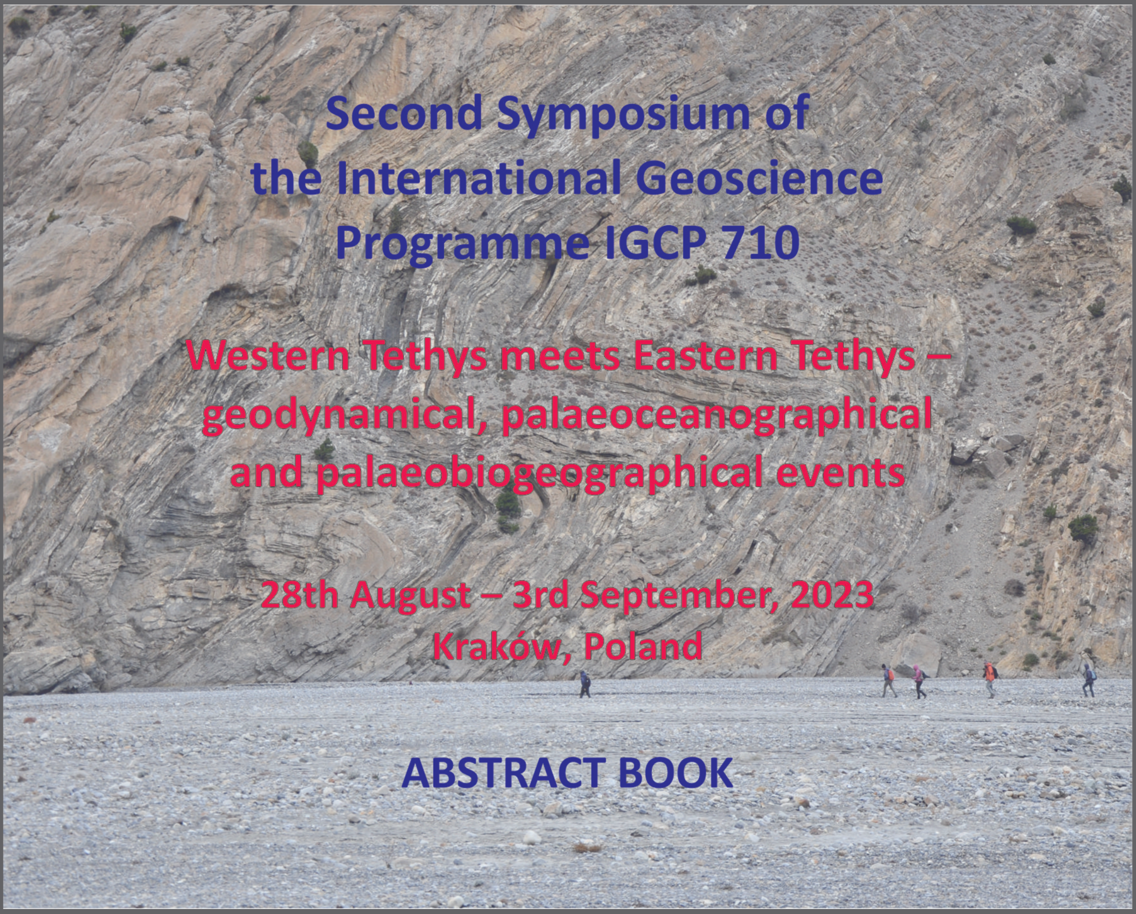
GeoTOURISM

GEOTURYSTYKA



Second Symposium of the International Geoscience Programme IGCP 710

Western Tethys meets Eastern Tethys – geodynamical, palaeoceanographical and palaeobiogeographical events

28th August – 3rd September, 2023
Kraków, Poland

ABSTRACT BOOK

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AGH University of Krakow

Volume 20 2023 Issue 1–2 (72–73)

Project 710
IUGS UNESCO IGCP
Western Tethys meets Eastern Tethys

UNESCO
United Nations
Educational, Scientific and
Cultural Organization

Dear Tethyan Friends,

We are glad that we can meet personally during the 2nd Symposium of the IGCP 710 Project, after the pandemic time, which disrupted our idea of regular, annual meetings. After the 1st virtual meeting during the autumn of 2021, we have now the chance to discuss face to face and go to the field together to touch „Tethyan" rocks for a better understanding of what happened hundreds/decades of millions years ago in our lovely ancient ocean. As you know, through your knowledge and experience, the Tethyan Ocean history, both in its western and eastern parts, is fascinating, but enigmatic from time to time, to say the least.

Generally, the geological history of the Tethys Ocean is broadly established. Yet many details are still unknown and many major questions remain, related to geotectonics, palaeogeography, palaeoceanography and palaeobiogeography. Improved understanding of the Mesozoic-Cenozoic ocean/climate history is based on accurate reconstruction of the distribution of continents and ocean basins and on opening and closing of seaways along the Tethys. There is little or no agreement about the number or size of separate basins, nor on their space-time relationships. Moreover, there is no consensus on the number and location of former micro-continents and on their incorporation into the present-day Eurasian-Mountain Belt. Geologists studying individual parts of these belts have been educated within different geological systems and adhere to different geological paradigms. Correlation between Western and Eastern Tethys is difficult, not only because of the large distances involved, but also because they are separated by the area of the huge Himalayan collision within which much of the pre-Paleogene tectonostratigraphic information has been lost. The aim of this IGCP project is to bring together geologists from the western and eastern parts of the former Tethys (Morocco/Iberia–SE Asia) to establish a common framework and a common tectonostratigraphic concept (latest Paleozoic–Mesozoic with emphasis on Permian–Jurassic).

On the one hand, UNESCO forms a special umbrella for the IGCP Projects, and on the other hand, it has been very active in supporting the ideas of "geoparks" and "geotourism" for years. For this reason, we decided to use an international magazine – *Geotourism* – to print our materials, both abstracts and a field trip guidebook. We hope it will be useful for both Tethyan friends and geotourism enthusiasts.

Enjoy Krakow during the stationary part of the Symposium and the Polish-Slovak-Czech Carpathians during a 5-day field trip!!

Michał Krobicki

IUGS
International Union of Geological Sciences

Ministerstwo
Edukacji i Nauki

Wydział Geologii, Geofizyki
i Ochrony Środowiska

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The articles published in “Geotourism” have been given a favorable opinion by the reviewers designated by the editorial board.

Cover photo: Folded Jurassic limestone layers of the Tethyan Sedimentary Sequence, outcropped along the Kali Gandaki valley, Nepal
Back cover photo: Dhaulagiri (8,167 m) and Tukuche (6,920 m) peaks in the Himalayas, view from Muktinath, Nepal

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Geodynamics of the Eurasian and Africa–Arabian collision zone as exemplified by the Black Sea–Caspian Sea region

Shota Adamia, Nino Sadradze*, Alexander Chabukiani,
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The lithosphere structure and geological evolution of the Caucasus and adjacent areas is determined by its position in the continental collision zone between the Eurasian and African-Arabian lithosphere plates, where convergence is still on-going at average rate of movement 10–30 mm/per year. The region located in the central part of the collision zone represents the lithosphere fragments collage of the Tethys Ocean and its continental margins. Within this area the system of island arcs, intra- and back arc bsins existed during Neoproterozoic–Early Cenozoic. Supra-subduction, mid-ocean ridges and within plate magmatic activity took place during Paleozoic–Early Cenozoic. In Late Cenozoic closure of the oceanic and backarc basins took place followed by the continent-continent collision, topography inversion and formation of modern structures in the region (Adamia *et al*., 1981, 2017; Dercourt *et al*., 1986). During the pre-collision stage there were not two, but three Tethys branches. The third of them is Van-Khoi oceanic branch. Number of palaeo-subduction zones (two or three?) is still debatable within the academic community. One research group (e.g. Sosson et al., 2010; Barrier *et al*., 2018) admits existence of two subduction zones: Peri-Arabian and Ankara-Erzincan-Sevan-Zangezur zones, whilst another group including the abstract authors refer to the presence of three subduction zones and aside from abovementioned zones consider the presence of the Khoy Ocean and third subduction zone related to one of the Neotethys branches (Adamia *et al*., 1981, 2017; Dercour *et al*., 1986; Stampfli, 2001).

According to Adamia *et al*. (1981, 2017), Dercourt *et al*. (1986), Daralogöz-South Armenian block and Nakhchevan (SAB) in the Late Paleozoic–Mesozoic–Early Cenozoic represent the part of the Iranian but not the Anatolian Microcontinent.

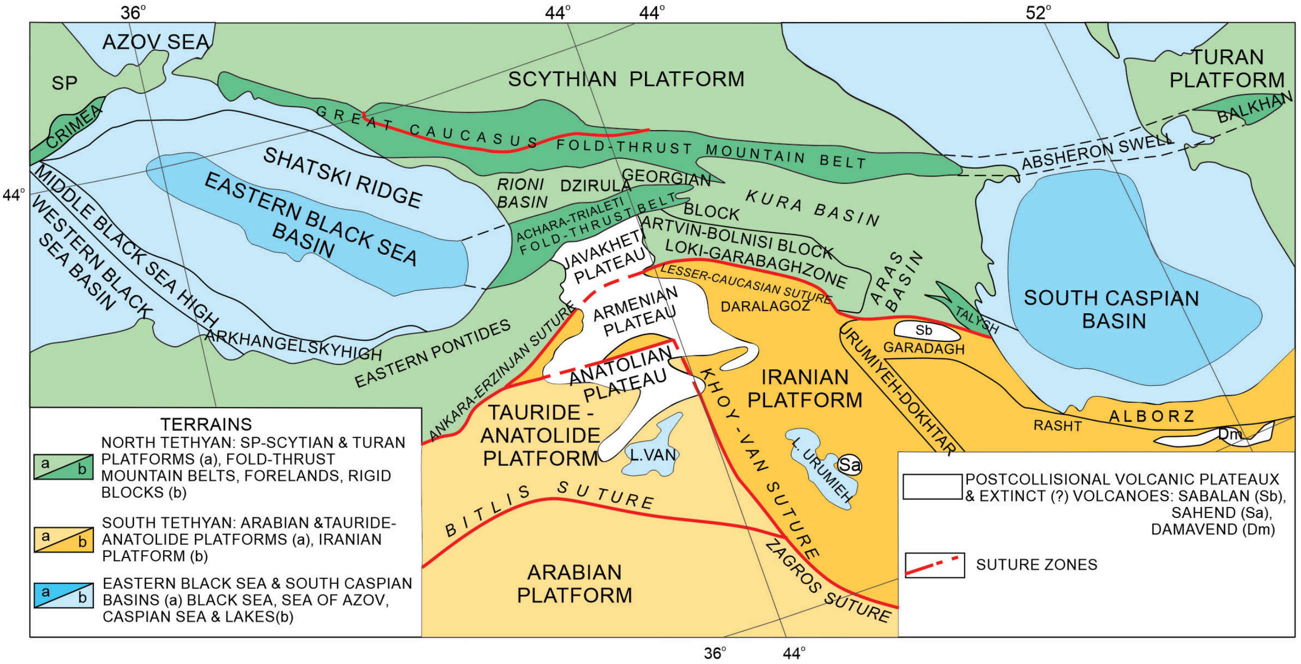

Fig. 1. The correlation map of the main tectonic units of the Caucasus and adjacent areas (Adamia *et al*., 2017)

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Remnant Neo-Tethyan ocean from the Ladakh Himalaya: constraints on their nature, age and tectonic setting

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The Indus and Shyok Suture Zones represent the remnants of the Neo-Tethyan ocean in terms of Nidar arc volcanics and Zildat ophiolitic melange in the eastern Ladakh, Dras Arc volcanics and Shergol ophiolitic melange in the western Ladakh along the Indus Suture Zone. The Shyok-Nubra ophiolitic volcanics of the northern Shyok suture zone, north of the Ladakh batholith, represent the remnant northern portion of the Neo-Tethyan. The Nidar-Dras arc volcanics represent intra oceanic arc that developed as the Indian plate was moving northwards around 140 My ago. These units preserve arc tholeiite, representing primitive arc which passed on to calc alkaline series as the arc matured. These rocks are characterised by depleted nature in terms of incompatible trace elements including rare earth elements and Sm-Nd isotopic characteristics. The Zildat-Shergol ophiolitic melanges are represented by N-MORB and Ocean Island Basalt (OIB) characteristics. These units have also preserved exotic blocks of limestone, physically mixed with other units of the ophiolitic melange.

The Shyok-Nubra volcanics are represented by enriched trace elements and isotopic characteristics, very different from those of the Indus Suture zone. They don't preserve ophiolitic melange, as observed in the Indus suture zone. Our tectonic model indicate double subduction of the Neo-Tethyan ocean, in the north it got subducted under the Tibetan plate giving rise to Andean type continental arc along the Shyok suture zone. In the south the Neo-Tethyan ocean got subducted under the same oceanic crust giving rise the intra-oceanic Mariana type subduction.

Thus, in the Ladakh Himalaya there is preservation of almost all components of the Neo-Tethyan ocean preserving the N-MORB and OIB type magmatism in the melange zone. The Andean and Mariana type arc components indicating very different tectonic settings. Neo-Tethyan ocean appear to have all the components that we observe presently in the Pacific-Atlantic ocean. These data will be presented and elaborated during my presentation.

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Successive dispersion, amalgamation and accretion of terranes of Myanmar from the Gondwana

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Myanmar represents an evolving continent of two crustal formation histories consisting of the Burma plate and the Indochina plate. The Burma plate (western part of Myanmar) consists of three distinct lithotectonic entities: 1) a continental fragment, 2) a subduction-related accreted complex (Neo-Tethys suture zone) in the westernmost part of Myanmar and 3) a coastal area. Eastern Myanmar that is western continuation of Indochina plate is composed of three tectonostratigraphic terranes: 1) Shan boundary belt (Meso-Tethys suture zone) in the western edge of Indochina plate, 2) Sibumasu terrane, 3) the Than Lwin Belt (Paleo-Tethys suture zone) in the easternmost part of Myanmar. The Than Lwin Belt is a tectonic linkage between Inthanon Zone of West Thailand in the south and Changning-Menglian belt of West Yunnan in the north (Aung, 2009). Shan Boundary Belt of Meso-Tethys suture in the western edge of Indochina plate extend to the south to Malay Peninsula. The Rakhine Western Ranges of Neo-Tethys suture at the westernmost part of Myanmar is a northern continuation of Andaman-Nicobar belt. Story of the Tethys is the story of extinctions of sea and telling that story was learned from clues in rocks and fossils. Biostratigraphic correlation between the known distribution of dominant Mesozoic representatives of *Monotis*, *Halobia*, and *Daonella* fauna and microfossil assemblages of Triassic age from Myanmar are made with those from neighboring countries of SE Asia for reconstruction of tectonic terranes for Myanmar. The terranes in Myanmar may have originated in Gondwana in Paleozoic (Figs 1, 2). The accretionary episodes which ended in early Tertiary, have been followed by post-accretionary deformation of strike- slip faulting of the Sagaing Fault in Myanmar; West Andaman Fault and Sumatra Fault System in Sumatra; and spreading in Andaman back-arc basin. To reconstruct the palaeogeography of Myanmar terranes distribution of Mesozoic representatives of *Monotis*, *Halobia*, and *Daonella* faunas and Tethyan fusulinids are used. Various species of thin-shelled pectinacid bivalves of Triassic faunas are dominant family and occur in open-marine strata of allochthonous accretionary terranes. These strata are related to different parts of single ocean: Tethys, palaeoequatorial ocean populated by these faunas containing Tethyan fusulinids. Their occurrences in mudstones, sandstones, shale and limestone are very important for Triassic sedimentary succession as diagnostic fossils. Distribution of these faunas and biogeographic studies are an importance in reconstructing post-Triassic intraoceanic plate boundaries and motion. Distribution of these faunas in Triassic marine strata of Shan Massif and correlation with those of neighboring terranes of Asia gave the evidences that Shan Massif was a part of Gondwana in Carboniferous-Permian time facing Paleo-Tethys Ocean. Shan Massif probably separated from Gondwana in Early Triassic time and moved northward from equatorial position. Ophiolites thrusted onto Mesozoic sequences of *Halobia* shales in pre-Middle Eocene (Rangin, 1996–1999). Their position above the metasedimentary rocks is similar to the *Halobia* shales of Sumatra which also lies on top of metasedimentary rocks of Permo-Carboniferous Sequences (Bender, 1983). All the Tertiary sequences of Central Myanmar Basin are considered to be deposited on the underlying Burma plate as basement. Initial collision between India and Burma plate in middle Eocene (45–35-Ma) and hard collision during Oligocene to Miocene (23 Ma) and Rakhine Western Ranges became uplifted during Middle Miocene to Late Miocene (Curray, 2005) by thrusting the remnants of NeoTethys sea floor and trench deposits to become Rakhine accretionnary wedge and ophiolites belt at the western part of Burma plate.

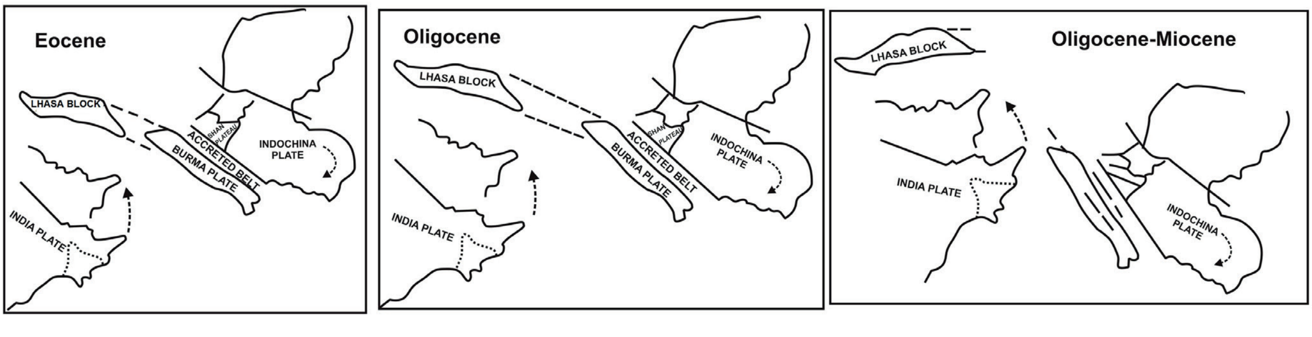

Fig. 1. Successive dispersion, amalgamation and accretion of tectonic terranes from Gondwana to the major continent in NE

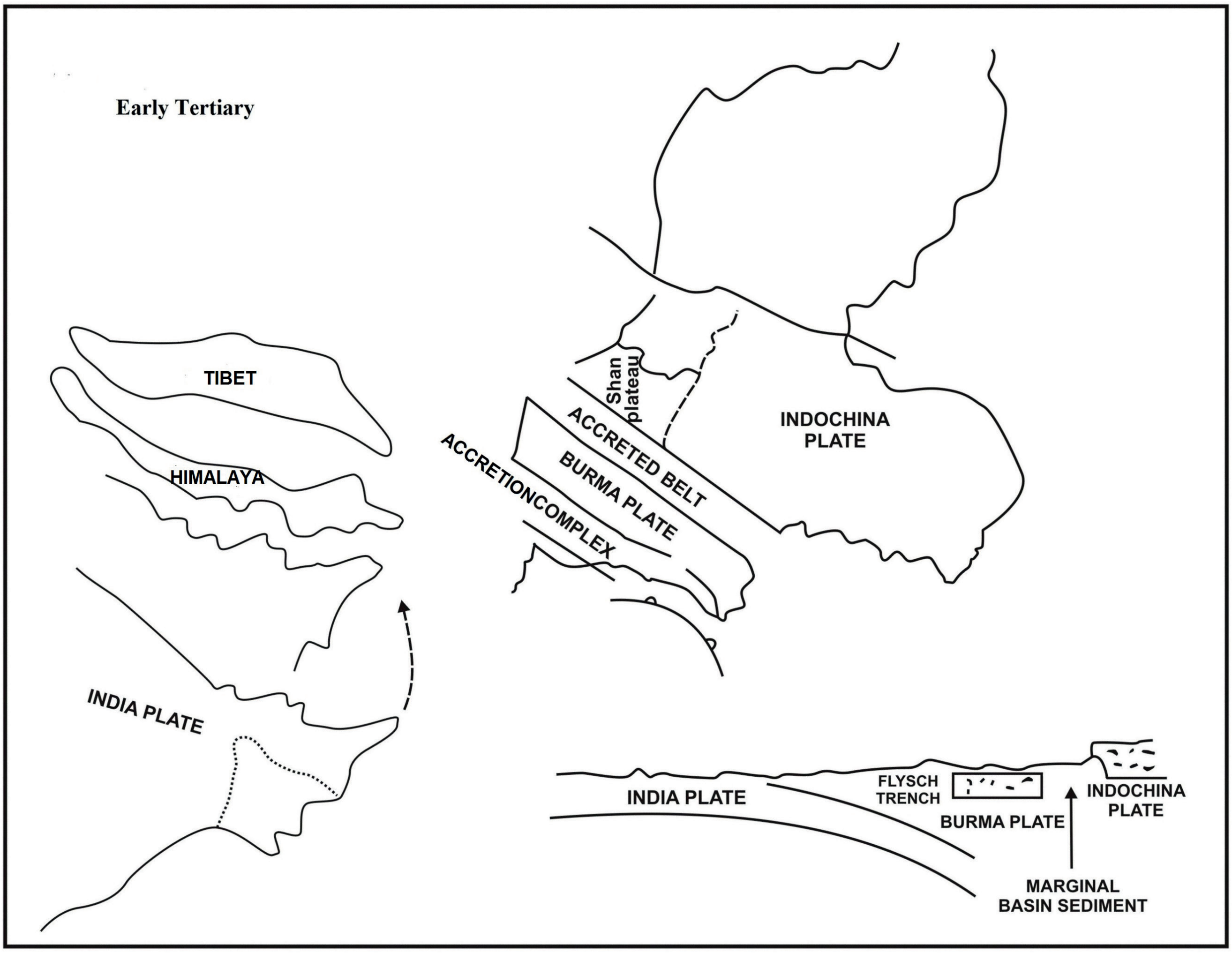

Fig. 2. Schematic representation of accretionary evolution of India plate and Burma plate in Early Tertiary

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The occurrence of Capitanian fusulinoidean fauna and giant bivalve Alatoconchidae from Khao Khwang Formation, Central Thailand

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Khao Khwang Formation is widely distributed in central Thailand. It is represented by Late Pennsylvanian to Middle Permian thick-bedded limestone with chert nodules. Rock samples belonging to this formation have been collected. They are light to dark grey, thick-bedded to massive limestone with black nodular cherts. The abundant and extraordinarily gigantic bivalve Alatoconchidae together with fusulinoidean fauna (*Verbeekina verbeeki*, *Colania douvillei* and *Pseudodoliolina pseudolepida*), fragments of coral, ammonoid, brachiopod, sponge, gastropod, etc. were observed. Based on the characteristic fusulinoidean fauna, it indicates Capitanian in age. Microscopically, limestone samples were classified as bioclastic rudstone and packstone. The detailed lithologic and carbonate microfacies observations, Alatoconchidae beds, deposited parallel to the bedding plane and related with oncoids and microbial, are autochthonous in shallow marine. Condensed accumulation of other fossil fragments found in the study areas might be transported by gravity flow.

Coevolution of Paleo-Tethys and Rheic: New tectonic constraints from Iran and Turkey

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In the Paleozoic, one large ocean once separated the Eurasia of the north and the Gondwana of the south, but it has two names, Paleo-Tethys and Rheic, suggesting different tectonic history. The Paleo-Tethys represent the ocean from east Asia to Middle East regions and vanished in Early Mesozoic, while the Rheic existed across the Europe and finally closed in Carboniferous. The two oceans coevolved for a long time, but the interaction and mutual effect at subduction and collision stages are not well understood. Initiation processes of ocean spreading, subduction and collision are crucial in plate tectonics, so resolving the timing for these turning points may greatly enhanced the precision and accuracy of reconstruction of the two oceans, especially for the western Paleo-Tethys.

In NE Iran, we find that all the Paleozoic clastic rocks record two major zircon U-Pb age groups peaked at ~800 Ma and ~600 Ma. Consistency in age patterns show a dominant provenance from Neoproterozoic basement of the north Gondwana and a long-lasting passive margin sedimentation after the spreading of the Paleo-Tethys. This environment was interrupted by initial collision between the Turan (Eurasia) and Central Iran (Gondwana) Blocks with massive coarse clastic deposition, i.e. the protolith of the Mashhad Phyllite, in a peripheral foreland basin on the Paleozoic passive margin. The Mashhad Phyllite yields a striking provenance change from passive margin to active margin. The Paleozoic ages reveal a long-lived subduction zone at the south Turan Block initiated since the latest Ordovician. More importantly, the provenance shift better constrains the initial collision timing with the maximum deposition age of the Mashhad Phyllite (~228 Ma) refining the evolution history of Paleo-Tethys.

Based on our new results and previous data, we compare the tectonic history of the Paleo-Tethys in its western segment with eastern Rheic, and further discuss the interaction between the Rheic and Paleo-Tethys. We find existence of a lateral subduction zone plays a crucial rule in initiating new subduction zone after an old oceanic plate vanishes and two continents collides, while a lateral collision can also result into shallowing of subducted slab and preservation of coeval compressional structures. These new insights help us to better interpret the emplacement of high-pressure metamorphic rocks during subduction and subduction zone jump when the Rheic and Paleo-Tethys coevolved.

Detrital zircon populations in Ediacaran Period sediments distinguish active from passive continent margins even when metamorphosed and help resolve the Gondwana-Panotia supercontinent/megacontinent argument

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Great thicknesses of sand and greywacke were deposited on the margins of megacontinents during the Ediacaran Period (620–542 Ma). Zircon age populations in sediments with long deep-time flat profiles distinguish passive margin sedimentation from shorter humped zircon profiles characteristic of sediments derived from volcanic arcs and their feeder zones in active margins.

