Field Trip A1: Southern Alps of Slovenia in a nutshell: paleogeography, tectonics, and active deformation

Bogomir Celarc[1], Marko Vrabec[2], Boštjan Rožič[2], Polona Kralj[1], Petra Jamšek Rupnik[1], Tea Kolar-Jurkovšek[1], Luka Gale[2] & Andrej Šmuc[2]

[1] Geološki zavod Slovenije, Dimičeva 14, 1000 Ljubljana, Slovenia
[2] Oddelek za geologijo NTF, Univerza v Ljubljani, Privoz 11, 1000 Ljubljana, Slovenia

Abstract

The field trip deals with different aspects of the evolution of the easternmost part of the Southern Alps in Slovenia. We will see and discuss:

- Middle Triassic to the Early Cretaceous paleogeography of the Julian Alps (Late Anisian carbonate-platform break-up, Late Triassic progradation of the Dachstein Platform and coeval formation of the intraplatform Tamar basin, Late Triassic - Early Cretaceous successions of the Slovenian Basin. Paleogeographic domains are now positioned in different tectonic blocks of the overlapping South Alpine and Dinaric thrust structures.
- Periadriatic fault system, major Oligocene-Miocene tectonic feature of the Alps, dextral strike-slip Sava fault, remarkable morphologically expressed tectonic line, which separates Julian and Kamnik-Savinja Alps and an active Vodice reverse fault at the contact between the Southern Alps and the Dinarides.
- The Upper Oligocene Smrekovec Volcanic Complex, one of several small and marginal sub-basins in the south-west of the Pannonian back-arc realm, considered to be post-collisional and related to slab breakoff processes.

Introduction

The field-trip area is located in the eastern part of the Southern Alps (NW and central N Slovenia, Fig. 1). They are situated between the Periadriatic fault, Labot (Lavanttal) fault and Ljutomer fault which are in the broader sense a part of the Balaton fault zone in the north, and South-Alpine thrust border and Sava fault in the south (PLACER, 2008) (Fig. 2). Julian Alps and Kamnik – Savinja Alps are predominately composed of Mesozoic carbonate rocks. In the Southern Karavanke also Paleozoic rocks are exposed. In the Julian Alps South Alpine and the Dinaric structures now overlap. They consist of two south-verging tectonic units, the Tolmin Nappe and the Julian Nappe. The Tolmin Nappe consists of several thrust sheets. Also Julian Nappe consists of minor thrust sheets, but it has not yet been satisfactorily resolved. The K–S Alps were displaced by approximately 40 km with respect to the Julian Alps along the Neogene dextral strike-slip Sava Fault. The Julian Alps and the K–S Alps exhibit a remarkably similar stratigraphic evolution in the Triassic. North of the Julian Alps and the K–S Alps the South Karavanke Mts. form a strongly elongated strike-slip-related system of sheared tectonic lenses south of the Neogene Periadriatic Line (PLACER, 2008). During the extensional evolution of the Pannonian Basin, connected with the activation of the Periadriatic Line (PAMIĆ & BALEN, 2001), volcanic activity created the Smrekovec Volcanic Complex, part of the small and marginal sub-basin, positioned on the Mesozoic basement of the Southern Alps. In the releasing overstep between major dextral strike–slip Sava and Žužemberk faults, Ljubljana Basin, filled with Quaternary sediments is positioned (VRABEC & FODOR, 2006). Smaller E-W oriented reverse faults that displace Quaternary sediments in the basin may indicate a recent change in the deformational regime from transtensional subsidence to transpression.

Figure 1: Geographic location of all field-trip stops.

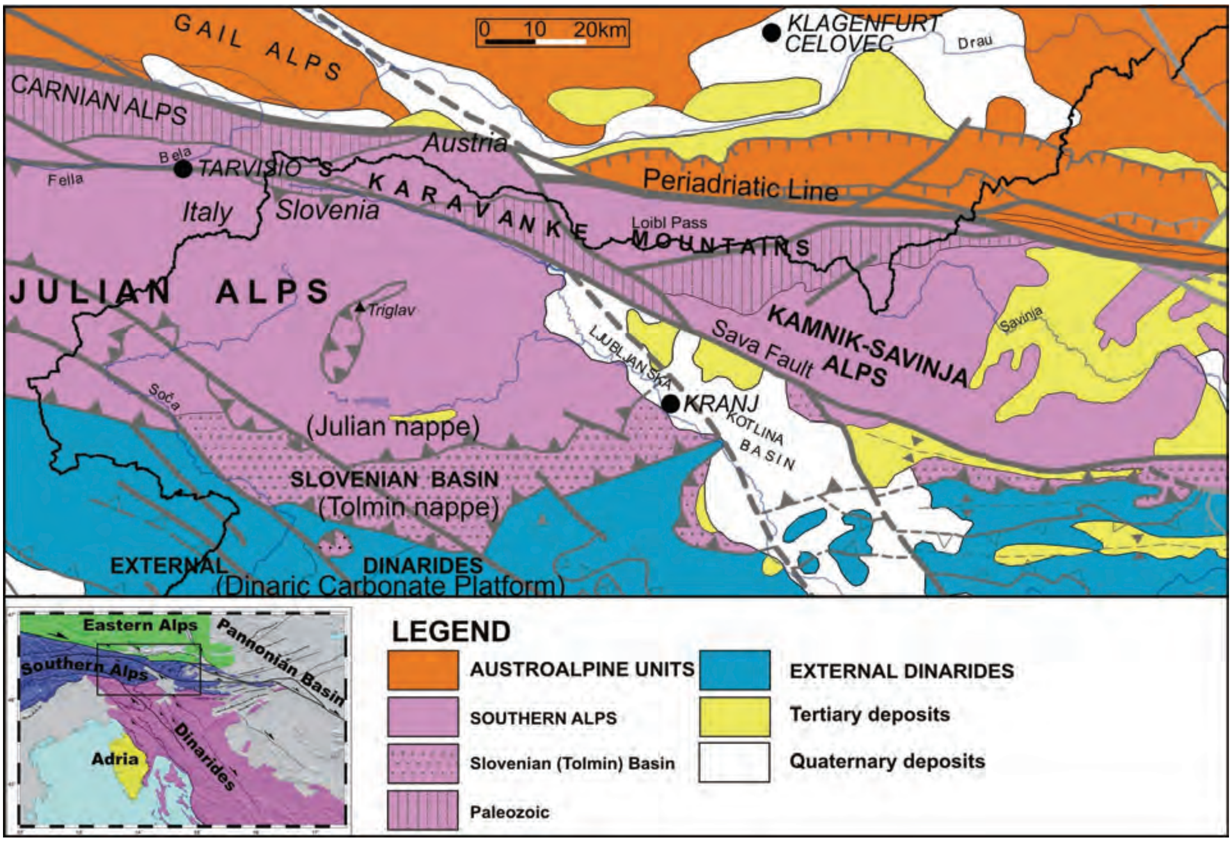


Figure 2: Macrotectonic subdivision of the NW and central N Slovenia (after PLACER, 2008).

Day 1

Middle Triassic carbonate-platform break-up and formation of small scale half-grabens (guided by Bogomir Celarc)

Introduction

The Late Anisan extension associated with differential subsidence, the rotation of blocks, coeval drowning and exposure of carbonate platforms was a widespread event in the Southern Alps and has been documented by numerous authors (e.g. BECHSTÄDT et al., 1978; FARABEGOLI et al., 1985; DE ZANCHE et al., 1993; GIANOLLA et al., 1998 and references therein; VENTURINI, 2006; Berra & CARMINATI, 2010). During the Middle and and also Late Triassic, this area was located on the southwestern shelf of the opening Meliata-Maliac Ocean (STAMPFLI & BOREL, 2002) that is now mostly considered to be an embayment of the Neotethys (e.g., SCHMID et al., 2008).

