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The Drava River

Environmental Problems and Solutions

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Editor

The Drava River

Environmental Problems and Solutions

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This book is dedicated to the memory of Prof. György Lovász (1931–2016), a committed researcher of the Drava and Mura Rivers.

Foreword

As an Italian scientist, it was my pleasure to accept the invitation to introduce the international readers to this valuable book on *The Drava River* and its environmental aspects, since this water course is not only one of the most interesting in Europe, from both the environmental and historical viewpoints, but also because its source is located in Italy, which is generally unknown. Actually, the Drava River crosses the Italian region of South Tyrol just for 10 km, before reaching Austria and flowing then in Slovenia, Croatia and Hungary with a total length of more than 700 km.

It is easy to understand how the Drava River, as a remarkable physical element, played a major role in the history and geopolitics of Central and Eastern Europe through time. As a matter of fact, it still marks the border between Croatia and Hungary for a long distance. On the other hand, the river's location in politically and militarily sensitive areas has prevented detailed scientific research to take place there until the 1990s.

The book shows the results of a 4-year research project on the environmental rehabilitation of the Hungarian Drava floodplain, providing, however, a wider overview of the environmental aspects of the watercourse and its surrounding areas. The Drava river is one of the most exploited in the World for hydroelectric purposes and, therefore, the effects of human pressure are tangible, but it still holds elements of remarkable environmental interest that deserve rehabilitation, preservation and enhancement.

As President of the International Association of Geomorphologists (IAG), I would like to underline the scientific value and originality of the book and how its contents match with the interest of presently active IAG Working Groups dealing with 'Geomorphological hazard', 'Geomorphosites' and 'Landform Assessment for Geodiversity'. The topics of the book were taken into account by a previous IAG Working Group on 'Human Impact on the Landscape' which was led between 2001 and 2009 by the editor of this book, Prof. Dénes Lóczy, who has long-standing experience in the field of human-induced transformation of the fluvial environment.

Finally, I would like to congratulate the Editor and all the Authors on this valuable publication since it provides the international community with a precious wide-spectrum contribution on an outstanding European fluvial environment.

Modena, Italy

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Chapter 1
Introduction

Dénes Lóczy

Abstract The first-ever comprehensive physical geographical monograph on the transboundary Drava River tackles diverse environmental problems from the viewpoints of hydraulic engineers, hydrobiologists, and ecologists active in the countries on the drainage basin. The impacts of some rehabilitation actions are also assessed. The book is dedicated to the memory of the late Professor György Lovász, a dedicated researcher of the Drava and Mura Rivers.

Keywords Hydrogeomorphology · Water and sediment regime
River and floodplain ecology · Nature conservation

Issuing at 1,228-m elevation in the Dolomites, the Drava (Drau, Dráva) is an important right-bank tributary of the Danube in southern Central Europe. The 725-km-long river connects countries and cultures from the Italian Alps in South Tyrol, the rivers and large lakes in Carinthia, and the Slovenian Alps all the way to the Carpathian Basin. Near Legrad, Croatia, it is joined by the Mura (Mur) River and forms part of the Croatian–Hungarian border in the Carpathian (Pannonian) Basin. This peripheral and militarily sensitive location explains why this river section and its floodplain had been so neglected in scientific research until the opening of the border zones after the political transformations in 1989–1990 and the end of the Serbo-Croatian war in 1995. The geographical diversity of the Drava catchment is well demonstrated by the fact that it forms a corridor from the Alpine area to the Pannonian biogeographical region.

The rapid-flowing Drava River has been harnessed by 22 hydroelectric power plants in Austria, Slovenia, and Croatia. In Slovenia there are two artificially constructed side channels. In spite being considerably regulated, the Drava River has preserved natural aquatic and wetland habitats along the middle and lower segments and hosts unique assemblages of flora and fauna, including several

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endemic species. Because of the former political divisions of Europe, however, no comprehensive analysis of all components of the river environment has ever been published.

The present volume summarizes the environmental issues concerning the river channel and the floodplain. It describes the diverse forms of human pressure (river regulation, damming and reservoirs, dredging, intensive agricultural use of the floodplain, etc.) and the environmental changes of hydrological regime, sediment transport, bank stability, biodiversity, etc. involved. Based on the findings of biomonitoring (Ábrahám 2005; Purger 2008) and the SEE River European pilot project (Bizjak et al. 2014), the transboundary nature of the river is emphasized and the resulting problems outlined. Special attention is devoted to the evolution and present conditions of the floodplain (drainage pattern, connectivity, oxbow lakes, and their vegetation). The significance of the main channel and cut-off meanders (oxbow lakes) of the Drava River for nature conservation (UNESCO Transboundary Biosphere Reserve and Ramsar and Natura 2000 sites) and ecotourism are described (expanding on research reports such as UNESCO 2012).

