GEOLOGY

János Haas, Károly Brezsnyánszky, Tamás Budai, László Fodor, Nóra Gál, Gizella Gombárné Forgács, László Gyalog, Gábor Katona, Gábor Kovács, Szilvia Kövér, Ferenc Lesták, Annamária Nádor, †András Nagymarosy, Péter Prakfalvi, Ágnes Rotárné Szalkai, Péter Scharek, Ferenc Síkhegyi, Gábor Szepessy, Teodóra Szőcs, Ákos Török, József Vatai, Zsuzsanna Vikor, László Zilahi-Sebess

Palaeogeographic conditions and evolution of the Carpatho–Pannonian Area

Hungary is situated in the Neogene Pannonian Basin within the Alpine (Mediterranean) orogenic belt extending from North Africa to Southeast Asia via the south of Europe and Asia Minor. The basement of the Pannonian Basin is quite complex mainly with rocks formed in the Palaeozoic 1, a part of it is a lithosphere fragment broken away from the Variscan orogenic zone 6.

The structure of Europe's crust – except the East European Craton as well as the Baltic Shield consisting of several billion years old rocks and not involved in the orogeny afterwards – was mainly formed by the orogeny from Late Cambrian to Early Devonian (500–400 Mya) following the Caledonian plate tectonic cycle, the Variscan orogeny finished in Late Palaeozoic (ca. 320 Mya) as well as the ongoing Mesozoic–Cenozoic Alpine orogeny started 250 Mya.

The pre-formation period of the Variscan orogenic belt may be dated back to the beginning of the Palaeozoic, the Pan-African orogeny, resulting in the amalgamation of the Proto-Gondwana supercontinent comprising of South America, India, Australia as well as Antarctica. In plate tectonic processes from the Ordovician to Devonian different continental lithospheric blocks – by the closure of interim basins with oceanic basement – successively collided and adhered to Laurussia. By the Early Carboniferous, a huge ocean, namely the Palaeotethys, was formed between Laurussia and Gondwana. Such plate tectonic cycle terminated in the Middle Carboniferous (ca. 320 Mya) by the collision of Laurussia and Gondwana and thus the formation of the Variscan orogenic belt. Consequently, there was a single supercontinent coming into being called the Pangea, surrounded by a sole, united world ocean Panthalassa 2.

In Europe, in the axis zone of the Variscan orogeny a quite intense rock alteration (metamorphism) took place, and a huge mass of granite formed due to the melting of colliding tectonic plates. Such central zone of the orogeny can be traced from the Massif Central to the south of Bohemian Massif via the Vosges and the Black Forest. Denudation of the evolved chains started immediately and intensely after their uplift; pebble, sand and clay from such denudation were accumulated in intermontane basins and mainly in foreland basins.

The southern part of chains formed in the Variscan orogeny was folded again in the Alpine orogeny, their rocks were metamorphosed and some parts were incorporated into the chains of the Alps and the Western Carpathians. The southern part of the basement of the Pannonian Basin is formed by the Tisza microplate (Tisza Mega-unit) which became detached from the Variscan mountain range adhered to the European plate in the Jurassic. This is reflected by features of its granitic rocks similar to those of granites of the same age in the Bohemian Massif. Upper Carboniferous fluvial rocks identified from boreholes in South Transdanubia have characteristics similar to sediments in the foreland basins of the Variscan ranges.

Limestone and marl were formed in the Early Carboniferous, between Laurussia and Gondwana, south of the subsequently uplifted Variscan orogenic belt, in shallower marginal sea basins of the Palaeotethys. Lower Carboniferous formations northeast of Lake Balaton might have belonged to this belt. In deeper inner basins directly connected to the open sea, alternating layers of sandstone and marl (flysch-type sediments), and later, in the Late Carboniferous shallow marine sediments were deposited. Such successions were deposited far from the collision zone only suffered a low-grade alteration in the Variscan orogeny. Carboniferous rocks in the Bükk Mts. might have formed in this palaeogeographic unit.

The fragmentation of Pangea started in the Permian in our region. Rapidly sinking troughs developed along faults in which fluvial sediments and volcanic rocks accumulated. Traces of trough faulting indicating the beginning of the Alpine plate tectonic cycle in the area of Hungary can be detected most significantly in the Tisza Mega-unit belonging to the Variscan orogenic belt. In the trough system in South Transdanubia fluvial and lacustrine sediments were deposited in a thickness of several thousand metres from Early Permian to Early Triassic.

In the southern foreland of the Variscan range, a wide zone capable of reception of the huge masses of terrigenous rock debris from intense denudation developed in the Late Permian 3. The Tisza Mega-unit, the central part of the Northwestern Carpathians west of this Mega-unit as well as most of the areas of the East Alpine units also belonged to this zone. Southward, on the flood plain and in restricted lagoons, evaporites (halite, gypsum and anhydrite) developed in arid climate. Gypsum and anhydrite in the area of Hungary developed in the same way are known in the Aggtelek Unit.

The area of the Transdanubian Range Unit might have been located between the Northern Calcareous Alps and the southern geosynclines of the Alps in the Permian, at the western end of the embayment of Palaeotethys. In the southern area of the Alps, during the Late Carboniferous – Early Permian, a series of narrow basins developed, filled with terrigenous clastic sediments and volcanic rocks in considerable thickness. The intrusion of the granite mass of the Velence Hills took place at this time in the Transdanubian Range. Troughs developed in the southern part of the Alps and were also filled up with terrigenous sediments and acidic volcanic rocks in the Middle Permian. The area of the Transdanubian Range was also a dry land but there was hardly any trace of volcanic activity here. Palaeogeographic setting and evolution of the two areas in the Late Permian are quite similar. Sedimentation on both areas started with the deposition of terrigenous fluvial sediments, and later in the late stage of the Late Permian, parts of the units facing the ocean were overrun by a shallow sea fringed by a wide tidal plain. Former terrestrial plains were inundated by the sea at the beginning of the Triassic period.

In the area of the Bükk Mts. – just like in the units of the Dinarides with similar rocks – Late Carboniferous shallow marine sedimentation was followed by subaerial exposition. There was terrigenous, and subsequently shallow marine sedimentation in the Middle Permian which continued in the Early Triassic.

At the beginning of the Early Triassic most of the Tisza Mega-unit still remained a dry land where deposition of fluvial sediments was still in progress but prevailing part of the region already belonged to the shallow marginal zone of the Palaeotethys. On the gently sloping basement connecting the coast to the deeper shelf rather similar successions with alternations of sandstone, marl, limestone and dolomite, and later in the early stage of the Middle Triassic dominantly dolomite and limestone were formed. At the beginning of the Middle Triassic certain parts of the Tisza Mega-unit being closer to the continent were also covered by a shallow sea.

During the Middle Triassic a new ocean (Neotethys) was about to be born at the northern edge of the former Gondwana continent simultaneously with the thrusting of Palaeotethys under the Eurasian Plate. Opening up of the new ocean reached our region in the Middle Triassic (ca. 240 Mya). Submarine trenches and highs developed, deep marine limestone was formed in the trenches. Above the attenuating continental lithosphere, in the axis of the later mid-oceanic ridge, basaltic volcanism started with lava flows intruding into the marine calcareous deposits.

In the developing ocean margin zones with continental basement, the sea basement also became dissected, in some zones there were intense volcanic activities in the Middle Triassic and at the beginning of the Late Triassic. Volcanic centres developed in the Dolomites, their diffused volcanic material reached the Transdanubian Range as well. Formation of trenches was also linked to magmatic activity in the Bükk Mts.

At the beginning of the Late Triassic (ca. 230 Mya) at the start of the spreading of the oceanic basement, subsidence of margins became general. Watercourses from already heavily denuded ranges of the Variscan orogenic belt spreading in the European oceanic margin – especially in humid climate periods – transported gravel and sand in large amounts to foreland terrestrial basins, accordingly to the subsiding basins of the Mecsek zone as well.

In the intensely subsiding, several thousand km wide zone of the ocean margin (shelf) covered with shallow water, deeper basins developed in the Middle Triassic and were filled with sediments of terrestrial origin in a more humid period at the beginning of the Late Triassic. On the even surface, up to the end of the Triassic terminated 200 Mya, several thousand metres thick limestone and dolomite accumulated. Simultaneously with the opening up of the ocean, on the attenuated basement of the shelf facing the ocean (just like in the Transdanubian Range), the formation of trenches was still going on, some marginal blocks downfaulted, and shallow marine sedimentation was replaced by deep marine conditions on such blocks. Traces of the latter were observed in the Aggtelek Mts.

In the area of the Bükk Mts. shallow marine sedimentation was not to continue subsequent to the Triassic period, however, accumulation of deep marine sediments concerning the whole area was about to start only in the Middle Jurassic.

In the western parts of the Southern Alps, intensely subsiding basins developed in the advanced stage of the Triassic indicating the initial phase of the formation of the Penninic ocean branch which may be linked to the formation of the Atlantic Ocean. Traces of similar progress may be observed in the western side of the Transdanubian Range, in the basement of Zala Hills as well as in the area of the Northern Calcareous Alps.

Simultaneously, trenches also developed in the Tisza Mega-unit. In the margin of the European Plate denudation of superficial ranges of the Variscan orogenic belt still provided sediments in huge masses to accumulate in continental depositional basins (Mecsek zone). As the climate became more humid, a sandstone-bearing succession intercalated with coal beds originated from lush vegetations of marine swamps were deposited. In a later stage of the Early Jurassic shores variegated with coal swamps were overrun by the sea almost everywhere, shallow marine and later deep marine sandstone and marl deposition became general 4.

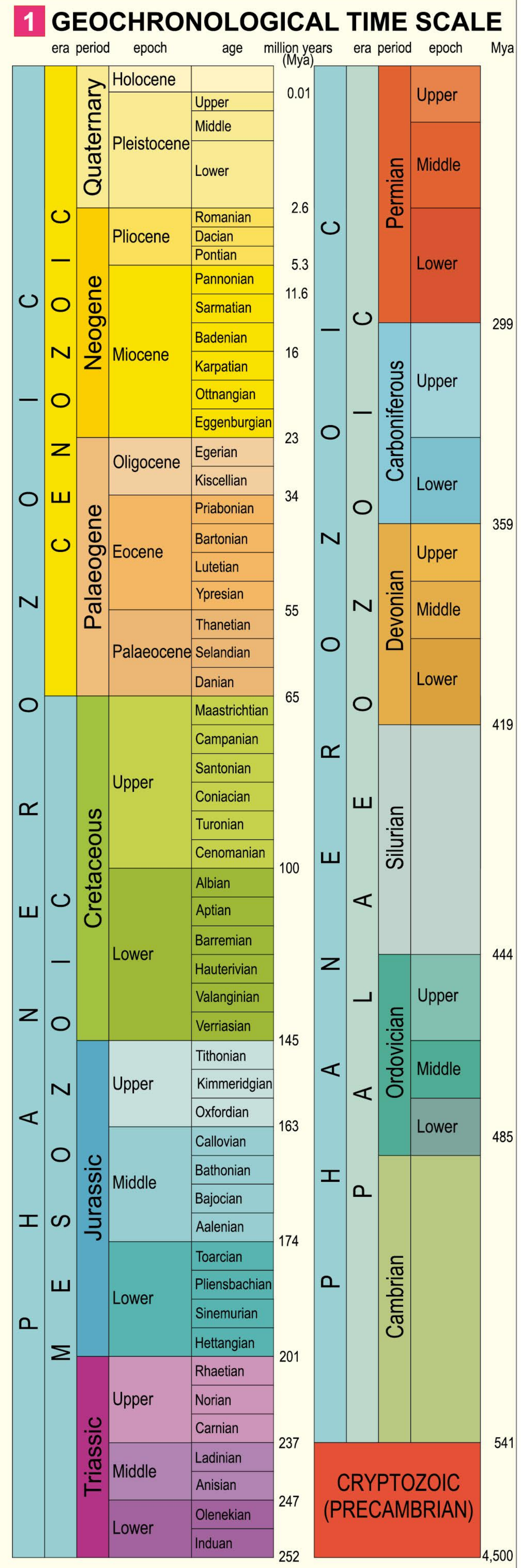
In remote zones off the continental margin, the very thick limestone and dolomite masses with considerable lateral extension, developed in the Late Triassic, broke up along faults in the early stage of the Jurassic, and typically red limestones were formed in the deepening sea above the developed unevenly subsiding blocks. Such sequence of events may be traced in that marginal zone of the Neotethys – from the southern part of the Alps to the Tisza Mega-unit via the Transdanubian Range, and the Central Western Carpathians – which was later detached from the European Plate by the opening of the Penninic ocean branch. Shallow marine sedimentation still proceeded in the margin of the Adriatic microplate in the Jurassic as well subsequent to the Triassic.

The beginning of the opening of the Penninic ocean branch as well as the spread of oceanic lithosphere may be dated back to the end of Early Jurassic (180 Mya). Remnants of the oceanic basement are under rock masses of the Austroalpine nappes and only outcrop in tectonic windows – in the Kőszeg Mts. – as a result of nappe down-slip. Opening up of the Penninic ocean branch from west to east led to the detachment of the Tisza Mega-unit from the European Plate in the Middle Jurassic. Such change is reflected in the Mecsek zone by the formation of deep marine limestone and chert replacing the accumulation of terrigenous influx. Similar rock types were also formed in zone sections facing the Neotethys between the Penninic ocean branch and the already closing Neotethys in the Middle and Late Jurassic.

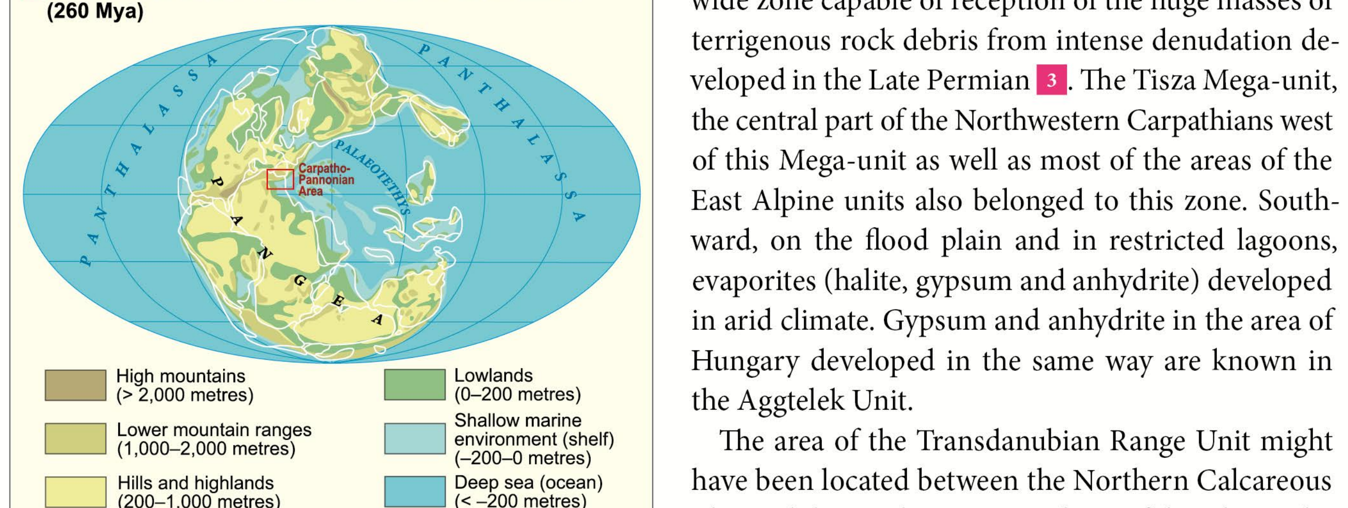
In our region, the closure of the Neotethys commenced in the Middle Jurassic. Later the oceanic basement predominantly consisting of igneous rocks (ophiolite) overthrust the continental margins surrounding the basin 5. During subduction of the oceanic basement and overthrusting onto the continental basement (obduction), clayey – siliceous rocks (mélange) formed comprising of small fragments and huge blocks of igneous rocks as well as sediments of marine origin well known in vast areas in the Dinarides as well as further to the east, along the closure zone of the former Neotethys. A sheared and far slipped block of such zone in later tectonic movements has reached the Bükk Mts. area.

In the Early Cretaceous (145–100 Mya) the opening of the Penninic ocean branch was still on, while the most of the basement of the Neotethys was pushed downwards, other parts were exposed by being piled up onto the ocean margin 7. Clasts of eroding oceanic basement origin also occurred in the northeastern part of the Transdanubian Range, while in the southeastern part deep marine limestone formation was still in progress. In the Mecsek zone of the Tisza Mega-unit facing the Penninic ocean, the attenuation of continental basement resulted in intense basaltic volcanism. The Villány–Bihor unit still remained a shallow area with shallow marine limestone formation. By the closure of sub-basins of the Neotethys, the Tisza Mega-unit as well as the Dacia Unit comprising of rocks of the Eastern and Southern Carpathians joined together and formed a single microplate (Tisza–Dacia Mega-unit).