Throughout the Southern Alps during the Illyrian, most of the previous platforms drowned with the onset of the basinal Buchenstein/Livinallongo Formation (GIANOLLA et al., 1998). However, there are reports of red-coloured radiolarian and locally ammonite-rich limestones (Ammonitico Rosso-type limestones) on top of shallow-water carbonates (FARABEGOLI & LEVANTI, 1982; KRAINER & MOSTLER, 1992; KOZUR et al., 1994; KOZUR et al., 1996; KRAINER, 1996). They are usually very thin and are overlain by volcanics and/or polymict conglomerates and sandstones which are equivalents to the Uggowitz Breccia, a well-known formation from the Carnian Alps and the western (Italian) part of the Julian Alps (GIANOLLA et al., 1998). Above those units, the Buchenstein (Livinallongo) Formation occurs and, in the upper part, this interfingers with the Schlern Dolomite which records platform progradation.

Map-scale geometry, neptunian dykes, the onset of volcanism, the presence of (mega)breccia and related palaeo-escarpments, the lateral variations in thickness and the wedge-shaped geometry of the lithological units provide evidence of syn-sedimentary block faulting and the formation of small-scale, relatively shallow half-grabens within the previously uniform Slovenian Carbonate Platform and indicates a clear tectonic control over the development of the Middle Triassic stratigraphy. The described extensional event is well correlated and genetically connected with the syn-rift formation of the neighbouring Slovenian Basin and other Southern Alpine basins that formed in connection with the opening of the Meliata-Maliac branch of the Neotethys Ocean.

Figure 3: Geographic location of Stops 1 and 2.

Stop 1 – Vratica Saddle (1799m): view to the Mt. Prisojnik (Middle Triassic) with small-scale halfgraben (Fig. 3)

In the ESE direction from the Vratica Saddle, the NW face of the Mt. Prisojnik (2547 m) exhibits well-exposed Middle Triasic succession (CELARC et al., 2013) (Fig. 4a, b). The lower part of the NW face of Mt. Prisojnik is composed of well-bedded, in places stromatolitic, Anisian (probably Pelsonian) dolomite and limestone with *Meandrospira dinarica* and *Physoporella pauciforata* (JURKOVŠEK, 1987; RAMOVŠ, 1987a). These rocks are overlain by an about 40 m thick succession of thin-bedded to platy dark-grey dolomite intercalated with thin horizons of reddish marlstone. In the upper part, around 2 m of green-coloured marl is intercalated.

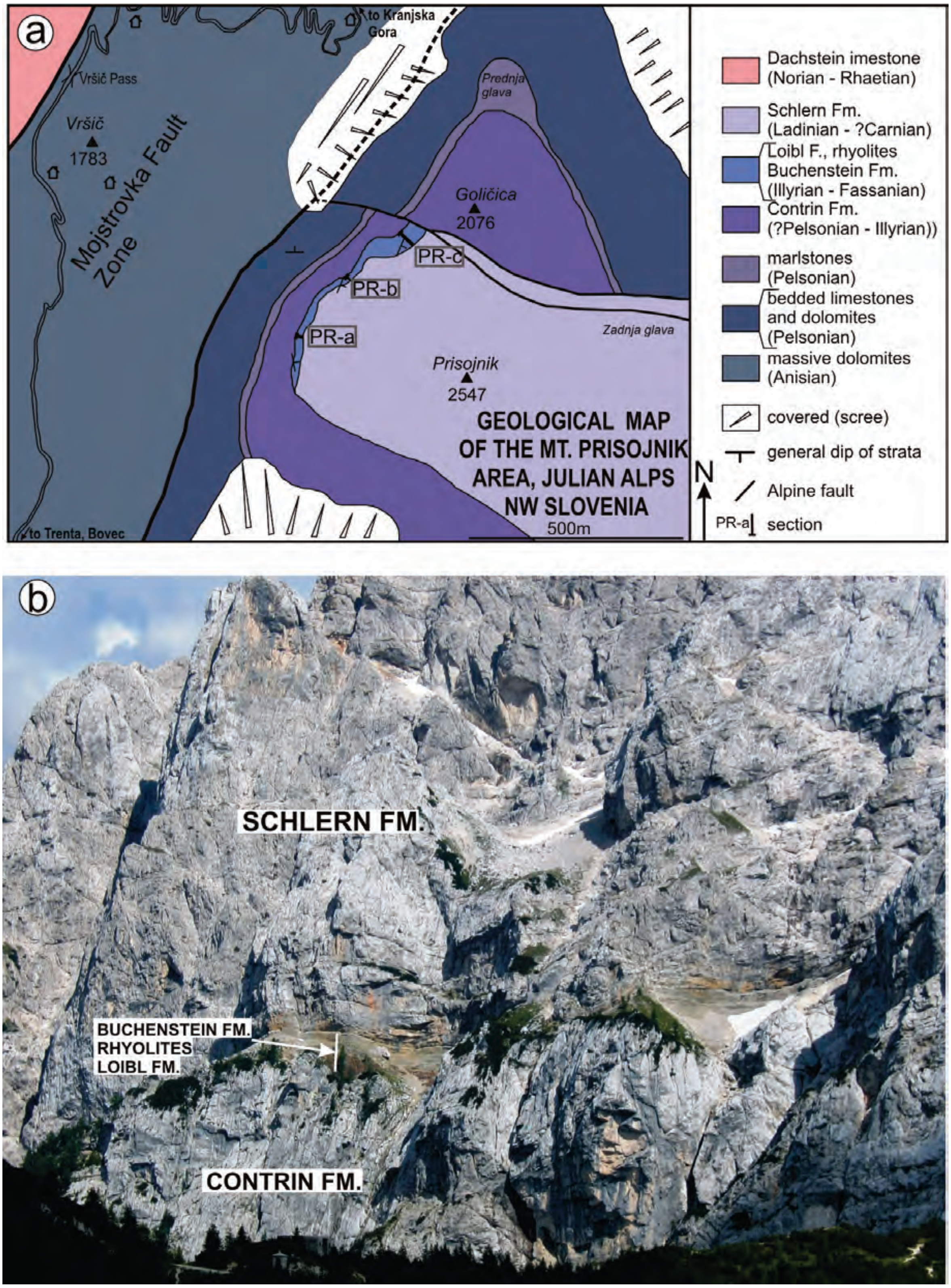


Figure 4: (a) Geological sketch map of the Mt. Prisojnik area. (b) Field photography of the NW face of Mt. Prisojnik with formations as shown on the geological map.

Above this there occur up to 200 m thick massive limestone of the Contrin Formation (?Pelsonian – Illyrian). The succession above the Contrin Formation and below the Schlern Formation (massive, partly dolomitized limestone) consists of the laterally discontinuous, up to several metres thick, Loibl Formation, tuff and rhyolite (0 to 20m), and the Buchenstein Formation (0 to 25 m thick). A slight angular unconformity is observable between the Contrin Formation and the overlying units. The upper part of the Contrin Formation is cross-cut with neptunian dykes which can reach several metres in the undeformed limestone. The Loibl Formation overlies the Contrin Formation with a sharp contact. In the lower part, it consists of distinctive nodular, light-red radiolarian-rich wackestone. Their age is Illyrian (upper part of the *Paraceratites trinodosus* Ammonoid Zone), according to the radiolarian and conodont dating.