An example of a single hump detrital profile is given by an Ediacaran Period volcano present in the Charnian Supergroup in the Anglo-Brabant Massif of the East Avalonia terrane. This Gondwana fragment was originally part of the West Africa craton and was subsequently accreted to Laurentia. A volcanic complex with sediments carrying an Ediacaran biota is overlain by Triassic sediments. The main phase of eruption at c. 561 Ma provides a single hump zircon age histogram with a few pre-eruption zircon xenocrysts up to 40 Ma older.

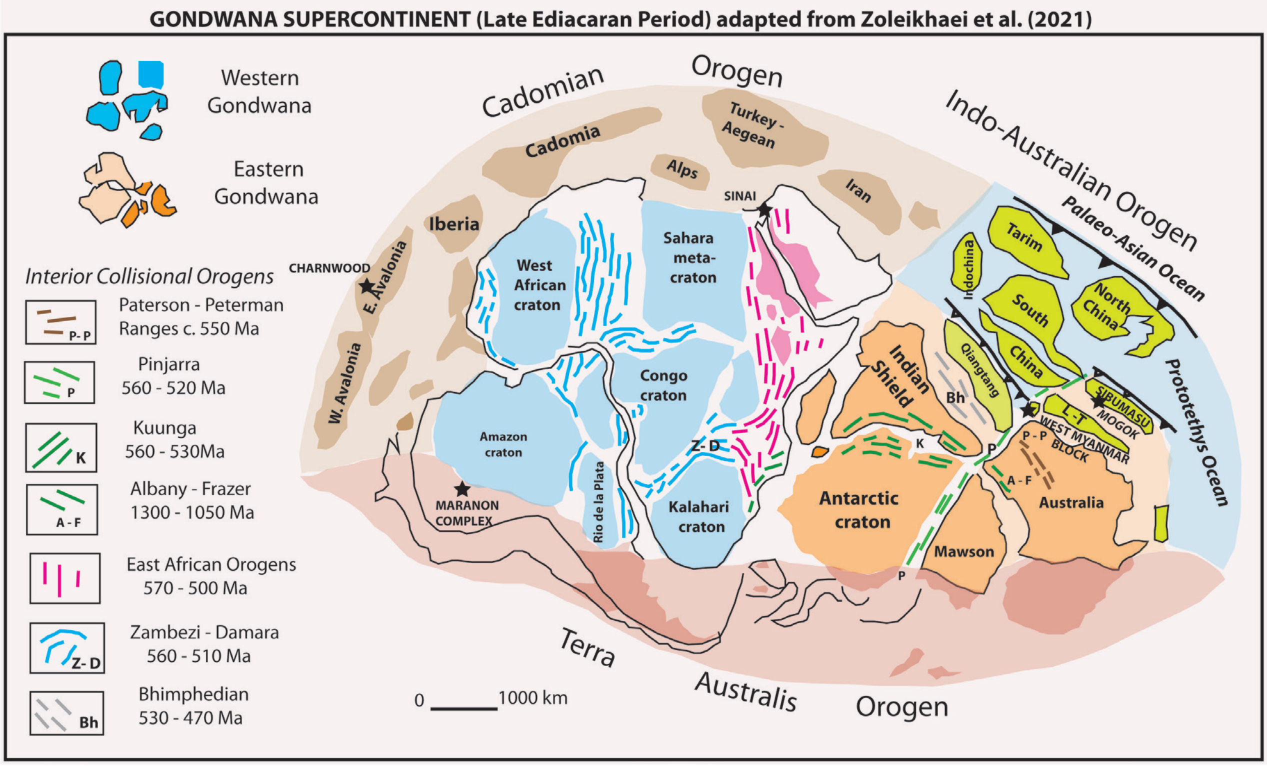

Fig. 1. Gondwana supercontinent (Late Ediacaran Period) (adapted from Zolekhaei *et al.*, 2021)

There are many examples of successive episodes of volcanicity on the margin of Gondwana during the Neoproterozoic. In the Marañon Complex of Peru on the western Proto-Andean margin of the Amazonia block there were volcanic episodes between 880–750 Ma and 615–550 Ma. During the early Ediacaran Period Laurentia was attached briefly to Amazonia-Gondwana megacontinent to form the Panotia supercontinent. The time of the breakup is disputed but as eastern Laurentia had a passive margin until c. 600 Ma, it appears to have split from Amazonia-Gondwana c. 880 Ma, in a rift-drift scenario that resembles that in the Permian when Sibumasu broke from the Gondwana supercontinent.

In the Myanmar area of Sibumasu thick Ediacaran Period clastic sediments on the Shan Plateau are known as the Chaung Magyi Group which transitions into the Cambrian and also is present in both the high- and low-grade metamorphic zones of the Mogok Metamorphic Belt (MMB). In the granulite-facies area of the MMB detrital zircons are rare except in simple mineralogy metasediments like in a psammitic gneiss west of Mogok town. Detrital zircons of dacitic and granitic composition are preserved as nuclei to the c. 180–20 Ma metamorphic zircons. The youngest magmatic single zircon was 514 Ma together with zircons from magma suites of which the most numerous were 965–910 Ma and 1100 Ma in age. A few older xenocryst zircons which were either magmatic zircons derived from trans-crustal magma systems or zircons transported from the weathering of Proterozoic igneous rocks in the interior of East Gondwana. The Mogok magmatic zircon suites can be matched with granitic plutons in the area such as the c. 500 Ma Tawnpeng batholith from which K-Ar ages of c. 980 and c. 830 Ma are known indicating that trans-crustal magmatism was active during the Neoproterozoic in this part of the former Gondwana margin.

In the MMB of Myanmar the magmatism associated with the subduction of Prototethys ceased around c. 510 Ma when the South China megacontinent collided with Gondwana in the Indo-Australia accretion orogeny. Neoproterozoic zircon suites in sediments from Myanmar-Sibumasu, Lhasa-Tenchong and the Tethyan Himalaya indicate that terranes on the margins of East and West Gondwana had similar magmatic histories and the volcanic arcs were continuous rather than inboard of each other as has been suggested.

The recently described Ediacaran Period detrital zircon data from the West Myanmar Block place this small block on the Gondwana margin somewhere between Lhasa and Sibumasu. However the Cambrian metasediments in the Naga Metamorphics and in the Katha and Kumon ranges provide a challenge in interpretation. The Katha-Kumon area recently has been suggested either to be a part of the Tethyan Himalaya sequence of India that was thrust onto the West Myanmar Block or the Katha-Kumon Ranges are a faulted slice of Sibumasu. Examination of their detrital zircon profiles alternatively suggests that these Cambrian metasediments in fact are basal units in the West Myanmar Block sediment sequence.

Refrerences

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Volcanism and sedimentation in the Paleogene Alpine peripheral basins: how did Alps look like?

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All the Paleogene represents a key period in the growth of the Alpine belt and the development of surrounding sedimentary basins. Nevertheless, one of the most intriguing timelapse is represented by 10 Ma, between ca. 40 and ca. 30 Ma, when the growing belt hosted volcanic complexes that lead to the accumulation of volcanogenic sequences within the Northern Alpine and the Southern Alpine foreland basins. Such sequences present peculiar characteristics that varies depending on the period and depocenter where they where accumulated. In addition, they represent the fundamental clue to reconstruct how the volcanic arc developed, which kind of volcanic activity characterized it, where the volcanoes were located and to speculate about how magmatism was produced before coming to the surface. Volcanic sequences are, in fact, extremely rare and confined to the west of the chain, disarticulated from the source-to-sink systems that supplied detritus to the depocenters, together with dikes crosscutting the southern part of the belt, so less is the geodynamic information gain from them. The present talk will review a decade of investigation carried out on stratigraphic, petrographic and geochemical data on the different volcanogenic sequences, trying to reconstruct the relationship between putative volcanic centers and the basins, as well as to understand the nature of the Paleocene volcanic arc/arcs. All the considered sequences are characterized by large amounts of volcanogenic detritus, and sometimes they rarely preserve pyroclastic deposits. Occasionally, such sequences are also mixed with non-volcanic detritus, a component useful in tracing provenance of sediments and giving clues about palaeoenvironments constituting the growing belt. Although beyond of being exhaustive, the present communication represents a first attempt in marking fundamental temporal and palaeogeographic steps in the evolution of a volcanic arc through several millions of years on one of the most fascinating orogenic belt.

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Rifting and closure of two branches of the Tethys; from Neotethys to Alpine Tethys

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The western termination of the Neotethys is marked by a complex interaction of several small oceanic basins which were formed and closed progressively. The western end of the Neotethys was opened from Permian to Middle Triassic; spreading started from Anisian. The rifting was associated with acidic, sometimes basic magmatism; Permian intrusions are widespear in certain zones (Eastern Alps), and together with Middle Triassic volcanites, played a role in weakening of the extending continental lithosphere.

The rifting process was interacting with evaporite tectonism in regions where Late Permian evaporites were formed potentially as a post-rift or intra-rift stage. Due to loading of the ovelying Early Triassic clastic-carbonate ramp sequence, and the still ongoing extensional deformation, and/or gravitational sliding of shelf domains toward deepening extended continental margin, salt tectonics probably started in latest Early Triassic. The uprising salt walls strongly influenced shelf and eventually slope deposition; the minibasins between salt walls often hosted carbonate ramp or platform development while collapsing salt structures could turn to deep “intra-platform” basins. The salt tectonics controlled the continuing facies differentiation during the Late Triassic. The development of salt-cored normal faults are not characteristic for a typical post-rift passive margin, but due to their relation to underlying salt, facies differentiation was maintained.

The earliest sign of rifting of the Alpine Tethys can be seen in the Late Triassic deep grabens (Southern Alps, southern Transdanubian Range). This is the reason that separation of salt-related deformation, and crustal extension is not evident in some zones. The closure of the Neotethys started with intra-oceanic subduction, probably with a double polarity, and the formation of a supra-subductional new oceanic lithosphere (the Vardar zone in some interpretations). The age of this process is somewhat controversial in different models. Isotopic ages of metamorphic sole of the Vardar ophiolites suggest 175–170 Ma while neutral to acidic differentiates in the eastern Vardar testify ongoing Late Jurassic oceanic magmatism (~155–155 Ma). A complex system of melange was formed under and in front of the emplacing upper plate Vardar ophiolite. While sub-ophiolitic melange with serpentinitic matrix formed below the overlying hot oceanic lithosphere, the sediment-hosted melange contains blocks from different zones of the passive margin and partly the overlying ophiolite. Stratigraphic ages indicate that this processes happend during the Middle and Late Jurassic. The obduction happened in latest Jurassic (Tithonian) indicated by reef limestone on top of ophiolites. This was followed by the imbrication of the underlying passive margine Adriatic continental lithospere during the entire Cretaceous and Cenozoic. Clastic foreland basins were formed within this lower plate supplied partly by the passive upper plate ophiolite.

The Alpine Tethys went on intensive rifting which ended with break-up in late Middle or in the Late Jurassic on its southern Piemont-Ligurian branch. The onset of subduction is not exactly clear but could happen in the Late Cretaceous resulted in high-pressure metamorphism of the oceanic domains in the Eocene (Tauern window). The Transdanubian Range of Hungary was situated between the two oceanic domains during the whole Mesozoic. While this unit has not been buried and only deformed modestly, the sedimentary events reflect the complex evolution. Middle Triassic rifting resulted in disruption of Early Triassic mixed siliciclastic-carbonate ramp into platform and somewhat deeper grabens. Small-scale synsedimentary faults and neptunian dykes testify this phase. Away from the break-up zone, the area underwent important post-rift subsidence compensated by platform carbonate sedimentation through the Late Triassic. However, the trace of initial Late Triassic rifting is present in forms of synsedimentary faults in the western side, closer to the future Neotethys. Following the earliest Jurassic decline of platform biota, the ongoing Alpine rifting disintegrated the entire TR carbonate platform into shallower, sediment free ridges and somewhat deeper grabens. This rifting and subsidence resulted in deposition of pelagic red nodular limestone in the Aalenian-Bajocian. After cherty sedimentation in the Callovian–Oxfordian, very modest extension appeared in the latest Jurassic. Although this phase could be considered as the final extension of the Alpine Tethys rifting far to the west, it is more probable that in fact this is due to slight downbending of the TR below the distal ophiolite emplacement to the east. The Neotethyan influence prevaild in the eastern TR during the Early Cretaceous. A clastic foreland basin was supplied by ophiolite and supra-ophiolite detritus of the obducted Neotethyan Vardar unit.

Structural cituation changed in the late Early Cretacoues, around 115 Ma (Albian). The entire TR underwent shortening. The unit, formerly the lower plate of the Neotethyan system, was emplaced, as the highest nappe, on to the other continental units of the Austroalpine system. Within the Eastern Alps, this was associated with intracontinental subduction initiated in zone of Permian magmatism having thermally weakened the lithosphere. The relationship of this subduction, and associated high to ultrahigh pressure metamorphism is not clear, but eventually could have connected to large-scale displacement of the Neotethyan subduction zone at its northernmost termination zone. The complete change of the TR, from lowermost position to upper plate, is the reflection of complex 3D geometry of overlapping oceanic domains and could happen in other Tethyan areas.

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Mesozoic tectonostratigraphy of the Western Tethys Realm – a review

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The Mesozoic sedimentary sequences in the Western Tethys Realm are incorporated in different mountain ranges, most of them located in the eastern Mediterranean area (Eastern and Southern Alps; Western, Eastern and Southern Carpathians; Dinarides, Albanides, Hellenides; units in the Pannonian realm: Pelso, Tisza), others are located to the west (e.g. the Apennine and the Betic Cordillera) These mountain ranges were formed since the Jurassic and experienced in parts polyphase mountain building processes and deformation, lasting until today. Therefore, the tectonostratigraphic evolution of the different Wilson cycles are in cases hard to assign to a specific cycle, because the evolution of the different Wilson cycles is overlapping. This resulted in contrasting palaeogeographic reconstructions and controversial regional tectonic interpretations.

In general, two different Wilson cycles can be distinguished. The older Wilson cycle reflect the geodynamic history of the Neo-Tethys (Meliata-Hallstatt, Maliac, Vardar, Pindos/Mirdita/Dinaridic oceans in other nomenclature), and the formed orogen is part of the Tethysides with following evolution as documented in the sedimentary record of the wider Adria plate:

- A Late Permian to Middle Anisian rift (graben) stadium with sedimentation of siliciclastics and carbonate ramp deposits in an epicontinental sea.
- A Middle Anisian to Middle Jurassic passive margin evolution after the late Middle Anisian oceanic break-up: a) The complex Middle to Late Triassic shallow- to deep-water carbonate platform evolution from the inner shelf (platform facies) to the outer shelf (open-marine basinal facies), and b) the Early to Middle Jurassic pelagic platform evolution.
- A Middle to Late Jurassic convergent tectonic regime triggered by ophiolite obduction (“active continental margin evolution”) with the interplay of thrusting, trench and trench-like basin formation, mass movements, and the onset and growth of carbonate platforms, followed by latest Jurassic to Early Cretaceous mountain uplift and unroofing.
- Final closure of the remaining open part of the Neo-Tethys (= Vardar Ocean) in Late Cretaceous to Paleogene times.

The younger Wilson cycle reflect the geodynamic history of the Alpine Atlantic (Ligurian, Piemont, Pennine, Vah, Alpine Tethys oceans in other nomenclature), and the formed orogen is part of the Alpides with following evolution as documented in the sedimentary record of the wider Adria plate:

- An Early Jurassic (Hettangian to Toarcian) rift (graben) stadium with sedimentation of fully marine deposits in areas the rift cross-cut the older proximal Neo-Tethys shelf and siliciclastics and carbonate ramp deposits in areas the rift cross-cut continental domains.
- A Middle Jurassic to Late Cretaceous passive margin evolution after the oceanic break-up since the Toarcian with formation of shallow-water platforms in latest Jurassic–earliest Cretaceous times in certain areas, but predominantly with deposition of hemipelagic sedimentary sequences.
- A Late Cretaceous to Paleogene convergent tectonic regime triggered by subduction and subsequent continent (wider Adria) – continent collision (Europe), followed by Neogene mountain uplift and unroofing.

In contrast to the fairly well understood Alpine Atlantic Wilson cycle a lot of open questions exist regarding the Neo-Tethys Wilson cycle. The main focus is therefore the time frame before the “Mid-Cretaceous” mountain building process with the rearrangement of tectonic units, i.e. the Mesozoic plate configuration in the Western Tethys Realm. Due to the fact that the “Mid-Cretaceous” and younger polyphase tectonic motions and block rotations draws a veil over the older Mesozoic plate configuration, several crucial and still topical questions remain, e.g.: 1) How many Triassic-Jurassic oceans existed in the Western Tethyan Realm. Show these oceanic domains different life cycles, i.e. is the opening and the closure of these oceanic domains contemporaneous or differ their age, and where are the suture zones? In general, two main types of contrasting interpretations/models remain: a) Multi-ocean reconstructions with several oceanic domains between continental blocks, and b) One-ocean reconstruction: an allochthonous model which interprets the ophiolites as overthrust ophiolitic nappe stack (or single ophiolite sheet) from the Neo-Tethys to the southeast to east.

2) Were the Southern Alps/Dinarides/Albanides/Hellenides, the Eastern Alps/Western Carpathians plus some Pannonian units (ALCAPA), some units in the Circum-Pannonian realm (e.g., Tisza Unit), and Pelagonia (including Drina-Ivanjica Unit) independent microplates between independent oceanic domains in Triassic-Jurassic times? Or have these units been scattered by polyphase younger tectonic movements modifying an united continental realm (north-western part of Pangaea) of the Triassic European shelf? The Early Jurassic Pangaea break-up resulted, e.g., in the opening of the Central Atlantic Ocean and its eastward continuation, the Alpine Atlantic.

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The eastern extension of the Avalonian terranes, the Prototethys and Paleotethys oceans

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Avalonia was an archipelago of microcontinents divided into West and East Avalonia. West Avalonia included south-eastern parts of Nova Scotia, eastern Newfoundland, New Brunswick, Florida(?), and New England, while East Avalonia included southern Ireland, southern Scotland, England, northern France, the Brabant Massif, Lusatia, northern Germany, and north-western Poland. Several crustal fragments such as the Bruno–Silesia terrane, Moesian terranes, Istanbul/Zonguldak terrane constituted an extension of East Avalonia (Golonka *et al*., 2023). These microcontinents detached from Gondwana during the Early Paleozoic times. Golonka *et al*. (2023) also portrayed a chain of microcontinents moving away from Gondwana across the Palaeoasian (Protothetys) Ocean. These chain included Scythian, Turan, South Kazakhstan, Junggar, Tarim and Indochina. The Rheic-Palaeotethys Ocean opened behind these microcontinents. Collision occurred between Avalonia, Laurentia and Baltica during Caledonian Orogeny. This collision also included Bruno–Silesia, Moesia terranes, Istanbul/Zonguldak, Scythian and Turan terranes (Golonka & Gawęda, 2012). The events involving Junggar, South Kazakhstan and Tarim are more speculative.

Indochina collided with South China along Song Ma–Truong Song–Ailaoshan suture during latest Silurian–earliest Devonian times. In northwestern Vietnam, the Late Silurian Song Chay complex granitoid is connected to this event. Moreover, the deep-water deposits such as Pa Ham formation were later replaced by shallow-water sedimentary formations, including the continental Lower Devonian red beds and Lower Devonian Nam Pia Formation composed mainly of terrigenous sediments and marl, medium-bedded to massive fine-grained limestone, representing shallow water sediments. The Lower Paleozoic greenschists of deep-sea origin were unconformably covered in many localities by Devonian redbeds (Son *et al*., 1978; Hung, 2010; Hung *et al*., 2023).

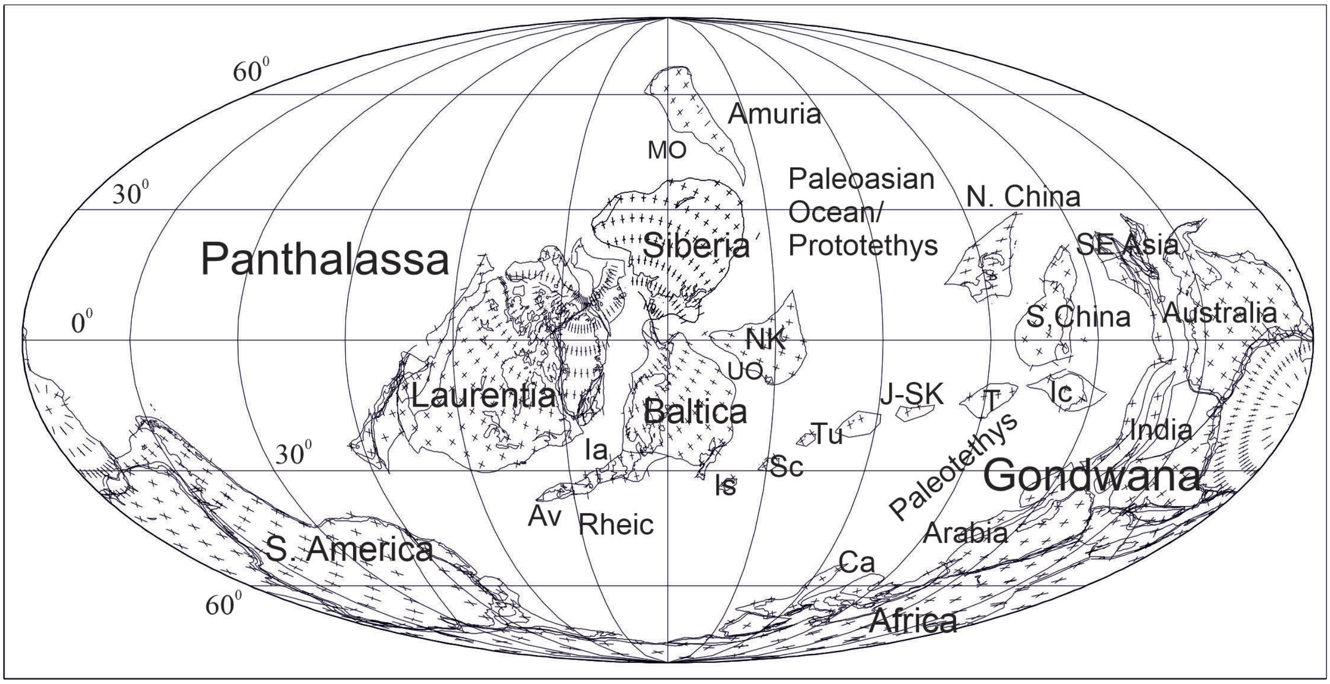

Fig. 1. Early Silurian palaeogeography. Abbreviations: Av – Avalonia, Ca – Cadomia, Ia – Iapetus Ocean, Ic – Indochina, Is – Istanbul, J–SK – Junggar–South Kazakhstan, MO – Mongol-Okhotsk Ocean, NK – North Kazakhstan, Sc – Scythian terranes, SK – South Kazakhstan, T – Tarim plate, Tu – Turan terranes, UO – Ural Ocean

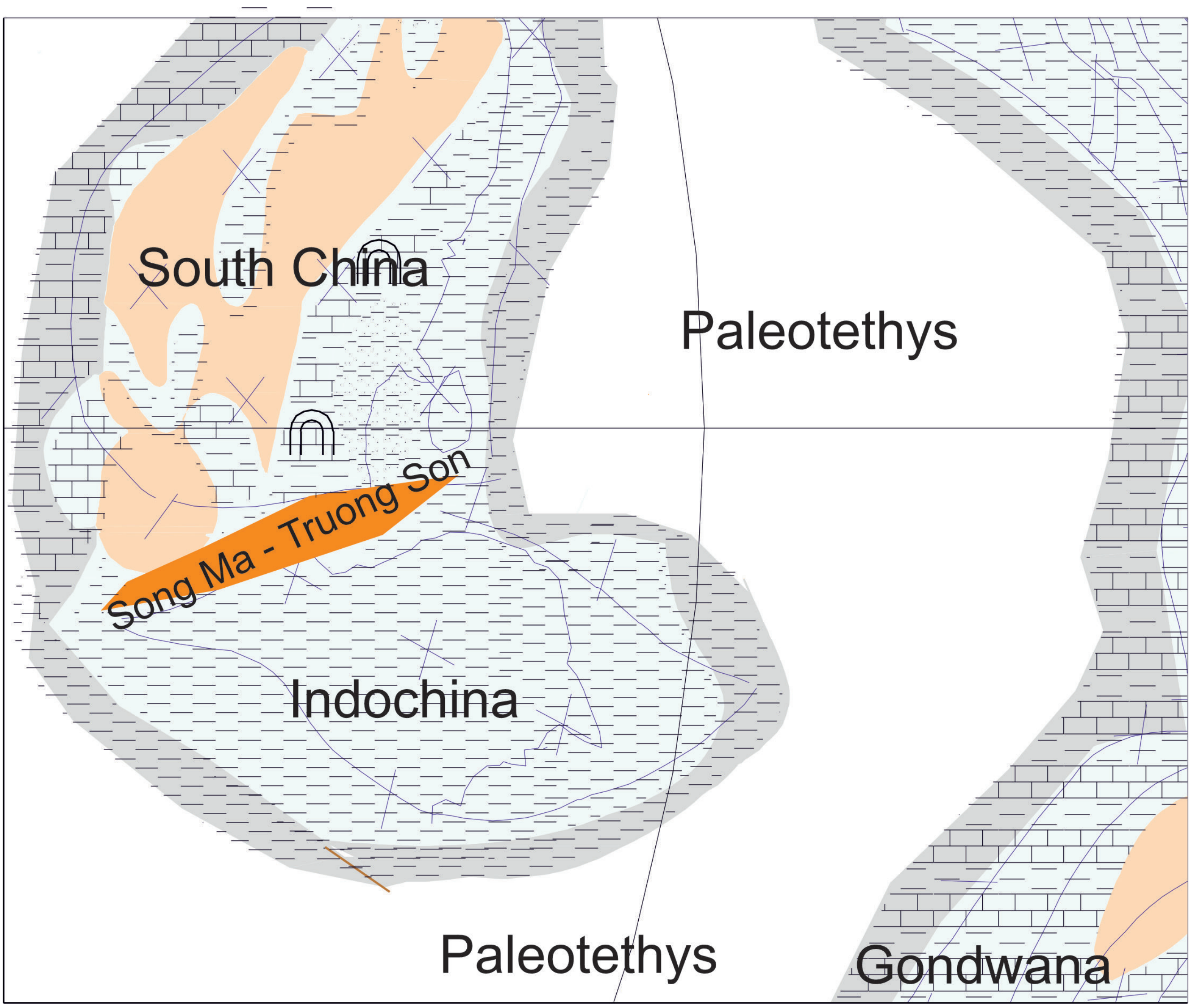

Fig. 2. Palaeogeography of Indochina and South China during latest Silurian–earliest Devonian

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Tectono-sedimentary evolution of the junction area between the Western and Eastern Carpathian nappe systems (Ukrainian Carpathians)

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The Carpathians contain the remains of the Western Tethys, the main of which are: continental/microcontinental fragments (Alkapa and Tisza-Dacia terranes) of the Tethys Ocean, now located in the Central (Inner) Carpathians, and (palaeo)accretionary prisms, building mainly the Outer Carpathians.