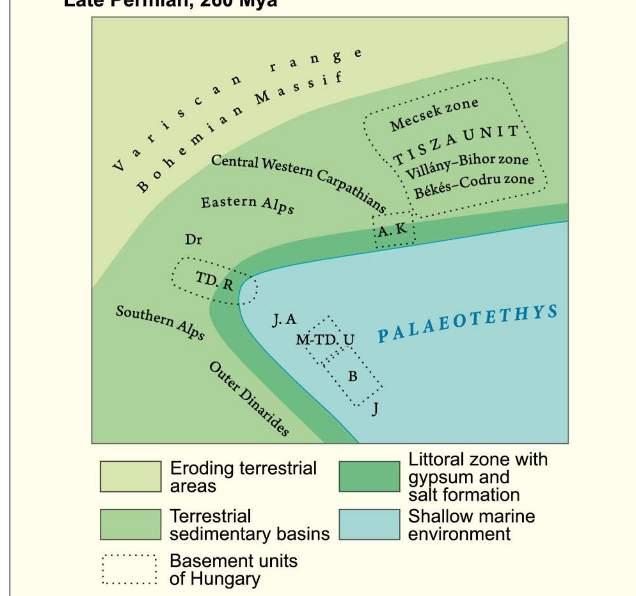
1 GEOCHRONOLOGICAL TIME SCALE



2 PANGEA SUPERCONTINENT IN THE LATE PERMIAN (260 Mya)

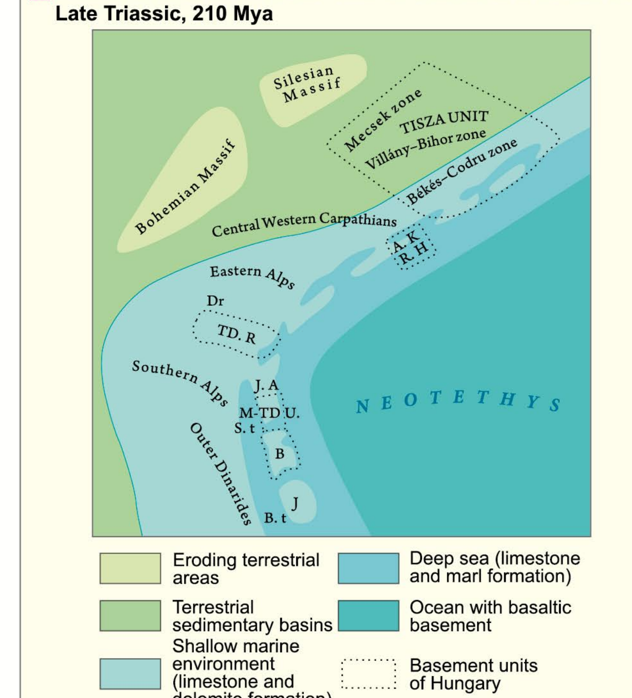


3 PALAEOGEOGRAPHIC SETTING OF GEOLOGICAL UNITS
Late Permian, 260 Mya



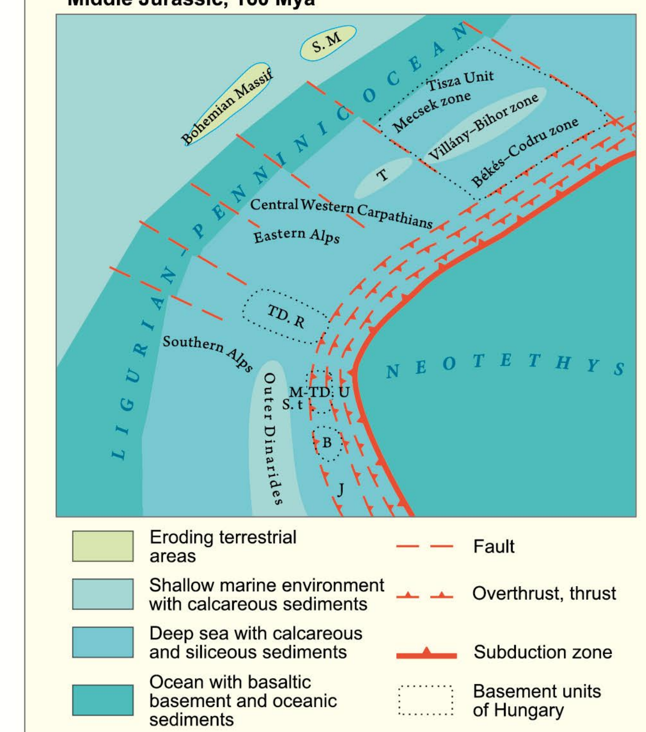
Explanation of abbreviations: A. K = Aggtelek Karst; B = Bükk Mts.; Dr = Ridge along Dráva River; J = Jadar (Dinarides); J. A = The Julian Alps; M-TD. U = Mid-Transdanubian Unit; TD. R = Transdanubian Range

4 PALAEOGEOGRAPHIC SETTING OF GEOLOGICAL UNITS
Late Triassic, 210 Mya



Explanation of abbreviations: A. K = Aggtelek Karst; B = Bükk Mts.; B. t = Bosnian trough; Dr = Ridge along Dráva River; J = Jadar (Dinarides); J. A = Julian Alps; M-TD U. = Mid-Transdanubian Unit; R. H = Rudabánya Hills; S. t = Slovenian trough; TD. R = Transdanubian Range

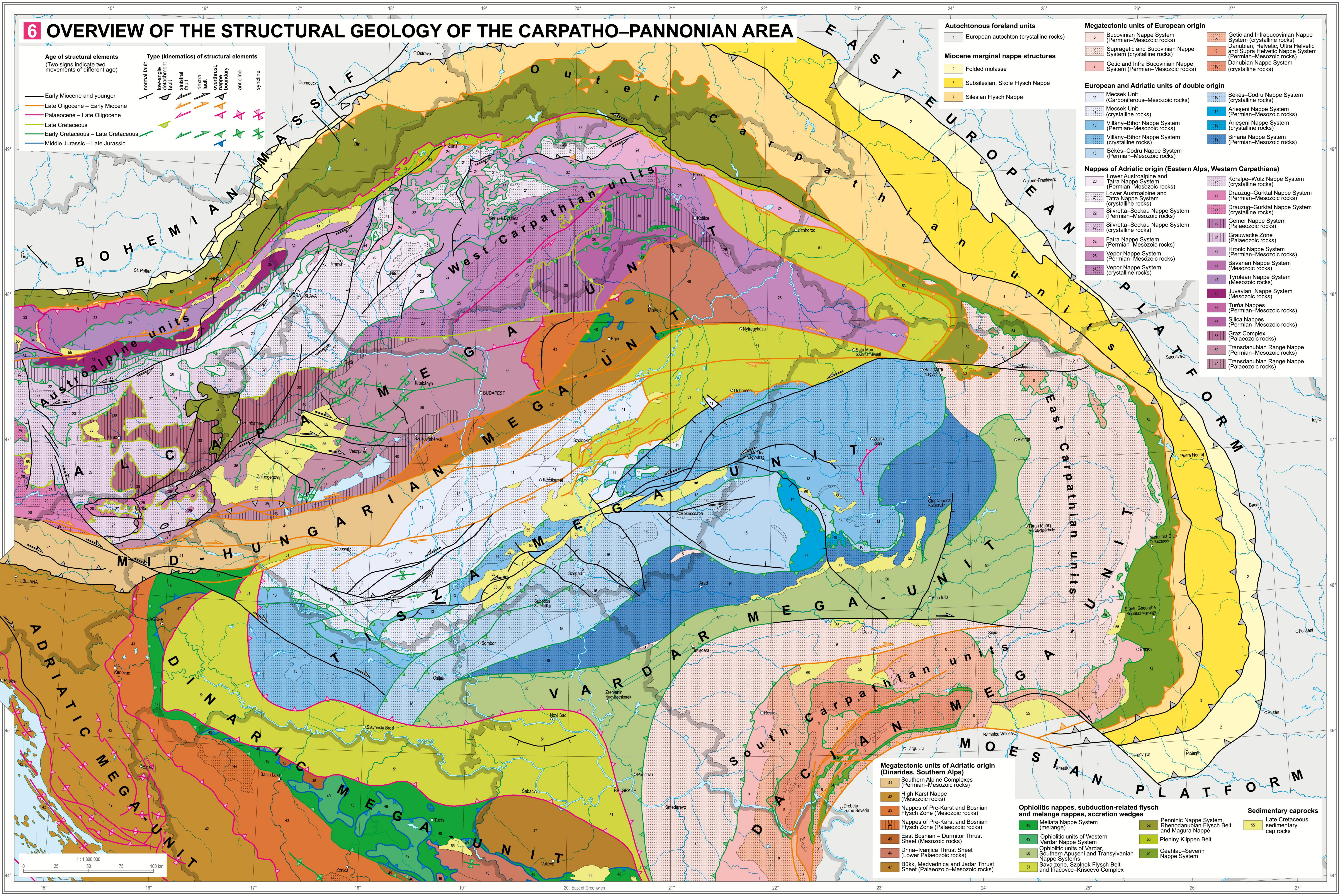
5 PALEOGEOGRAPHIC SETTING OF GEOLOGICAL UNITS
Middle Jurassic, 160 Mya



Explanation of abbreviations: B = Bükk Mts.; J = Jadar (Dinarides); M-TD. U = Mid-Transdanubian Unit; S. M = Silesian Massif; S. t = Slovenian trough; T = Tatras; TD. R = Transdanubian Range

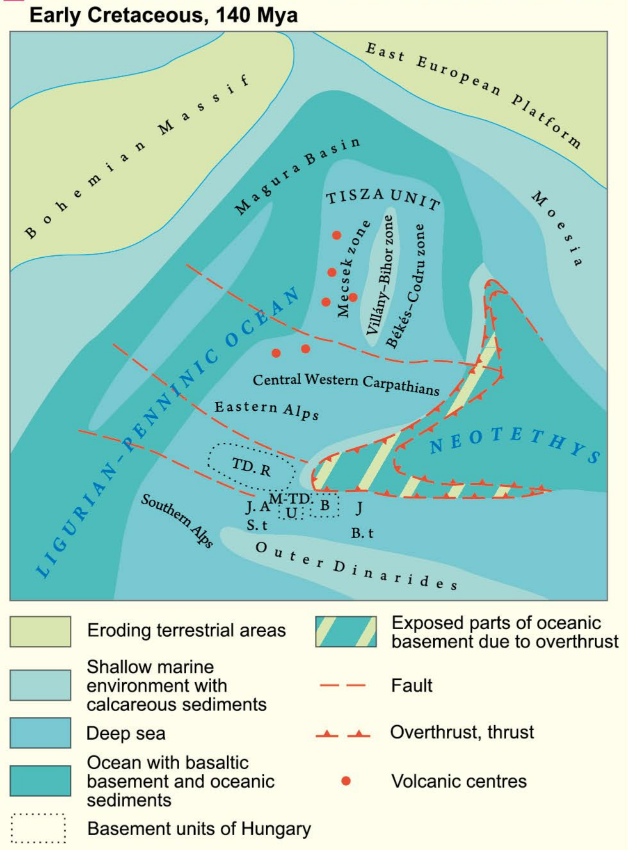
©Geographical Institute, MTA CSFK www.nationalatlas.hu, Budapest, 2018

6 OVERVIEW OF THE STRUCTURAL GEOLOGY OF THE CARPATHO–PANNONIAN AREA



©Geographical Institute, MTA CSFK www.nationalatlas.hu, Budapest, 2018

7 PALAEOGEOGRAPHIC SETTING OF GEOLOGICAL UNITS
Early Cretaceous, 140 Mya



Explanation of abbreviations: B = Bükk Mts.; B. t = Bosnian trough; J = Jadar (Dinarides);J. A = Julian Alps; M-TD. U = Mid-Transdanubian Unit; S. t = Slovenian trough; TD. R = Transdanubian Range

Due to the subduction of the Penninic ocean branch started at the end of the Early Cretaceous (ca. 110 Mya) and intensified in the Late Cretaceous as well as plate movement of the African Plate northward, collisions of microplates between the African and Eurasian Plates (Alcapa and Tisza–Dacia Mega-units) began. Collisions led to the deformation of rocks of the microplates, formation of rock masses sheared from their basement (nappes) and piling up onto each other as well as the alteration of rocks (metamorphism). This may already be considered as the overture of the Alpine orogeny when vast areas previously overrun by the sea were subaerially exposed and their erosion started. Probably the mass of the Transdanubian Range was also sheared from its original basement and suffered a trough-like deformation.

The early stages of the Cretaceous brought remarkable tectonic events for the Tisza Mega-unit as well with rocks piled up onto each other, sometimes forming tectonic nappes sheared from their original basement. Rocks elevated from the sea by the orogeny began to be eroded intensely, while the subsiding basement with heavy nappes formed new basins that were invaded by the sea later. The erosion of elevated ranges resulted in the deposition of flysch-type successions of sandstone and marl in high volumes in the foreland basins of nappes, first in the Villány–Bihor zone and subsequently in the Mecsek zone as well.

Step-by-step plate collisions taken place in the Transdanubian Range in the late stage of the Cretaceous (ca. 90 Mya), and also in the Palaeocene (ca. 65 Mya) followed by a short transgression phase resulted in the tectonic uplift as well as subaerial exposition of the area. As a result, karstification of previously formed limestones and dolomites began. Both in the terrestrial stage of the Late Cretaceous and in terrigenous-erosional period of the whole Palaeocene (ca. 20 million years), bauxites indicating warm-wet climate formed in karst depressions by terrestrial weathering in the Transdanubian Range.

In periods between collisions, however, the area began to subside. Terrigenous sedimentation was terminated by gradual transgression from southwest to northeast in the Middle and Late Eocene (ca. 45 Mya). During slow transgression in a gradually shifted coastal environment spacious marine swamps, lakes developed in the first place where coal seams formed in some places in still warm and wet climate. Later as the sea advanced further shallow marine environments developed on islands due to transgression where limestone was formed out of the accumulated shells of giant protozoa (larger foraminifera). Deposition continued with the formation of deep marine marl in the constantly deepening marine environment.

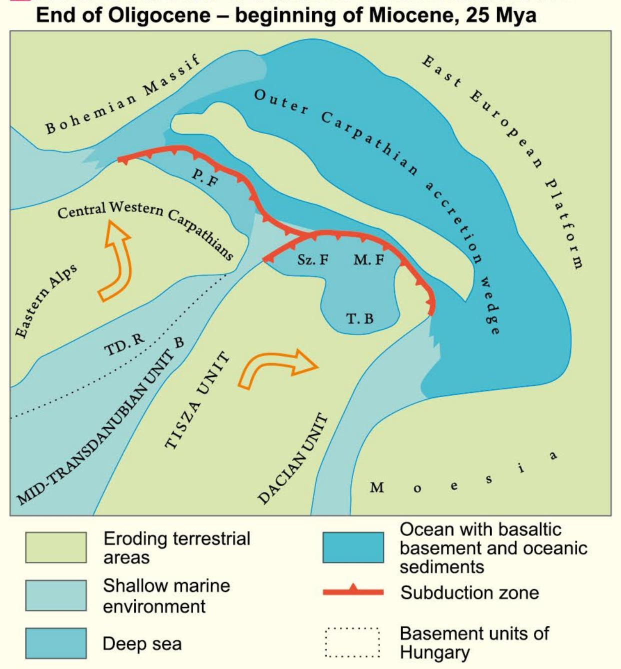
At the beginning of the Late Eocene (ca. 38 Mya) the sea advancing from southwest to northeast in the area of the Transdanubian Range also reached the areas of Buda Mts. and Pest Plain. In this period deep marine marl formed in the area of the mountains, while in newly subsided basins in North Hungary (Palaeogene basin) shallow marine limestone was deposited. This was followed by further intense subsidence at the end of the Late Eocene in North Hungary, resulting in deposition of deep marine marl while the area west of the fault line (Buda Line) stretching along the western side of the Buda Mountains of the Transdanubian Range remarkably elevated and eroded.

South of Lake Balaton, parallel with a fault zone stretching from northeast to southwest (Balaton Line) andesitic–dacitic volcanic centres can be identified in the Velence Hills, in the basement of Zala Hills and Pest Plain as well as in the Mátra Mts., in the vicinity of Recsk. Such volcanic range was active from the Late Eocene to the Early Oligocene (ca. 40–30 Mya). Also, at the beginning of the Eocene deep marine sandstone (flysch) was formed in the northern margin of the Mecsek zone of the Tisza Mega-unit.

As a result of the collision of the African and Eurasian Plates, the Alcapa and Tisza–Dacia microcontinents got into a strong compressional stress field, which resulted in their 'rejection' to northeast from the Southern Alpine–Dinaridic region. The earliest date of such rejection may be the end of the Eocene (ca. 34 Mya) but the most intensified movement might have happened in the Oligocene–Early Miocene (30–20 Mya) 8.

Flysch from sediments rushed down on slopes in foreland basins of microplates pushed toward northeast was accumulated in the so-called Inner Carpathian flysch basins, then with ongoing transition to northeast in the outer Carpathian flysch areas. Huge shallow marine embayment of the Transylvanian Palaeogene basin in the area of the Tisza–Dacia Mega-unit was connected to the inner Carpathian flysch basins from the south. Sediments of the inner zones of the outer Carpathian flysch units folded from the Late Eocene. During the Early Miocene sediments accumulated on subducting microplates piled up. Few parts might have emerged as mainlands but most of them were still covered by water in the Palaeogene. However, in the Early Miocene in the outmost zone near the European Plate there was only a narrow trough spreading filled also with flysch and directly connected to the East Alpine molass zone westward. The two microplates also moved along each other by a remarkable transform fault system, main elements of which are still recognizable known as the Mid-Hungarian Lineament and the Balaton Line. Parallel to this fault system, Palaeogene shallow marine sub-basins developed in the area of Hungary, partly in the area of the Transdanubian Range Unit, partly in the Bükk and the Mid-Transdanubian sub-units of the Mid-Hungarian Unit. Connected to the latter, such rocks can be identified in the area of today's Croatia and Slovenia that are the masses of former, unified Palaeogene basin.