The contact with overlying tuffs is not exposed. Red rhyolite with flow structures emerges from the scree around 10m above the tuffs. Toward the SW, they are thinning and onlapping the Contrin Formation and the Loibl Formation. The Buchenstein Formation lies with sharp contact on the rhyolite and is approximately 25 m thick. In the lower part, the formation consists of grey platy nodular limestone, mostly wackestone, with thin laminated siltstone-sandstone intercalated between individual layers. In the upper half of the section, the bedding planes are planar and there is no siltstone or marlstone intercalated. In some beds, abundant, well-preserved resedimented algae are present.

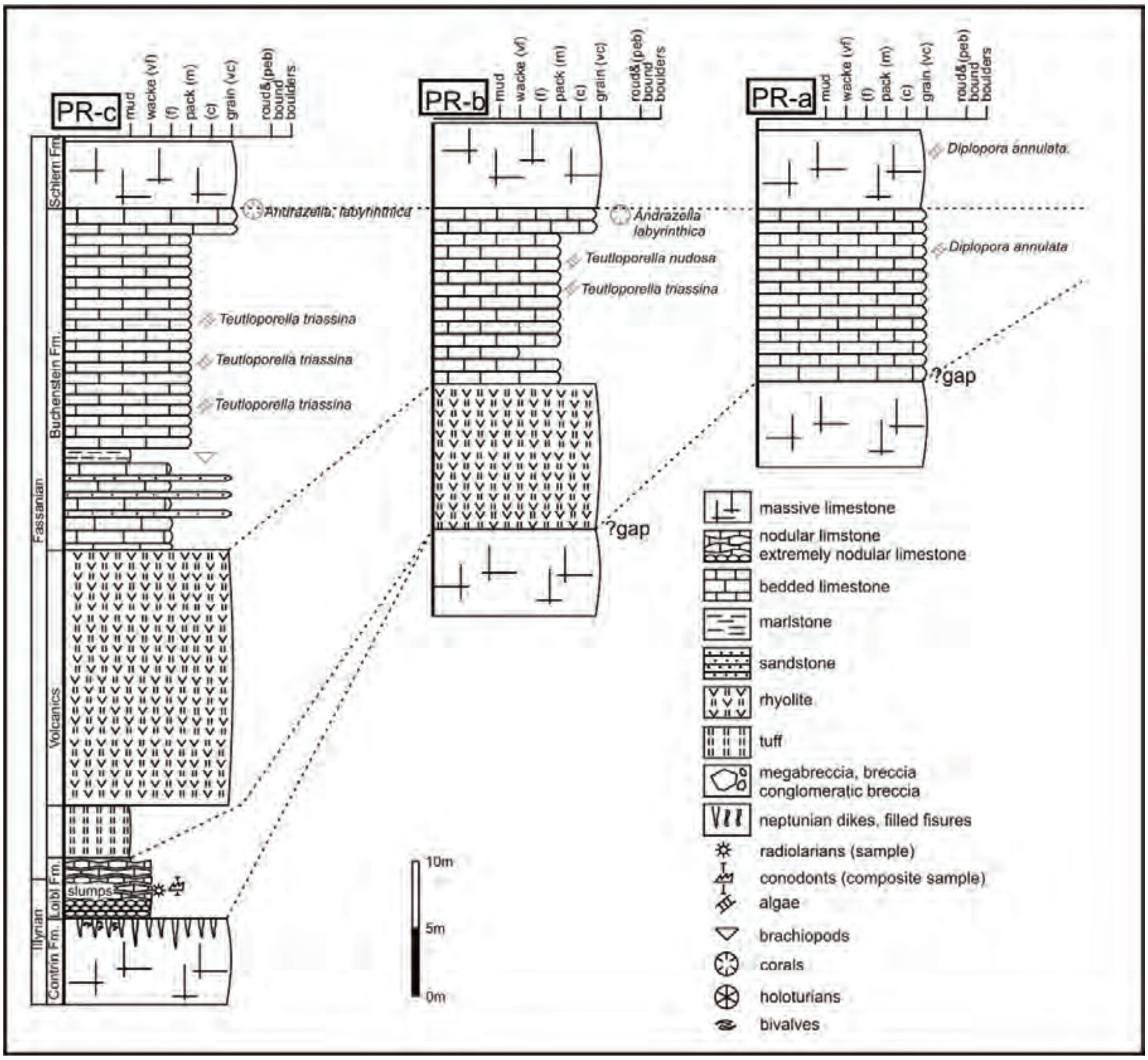


Figure 5: Stratigraphic logs of the sections in the Mt. Prisojnik and their correlation. For location of the sections see Fig. 4a.

Laterally, the red limestone of the Loibl Formation wedges out, also rhyolites thickness decreases. Limestones of the Buchenstein Formation directly overlie the Contrin Formation and consist predominantly of thin-bedded peloidal packstone and wackestone with subrounded algal fragments. Grainstone prevails in the upper part. Even more laterally, the Buchenstein Formation gradually wedges out. Between the Contrin Formation and the Schlern Formation, only a few metres of thin-bedded, graded predominately algal grainstone and rudstone are present.

Small-scale hafgraben geometry in the Mt. Prisojnik is evident from: (1) mapping-scale geometry of the basin infill between the underlying Contrin Formation and the overlying Schlern Formation and their mutual boundaries; (2) lateral and vertical variations in facies types and (3) lateral variations in thickness of the basin fill (Fig. 5).

Progradation of the Dachstein carbonate platform (guided by Bogomir Celarc)

Introduction

A distinct transgression pulse, recognized above the former Ladinian – Carnian platforms or Raibl Group, deepening, formation of the basin(s) and progradation of the rimmed Main Dolomite or Dachstein Limestone platforms, was recognized in the Julian Alps (LIEBERMAN, 1978; RAMOVŠ, 1986a, 1986b, 1987b; JURKOVŠEK, 1987; SCHLAF et al., 1997a, 1997b; DE ZANCHE et al., 2000; GIANOLLA et al., 2003; CELARC & KOLAR-JURKOVŠEK, 2008). According to paleogeographic studies, the Slovenian part of the Julian Alps formed an isolated platform between the Slovenian Basin and the Hallstatt – Meliata Ocean (e.g. HAAS et al., 1995; ZIEGLER & STAMPFLI, 2001; STAMPFLI & BOREL, 2002).

Stop 2 – Mt. Slemenova špica (1909m): view to the Mt. Škrlatica (progradation of the Dachstein carbonate platform)

From the Mt. Slemenova špica, in the E direction, the NW face of the Mt. Škrlatica (2740 m, part of the Martuljek Mountain Group), the progradation geometry of the Dachstein platform is exposed at the seismic-scale. This is one of the rare "text-book" examples where complete transect from basin floor, adjacent slope (clinoforms), reef and lagoon is exposed (Fig. 6a).

In the lower part, the mountain face consists of the Razor limestone (Lower Carnian), with cyclic bedded limestones, organized into 1-1,5m thick, predominately shallowing upward symmetric cycles. Shallower subtidal facies is represented by an abundant oncoidal horizonts. Intertidal - supratidal facies is recognizable by laminated grainstones, which are often dolomitized, and with horizontal microbial laminites. Fenestral pores (loferites) are very common in these horizons.

With the sharp, discordant contact, follows, thin, up to 25 m thick, darker band of the Martuljek platy limestone (Upper Tuvalian - Lower Norian – dated with conodonts), consisting of reddish, platy pelagic limestones. The Lower member is composed of reddish (rarely grayish) sometimes indistinctly bedded pelagic limestone (bioclastic wackestone to packstone). The Upper member is composed of light grey to white platy and thin bedded often dolomitized limestones (coral and crinoid grainstones and rudstones) and represents toe-of-the-slope facies (Fig. 6b).