A review of ongoing and planned rehabilitation measures illustrates the difficulties in finding solutions to environmental problems. Relying on environmental monitoring, the difficulties of ensuring proper water availability for the floodplain are studied in detail. The benefits and deficiencies of ongoing rehabilitation projects are outlined. Since a collection of papers have been published recently in three languages (Hungarian, Croatian, and English) on the achievements of the revitalization of side-arms along the lower Drava River (Purger 2013), the biological aspects of rehabilitation are not treated here in detail. The reader is kindly asked to refer to that book for further information.

The international team of authors (representing the countries crossed by the Drava River: Austria, Slovenia, Croatia, and Hungary) approach the topics of the individual chapters from different aspects (including regional physical geography, fluvial geomorphology, water management, hydraulic engineering, forest ecology, hydrobiology, nature conservation). Each chapter summarizes the findings of national research on the Drava—often only available in the native language of the particular author and made public in English here for the first time. The need for international cooperation in solving the environmental problems is often emphasized. The contributors hope that from the chapters of the book supply the reader with a many-sided picture of this European river, which has been neglected in scientific research for a long time.

In the structure of the book, there is some bias in favor of the Drava floodplain in Hungary, the problems of which are treated in seven chapters. The reason is that this publication is mainly the outcome of four years of research within the framework of the project “Rehabilitation potential of the Hungarian Drava floodplain”, which was supported by the Hungarian Scientific Research Fund (OTKA, contract no K 104552), now managed by the National Office for Research, Development and Innovation (NKFIH). The project leader was the editor of the book. He is grateful for the funding between 2012 and 2017.

The volume is dedicated to the memory of Prof. György Lovász (1931–2016), who was among the first researchers to study the water regime of the Drava and Mura Rivers from a hydrogeographical aspect as early as the 1960s (Lovász 1972).

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Chapter 2
The Drava Basin: Geological and Geomorphological Setting

Dénes Lóczy

Abstract The Drava catchment comprises three major geological units of the Eastern Alps and their southeastern foreland:

1. the Austroalpine Nappe System (with a small portion of the High Tauern Window),
2. the Southalpine Nappe System (with the eastern Dolomites) and
3. the southwestern margin of the Pannonian (Carpathian) Basin.

Mountain building in the Alps started in the Cretaceous driven by lithospheric plate movements: the northward drift of the African plate and its microplates. The plate tectonic evolution was also controlled by the opening and closure of two oceans: from the Triassic to the Middle Jurassic the Neotethys extended from the east to the west; the Piemont-Penninic Ocean existed from the Middle Jurassic to the Late Cretaceous and evolved parallel with the opening up of the Atlantic Ocean. The principal tectonic units of the upper Drava catchment are divided by the marked Peri-Adriatic Lineament system. Although with lower intensity than in the Western and Central Alps, the orogeny still goes on today on the eastern end of the mountain arc. Huge horizontal displacements of blocks are observed in the form of strike-slip faults, which control the overall drainage pattern (e.g., in the Gail Valley). According to age, the rocks of the Eastern Alps range from metamorphosed Paleozoics (e.g. in the Tauern Window, Austria) to the late Holocene alluvia of the Lower Drava Valley (e.g. at the Kopački rit in Croatia). Rock variability is also great with regard to resistance to erosion. The most spectacular landforms are the high-mountain glacial and karst assemblages, the dolomite cliffs and pinnacles, earth pyramids, deep ravines, marked landslide features, narrow gorges with waterfalls, and caves in limestone. There are overdeveloped cutoff meanders and undercut bluffs in the lowland section.

Keywords Geological evolution · Tectonics · Nappe systems · Lithology Geomorphic processes · Landforms · Eastern Alps · Pannonian basin

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2.1 Introduction

Ever since the Austrian mountaineer and geologist Otto Ampferer (1875–1947) proposed the so-called "undercurrent theory" (Unterströmungstheorie) in 1906 (Ampferer 1906), intensive studies on the mobility of the Earth's crust in the Alpine region have been conducted and led to the identification of nappe systems. The hypothesis, at first neglected by the academic world, became fully accepted in the 20th century, when the tectonical, petrographical, and mineralogical properties of Alpine nappe systems were disclosed. In Austrian geology, the nappes of the Eastern Alps were subdivided into the lowest Penninic Nappe Complex (exposed in the High Tauern window) and overlying Austroalpine Nappe Complex (Bögel and Schmidt 1976; Scarascia and Cassinis 1997; Stüwe and Schuster 2010). In the 21st century the radiometric ages for subduction (e.g. Thöni 2006) and nappe metamorphism (Froitzheim and Schmid 2008) began to be determined as well as the pre-Triassic plate tectonic configurations were reconstructed (Pfiffner 2014). Recently, information on the deep structure of the Eastern Alps is available from the findings of the German-Austrian-Italian TRANSALP seismic reflection profiling project completed in 2003 (Lüschen et al. 2004). Among other results, the project revealed tectonic shear zones in the lower crust at the contact of the European and the Adriatic plate as well as the steeply dipping structures of the Tauern Window (Fig. 2.1).