8 PALAEOGEOGRAPHIC SETTING OF GEOLOGICAL UNITS
End of Oligocene – beginning of Miocene, 25 Mya



Explanation of abbreviations: B = Bükk Mts.; M. F = Maramureş Flysch Basin; P. F = Podhale Flysch Basin; Sz. F = Szolnok Flysch Basin; T. B = Transylvanian Basin; TD. R = Transdanubian Range

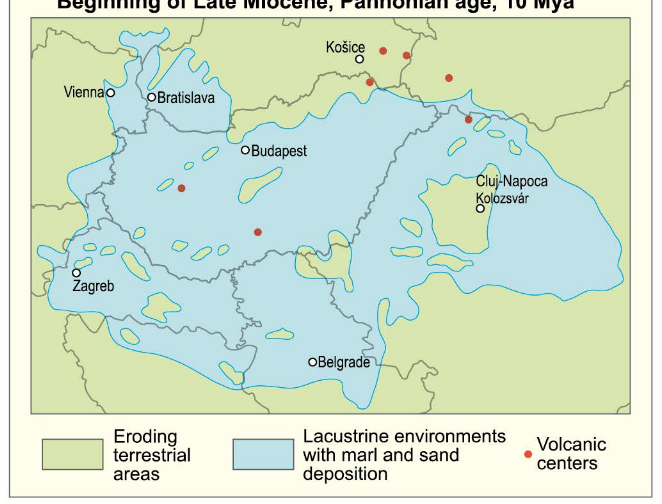
In the Late Oligocene in the eastern part of the Buda Mts. and east of it there was deep marine sedimentation. In the earlier phase of the Oligocene, in the northern forelands of the Bakony and Vértes Mts. terrigenous, dominantly fluvial sedimentation was in progress. The most of the Gerecse Mts. and the Dorog Basin were restricted lagoons, more or less isolated from the sea at that time, with alternations of sediments of brackish and saline water. The sand coast of sea basin stretched along the area of the Buda Mts. and the Cserhát Mts. In the Pest Plain, in the Salgótarján Basin as well as in the northern foreland of the Mátra and Bükk Mts., fine-grained sediments were deposited in deeper sea basins. The eastern margin of the sea basin can be identified in the Bükkalja region where various sediments (from deep marine to shallow lagoonal as indicator of regression) were formed.

The advancement of microplates toward northeast was still on in the early stage of the Miocene, and only stopped in the Middle Miocene (ca. 16 Mya). The Outer Carpathians were folded and elevated. The Alcapa Mega-unit rotated anticlockwise by 30–45°, while the Tisza–Dacia Mega-unit rotated clockwise by 60–70°. The latest rotations took place in the Sarmatian (ca. 11–13 Mya).

In the Early Miocene newer series of basins developed parallel to those in the range zone in the Tisza Mega-unit. The extensional tectonic evolution of the Pannonian Basin started at this time and was followed by a long-lasting explosive rhyolitic volcanism. By the beginning of the Badenian age of the Middle Miocene (ca. 15 Mya) the subsidence of the sub-basins of the Pannonian Basin became intensive in most of the area of today's Hungary. Vast areas – just like the Békés depression and Makó trough, furthermore the southern part of the Danube–Tisza Midland, the basin of the Kisalföld (Little Hungarian Plain) as well as the area between Lake Balaton and the Mecsek Mts. – became deep-water basins where formation of fine-grained clay was in progress. The Börzsöny, Cserhát and Mátra Mts., southern foreland of the Mecsek Mts. and the West Bakony Mts. became a shallow marine environment where mainly sandstone and limestone were formed. High volume islands and landmasses like the Transdanubian Range, most of the Bükk Mts., the Northern Tiszántúl region, the central part of the Alföld (Great Hungarian Plain) as well as the Mecsek Mts. were elevated from the sea in this period. By the Late Badenian and Early Sarmatian, the subsidence of the Pannonian Basin became general almost in the whole area of the country.

Centres of the Badenian rhyolitic and andesitic volcanism buried by younger sediments have been explored by deep boreholes from the Zala Hills to the central part of the Alföld via the northern foreland of the Mecsek Mts., approximately parallel to the Mid-Hungarian Lineament, while volcanic structures of the Visegrád, Börzsöny, Cserhát and Mátra Mts. elevated to the surface. The main phase of the volcanism in the Tokaj (Zemplén) Mts. falls within the Sarmatian age.

9 PALAEOGEOGRAPHIC SETTING OF GEOLOGICAL UNITS
Beginning of Late Miocene, Pannonian age, 10 Mya



In the late period of the Miocene (in the Pannonian Age) almost the whole of the Carpathian Basin became a lake. The Pannonian Lake (which is actually a 'remnant sea') reached its maximum extent 9.5 Mya 9. Then the continuous water surface – covering such recent ranges as the most of the Transdanubian Range or the Bükk Mts. – was continually connected to the Vienna and Transylvanian basins in respect of hydrogeography. Only a few ranges rose above water level such as peaks of the Apuşeni Mts. in Transylvania or the Slavonian inselbergs. At the beginning of the Pannonian age northeastern members of the Inner Carpathian volcanic arc showed the highest activity. In the volcanic Vihorlat–Gutâi Range there was a widespread andesitic and rhyolitic volcanic activity for several million years.

Huge masses of fluvial sediments from the denudation of the ranges of the Alps and the Carpathians filled up the Pannonian Lake gradually in the later phase of the Pannonian Age and in the Pliocene. The last parts that were filled up ca. 4 Mya are known southward, in areas of today's Serbia and Croatia. Alkali basaltic volcanism of upper mantle origin started at the end of the Miocene (ca. 7.5 Mya) and still lasted in the Pliocene, moreover in the Early Pleistocene (ca. up to 1 My) it can be observed as well over wide areas (Alpokalja/Eastern Alpine Foreland/region, Kisalföld, South Bakony Mts., Tapolca Basin 1, Medves Region, Danube–Tisza Midland).

During the Pliocene and the Pleistocene the area of Hungary finally became a dry land. In the Pleistocene hills and medium-height mountains were uplifted by 300–500 m, while plains and basins subsided even by several hundred metres. On highs elevated from plains as well as some hillsides young, air-borne and wind-eroded sediments (loess, drift sands) were spread. In mountains and hills erosion is still in progress, while in some slowly subsiding basins (Kisalföld, Southeastern Tiszántúl) as well as in river valleys there is still fluvial and paludal sedimentation.

Engineering geology

Engineering geology is a branch of geology applying geological knowledge in engineering analysis, planning, design, contributing geological solutions to engineering and environmental problems as well as providing an opportunity to manage interactions between mankind and geological environment and avert geological hazards. Terms for engineering geology are determined by topographic, hydrographic and geological conditions. Beside natural processes, anthropogenic impacts (e.g. building and construction, mining, water extraction) also influence the engineering geological classification of a given area significantly. Map 10 illustrates engineering geological categories arising from natural conditions, and engineering geological impacts induced by human activities separately.

As for engineering geological conditions and risks, plains, hillsides and low mountains can be sharply separated the differences between the topography and morphology of which are reflected in the engineering geological characteristics of formations making up their areas. While there are mainly young, fluvial and air-borne, relatively loose sediments on plains, the hillsides – except valleys – are made up of more resistant and generally older sediments. Main masses of medium-height mountains are made up of older and more solid formations. Such differences can be perceived by map 10 presenting rocks by their compressive strength (load bearing capacity). Rocks with unfavourable, low, moderate or even good bearing capacity can be distinguished, however, bearing capacity can also be high in extreme cases. For the first categories, soft clays out of sedimentary rocks, while for the latter some hard limestones, andesite, basalt and granite are the best examples. Based on the value of compressive strength the volume and loading capacity of a structure to be built on a given rock can be defined.

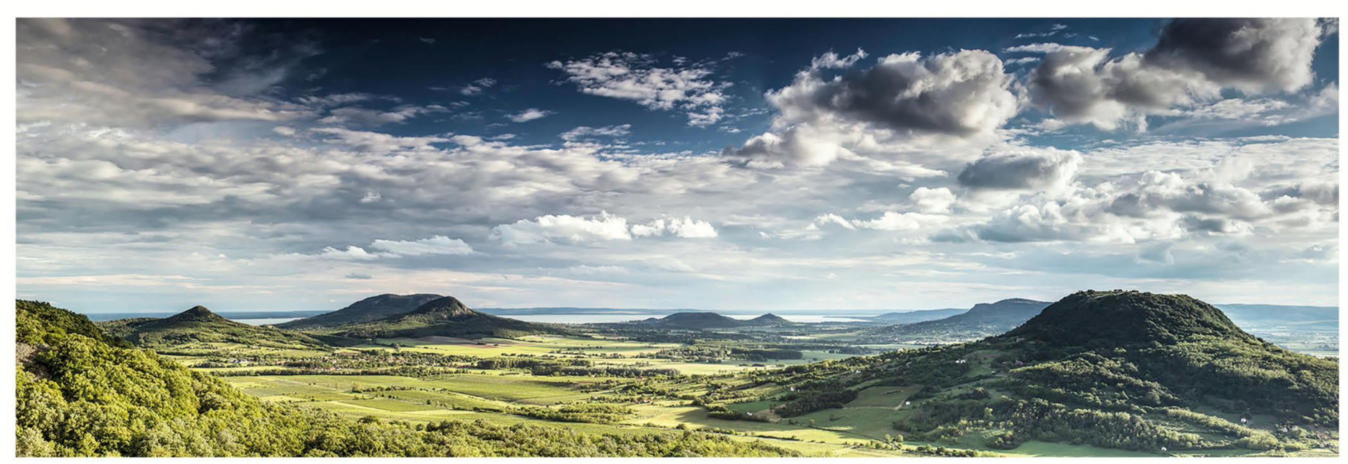
Based on the topography flat, slightly and steeply sloping areas can be distinguished. This is reasonable because the value of gradient defining how stable a given rock can be makes a difference. In unfavourable engineering geological conditions, the rock material making up the slope may move inducing different mass movements even in the case of a very slight slope. In addition to this, the stability also depends on the degree of water saturation and fragmentation of rocks. Mass movements can also be classified according to their shape, velocity and the trajectory of moving rock mass. Steep but not mass-movement-prone stable slopes and bluffs as well as steep banks exposed to mass movements can be distinguished. Red lines on the map mark steep slopes where petrologic and topographic conditions are suitable for potential mass movements, primarily landslides. These are typically associated with banks and developed along smaller or greater rivers (river Danube, Rába, Hernád) as well as bluffs along Lake Balaton. As for sections of river Danube at the Alföld, banks are mainly made up of Neogene loess formations on which sliced landslide (e.g. Dunaföldvár) as well as rock falls came into being (this is more detailed in chapter *'Natural hazards'* in our Atlas), while movements on loose sediments of the Pannonian age – mainly in the vicinity of Érd – represent a different type.

The top subsoil sedimentary cover is easily and regularly reworked even in the case of the slightest slope. The reworked sediment may be either stable (the slope remains stable) or prone to any movement. That is why not only steep slopes may slide but there are a few slighter slopes prone to any surface movement. Such and other surface movements (slumps, mudflows, rock falls) as well as locations where such processes have taken place are marked by a red cross. Areas where swelling clays are present can endanger human life or cause any damage to property, and rocks prone to compression (e.g. peat) or areas covered by quicksand due to load and vibration (e.g. earthquake) pose a similar risk.

A further engineering problem is the occurrence of subsurface waters (shallow groundwater, groundwater, karst water). The soaking of the subsoil on the one hand may cause damage to buildings and built structures (e.g. bridges), on the other hand it could make building on certain areas complicated because the bearing capacity of soaked soils is decreased, so garages and cellars to be built may take water in. That is why there is a separate sign on the map for areas with contiguous water mass relatively close to the surface (above -2 metres). At the planning stage surface waters, marshes and wetlands also have to be taken into consideration.

Natural engineering geological conditions are increasingly influenced by human activities. The impact can be favourable (stabilization of slopes prone to slide) but also harmful (under cellaring of settlements and the collapse of such cavities). The map – due to its scale – presents impacts of human activities for locations concerned by it to a larger scale, endangering human life and the environment or resulting in a financial risk. It presents most common rock, sand and clay exploitation sites as well as locations concerned by mining of ores and other mineral raw materials as well. As for stability, building in the area of closed mining sites could be problematic in the future. Oil and gas exploitation as well as water extraction can also have engineering geological impacts (e.g. subsidence may occur). Especially subsurface galleries and adits of mining as well as areas with a high number of cellars are potential sources of geological hazards because – in case of improper establishment or due to water intrusion – they may lose their stability, may collapse causing rupture towards the surface (the same may take place in natural caverns as well).

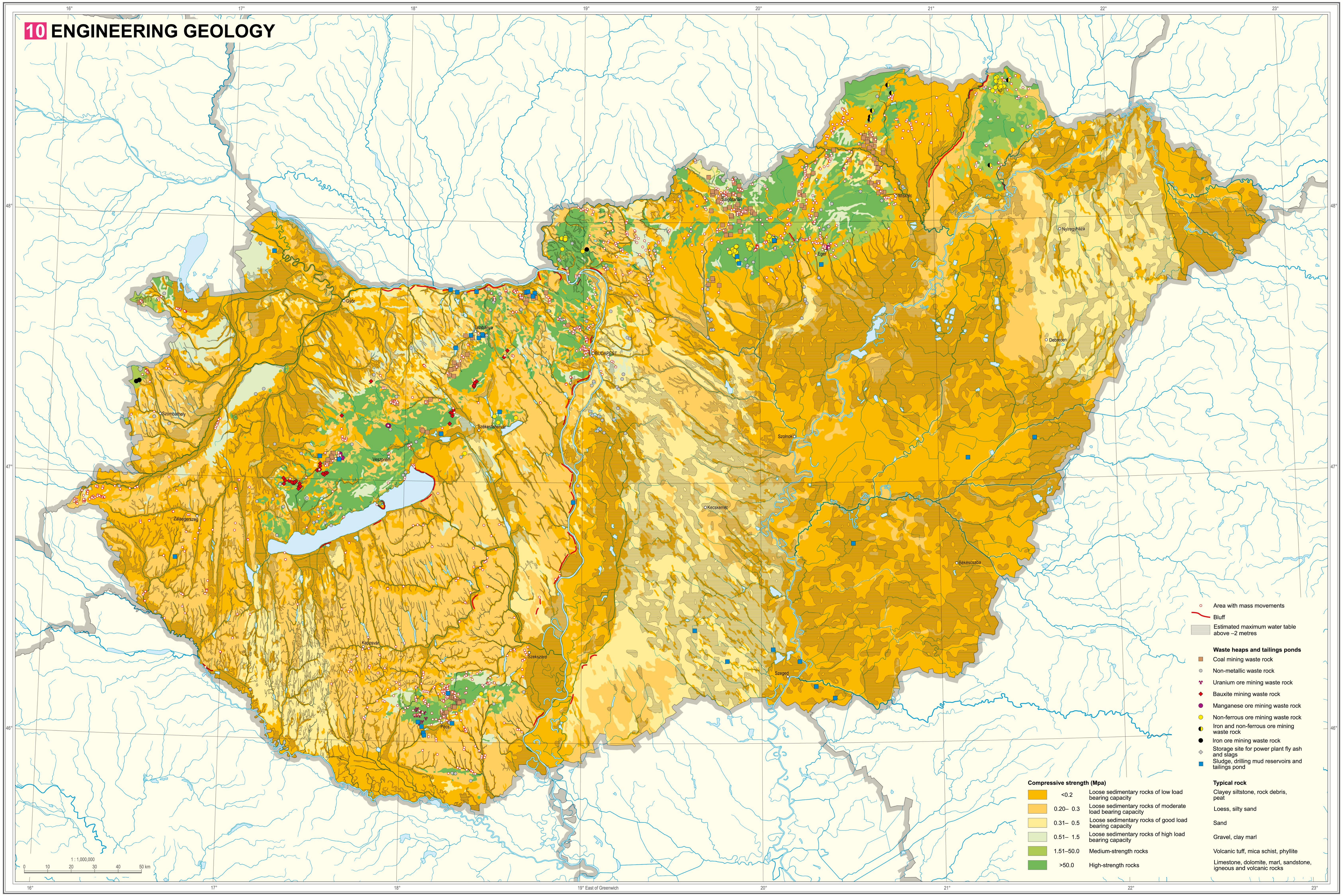
Waste heaps related to mining are also present on the map. Closed and not properly rehabilitated mines also present environmental risks (e.g. may cause water contamination). Heaps of by-products, power plant slags and fly ashes of metal working (some of them are hazardous waste) are only present on the map if they cover large territories and are of high-risk. Some of them are particular e.g. storage sited of red mud generated during alumina production. Areas formerly contaminated but nowadays considered to be clear (such as areas of former Soviet barracks, closed industrial sites) as well as old landfill sites established according



1 *Pannonian basaltic hills of the Tapolca Basin*

©Geographical Institute, MTA CSFK www.nationalatlas.hu, Budapest, 2018

10 ENGINEERING GEOLOGY



©Geographical Institute, MTA CSFK www.nationalatlas.hu, Budapest, 2018

to outdated environmental regulations are also considered as sources of hazard from environmental geological aspects.