The Ukrainian Carpathians occupy the junction where the Western Carpathian and Eastern Carpathian nappe systems converged. In the presented work, author try to reconstruct the tectono-sedimentary evolution of the Eastern and Western Carpathian nappe systems in the junction area on the basis of own and published geomapping works, stratigraphic, sedimentological and structural research using existing restorations (see van Hinsbergen *et al.*, 2020 and references therein).

The Central Western Carpathian nappes (part of the Alcapa Terrane) are not exposed in Ukraine and probably buried under Neogene Transcarpathian Depression. The Central Eastern Carpathian nappes (part of the Tisza-Dacia Terraine) are represented in Ukraine by the Marmarosh thick-skinned basement nappes, that were formed in the Early Cretaceous time and overlapped by the latest Early Cretaceous–Paleogene post-nappe sedimentary cover. Between the Central Eastern and Central Western Carpathian nappe systems, the Pieniny Klippen Belt suture zone and Monastyrets Nappe filled with Paleogene flysch are developed.

The structure of the junction between the Outer Eastern and Outer Western Carpathian nappe systems is more complicated. In Ukraine, the Outer Carpathians are made up of a several stacked nappes filled with Cretaceous–Neogene, mainly flysch sediments uprooted from their original substratum.

In the Eastern Carpathian segment of Tethys at the Late Jurassic and/or Early Cretaceous, Ceahlau-Severin ocean (called Fore-Marmarosh one in Ukraine) was opened between the Dacia continental block (part of the Tisza-Dacia Terrane) and the Eurasian continent (van Hinsbergen *et al.*, 2020 and references therein), that suggested by rift oceanic and continental basalts occurring under the Cretaceous flysch of the Outer Eastern Carpathian. Sinking of the Dacia (micro)continent into a subduction zone existed in the Neotethys ocean and inclined to the west (van Hinsbergen et al., 2020), could have caused the east-directed thrusting of the thick-skinned Marmarosh Nappes towards the Ceahlau-Severin ocean. Ahead the Marmarosh nappe pile, the Eastern Carpathian Internal flysch thin-skinned nappes such as the Kamyanyi Potik, Rahiv, Burkut, Krasnoshora, Svydovets and Chornohora ones were formed. Coarsening upward and regular younging of the stratigraphic successions from inner to outer nappes suggest their attribution to the accretionary wedge growed in the Early Cretaceous–Paleogene time due to the subduction of the Outer Carpathian flysch basin basement under the Marmarosh pile.

In the Western Carpathian segment, the Pieniny Klippen Belt accretionary wedge began to rise in the Late Cretaceous due to subduction of the Penninic oceanic domain under the Central Western Carpathians (part of the Alcapa Terrane) accompanied by detaching and grouping together originally very distant lithofacies (Plašienka, 2018 and references therein). The Western Carpathian Internal flysch nappes such as the Magura and Dukla units were attached to the Fore-Alcapa prism during the Middle Eocene–Oligocene, accordantly to outward shifting and uplifting of the trench-like Magura and Krosno lithofacies during this time.

Closuring of the Monastyrets “between-terrainian” flysch basin at the late Eocene suggests the collision of the Alcapa and Tisza–Dacia terranes at the turn the Eocene and Oligocene. As a result, the Fore-Alcapa and Fore-Tisza-Dacia wedges were incorporated within an amalgamated internal wedge system that limited from the SW the Outer Carpathian basin. This unificated Menilite–Krosno basin was gradually uplifted and its deposits were subsequently thrusted as the external Silesian, Skyba and Boryslav-Pokyttya nappes onto the Miocene Carpathian Foredeep.

Sedimentological and structural data suggest northeastward shift/migration of the wedge front–trench/foredeep–forebulge during Carpathian evolution. In addition, the junction of the Eastern and Western Carpathian accretionary wedges is complicated by strike-sleep movements.

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Reappraisal of the Changning-Menglian Belt as a Suture Zone for the Tethys in Western Yunnan, China: Late Paleozoic faunal and sedimentary evidence

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The Changning-Menglian Belt in western Yunnan, China has long been considered a major Tethyan suture in SE Asia, based mainly on fragmented Paleozoic ophiolites, slices of Devonian-Triassic radiolarian cherts and possible seamount limestones of Permo-Carboniferous age (Fig. 1). However, some students also argued for a setting of passive continental margin for this belt and a cryptic suture further east representing the vanished Tethyan Ocean (Ridd, 2015).

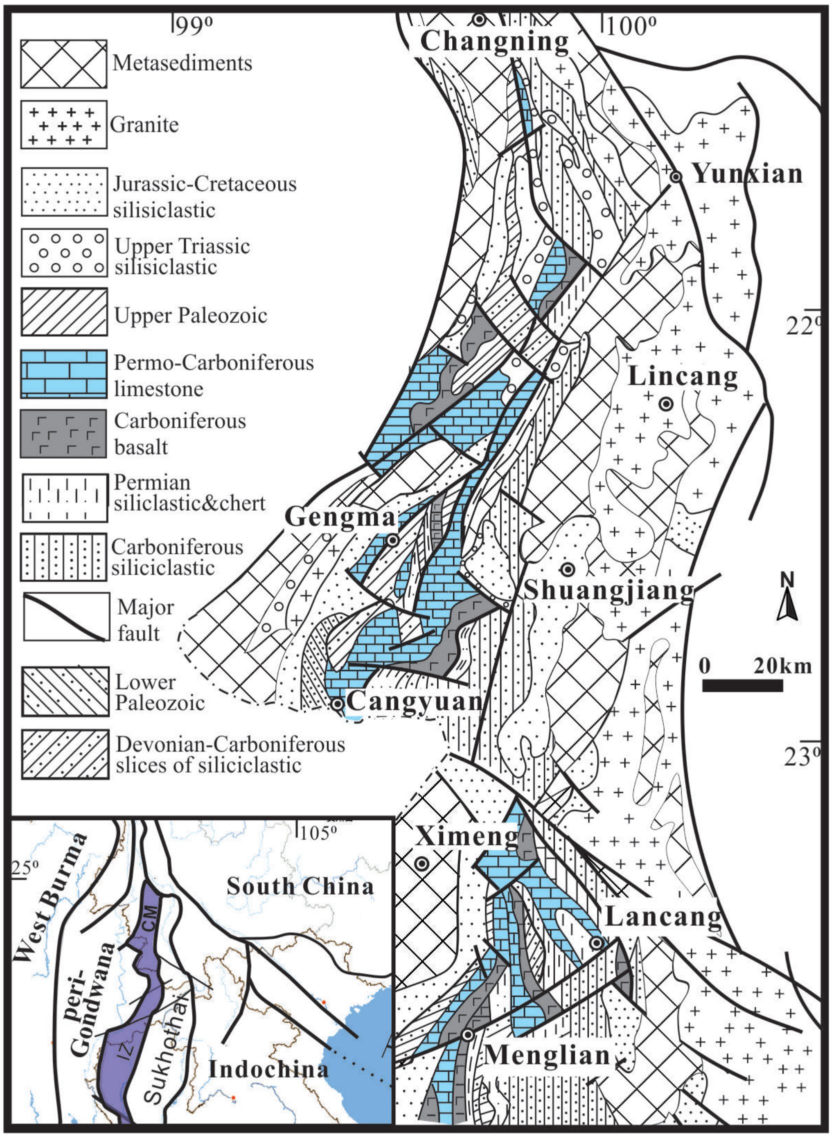

Fig. 1. Simplified geological map of the Changning-Menglian Belt in western Yunnan, China (modified after Zheng *et al.*, 2019)

To evaluate this hypothesis, we have been studying late Paleozoic strata and fusulinids in this belt for years. We recently collected late Carboniferous to Middle Permian fusulinids from various sections in this belt, including ascendingly *Triticites* assemblage, *Sphaeroschwagerina sphaerica* assemblage, *Eoparafusulina* assemblage, *Chalaroschwagerina solita* assemblage and *Neoschwagerina* assemblage. Further comparison reveals that the fusulinid taxonomy in this belt still differs from that in S China. For instance, the Early Permian fusulinids in this belt generally lack *Pseudoschwagerina*, a typical Cathaysian element. Moreover, quantitative analysis (Rarefaction) confirms that the generic diversity in this belt remains lower than in S China. These results supports that a substantial portion of the Permo-Carboniferous limestones in this belt originated from seamounts located far from the northern Gondwana margin, meanwhile slightly south of the equatorial region, also considering the couplet of carbonates and underlying basalts (OIB type).

Furthermore, petrographic and geochemical analyses of the Carboniferous siliciclastic Nanduan Formation demonstrate a mature continental provenance and two peaks of detrital zircon ages (ca. 950 Ma and ca. 550 Ma) (Zheng *et al*., 2019). Notably, these two peaks are also shared by metasedimentary rocks (e.g., the Ximeng and Lancang Groups) widespread in this belt as well as peri-Gondwana blocks. These data suggest that the Paleozoic siliciclastics covering this belt's eastern and western parts were derived from the Gondwana margin. Therefore, significant siliciclastic inputs from the Gondwana margin over much of this belt contradict the implied vast Paleozoic ocean in this belt. In contrast, the siliciclastic Nanpihe Group (Devonian-early Carboniferous) in the central part demonstrates a detritus source from continental arcs and clusters of detrital zircon ages of ca. 435 Ma and ca. 950 Ma, which correlates well to Silurian magmatism in the Simao and S China blocks.

In conclusion, we propose that the Changning-Menglian Belt was part of the passive continental margin on the eastern flank of the Baoshan-Shan Block during the late Paleozoic, while and tectonostratigraphic slices of seamount limestones, Nanpihe Formation or even ophiolites are allochthonous and were displaced to their present position during the Late Triassic closure of the Tethys.

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Geological history of the NW Indian Plate Tethyan passive margin in the Salt Range, Pakistan

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The generally east-west trending Salt Range, located in northern Pakistan, is a part of the foreland zone of the Himalayan Fold and Thrust Belt (HFTB). The 5,000–1,000 m thick Precambrian to Pleistocene sedimentary archives of the Salt Range provide an excellent opportunity for the reconstruction of sedimentation style, palaeoclimatic conditions, and tectonic history of the northwestern margin of the Indian Plate. The Precambrian evaporites of the Salt Range Formation are the oldest rocks in the area and represent the westward extension of the Precambrian evaporitic belt that includes the Hormuz Salt Basin (Iran) and Ara Salt (Arabian Plate). A highly weathered igneous body “Khewrite” occurs in the upper part of the formation and can be correlated with the volcanic record during the Ediacaran-Cambrian transition in the Arabian Plate. The clastic-dominated Lower Cambrian succession in the area is directly overlain by the Permian Tobra Formation and with a gentle angular unconformity. The poorly sorted conglomerates of the Tobra Formation indicate deposition during the Permo-Carboniferous glaciation and the irregular distribution of the Tobra and Dandot formations in the area supports their deposition during the syn-rifting phase of the Neo-Tethys opening. The overlying Upper Permian and Mesozoic strata indicate deposition on the northwestern passive margin of the Indian Plate facing the southern margin of the Neo-Tethys. This represents the drift sequence with multiple phases of passive margin rejuvenation during the Mesozoic. The drift sequence is unconformably overlain by the Paleocene Hangu Formation. Karst bauxites mark this contact and hint at exhumation and exposure in the distal part of the underthrusting plate margin. The Hangu Formation grades upward through the Lockhart Limestone into black shales of the Patala Formation supporting deepening and the possible establishment of a trench setting in the area. The presence of thick evaporites of the Bahadar Khel Salt and Jatta Gypsum in the western part of the area (Kohat Plateau) indicates a restricted lagoonal setting during the closure of the Neo-Tethys during the Eocene. The absence of the Oligocene strata hints at the uplift and exhumation of the area during the Himalayan Orogeny. The Neogene strata of the area consist of fluvial-continental detritus and represent molasse sedimentation. Thermal history modelling based on Apatite Fission Tract (AFT) data indicates three major cooling (uplift) episodes separated by two burial phases in the area. The first cooling event (ca. 520 Ma) coincides with the emplacement of the Mansehra Granite just north of the area (ca. 516 Ma) and supports exhumation correlatable with the Pan-African Orogeny. This was followed by the first burial phase (ca. 500–370 Ma) that supports Late Cambrian–Devonian sedimentation in the area. The second cooling event (ca. 300–280 Ma) coincides with the initial rifting and exhumation associated with the Neo-Tethys opening. Therefore, it appears that the Late Cambrian–Devonian strata were deposited in the Salt Range but were subsequently eroded during the exhumation induced by the Neo-Tethys opening during Permo-Carboniferous. This was followed by Neo-Tethyan passive margin deposition throughout the Mesozoic. An additional cooling episode is observable at around ca. 60 Ma and is supported by the presence of karst bauxites at the base of the Hangu Formation. Provenance analysis of the Paleocene strata suggests that detritus for the Hangu Formation was supplied from the south (Indian Plate). The overlying Patala Formation indicates the onset of sediment supply from the north and hence the uplift of the Himalayan Orogen. The overlying Kuldana Formation supports detritus supply only from the north verifying the Neo-Tethys closure by the end of Eocene. Thus the Paleogene strata represent syn-collisional deposition of the Neo-Tethys in the Salt Range. The second burial event (ca. 20–6 Ma) occurred during the Neogene in response to molasse sedimentation in the foreland of the uplifting Himalayan Orogen that was followed by the final cooling and uplift event (ca. 4 Ma) along the Salt Range Thrust. Thus the stratigraphic successions of the Salt Range provide key information regarding the reconstruction of the northwestern Neo-Tethyan margin of the Indian Plate which can help in the understanding of Neo-Tethyan tectonics in regional and global context.

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Geochemistry of the Triassic–Jurassic lateritic bauxites of the Salt Range: implications for eastward extension of the Tethyan bauxite deposits into Pakistan

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Bauxite deposits are residuals of intense lateritic weathering under warm and humid palaeoclimates. The Triassic–Jurassic Boundary (TJB) interval in the Salt Range, Pakistan, provides one such case of bauxite deposits formation along the SW tropical Neo-Tethyan passive margin. Thick, red bauxites/bauxitic clays occur at the contact of the Upper Triassic Kingriali Formation and the Lower Jurassic Datta Formation. These bauxites are rich in kaolinite, haematite, boehmite (Al_2O_3 and Fe_2O_3), and are depleted in silica (SiO_2). Geochemical proxies of the succession signal intense chemical weathering of the parent siliciclastics under Mesozoic "greenhouse" conditions. Certain trace elements and Rare Earth Elements (REEs) are enriched up to seven times compared to mean Upper Continental Crust (UCC) values. These bauxites are synchronous with the Amir-Abad bauxites of the Alborz Mountains, central Iranian Plateau, that occur between the thick Triassic dolomite/dolomitic limestones of the Elika Formation and the Lower Jurassic Shemshak Formation. Thus, the Salt Range, Pakistan, provides evidence for the eastward extension of the Irano-Himalayan bauxites that are extended westward into Mediterranean bauxites, and the western Tethys by correlation with European bauxites. The TJB bauxites in the Salt Range support increased chemical weathering on the SW Neo-Tethyan passive margin and correspond to an associated sea-level fall during this time interval. This supports the Neo-Tethyan tectonics contribution in the formation of bauxite deposits during the Triassic–Jurassic in addition to the widely studied karst-bauxites that formed in response to the subduction and orogenic processes in the Paleo-Tethys.

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The earliest Cretaceous carbonate platform destroyed by volcanism from the Ukrainian/Romanian Carpathians – reconstruction based on microfacies

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There is a unique tectonostratigraphic unit called Kaminnyi Potik occur in the Ukrainian-Romanian Carpathian transborder zone. In the Ukrainian part numerous outcrops of this unit can be observed in many streams near Rachiv city, but its most spectacular occurrence is in the Chyvchyn Mountains. The whole complex consists of volcanogenic-sedimentary rocks and is divided into two Berriasian formations: Chyvchyn and Kaminnyi Potik. In the section of the Chyvchyn Formation, at the base, there are pillow lavas (basalts and andesites/trachyandesites) and volcano-sedimentary breccia with clasts of lava, coral limestones and radiolarites (submarine debris flows), and peperites as well. The Kaminnyi Potik Formation is made up of fine-grained hyaloclastic and carbonate debris flows of a flysch character (including organodetrital limestones with fragments of: corals, bryozoans, echinoderms bivalves and foraminifera), which overlying breccias and coral limestones of the Chyvchyn Formation. The profile ends by thin-bedded cherty limestones.

The thin sections analysis revealed the following microfacies: oolithic-echinoderm packstone/grainstone; coral lithoclastic quartz packstone/grainstone; oolithic-lithoclastic wackestone/packstone; lithoclastic-echinoderm packestone; lithoclastic packestone; radiolarian echinoderm packestone; radiolarian wackestone; radiolarian-calpionellid wackestone and mudstone. Pyroclastic material is often present in the matrix.

The ooids observed in the thin sections and the remains of fauna such as corals, echinoderms and bivalves suggest that the original material came from a carbonate platform that was sheltered by a coral reef. As a result of volcanic eruptions and possibly accompanying earthquakes, the platform has been destroyed and its traces are visible in clasts. Sedimentological character of submarine debris flows, (e.g. fractional graiding, mixture of shallow-water fauna and lithoclasts with deep-marine microfauna (radiolarians and calpionellids) and hyaloclastic material present in the matrix document short-term episodes of a catastrophic nature, leading to the redeposition of shallow-water sediments to the deeper parts of the basin.

Sequence stratigraphy of the Upper Cretaceous–Eocene Belqa Group of Jordan (southern Tethys margin)

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The Belqa Group of Jordan (Upper Cretaceous–Eocene) contains a remarkable succession of sedimentary lithofacies, including chalk, sandstone, chert, phosphorite, oyster mounds and organic-rich marls deposited along the passive southern margin of the Neo-Tethys Ocean.

The Belqa Group is now outcropping in spectacular wadis where they can be studied in detail. The exceptional outcrops exposures provide unique opportunities for studying three-dimensional spatial facies variations. However, this 3D facies distribution requires robust time control and the combination of modern sequence stratigraphic concepts and high-resolution dating methods. We report the establishment of a regional sequence stratigraphic model that provides the temporal framework for further detailed sedimentological, palaeontological and geochemical studies.

Preliminary results show a stratigraphic organization in four major depositional sequences (3rd order), which are broadly in agreement with the lithostratigraphic formations. The age dating is based on new nano-fossil analyses and C/O and Sr isotope stratigraphy. A subdivision into higher-frequency sequences (4th/5th order) significatively improves the resolution of the stratigraphic framework and our understanding of spatio-temporal distribution of the sedimentary facies. The four sequences are:

1) The B1 sequence (Upper Coniacian-Santonian), characterized by a transgressive phase of chalk-rich sedimentation (coccolithophore-dominated) and a regressive phase of a prograding siliciclastics with a distal transition to the first phosphorite-chert facies. 2) The B2 sequence (Lower Campanian) also starts with a transgressive chalk dominated facies and subsequently develops into a chert-dominated marl facies (radiolarian-dominated). The chert is locally associated with thin phosphates and coquinas, as well as organic-matter rich facies in proximal marine settings. 3) The B3 sequence (Upper Campanian) is also characterized by a transgressive chalk dominated facies. The regressive phase is constituted by dm- to m-thick phosphorite beds that were deposited coevally with giant oyster banks (decameter scale). 4) The B4 sequence (Maastrichtian-Paleocene) represents a dramatic facies change to organic-rich pelagic marls, and can probably be further subdivided.

This sedimentary succession highlights both gradual and rapid changes in biogenic productivity and geochemistry. These changes are punctuated and partly driven by significant relative sea-level changes, and likely also larger scale palaeoceanographical processes that are the focus of future work.

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Geological origin of the Permian bedded chert succession distributed in Central Plain of Thailand

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The geotectonic divisions, which are distributed as narrow zones in the north-south direction, are clear in the northern Thailand, but not clearly recognized in the Central Thailand. The Chao Phraya Plain, which occupies the central part of Thailand, is broadly covered with Quaternary sediments. Therefore, the basement rocks of the Paleozoic and Mesozoic are scattered in the form of residual mounds, and due to the lack of stratigraphic and age-determination data, the geological origin of these rocks have been not sufficiently discussed. In this presentation, we will report the results of a study on the geological belongings of bedded chert sporadically exposed in the Chao Phraya Plain, Central Thailand by the microfossil age and geochemical characteristics.

The study areas are Thung Saliam (TS) (50 km northwest of Sukhothai) in the northern part of the plain and the Nakorn Sawan–Uthai Thani (NS-UT) area in the central part of the plain. About 20 outcrops of chert were surveyed in both areas. The cherts are distributed in scattered, and most of the cherts are recrystallized and are considered to have undergone contact metamorphism. Chert of the TS is well-bedded with red and the direct contact relationship is unknown, but tuff and limestone (marble) are exposed around it. Chert of the NS-UT is also well-bedded with red, black, gray and milky white in color. Altered slatey shale and sandstone accompany the chert and form monadnocks. These cherts might be categorized into typical pelagic cherts because they contain radiolarian tests and sponge spicules in a matrix consisting of very fine clay minerals and microcrystalline quartz, and do not contain coarse-grained terrigenous materials.

Sashida & Nakornsuri (1999) reported the occurrence of *Pseudoalbaillella simplex*, *Ruzencevispongus* sp., and so on from the TS chert and they assigned their age to Wolfcampian. Whereas, Saesaengseerung *et al*. (2007) report radiolarian occurrence of the *Ps. loemntaria* Assemblage (Artinskian) and *Follicucullus scholasticus* Assemblage (Capitanian-Wuchiapingian) from the NS-UT chert.

Whole-rock chemical analysis was performed on three sections their ages were determined by radiolarians. In the Chondrite-normalized REE pattern, TS chert indicates negative anomaly of Ce, and NS-UT chert shows relatively flat and profile of the downward-sloping in the LREE. The geological age of the study sections and their REE patterns are similar to those observed in the Sa Kaeo area in southeastern Thailand.

The Permian bedded cherts exposed in TS and NS-UT areas are often accompanied by thin layers of fine-grained siliciclastics and tuff, which are weakly metamorphosed and foliated. Since the chert itself has a relatively thin thickness (several meters to 10–20 m) in each outcrop, and basically has a north-south strike. These cherts occurrence and lithofacies of both areas are similar and indicate that cherts of both areas are geologically comparable as pointed out by Ueno *et al*. (2012).

Ueno *et al*. (2012) clarified that the central part of Thailand, where the geotectonic division was unclear, can be divided into three geotectonic units from west to east: Sibumasu Block, Sukothai Zone and Indochin Block. However, the origin of the Permian chert has not been clarified. Paleozoic and Mesozoic cherts distributed in Thailand remind us bedded cherts deposited in the Paleo-Tethys from the Devonian to the Triassic. However, no cherts other than the Permian have been reported in the central part of mainland Thailand. Instead of the Paleo-Tethys chert, the Sa Kaeo-Chanthaburi suture and the Nan-Uttaradit suture are well-known as geological units containing Permian chert in southeastern Thailand. These sutures have been understood as a closed remnant of the Permian to Triassic back-arc basin stretched between the Indochina Block and the Sukhothai Arc. The fact that the Permian cherts of the central plain are distributed in the eastern part of the Sukhothai Zone and near Indochina Block suggests that these Permian cherts comparable to the Permian chert of the Sa Kaeo-Chanthaburi Suture. In addition to the geological evidence, the geochemical features of the Permian chert represented by the REE pattern are similar to those of the Permian chert in the Sa Keo area. Line of evidence mentioned above suggests that the Permian bedded chert distributed the central Thailand (TS and NS-UT areas) have originated to the Permian chert of the Sa Kae-Chanthaburi or Nan-Uttaradit sutures which is a remnant of back-arc basin.

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Palaeoenvironmental and palaeoclimatic records in the Niedzica Succession sediments (Pieniny Klippen Belt) in the light of geochemical and chemostratigraphical analysis

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The Middle–Upper Jurassic sediments of the Niedzica-Podmajerz section was the subject of integrated study, including sedimentological, geochemical and stratigraphic analysis. The studied section is located in the Pieniny Klippen Belt area and belongs to the Niedzica unit. The section is characterized by continuous exposure of Jurassic carbonate-silica deposits extending from the Bajocian to Kimmeridgian, showing a transition from crinoidal limestones representing typical neritic facies to pelagic facies, i.e. radiolarites and red nodular limestones. The following lithofacies were distinguished in the studied section: grey crinoidal limestones (Smolegowa Limestone Formation), red crinoidal limestones (Krupianka Limestone Formation), red nodular limestones (Niedzica Limestone Formation), radiolarites (Czajakowa Radiolarites Formation) and red nodular limestones (Czorsztyn Limestone Formation).