Around 300 m thick Dachstein reef limestone with corals and sponges as main frame-builders (Upper Tuvalian – Norian), consisting of hard-to-distinguish slope and reef margin facies is positioned on top of the Martuljek Platy Limestones and they partially interfinger. Due to the steep terrain, these limestones haven't been yet studied in detail in order to establish classic reef zones (fore reef, reef front, reef crest, back reef). The highest stratigrafic unit in the upper part of the mountain is well bedded, cyclic bedded Dachstein Limestone (Norian – Rhaetian), more than 1000m thick, onlapping reef limestones (Fig. 6c).

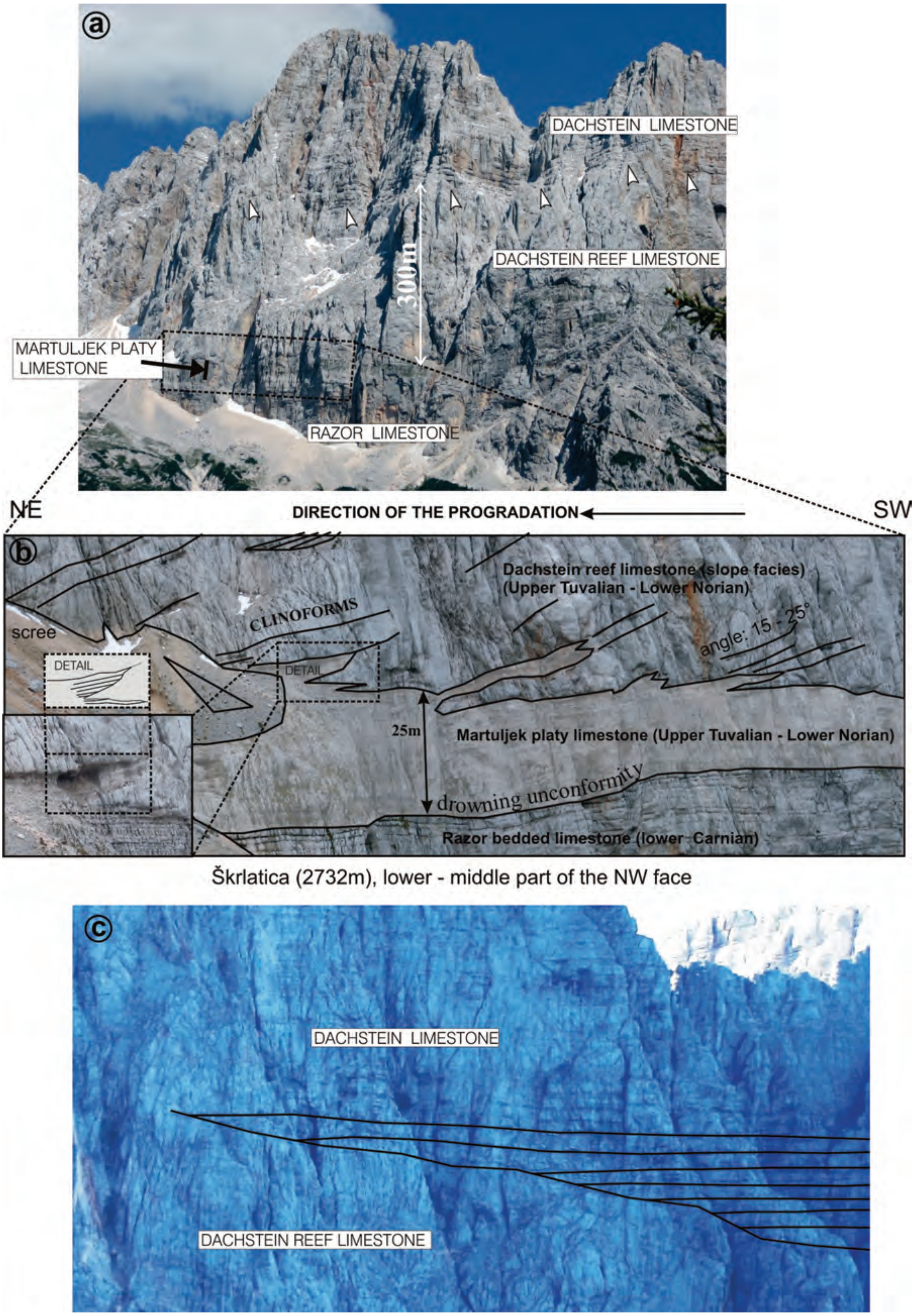


Figure 6: Facies interpretation and progradational geometry in the NW face of Mt. Škrlatica. (a) Large scale facies interpretation. Arrows indicate contact between Dachstein reef limestone (slope and margin facies) and bedded Dachstein Limestone (inner plarform facies). (b) Interpretation of facies relationship with detail of toe of slope interfingering between Martuljek platy limestone (Upper Member) and reef limestone. (c) Bedded Dachstein limestone onlapping massive reef limestone.

Progradation geometry of the Dachstein platform passing into the basin is exposed parallel to the direction of the platform advance.

Interfingering of the thin bedded reef-debris limestones (Martuljek platy limestone – Upper member) and clinostratificated reef-debris limestones of the slope facies (Dachstein reef limestone) is clearly visible. The lithologic boundary in Mt. Škrlatica can be interpreted as a climbing progradadion in the sense of BOSELLINI (1984), yet generally, the boundary is horizontal. Thin bedded limestone~~s~~ exhibit low angle onlap against the upper boundary of the intermediary wedge of the slope limestone intercalated in the Martuljek platy limestone. The Upper member of the Martuljek platy limestone slightly thickens basinward, while individual beds thin in the same direction.

Clinoforms are expressed as discontinuities in the slope limestones with an inclination of around 15-25° and dip in the NE direction. Their configuration is oblique-parallel. We interpret this pattern as the horizontal downlap plane (BOSELLINI & STEFANI, 1991; MAURER, 2000) which indicates rapid progradation of the platform.

The upper boundary of the slope and the margin with the Dachstein Limestone is expressed as low angle onlap against a massive margin. This relationship points to the slow relative subsidence in the Early Norian and progradational dominated highstand systems tract.

The coral reef margin in the upper part is macroscopically similar to the slope, so its exact thickness is unknown. Based on the clinoform dip and the opposite direction of the onlapping surface, the progradation is in the SW – NE direction.

Estimating the water depth at the Hallstatt basin – Dachstein reef platform connection in the NCA is a topic of recent debates. KENTER & SCHLAGER (2009) calculated at least 300m, probably more than 500m for the Gosaukamm. At the Gosausee deep estimating ranges between 200-250m (MARTINDALE et al., 2013). In the Mt. Škrlatica it could be directly measured and amounts 300m.