The mountainous upper Drava basin mostly occupies the southern zone of the Austroalpine Nappe System, which overlies the Penninicum in the Eastern Alps. The main units are the crystalline Central Eastern Alps with the tectonic windows, the Gailtal Alps, the Karawanks and the eastern margin of the Dolomites with the Lienz Dolomites (East Tyrol) in the source area of the river. The 700-km-long Peri-Adriatic Lineament with its branches is the most significant lineament system of the whole Alps (Bartel et al. 2014). Its straight alignment controls the longitudinal valleys typical of the Austrian Alps (the Puster and Gail valleys). To the south, the Dinaric Nappes with southern vergence (opposed to the northern vergence of other nappes) show moderate displacements.

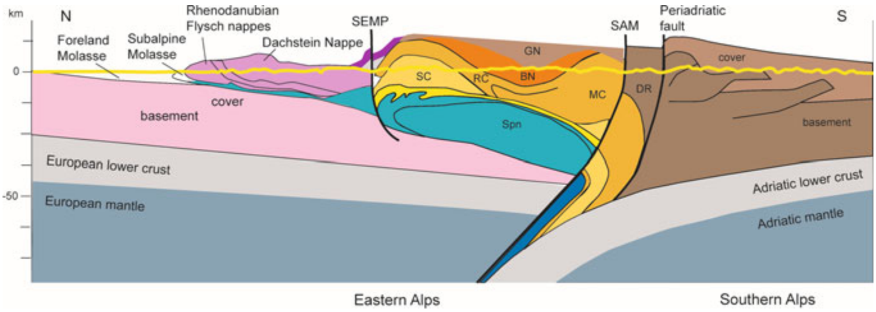

Fig. 2.1 Profile across the Eastern Alps based on findings of the TRANSALP Project (after Schmid et al. 2004, 2013)

The Drava crosses the Klagenfurt Basin and the Mura the Styrian Hills (or Graz Basin) (Ebner and Sachsenhofer 1991) and together enter the extensional Pannonian (Carpathian) Basin (Fodor et al. 1999; Haas 2012).

2.2 Geological Evolution of the Eastern Alps

The Alps have several ‘forerunners’. Traces of mountain building, Carboniferous flysch-like clastics, sandy, and pelitic turbidites have been identified in the Carnic Alps at 300–350 m depth (Schönlaub and Heinisch 1993), and Variscan orogeny is assumed to have affected the crystalline basement (‘Altkristallin’) of the Saualpe-Koralpe and in the Gurktal block. An early orogenic phase is also evidenced in Late Permian conglomerates and breccias (Krainer 1993).

The early history of the present-day Alps begins with the break-up of the megacontinent Pangaea in the Permian (Oberhauser 1980). The rock masses which build up the mountain arc mostly derived from sediments deposited in the Neotethys (Meliata) Ocean (Frisch et al. 2011), a major Mesozoic sedimentation basin. For instance, the dolostone series of the Middle to Late Triassic carbonate platform of the Dolomites reaches more than 1,000 m thickness (Bosellini et al. 2003). Also more than 3,000 m of Permo-Mesozoic sediments were deposited on top of the thermally subsiding Adriatic microcontinent, a broad carbonate shelf (Schuster et al. 2013).

During the Mesozoic, the present Alpine region showed variable and rather complicated patterns of oceanic basins and land masses. A variety of sedimentary environments have been reconstructed: rift zones, deep-sea basins, shelf seas, and submarine rises (Pfiffner 2014). The resulting rock assemblages are called mélange in the Alpine region. Rifting was accompanied with collisions (Frisch 1979). The Adriatic (or Apulian) microplate was detached from Africa on the Jurassic/Cretaceous boundary (Schuster and Stüwe 2010). Ophiolite zones (sutures) were created on its margins when in the Middle Cretaceous continental collision started and the Austroalpine sediments were overthrust over the Penninic unit (Siegesmund et al. 2008). The compression had lasted to the early Paleogene, when the Penninic Ocean closed and was consumed by subduction underneath the Adriatic plate (Schuster and Stüwe 2010). Between 135 and 15 Ma, the nappe systems of the Alps formed in connection with south- to southeast-dipping subduction (Froitzheim et al. 2008). Through ^{40}Ar dating high-pressure metamorphism the time of subduction reaching to over 20 km depths can be estimated at 90 Ma BP (Berger and Bousquet 2008). Intraoceanic subduction and the emplacement of ophiolite nappes onto the Adriatic margin are documented since the Middle Jurassic (Schuster et al. 2013) and continued even after the closure of the last ocean remnants (in the Eocene, ca. 40 Ma ago). Exposed in the Tauern Window, the youngest eclogites, attesting to these processes, are only about 32 Ma old (Froitzheim et al. 2008).