Geothermal conditions, thermal waters

The outstanding conditions of Hungary in Europe in terms of geothermal energy are due to its geological setup. During the development of the Pannonian Basin the lithospheric plate were remarkedly attenuated due to tectonic tensile forces, the underlying hot asthenosphere, getting closer to the surface, provides significant heat flow (in general 90–100 mW/m², opposite to that of the 60 mW/m² for continents). Exponential growth of temperature with depth (value of geothermal gradient) is about 4.5–5 °C/100 m in most of the country, therefore at a depth of 500 m the average temperature is 35–40 °C, while at 1,000 m depth 55–60 °C, and at a depth of 2,000 m 100–110 °C could be measured, however, at some depths the temperature may reach 120–130 °C as well. In more than 70% of the area of Hungary thermal water with a temperature of 30 °C could be recovered from subsurface clastic sedimentary rocks or fractured limestone, dolomite as thick as more a thousand metres.

As for Hungary, the total recharged geothermal heat output from depth by thermal conduction is 8.37 GW equalling to heat quantity of 264 PJ/year. This is 24% of the national primary energy need (1,085 PJ in 2010). At the same time, only a certain fraction of theoretically available thermal resources of subsurface fluids (thermal waters) stored in the rock framework as well as in pores, fractures can be exploited and utilized with present technologies. The reason is while the thermal resources on Earth produced in the Earth's crust by the decay of isotopes are constantly recharged and so unable to be depleted, the same cannot be said about subsurface waters carrying heat. Only a certain volume can be extracted without the decrease in pressure and yield of deep reservoirs which is recharged by natural infiltration from the surface (precipitation), or re-injected to the original deep reservoir subsequent to the utilisation of the heat of water for energetic purposes. Considering all aspects, the sustainable (recharged), real, annual deep geothermal capacity of the Pannonian porous basin sediments is 30 PJ/year, while from the formations making up the basement is 130 PJ/year.

Regarding geological conditions of the Pannonian Basin, two main thermal aquifer formations can be distinguished. The several thousand metres thick Upper Miocene–Pliocene (Pannonian) sandy, clayey, marly sequence filling up the basin was accumulated by rivers heading to the basin from the ranges of the Alps and the Carpathians elevated simultaneous with the subsidence of the basin. Within this sequence the main thermal aquifer successions are the 30–100-m-thick, dominantly sandy units being hydraulically connected to each other and deposited in the margins of the advancing shelf of fluvial systems formerly filling up the basin (Upper Pannonian thermal water succession). Such formations can be found inside the basin (in the central and southern parts of the Alföld) at depths of 700 to 2,000 metres where temperatures are 60–110 °C. The Upper Pannonian sandy successions under hydrostatic pressure have favourable hydraulic parameters in terms of thermal water extraction: their pore space volume may reach 20–30%, and water conductivity 4×10–6–5×10–5 m/s. Waters are in general alkalic $NaHCO_3$-type with low to medium dissolved solid content. Such aquifers are widely utilised for balneological as well as thermal purposes directly (primarily in the Alföld for heating foil tunnels and greenhouses as well as cities) 11.

Another significant thermal aquifer formation group can be associated with the karstified Palaeozoic and Mesozoic carbonate formations composing the sedimentary basement as well as the remarkable fault zones of fractured-weathered crystalline rocks with increased hydraulic conductivity. Temperatures at several thousand metres deep in the basement exceed 100–120 °C in many places therefore reservoirs in the basement composed of carbonate and crystalline rocks may be capable of combined power and heat generation as well. In some places (e.g. Fábiánsebestyén, Nagyszénás) overpressured deep reservoirs are also known in the basement as being potential locations of electric power generation in the future. Thermal karst waters being part of active regional water flows, stored in the carbonate basement and recharged from the surface are usually $CaMgHCO_3$ type and have low dissolved solid content, while there are NaCl-type waters with high dissolved solid content in closed reservoirs remote from regional water flows lacking recharge.

Beside these two thermal aquifers, the Miocene carbonate-sandy reservoirs of local importance are also worth mentioning. These are typically some 10 metres thick formations, hosting thermal waters, with cap-like covering to riffles in some places and high dissolved solid content in general. Their small volume and high dissolved solid content are the limits of potential indirect heat and possibly combined power and heat generation. Other perspective areas of future electric power generation (as well as combined power and heat generation) are the crystalline (mainly granitic) rocks between the depths of 3 km and 5 km in the basement being also the key areas for projects targeting enhanced geothermal systems (EGS) mainly in the southern part of the Alföld.

In Hungary there are ca. 950 operating thermal wells. Most of the utilised thermal water resources are used for bathing, agricultural and industrial purposes. Direct heat utilisation for energetic purposes is limited. Power generation based on geothermal energy practically does not exist but there are three projects under preparation targeting such purposes.

There is district heating in 650,000 flats of 95 settlements in total in Hungary, however, heating systems mostly fuelled by imported gas are substituted or complemented by geothermal heating only in 8 settlements. The installation of geothermal heating systems in Szentlőrinc (in 2011), Miskolc (Mályi) (in 2013) and Győr (in 2015–2016) was a major development. In addition, about a dozen settlements have so-called 'thermal district heating', especially the heating of public buildings (municipal buildings, town hall, library, school, etc.) has been realized using thermal water but residential properties, industrial customers, etc. are also connected to the recently constructed thermal water pipelines. Such district heating systems were constructed in the past few years in several settlements (e.g. Törökszentmiklós, Mezőberény, Szeged), and former systems were extended (e.g. Veresegyház). On the whole, the importance of geothermal district heating as well as heating with thermal water increased in recent years 11. Such special heating is available in 21 settlements and there is an opportunity for remarkable improvements in regions with favourable geological conditions by adequate state aids. As for agricultural use of geothermal energy (mainly heating of greenhouses, foil tunnels), Hungary is among the European elite. Further capacity enhancement is primarily hindered by limited water resources especially in the Alföld with remarkable over-extraction but aspects of sustainable thermal water management would be reassuringly manageable by enhancing the rate (which is low at present) of reinjection.

Classic field of utilisation of thermal water is usage as medicinal water (balneology). Several thermal and medicinal waters having well-deserved reputation are utilised in more than 150 municipal thermal baths. Several world renowned thermal and medicinal waters are utilized in more than 150 settlements nowadays. While $NaHCO_3$ type thermal waters in the Upper Pannonian sequence are exploited for agricultural utilisation in 86%, water composition and water type of medicinal and bathing waters in balneology varies within a wide range as well as their temperature varies on wide scale. The most common is the utilisation of $NaHCO_3$ and $NaHCO_3Cl$ type waters with temperatures between 35 °C and 68 °C, characterized by a mean temperature of 48 °C, with proportions of 45% and 25%, respectively. Their medicinal property also depends on the presence and concentration of other components like sulphur, iodine, bromide and radon. Thermal waters used as drinking water at present are mainly (in 92%) $NaHCO_3$ and $CaMgNaHCO_3$ type and their temperature varies between 30 °C and 35 °C. Lukewarm groundwater at shallow level used as thermal water is significant in regions (e.g. Southeastern Hungary) where contamination of near-surface groundwater due to either natural (e.g. arsenic) or human reasons is remarkable.

*The essence of **geothermal heat pump** (or ground-source heat pump) **technology** is that low temperature (4–15 °C) heat of shallow beds (0–150 m deep) is transferred to a heat pump through a ground heat exchanger by means of a heat carrier fluid. The heat exchanger cools down the heat carrier medium on the primary side by using auxiliary power (electricity), then on the secondary side it warms up the heat carrier medium to be used for heating. Geothermal heat pumping can also be used for cooling, its return rate and sustainability further improve beside seasonal needs for heating and cooling. Considering the climate of Hungary, this advantage may predominate in the case of buildings with increased need for cooling (e.g. mainly commercial and office buildings). However, the distribution of heat pumps in Hungary is still regrettably low.*

Underground drinking water sources

Most of the precipitation falling down onto the surface runs down into surface watercourses, standing waters, seas. A portion of it gets back to the water cycle due to evapotranspiration of plants, a smaller portion infiltrates into the subsurface. A proportion of water not used by plants and infiltrating through the soil or near-surface rocks reaches the underground water table (or groundwater table according to its former name) through pores and fractures of rocks under which the cavities of rocks (pores, cracks) are saturated. Such water is called groundwater. Receptive successions are the aquifers. These are subsurface layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the extraction of significant quantities of groundwater.

Most of the groundwaters are from precipitation, a smaller amount is water closed (trapped) in pores of sediments from marine, lacustrine or possibly fluvial environment. In urban, municipal environments in the case of defects or leakage of pipelines, most of the effluents infiltrate into the groundwater as well. Similar to surface waters, most of the groundwater is in a constant motion and has different flow paths 12. Some of them lead through clastic sedimentary rocks of basin or hill origin, tapped in a short period of time (from one day to some 10 years) by local flow systems in shallow porous aquifers extending to some 10 metres of depth, and appear again as springs as well as in watercourses or standing waters. Intermediate and large regional flow systems are typical for porous aquifers, with waters aged from several hundred years to several ten or even hundred thousand years. For determining the age of waters, namely the elapsed time between infiltration or trapping as well as the date and location of examination, quite often isotope analyses are carried out.

Aquifers are often transboundary therefore the joint extraction of the same aquifer by neighbouring countries is not rare requiring co-ordinated water management in the long-term.

In most European countries groundwater has always had a key role in water supply. According to the *River Basin Management Plan* (*RBMP*) the groundwater resources of Hungary are 2,410 million m³/year of which ca. 745 million m³ annual volume is used by wells and spring-based waterworks.

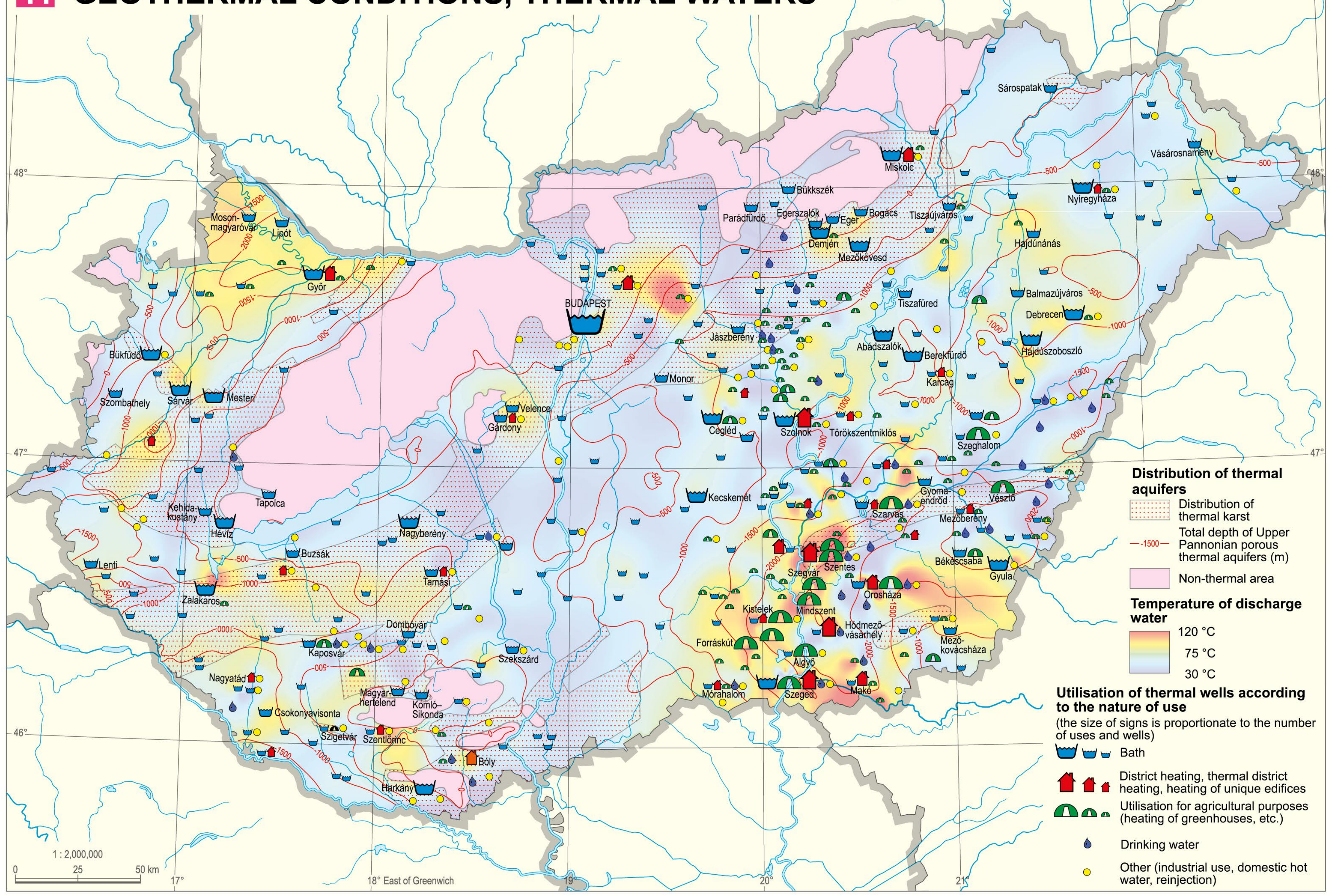
In case the aquifer can be used as drinking water supply, it is called drinking water aquifer.

The source of drinking water may be surface water as well as groundwater. 92% of the drinking water supply utility in Hungary is from groundwater. Drinking water is provided in all settlements, mainly (ca. in 96%) directly led into households, while – for the remaining 4% – people get water from the utility systems either led to their building plots or installed within 100–150 m range. The domestic water consumption is 110 l/day in general, 400 million m³/year in total.

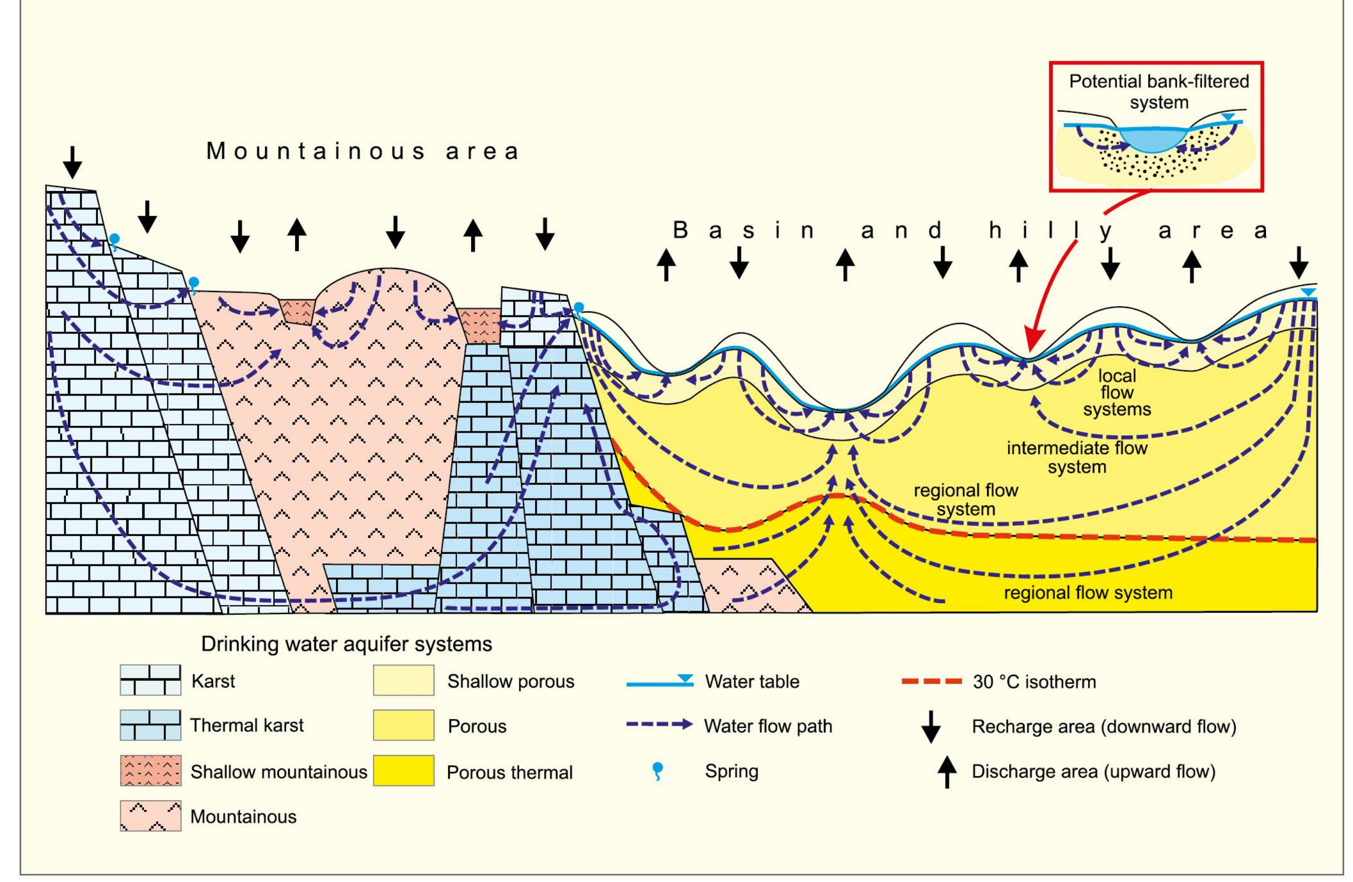
Drinking water sources are mainly supplied from groundwater colder than 30 °C and stored either in porous Pleistocene–Holocene or Upper Pannonian formations, however, older carbonate formations (limestone, dolomite) have a key role as well 13. Porous aquifers are the most wide-spread for drinking water supply and also the largest hydraulically interrelated body groups of groundwater in Hungary. The maximum depth suitable for drinking water extraction is typically 400 m in the Alföld because – due to the high geothermal gradient – under this depth water temperatures exceed the 30 °C limit value which is less suitable for drinking water supply.