Based on a multidisciplinary dataset, the palaeoenvironmental interpretation was proposed. The results of magnetic susceptibility (MS), gamma-ray spectrometric measurements, $CaCO_3$ content, $\delta^{13}C$ analysis and concentrations of major and trace elements data indicate a rapid change in sedimentary conditions at the Callovian–Oxfordian boundary. Variations of $\delta^{13}C$ from the Niedzica-Podmajerz indicate global changes in biological productivity, ocean circulation and burial of organic matter in the Tethys area, analogies of which can be found, for example, in Fatricum Domain in the Tatra Mountains. Records of MS, elements K, Th, Al, as well as Ti/Al and Zr/Al proxies indicate probably a period of increased (Lower Bathonian–Upper Callovian) and decreased (Oxfordian) detrital supply to the sedimentary basin. This process was most likely climatically controlled. The $CaCO_3$ results indicate the variability of carbonate production. The lowest values of calcium carbonate (<20%) in Niedzica-Podmajerz section was recorded in the middle part of the radiolarites of the Czajakowa Radiolarite Formation, corresponding to the phase of the carbonate crisis. From this interval, the amount of carbonates in the rocks gradually increases, indicating a return to carbonate sedimentation. These fluctuations probably reflect changes in the position of the ACD and CCD.

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Red algae grains from the Żurawnica Sandstone Member in the Sucha Beskidzka area (Magura Nappe, Polish Outer Carpathians) as the indicator of shallow water palaeoenvironment on the intrabasinal Tethyan ridge

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The Żurawnica Sandstone Member was deposited in the Paleocene on the northern slope of the Magura Basin in the western part of the Tethys. It is built of clastic material transported by gravitational currents from shallow parts of the Foremagura Ridge (Cieszkowski *et al*., 1999), which was an uplifted intrabasinal structure. At the top of the Żurawnica Hill (Beskid Makowski, location known as Kozie Skały) a well-exposed section crops out. It is a part of flysch succession of the Magura Nappe (Cieszkowski *et al*., 2006). In the lower part of the section thick-bedded sandstone with red algal grains occurs. Algal remnants were redeposited from the photic zone of the carbonate platform, which developed on the Foremagura Ridge. Their structure-taxonomic differentiation allows to reconstruct algal palaeoenvironment. The red algae are represented by Sporolithaceae, Melobesioideae, and Mastophoroideae genera. They correspond to three algal facies: debris, algal pavement facies, and Melobesioideae rhodolith pavement facies.

Sand-sized red algal grains are the most numerous. They are fragmented and well rounded crustaceous algal thalli, typically with no traces of bioerosion. They represent algal debris facies, which was developed in high energy environment (Nebelsick *et al*., 2005). Red algae grains could be fragmented and rounded during turbidity transport, but considering the different degree of abrasion, especially in gravel fraction, it should be assumed that the rounding took place before the turbidity transportation.

Two types of gravel grains are present: not rounded algal limestone clasts and rhodoliths. The non-rhodolith grains are built of encrusting (layered and foliose), warty, and lumpy algal crusts. Rhodoliths can be divided into two types: irregular and regular ones. Irregular rhodoliths are up to 3 cm in diameter. They contain large nuclei constituting grain skeleton. Both non-rhodolith grains and irregular rhodolits are polygeneric and contain numerous benthic organisms (bryozoans, encrusting foraminifera, and bivalves) between algal lamella, as well as constructional voids. They are bioeroded. They are elements of algal pavement facies for which the occurrence of the algal buildups with irregular rhodoliths in areas, where the energy of the environment is a bit higher is typical (Nebelsick *et al*., 2005, 2013; Bassi *et al*., 2017). The regular rhodoliths, up to 0.5 cm in size, contain small carboniferous nuclei. Typically, they are unigeneric (Sporolithaceae, Melobesioideae) and not contain other benthic organisms. Lack of constructional voids was observed in thick algal encrustation. Only encrusting growth form was observed. Regular rhodoliths are typically developed as a main part of Melobesioideae rhodoliths pavement facies, which is rather "deep" water facies of high energy environments (Adey, 1986; Bassi *et al*., 2017).

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Early Triassic conodonts in Western Tethys

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Conodonts are phosphatic, tooth-like elements of extinct jawless vertebrates that are classified in the independent class Conodonta. Due to their rapid evolution, wide palaeogeographic distribution and high resistance, conodonts are one of the most significant microfossil groups in the biostratigraphy of the Paleozoic and Triassic. Animals with conodonts were bilaterally symmetrical, exclusively marine organisms, where they inhabited a variety of habitats. These include both open sea habitats, whereas some species adapted to shallow habitats of epicontinental seas. For this reason, conodonts are extremely important for understanding of the palaeoecological and palaeogeographic conditions of the Paleozoic and Triassic. They were unquestionably one of the most successful animal groups, since they existed more than 300 million years and their elements are widely used as index fossils.

Conodonts have shown their value for Triassic biostratigraphy. Based on international criteria the Permian-Triassic system boundary is defined with the first appearance of the conodont species *Hindeodus parvus* (Kozur & Pjatakova). The Permian-Triassic interval strata of the GSSP section in Meishan (China) are next to the platform-bearing gondolellids marked by the presence of *Hindeodus-Isarcicella* population that enabled to introduce also a conodont zonation for shallow facies. A standard conodont zonation is, except for the two lowermost Triassic zones, based on gondolellid genera that lived in deeper water: *Clarkina*, *Sweetospathodus*, *Neospathodus*, *Novispathodus*, *Borinella*, *Scythogondolella*, *Icriospathodus*, *Triassospathodus* and *Chiosella*. Certain Dienerian and Smithian strata of Western Tethys are marked by shallow water and euryhaline genera and due to the absence of global biozonation markers, a stratigraphic value of some genera (*Hadrodontina*, *Pachycladina*, *Eurygnathodus*, *Foliella*, *Platyvillosus*) is recognized. These shallow water genera were ecologically controlled (temperature, oxygen levels) that have been adapted to the epicontinental ramp environment and were particulary instrumental in forming the western part of the Tethyan province.

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Geodynamics of Sibumasu Block in Southern Thailand: Interpretation from Heat Flow Map

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Southern Thailand, located on the thick and stable Sibumasu continental block, is known for its high heat flow despite lacking volcanic activity (Sautter *et al*., 2017). This study employs the Curie Point Depth (CPD) calculation, an indirect method, to evaluate land heat flow (e.g., Hsieh *et al*., 2014; Li *et al*., 2017; Qudsi, 2019). By analyzing airborne magnetic data and utilizing spectral analysis, the study generates CPD, thermal gradient, and heat flow maps for southern Thailand (e.g., Carrillo-de la Cruz *et al*., 2020; Núñez Demarco *et al*., 2021). The findings reveal heat flow values ranging from 61.54 mW/m² to 154.25 mW/m², with an average of 90.36 mW/m², surpassing the typical heat flow of 65 mW/m² for continental crust (Turcotte & Schubert, 2002). The study identifies five distinct zones characterized by higher heat flow compared to the surrounding areas: the Ranong fault zone (RF), Khlong Marui fault zone (KMF), coastline of Surat Thani and Nakhon Si Thammarat, Trang and Satun zone, and the Bentong-Roab suture (BRS). The RF and KMF represent active strike-slip faults that penetrate the continental crust into the upper mantle (Kanjanapayont *et al*., 2012; Sautter *et al*., 2017), while the BRS denotes a weak zone marking the suture between Sibumasu and Indochina terranes (Metcalfe, 2000), potentially extending into the mantle. The elevated heat flow observed along the coastline of Surat Thani and Nakhon Si Thammarat, as well as in the Trang and Satun zone, may be influenced by burial faults or fractures. Interpretation with P-wave tomography suggests a possible high heat mantle anomaly under southern Thailand (Huang *et al*., 2015). These initial findings suggest that the high heat flow in the thick and stable continental crust of Sibumasu originates from mantle upwelling caused by surrounding subducted plates under Eurasia. These heat sources manifest through weak zones in extensional regimes such as the RF, KMF, and possible undefined burial faults or fractures, as well as the BRS. The study provides preliminary understanding of present-day geodynamics of the Sibumasu block and its potential implications for mineral resources, petroleum exploration, geothermal energy, and carbon capture and storage.

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Permian *versus* Jurassic geotectonic position of the Lhasa block – facts and controversies

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The Cimmerian Continent (or Cimmeria, Cimmerian terrane, Cimmerian blocks) was detached from eastern Gondwana in the Late Paleozoic as a sliver/ribbon of continental strip rifting elements. Recently, these elements belong to an almost continuous long belt (ca. 13,800 km) from central Italy trough Greece, Turkey, Iran, Afghanistan, Tibet, SW China, Myanmar, Thailand up to Indonesia (Sumatra). The palaeogeographic position and relationship of some elements during Permian-Mesozoic times is still matter of discussion. The Qiangtang and Lhasa blocks (present-day Tibet) belong to these elements and their location in space and time and their relationship causes a lot of controversies. Their position alongside eastern Gondwana in the mid-Early Permian (ca. 290–285 Ma) are suggested both by palaeomagnetic and facies studies. Palaeomagnetic studies indicated this position one decade ago, which has been confirmed by recent studies. The Cimmerian Continent [Iran (Alborz)-Qiangtang-Baoshan-Tengchong-Sibumasu] was separated from the Gondwanian part of Pangea during mid-Early Permian time by rifting and drifting. Northwards migration of it took place during Permian-Triassic times caused wide opening of the Bangong-Nujiang Tethyan Ocean and closing of the Paleotethys Ocean but the Lhasa block was still southern margin of the Bangong-Nujiang Ocean. The Triassic Indosinian Orogeny has been one of the most spectacular geotectonic event reflecting collision of this continent with Indochina block and closure of the Paleotethys Ocean. The separation of the Lhasa block from Gondwana is enigmatic but most probably took place during earliest Jurassic times. This separation was followed by quick shift northward.

Intensive sedimentological studies of the Late Triassic (Carnian-Norian) several flysch-type turbidites in the eastern Tethyan Himalaya (e.g. Qulonggongba, Pane Chaung, Langjiexue, Quehala, Duoburi formations/groups) indicate that their provenance was connected with Lhasa block, which has been their source area during early-stage evolution of the Neotethys. The late Early Permian rift-related basaltic magmatism in northern Baoshan (in SW China) and sourrounding regions was connected with first step of separation from Gondwana margin of this block (together with South Qiangtang and Sibumasu blocks and simultaneously with opening of the Bangong-Nujiang Ocean before the Middle Permian) – independently of Lhasa block which was separated later, the most probably during Late Triassic or Triassic/Jurassic transition time with very wide space of the Bangong-Nujiang Tethyan Ocean between Qiangtang and Lhasa blocks (2,600 km ±710 km – 23.4° ±6.4° during the Middle Jurassic with its maximum width in the Late Triassic).

From the palaeobiogeographic point of view, the worldwide distribution of Pliensbachian-Early Toarcian large bivalves of the so-called *Lithiotis*-facies, dominated by *Lithiotis*, *Cochlearites*, *Litioperna* genera revealed by the authors' studies, indicates very rapid expansion of such type of bivalves alongside southern margin of Neotethys, and could be good evidence of palaeogeographic position of the Lhasa block in this time. Himalayan and Tibetan (Nyalam area) occurrences of *Lithiotis* and/or *Cochlearites* bivalves could help to place the Lhasa block nearby the Gondwana during Early Jurassic times. This palaeobiogeographic research contradict another interpretation based on different fossils (Permian fusulinids and brachiopods) interpreted as subtropical fauna, which could occur in low subtropical latitudes together with other parts of the Cimmerian Continent.

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Late Cretaceous palaeoenvironmental and tectonostratigraphic reconstructions on the Polish sector of Peri-Tethys

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The study area is located in the central part of the Carpathian Foreland in Poland (Fig. 1), and the analysed interval includes mixed carbonate-clastic sediments of the Upper Cretaceous and the uppermost part of the profile of carbonate sediments of the Upper Jurassic. The sedimentation of the studied formations during the Late Jurassic and Cretaceous took place in the shelf zone of the northern, passive margin of the Tethys Ocean. The western Tethys, unlike its eastern margins, was not a single open ocean; rather, it covered many small plates, Cretaceous island arcs and microcontinents (Palcu & Krijgsman, 2023). The spatial range of the subbasins created between these islands was significantly limited, resulting in a large diversity of palaeoenvironments and the mixed carbonate-clastic sediments of a shallow sea.

The entire Upper Jurassic to Cretaceous complex can be viewed as a carbonate platform that lasted almost until the end of the Late Cretaceous with an episode of Early Cretaceous erosion. The sedimentary cover formed at that time initially reached considerable thickness (presumably about 2,000 m). Dislocation and bathymetric differentiation within the carbonate platform initiated the development of a complex depositional environment. During the Late Cretaceous, the syndepositional activity of NW-SE dislocation sequences resulted in an extensive flexural deflection within the Upper Jurassic-Lower Cretaceous sedimentary complex and lowermost part of the Upper Cretaceous complex.

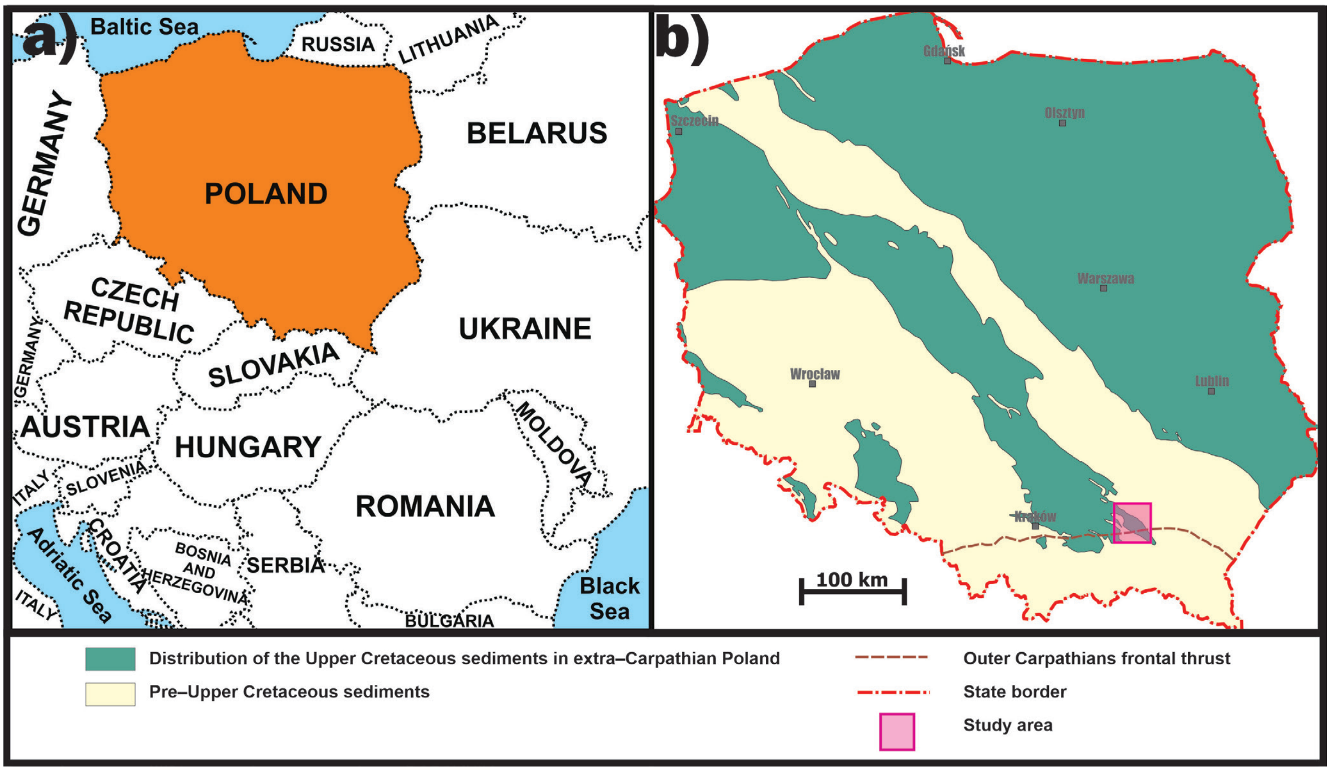

Fig. 1. Location of the study area: a) generalised outline of Central Europe; b) distribution map of the Upper Cretaceous formations in extra-Carpathian Poland (modified after Walaszczyk *et al.*, 1999).

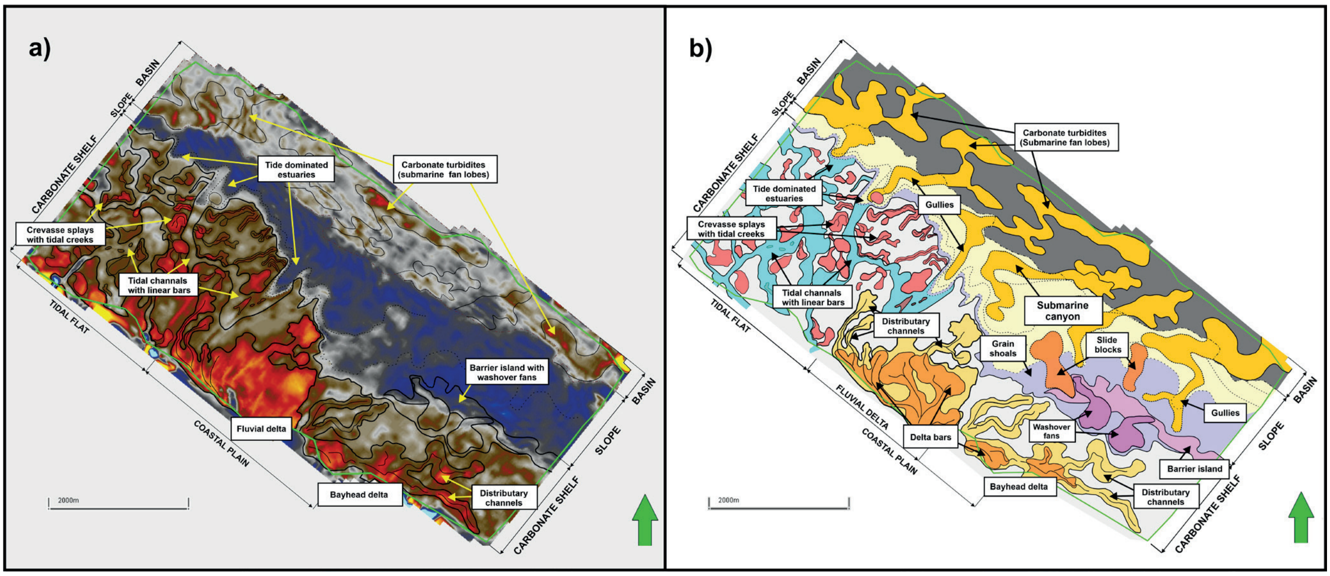

Fig. 2. Interpretation of the elements of palaeoenvironment for the correlated intra-Upper Cretaceous seismic horizon: a) based on the First Derivative attribute map; b) comprehensive model based on the analysis of several different seismic attribute maps (Łaba-Biel *et al.*, 2023).

The resulting accommodation space was filled with a complex of Upper Cretaceous carbonate formations within which there are intervals with a significant share of siliciclastic material. At the end of the Late Cretaceous as well as in the Paleocene, movements of the Laramie phase led to the re-uplift of the analysed part of the Carpathian Foreland. During this tectonic episode, the reactivation of an older fault system occurred, mainly in the NW-SE directions. The Upper Cretaceous formations deposited in the flexural depression underwent a partial inversion and intensive erosion process, lasting until the beginning of the Neogene, which contributed to the reduction of thicknesses or the removal of some of the Upper Cretaceous formations, especially in the areas, adjacent to the major dislocations. The material for analysis consisted of 3D seismic data and geological information from the wells. In the scope of the project, we approached linking 3D seismic image and well data to reconstruct, as detailed as possible, the palaeoenvironment of the studied segment of the Late Cretaceous basin based on the chronostratigraphic method. The analysis shows various palaeomorphological elements that can bring insight into the sedimentation environments (Fig. 2). The significant influence of tectonic processes on the depositional history of the sedimentary basin was also evidenced. The tectonostratigraphic interpretation divided the Late Cretaceous sediments into two different tectonic phases (Łaba-Biel *et al.*, 2023). Analysis of a thick Miocene interval that overlies directly on the Mesozoic formations enabled to reason about the influence of the Alpine orogenesis on the study area that was manifested by the reactivation of major regional faults in the central part of the Carpathian Foreland. This phase is directly related to the stage of progressive closure of the Tethys Ocean due to the collision of tectonic plates.

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Stratigraphy of the Jajarkot nappe: finding the rocks of the Tethys province

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There are several thrust sheets in the Lesser Himalayan region of Nepal. The Jajarkot nappe is one of them. It is located immediately west of the Kahun Klippe and east of the Karnali Nappe. There is no unified stratigraphy established for this thrust sheet. In the present research, an attempt was made to establish the stratigraphy of the Jajarkot nappe to fulfill the research gap. Previously described by Fuchs & Frank (1970) and Sharma (1980), the Jajarkot nappe in western Nepal have two distinctive crystalline lithological units: the Chaurjhari Formation and Thabang Formation. The previous unit consists of garnet-grade schist, and quartzites, with intrusions of basic rocks and granites, while the later unit consists of grey to brown crystalline limestones with biotite-quartz-schists. An unconformity is observed above the Thabang Formation. The younger geological unit above the unconformity is mapped as the Jaljala Formation, which is composed of fine-grained calcareous sandstone and calcareous siltstone with minor proportions of limestones and grey-green slates. At present work, a preliminary geological study was carried out to work on the stratigraphy of the Jajarkot nappe in the Jaljala areas at 1:25,000 scales. Fossils of crinoids are found in the rock unit of the Jaljala Formation. These fossils are considered the index fossils of the Silurian. In this case, the Jaljala Formation would be equivalent to the rocks of the Tethyan affinity, and further study is under progress. The concept that the thrust sheets are moved from north to south in the Himalayas will be evidenced by these findings. An attempt is made to correlate the presently found fossils with the crinoids of the Phulchauki Group of the Kathmandu nappe and with the root zone of the Tethys succession.

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Temporal and spatial heterogeneity of the Ailaoshan–Song Ma–Song Chay ophiolitic mélange, and its significance on the evolution of Paleo-Tethys

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The ophiolite is the direct evidence to restore the oceanic evolution, and it is used to identify the convergence boundary of the plates. Compared with ophiolite, ophiolitic mélange, especially its matrix, contains more information about the evolution of ocean. The evolution of eastern Paleo-Tethys, between the South China and Indochina blocks, recorded the whole process of rifting from Gondwana and their northward migration and convergence. To understand the tectonic implications from matrix of ophiolitic mélange, the Mesozoic Paleo-Tethys Ailaoshan–Song Ma–Song Chay suture zone located in the North Vietnam–Southeast Yunnan region acts as an ideal study area. Based on the structural geology, we reviewed previous zircon U-Pb dating and Lu-Hf isotopic analyses on the detrital zircon from the Ailaoshan–Song Ma–Song

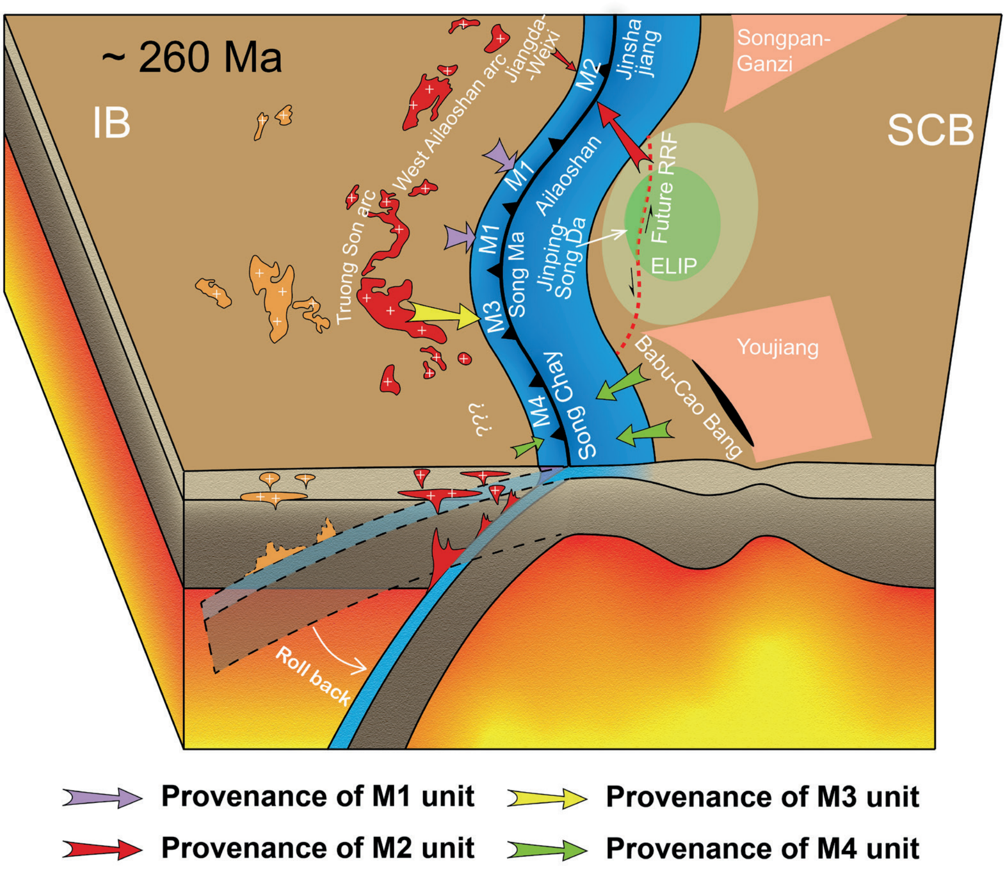

Fig. 1. Palaeogeographic reconstruction of SCB and IB at 260 Ma. Arrow indicated palaeo-currents

Chay ophiolitic mélange. Accordingly, we subdivide the matrix of these ophiolitic mélange into four parts (M1, M2, M3, and M4; Fig. 1). M1 is mainly located in the middle segment of the Ailaoshan–Song Ma belt. It shows age peaks of 440 Ma and 960 Ma with $\varepsilon_{Hf}(t)$ values of −19.6 ~ +10.3. M2 is mainly located in the NW segment of the Ailaoshan–Song Ma belt, showing a dominant age peak of ~260 Ma. Particularly, it has $\varepsilon_{Hf}(t)$ values of −28.9 ~ +8.1. M3 is mainly located in the SE segment of the Ailaoshan–Song Ma belt, showing the peaks at ~250 Ma, 440 Ma, and 960 Ma with $\varepsilon_{Hf}(t)$ values of −21.9 ~ +10.1. M4 is mainly located in the Song Chay belt, showing the peaks at ~310 Ma, 470 Ma, 610 Ma, 770 Ma, and 965 Ma with $\varepsilon_{Hf}(t)$ values of −28.2 ~ +10.8. The geochronological data of the detrital zircon from the matrix of the Ailaoshan–Song Ma–Song Chay ophiolitic mélange zone, documents a temporal heterogeneity between the M1, M2, M3, and M4 units, which formed at 310–270 Ma, 265–250 Ma, 245–240 Ma, and 310–255 Ma, respectively. The different components and provenances of each unit reflect a strike-parallel heterogeneity (Fig. 1). The M1 unit was mainly sourced from the Paleozoic sedimentary rocks of the Indochina Block (IB). The main provenance for the M2 unit is Emeishan Large Igneous Province (ELIP). The magmatic arc developed in the IB provided the materials for the M3 unit, and the detrital materials of the M4 were mainly sourced from the South China Block (SCB) (Fig. 1). The Cenozoic strike-slip deformation led to an inverted geometry of the M1, M2, and M3 units, accounting for a strike-perpendicular heterogeneity straight to the strike of the orogenic belt. The temporal, strike-parallel, and strike-perpendicular heterogeneity help us to decipher the tempo-spatial evolution of the Paleo-Tethys. The M1, M2, M3, and M4 units contain information from different evolutionary stages, likely recording the comprehensive history of the ancient oceanic basin. Importantly, our results demonstrate that both the active continental margin of the IB and the passive continental margin of the SCB acted as provenance sources that supplied significant amount of detrital material in the ophiolitic mélange matrix, indicating that the Paleo-Tethys Ocean was a “narrow” or “limited” ocean rather than the archipelagic ocean proposed before.