Tamar Valley (Carnian-Norian–Rhaetian intraplatform Tamar Basin in the footwall block and Dachstein platform in the hangingwall block of the Resia – Val Coritenza backthrust) (guided by Bogomir Celarc)

Introduction

Julian Nappe with the Dachstein limestone is thrusted in the Tamar Valley on the Norian-Rhaetian basinal succession, while on the Italian side of Mt. Mangart, thrusted blocks consist also of Jurassic (and partially Lower Cretaceous) lithological units on top of the basinal and platform Triassic succession, respectively (ASSERETO et al., 1968). The similar succession is described also in the South Karavanke between Frauenkogel/Dovška Baba and Kahlkogel/Golica (KRYSTYN et al., 1994) and probably belongs to the same basin, now displaced along Sava Fault. A Late Tuvalian – end Triassic facies polarity (Fig. 7), characterized by the SW-NE progradation of the Dolomia Principale platform (DE ZANCHE et al., 2000; GIANOLLA et al., 2003) is clearly represented. In the west (Dogna Valley, Raibl area in Italy), terrigenous influenced Julian and Lower Tuvalian formations filled Middle Triassic, while more to the east, Cassian Dolomite conformably overlies the Schlern Dolomite. The area was sealed and flattened with deposition of the widespread Tor (Heiligkreuz) Formation and the carbonate bank of the Portella Dolomite (DE ZANCHE et al., 2000; GIANOLLA et al., 2003; PRETO et al., 2005). In the Late Tuvalian, drowning triggered deposition of the basinal Carnitza Formation and coeval progradation of the Dolomia Principale in the west (from direction of Dolomites), while in the Mangart area (Mt. Privat), and in the Tamar Valley, basinal conditions prevail from Late Tuvalian to the end of Triassic, with Norian cherty dolomites, followed by basinal dolomites and Rhaetian platy limestones.

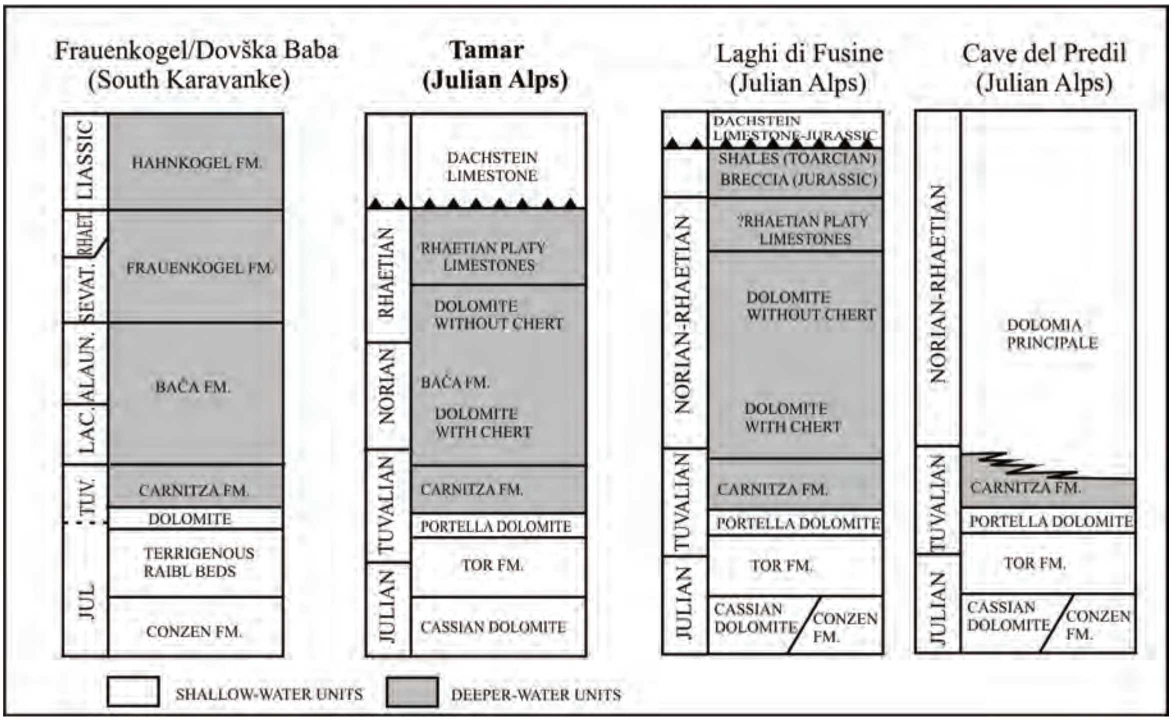


Figure 7: Upper Triassic stratigraphic columns and correlation of the Tamar Basin between Cave del Predil (Julian Alps – Italy), Laghi di Fusine (Julian Alps – Italy), Tamar (Julian Alps – Slovenia) and Frauenkogel/Dovška Baba (Karavanke – Austria and Slovenia)

Stop 2 – Mt. Slemenova špica (1909m): Tamar Valley

The stratigraphic succession in the lower parts of the NNW – SSE to N-S directed Tamar Valley belongs to the footwall block of the north-verging Resia – Val Coritenza backthrust (Fig. 8), probably related to the Alpine thrusting (PONTON, 2002).

Figure 8: Mountains above Tamar Valley. Resia – Val Coritenza north verging backthrust separates Tamar Basin (Upper Tuvalian – Rhaetian basin interval) in the footwall and Dachstein limestone in the hangingwall. Photography taken from Mt. Ponca ridge.

Stratigraphy of the Tamar Basin

The stratigraphic succession is exposed in the lower slopes of the Mt. Mojstrovka and Mt. Travnik in the S to SSW direction from Mt. Slemenova Špica. Cassian Dolomite is the lowest unit, composed predominately of massive to the indistinctly bedded dolomites, with rarely present stromatolites and oncoides. With the sharp contact follows the Tor Formation. This, 50m thick unit is thin – layered shallow-water fossil rich terrigenous carbonate unit, with alternation of marlstones, marly limestones, thin-bedded dolomites and limestones, suordinately calcarenites, rich in bivalves, gastropods, foraminifers. The age of the formation is Julian – Tuvalian. Above the Tor Formation is positioned 12 m thick massive dolomitic unit, without sedimentological textures and fossils. It corresponds to the Portella dolomite from Cave del Predil area (GIANOLLA et al., 2003). Carnitza Formation is around 55 m thick and is composed of well-bedded gray to dark-grey platy dolomites with rare up to 7 cm thick black (rarely green) claystone intercalations. Bedding is planar or wavy. Parallel lamination and bioturbation are common. According to the conodonts, the age of formation is Middle to Late Tuvalian. Above the Carnitza Formation, Bača Formation (sensu KRYSTYN et al., 1994) is positioned. The transition is gradual, marked by appearance of chert nodules and a decrease of the clay content. It is composed of the thin to medium-bedded dolomites with abundant black, brown or red colored chert nodules. Dolomite-cherty breccias and synsedimentary slides are common. In the upper part massive or indistinctly bedded dolomites without chert prevail. The total thickness of the formation is around 300 m. In the lower part of the dolomites with chert, conodonts indicate Middle – Late Tuvalian age, in the upper part of the dolomites with chert condonts indicate Middle – Late Norian age. In the lower part of the dolomites without chert, conodonts indicate Late Norian – Early Rhaetian age and in the uppermost part of the dolomites without chert, conodonts indicate Rhaetian age. The uppermost formation is 49 thick, and is cut with thrust at the top. It starts with 10-20 cm thick marlstone beds, interchanging with fine- to medium- coarse graded, 40 cm thick rudstone. A fairly uniform sequence of the dark bituminous and laminated platy limestone follows, interchanging with few up to 1cm thick marlstone beds. Small nodules and thin lenses of chert are rare. Bedding is often disturbed by folds and slumps. In the upper part of the sequence, up to 3m large "cipit" boulders of beige wacke- to packstones and dark grey packstones lie among platy limestones. The Rhaetian age is determined with foraminifers from rudstones and "cipit" boulders, derived from the platform.

The hangingwall block above Canin – Val Coritenza backthrust is composed of the cyclic bedded sub- to peritidal Dachstein Limestone, which builds prominent steep faces of the Mt. Mojstrovka and Mt Travnik and also Mt. Ponce ridge at the opposite side of the Tamar Valley.