As a generic term, typically fractured, karstified limestone and dolomite rocks are called karst aqui-

11 GEOTHERMAL CONDITIONS, THERMAL WATERS



12 MAIN DRINKING WATER AQUIFERS AND TYPICAL FLOW SYSTEMS



Drinking water is potable – both from chemical and biological aspects – water that meets the standards on drinking water quality. This is regularly tested not only in Hungary but in several countries as well. Standards on quality of water intended for human consumption are laid down in Council Directive 98/83/EC, in Hungary this is regulated by Government Decree No. 201/2001 on the requirements and monitoring of drinking water quality.

fers being regional drinking water aquifers as well. There are broad karst drinking water aquifers in the Transdanubian Range where the very thick Mesozoic, mainly Triassic limestone and dolomite rocks are called main karst aquifers. They are in close hydraulic relationship with karst waters stored in younger overlying (e.g. Eocene) limestone types. Operating and potential karst drinking water aquifers can be found in the Mecsek and Villány Mts., in Aggtelek Karst as well as in the Bükk Mts. In other mountainous areas aquifers dominantly formed by fractured or regionally fractured porous rocks making up the aquifers have a key role in drinking water supply. Mountainous fractured aquifers are generally poor considering their water supply potential.

In the margins of mountains or in areas where the porous sediments of basins are good aquifers (e.g. Szigetköz), the shallow porous drinking water aquifers provide or may provide drinking water supply. Shallow aquifers and karst drinking water aquifers are sensitive to meteorological effects, therefore to extreme climatic conditions as well, and due to exposition to anthropogenic impacts the risk of contamination is higher than in the case of different aquifers.

Bank-filtered aquifers, the role of which is quite important in drinking water supply are also worth mentioning. Most of the bank-filtered water resources originate from surface water that is stored in the underground system for only a short period of time, the rest is from the groundwater of the background (shallow aquifers far from the river bed) extracted by wells located either in the river bed or near the bed. The drinking water supply of Budapest is fully provided by the bank-filtered system, the most of such system is considered as perspective water resources.

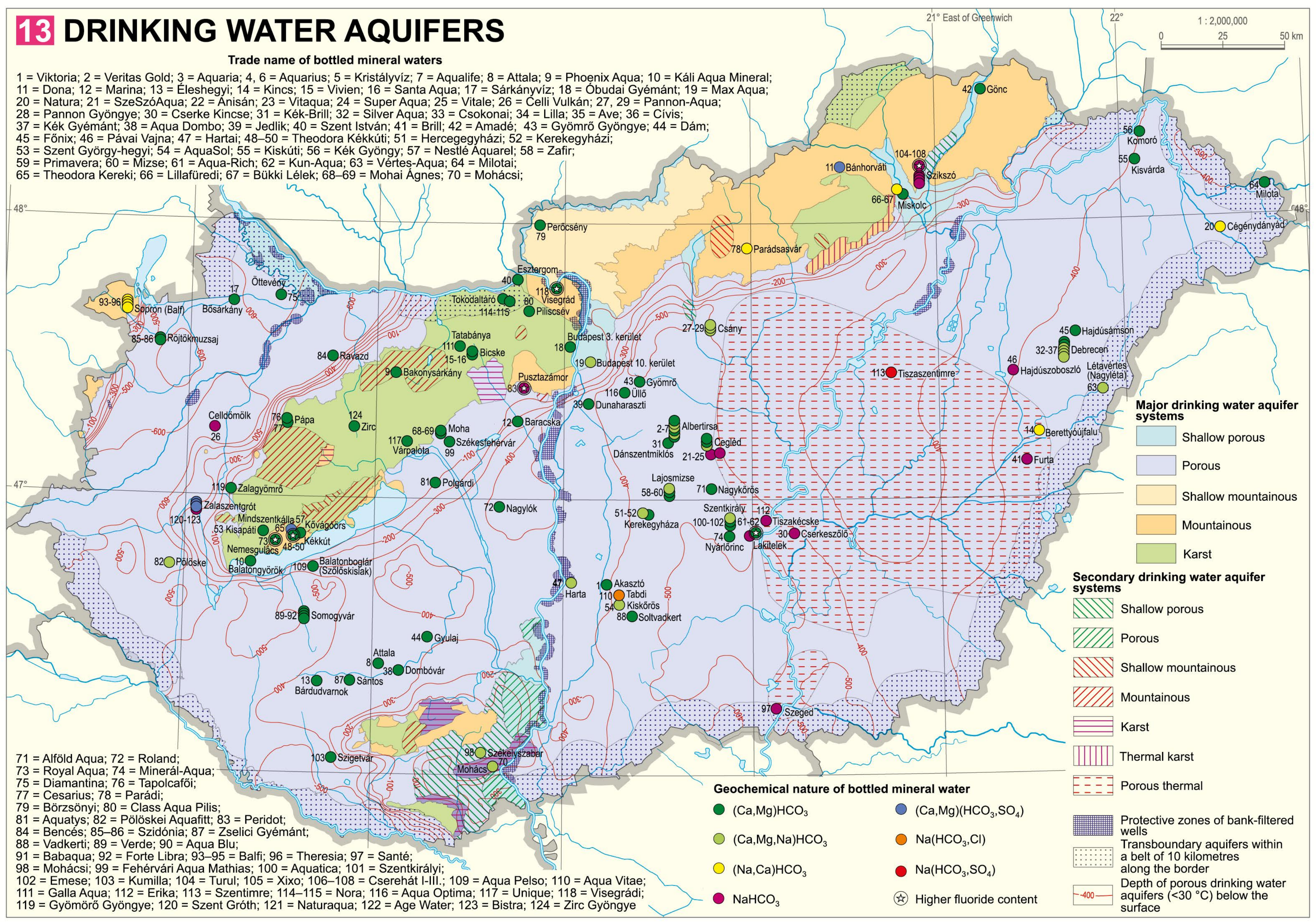
Considering the major chemical components, water extracted by wells and spring-based waterworks is of good quality throughout the country. The most frequent problem – especially in the southern part of the Alföld – is the arsenic content of natural (geological) origin above the limit value of 10 μg/l, affecting water supply of 88 settlements in 2014, however, such problems have been solved at an increasing number of settlements. Boron and fluoride content of natural origin of some drinking water aquifers is above the limit value (1 mg/l and 1.5 mg/l). As for boron, water supply of 14 settlements was considered in 2014. The occurrence of ammonium, iron and manganese in drinking water above the limit value is not directly harmful to health.

Mineral waters

Hungary is not only rich in good quality cold and thermal waters but also conditions are outstanding for mineral waters considering their variety and quality. Most mineral waters are sold bottled. Previously, waters with dissolved solid content higher than 1,000 mg/l or at 500 mg/l with certain sodium, calcium, magnesium, fluoride and iodide concentrations were considered mineral water. EU legislation contains no such restrictions therefore such criterion – as a result of legal harmonization – is the result of national mineral water rating subsequent to Hungary joining the EU. At present natural mineral water is considered any water from protected subsurface aquifers, originally free of contamination and has advantageous features for health due to mineral and trace element contents and other components, as well as unequivocally distinguishable from drinking water, its composition and temperature is within boundaries of natural fluctuation as well as it meets the standards from chemical and microbiological aspects (Ministerial Joint Decree No. 65/2004.).

Domestic annual mineral water consumption per capita increased significantly in the past few years, from 3 l in 1990 to 105 l in 2007 and to 126 l in 2015, however, – despite this increase – it is still lower than values in France, Germany (140 l/capita) and especially Italy (180 l/capita).

In March 2014, 123 types of mineral water were legally in commercial trade in Hungary 13. About 60% of bottled mineral waters are $CaMgHCO_3$ type extracted mainly from either karst aquifers or the upper zones of porous basin sediments, typically in recharge (downward flow) areas of intermediate and regional flow systems. In some cases, waters originating from Mesozoic or Miocene rocks have 20 to 25% sulphate contents. Further 13% of bottled mineral waters are $NaHCO_3$ type, extracted mainly from zones of upward flow in the Alföld, or where sodium becomes the determinant cation due to ion exchange in the subsurface water flow (e.g. aquifers of Upper Pannonian sedimentary sequences). Some bottled mineral waters have higher fluoride contents.



Mineral raw materials

Mineral raw materials of Hungary are state properties in their natural state and at the location of occurrence. Such treasures are part of our natural resources and national assets. The official national inventory of Mining and Geological Survey of Hungary established in 2017 as well as its legal predecessor, the Hungarian Office for Mining and Geology, kept records of more than 3,500 occurrences at the end of 2015, classified into three groups: fuels, ores and non-metallic mineral raw materials. Data of geological resources, i.e. total volumes of mineral raw materials verified by research data are included in the inventory.

Fuels

Fuels include hydrocarbons (crude oil, natural gas), coals (black coal, brown coal, lignite) as well as uranium-bearing mineral raw materials. Recently, we conventional and non-conventional hydrocarbons are distinguished, typically in low permeable reservoir rocks and requiring special mining technologies for exploitation. At present, bringing the latter ones (e.g. shale gases, Makó trench) into production is a major technological challenge for the hydrocarbon industry.

Hydrocarbon prospecting was initiated in Hungary already in the late 19th century but the first productive boreholes were only drilled regarding the present area of the country in the second half of the 1930s (the most well-known locality is at Budafa). Development and subsequent exploitation of occurrences in the Alföld were initiated from the mid-20th century. The inventory included 300 mainly small and medium-sized occurrences in the Southwestern Transdanubia and the Alföld in 2015. As for spatial distribution, crude oil is typical in Southwestern Transdanubia, while natural gas is found mostly in the Alföld. There are some occurrences of smaller importance in the southern part of the Bükk Mts. and the Kisalföld 14.

In the past two decades the annual production of crude oil decreased from 1.8 to 0.64 million tons, while the annual production of natural gas dropped from 5 to 1.9 billion m³. The total volume of crude oil resources is 649.6 million tons, while for natural gas it is about 4,116.3 billion m³.

Another group of fuels is coals. There are coal seams of different type and age in Hungary. Jurassic black coal, Cretaceous, Eocene, Oligocene and Miocene brown coal as well as Pliocene lignite seams are well-known.

There are black coal seams in the Mecsek Mts., brown coal seams in the Transdanubian Range (Tatabánya, Oroszlány, Dorog–Pilis coal basins, the northern foreland of Bakony Mts., in the vicinity of Ajka and Várpalota) as well as in the North Hungarian Range (Borsod and Nógrád coal basins). Lignite seams with remarkable resources are found in the forelands of the Bükk and Mátra Mts. as well as at the western border region, around the village of Torony.

Coal production in Hungary has been decreased significantly since the 1990s. Underground brown coal mines have been closed gradually, the production of black coal 2 terminated at the end of 2004. There were only a few brown coal mines operating in 2012. Beside the last coal mine to be closed (Márkus Hill brown coal mine with the total production of 0.7 million tons in 2012) production was still ongoing for residential purposes at 4 minor open-cast mines: in Transdanubia (Dudar V.–Nagyesztergár as well as in the Borsod Basin (Feketevölgy II. open-cast, Sajókaza III–IV.). Lignite production reached the highest volume out of coals in the past 20 years. The two largest


2 *Former open-cast mine of Jurassic black coal next to Pécs*

lignite open-cast mines (Bükkábrány, Visonta) produce ca. 9 million tons of lignite annually, used in the power station of Visonta for generating electricity.

On the whole, in the last two decades the production of black coal dropped from 1.4 million tons to 0 t, the production of brown coal from 8.4 to 0.16, at the same time the production of lignite increased from 6.6 to 9.1 million tons.

In regions concerned by mine closure there are still 245 coal seams with remarkable resources recorded in the national inventory, namely 1,625 million tons of black coal, 3,195 million tons of brown coal and 5,715 million tons of lignite.

According to the international nomenclature, uranium also belongs to fuels. In Hungary uranium-bearing rock masses are known in the Mecsek Mts. where production of uranium took place for years but mining was stopped in 1997. In the past few years outcomes and resource data of former explorations were re-assessed, therefore 26.8 tons of uranium resource distributed in 6 deposits was recorded in the inventory at the beginning of 2015.

Hungary has significant resources of carbon dioxide (44.9 billion m³). The majority of CO_2 production takes place in the Kisalföld, and it is used mostly in the food industry. Volume of production decreased from 0.4 billion m³ to 0.1 m³ tons in the past 20 years.

Ores

Hungary used to have a history looking back to several hundred years, once significant and world-famous ore mining took place mostly in areas outside the present boundaries of Hungary. In the past few decades the ore mining activity practically terminated. Production of iron ore 3 and sulphide ores (copper, lead, zinc) was terminated in 1985. Subsequently, the world-famous bauxite production was gradually decreased, from 1.7 million tons to 8,000 tons within 20 years. Beside bauxite, the only ore production is limited to manganese ore though the production has been halved to 0.06 tons (as compared to the production 20 years ago) 15. Though Hungary has significant copper ore resources in the vicinity of Recsk but economic conditions of the past decades could not make the commencement of production possible. There are


3 *Abandoned open-cast mine of the former sideritic iron ore mine in Rudabánya*

ore resources of 282 deposits in the inventory. The most significant ore resources are as follows: iron ore 43.1 million tons, lead and zinc ore 90.8 million tons, copper ore 781.2 million tons, precious metal ores 36.6 million tons, manganese ore 79 million tons and bauxite 123.9 million tons.

Non-metallic mineral raw materials

Non-metallic mineral raw materials include more than 60 types of solid mineral raw materials – excluding fuels and ores – of different geological age and formation usable in numerous fields of the national economy. The known resources of non-metallic raw materials are 22,379 million tons in total. Such an amount of resources is distributed between 2,250 occurrences. The total volume of exploited non-metallic mineral raw materials in 2015 exceeded 55 million tons. Mineral raw materials exploited in highest volumes are gravel, sand, types of clay, different carbonate formations (e.g. limestone, dolomite, marl) as well as volcanic effusive rocks (andesite, basalt, rhyolite) and their volcaniclasts such as different volcanic tuffs, tuffites. Production of perlite and peat-like materials is also significant. Moreover, in more or less volume, other mineral raw materials (e.g. illite, kaolinite, bentonite, zeolite) are exploited, often for special purposes 15.