As a result of the TRANSALP project (Lüschen et al. 2004), two different concepts of continental collision in the area of the present Eastern Alps have emerged (Fig. 2.2):

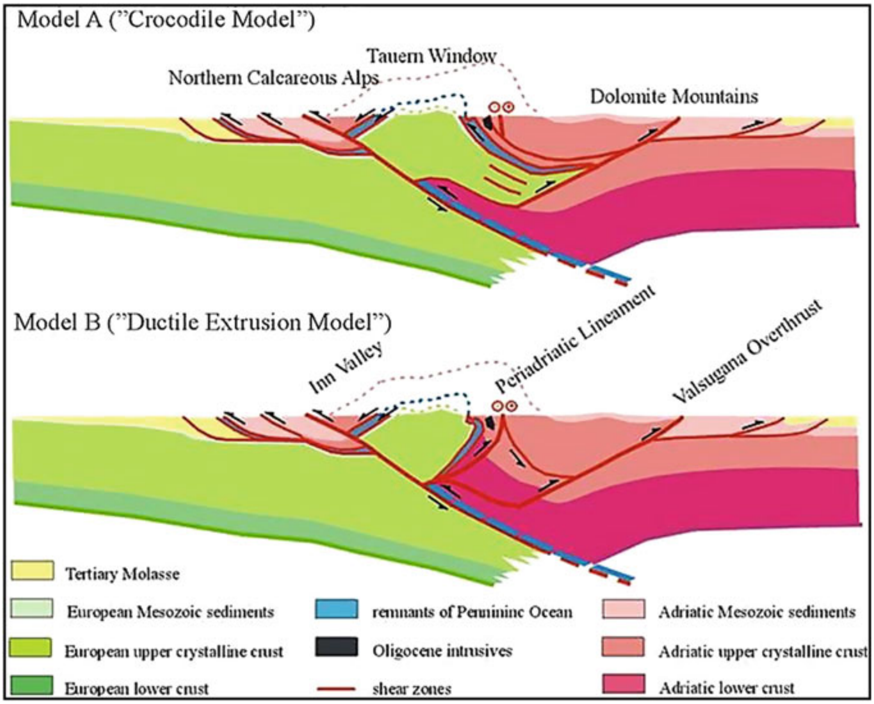

Fig. 2.2 The Ductile Extrusion and the Crocodile Models for continental collision (after Lüschen et al. 2004)

1. the Ductile Extrusion Model (Castelarin et al. 2001) is founded on the decisive role of the Peri-Adriatic Fault in the collision process: the fault of rigidly straight alignment controls the shape of the collision front and the exhumation of the Tauern Window, while
2. the Crocodile Model (Lammerer et al. 2001) does not attach much significance to the Peri-Adriatic Fault and assumes a z-shaped collision front ("double crocodile" structure).

The grade of Cretaceous metamorphism for the Upper Central Austroalpine Nappe (UCAN, comprising the Northern Graywacke Zone, the Graz Paleozoic, the Gurktal Nappe and the small Steinach Nappe) was significantly lower than in the Lower Central Austroalpine units (Schuster et al. 2013). The UCAN incorporates some slightly metamorphosed Paleozoic rocks in the Northern Karawanks, with pillow basalts and deep sea sediments. Cretaceous metamorphic rocks in the Eastern Alps include a wide range of schists with mica, garnet, staurolite, disthene, and felspar minerals (Schuster et al. 2004).

The beginning of the uplift of the southern mountain ranges (Ötztal, Gurktal Alps, and the 'Drauzug' range) along thrust faults, is dated to ca 92 Ma ago

(Schuster and Stüwe 2010). Accompanied by major lateral displacements, uplift can be reconstructed from the regional distribution of metamorphic rocks (Oberhänsli and Goffé 2004). The resulting late Cretaceous landscape resembled the present Adriatic coastal archipelago of Croatia.

After the closure of the Penninic Ocean, huge shearing forces, related to the final stage of collision, resulted in the slab break-off of the subducting oceanic lithosphere from the continental one and 43–24 Ma ago tonalitic-granodioritic plutons (Rieserferner, Ibisten-Unterplanken-Kandellen/Tesido-Planca-Gandella, Lesachtal, Hollbruck) formed at 10–15 km depth along the Peri-Adriatic Lineament and its branching faults (Nemčok et al. 1998; Schuster et al. 2013), in the zone of the lowest-grade metamorphism. The Karawanks tonalitic pluton (32–28 Ma ago) represents the easternmost outcrop of the Oligocene intrusions along the Peri-Adriatic Lineament (Fodor et al. 2008).

The Paleogene saw the beginning of a rapid west to east extension of the lithosphere in the Eastern Alpine area (Schuster and Stüwe 2010). Parallel to the subduction of the Carpathians, this led to marked lateral extrusion and gradual thinning of the Alps between 20 and 10 Ma ago (Froitzheim et al. 1994). At that time, the eastern foreland of the Eastern Alps began to take shape. Recently, field evidence (scratched flowstone in a cave disrupted by a fault) was found for the Holocene activity of the Salzachtal-Ennstal-Mariazell-Puchberg (SEMP) fault, a major strike-slip system responsible for this extrusion (Plan et al. 2010).