Day 2

Stop 3 – Koroška Bela: Sava fault (Fig. 9) (guided by Marko Vrabec)

The dextral strike-slip Sava fault is a major NW-SE-trending regional fault in the easternmost exposed part of the Periadriatic fault system (e.g. VRABEC & FODOR, 2006; Fig. 10). Between the Sava fault and the Periadriatic fault proper a complex transpressional shear lens developed, where complex rotations of fault-bounded blocks were documented with paleomagnetic data (FODOR et al., 1998).

The Sava fault is traditionally interpreted to connect westward with the E-W trending Fella reverse fault of the northeastern Italian Southern Alps, although its direct linkage with the Periadriatic fault accross the Carnic Alps seems more plausible from both geometrical and kinematic considerations (FORKE et al., 2008). Due to incision of the upper Sava river valley along the fault trace, the fault has a marked topographic expression, which continues into central Slovenia where the fault separates the Quaternary Ljubljana basin from the northbounding mountain ranges (Fig. 11). Further to the east, the fault is interpreted to bend in the E-W orientation and to eventually connect with other faults of the Periadriatic fault system, like the Šoštanj fault and the Labot (Lavanttal) fault (KAZMER et al., 1996; PLACER, 1996; FODOR et al., 1998).

The amount of displacement on the fault was estimated from dextral separation of various Oligocene formations that crop out on both sides of the fault. Estimates range from 25 km (HINTERLECHNER–RAVNIK & PLENIČAR, 1967), 40 km (KAZMER et al., 1996) to 65–70 km

(PLACER, 1996), though we find the lower estimates more realistic. The time span of the activity of the fault is also not very well constrained by geological criteria. Folding and reverse faulting of mid-Miocene sediments in the restraining bend of the fault north of Ljubljana limit the main slip phase to post 12 Ma (VRABEC, 2001).

Several indications exist for the recent activity of the fault. The rectangular Ljubljana basin, filled with Quaternary sediments, is interpreted as a pull-apart depression in a releasing overstep between the Sava fault and the Žužemberk fault (e.g. VRABEC, 2001). A GPS study of active displacements in the eastern part of the Peraidriatic system implies a slip rate of around 1 mm/yr on the Sava fault (VRABEC et al., 2006). More recently, a line of supporting geomorphological evidence, like dextral shifts of the drainage network and displacements of Quaternary-Holocene alluvial fans was documented along the fault (JAMŠEK-RUPNIK et al., 2012, 2013a; JAMŠEK-RUPNIK in preparation).

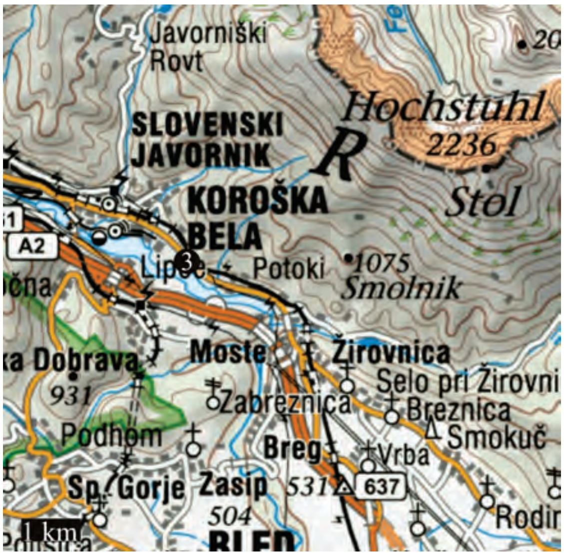


Figure 9: Geographic location of Stop 3.

Figure 10: Trace of the Sava fault on the simplified tectonic map of the region (modified after VRABEC & FODOR, 2006). Digital terrain model from SRTM data (Shuttle Radar Topography Mission), accessible from Global Land Cover Facility (http://www.landcover.org). DF – Drava fault, FF – Fella fault, HF – Hochstuhl fault, IF – Idrija fault, LF – Labot (Lavanttal) fault, PAF – Periadriatic fault, RF – Raša fault, SF – Sava fault, ŠF – Šoštanj fault, ŽF – Žužemberk fault

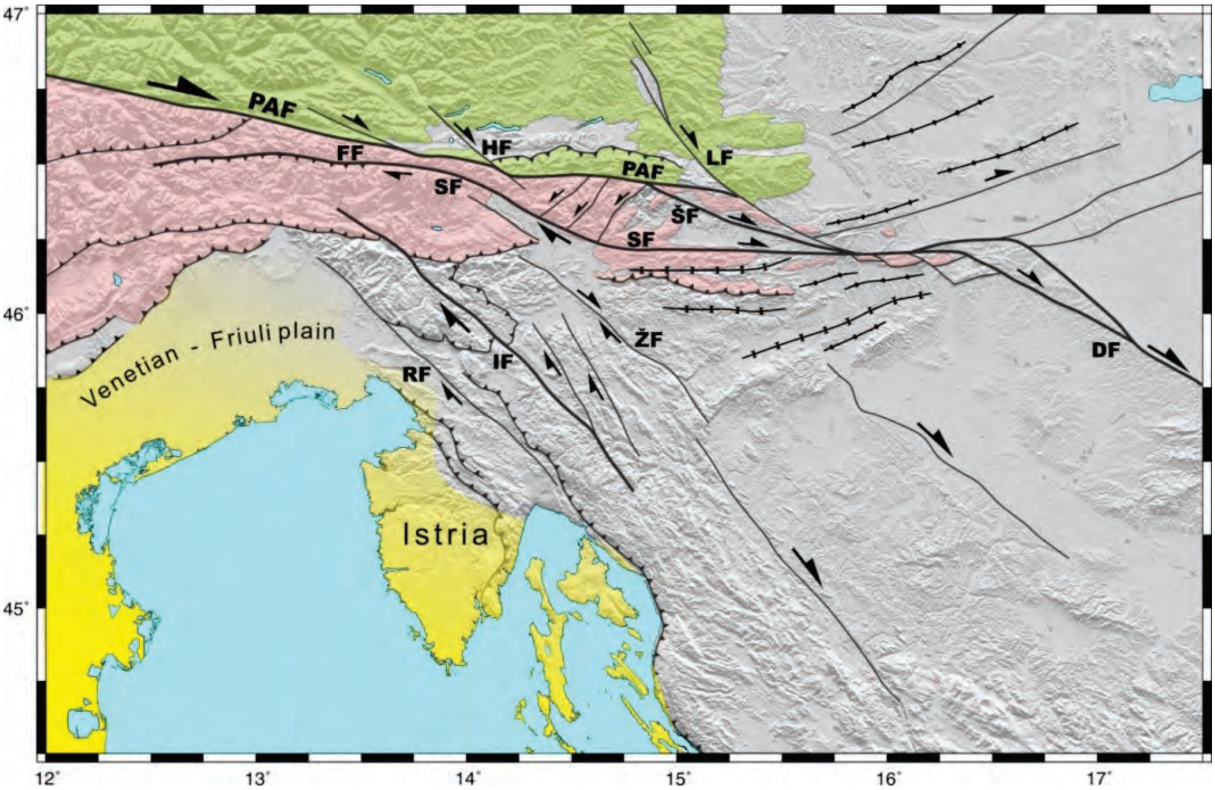


Figure 11: Spectacular topographic expression of the Sava fault in northwestern Slovenia. View is towards the east from the exit of the upper Sava river valley towards the Ljubljana basin. In front of the image the linear Završnica valley and its parallel ridge run along the Sava fault. Further towards the southeast, a prominent break in hillslope and faceted mountain faces, both indicating the location of the fault, are clearly visible. Image source: Google Earth.