Geology of regions of Hungary

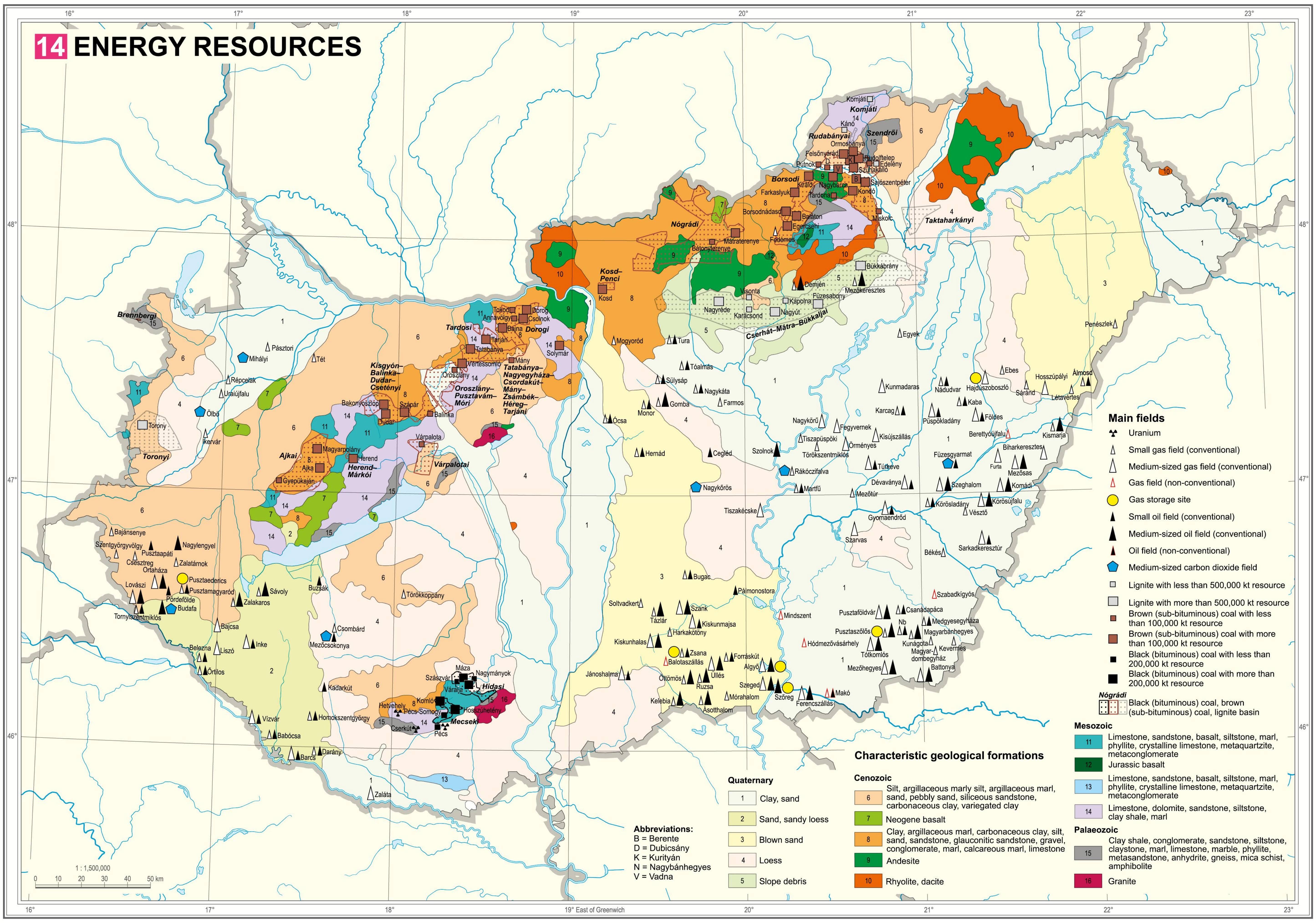
The surface of Hungary is composed of variable rock types formed in different ages of the Earth's history 16. The situation is more varied if subsurface geological conditions 17 18 are also considered. The overview of the geological setting of a given region is made using data of geophysical measurements and deep boreholes. Based on the most characteristic geological features, the following regions can be distinguished:

Alföld (Great Hungarian Plain)

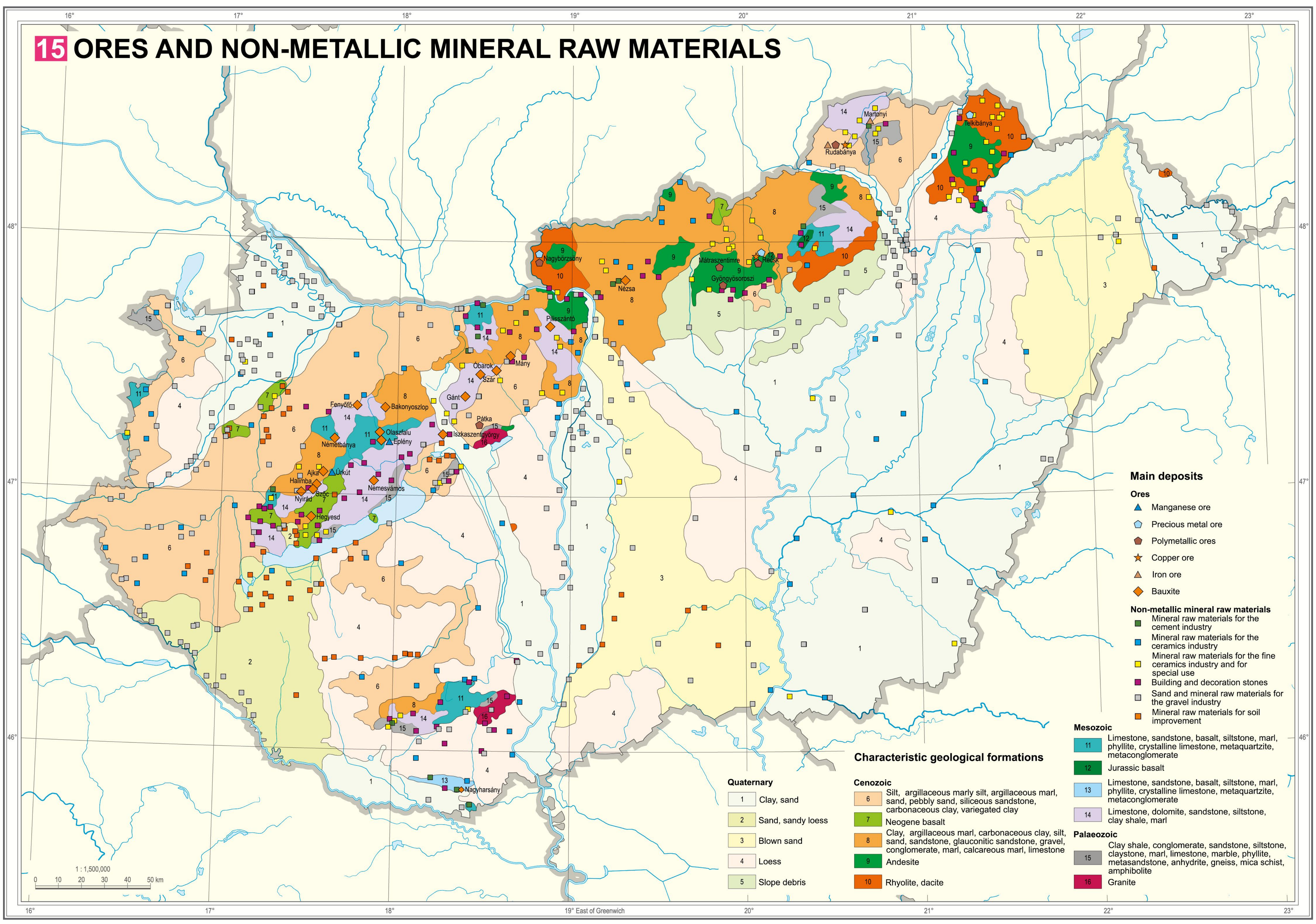
The Alföld is a broad basin filled up during the Late Neogene and the Pleistocene–Holocene. The surface of its basement is dissected, the geological setting is complex. In its southern and central parts the Neogene basement belongs to the Tisza Mega-unit, while the northern part is made up of rocks of the Mid-Hungarian Unit. Most of the basement belonging to the Tisza Mega-unit is composed of metamorphic rocks (gneiss, mica schist) and granite formed in the Variscan orogeny, overlain by Mesozoic rocks in some zones. In the north, in the Tiszántúl region strongly deformed, thick Cretaceous and Palaeogene marl and sandstone (flysch) form the basement. North of the Mid-Hungarian Lineament dominantly Mesozoic carbonate rocks underlying the Cenozoic successions have been revealed by boreholes.

In the early evolutionary stage of the Pannonian Basin, at the beginning of the Middle Miocene a series of tectonic troughs (e.g. Jászság and Nyírség regions, Derecske depression, Makó trough and Békés depression) were formed, and later during transgression they became deep basins.The in-between highs were gradually run over by shallow water. In the Late Miocene the whole area became the part of the Pannonian Lake. In more rapidly subsiding sub-basins the thickness of Neogene formations varies from 3,000 to 7,000 m, while in other areas it did not exceed 2,000 m. Filling up of the Pannonian Lake started ca. 8 Mya in the northern part and terminated in the southern region of the Alföld 5 Mya, resulting in the development of a fluvial-paludal environment instead of lacustrine sediments. The thickness of domi-

14 ENERGY RESOURCES

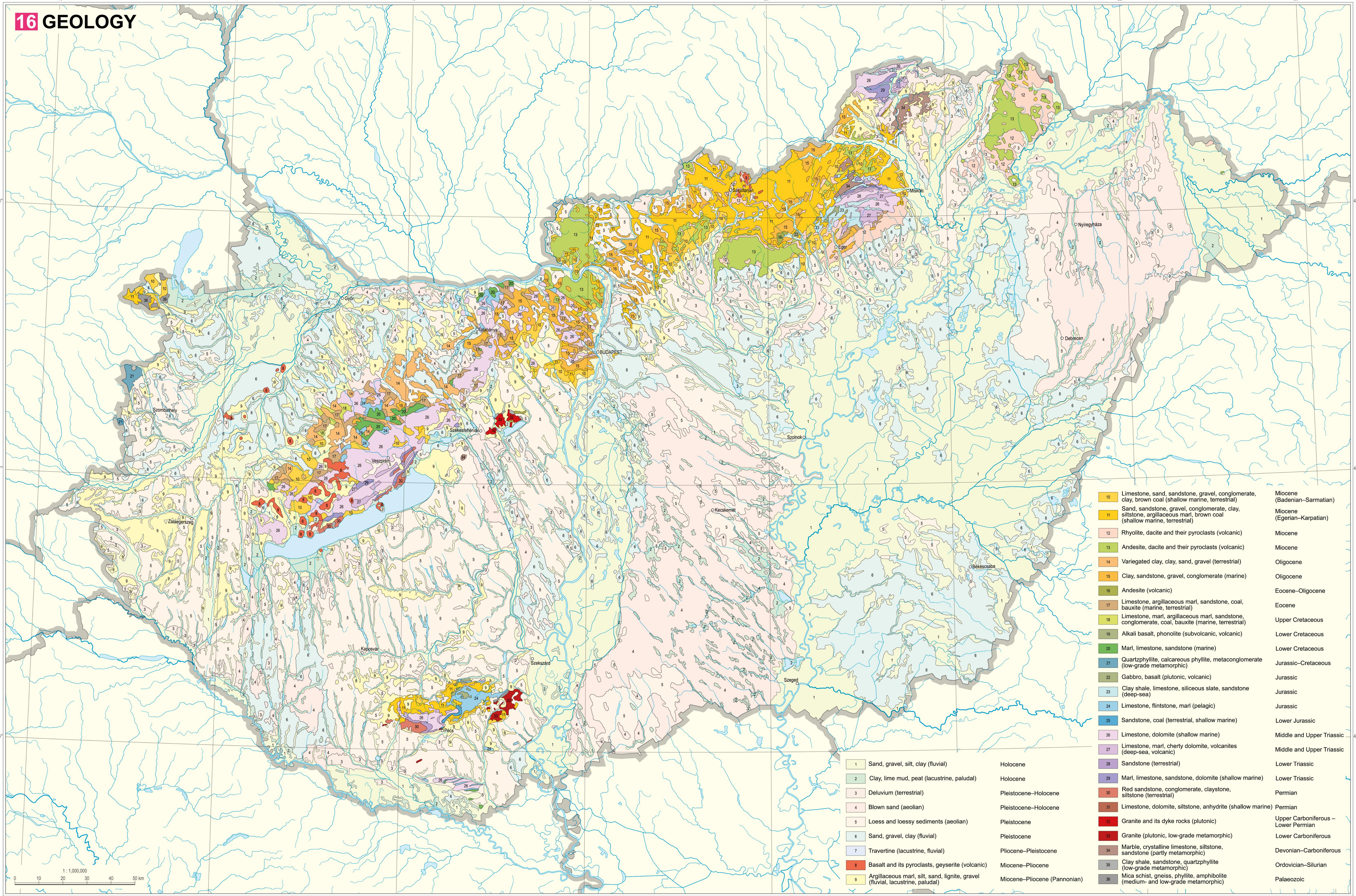


15 ORES AND NON-METALLIC MINERAL RAW MATERIALS



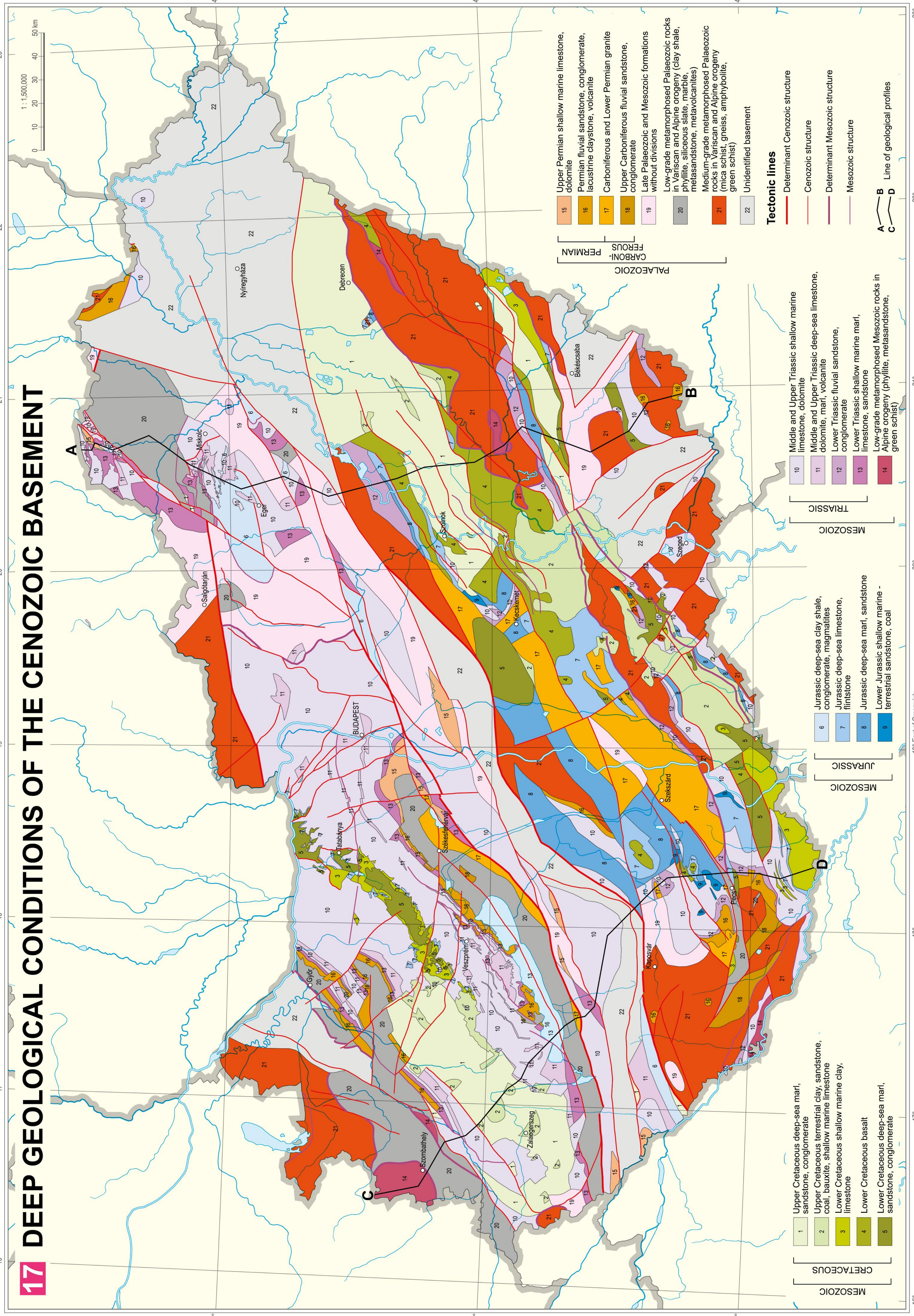
II.