Deciphering complex facies distribution in a narrow basin: the western fragment of Skole Nappe (Campanian–Paleocene, Ropianka Formation, Polish Outer Carpathians)

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The evolutionary history of the Skole Basin during the Campanian–Paleocene period exhibits several cycles of progradational and retrogradational movement, accompanied by shifts from carbonate to siliciclastic-dominated sedimentation, which are recorded in the Ropianka Formation deposits (Kotlarczyk, 1978). These changes are primarily driven by fluctuations in relative sea levels and tectonic activity (Kotlarczyk, 1988; Kędzierski & Leszczyński, 2013). The study area is located south of Tarnów and encompasses western part of the Skole Nappe, the most external major tectonic unit in the Polish Outer Carpathians. Skole Nappe stands as a folded and thrust remnants of sedimentary infill of the Skole Basin, being one of a several deep-water basins located at the northern margin of the Tethys Ocean (Ślączka *et al*., 2012). The progradational-retrogradational cycles initiate with the appearance of sand-rich bodies at the lower part of the sedimentary log, which gradually diminish up the section. The depositional environment of the study area contains a broad range of distinguished submarine fan setting including channel-fill deposits, the transition zone between channels and lobes, and various sub-environments within depositional lobes such as the lobe axis, off-axis and lobe fringe, distal fringe, and interlobe areas. The intricate distribution of facies throughout the studied time interval can be attributed to the basin's asymmetry, characterized by a steep southern slope and a gentler northern slope, as well as the influence of multiple sediment sources. The significant aggradation of specific depositional elements, variations in calcareous sediment content, and changes in palaeotransport directions indicate the presence of morphological obstacles and/or the semi-confined nature of the Skole Basin in the study area.

Further field investigations have identified two distinct submarine depositional settings characterized by sediment bypass: channel-lobe-transition zone and marl-dominated lower slope or base-of-slope bypass zone. Despite domination of marls, the second type of bypass zone tends to show two different end-member variants. The first type involves a higher proportion of thin- and thick-bedded coarse-grained lag deposits, while the second type consists of dune scale bedforms with intraformational. Log with more intermediate characteristics occurs as well, reflecting the spatial continuum of facies changes in the marl-dominated bypass zone and transition to the marl-dominated lower slope and base-of-slope deposits. Record of intervals with siliciclastic sediment bypass within areas of predominantly marly deposition can serve as valuable indicators of turbidite system progradation despite relative sea-level highstand connected with carbonate production. Moreover, such deposits may indicate small-scale sea-level changes or tectonic pulses within deep-water monotonous sedimentary successions predominantly composed of fine-grained sedimentation.

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Ordovician spatial patterns of climate change inferred from isotope thermometers

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Ordovician was an extremely turbulent period for the Earth system, where the Great Ordovician Biodiversification Event (GOBE) occurred in the early-middle Ordovician. Many hypotheses were proposed, taking into account both biotic and abiotic factors. One such hypothesis posits that global cooling led to a transition from greenhouse to icehouse climate systems, which further triggered feedback mechanisms such as increased oceanic circulation, bio-productivity, and oxygenation during the middle Ordovician. Direct evidence, however, is still scarce. Here, we have compiled a comprehensive dataset of $\delta^{18}O$ (10,636) from carbonate rocks and fossil shells as well as clumped isotope temperature data (Δ_{47}; 88) spanning the entire Ordovician. Our study investigates climate change from both temporal and spatial perspectives.

We assessed the effects of the late diagenesis alteration, lithological differences, different depositional environments and water depths on the carbonate $\delta^{18}O$, and corrected the latitudinal effect of the $\delta^{18}O$ in seawater. The latitudinal temperature gradient (LTG) was introduced to account for the spatial patterns of climate change, which here refers to the difference in sea-surface temperature between low (<20°) and low-to-middle (20–40°) latitudes. We observed a gradual increase in the LTG from Tremadocian to Dapingian, indicating an amplified thermal contrast between low and low-middle latitudes. It suggested a remarkable climate cooling and shift towards an icehouse climate state, coinciding with the GOBE. From Darriwilian to Sandbian, the LTG weakens significantly and the temperature difference decreases, which is consistent with the plateau of global temperatures and the slow change in species diversity. After Sandbian, a progressive steepening of LTG was observed, which provides the first evidence for low paradoxical atmospheric CO_2 at the Late Ordovician. Our study supports the global cooling hypothesis and sheds light on the links between climate change and biological evolution across the Ordovician.

Palaeobiogeography of Late Bajocian–Tithonian ammonites of northeastern Iran

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Jurassic rocks are widely distributed and superbly exposed in the Alborz Mts. (northern Iran) and Koppeh Dagh (northeastern Iran). The Lower Jurassic and large parts of the Middle Jurassicare characterized by a thick siliciclastic succession, whereas the Upper Bajocian to Tithonian rocks are predominantly carbonates, which represent a platform, slope and basin system. The Upper Bajocian-Tithonian ammonite faunas the NNE Iran are mostly of Submediterranean affinity, but elements of Subboreal, Mediterranean, and Ethiopian provinces are occasionally intermingled. Palaeobiogeographically the Late Bajocian to Bathonian ammonites belong to Submediterranean Province, as elsewhere in north and central Iran. This is supported by the occurrence of ammonites such as Garantiana and Morphoceras and some cosmopolitan taxa such as Cadomites and Oxycerites. In order to unravel the origin of the faunal elements and their migration routes, the relationship of the ammonite fauna of Iran to that of other regions was evaluated. On the whole, at the species level, the Toarcian to Early Bajocian ammonite faunas of northern and central Iran show a close relationship to that of northwestern Europe. A characteristic feature of this fauna is the scarcity of Phylloceratidae (accounting for less than 1% up to 3%) and the absence of Lytoceratidae. Remarkably, from Late Bathonian onward to Kimmeridgian, Phylloceratidae account for more than 50% of the ammonites fauna. Palaeogeographic reconstructions show the position of the Iranian plate (North and Central Iran) during the Middle Jurassic time at the southern margin of Eurasia at a palaeo-latitude of around 30° N which rather corresponds to European regions (Enay & Cariou, 1997). The open migration routes across pericontinental shelf seas along the northern Tethyan margin that were approximately parallel to palaeo-latitudes may explain the strong affinities of the Late Bajocian–Bathonian ammonites of northern and Central Iran to those of the Submediterranean Province. The Callovian ammonite fauna has a typical northwest Tethyan character, and belong to the Submediterranean faunal province (Seyed-Emami *et al.,* 2013), and are largely dominated by Phylloceratidae ammonites. These pelagic taxa that preferred open oceanic conditions are accompanied consistently by Perisphinctidae, Reineckeiidae, Oppeliidae (Hecticoceratinae), Macrocephalitidae , Tulitidae, Aspidoceratidae (Parawedekindia, Peltoceras). On the other hand, this is supported by the occurrence of Submediterranean ammonites such as Macrocephalites, Pachyceras, and some cosmopolitan taxa such as Hecticoceras and Reineckeia. Some taxa from the Oxfordian- Kimmeridgian belong to the Western Tethys Province (Sequeirosia and Passendorferia) or Subboreal Province (Cardioceras). It is remarkable that, besides some cosmopolitan ammonites, there is no direct connection with faunas from southwestern Iran, western India and the southern Tethys.

Finally, the Tithonian ammonite faunas of northeastern Iran are mostly of Submediterranean affinity (Seyed-Emami *et al.,* 2013). However elements of the Mediterranean faunal provinces occasionally occur. In order to unravel the origin of the faunal elements and their migration routes, the relationship of the ammonite fauna of Iran to that of other regions need to be analysed in the future. Especially the appearance of several allegedly regionally restricted Ataxioceratidae such as Phanerostephanus, Nannostephanus, Nothostephans and the Oppeliidae as Oxylenticeras, which occur in Ethiopian Province (Page, 2008) is of great palaeobiogeographical interest.

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Bulldoze and rebuild: Modifying cratonic lithosphere via removal and replacement induced by continental subduction

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Establishing the mechanisms for craton modification is critical for understanding cratonic stability and architecture. Both plate tectonics and mantle plumes can cause weakening, mechanical decoupling, and even lithospheric removal. But craton modification – craton destruction accompanied or followed by craton rejuvenation – has received less attention. It is well-known that oceanic subduction dominantly destroys cratonic lithosphere with replacement to a lesser degree, and mantle plumes have been related to both destruction and rejuvenation. The role of continental subduction in craton modification, however, remains a comparatively open question. The North China Craton, as a previously stable continent with a lithosphere of more than 200 km since the Paleoproterozoic, was reworked and substantially destroyed since the Mesozoic, with intensive destruction occurring in the Early Cretaceous. Earlier in the Mesozoic, North China Craton experienced a continent-continent collision (as the upper plate) with the South China Block, forming the Sulu orogenic belt, providing an opportunity to understand the potential for craton modification due to deep continental subduction.

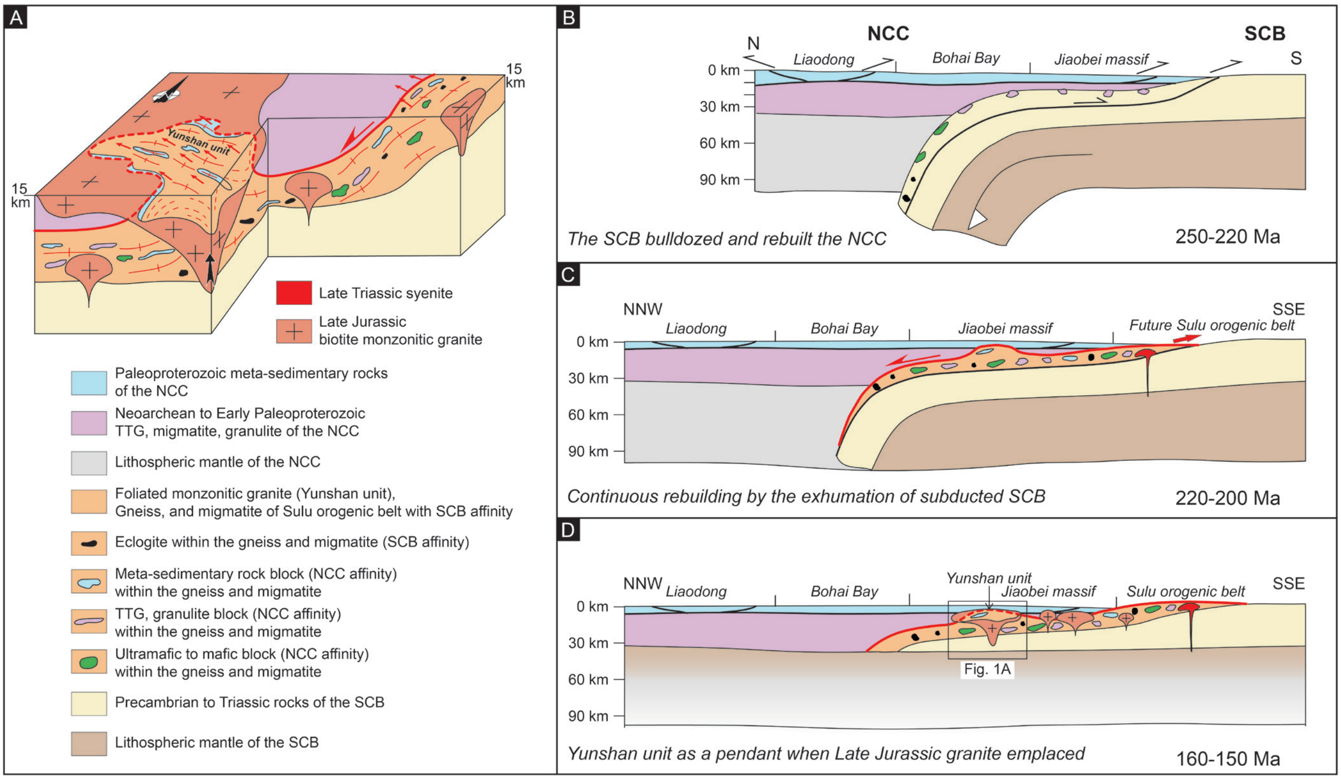

Fig. 1. "Bulldoze and rebuild" model of craton modification during continental subduction: A – geometry of the Yunshan unit in the Late Jurassic; B–D – tectonic evolution accounting for the 200-km-long tract of North China Craton (NCC) lithosphere below 16–20 km that was bulldozed and replaced by the subducted South China Block (SCB)

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In the North China craton, we report the presence of material (i.e., Yunshan unit) sourced from the underlying subducted plate. It is composed of foliated monzonitic granite and metamorphic sedimentary rocks that locally experienced crustal anatexis. Through detailed zircon U-Pb dating, it formed at latest Triassic (ca. 212 Ma). Importantly, the 800–700 Ma inherited zircons from the Yunshan foliated granite resemble those from the South China Block rather than the North China Craton. According to structural and magnetic data, the fabrics of the Yunshan foliated granite, characterized by gentle magnetic/mesoscopic foliations and conspicuous NW-SE-trending magnetic/mesoscopic lineations with a top-to-the-NW shearing. Its geometry, kinematics, and timing all compare favorably with the latest Triassic extensional structure accounting for the exhumation of the Sulu orogenic belt. We thus interpret the Yunshan unit to have been sourced from the subducted South China Block, then exhumed and emplaced into the overriding North China Craton (Fig. 1A).

Combining our new results with previous geological and geophysical data, we argue that from 250–220 Ma a 200-km-long tract of North China Craton lithosphere was bulldozed by the subducted South China Block, resulting in a lithospheric suture far from the suture zone at the surface. This lithospheric removal occurred at mid-lower crustal levels (16–20 km depth) – much shallower than previously thought possible. The bulldozed North China Craton lithosphere was simultaneously replaced by the reworked underlying South China Block plate. Such a “bulldoze and rebuild” lithospheric modification process minimized asthenosphere-lithosphere interaction, thus preventing the North China Craton from further modification (Fig. 1B–1D). Because there was essentially no net loss of lithosphere during deep continental subduction, the North China Craton largely maintained its stability for the time and did not suffer intensive destruction until later Early Cretaceous palaeo-Pacific oceanic subduction. This “bulldoze and rebuild” model can thus account for how a craton can maintain its stability during a collision with another continental plate.

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Tracing palaeocurrents from the Arctic Realm into the Tethys Ocean: the use of glendonite as an indicator for cold bottom water masses

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Today, the global conveyor belt of ocean currents is controlled by the configuration of continents and the climate. Conversely, ocean currents influence water and air temperatures as well as the amount of rainfall on a regional to local scale. In addition, they govern species distribution patterns, sedimentation patterns and the dispersal of nutrients in both oceans and epeiric seas. Therefore, the reconstruction of palaeocurrents is crucial for the understanding of ancient environments and the past climate.

An important driver for the global ocean circulation is the formation of deep water. However, deep-water production is difficult to estimate, and its circulation is difficult to reconstruct, not only today but especially in the geological record. Palaeocurrent reconstructions are often based on the temporal and spatial distribution of marine species. In this presentation, a new approach is proposed which uses the occurrence of glendonites as a proxy for cool bottom currents. Glendonites are pseudomorphs after the hydrous carbonate mineral ikaite ($CaCO_3 \cdot 6H_2O$) which only forms in environments characterised by near-freezing temperatures. Throughout the Phanerozoic, glendonites can be found in successions which were deposited in high latitudes. However, examples of glendonite occurrences in mid-latitudinal sections are also reported. One of these examples are upper Pliensbachian (Lower Jurassic) glendonites from a shallow-marine succession in South Germany which was located in the European epicontinental sea – an area, where it was technically too warm to form the precursor mineral ikaite. Based on petrographical and sedimentological investigations as well as stable isotope analyses it is concluded that a low temperature was the main factor for ikaite formation in the studied section. To explain the low water temperatures, a model for a thermohaline circulation in the European epicontinental sea is proposed. The cool climate in the late Pliensbachian initiated the growth of sea ice in high latitudes, leading to the formation of cold and saline bottom waters analogous to the modern formation of North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW). The cold bottom current flowed southward from the Arctic Realm through the Viking Corridor into the European Epicontinental Sea, thereby causing a massive cooling of the deeper parts of the epeiric sea, which led to the formation of ikaite in temperate areas. After passing the shelf, the bottom current entered the Western Tethys, probably forming a deep water mass.

The proposed model can help to explain mid-latitudinal glendonite occurrences not only in the Pliensbachian, but also in other areas and time slices which are characterised by cooling. Moreover, it enables the use of the pseudomorph as a tracer for cold bottom currents which can be a helpful tool for the reconstruction of global ocean current patterns.

The Banda Arcs and Carpathia/Pannonia: new insights on the Tethys Twins

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The Outer Banda and Carpathian arcs, of eastern Indonesia and Europe respectively, are examples of the highly arcuate fold-and thrust belts enclosing extensional basins that have been named oroclines. Both regions have experienced large scale extension within what is, overall, a compressive regime created by the convergence of major continental blocks and, despite major differences stemming from the quasi-oceanic setting of the one and intracontinental the setting of the other, there are reasons to suppose that comparative studies may produce insights into the evolution of both areas (Milsom, 2000). Processes in the Banda region are in some respects more open to direct examination, because extension is more recent, deep seismic activity is more widespread and basement structures are not concealed beneath thick sediment cover. To a considerable extent these advantages have compensated for the disadvantages of poor access and a relatively sparse database. The final two decades of the Twentieth Century saw rapid advances in understanding the area in terms of both geology and geophysics.

In the first decade of the 20th century the techniques of seismic tomography began to be applied (Hall & Spakman, 2003) and confirmed the earlier interpretation, based on hypocentre locations, of the presence of a single, scoop-shaped, slab underlying the Banda Sea (Milsom, 2001). Intensive field and laboratory studies of Seram, the largest island in the northern part of the Outer Arc, then identified exposures of rocks metamorphosed at ultra-high temperature in the vicinity of the crust-mantle boundary, which led to the abandonment of the earlier interpretations of the associated ultramafic rocks as ophiolitic (Pownall *et al*., 2013). The extreme extension that brought these rocks to the surface also affected the subducted lithosphere that underlies the Banda Sea, and is one of the many pointers to the importance of asthenospheric flows in creating the present situation.

While similar in many respects, the Carpathia-Pannonia area shows an orocline at a much later stage in its evolution, with some evidence concealed by later overprinting and some processes that would have been important in earlier stages now no longer occurring. On the other hand, some other aspects of orocline formation are likely to be better displayed there than in the Banda region.

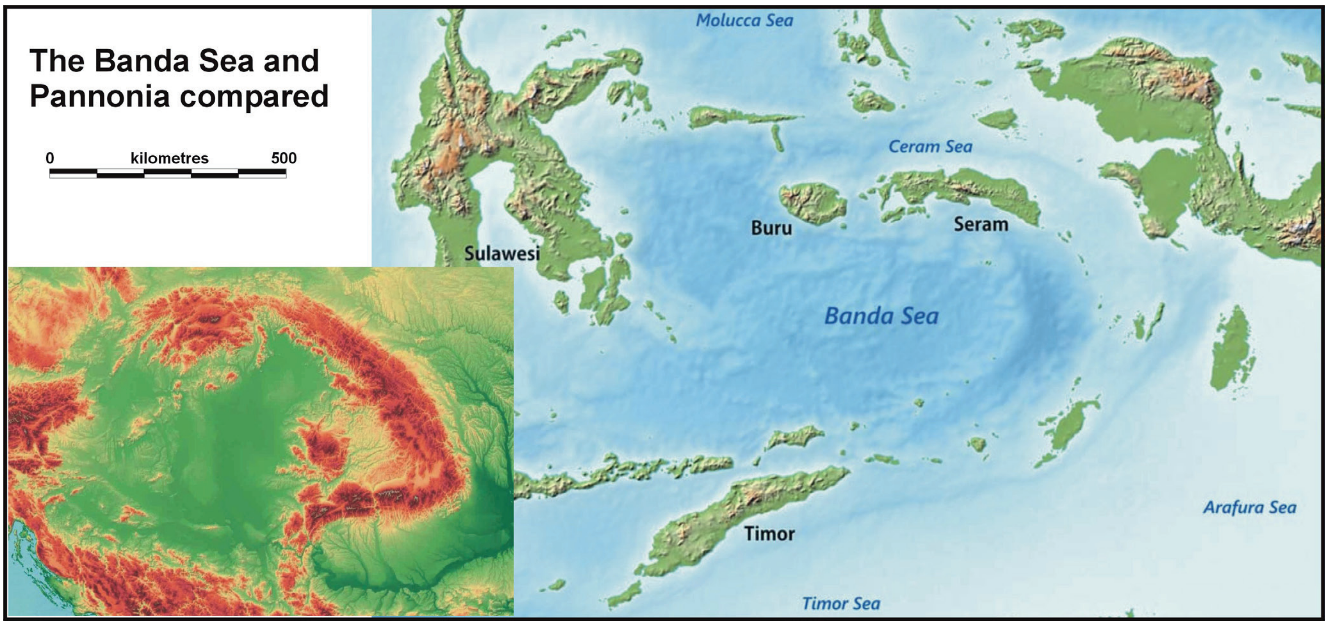

Fig. 1. The Banda Sea region and the Carpathian/Pannonian Basin regions, to common scale (Banda Sea: Freeworld maps https://www.freeworldmaps.net/ocean/bandasea; Carpathia/Pannonia: Global Mapper image based on SRTM topographic grids)

The now increasingly well determined history of the destruction of the Western Tethys and the development of the Alps-Carpathian-Dinarides orogen (e.g. Handy *et al*., 2015) offers strong support for theories involving mantle flow as a key factor in orocline formation.