Stop 4 – Mt Kobla, trail from Vrh Bače: key-area for understanding geology of the eastern Southern Alps (guided by Boštjan Rožič)

Mt Kobla (southern Julian Alps, NW Slovenia, Fig. 12) is a key-area for understanding the paleogeography, as well as the structure of the Julian Alps. These form the eastern continuation of the Southern Alps and are characterized by south-vergent thrusting (PLACER, 2008). Julian Alps are composed almost exclusively of Mesozoic sedimentary rocks, deposited on the southern passive continental margin of the Neotethys and the Alpine Tethys Oceans. On a smaller scale, two major paleogeographic units are recognized: Slovenian Basin (SB) that exhibits continuous Middle Triassic – Cretaceous pelagic sedimentation, and the Julian Carbonate Platform (JCP), that is characterized by Triassic to Early Jurassic shallow-water carbonates and occasional small-scale intraplatform basins (BUSER, 1996). In the Early Jurassic this unit was dissected into blocks with different subsidence rates. During the Middle Jurassic, major part of the subsiding platform turned into submarine plateau known as a Julian High, whereas some parts subsided more drastically and become deep-water basins known as Bovec Through and Bled Basin (ŠMUC & GORIČAN, 2005, KUKOČ et al., 2012). Until the end of the Jurassic the entire area became leveled with the SB. JCP Successions cover major part of the Julian Alps and structurally form the Julian Nappe and a Slatna Klippe, whereas the successions of the SB outcrop in the southern foothills of Julian Alps and compose the structurally lower Tolmin Nappe. The latter is further divided in three lower-order thrust units: basal Podmelec Nappe, intermediate Rut Nappe and the highest Kobla Nappe (BUSER, 1986).

Figure 12: Geographic location of Stop 4 (beginning and end of the trail). For the trail course, see Fig. 13.

Julian Alps are predominantly composed of Late Triassic Dachstein Limestone that is more than 1200 meters thick, whereas younger beds occur only sporadically (Buser, 1986). Unique area that exhibits continuous Late Triassic to earliest Cretaceous succession is the Mt Kobla (Figs. 13 and 14): southern slopes are composed of SB succession, whereas on the northern slopes the chronostratigraphic equivalents of the JCP outcrop. In the Mt Kobla the tectonic contact between the units is exceptionally not a thrust but a N-ward dipping steep fault that presumably postdates the main Miocene thrusting. Additionally, a small Krevl tectonic block is nestled between the major units and is composed of SB-JCP transitional zone (TZ) successions (Rožič & Šmuc, 2009).

Climbing the Mt Kobla from northern or southern side thus represents a walk through Late Triassic to earliest Cretaceous sedimentary history of the two main paleogeographic units of present-day Julian Alps.

Norian-Rhaetian: JCP is characterized by Dachstein Reef Limestone (Turnšek & Buser, 1991) that passes to loferitic facies towards inner platform (Fig. 15a). SB succession is characterized by Norian Bača dolomite; a bedded dolomite with chert nodules. Two intervals of dolomitic breccias occur in the lower part of the formation and indicate Norian tectonic events (Gale, 2010). It is overlain by late Norian-Rhaetian Slatnik Formation composed of bedded hemipelagic limestone with chert nodules and calciturbidites that become more abundant towards the top of the formation and record platform progradation (Fig. 15b). Triassic/Jurassic boundary is marked by several meters thick interval composed almost exclusively of thin-bedded hemipelagic limestones (Rožič et al., 2009; Gale et al., 2012).

Hettangian –Pliensbachian: After demise of reefs, the Jurassic JCP succession starts with ooidal/peloidal limestone (Fig. 15c). In the Pliensbachian it is replaced by crinoidal limestone, limestone breccias and bioclastic limestone with abundant juvenile ammonites, sponge spicules and crinoids (Rožič & Šmuc, 2009). Neptunian dykes with crinoids and reddish matrix cut all lithologies (Fig. 15e). Equal facies association starts the succession of the TZ. Similar turnover is directly reflected in SB, where this period is marked by Krikov Formation that is dominated by calciturbidites composed firstly of ooids and peloids (Fig. 15d) and later of crinoids and lithoclasts (Fig. 15f) (Rožič, 2009, Goričan et al., 2012a). Neptunian dykes, limestone breccia and abundant lithoclasts in calciturbidites indicate that initial drowning of the platform is a result of accelerated subsidence and tectonical disintegration of the platform margin.

Toarcian: Very thin layer of marls that are presumably of Toarcian age mark the JCP and TZ as well as SB successions (Fig. 15f,g). Basin-ward the equal succession thickens to 130 meters (Rožič, 2009, Rožič & Šmuc, 2011). Marls are known here as the Perbla Formation, reflecting Toarcian Oceanic Anoxic Event.

