is filled up with olistoliths and olistostromes coming from the eroded Inner Carpathians Mesozoic nappes and then covered by Paleogene deposits. The so formed “Pieniny wildflysch” is stacked on top of the outer tectonic units during the Oligocene, when the Podhale Basin starts forming as wedge-top basin on the IC successions. According to Nemcok et al., 2006, thrusting lasts till the Lower Miocene in the western part of the Polish Carpathians and till the Middle Miocene in the Ukrainian region. The compression affects the Cretaceous to Paleocene successions belonging to the OC basin during the Oligocene. Then it starts involving also the basement reactivating some normal faults in reverse sense of motion. The accretionary wedge is affected by normal faulting even during the last stage of the orogenesis. High-angle normal faults occur in the Western Polish Carpathians, whereas low-angle normal faults affect only the Eastern region. In the Ukrainian Outer Carpathians extensional tectonics is missing and the main post-thrusting structures are essentially strike-slip faults. This tectonic scenario is confirmed by the predicted thermochronometric ages obtained processing the restored cross-sections with FETKIN. The processing provided good results especially for the section across the Western Polish Carpathians where the predicted ages fit the measured ones. In this case the tectonic and thermal modelling confirm the occurrence of syn-thrusting erosion controlling the exhumation process. The thermal modelling shows that the foreland and the outermost tectonic units of the Outer Carpathians are not reset, as well as part of the Podhale Basin and the Oligocene basin south of the Sub-Tatra fault. The inner part of the Outer Carpathians is characterized by cooling ages ranging between 25 and 10 Ma (AFT ages) getting younger in correspondence of the Oligocene deposits of the Podhale Basin and Tatra Mts. (9-13 Ma). The AHe ages range from 15 Ma in the Outer Carpathians, to 9-5 Ma in the Podhale Basin and Tatra Mts region.
Discussion

The integration of structural and thermal modelling allows us to understand the evolution of the Central-Western Carpathians and their foreland. The structures of the Carpathian chain are strongly controlled by the morphology of the basement and the thickness of the post-rifting successions. The reactivation of deep basement normal faults in reverse sense of motion produces the imbrication of the basement in the Inner Carpathian region. The erosion of the Mesozoic basement cover and the sedimentation of the resulting olistoliths and olistostromes in the Upper Cretaceous matrix, produces the Pieniny wildflysch north of the IC belt.

The PKB has been interpreted for years as suture zone of an ancient ocean (Birkenmajer, 1955). Roca et al, 1995, have been one of the first authors suggesting the lack of an oceanic crust between the IC and OC domains, without providing a clear tectonic scenario to explain the role of the PKB in the Carpathians orogenesis. According to our model the PKB is the foreland basin of the IC arc since there is no outcropping oceanic crust.

A combination of thin and thick skinned tectonics can be applied to explain the structures of the OC. The compression starts involving the OC successions during the Eocene and then during the Miocene it starts reactivating the normal faults cutting through the basement.

The shortening recorded for the Polish Carpathians is around 46% in the Westernmost sector, increasing up to 59% in the Easter part. On the other hand, the Ukrainian Carpathians are characterised by a constant shortening, around 51% along all the chain. These three area are different also in term of exhumation processes. The Western Polish Carpathians exhumation is controlled by erosion coeval with thrusting whereas the Eastern sector is characterised by a more rapid cooling rate controlled by low-angle normal faulting (Andreucci et al., 2013). The lack of normal faults in the Ukrainian sector suggests the occurrence of a post thrusting erosional phase during the Upper Miocene.

Future work

Next year will be dedicated to the thermal testing of some of the sequentially restored sections, especially across the Ukrainian Carpathians, and the integration of thermochronometric data. This work will be carried out in collaboration with some researchers from University of Roma Tre and ENI.

References


ANCZKIEWICZ,A., A., ŚRODOŃ, J., and ZATTIN, M. 2013 Thermal history of the Podhale Basin in the internal Western Carpathians from the perspective of apatite fission track analyses. Geologica Carpathica, 64, 2, 141—151.


SUMMARY OF ACTIVITY IN THIS YEAR

Courses:

R. J ANGEL: “Scientific communication”, Department of Geosciences, University of Padua.
M. KEEN: “Advanced Sequence Stratigraphy”, University of Glasgow.
R. BROWN: “Structural Geology”, University of Glasgow.
MOLNAR P.: “Geodynamics of mountain buildings and its interaction with climate” University of Roma 3

Communications:


Posters:


CASTELUCCIO, A., ANDREUCCI, B., JANKOWSKI, L., KETCHAM, R., A., MAZZOLI, S., SZANIAWSKI, R., and ZATTIN, M., Coupling low-temperature thermochronometry and sequential restoration of balanced cross-sections: new constraints on the tectonic evolution of the Western Carpathians (Poland, Slovakia and Ukraine). GSA 2013: 125th Anniversary Annual Meeting and Expo, 26th-30th October, Denver, Colorado (USA)

Publications:


Other:

January-June: Internship at Midland Valley Exploration, Glasgow (UK);
June 22nd-29th: fieldwork in the Holy Cross Mountains, Poland;
September 14th-30th: Visiting period at Jackson school of Geosciences, University of Texas, Austin (TX).