In the Late Oligocene, a prominent basement uplift of crystalline rocks emerged in the Tauern Window (Lammerer and Weger 1998). On its southern side, the steep Pustertal Fault, a section of the Peri-Adriatic Lineament, separates the Eastern Alps from the Dolomites. In the Tauern Massif, crustal thickening generated massive uplift between normal faults, the Brenner Fault in the west and the Katchberg Fault in the east (Pfiffner 2014). During the Miocene and Pliocene, the Penninic and even the Helvetic nappes were exhumed over a 20 × 150 km area (Bousquet et al. 2008). The rate of uplift here is still among the highest in the whole Alps, manifested in the rapid incision of the Isel and Möll river systems.

The tectonic evolution of the Dinarides (which started in the Eocene) influenced the Miocene deformations of the Dolomites and the Karawanks (Frisch et al. 2000). Further, plutons formed (e.g. the Pohorje Pluton, Fodor et al. 2008) near to the Peri-Adriatic Lineament. Between 10 and 7 Ma ago, intense basalt volcanic activity took place in Styria. Oligocene to Miocene flysch sedimentation (clay, marl, conglomerate, cross-bedded sandstones) occurred in the intermontane (Klagenfurt and Styrian/Graz Basins) and foreland basins. In the Oligocene and Miocene, deposits of similar character, molasse (e.g. 'Tonmergel' clay marl, 'Nagelfluh' conglomerate, marine turbidites), accumulated above the flysch, but this time with less tectonic deformation.

The next step in the evolution of the Alps includes the development of drainage patterns in the Miocene and Pliocene. The uplift of the Alps, manifested in large-scale thrusts and faults, generated weathering and intense (fluvial) erosion.

The ancestral rivers kept their courses on the substratum, preserved their gradient and stream power and incised deeply into the surface (Pfiffner 2014). The relative relief between mountain peaks and valley floors 5–15 Ma ago was probably similar to that of today.

In the Pleistocene, however, at least 15 cold periods and thousand-meter thick ice sheets brought about major transformation of the topography (van Husen 2000). Overdeepening may have affected the upper Drava Valley, too. Glacial and meltwater processes built a series of landforms of subglacial and glaciofluvial (meltwater) origin. Today such a landform assemblage, which prevailed in the Little Ice Age for the last time, is replaced by a variety of periglacial processes and landforms (Seppi et al. 2015). Mass movements are also very active geomorphic agents in the Alps (Székely et al. 2002; Proske and Bauer 2016).

From the analysis of Alpine river systems it was pointed out that the ice-free Mura and Drava catchments are characterized by channels in morphological equilibrium and only few evidence of strong tectonic activity is shown (Robl et al. 2008). Over the past 4 Ma uplift along the eastern edge of the Alps was estimated to less than 1 mm y^{-1} (Brückl et al. 2010) or 0.1–0.15 mm y^{-1} (Wagner et al. 2011)—one order of magnitude lower than geodetically observed uplift rates. Recently, it was proven that about 90% of the geodetically measured ground uplift in the Alps can be explained by post-glacial rebound in response to deglaciation after the Last Glacial Maximum. An interesting finding of recent research (Tesauro et al. 2005) is that horizontal movements in the Southern Alps also continue to our days: there is an average displacement in north-northwestern direction at a rate of 1.2 mm y^{-1}.

2.3 Geological Evolution of the Lowland Catchment

The Lower Drava Basin has a basement of medium-grade metamorphic rocks and carbonates which is overlain by a more than 6000-m thick sedimentary succession: Lower Miocene terrestrial conglomerates, sandstones, and marls; Middle Miocene deep marine marls and clays and shallow marine limestones. A major regional unconformity is observed between Middle Miocene synrift and Upper Miocene (Pannonian) postrift sediments (Kókai and Pogácsás 1991). The sediments derived from lacustrine deposition in Lake Pannon until 6.8 Ma ago; from this time a south-eastward prograding delta system controlled sedimentation (Haas 2012). In the Pleistocene, the Drava already followed the west-northwest to east-southeast directed axis of the depression, which was gradually shifting in southwestern direction.

2.4 Geological Units and Remarkable Landforms

To understand the problems concerning the Drava River, the physical environment of its drainage area has to be presented to the reader. Therefore, brief summaries of the geographical location, geological buildup, topographic character, and typical landforms of the landscape units the river crosses are provided in this section.

2.4.1 Dolomites

The Drava rises on the northern slopes of the Dolomites above the Puster Valley, near Dobbiaco/Toblach (Italy), at 1,450 m elevation (Sailer and Scaglione 2011). The major magmatic and tectonic events which influenced the evolution of the Dolomites include Permian and Triassic volcanism and rifting; rifting associated with the opening of the western Neotethys and Neogene compression and thrusting, resulting in uplift over the past 10 Ma (Bosellini 1998; Bosellini et al. 2003). Permian volcanics, evaporates, and carbonates are overlain by Lower to Middle Triassic shallow and deep marine carbonates and volcanics (Schlager and Thalmann 1962; Hauser 1995). The Middle and Upper Triassic dolostones (*Dolomia Principale*) are the most characteristic formations.

Typical landforms of this high-mountain relief are the dolomite towers (Neukirchen 2011) with subvertical slopes, of which the best known is the Tre Cime di Lavaredo/Drei Zinnen (2,999 m). Rapid mechanical weathering produces extensive debris slopes at mountain feet. Only a small eastern section of the Dolomites belongs to the Drava catchment.