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New biostratigraphical and geochemical data from the mélange complexes of the Meliata Unit s.s., Čoltovo village (Western Carpathians, Slovakia)

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The surrounding of the Čoltovo village is a well-known location related to the Meliata Superunit (especially Meliata Unit s.s.). The Meliata Unit is represented by intricate mélange complexes linked to the closure of the ancient Meliata Ocean, as a significant part of the Western Carpathians geological story. In general, Meliata complexes are divided into HP/LT Permian to Jurassic metamorphosed clastic sediments, carbonates and basic volcanics (Bôrka Nappe) and complexes of "mixed chaos" of the Jurassic low grade shales with huge Triassic olistostrome bodies (Meliata Unit s.s.), the latter being the main subject of this work. Outcrops near the village of Čoltovo along the slopes of the W–E trend on the Slaná River bank provided limited information only. Therefore, new parts were excavated in March/2022. After removal of debris, the very complex internal structure of the mélange can be clearly detectable. This new section is composed of six individual outcrops (ČLP1 to ČLP6 from left to right) and consists of two contrasting lithological parts. The eastern part is mainly characterized by strongly weathered gray fine-grained shales and tuffs containing blocks of lithologically variable rocks. These are mainly represented by basic volcanics and dark coarse-grained Jurassic crinoidal limestones. The western part of the section consists of red and white fine-grained siliciclastics with basic volcanic material, and blocks of dark red, green and purple radiolarites. In the upper parts of the outcrops, layers of dark crinoidal limestones, shales and conglomerates of the Jurassic age are present. The connection between these beds and the mélange is documented by their presence as blocks in the left part of the section. The mélange complexes are overstepped by the Lower Miocene organodetritic limestones, sandstones and breccias (Bretka Beds). Three samples from the western part of the new outcrops gave identifiable Middle Triassic radiolarians. In addition, an old outcrop to the east of the newly excavated section, provided a productive sample with Upper Triassic radiolarian microfauna. Our research was also focused on geochemical analyses of radiolaria-bearing siliciclastics and basic volcanics, aiming at understanding the palaeoenvironment of the Meliata Ocean. All of the sediment samples gave similar results, which point to shallow marine environment, close to the continental margin. The geochemical data indicate a mature continental sedimentary provenance. Based on these data, we interpret the source of the samples located to the north of the Meliata Ocean (possibly Permian clastics of the Gemer Unit). Basic volcanics sample from the right side of the section confirms basalt/basaltic andesite composition. From the study of the Čoltovo section it seems the sedimentary matrix of the olistostrome probably originated from a passive continental margin and it is mixed with advanced ophiolite-bearing nappes within a Jurassic accretionary mélange (Meliata Unit s.s.).

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Mafic and ultramafic associations of ophiolite (possible Tethyan ophiolite) in the Panlin-Pyaunggaung area, Mogok, Myanmar

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The Panlin-Pyaunggaung area is situated within the Mogok Metamorphic Belt (MMB) in Myanmar. The MMB extends for over 1,000 km along the western part of Shan-Thai Terrene (also known as Sibumasu Terrene) from the Andaman Sea as a narrow linear belt, then sharply bends east-northeastward through the northern part of Mogok including Panlin-Pyaunggaung area toward the China-Myanmar border and finally further northward into the East Himalayan Syntaxis. It comprises a sequence of regionally high-grade metamorphic rocks, representing the amphibolite-granulite facies grade belt intruded by granitoid rocks of various ages. Metamorphic rock units exposed in the area are marbles, calc-silicates and gneisses. Igneous rocks are peridotite, dunite, serpentinite, gabbro, granite, leucogranite, syenite and pegmatite. The ultramafic rocks (Pyaunggaung peridotites) mainly occur in the northern part of Mogok and have been considered as tectonites. Ophiolite sequence which consists, from bottom to top, of upper mantle peridotites/dunites, layered ultramafic-mafic rocks, layered gabbros, and felsic dikes occurs in the area indicating the typical lower part of ophiolite suite. The present ultramafities are mainly dunite-peridotite (harzburgitic or dunitic composition). Magnetic susceptibility of ophiolites reflects the highest point ($39.75 \cdot 10^{-3}$ SI units). It is found that the chromite spinel observed in ophiolites and it contains high Pm, Cr, Ni & V. These criteria suggested that ophiolites in the area were deep seated origin coming from the upper mantle source. Panlin-Pyaunggaung Ophiolites in the area fall within the field of the Alpine-type peridotite. High Ni–Low Al content corresponds to the suprasubduction zone (SSZ) ophiolites and might have a similar tectonic stetting of Tagaung-Myitkyina Ophiolite Belt in Myanmar.

Geochemical features of the mafic rocks in the Khangai-Daur belt, central Mongolia

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The Late Paleozoic–Early Mesozoic accretionary complexes of the Khangai-Daur belt, in central Mongolia, lie between the Siberian craton and the North China block. These complexes consist of Silurian mafic rocks (basalt, dolerite, and gabbro), Silurian–Devonian radiolarian cherts, and Carboniferous clastic rocks. While the mafic rocks are considered oceanic island alkaline, few studies have been conducted, and their classification is still under discussion. Understanding the petrogenesis and tectonic setting of these mafic rocks within the accretionary complexes is crucial for comprehending the tectonic evolution of ancient oceanic plates.

This study involves geochemical analyses of 39 mafic rock samples and whole rock Sr-Nd isotopes from 24 mafic rock samples collected from four localities within the Khangai-Daur belt: Uubulan, Ikh-Oortsog, Takhilt area in the Ulaanbaatar terrane, and the Burd area in the Kharhorin terrane. Geochemically, all mafic rocks from the Uubulan, Ikh-Oortsog, and Takhilt area exhibit the signature of ocean island basalt (OIB). They are characterized by alkaline affinity with enrichment in large ion lithophile elements (LILE) and light rare earth elements (LREE), as well as depletion in high field strength elements (HFSE) and heavy rare earth elements (HREE), resulting in a high concentration of ($(La/Yb)_{cn}$ = 4.5–15.6). In contrast, the mafic rocks from the Burd area exhibit tholeiitic-like affinity with less enrichment in LILE and LREE, and depletion in HFSE and HREE, resulting in a concentration of ($(La/Yb)_{cn}$ = 1.4–3.0). Therefore, the Ti/Y vs. Nb/Y and Ti vs. Zr ratio diagrams suggest that the samples were formed in a within-plate setting.

Our latest study reveals that the hornblende K-Ar age (412.7 Ma ±8.6 Ma) of the mafic rocks and the reconstruction of the oceanic plate stratigraphy of the accretionary complex at Uubulan indicate a Late Silurian age. The Sr-Nd isotopic compositions ($(^{87}Sr/^{86}Sr)_i$ = 0.7040–0.7078, $\varepsilon Nd(t)$ = 5.0–9.3) suggest that the magmas were derived from a deep OIB reservoir, indicating slightly heterogeneous magma sources. Overall, the results of this study suggest that alkaline and tholeiitic magmatism may have occurred during the Late Paleozoic within the oceanic plate between the Siberian craton and the North China blocks.

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A silicified wood from the Early Cretaceous sediments in the Kaligandaki Valley, west central Nepal

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A silicified wood has been discovered from the Tethyan Cretaceous (Berriasian) deposits belonging to the Kagbeni Formation of north Central Nepal. The wood exhibits anatomical features which are well in accordance with *Araucarioxylon nepalense* described by Barale *et al*. (1976) from another locality in the Kagbeni Formation near Kagbeni in the Thakkhola Valley in Central Nepal. It is a pycnoxylic wood with mostly uniseriate and rarely biseriate bordered pits on radial tracheid walls. According to recent taxonomic opinions this type of wood should not be treated as *Araucarioxylon*, but as *Agathoxylon* Hartig. Thus we propose the name *Agathoxylon nepalense* comb. nov. for this type of wood. The sandstones of the Kagbeni Formation have been interpreted as delta-deposits, with a major flow direction from the south. This suggests that the wood originated from the northern margin of Indian sub-continent.

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Radiolarian age and geochemical characteristics of the Permian bedded chert sequence in the Soi Dao area, Chanthaburi, Southeast of Thailand

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Permian chert and siliceous mudstone in the Soi Dao, Chanthaburi Thailand are extracted the details on radiolarian assemblage and age, change of depositional environment, and geochemical characteristics. Permian radiolarians were obtained in three study areas (ASD01, ASD14 and ASD09); which radiolarian age of each section is as follows: ASD01: Early Asselian to Early Sakmarian, ASD14: Late Sakmarian to Artinskian, and ASD09: Capitanian to Early Changhsingian. Considering the lithofacies, ages, and chemical composition of the rocks, a preliminary stratigraphy consisting of basaltic rock, radiolarian bedded chert, siliceous mudstone, and coarse-grained clastic of alternation of sandstone and mudstone in ascending order can be reconstructed. Data on geochemistry analysis, particularly chondrite-normalized REEs patterns of chert and siliceous mudstone, present a gradual change in that degree of the Ce negative anomaly decrease toward the stratigraphical upper position. These changes indicate that the depositional site of the Permian rocks transferred from a state of high hydrothermal activity to a state of weakened activity and that the influx of terrestrial clastics increased. Permian bedded cherts accompanied by basalts and siliceous mudstones recognized in the study area closely resemble to the Paleo-Tethys bedded cherts in terms of their lithofacies and microscopic features; however, their depositional period is much shorter than that of the Paleo-Tethys, indicating that it was deposited in another oceanic basin. The chemical compositions also show that the influence of hydrothermal activity weakened from the strong state, and the terrigenous clastics rapidly supplied.

Evolution of the Western Tethys as seen from the Western Carpathians' perspective

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The palaeogeographic positions of the pre-Cretaceous Tethys "western ends" (Kovács, 1992) and their relationships to easterly located oceanic domains remain to belong to the most challenging issues in deciphering the structure and tectonic evolution of the European Alpides (e.g. Schmid *et al*., 2020). Due to the westward increasing paucity of direct indications of ancient oceanic domains and their discontinuous occurrences, a number of sometimes considerably different reconstructions have been proposed by several authors. All these are based on various data and authors' preferences; therefore achievement of a widely accepted model seems not to be probable at present.

In general, searching for evidences of former oceanic domains in the nappe edifice of collisional mountain belts, commonly in the suture zones, is based on several fundamental criteria: 1) ophiolite slivers and ophiolite-bearing mélanges as vestiges of consumed oceanic lithosphere; 2) blueschist- to eclogite-facies metamorphosed units recording the subduction/exhumation processes within a subduction channel and/or accretionary prism; 3) deep-marine synorogenic sedimentary complexes like wildflysch or olistostromes; 4) mixture of these in chaotic units within an accretionary wedge; and 5) a specific case of intraoceanic subduction resulting in ophiolite obduction, but this is not considered as a continental collisional tectonic setting. Indirectly, position of past oceanic basins can be detected by: a) secondary occurrences of an oceanic crust-derived detritus, including the heavy mineral spectra, in syn- to early post-orogenic sedimentary clastic formations and clues to their source areas; b) shelf-slope-continental rise facies polarity of former passive margins; c) progradational trend of collisional thrust stacking of the lower plate with a suture (often totally destroyed) in the uppermost structural position in the rear part of an orogenic pro-wedge; d) subduction-related calc-alkaline magmatism accompanying the active margin; e) upper plate back-arc extension, or retro-wedge thrusting opposite to the pro-wedge in a bivergent orogen with the suture in its axial zone; f) major crustal-scale discontinuities revealed by deep seismic sounding connected to surface fault zones separating palaeogeographically distinct domains indicating possible plate boundaries.

All these potential clues have been considered while reconstructing the Mesozoic tectonic evolution of the Western Carpathians (Plašienka, 2018 and references therein). It should be noted that no single criterion characterized above, even not a few indirect signs are enough to define a particular orogenic zone or unit as an evidence for an oceanic suture. There is only one Western Carpathian zone which fulfils most of them. It is represented by units and rock complexes grouped in a tectonic superunit known as the Meliaticum and respective oceanic realm as the Meliata Ocean. The Meliata-related units bear clear signs of criteria 1, 2, 3, 4 and indirect indicators a, b, c and e. Whatever different are the interpretations of the Meliata Ocean origin (e.g. born as a back-arc basin initiated by the northward subduction of Palaeotethys, or simply as a northern margin or embayment of Neotethys), or even its existence as an independent domain (regarded as a facies zone only), all palaeotectonic interpretations of the Alpine tectonic evolution of the Western Carpathians have to take into account these pieces of evidence.

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U-Pb and K-Ar geochronology of the subvolcanic rock pebbles from the Cretaceous and Paleogene gravelstones and conglomerates of the Pieniny Klippen Belt (Carpathians; Poland, Slovakia) – relevance for tectonic evolution and palaeogeography

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In the Pieniny Klippen Belt (PKB), the Cretaceous and Paleogene conglomerates and cohesive debrites commonly contain pebbles and blocks of the subvolcanic rocks among other, mainly sedimentary rocks (e.g. multicoloured sandstones, oolitic limestones, dark bivalve coquinas, dolostones, etc.). This detritus was interpreted as derived from the Andrusov Ridge located south of the PKB basin (Birkenmajer, 1988). Age of these subvolcanic rocks, regarded to represent subduction-related igneous activity, was previously constrained by K-Ar whole rock dating as c. 140–90 Ma, leading to suggestion that during Late Jurassic to Early Cretaceous PKB basin developed on oceanic lithosphere, subducted during at the end of Early Cretaceous (Birkenmajer, 1988).

Within this study, the geochemical composition, the K-Ar whole rock age and the U-Pb zircon ages of the above mentioned subvolcanic rocks were studied. The pebbles are well rounded. They are represented by granitic and subvolcanic andesitic-type rocks (mainly andesite, basaltic andesite, basaltic trachyandesite, trachyandesite and rhyolitic pebbles, and rare dacite, tephrite, trachybasaltic and basaltic pebbles). Domination of andesitic pebbles, bimodal spectrum of volcanic rocks with high content of SiO_2 (rhyolites, dacites) and Na_2O and K_2O within mafic and transitional ones is observed. Their petrographic character and geochemical analysis of concentration of rare elements with $MgO > 2\%$ ratio and La/Yb 4–35, $Sc/Ni < 1.5$, $Sr/Y < 20$, $Ta/Yb > 0.1$, $Th/Yb > 1$ values, indicate magmatic island arc of active continental margin similar to Andean-type subduction regime.

The K-Ar whole rock dating was performed for 17 samples. The obtained ages cover mainly the Early Cretaceous time span, with the most data representing the Barremian-Albian, therefore are coherent with Birkenmajer (1988) results. However, the U-Pb SHRIMP zircon dating reveled different results. Most of the analyzed subvolcanic rock samples (9) give ages in the narrow range of c. 270–266 Ma. The ages are based on concordant data with amount of measured point in a range of 20–30, and are characterized by low error bars, usually lower than ±2 Ma. In addition, one sample of subvolcanic rock gave lower quality results, with a few youngest, partly concordant, zircons grains giving the age of 251.0 Ma ±8.5 Ma. Moreover, one sample of orthogenesis was analyzed, which is regarded to represent crust on which the volcanic arc developed. In this case the U-Pb SHRIMP zircon dating result is 493.9 Ma ±4.1 Ma.

We regard these pebbles/blocks to be derived from the Inner Carpathians, assuming therefore lack of the Andrusov Ridge located south of the PKB basin (comp. Plašienka, 2018). The results of K-Ar whole rock dating is representative for intensive diagenetic overprint, rather than age of the rock. The U-Pb data clearly indicate, that subduction-related magmatic arc developed during the middle Permian (Guadalupian). This follows, that the oceanic crust was of the middle Permian or older age, and thus cannot be related to the Jurassic-Early Cretaceous development of the PKB basin. The magmatic arc was presumably connected with southern margin of Laurusia and subduction of oceanic crust of the Paleotethys (proto-Vardar Ocean?).

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The margins of the Early Jurassic Trento Platform (Southern Alps)

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Examples of Lower Jurassic carbonate platform margins are rare, probably due to the scarcity of good outcrops. One of the major palaeogeographic units of the Mesozoic Tethys, the Trento Platform, however, shows two different margin types facing the Belluno and the Lombardian basins.

While the western margin, facing the Lombardian Basin, is showing an ooidal unit with frequent mud mounds (Massone Oolite), the eastern margin was poorly characterized, mainly due to difficult stratigraphic definition and problematic accessibility of outcrops. The eastern platform margin characteristics are strictly controlled by tectonic activity and the type of carbonate factory; the differences between the eastern and the western margin could be linked to windward-leeward position of the platform margin, more protected to the west than to the east.

Subsidence increased since Late Triassic, due to the opening of the Alpine Tethys, defining shallow water areas, dominated by subtidal and peritidal muddy carbonates, and deeper basins, such as the Belluno and Lombardian Basin. More than 500 m of mud-dominated carbonates developed until Early Sinemurian, when major switch in the carbonate factory occurred. The Hettangian-Early Sinemurian margin is usually not well exposed and is strongly dolomitized and appears to be a tectonically controlled escarpments.

Since Late Early Sinemurian, the carbonate factory changed and led to a huge production of peloids and ooids, promptly shed in the surrounding basin: in the Eastern Trento Platform we recognize a 400/500 m thick wedge of Sinemurian to Pliensbachian ooidal calcarenites pinching-out towards the basin, with scattered bioconstructions made of calcareous sponges across the margin. This wedge pinches out also towards the platform interior, showing that the ooids were poorly preserved on the platform top. The preserved slope shows an angle of about 20-25°. In the western margin, the resedimented ooids are more limited, probably due to the limited size of the marginal carbonate factory.

In the Late Pliensbachian, probably in the Margaritatus zone, a drowning phase affected part of the eastern carbonate platform, switching to encrinitic calcarenites, while in the western one carbonate production continued until Bajocian. These encrinites are extremely thin on the platform top, but a resedimented wedge in the proximal basin highlights the position of the topographic margin.

The margins of the Trento Platform is a rare example of Early Jurassic carbonate platform margin that can be used as a reference for coeval carbonate platform depositional systems.

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Palaeogeographic perturbations in the key-area between the Alpine Tethys and the Neotethys Realms during the time of tectonic overturns: Jurassic of the Alpine-Dinaric transition zone

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The major Mesozoic palaeogeographic disintegration of the present-day transitional area between the Alps and the Dinarides (Slovenia) occurred due to the Middle Triassic rifting event related with the opening of the Neotethys Ocean. By the Norian, three major palaeogeographic units were formed: the Dinaric (Adriatic, Friuli) Carbonate Platform (DCP) in the south, intermediate, E-W extending Slovenian Basin (SB) and the Julian Carbonate Platform (JCP) in the north. The platforms were characterized by a Dachstein type platform, while the basin was filled with hemiplegic and resedimented limestones, most of which are now dolomitized. To the west, there was a shallow water "bridge" between the two platforms. After the Triassic-Jurassic Boundary crisis, the palaeogeographic setting was preserved, but the margins of the platforms turned into ooidal factories. During the Early Jurassic, SB was almost exclusively filled with ooid calciturbidites from the north, which can be explained by the wind/leeward position of the basin with respect to the particular platform. The first rifting phase of the opening Alpine Tethys, generally dated to the earliest Jurassic, is poorly expressed in this area. The main products are limestone breccias that occur in the western part of the SB. In contrast, the second rifting phase (dated to the Pliensbachian in Slovenia) completely disintegrated JCP. The margins subsided first and were characterized by open shelf conditions with crinoid meadows, while the inner parts of the JCP remained shallow-marine. In the SB, the initial subsidence can be seen in the altered composition of the calciturbidites. Namely, the ooid/peloid dominated resediments changed to crinoid/lithoclast dominated. In the Toarcian, sedimentation ended on most of the JCP, with only sporadic marls occurring at the margins. At the same time, the sedimentary environment of the DCP also deepened and nodular or crinoid limestone was deposited. The SB is characterized by uniform clay-rich sediments that vary greatly in thickness, indicative of differential subsidence caused by the second rifting phase. In the Middle Jurassic, shallow-water sedimentation re-established on the DCP, the margin being characterized again by ooidal shoals, the sedimentation of the SB gradually changed to siliceous limestone, while the JCP and the "bridge" between the JCP and DCP are characterized by non-sedimentation. The last important Jurassic change occurred during the Bajocian-Bathonian stages. Condensed Ammonitico Rosso-type limestone began to be deposited on the "bridge" and the JCP, while sedimentation in the SB changed to pure radiolarite. In the past, this was interpreted as a result of thermal subsidence associated with oceanization of the Alpine Tethys. However, studies in the last decade suggest a more complex tectonic evolution. Because the area in question lies between the opening Alpine Tethys to the west and the concurrent onset of subduction of the Neotethys to the east, it has been subject to strong differential subsidence between the large-scale DCP and all units north of it. The exact nature of the tectonic deformation is not yet clear, but a transtensional regime is most probable. These events resulted in the disintegration and collapse of the northern DCP margin, as evidenced by the sedimentation of limestone breccia megabeds along the entire SB southern margin. These megabeds not only indicate enhanced tectonics, but also provide important information about the pre-Middle Jurassic architecture of the DCP margin, which is no longer preserved. They consist of very diverse limestone lithoclasts and an ooid packstone matrix. Analysis of the clasts revealed that the Late Triassic DCP margin was characterized by Dachstein-type reefs and the Early Jurassic by ooid shoals. In the interior of SB, these strata merge into ooid calciturbidites interlayered between radiolarite and become completely wedged in the northern part of the basin. Corresponding gravity-flow deposits also sedimented on the subsided "bridge" between the DCP and the JCP, and even on the northern margin of the DCP itself. An important difference is the simpler composition of the resediments in this area. Namely, they consist entirely of Middle Jurassic platform margin and slope lithoclasts. This is explained by the less pronounced palaeotopography between the active platform and submerged "bridge", which did not allow erosion of the older platform limestone (as observed in SB). The described collapse of the DCP margin caused it to retreat, and marginal reefs formed over the underlying inner platform limestones in the Late Jurassic. The emersion phase in the Kimmeridgian ended reef growth and the margin turned back into ooid rich shoals. At the same time, the SB was characterized by continuous radiolarite sedimentation and drowned JCP together with the "bridge" with the Ammonitico rosso facies, characterized by several stratigraphic gaps. Rare calciturbidites are interbedded in areas near the DCP (southern SB and a drowned "bridge"). At the end of Jurassic, all areas north of the DCP show uniform sedimentation of the Biancone Limestone Formation.

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Factors controlling a depositional architecture in synorogenic Outer Carpathian basins – an example of Oligocene-age successions from the Fore-Magura Unit, Poland

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A Fore-Magura Unit is strongly tectonically-engaged tectonic unit of the Polish Outer Carpathians, sandwiched between Magura and Silesian nappes. Due to poor and sparse exposure of the Fore-Magura Unit, which is covered by the Magura Nappe, there has been no comprehensive interpretation of depositional systems of the Fore-Magura Basin (Eocene–Oligocene), a part of the Paratethys realm. Therefore, in order to broaden our knowledge about depositional conditions in this part of the Outer Carpathian basins, two turbidite sequences (Szczawa and Klęczany) were subjected to detailed lithofacies and sedimentological analysis.

The 100 m thick Szczawa section is predominantly composed of thin and medium thick turbidite sandstones associated with co-genetic turbidite mudstones, which thickness greatly exceeds that of underlying sandstone. The latter ones show another peculiar features, like opposite palaeocurrent directions between base and top of a bed, mud-rich banded and heterolithic structures, and combined-flow bedforms, including small-scale hummocky-type structures. All those sedimentary features reflect deposition from mud-rich low-density turbidity currents enclosed within small confined basin, which prevent each flow from further down-current propagation, and eventually resulted in trapping (ponding) of the whole flow within confinement, a process associated with flow reflections and internal Kelvin-Helmholtz waves propagation (Siwek *et al*., 2023). This mini-basin can be situated on the southern flank of the Fore-Magura Basin, i.e., on the slope of the Fore-Magura Ridge (Siwek *et al*., 2023).

The 170 m thick succession at Klęczany is composed of thick-bedded amalgamated sandstones, grading into sandstone-mudstone turbidite sequences. The former reflect deposition from high-density turbidity currents and hybrid flows, and are stacked into a few to over ten metres thick tabular lobes, and can be interpreted as lobe axis or distributary channel deposits. These lobes are often topped by so-called 'bypass' facies indicating the moment a lobe attained a critical thickness which prevented the accommodation of new deposit, thus heralding a feeder channel avulsion. The recurring process of lobe building and feeder channel avulsion resulted in compensational stacking of subsequent lobes (Piazza & Tinterri, 2020). The upper part of the Klęczany section reflects deposition from low-density turbidity currents and aggradation of turbidite beds into upward-thickening sequences resulting from lateral compensation and/or forward progradation of subsequent lobes. Considered as a whole, the Klęczany succession is fining upward, and shows decrease of sand net-to-gross, accompanied by increase of more distal facies. Therefore, that depositional system can be situated within single submarine base-of-slope fan featured by retrogradational stacking pattern.

Ponded turbidite beds, together with their whole inventory of sedimentary structures, are an evidence of the crucial influence of structural confinement on unrestricted flow propagation on the seafloor. The presence of structural confinement on the basin slope may have been associated with regional compression and tectonic activity of the Outer Carpathian basins. In the case of the Klęczany section, short-term autocyclicity is manifested in compensational lobe stacking pattern and cyclic feeder channel avulsions. A long-term variability, probably covering the whole Fore-Magura realm, can be identified with one sequence stratigraphy cycle – from forced regression resulting from sea-level falling stage to sea-level lowstand, reflected in the transition from amalgamated massive sandstones to sandstone-mudstone turbidite sequences (Catuneanu, 2006). Alternatively, the uplift-denudation cycle due to tectonic activation of source area (Mutti *et al*., 2003) can be considered as an explanation of retrogradational stacking pattern of the Klęczany Fan, with eustatic sea-level fall involved (Pszonka *et al*., 2023).

To conclude, the regional and local changes of depositional conditions in deep-water basins can be related to tectonics, as well as to eustatic short- or long-term sea-level changes, or combination of both, and can give the readable rock record in sedimentary successions accumulated especially in synorogenic marginal basins (Pszonka *et al*., 2023). These include foreland-type Outer Carpathians basins during Oligocene times, which were located in the Central Paratethys isolated from the Tethys Ocean during Eocene-Oligocene geotectonic reconstruction of the Circum-Carpathian realm.