16 GEOLOGY

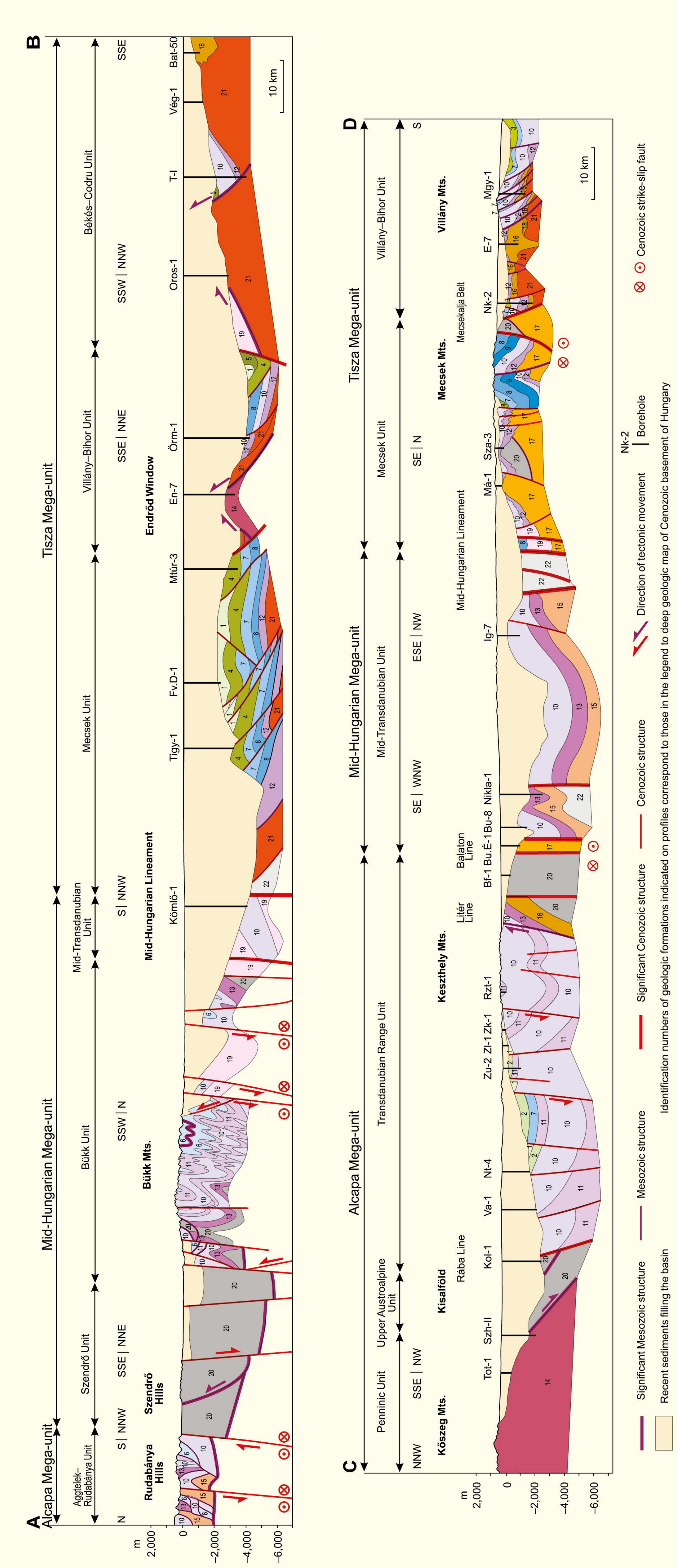


1 Sand, gravel, silt, clay (fluvial) Holocene
2 Clay, lime mud, peat (lacustrine, paludal) Holocene
3 Deluvium (terrestrial) Pleistocene–Holocene
4 Blown sand (aeolian) Pleistocene–Holocene
5 Loess and loessy sediments (aeolian) Pleistocene
6 Sand, gravel, clay (fluvial) Pleistocene
7 Travertine (lacustrine, fluvial) Pliocene–Pleistocene
8 Basalt and its pyroclasts, geyserite (volcanic) Miocene–Pliocene
9 Argillaceous marl, silt, sand, lignite, gravel (fluvial, lacustrine, paludal) Miocene–Pliocene (Pannonian)
10 Limestone, sand, sandstone, gravel, conglomerate, clay, brown coal (shallow marine, terrestrial) Miocene (Badenian–Sarmatian)
11 Sand, sandstone, gravel, conglomerate, clay, siltstone, argillaceous marl, brown coal (shallow marine, terrestrial) Miocene (Egerian–Karpatian)
12 Rhyolite, dacite and their pyroclasts (volcanic) Miocene
13 Andesite, dacite and their pyroclasts (volcanic) Miocene
14 Variegated clay, clay, sand, gravel (terrestrial) Oligocene
15 Clay, sandstone, gravel, conglomerate (marine) Oligocene
16 Andesite (volcanic) Eocene–Oligocene
17 Limestone, argillaceous marl, sandstone, coal, bauxite (marine, terrestrial) Eocene
18 Limestone, marl, argillaceous marl, sandstone, conglomerate, coal, bauxite (marine, terrestrial) Upper Cretaceous
19 Alkali basalt, phonolite (subvolcanic, volcanic) Lower Cretaceous
20 Marl, limestone, sandstone (marine) Lower Cretaceous
21 Quartzphyllite, calcareous phyllite, metaconglomerate (low-grade metamorphic) Jurassic–Cretaceous
22 Gabbro, basalt (plutonic, volcanic) Jurassic
23 Clay shale, limestone, siliceous slate, sandstone (deep-sea) Jurassic
24 Limestone, flintstone, marl (pelagic) Jurassic
25 Sandstone, coal (terrestrial, shallow marine) Lower Jurassic
26 Limestone, dolomite (shallow marine) Middle and Upper Triassic
27 Limestone, marl, cherty dolomite, volcanites (deep-sea, volcanic) Middle and Upper Triassic
28 Sandstone (terrestrial) Lower Triassic
29 Marl, limestone, sandstone, dolomite (shallow marine) Lower Triassic
30 Red sandstone, conglomerate, claystone, siltstone (terrestrial) Permian
31 Limestone, dolomite, siltstone, anhydrite (shallow marine) Permian
32 Granite and its dyke rocks (plutonic) Upper Carboniferous – Lower Permian
33 Granite (plutonic, low-grade metamorphic) Lower Carboniferous
34 Marble, crystalline limestone, siltstone, sandstone (partly metamorphic) Devonian–Carboniferous
35 Clay shale, sandstone, quartzphyllite (low-grade metamorphic) Ordovician–Silurian
36 Mica schist, gneiss, phyllite, amphibolite (medium- and low-grade metamorphic) Palaeozoic
1 : 1,000,000
0 10 20 30 40 50 km
19° East of Greenwich
BUDAPEST
Győr
Tatabánya
Székesfehérvár
Veszprém
Szombathely
Zalaegerszeg
Kaposvár
Szekszárd
Pécs
Kecskemét
Szeged
Szolnok
Békéscsaba
Debrecen
Nyíregyháza
Miskolc
Eger
Salgótarján

17 DEEP GEOLOGICAL CONDITIONS OF THE CENOZOIC BASEMENT



18 GEOLOGIC PROFILES TO DEEP GEOLOGIC STRUCTURAL MAP OF THE CENOZOIC BASEMENT



4 *Pipe of Pannonian basalt volcano on Ság Hill*

nantly fluvial, paludal, sometimes terrigenous, aeolian Pleistocene sediments exceeds 50 m in general but in some, still subsiding sub-basins it may reach 500 m as well.

Kisalföld (Little Hungarian Plain)

The Kisalföld is also one of the sub-basins of the Pannonian Basin. Its basement in the northwestern part is made up of moderately metamorphosed rocks (mica schist, gneiss) belonging to the Lower Austroalpine nappe system as well as weakly metamorphosed Palaeozoic rocks (phyllite, metasandstone, dolomite) similar to those in the Upper Austroalpine nappe. In the southeastern part weakly metamorphosed Palaeozoic rocks belonging to the Transdanubian Range Unit are overlain by Permian and Triassic sedimentary rocks.

Linked to the early period of the development of the Pannonian Basin, highs and basins bordered by faults evolved in the Middle Miocene. Transgression took place in its central part ca. 18 Mya, producing clayey sediments in the deeper, inner parts of the basins, while sandstones and limestones were formed in shallower marginal parts but in some places terrigenous sediments (gravel, clay) accumulated. Sedimentation was followed by an intense volcanic activity up to the early phase of the Late Miocene resulting in the formation of volcanic rockmass exceeding 1,500 m. This area also became part of the Pannonian Lake ca. 12 Mya. In deeper parts of the lake divided by peninsulas and islands clayey sediments, in the margins and in shallower parts gravelly-sandy sediments were deposited. Rivers from neighbouring ranges gradually filled up the lake by building huge delta systems, accumulating a thick sandy sedimentary mass. This process took place ca. 9 Mya in the area of the Kisalföld. Subsequent to becoming a dry land, a fluvial-paludal sedimentation was in progress, the thickness of Late Miocene and Pliocene fluvial deposits may even exceed 1,000 m. In the meantime, in the Pliocene ca. 5 Mya, an explosive basalt volcanism was started and resulted in the formation of volcanic tuff rings (Ság Hill 4, Kis-Somlyó Hill in the Kemenesalja region). Subsidence and sedimentation were still on in the Pleistocene and the Holocene, the most intensely subsiding central part of the basin (in the vicinity of Győr) further, some 500-m-thick fluvial and air-borne sediments were deposited.

Alpokalja (Eastern Alpine Foreland)

As the appendage of the Styrian Pre-Alps belonging to the Central Eastern Alps, the Palaeozoic and Mesozoic metamorphic rocks of the Sopron and Kőszeg Mts. form the easternmost superficial ridges of nappe system of the Eastern Alps. The Sopron Mts. is mainly composed of mica schist and gneiss belonging to the Lower Austroalpine nappe system. Metamorphism may be linked predominantly to the Variscan orogeny that took place in the Carboniferous but nappe over-

5 *Middle Miocene shallow marine limestone in a former quarry at Fertőrákos; today it is a nature conservation interpretation site and a theatre as well*

thrusts occurred during the Alpine orogeny initiated in the Cretaceous also altered the mineral composition and the structure of rocks. Metamorphic rocks of the Kőszeg Mts. are dominantly phyllites formed by the alteration of Jurassic–Early Cretaceous marine sedimentary rocks (conglomerate, sandstone, marl). There are rock masses of smaller extension formed by low-grade alteration of igneous rocks (basalt, gabbro) making up the former oceanic basement. In the Early Miocene in small basins developed in the Sopron Mts., beds of fluvial gravel, and later lacustrine clay, silt and sand intersected by coal beds were deposited, during transgression while in the Middle Miocene near-shore gravelly and deep-water clayey sediments developed. Later – by filling up the basin – shallow marine, fossil-rich limestone 5 was formed, followed by gravelly delta sediments and finally gravelly-sandy lacustrine sediments were deposited in the Late Miocene.

Transdanubian Hills

Its westernmost parts, the Zala Hills and the Central Dráva Plain – tectonically the former Zala and Dráva basins – are tectonic depressions formed in the early stage of the formation of the Pannonian Basin (Lower and Middle Miocene). They became sub-basins of the Pannonian Lake in the Late Miocene. Due to a diverse earlier development, their basements are made up of very different rocks. The basement of the North Zala Basin belongs to the Transdanubian Range Unit, accordingly it is made up of Triassic dolomite, limestone and marl, Upper Cretaceous limestone and marl, Eocene limestone, marl as well as volcanic andesite, andesite tuff as thick as 1,000 m. From the Middle Miocene thick marine sediments, then a lacustrine succession and later mainly sandy delta sediments were deposited. Finally in filled in lake basins fluvial – lacustrine sediments developed. At the same time, the basement of the South Zala Basin belongs to the Mid-Transdanubian tectonic unit. South of Lake Balaton there are predominantly Triassic limestone and dolomite, further to the south weakly metamorphosed Triassic and Jurassic limestones can be found in the basement of basins, overlain by Early Miocene fluvial conglomerate. In tectonic troughs formed in the early development phase of the Pannonian Basin thick rhyolite tuff (ignimbrite) accumulated. In the initial phase of transgression in the Middle Miocene, several hundred metre-thick gravel was deposited, then in the inner parts of basins a thick sediment mass consisting of alternating silt, clay and argillaceous marl layers accumulated in the deepening sea, while in shallow margins limestone formed. The Late Miocene lacustrine succession is quite similar to that in the North Zala Basin.

In the basement of the Dráva Basin Palaeozoic rocks moderately altered in the Variscan orogeny, Carboniferous sandstones and Mesozoic carbonate rocks can be found, overlain by a succession consisting of Early Miocene conglomerate, sandstone and argillaceous marl reaching a thickness of 2,000 m in some places. During transgression in the Middle Miocene, marine marl and clay were deposited in the deeper parts and limestone in the shallower margins. In the Late Miocene clayey sediments in the Pannonian Lake, a 1,000-m-thick, mainly sandy sediment in the prodelta while – subsequent to filling up at the very end of the Miocene and in the Pliocene – a 2,500-m-thick fluvial-paludal sediment formed. Subsidence was still on in the Pleistocene, resulting in the formation of a further 250-m-thick fluvial sediment.

In areas of the Transdanubian Hills between the Transdanubian Range and the Mecsek Mts. under Cenozoic rocks, Triassic carbonate rocks of the Mid-Transdanubian Unit to the north, Palaeozoic igneous and metamorphic as well as Mesozoic formations of the Tisza Mega-unit composed of varied rocks to the south can be found. Subsequent to the deposition of the thick Early Miocene fluvial conglomerate and sandstone, thick rhyolite tuff (ignimbrite) were formed in tectonic troughs. During transgression initiated in the Middle Miocene, clayey rocks formed in relatively deep and open seas, then in the early stage of the Late Miocene dominantly shallow marine calcareous sediments were deposited which was followed by the formation of sandy and fluvial-paludal sediments deposited in prodeltas of the Pannonian Lake. However, intensive subsidence did not proceed in this area during the Pliocene and the Pleistocene.

The oldest rocks of the Mecsek Mts. being the most salient part of the hills south of the Mecsek Mts. as well as the Villány Mts. are in the Mecsekalja fault zone stretching along the southern border of the Mecsek Mts. and to the southeast, in the Geresd Hills. There are igneous, namely granite masses intruded in the Early Carboniferous and cropping out on the surface in the latter area. South of the Mecsek Mts. – overlain by only thin Pleistocene – Pliocene sediments in some places – also metamorphic rocks (mica schist, gneiss, amphibolite, and subordinately serpentinite and marble) formed in the Variscan orogeny can be found, superposed by anthracite-bearing Carboniferous grey sandstone and later on by Permian fluvial red sandstone, siltstone and volcanic rocks (rhyolite). In western part of the Mecsek Mts. the most complete, ca. 3,000-m-thick Permian series can be found mainly made up of successions of fluvial red sandstone, conglomerate and lacustrine claystone as well as rocks of volcanic origin (rhyolite). The sandstone itself hosts the formerly exploited uranium ore. At the beginning of the Triassic terrigenous sandstone, conglomerate and siltstone were formed 6, and later on due to transgression in the Middle Triassic siltstone, anhydrite, gypsum and dolomite, later limestone deposited as thick as several hundred metres. In the Late Triassic fluvial sediments developed again. They are superposed by the Jurassic series exceeding 3,000 m interbedded with coal seams 2. Due to the permanent deepening of the sea, deep marine marl further and further from the shores, later on red and white beds of limestone were deposited, while a basaltic volcanism took place at the beginning of the Cretaceous.

6 *The so-called 'Babás-szerkövek' (Babe stones) above Kővágószőlős made up of Early Triassic fluvial sandstone*

The Jurassic and Triassic formations of the nearby Villány Mts. are markedly different from those in the Mecsek Mts. In deep and shallow marine periods of the Jurassic limestones were formed, then at the end of the Jurassic there was a short regression period with bauxite formation. At the beginning of the Triassic in the slowly advancing sea several hundred metre-thick fossil-rich limestone, later in deep seas marl and sandstone accumulated. In most of the Cenozoic the area was a dry land. In the Early Miocene a thick fluvial succession developed in the northern foreland of the Mecsek Mts. as well as in intermontane basins. In some places rhyolite tuff and andesite are superposed on such succession or directly on the Mesozoic rocks. In the Middle Miocene nearshore shallow marine limestone, in the deeper parts of the basins sand, silt, clay and argillaceous marl were formed. Sedimentation of the Pannonian Lake commenced with the deposition of gravel in general. This is overlain by a succession of calcareous marl and argillaceous marl deposited in open lake, and finally sandy delta sediments were deposited.

Transdanubian Range

The 250 km long Transdanubian Range stretching from southwest to northeast are made up of rocks of different age and nature, however, mostly limestone and dolomite formed in the Mesozoic can be found on the surface. The oldest rocks occur in the Balaton Highland as well as in areas between Lake Balaton and

7 *Late Triassic shallow marine dolomite in the Séd valley of Veszprém*

Lake Velence. These are marine sedimentary rocks formed in the early period of the Palaeozoic (Ordovician, Silurian, Devonian) altered into phyllite during the Variscan orogeny. In the early period of the Permian granite composing most of the Velence Hills. intruded into such rocks. In the late period of the Permian the phyllite in southern part of the Balaton Uplands was superposed by the ca. 500-metre-thick red conglomerate and sandstone of fluvial origin. This was also overlain by some hundred metres thick succession of marl, sandstone, limestone and dolomite formed in shallow marine environment of the early period of the Triassic. This is covered by deep marine cherty limestone with volcanic tuff intercalations formed in the Middle Triassic. At the same time ca. 1,000-m-thick shallow marine dolomite developed in the northeastern side of the Transdanubian Range stretching from the vicinity of Veszprém to the Buda Mts.

At the beginning of the late stage of the Triassic period, most of the area of the range became a shallow marine environment, and in the following 20 million years a 2,000–3,000-m-thick dolomite 7 and limestone formed on the steadily subsiding basement. Such karstifiable rocks make up the most of the Keszthely, Bakony, Gerecse, Vértes, Pilis and the Buda Mts. In the Jurassic the formation of shallow marine carbonate sediments was replaced by development of dominantly red limestone types deposited in the more and more deepening and opening sea. In later phases of the Cretaceous deep marine conditions prevailed but while chert lens-bearing white limestone formed in the Bakony Mts., simultaneously very thick grey marl and sandstone deposited in the Gerecse Mts. In the middle part of the Cretaceous (ca. 110 Mya) the formerly developed rocks were piled up by tectonic forces and a huge, northeast–southwest oriented trough (synclne) came into being. Due to orogenic forces the area elevated, became a dry land for a longer period, there was intense erosion in margins of the syncline. As a consequence, in vast areas Triassic limestones and dolomites prone to karstification were exposed, bauxite accumulated in karst depressions. Subsequently, the inner part of the syncline was flooded again by the sea resulting in the deposition of clay, marl and limestone. Elevation and erosion followed by bauxite accumulation, coal formation in lacustrine and shore marshes, the process of shallow marine and deep marine sedimentation as a whole repeated at the very end of the Triassic and even in the Eocene.