2.4.2 Carnic Alps

The geology of the main ridge of the Carnic Alps (highest peak: Hohe Warte, 2,780 m), which runs from west to east along the Lesachtal and Gail Valleys, is very complex (Schönlaub 2012). The valleys (in fact, a single valley with two names) are part of the Peri-Adriatic Lineament system, the geological boundary between the South Alpine and the Austroalpine nappe systems (Krainer 1995). With the fault running along the axis of the valley in both Pustertal, the valley of the Drava, and the Gail Valley, rocks on both sides are quite different. While to the north the Zillertal Alps and Hohe Tauern are composed of crystalline rocks (granite, gneiss), to the south carbonates (limestones, dolostones) prevail. In the Kellerwand and Hohe Warte region 1,300-m thick Paleozoic (Silurian to Carboniferous) carbonates rise to 2,000 m elevation (Buchenauer 1986).

In addition to the richness in rock types, the mountains are made even more interesting by geomorphic features: the 1,500-m-high cliffs (Kellerwand), narrow gorges (Garnitzenklamm), an ice cave (at Obstans, with entrance at 2,300 m elevation), finger lakes (Weiβensee), landslide-dammed lakes (Bodensee), and the richness in Paleozoic and Mesozoic fossils (graptolites, ammonites, sea urchins, sea lilies, bivalves, gastropodes).

2.4.3 High Tauern

The High Tauern Mountains are the highest not only in the Drava catchment, but also in the entire Eastern Alps (Grossglockner, 3,798 m). Only the southern (Carinthian) slopes belong to the catchment. The foremost geological curiosity is the exhumation of the Penninic and Helvetic Nappe Systems from below the Austroalpine Nappes (the Tauern Window) (Krainer 2005). Its severe Miocene overprint by doming and lateral extrusion was most probably triggered by high pressure related to the indentation of a microplate from the south (Schmid et al. 2013).

The Mura, the most important tributary to the Drava, rises in the High Tauern, near Mur, at 1,898 m elevation. Sights of geomorphological interest in the southern foreland of the High Tauern include the earth pyramids at Stronach, carved out by erosion from morainic deposits and the gorges of Daberklamm (incised in calcareous mica schicht) and the Iselschlucht (formed along a north-to-south fault).

2.4.4 Gailtal Alps

The Gailtal Alps is a narrow mountain range wedged between the valleys of the Drava and Gail Rivers. From the west the range starts with the anticline of the Lienz Dolomites (Fig. 2.1), which rise at the confluence of the Drava with the Isel. The Isel is a glacier outlet with average discharge (39 $m^3\ s^{-1}$) almost three times larger than the Drava (14 $m^3\ s^{-1}$). The highest peak, Große Sandspitze (2,770 m) rises more than 2,000 m above the Drava Valley. The mountains are mainly built of Upper Triassic Hauptdolomit. A spectacular gorge is the about 2-km-long Galitzenklamm, where, in addition to main dolomite, sandstone and reddish limestone strata are also exposed.

The Gailtal Alps in a narrow sense is a 65-km-long and 15-km-wide mountain range (Reiβkofel, 2,371 m), part of the so-called ‘Drauzug’ ranges of west to east strike along the Peri-Adriatic Lineament. Their mostly carbonate rocks range in age from Permian to Mesozoic (high-mountain topography) in the north with some Paleozoic magmatics and quartz phyllites (middle-mountain topography) in the south (Figs. 2.3 and 2.4).

Fig. 2.3 View of the Lienz Dolomites from Ainet, near Lienz, East Tyrol (photo by D. Lóczy)

Fig. 2.4 View of the crest of the Southern Krawanks from Pyramidenkogel. *Source* summitpost.org

2.4.5 Gurktal Alps

The Gurktal Alps are mountain ridges rising between the Mura and Gurk Rivers above 2,000 m (Eisenhut, 2,441 m) (Schuster and Stüwe 2010). In the east, the Metnitz Valley splits the range into two ridges, mostly built of numerous varieties of Paleozoic metavolcanic rocks, phyllites, mica schists, siliceous schists (constituting the Alpine 'Altkristallin') as well as Triassic marbles and dolomites. The peaks are typically rounded knocks, locally called Nockberge. At higher elevations glacial landforms dominate: tarn lakes occupy glacial cirques.

2.4.6 Klagenfurt Basin

Surrounded by the phyllites and greenschists of the Gurktal Nappe, the Klagenfurt basin has a basement of slightly metamorphosed Paleozoic sediments and volcanics. With 1,750 km^2 area, it is the largest intramontane basin of the Alps. The west-to-east stretching Sattnitz Range in the south is composed of Tertiary flysch conglomerates and coal-bearing fine sediments. The basin fill is thick morainic and glaciofluvial gravelly-sandy deposits, resulting from the 700-m-thick Pleistocene ice sheet and its melting.