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Reddish multiphase infillings in the megalodontid bivalves and solution voids in Julian Alps – NW Slovenia

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At a nature-preserve protected site in the Julian Alps (NW Slovenia), in the Pod Peski valley, red fillings of megalodontid bivalves occur within the Upper Triassic Dachstein limestone. Based on optical and cathodoluminescent microscopy and X-ray fluorescence (XRF) analysis, four generations of shell fillings were recognized, some of which contain both cement and sediment subgenerations. Logging and sampling of the limestone sequence a few meters below and above the "main" layer containing the megalodontids mentioned above revealed that the limestone is characterized by solution voids similar to the megalodontids. Namely, these voids are also filled with reddish multigeneration sediment with alternating calcite cement. Adjacent neptunian dykes were studied to clarify their influence on the last generation fillings. Two of them, located directly on the "main" layer with red-filled megalodontids, contain planktonic foraminifera, indicating Middle Jurassic or younger age. The next two neptunian dykes are located directly above the "main" layer, and one contains clasts with calpionellids characteristic of the Late Jurassic/Early Cretaceous. The last dyke explored is located a few tens of meters from the "main" layer and is several hundred meters long. In a few sample from this dyke Early Cretaceous planktonic foraminifera were identified. Microscopic analysis revealed that the reddish sedimentary fillings are part of a complex palaeokarst system that produced the first three generations of fillings, and in the last (fourth) generation we noted similarities between the megalodontid fillings and neptunian dykes on the "main" bedding plane. In addition, a Santonian–Maastrichtian sedimentary fill with globotruncanid foraminifers were discovered in the upper part of the succession in one of the solution voids.

Unraveling the collisional history of the Western Carpathians through deep geophysical sounding

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The ALpine-CArpathian-PAnnonian (ALCAPA) block is one of the terranes involved in the Alpine-Tethys suture along with the North European Plate. In the Western Carpathians, this suture is supposed to be represented by the Pieniny Klippen Belt (PKB) which is a few kilometres wide and about 600 km long unit between the Outer Western Carpathians (OWC) and Central Western Carpathians (CWC) (Plašienka *et al*., 1997; Schmid *et al*., 2008).

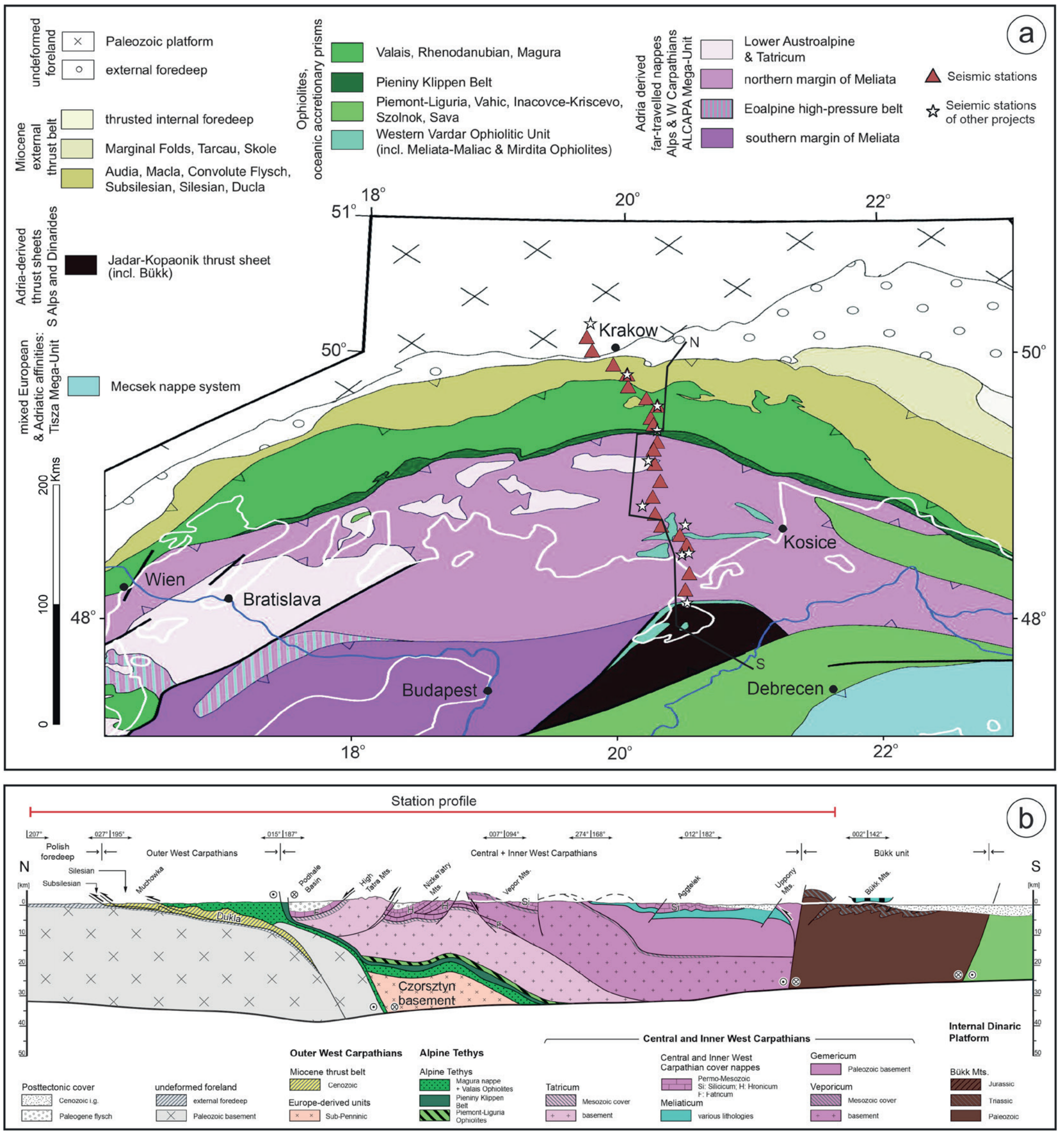

Fig. 1. Geological map of the Western Carpathians and surrounding region (the red triangles are the station locations) (a) and cross-section across the Carpathians (b) showing the extent of this profile (Schmid *et al*., 2008)

Unlike the Neotethian suture in the Western Carpathians, the PKB does not show the typical characteristics of a suture. The PKB is a sub-vertical unit with mainly shallow marine limestone and flysch deposits in a conspicuous "block-in-matrix" structure (Plašienka *et al*., 1997). The presence of "exotic" sediments in the PKB and the southernmost units of the OWC along with their shallow marine deposition environment led to the theory proposing the presence of a continental sliver called the Czorsztyn Ridge in the Alpine Tethys, dividing it into two oceanic/marine basins: the Magura Ocean to the north and the Vahic Ocean to the south (Plašienka, 2018). This controversial continental fragment possibly forming the basement for PKB successions, and its structural relationship with the adjoining OWC and CWC units, make it the main target of this project. The objective is to find evidence of the presence of this continental block, the Czorsztyn Ridge, which may have subducted along with the Vahic oceanic lithosphere underneath the CWC (Schmid *et al*., 2008).

A passive seismic experiment will provide insight into the deep lithospheric structure across the PKP, testing the presence of a tectonic suture along with relaminated remnants of the Czorsztyn Ridge, and potential remnants of subducted or underthrusted lithosphere. Eighteen broadband stations have been deployed in a ~N-S transect (Fig. 1a) under the umbrella of the AdriaArray initiative, cutting across the PKB and Neotethian Meliata suture to the south. The data obtained during up to three years will complement 10 other permanent and temporary broadband stations, forming an approximate 370 km long profile and will be used to perform receiver function analysis and build structural and velocity models of the lithosphere (i.e., Schiffer, 2014; Schiffer *et al*., 2023) beneath the Western Carpathians. The horizontal extent of the imaging is shown in Figure 1b.

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Tectonics of the northern Carpathians basement in the light of electromagnetic and gravity data analysis

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The northern part of the Carpathians covers the north-eastern area of the Western and north-western of the Eastern Carpathians. The basement of the Carpathians in this zone is of a transitional nature and is relatively poorly explored, which results from its deep burial, in particular under the so-called Outer Carpathians. The interpretation of the tectonics and geodynamics of the basement depends to a large extent on the analysis of large scale geophysical data. In this area, regional seismic surveys were carried out mainly using the so-called deep refraction and numerous geophysical works using gravity, magnetic, geomagnetic and magnetotelluric methods. The subject of the presented work is a review of the regional image of electromagnetic and gravity studies carried out in this area, with particular emphasis on the territory of Poland, within which the authors carried out numerous research works. Electromagnetic research allows for the construction of a regional model of basement resistivity distributions and the determination of general outlines of its geometry as well as the formulation or testing of the concept of its geodynamical interpretations. An auxiliary role in this aspect is played by gravity data allowing to recognize the density distribution of the basement and constituting a set of additional data for integrated interpretation. The area outside the territory of Poland was presented on the basis of literature data, creating an extensive regional background for the results of research related with the participation of the authors in Poland. Within the Polish Carpathians, there is a structural reconstruction of the Carpathian overthrust and its basement, as well as a clear change in the nature of geophysical fields, e.g. the system of gravity field anomalies. Due to the deep burial of the Carpathian overthrust in this area and the complex structure of the orogen, which hinder effective drilling penetration, its fragmentary and uncertain recognition is based mainly on geophysical surface studies. The complex structure of the orogen reduces the effectiveness of the use of the seismic reflection method, the participation of which is limited in practice to the recognition of the basement in the marginal zone of the Carpathian overthrust. In the remaining area, alternative methods of surface geophysics are used, i.e. the magnetotelluric and gravity method. An important role in recognizing the basement of the Eastern part of the Polish Carpathians was played by magnetotelluric soundings that cover the above mentioned area with a relatively dense network of several generations of measurement points. The results of the interpretation of the MT soundings were used to construct a resistivity model, which was verified by new results of regional processing of seismic data and magnetotelluric and gravity modelling. The visualization of resistivity distributions was presented through maps interpreted at selected depth levels and in the resistivity cross-sections form. Resistivity distributions are the basis for interpreting tectonic zones marked as resistivity contrasts. Forward modelling and inversion of gravity data were used to verify resistivity structural models.

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Reconstruction of the Miocene depositional architecture of the Carpathian Foredeep basin based on geophysical data

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The Carpathian Foredeep in Poland is divided into two parts, eastern and western, with different tectonic frameworks and conditions of the Neogene sedimentary fill. The boundary is the so-called Krakow Ridge associated with the contact of two regional tectonic units: Upper Silesian and Malopolska blocks. The width of the Foredeep varies regionally and significantly differs in the western and eastern parts. It was developed within the epi-Variscan platform. Two zones can be distinguished in the Foredeep: the inner (older) zone and the outer zone. The subject of the presented work is the eastern part of the outer zone of Foredeep located in front of the head of the Carpathian thrust and filled mainly by autochthonous Miocene formations. The meridional width of this zone of the basin varies from about 10 km in the vicinity of Krakow to nearly 100 km in the central part. Its tectonic framework is defined from the south and south-west by marginal structures of the Carpathian overthrust and tectonic units of the folded Miocene. From the north-east and north-west, the border is marked by a system of faults in the foreground of Roztocze Upland and the Holy Cross Mountains. In the Sub-Cenozoic basement, a set of large faults of NW-SE length, with different times of formation and activity, is marked. These faults locally define horst structures and tectonic grabens. Some of the faults continue under the Carpathians, under which there is also a system of transversal faults in relation to the main axis of the orogeny. The influence of the tectonic structures of the basement is noticeable within the Miocene cover by faults disappearing towards the surface and continuous deformations of the adaptive type.

The outer foreland basin is filled with marine molasse type deposits of the unfolded autochthonous Middle Miocene with a thickness of up to approx. 3.500 m. The complex of Miocene formations is formed, in the lower, south-western and central part, by strongly differentiated submarine fan deposits accompanied by basin plain formations and gravitational flow deposits, including turbidite deposits characteristic of flysch sedimentation. The outer part of the fans smoothly transitions into the zone of fine-clastic sedimentation of the basin plain. Above the complex of submarine fan sediments, there are thick complexes of sediments of deltaic origin, which are also intensively variable facies, creating a set of channel (coarse-grained) and extra-channel (fine-grained) facies. The highest, relatively thin part of the sediments is formed by shallow coastal shelf formations. Submarine fans and river deltas developed mainly in the zone of the south-western and southern coasts of the Miocene reservoir, surrounded by river mouths providing an abundant supply of material from the rising and eroded Carpathians. In the north-eastern and locally even in the middle part of the basin, sediments may appear, for which the feeding area was located in the hinterland of the northern and north-eastern coast of the Miocene Sea.

The limited scope of extraction of drill cores resulting from the exploratory and exploitation nature of drilling makes it necessary to use borehole and surface geophysical data to reconstruct the depositional architecture. Processing and interpretation of geophysical data for a complex of Miocene sediments with such characteristics are problematic and ambiguous. Numerous sources of sedimentary material supply in the form of river mouths and submarine channels cause a significant diversification of the depositional architecture of the Miocene basin, making it difficult to trace uniform stratigraphic and lithological and facies boundaries. Sedimentary conditions cause, on the one hand, a certain monotony of the sediments, dominated by clastic formations, enriched by evaporate sediments horizons, and on the other hand, great lateral and depth facies differentiation. Geophysical well-logging data allows to recognize the lithological and facies variability of sediments and to determine the sequence of changes along the borehole trajectory. Seismic reflection data was used to track lateral variability. For the seismic reflective method, the reflective boundaries, characterized by a significant, abrupt change in acoustic impedance, are of primary importance. Within the Miocene basin, numerous reflective boundaries with high lateral variability and non-obvious stratigraphic identification are observed. In a complex of siliciclastic deposits, seismic wave reflections are recorded from the boundaries separating fine-grained lithofacies and medium- and coarse-grained facies. Due to the dominance of deltaic sediments and submarine fans in the depositional architecture of the Miocene complex, the regional continuity of such boundaries is problematic, and their unambiguous stratigraphic identification is practically impossible. To sum up, intense lithological and facies variability of clastic deposits, both lateral and vertical, should be expected within the Miocene complex. The sediments of individual fragments of submarine fans and deltas overlap each other, and there may also be overlaps with the sediments of neighboring fans. Such characteristics of the complex translate into a variable seismic pattern with numerous reflective boundaries and intense lateral variability of the seismic signal characteristics.

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Foraminifers from the early basin of the Polish Outer Carpathians: relationship with the Western and Eastern Tethys (Tithonian)

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The formation of the Polish part of the Outer Carpathian Basin was initiated by the rifting process which led to the collapse and disintegration of the southern margins of the European Platform in the Late Jurassic. Fragments of carbonate platform were incorporated into the basin structures which divided the area into several sedimentary zones located at different depth. Under these conditions, most of the carbonate sediments were transported to the basin in the form of submarine landslides and gravity flows of varying densities, or accumulated during pelagic sedimentation. These deposits belong to two formations exposed in the westernmost part of the Polish Outer Carpathians, located near the Polish-Czech border. The first is mainly represented by the Tithonian marls (Vendryne Fm.) which also contain redeposited carbonate rocks and fossils (Oxfordian-Tithonian), the second is composed of limestones and marly shales of the late Tithonian-Berriasian (Cieszyn Limestone Fm.). These oldest sedimentary rocks in the Polish Outer Carpathians contain mainly benthic foraminifers and very scarce plankton occurring in exotic blocks and sometimes directly in sediments forming both formations. The first group includes forms with calcareous walls and also cemented with siliceous or calcareous material. Calcareous benthic forms belong mainly to Vagulinidae (*Vaginulina*, *Vaginulinopsis*, *Astacolus*, *Citharina*, *Citharinella*, *Lenticulina*, *Palmula*), Nodosariae (i.e. *Frondicularia*, *Nodosaria*, *Dentalina*), Epistominidae (*Epistomina*), and Polymorphinidae (*Guttulina*), while agglutinated taxa are represented by Verneulinidae (*Uvigerinammina*, *Paleogaudryina*, *Belorussiella*, *Verneuilina*), Andercotrymidae (*Praedorothia*, *Protomarssonella*, *Pseudomarssonella*) and Textulariopsidae (*Bicazammina*, *Hagimashella*, *Textulariopsis*). They can be related to the Jurassic shelf microfauna, which are known both from the Tethys and the European Platform. Among foraminiferal benthos there are also very rare agglutinated taxa belonging to several genera: *Melathrokerion*, *Buccicrenata*, *Alveosepta*, *Pseudocyclammina*, and the more common calcareous forms of *Andersenolina*, *Neotrocholina*, *Trocholina*, *Paalzowella*, as well as of *Discorbis*, which inhabited shallow marine environments formed around the elevations within the basin as well as on its coast.

Recently, apart from the benthic microfauna isolated Globigerina-like forms have been also found in the Tithonian deposits. These few forms resemble early planktonic foraminifera of the Western Tethys (*Gl. oxfordiana*, *F. hoterivica*) as well as the taxa known epicontinental and sub-Tethyan seas located north (*“Gl.” stellapolaris*) and east (*Gl. balakhmatovae*, *G. terquemi*) of the studied area.

The taxonomy, abundance and state of preservation of the described foraminifera from the early basin of the Polish Outer Carpathians indicate a connection with the gradually degraded areas of the platform inhabited by benthic and plankton communities from both the Tethyan and Boreal seas. The studied foraminifera resemble the microfauna of Western and Eastern Tethys and adjacent platforms.

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Larger Benthic Foraminifera from Paleocene–Eocene carbonates, Eastern Tethys, Meghalaya NE India – their comparison with Western Tethys and palaeobiogeographical significance

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India–Asia plate collision and uplift of the Himalaya took place during Paleocene–Eocene time (50 Ma). The extension of western Tethys Sea from Europe to Asian eastern Tethyan region has been correlated by assemblages of Larger Benthic Foraminifera (LBF). Global correlation and paleobiogeography of the eastern Meghalayan and western Tethyan Sea is discussed on the basis of SBZ of Paleocene–Eocene foraminifera assemblages (Fig. 1). Paleocene–Eocene Lakadong Limestone and Umlatodoh Limestone were deposited in shallow marine carbonate ramp depositional environment in Shillong Plateau, Meghalaya, NE India. The sedimentation basin is part of the Eastern Tethys and LBF and calcareous algae is the major carbonate facies. Coral reefs are not developed in these carbonates in contrast with the western Tethys limestones in Adriatic Platform and western European –Alpine region (Tewari *et al.*, 2007).The LBF and algal assemblage in both the limestones is consistent with other parts of Eastern Tethys in Eastern India and Tibet (Hottinger, 1971; Scheibner & Speijer, 2008, Tewari *et al.*, 2010).

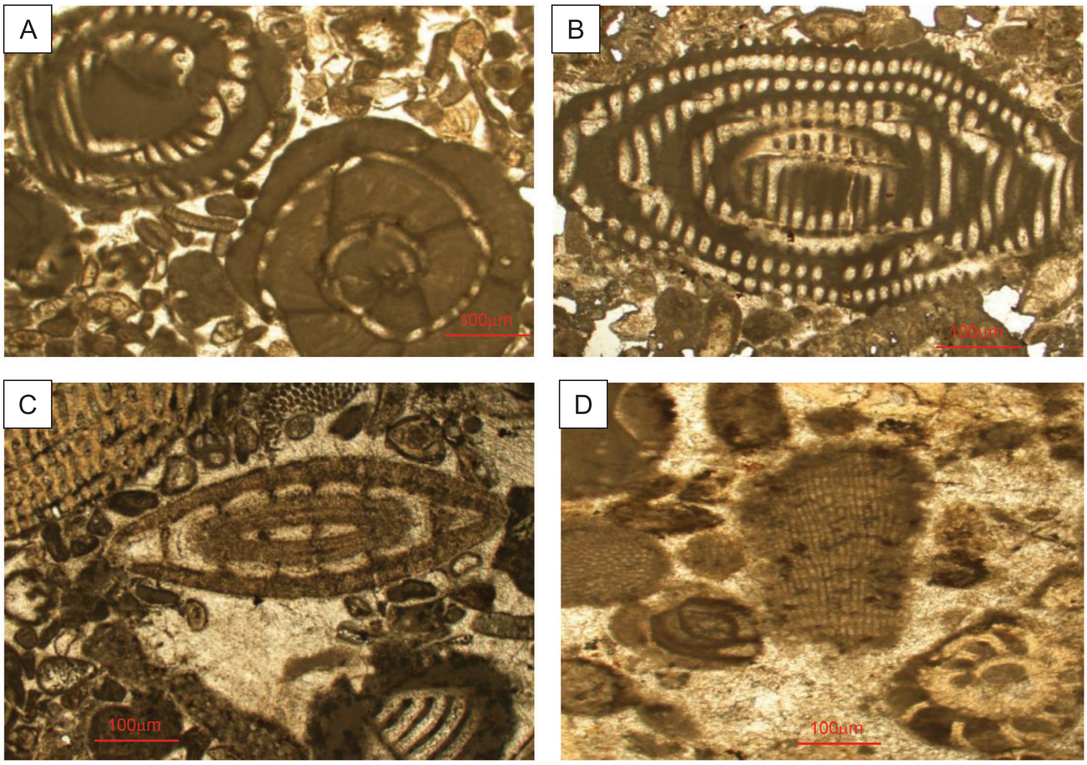

Fig. 1. Benthic Larger Foraminifera – algae assemblage from Eastern Tethys: A – *Alveolina* cf. *aramea* Hottinger – two sections, Ilerdian, SBZ 5; B – *Alveolina* cf. *vredenburgi* Davis and Pinfold (ex. *Alveolina cucumiformis*); C – *Assilina* sp. and *Discocyclina* sp.; D – Calcareous algae-foram (*Solenopora* sp. and *Miscellina* sp., SBZ 4) from Paleocene Lakadong Limestone, Meghalaya, India

The latest Paleocene (Biozone SBZ4) miscellanids and ranikothalids are replaced by Early Eocene alveolinids and nummulitids, which dominates LBF assemblages in the western Tethyan realm at the P-E boundary (Scheibner & Speijer, 2008), Thanetian (SBZ4 Biozone) is equivalent to Tethyan platform stage II (Scheibner & Speijer, 2008). In standard biozones Ilerdian (SBZ5-SBZ6), a general reorganization in LBF communities is recorded with a long life and low reproductive potential (Hottinger, 1971). However, in the Meghalayan LBF assemblages of the lowest Eocene (biozones SBZ5/6) are still dominated by *Ranikothalia* and *Miscellanea,* while new LBFs that first emerged within this time interval elsewhere (e.g. *Assilina*, *Alveolina* and *Discocyclina*) are less important and *Nummulites* are absent. Later, in the Early Eocene there was a gradual diversification of *Discocyclina* and *Assilina* species (Fig. 1), while *Ranikothalia* disappeared and *Miscellanea* became less important by the end of the SBZ5/6 biozones. Similar LBF assemblages have been recorded in other parts of east Tethys in western India and Tibet (Scheibner & Speijer 2008; Tewari *et al.*, 2010 and references therein). Such LBF assemblages in east Tethys thus differ from west Tethys. Palaeobiogeographical barriers must have existed between India and Eurasia during early collision of Indian Plate with Eurasia Plate around 50 Ma (Tewari *et al*., 2010 and references therein). These barriers prevented migration of certain LBF species of *Nummulites* and *Alveolina* between these two palaeogeographic regions. LBF dominated facies in the other basins of Meghalaya like Umlatodoh Limestone are well developed in low latitude. However, mixed coral-algal reefs and LBF facies were sparse in low-mid latitude carbonate environments (Adriatic Platform of Italy-Slovenia, Oman, Egypt, Libya, NW Somalia; Tewari *et al*., 2007, 2010; Scheibner & Speijer, 2008 and references therin). In contrast to west Tethys, corals are absent in Eastern Tethys (calcareous algae is present in SBZ3 and SBZ4 Biozone, Fig. 1) in the Meghalaya and other low-latitude eastern Tethys (Scheibner & Speijer, 2008). Carbonate ramp (shallow tidal flat) carbonate environments were dominated by LBFs from Early to Late Paleocene (SBZ4, SBZ5, biozones; Fig. 1). It is interpreted that the collision of the Indian and Asian plates must have generated this difference in palaeobiodiversity by creating barriers, which prevented migration of certain LBFs (*Nummulites*) from west to east. Later, in the Early Eocene (SBZ6, SBZ7-SBZ8 biozones), recorded from younger Umlatodoh Limestone in the upper part gradually replaced by LBF dominated facies in the east, with highly diversified LBF species of *Nummulites, Discocyclina*, *Discocylina jauhrii* etc.), indicating stable shallow marine environmental conditions. Stable carbon and oxygen isotope analyses from Paleocene–Eocene Lakadong Limestone and Umlatodoh Limestone strongly supports a shallow marine carbonate platform deposition in Eastern Shallow Tethys, Meghalaya, India (Tewari *et al*., 2010)

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The evidence of Palaeotropics and the Gondwana-derived terrane: an alternative scenario of the Palaeotethys divide in SE Asia

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Along the Northern part of the West Thailand Region (NWTR), a long-lasting belt of radiolarian cherts, separates Pennsylvanian to Permian palaeotropical limestones of the Inthanon Zone to the east from Permian limestones in the west containing a temperate marine fauna in the Roadian and a biogeographically distinctive fusulinid fauna in the Wordian. Highly abundant but low diversity of Kungurian radiolarians in silicified shales as well as temperate faunas in limestones from the south and the west of Thailand, respectively support constrains in the temperate environment during the period of deglaciation in peri-Gondawana. The well-known underlying diamictite and overlying temperate sediments with the succeeding fully tropical limestone sequences support a gradational palaeoclimate transition. Devonian faunas found in condensed sequences of the NWTR were deposited in a deep platform or ramp environment. A lack of basalts in the NWTR does not suggest oceanic environments for any Palaeozoic sequence within the NWTR and a paucity of basalts in the northwestern part of the Inthanon Zone also does not provide good evidence of an oceanic realm. Indeed, ‘continental margin’ Carboniferous sandstones appear to underlie the palaeotropical limestones and their plant fossils and their benthonic faunas do not suggest oceanic conditions in the northwestern Inthanon Zone. We, therefore, suggest that an autochthonous or para-autochthonous Inthanon Zone origin for these Carboniferous sandstones is more likely than deposition within a subducting Palaeotethyan Ocean.