8 *Pannonian columnar basalt in the quarry pit of Hegyes-tű Hill in the Balaton Uplands*

Subsequent to the Eocene (ca. 30 Mya) the most of the Transdanubian Range also became a dry land and was the target area for deposition of fluvial sediments in the Late Oligocene, except the northern part where marine sedimentation was not interrupted and shallow marine sediments of the Late Eocene were superposed by clay and marl developed in deeper sea in the Oligocene. In the Early and Middle Miocene the most of the Transdanubian Range was a dry land, shallow marine gravelly-sandy sediments and limestones developed sporadically. In the early phase of evolution of the Pannonian Lake the Transdanubian Range were a peninsula, subsequently most of its area was suffused by the lake. In the late stage of the Miocene (ca. 8 Mya) basaltic volcanism was initiated in the Southern Bakony Mts., particularly in the areas of Kab Hill and Agár Summit, the Tapolca Basin 1 as well as the Balaton Uplands (e.g. Tihany, Hegyes-tű Hill 8, Badacsony Hill), and lasted till the Late Pliocene. Finally, in the Pleistocene the range elevated remarkedly, there was denudation in most areas, fluvial terraces developed in some of its area along river Danube, while travertine formed in the Gerecse and Buda Mts.

North Hungarian Range

Geologically it is a quite complex and varied unit comprising of ranges and hillsides made up of sedimentary and volcanic rocks formed in different stages of the Earth's history as well as basins filled up with young (in a geological sense) sediments. In the southwestern part of the Cserhát Mts., Mt. Naszály as well as the Romhány and Csővár blocks belong to the Transdanubian Range Unit in geological sense, at the same time the volcanic rocks of the Visegrád Mts. can be considered as parts of the North Hungarian volcanic range.

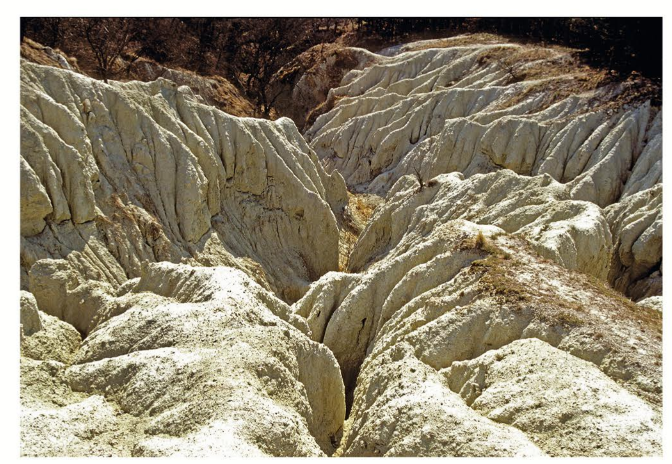
The oldest formations crop out in the northeastern part of the region, in the Szendrő and Uppony Hills. Shallow and deep marine rocks formed in the first half of the Palaeozoic (Ordovician–Carboniferous) can be found here that underwent low-grade metamorphism in the Alpine orogeny and altered into phyllite, crystalline limestone and marble. The Bükk Mts. is made up dominantly of Carboniferous, Permian, Triassic and Jurassic rocks that also underwent low-grade metamorphism and intense tectonic deformation in the Alpine orogeny. The northern part of the Bükk Mts. is made up mainly of Carboniferous and Permian schists and limestones, while the central plateau consists mainly of Triassic dolomite, limestone as well as volcanic rocks. In the western part of the mountains Jurassic deep marine shale and conglomerate as well as basalt and gabbro crop out. Such rocks are overlain by Eocene shallow marine limestone in some places.

9 *Karren surface of Middle Triassic limestone above Lake Aggtelek*

The Rudabánya Hills is made up of overthrust sheets of Triassic and Jurassic rocks (silty-clayey and carbonate rocks), while the Aggtelek Karst is dominantly built up by shallow marine Triassic limestone 9 rich in karst phenomena.

In the western part of the North Hungarian Range there are sedimentary and volcanic rocks formed in the Cenozoic. Mesozoic carbonate rocks of the Transdanubian Range Unit, Palaeozoic and Mesozoic formations belonging to the Bükk Unit as well as metamorphic rocks of the Vepor Unit of the Northwestern Carpathians can be found in the basement. Subsequent to a long terrestrial, erosional period, the area was invaded by a shallow sea in the Late Eocene (ca. 37 Mya), resulting in the deposition of limestone. This was followed by the formation of deep marine marl in some places in the Early Oligocene with a thickness exceeding 1,000 m. At the very end of the Eocene, evolution of the andesitic stratovolcano rocks of which are known east–northeast of the main ridge of the Mátra Mts. (Mátrahát). During the Late Oligocene–Early Miocene marl and siltstone inside the basin, and shallow marine sandstone were deposited along the margins. Subsequent to the filling up of the basin there was terrigenous sedimentation in progress based on sediments from the erosion of the surrounding mountainous areas. In the first half of the Miocene it was followed by the deposition of rhyolite tuff 10 in vast areas, then the sea advanced again and coal seams were formed in marine swamps in Etes, Ózd and Sajó troughs. At the beginning of the Middle Miocene a 600–800-m-thick succession of alternating sand, silt and clay beds were deposited inside the basins, sand, gravel and rhyolite tuff were accumulated in the margins, then shallow marine conglomerate and limestone comprising of fossil masses were developed. Simultaneously, an intense andesitic volcanism initiated 15–16 Mya, building up the main masses of the Visegrád, Börzsöny and Mátra Mts. as well as a part of the Cserhát Mts. The thickness of stratovolcanic successions made up of lava rocks, volcanic breccias and tuffs may reach a thickness of 1,000–2,000 m.

At the end of the Middle Miocene, the area of such mountains was already a dry land, only shallow marine limestone was formed in some places in their southern margin. Fluvial sedimentation became dominant in Zagyva, Sajó and Ózd troughs, in the zone of the Pannonian Basin facing the Alföld deltas were developed. At the end of the Middle Miocene (ca. 13 Mya) volcanism started in the Tokaj (Zemplén) Mts. which was also in progress in the Late Miocene and terminated ca. 10 Mya. In the end, a 1 to 3-km-thick volcanic succession comprising of rhyolite, dacite and andesite came into being. In the meanwhile, the southern regional zone of the medium-height mountains became part of the Pannonian Lake, then – by advancement of the delta system – lignite formed in a paludal environment overlaying lacustrine sediments in the forelands of the Mátra and Bükk Mts. In the Medves Region basalt volcanos were active from the end of the Late Miocene (from 6 Mya) to the Pleistocene 11.



10 *Eroded surface of Early Miocene rhyolite tuff in the vicinity of Kazár*

11 *Lamellar basalt of the top level of the Kis-Salgó Hill (or Boszorkány-kő) in the Medves Region*

©Geographical Institute, MTA CSFK www.nationalatlas.hu, Budapest, 2018

MNA Natural Environment

Volume editors
Károly Kocsis (Editor-in-chief), Gábor Gercsák, Gergely Horváth, Zoltán Keresztesi, Zsombor Nemerkényi

Chapter editors
Zita Bihari, Károly Brezsnyánszky, Péter Csorba, †Gábor Fekete, Gyula Gábris, János Haas, Gergely Horváth, Attila Kerényi, Gergely Király, Károly Kocsis, Zsolt Molnár, László Pásztor, Ferenc Schweitzer, József Szabó, Mária Szabó, János Tardy, Gábor Timár, György Varga, Zoltán Varga

Revised by
János Bölöni, Károly Brezsnyánszky, Mihály Dobróka, Ilona Keveiné Bárány, Károly Konecsny, Zoltán Korsós, Dénes Lóczy, Gábor Magyar, János Mika, V. Attila Molnár, András Schmotzer, Anna Solt, György Szabó, József Szabó, Zoltán Szalai

English translation by
Zoltán Bálint, Endre Dobos, Gábor Gercsák, Krisztián Klima, Krisztina Labancz, Györgyné Laczkó, Dénes Lóczy, Richard William McIntosh, Erika Michéli, Brigitta Palotás, László Pásztor, András Schmidt, Péter Szabó, Tamás Telbisz, Eszter Tímár, Gábor Timár, László Tóth, Zoltán Varga

English translation revised by
Iain Coulthard, Gábor Gercsák, Daniel Kibirige, Richard William McIntosh, Robin Lee Nagano, Philip Sansum

Cover design
Gáspár Mezei – Geographical Institute, MTA CSFK, Ildikó Kuti – Civertan Bt.

Design and typography
Ildikó Kuti – Civertan Bt.

Printing
Pannónia Nyomda Kft. (Budapest)

Publisher: László Szarka (Director general)
Hungarian Academy of Sciences (MTA), Research Centre for Astronomy and Earth Sciences (CSFK), www.csfk.mta.hu
©Geographical Institute, MTA CSFK www.mtafki.hu, Budapest, 2018

The publication is supported by
Hungarian Academy of Sciences (MTA)
Ministry of Human Capacities (Emmi)

Closing date of editing: 31st October 2018

ISBN 978-963-9545-58-8ö
ISBN 978-963-9545-57-1

NATIONAL ATLAS OF HUNGARY
NATURAL ENVIRONMENT

Authors
Szilvia Ádám
†László Alföldi
Réka Aszalós
György Babolcsai
Zoltán Barina
Dénes Bartha
Judit Bartholy
Zsombor Bartos-Elekes
Teodóra Bata
Ákos Bede-Fazekas
Zita Bihari
Marianna Biró
Attila Borhidi
János Bölöni
Károly Brezsnyánszky
Tamás Budai
Szabolcs Czigány
Bálint Czúcz
István Csepregi
János Csiky
Péter Csima
Péter Csorba
Gábor Csüllög
István Dancza
Laura Dobor
Endre Dobos
Szabolcs Fábián
Tamás Fancsik
Edit Farkas
Sándor Farkas
István Fazekas
†Gábor Fekete
Zita Ferenczi
László Fodor
Nándor Fodor
Sándor Frisnyák
Gyula Gábris
Nóra Gál
Attila Galsa
†Judit Gerhátné Kerényi
Gizella Gombárné Forgács
László Gyalog
János Haas
László Haszpra László
Katalin Homokiné Ujváry
Ferenc Horváth
Gergely Horváth
Gábor Illés
Krisztina Iványi
Gábor Katona
Attila Kerényi
Balázs Kevey
Gergely Király
Gábor Kiss
Károly Kocsis
László Kollányi
Éva Konkoly-Gyuró
Gábor Kovács
Tamás Kovács
Szilvia Kövér
Mónika Lakatos
Ildikó Lázár
Nikolett Lepesi
Ferenc Lesták
Dénes Lóczy
József Lóki
László Lőkös
János Maginecz
Donát Magyar
Enikő Magyari
Ákos Malatinszky
Gergely Mányoki
Gábor Mezősi
Erika Michéli
Gábor Mikesy
Attila Molnár V.
Zsolt Molnár
Péter Mónus
Annamária Nádor
†András Nagymarosy
Gábor Négyesi
Ákos Németh
Csaba Németh
Beáta Papp
László Pásztor
György Pátzay
†Márton Pécsi
Gyula Pinke
Ervin Pirkhoffer
Rita Pongrácz
Péter Prakfalvi
Mária Putsay
Ágnes Rotárné Szalkai
Péter Scharek
András Schmidt
Dávid Schmidt
András Schmotzer
Ferenc Schweitzer
Ferenc Síkhegyi
Anna Solt
Imelda Somodi
Pál Sümegi
József Szabó
Mária Szabó
Szabó Péter
József Szalai
Miklós Szalay
Sándor Szegedi
Árpád Szentiványi
Gábor Szepessy
Gabriella Szépszó
Péter Szilassi
Ferenc Szmorad
Teodóra Szőcs
Gergely Szövényi
Erzsébet Szurdoki
Ágnes Tahy
László Tamás
János Tardy
Tamás Telbisz
Viktor Tiborcz
Gábor Timár
Ágnes Tirászi
György István Tóth
László Tóth
Ákos Török
Zoltán Túri
Orsolya Udvardy
György Várallyay
Gábor Varga
György Varga
Zoltán Varga
Mária Vasvári
József Vatai
Zsuzsanna Vikor
András Vojtkó
Tünde Andrea Zagyva
László Zilahi-Sebess
Zita Zsembery

Chief cartographers
Norbert Agárdi
Zoltán Keresztesi
Fanni Koczó
Anikó Kovács
Gáspár Mezei
Zsombor Nemerkényi
Renáta Szabó

Contributors to cartography
Gergely Bagaméri
Éva Balázs
Ádám Barancsuk
Zsanett Butor
Anna Gertheis
Zoltán Gulyás
Réka Kiss
Csaba Szigeti
József Sziládi
Zsuzsanna Veszely

Technical staff
Margit Laczkó
Árpád Magyar
István Poór

©Geographical Institute, MTA CSFK www.nationalatlas.hu, Budapest, 2018

INSTITUTIONS SUPPORTING AND CONTRIBUTING TO THE PUBLICATION OF THE NATURAL ENVIRONMENT VOLUME OF THE NATIONAL ATLAS OF HUNGARY

Eötvös Loránd University (Eötvös Loránd Tudományegyetem, ELTE)
- Faculty of Informatics, Department of Cartography and Geoinformatics (Informatikai Kar, Térképtudományi és Geoinformatikai Tanszék)
- Faculty of Science, Institute of Geography and Earth Sciences (Természettudományi Kar, Földrajz- és Földtudományi Intézet)

General Directorate of Water Management (Országos Vízügyi Főigazgatóság, OVF)

Hungarian Academy of Sciences (Magyar Tudományos Akadémia, MTA)
- Centre for Agricultural Research, Institute for Soil Sciences and Agricultural Chemistry (Agrártudományi Kutatóközpont, Talajtani és Agrokémiai Intézet)
- Research Centre for Astronomy and Earth Sciences (Csillagászati és Földtudományi Kutatóközpont)
- Centre for Ecological Research, Institute of Ecology and Botany (Ökológiai Kutatóközpont, Ökológiai és Botanikai Intézet)

Hungarian Central Statistical Office (Központi Statisztikai Hivatal, KSH)

Hungarian Meteorological Service (Országos Meteorológiai Szolgálat, OMSZ)

Mining and Geological Survey of Hungary (Magyar Bányászati és Földtani Szolgálat, MBFSZ)

Ministry of Agriculture (Földművelésügyi Minisztérium, FM)
- State Secretariat for Environmental Affairs, Agricultural Development and Hungaricums (Környezetügyért, Agrárfejlesztésért és Hungarikumokért Felelős Államtitkárság)

Ministry of Defence (Honvédelmi Minisztérium, HM)
- Zrínyi Mapping and Communication Servicing Non-profit Ltd. (Zrínyi Térképészeti és Kommunikációs Szolgáltató Közhasznú Nonprofit Kft.)

Ministry of Human Capacities (Emberi Erőforrások Minisztériuma, Emmi)

National Agricultural Research and Innovation Centre (Nemzeti Agrárkutatási és Innovációs Központ, NAIK)
- Forest Research Institute (Erdészeti Tudományos Intézet)

National Food Chain Safety Office (Nemzeti Élelmiszerlánc-biztonsági Hivatal, NÉBIH)
- Directorate for Plant, Soil and Agricultural Environment Protection (Növény-, Talaj- és Agrárkörnyezet-védelmi Igazgatóság)

National Institute of Environmental Health (Országos Közegészségügyi Intézet, OKI)

National University of Public Service (Nemzeti Közszolgalati Egyetem, NKE)
- Institute of Disaster Management (Katasztrófavédelmi Intézet)

Szent István University (Szent István Egyetem, SZIE)
- Faculty of Agricultural and Environmental Sciences, Institute of Environmental Sciences (Mezőgazdaság- és Környezettudományi Kar, Környezettudományi Intézet)
- Faculty of Agricultural and Environmental Sciences, Institute of Nature Conservation and Landscape Management (Mezőgazdaság- és Környezettudományi Kar, Természetvédelmi és Tájgazdálkodási Intézet)
- Faculty of Landscape Architecture and Urbanism (Tájépítészeti és Településtervezési Kar)

University of Debrecen (Debreceni Egyetem, DE)
- Faculty of Science and Technology, Institute of Biology and Ecology (Természettudományi és Technológiai Kar, Biológiai és Ökológiai Intézet)
- Faculty of Science and Technology, Institute of Earth Sciences (Természettudományi és Technológiai Kar, Földtudományi Intézet)

University of Miskolc (Miskolci Egyetem, ME)
- Faculty of Earth Science and Engineering, Institute of Geography and Geoinformatics (Műszaki Földtudományi Kar, Földrajz-Geoinformatika Intézet)

University of Pécs (Pécsi Tudományegyetem)
- Faculty of Sciences, Institute of Geography and Earth Sciences (Természettudományi Kar, Földrajzi és Földtudományi Intézet)

University of Sopron (Soproni Egyetem, SoE)
- Faculty of Forestry, Institute of Botany and Nature Conservation (Erdőmérnöki Kar, Növénytani és Természetvédelmi Intézet)
- Faculty of Forestry, Institute of Forest Resources Management and Rural Development (Erdőmérnöki Kar, Erdővagyon-gazdálkodási és Vidékfejlesztési Intézet)

University of Szeged (Szegedi Tudományegyetem, SZTE)
- Faculty of Science and Informatics, Institute of Geography and Geology (Természettudományi és Informatikai Kar, Földrajzi és Földtudományi Intézet)