2.4.7 Karawanks

The Karawanks are a double range of 120 km length and 20–40 km width. The Southern Karawanks of Triassic limestones (highest point: Hochstuhl 2,237 m) rise in the eastern continuation of the Carnic Alps, while the more dissected Northern Karawanks (Hochobir, 2,139 m) belong to the 'Drauzug' ranges (granite and tonalite overlain by Mesozoic carbonates) (Poltnig and Herlec 2012). Orogeny is also manifested in a lateral shift over a distance of 250 km to the east (dextral displacement) along the Peri-Adriatic Lineament, which separates both ranges. Tectonics also brought about several 'flower structures' as well as Paleogene gabbro and syenite and Oligocene tonalite intrusions and volcanic pyroclastics in the south. Various grades of metamorphism can be observed in the suture zone of continental plates. The sediments of the Palaeo- and Neotethys Oceans (Ordovician to Lower Cretaceous platform carbonates) are predominant. Ore formation produced lead molybdate (wulfenite) and zinc deposits at Topla. Topla is the type locality of the rare tourmaline variety, dravite, named after the Drava River.

The high-mountain topography is shaped by glacial, glaciofluvial, and karst processes. The best known river gorge is the Tscheppaschlucht, a collapsed cave with a natural arch. Potholes and plunge pools below waterfalls are both carved by intense eversion.

2.4.8 Seetal Alps–Saualpe

Together with its northern continuation, the Seetal Alps (highest point: Zirbitzkogel, 2,396 m) and the Saualpe (highest point: Ladinger Spitz, 2,079 m) are part of the crystalline Eastern Alps stretching between the valleys of the Mura and the Drava (Schönenberg and Weissenbach 1975). The most common rock types, according to the grade of metamorphism, are mica schist, gneiss, phyllite, quartzite, and different volcanics (Fritsch 1964). The Permo-Mesozoic carbonate cover has been stripped from the basement during the Cretaceous subduction, but some detached limestone or dolomite klippen (like Ulrichsberg and the 175-m-high hill with the castle of Hochosterwitz) rise above the middle-mountain ridges with subdued relief.

2.4.9 Koralpe

The Koralpe rise between the Drava and Sulm Valleys. The highest peak is Großer Speikkogel (2,140 m), which is built of magmatic rocks (gabbro—Schuster and Stüwe 2010). The same pluton is also exhumed in the Slovenian Pohorje. The Permian to Mesozoic rocks were completely stripped off during an early Alpine orogenic event in the Lower Cretaceous, by the Pleistocene glaciations and post-glacial erosion. Thus, the metamorphic (gneiss) ridges of the Koralpe-Wölz Nappe were heavily denuded into flat surfaces (Rantitsch et al. 2009). The occurrence of eclogite and pegmatite (with spodumen, a lithium aluminium inosilicate) makes the Koralpe a mountain range of geological and economic interest.

2.4.10 Pohorje

South of the Drava, the Pohorje is an Alpine mountain block of ca 50 km east-to-west and 30 km north-to-south extension (840 km^2). The highest peak is Črni Vrh, 1,943 m (in German: Schwarzkogel). Its core is a late Early Miocene tonalitic pluton (with granodiorite and dacite) surrounded with Paleozoic metamorphic rock (Fodor et al. 2008). (The only known occurrence of cizlakite, quartz monzogabbro, a green plutonic rock, in the world is located near the village Cezlak of the Pohorje.) In the southern Pohorje white marble was already quarried in Roman times. “The highest pressures of the Cretaceous metamorphism of the entire Alps are reached in the eclogites of the Pohorje massif (3.0–3.1 GPa, 760–825 °C)” (Fodor et al. 2008).

2.4.11 Low Tauern

The Low Tauern (Niedere Tauern) is the northern watershed of the Mura basin. It embraces three mountain blocks

- the Schladming Tauern (highest point: Hochgolling, 2,863 m) in the west;
- the Wölz Tauern in the centre (Greim, 2,474 m) and
- the Rottenmann Tauern (Groβer Bösenstein, 2,449 m) in the east.

The rocks are mostly metamorphic (gneiss, mica schist, phyllite, marble), greywacke, and quartzite. The topography is typically glacial with troughs, cirques, tarns, and morainic landforms.

All sections of the mountains abound in picturesque tarns. In the foreland of the Wölz Tauern the Puxerloch is an opened-up cave with castle ruins.

2.4.12 Eisenerz Alps

Between the Low Tauern and the Hochschwab, on the northernmost boundary of the greywacke zone (Schönlaub 1982), the Eisenerz mountains rise to 2,165 m (Eisenerzer Reichenstein). The constituent rocks are mostly Paleozoic greywacke, Devonian metamorphosed calcareous rocks and Triassic schists. The Mesozoic of the carbonate nappe (Kalkalpendecke) only occur on the northern slopes, outside the Mura catchment.