A strong contrast between the ‘temperate’ Permian limestones of the NWTR and the tropical limestones of the Inthanon Zone further emphasises the Mae Yuam/Mae Sariang Fault Zone (MYMS FZ) as a reactivated oceanic boundary between Gondwana and ‘Cathaysia’ and is supported by the oceanic lithosphere origin of the detrital Cr spinels in the Triassic foreland basin siliciclastics of the NWTR. The limestones of the Inthanon Zone range from Visean to Permian and possibly Triassic and were deposited in shallow, tropical seas for over 90 million years. This longevity is either not possible or highly unlikely for shallow marine carbonates on volcanic seamounts supported on subducting (and therefore cooling and sinking) ocean crust (Huppert *et al*., 2020) but is possible on isolated carbonate platforms on continental crust separated by narrow basins with limited volcanism. Carboniferous sandstones and Devonian-Permian radiolarian cherts from the Inthanon Zone are continental marginal and are neither pelagic nor oceanic and are interpreted as deposited in extensional, deeper basins between the isolated carbonate platforms.

We suggest an alternative hypothesis to the overthrust/allochthon model where the NWTR is the eastern platform margin of the Sibumasu Terrane from the Devonian through to the Triassic and separated from the Inthanon Terrane by an ocean in the position of the MYMS FZ. It is suggested that Inthanon rifted from Gondwana in the Early Devonian and the NWTR, as part of the Sibumasu Terrane, rifted off in the early Permian. As the Inthanon Terrane ribbon continent drifted northwards the continental crust thinned and extended and small rift basins allowed basalts to be extruded associated with deep-water, continental margin, hemipelagic, non-hydrothermal radiolarian oozes. Isolated carbonate platforms were established on Carboniferous sandstone bases and were separated by deep-water but non-pelagic extensional basins. Turbidites originating on the carbonate highs supplied carbonates clasts containing Devonian through Permian conodonts, to the adjacent basins (Udchachon *et al*., 2018). We provisionally suggest that the Sukhothai Terrane rifted with Inthanon with its older siliciclastic successions of the Siluro-Devonian (?) Khao Kieo Formation and the unconformably overlying Carboniferous (Dan Lan Hoi Group) (Bunopas, 1982; Ueno & Charoentitirat, 2011) supplying siliciclastic and volcaniclastic debris to the Inthanon Zone. This hypothesis is broadly in accord with Dew *et al*.’s (2018) ‘explanation A’ for the crustal geochemistry of the northern Thailand terranes. In the early Permian (Kungurian) Sibumasu was probably in cool to temperate seas but by the middle Permian, the NWTR had rifted from Gondwana and was in the southern hemisphere tropics (13° ±2° S, Zhao *et al*., 2020). Terrane collision occurred during the Triassic (Ishida *et al*., 2006; Mitchell *et al*., 2012; Cai *et al*., 2017; Hara *et al*., 2021) with the establishment of a thrust front along the Mae Sariang Thrust Zone and the deposition of the mainly siliciclastic Mae Sariang Group on the NWTR within a foreland basin.

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Mid-oceanic seamount carbonates in Eastern Paleotethyan suture zones

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Mid-oceanic seamount-capping (atoll-type) carbonates make a popular stratigraphic entity in the geology of Japan since they are often seen as various-sized (but usually large and typically huge) exotic blocks within ancient (mostly Permian to early Cretaceous) accretionary complexes distributed in the Japanese Islands. These carbonates consist of very thick and pure (in the sense that it lacked input of continental detritus), usually massive and fossiliferous, shallow-marine limestone, and rest on oceanic-island basalts (OIB) of hot-spot origin, formed in the Panthalassa Ocean. Stratigraphically, they comprise a unique sedimentary succession that records long-term (sometimes over 80 myr.), continuous, shallow-marine environmental and biotic changes during late Paleozoic and early Mesozoic times of the oceanic sector with a stable tectonic setting, and can only be found within the accretionary orogen in the context of Ocean Plate Stratigraphy (OPS). Thus, the mid-oceanic seamount carbonate succession is a "surefire" geological item for the investigation of the ancient subduction zone and suture zone. On the basis of my research expertise working on these mid-oceanic carbonates in Japan over many years, especially in the Carboniferous–Permian Akiyoshi Limestone known as the most typical seamount-capping atoll-type carbonate body in the Panthalassa Ocean, I exported this, essentially "made-in-Japan" and "cultivated-in-Japan", geological concept of "mid-oceanic seamount carbonates within the accretionary orogen" to Southeast Asian geology, for better understanding the general geotectonic subdivision and evolution of the relevant region, especially for clarifying the position of Paleotethyan suture zones and the geohistory of the Eastern Paleotethys Ocean.

In today's Southeast Asia, Paleotethyan mid-oceanic seamount carbonates are distributed in Northern Thailand and western Yunnan, SW China where Gondwana and Tethys meet together. Of these two regions, Northern Thailand is subdivided into three basic geotectonic domains; from east to west the Cathaysian Indochina Block, Sukhothai Zone (a Permian–Triassic island arc developed along the Indochina margin), and peri-Gondwanan Sibumasu Block. In the eastern part of Sibumasu, a geotectonically peculiar area called the Inthanon Zone can be identified on which Paleotethyan oceanic rocks including the Carboniferous–Permian Doi Chiang Dao Limestone of mid-oceanic seamount origin are widely distributed. This limestone succession, sometimes making kilometer-sized huge limestone blocks, is estimated to be 1000 m thick or more, and consists mostly of shallow-marine fossiliferous massive limestone without siliciclastic intercalation throughout. Basalts having intra-plate (oceanic volcanic island) geochemistry are observed at the base of the succession. Foraminifers, especially fusulines, are the fundamental fossil group for establishing its detailed chronostratigraphy, and they clarified that the limestone continuously accumulated from the Visean (middle Early Carboniferous) to the Changhsingian (latest Permian) over the time of 90 myr.

In western Yunnan, the Changning–Menglian Belt is defined between the Lincang Massif (a Permian–Triassic island arc system formed along the easterly Simao Block with Cathaysian affinity) to the east and the peri-Gondwanan Baoshan Block to the west. The Changning–Menglian Belt, subdivided into the East, Central, and West zones, entirely has been regarded as a closed remnant (suture zone) of the Paleotethys Ocean, but actually it is only in the Central Zone where oceanic rocks are distributed. Paleotethyan mid-oceanic carbonates in this belt are called the Banka Limestone, which is over 1200 m in total thickness and generally massive and pure, being free from continental siliciclastic input for the entire succession spanning nearly 90 myr. Foraminiferal (mostly fusuline) biostratigraphy suggested continuous deposition ranging from the Visean to the Changhsingian without significant hiatus in the succession. Thus, the Banka Limestone in western Yunnan is exactly correlated in view of lithostratigraphy, chronostratigraphy, and tectonostratigraphy to the Doi Chiang Dao Limestone in Northern Thailand.

In a broad geotectonic perspective, the Paleotethyan oceanic rocks including the Doi Chiang Dao Limestone, distributed in the Inthanon Zone are considered to form various-sized tectonic outliers upon autochthonous basement rocks of Sibumasu now, which consists of early Paleozoic–Triassic sedimentary, meta-sedimentary, and igneous intrusive rocks. Similarly, those distributed in the Central Zone of the Changning–Menglian Belt are structurally resting by almost flat-lying faults (thrusts) upon siliciclastic rocks of the West and/or East zones, which presumably represent passive-margin (continental slope) sediments of the westerly, Gondwanan Baoshan Block. These mid-oceanic rocks are interpreted to have been once incorporated within an accretionary prism formed by the subduction of the Paleotethyan oceanic lithosphere beneath the Permian–Triassic island arc system represented by the Lincang Massif–Sukhothai Zone. The resultant collision of the Cimmerian (peri-Gondwanan) Sibumasu–Baoshan Block to the Cathaysian Indochina–Simao Block, thus the closure of the Paleotethys Ocean in present-day Southeast Asia, at around Triassic–Jurassic boundary time emplaced rocks of the accretionary complexes (containing Paleotethyan oceanic rocks as exotic blocks) onto the marginal part of the Sibumasu–Baoshan Block as large thrust sheets (nappe).

West to East in the Cretaceous – Greenhouse climate events and sea-level change

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The Cretaceous greenhouse climate interval was characterized by intervals of extreme hothouse climate that lead to environmental Earth System events like the Oceanic Anoxic Events. In addition, the potentially ice-free hothouse, besides high magmatic activity due to final Pangaea breakup, fostered maximum sea-level with prolonged highstands more than 250 m above today's sea level. The mid-Cretaceous interval, between OAE 1a (early Aptian) and OAE 2 (late Cenomanian), constitutes the time of most pronounced hothouse intervals leading to (nearly) global OAEs due to eutrophication of oceans, plankton blooms, expansion of oxygen minimum zones up to the photic zone, and down to the deep-sea bottom. This resulted regionally in black shale deposition and a minor extinction event of e.g. about 25% of planktic foraminifera.

Taking OAE 2 as a case study, which constitutes the Cretaceous Thermal Maximum interval of at least more than 30–35°C equatorial ocean surface temperatures, high-precision stratigraphy based on cyclostratigraphy, astrochronology and numerical dating, a 300 to 700 ka OAE carbon isotope excursion interval can be reconstructed, ending in a recovery phase up to 1 Ma. Cyclostratigraphy results in 100 ka and 405 ka eccentricty signals, most significant in Tethyan areas and other lower latitude realms. Obliquity signals may be present in higher latitudes and may relate to higher precipitation, humid-arid and megamonsoon cycles. However, also during OAE 2, a significant cooling event, the Plenus Cold Event, is present, and may have resulted in intermittent ice shields on Antarctica. This cold snap is still represented in southern Tethys sections such as Tunisia based on stable isotopes and faunal migrations.

Climate and temperature-have driven eustatic sea-level fluctuations, modulating the high sea level of the Cretaceous resulting from magmatic processes. During ice-free hothouse times, aquifer eustasy was the main process driving global sea level, at least on an amplitude of 30–50 m. Intermittent ice shields may conteract aquifer eustasy with higher magnitude glacial eustasy during cooler greenhouse phases like the Plenus Cold Event, but this is still under exploration. Major hothouse sea-level cycles have a cyclicity of about 1–1.2 Ma, showing precession- and eccentricity-modulated long-obliquity cycles in pelagic and shallow-water successions. This builds the basic sequence stratigraphy cycles during prominent greenhouse intervals of the Earth system, at least during the Mesozoic. Linking such greenhouse times models to our Anthropocene warming planet indicates a stronger hydrological cycle during warming and rising sea-levels.

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Aptian greenhouse climate and icehouse interludes – alpine Tethyan archives revisited

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In this study we revisit two Cretaceous archives in the Alps, and we test hypotheses of major sea level falls related to ice age interludes in the Aptian. The first of the two successions in focus was formed along the northern margin of the alpine Tethys and is today preserved as Garschella Formation in the Helvetic nappes of Switzerland. Aptian phosphorites of the Luitere Beds containing *Deshayites deshayesi* and *Dufreonia* are overlain by up to tens of meters of siliciclastic shales, the Gams Beds. Gams Beds with low carbonate content are poorly dated, according to available biostratigraphies they are of Late Aptian age (*nolani* ammonite zone). Gams Beds are covered by up to 15 m glauconitic bioclastic sandstones and limestones (Brisi sandstone and limestone).

The second locality we have revisited is Zürs in the Northern Calcareous Alps (NCA, Vorarlberg, Austria). There, a condensed succession of Jurassic-Cretaceous age records Southern Tethyan ocean history of a "submarine bank". Jurassic radiolarian cherts are overlain by pelagic limestones of earliest Cretaceous age followed by an Aptian phosphorite hardground. These phosphorites are covered by an up to several meter thick succession of reworked crinoidal limestones and then by several tens of meters of "Kreideschiefer" (Lech Formation), which are of Albian to Cenomanian in age. Phosphorites at both localities record a time of hardground formation related to changes in Tethyan oceanography, triggered by a major perturbation of the global carbon cycle and by corresponding changes in climate and oceanography. Condensed sedimentation records intense current activity on submarine highs and along the northern Tethyan shelf. Remarkable is the poorly understood change in sedimentation following hardground formation at both locations during Late Aptian time. The Helvetic Gams Beds (Garschella Fm.) record increased shedding of siliciclastics along the northern Tethys, either related to increased weathering or to a drop in sea level. We propose, that an eustatic drop of seal level explains observed northern Tethyan shifts in Late Aptian sedimentation. A corresponding drop in sea level is recorded at other localities as the Oman Mountains, along the Algarve coast in Portugal or in the Basque-Cantabrian Basin. There, most prominent "cold snaps" or "ice age interludes during Aptian greenhouse climate" are dated as martinoides to nolani ammonite zone, they coincide with the deposition of the Gams Beds.

Bioclastic limestones in the Helvetic succession and in the NCA record carbonate shedding at a time of renewed sea level rise following a major Aptian sea level drop. The Late Aptian prograding carbonate system of the NCA, considered as the source of crinoidal sands, was positioned along the northern margin of the evolving Eastern Alps while Brisi carbonate sands where shedded from a Northern Tethyan carbonate ramp. The Aptian condensed sediments of Helvetics and of NCA are indicators of extreme shifts in Aptian climate triggered by perturbations of the global carbon cycle. The Aptian-Albian Zürs succession provides additional information on the rapid transition of a passive continental margin with pelagic sediments into an Austroalpine foreland basin represented by "Kreideschiefer".

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Pseudo-shallow marine features in deep marine gravity-flow successions: lessons from the Menilite Beds at Skrzydlna (Oligocene; Western Outer Carpathians)

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Quite common in publications devoted to the marine and lacustrine environments are differences of opinion on bathymetry of the basin receiving detrital sediment, especially when sedimentary structures are interpreted as indicators of specific depth-defined environments (following classic textbooks). However modern studies of deep-water environments, experimental work, modelling and numerous outcrop studies of ancient successions mitigate against such an approach. In this respect, the flysch succession of the Menilite Beds strata at Skrzydlna, which contains a variety of features that can confuse a cursory observer seems to serve as a universally applicable example.

The succession at Skrzydlna records deposition in the western part of the synorogenic Dukla Basin during the Oligocene. The Menilite Beds are considered by most authors as deep marine deposits (the bathyal zone). The exposed section, almost 200-metre thick, is divided into three lithological intervals, each of which represents a radically different type of sedimentation. These are: i) a fine-grained association of terrigeonous and hemipelagic sediments; ii) infill of a canyon incised by about 40–50 m into the underlying strata, wider than outcrop and dominated by an olistostromal succession of debris flows with pebbles, boulders, slide and slump sheets; iii) succession of turbidites forming three fining-upwards sequences and ranging from thick, massive, amalgamated sandstones deposited by high-density flows in laterally migrating outcrop-scale channels, through 'normal' turbidites forming complete Bouma sequences (Ta-e), containing dunes and fining to Tce in the uppermost associations of thin-bedded sandstones and shales. These features suggest rapid uplift of the source area resulting in canyon incision and sudden onset of the olistostrome deposition that evolved upwards into proximal turbidite-fan sequence, which subsequently retrograded due to decreasing intensity of supply.

The oldest interval (i) consists of predominantly fine-grained facies, most characteristic of the Menilite Beds at their regional development. These are dark mudstones deposited in anoxic to dysoxic conditions and containing thin layers of fine-grained sandstones — turbidites with Bouma Tab; Tbc; Tabc; Tabe intervals, a 2–3 m thick intercalation of massive amalgamated sandstone, dark cherts, and locally silicified marls and limestones. The latter contain isolated lenses of medium-grained sandstone current ripple marks indicating three palaeocurrent directions. Two sets represent bipolar distribution of palaeocurrents, typical of shallow sea/shelf sediments reworked by tidal currents. However, these are interpreted here as the products of tidal currents reworking bottom sediments of the bathyal zone, the case known from contemporary environments. In this context, the third direction, perpendicular to the bipolar flows does not represent reworking by littoral current on shelf but deep marine contour current.

The main channel, or canyon (ii) incised into the slope sediments fed the depositional system with olistostrome deposits supplied from the rapidly uplifted source zone. Above there is a thinning upwards, turbidite sequence of four sub-complexes (A-D): A – conglomerate and sandstone fill three laterally migrating narrow, outcrop-scale erosional channels with a maximum depth of 15 m; B – two shallow (up to 2 m deep) distributary channels filled with very thick, massive or normally graded sandstones; C – turbidites Tb, Tc, Tbc with single occurrences of hummocky-like cross stratification and sandstone beds forming dunes at the mouth of distributary channels; D – less ordered interval of thick-, medium- and thin-bedded sandstones interbedded with mudstones, forming various incomplete sequences of Bouma intervals.

Interbeds of hummocky-like cross stratification, commonly found on the shelf, are interpreted in the deep-sea environment as the effect of Kelvin-Helmholtz instability or other complex flow processes, e.g. reflections of turbidity currents. A few occurrences of ripplemarks symmetrical in outer shape show unidirectional cross-lamination in cross section. These were modified by erosion that could have resulted from occasional extremely violent storms or flow reflections off channel margins. In spite of the external shape reminiscent of symmetrical ripplemarks these features do not possess the internal structure of composite cross laminae characteristic for oscillatory reworking of sand by prolonged, rhythmic action of waves. Solitary current ripplemarks showing flow directions opposite to the main transport direction are antidunes or deposits of currents reflected/deflected by channel sides.

In summary, in spite of geometrical and structural similarity to the features traditionally considered as formed on shelf, the structures described here, assessed in association with facies and evidence referred to in the introductory paragraphs, fall into the category of deposits known also from below the ‘normal’ wave base and below the shelf edge, i.e. in the slope region. Hence from deep-sea environment for which the occurrence of bipolar currents, dunes, hummocky cross-stratification and symmetrical ripplemarks are neither typical nor diagnostic, but do exist.

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Jurassic and Cretaceous evolution of Tethys: Palaeoceanographic events

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Jurassic and Cretaceous evolution of Tethys Ocean is characterized by extension of oceans basins, rifting, development of carbonate platforms and sea level fluctuations. Ocean basins and platform margins were sides of records of collaboration of oceanic, sea level and climate changes in different scales. Deposition of organic sediment increased on the margins of the ocean basins at certain time intervals due to changes in oceanic circulation and chemistry, productivity, climate and sea level. Oceanic Anoxic Events (OAE) stated to took place at aperiodic time intervals and generally associated with organic matter deposits and anoxic water columns. Records of oceanic anoxic event can also be associated by potential source rocks in Jurassic and Cretaceous along Tethys Ocean basins and can be tracked by stable isotope shifts, turnover of fossil groups, presence of black shales/organic rich mudstones, change in redox sensitive elements. Volcanic contribution in oceans is also considered as one of the collaborators of OAE generations. OAE records in Jurassic is seen in Toarcian interval and stated as Toarcian OAE. In Cretaceous, OAE records can be stated as Weissert, Faraoni, Selli (OAE1a), Noir, Fallot, Jacop, Kilian, Paquier (OAE1b), Leenhardt, Amadeus (OAE1c), Breistroffer (OAE1d), Bonarelli (OAE2), and OAE3. Generally, Cretaceous OAE are globally correlated or at least hemispherical. Some of them can be weakly correlated due to different duration and magnitude. Stratigraphic positions of OAE can also be used better marker levels in sequence stratigraphic interpretations. Therefore, positions of OAE are very important in terms of higher resolution for platform to basin correlations and even basin to basin. Cretaceous Oceanic Anoxic Events in eastern Tethys Ocean in Pontides and Taurides can be seen in Cretaceous successions (Mid-Barremian, Aptian, Albian, Cenomanian-Turonian) of Central Pontides (NW Turkey) and Central Taurides (S Turkey) (Yilmaz *et al*., 2004, 2010, 2012) as presence of black shales. The Mid-Barremian black shales (MBE) have been recorded within turbidite succession in deep marine setting in central Sakarya zone of Pontides following the drowning of the platform (Yilmaz *et al*., 2012). 2‰ shifts in carbon isotope curve is recorded in parallel with European basins, but with low TOC value. The Aptian black shales (OAE1a) are recorded in pelagic carbonate slope environments in central and north of Sakarya zone of Pontides and represented by a negative carbon isotope shift with 2‰, and TOC around 2% (Yilmaz *et al*., 2004; Hu *et al*., 2012). In Sakarya zone of Pontides, OAE2 is recorded in pelagic slope carbonates with carbon isotope curve more than 1‰ positive shift and >2% TOC. Another OAE2 was recorded in Antalya Nappes of Taurides without carbon isotope curve but TOC > 20% (Yurtsever *et al*., 2003, Bozcu *et al*., 2011). OAE1a equivalent in Tauride Carbonate platform can be interpreted as presence of dark colored thick stromatolite bearing platform carbonates transgressivley overlying the karstic sequence boundary. The OAE1a and OAE2 levels recorded in Turkey can easily be correlated with European examples and mainly controlled by sea level and tectonics in large-scale and climate and oceanographic changes in small-scale. The most extensive distribution of the OAE records in Turkey belong to OAE1a and OAE2, and display potential for source rocks for hydrocarbon exploration.

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Geoexpeditions with *Lithiotis*-type bivalves – field works of Student Scientific Association "Strati" (AGH University of Krakow)

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Student Scientific Association of Stratigraphy "Strati" at AGH University of Krakow is a research group founded in the 1990s. Their main focus has been on the evolution of the Tethys Ocean during the Jurassic and Cretaceous periods and the geology of Alpine system. They have conducted research in the Polish Carpathians, Eastern Carpathians (Ukraine, Slovakia, Romania), High Atlas (Morocco), Albanian Alps (Albania), and the central Thakkhola region of the Himalaya in Nepal.

Currently, their aim is to undertake a scientific expedition to the Ladakh region in the Indian Himalayas. This project is closely related to their previous works, where they studied Early Jurassic buildups created by bivalves of the so-called *Lithiotis* facies. These biostructures occurred alongside of the southern margin of the Early Jurassic Tethys Ocean. The Association aims to conduct palaeontological, palaeoecological, sedimentological, and palaeobiogeographical analyses to gain insights into the appearance of *Lithiotis* buildups in the Pliensbachian and their disappearance by the end of the Early Toarcian time the most probably due to Toarcian Anoxic Event within Tethys Ocean.

Fig. 1. Members of Student Scientific Association "Strati" on the trip to Kali Gandaki valley (Nepal, 2019)

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After a faunal crisis during one of the major mass extinctions (known as "The Great Five") at the Triassic-Jurassic boundary, "reef-like" environments began to rebuild their biocenoses. One of the first groups of marine invertebrates that started forming organic structures after this crisis were *Lithiotis*-type bivalves. The most characteristic representatives of this group belong to the following genera: *Lithiotis*, *Cochlearites*, *Lithioperna*, and *Mytiloperna*.

A detailed sedimentological and palaeoecological analysis of the Ladakh/Zanskar profiles will be the main objective of the next expedition, with similar occurrences of *Lithiotis* bivalves in other parts of the "Tethys world" serving as a comparative material.

Detrital rutile U-Pb geochronology of the Alpine convergence in the External Western Carpathians

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The Carpathian Flysch Belt represents a Paleogene accretionary wedge (External Western Carpathians – EWC) located in front of the narrow Pieniny Klippen Belt zone and the Cretaceous Central Western Carpathian nappe stack. The Flysch Belt is formed of several nappes thrust over the slope of the European Platform in the Miocene. This study is focused on the uppermost Magura Nappe, which consists of the Rača, Bystrica and Krynica subunits. As there are no relics of pre-Miocene oceanic crust in the EWC, the sedimentary rocks of the Flysch Belt are the only source of information available about the Alpine collisional events. U-Pb geochronology was applied to detrital rutile from sandstones of the Magura Nappe in order to better understand the closure of the Alpine Tethys in the Western Carpathians. Ten medium-sized sandstone samples were collected across the Bystrica and Krynica subunits in the Nowy Targ region in southern Poland. The samples represent synorogenic clastic sediments with inferred deposition ages between the Late Cretaceous and Oligocene. Approximately 200 rutile grains were separated from each sandstone sample and around half of them were selected for further analyses. The age and appearance (shape, inclusions, zoning etc.) of the dated rutile show significant variations, suggesting derivation from various sources. The most prominent age peaks represent the Variscan (c. 400–280 Ma) and Alpine (c. 160–90 Ma) tectonic events which are well-pronounced in all but the oldest dated sample. It is also noteworthy that four distinct Alpine signals were detected in our rutile data set. The two most prominent peaks with ages of 137–126 Ma and 115–105 Ma are found in majority of the samples. In two sandstone samples, deposited between the Eocene–Oligocene and the Late Cretaceous–Paleocene, the youngest peak of 94–90 Ma appears. Another peak of 193–184 Ma is also present in these two samples, as well as in another sandstone deposited between the Paleocene and the Eocene. In addition, most samples show few Proterozoic ages (approx. 1770 Ma, 1200 Ma, 680 Ma and 600 Ma). Since metamorphic rutile requires relatively high pressure to crystallize, its formation in the course of an orogeny is possible in a subduction setting. Hence, our new age data may reflect tectonic events related to subduction of oceanic crust and overlying sediments. Tentatively, we propose that recognizable events include the Jurassic subduction of the Meliata Ocean (~180–155 Ma), the Early Cretaceous thrust stacking of the Veporic and Gemeric domains (140–105 Ma) and possibly the Late Cretaceous subduction of the Váh Ocean (c. 90 Ma). In addition to dating, the Zr content of the rutile formed during the Alpine orogeny was measured by electron microprobe at the AGH University in Krakow. The amount of Zr varies between 37–420 ppm in almost all grains, with the exception of 4 rutile grains where ~1100 ppm was reached. The Zr in rutile thermometer, based on the approach of Kohn (2020) was used to calculate the possible metamorphic conditions at 450–650°C and >7.5 kbar. This data set corroborates formation of the Alpine rutile under relatively high pressure and rather low to moderate pressure/temperature gradient, i.e. typical of subduction-related tectonic environments.

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