2.4.13 Hochschwab

To the east the greywacke zone continues in the Hochschwab massif (elevation: 2,277 m). This mountain block of 590 km^2 area (mostly outside the Mura catchment), however, is built, in addition to Paleozoic rocks in the southern part, of Triassic shales and carbonates (limestones and dolomites) in the north. Hochschwab is a good example of crested glaciokarst. The massif is infamous of major landslides and famous for its caves (including the 20.2-km-long Frauenmauerhöhle in Middle Triassic limestone).

2.4.14 Schneealpe

The Schneealpe (1,903 m) is another heavily karstified massif of Triassic limestones with hundreds of caves and dolines. It is among the areas from where the First Vienna Water Main gains drinking water for the Austrian capital.

2.4.15 Fischbach Alps

The Fischbach Alps (highest summit: Stuhleck, 1,782 m) stretch from Bruck an der Mur to the Semmering Pass in the east. Mostly built of schists, Mesozoic carbonates and quartzites occur in the east. The 1.3-km-long Bärenschützklamm gorge of the Mixnitz stream in Almenland is a popular touristic destination.

2.4.16 Styrian (Graz) Basin

Subsidence in this major intramontane basin of the Eastern Alps is due to a single phase of synrift extension in the early Middle Miocene (Ebner and Sachsenhofer 1991). The 4,000-m-thick sequence of marine, lacustrine, and fluvial sediments is interrupted by volcanics of 17–13 Ma age. Late Miocene basin fill mostly consists of limnic-fluviatile deposits, which were uplifted during the Pliocene (Pfiffner 2014). The present hilly topography is formed by erosional processes on these sediments and a second suite of basaltic volcanics. A good example of the 40 basalt volcanoes with tuff rings is Riegersburg.

2.4.17 Pannonian (Carpathian) Basin

Leaving the Styrian Basin, the Drava and the Mura enter the Pannonian Basin. It is a classical back-arc basin, developed as a result of the extension and related thinning of continental lithosphere formed in the Miocene in response to the rapid rollback of a continental slab (Balla 1986; Horváth et al. 2006; Matenco and Radivojević 2012). The extension probably began ca 20 Ma ago, followed by a peak tectonic activity along normal faults during Middle Miocene times. From the Miocene to the Quaternary boundary, the counterclockwise rotation of the indenting Adriatic subcontinent determined tectonic evolution and the inversion of the whole basin (Fodor et al. 1999).

The Drava crosses the southwestern portion of the basin, the Drava Graben, in physical geography: the Drava Plain, with a long subsidence history and a thick sedimentary fill accumulated in Lake Pannon and later by river deltas.

2.4.18 Mura Hills (Goričko and Prekmurje)

The Mura Hills (404 m) are carved by water erosion from marine and fluvial sediments deposited in the Mura Graben. After the subsidence stopped, parallel river channels were oriented to flow more and more towards the south. In the

Pleistocene, the deposits of Alpine glaciers (pebbles and sands) were transported here and accumulated in terraces covered by finer materials.

2.4.19 Zala Hills

Another typical Pannonian hilly landscape is found in the Zala Hills (highest point: Kandikó, 302 m). The Paleozoic-Mesozoic metamorphic basement is overlain by Mesozoic and Paleogene marls and limestones. In the Miocene terrestrial (fluvial gravels) and marine siltstone, clay) also accumulated in the sedimentary basin (Hámor 1998). Uplift began after Lake Pannon filled up. The present-day hilly landscape was formed by Pleistocene fluvial erosion. Mineral oil reserves gave economic importance to the hills.

2.4.20 Ivanšćica

Part of the Croatian Zagorje region, the Ivanšćica Mountains rise to 1,061 m above the neighboring plains. Prevalently composed of Triassic carbonates with some clastic sediments, remnants of obducted ophiolite derived from the Neotethys Ocean are also exposed here. The landforms are of karstic origin. Volcanic eruptions 22 Ma ago produced the Lepoglava agate, a semiprecious stone.

2.4.21 Kalnik

In Mt. Kalnik (highest point: 642 m) large Triassic basalt blocks incorporated into the Jurassic ophiolite mélange are exposed. Middle Triassic to Lower Cretaceous interlayered chert, siliceous shale, mudstone, and limestone strata also occur.

2.4.22 Bilo

The Bilo Hills (Rajčevica, 309 m) of northwest to southeast strike stretch parallel with the lower Drava along 80 km length in Croatia. The low and wide ridges are built up of Quaternary clastic sediments.

2.4.23 Southern Zselic

This hilly region is a system of alluvial fans of Miocene-Pliocene sands and clays, covered with Pleistocene loess and heavily dissected by fluvial erosion. The highest point is 265 m.

2.4.24 Inner Somogy Hills

Inner Somogy is built up of 100–400 m of Neogene sandy-gravelly sediments and 5–8 m of Pleistocene blown sand. In the centre the north-to-south Marcali loess ridge rising to 192 m. The Somogy Hills are actively affected by compression and strike-slip type movements along lineaments related to the Peri-Adriatic fault system. Where the Drava undercut the hilly ridge reaching the channel at right angles, the high bluff of Heresznye was created (Fig. 2.5).

Fig. 2.5 The high bluff of Heresznye above the Drava, Hungary (photo by D. Lóczy)