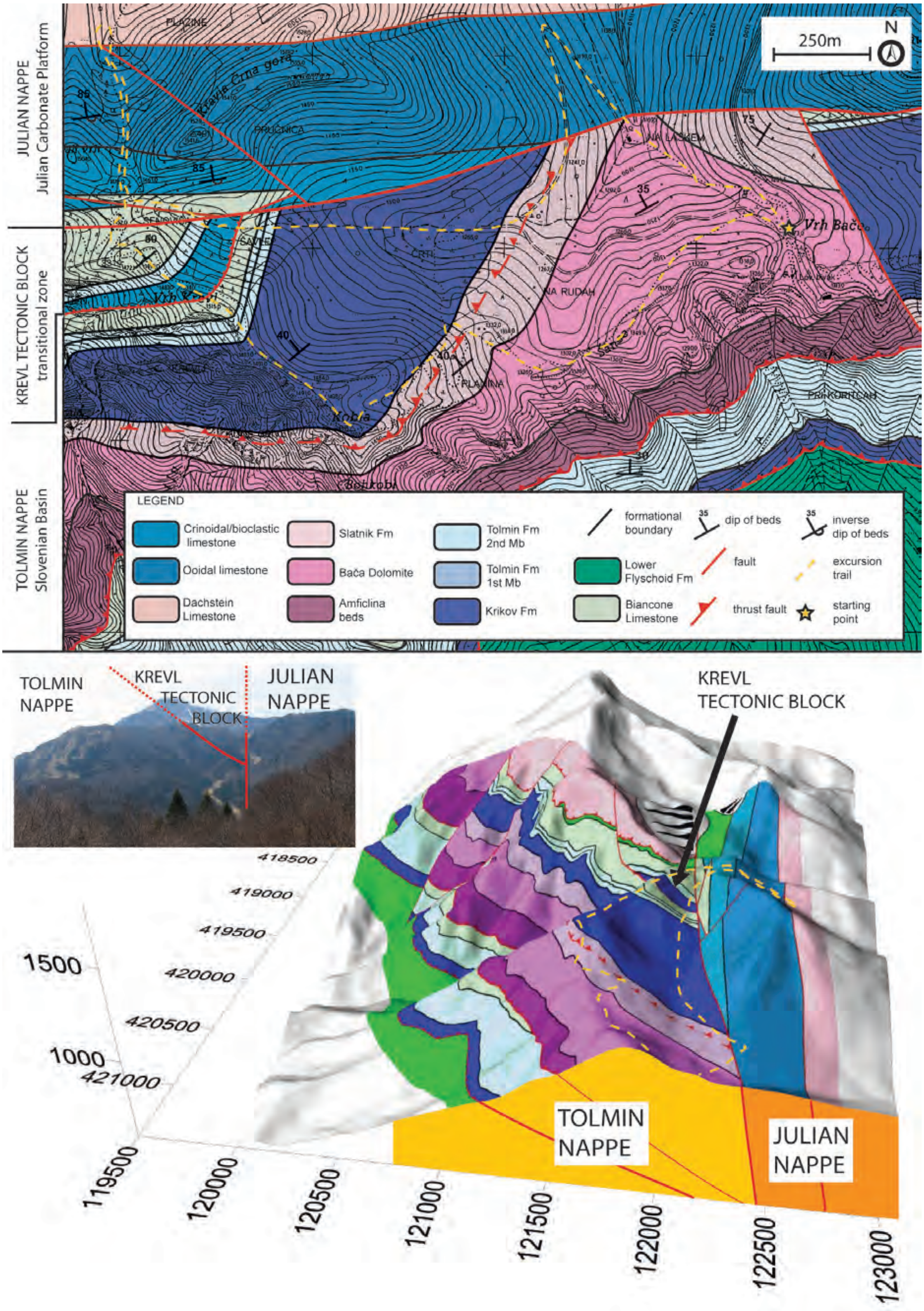


Figure 13: Geological map and 3D model (view from E to W) of Mt Kobla area with excursion trail. Photograph: Kobla area with main tectonic units as viewed from east-located Mt. Slatnik.

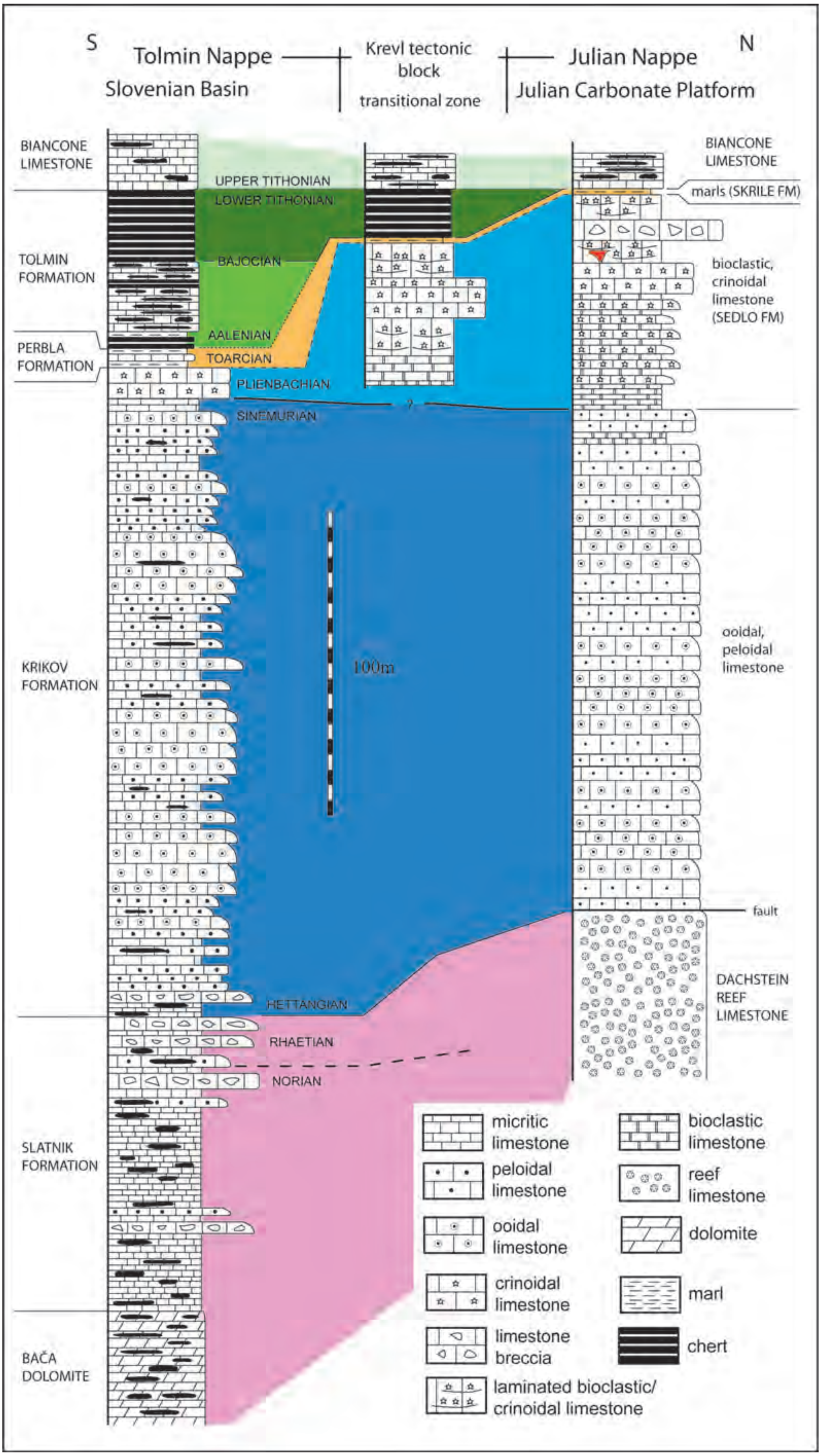


Figure 14: Schematic stratigraphic columns of the three tectonic units of the Mt Kobla Area.

Aalenian: There is no sedimentary record on the JCP and TZ and consequently it is not known if this unit was subaerially exposed or subjected to submarine erosion or at least non-deposition. In the SB the marls are gradually replaced by hemipelagic siliceous limestones (ROŽIČ, 2009).

Bajocian-Lower Tithonian: These are still no sediments on a JCP on Mt Kobla, but condensed Ammonitico Rosso-type limestone is known from the central part of the drowned platform (ŠMUC, 2005, ŠMUC & ROŽIČ, 2010). Simultaneously, the SB succession turns into pure siliceous pelagic sedimentation (ROŽIČ, 2009; GORIČAN et al., 2012b) (Fig. 15h) that is deposited also on the TZ that obviously subsided to basinal depths. Manganese nodules are known at the base of siliceous depostis on the TZ. A facies change in all units is simultaneous and is related to regional subsidence. The entire Aalenian to Lower Tithonian succession of the SB was defined as Tolmin Formation (ROŽIČ, 2009).

Upper Tithonian-Berriasian: SB, TZ and JCP successions are characterized by Biancone-type limestone; i.e. limestone with calpionellids (Fig. 15g, h), which indicates that entire region at the end of the Jurassic became paleotopographically leveled (ŠMUC, 2005, ROŽIČ, 2009, KUKOČ et al., 2012).

Figure 15 (next page)**:** Lithologies and microfacies of discussed formations. (a) Dachstein reef limestone (Norian-Rhaetian): colonial corals. (b) Slatnik Formation (Late Norian-Rhaetian): hemipelagic limestone with irregular chert nodules. Micrograph: reef-dwelling foraminifera *Kaeveria fluegeli* in a calciturbidite. (c) Ooidal/peloidal limestone (Hettangian-Pliensbachian): steep (inverse) bedding on the Mt Kobla skiing ground. Micrograph: peloidal grainstone with rare ooids. (d) Krikov Formation (Hettangian-Pliensbachian): thick calciturbidic beds in western cliffs of Mt Kobla. Micrograph: large, compacted ooids in a calciturbidite. (e) Redish neptunian dykes in a pliensbachian crinoidal limestone. Micrograph: bioclastic wackestone with ammonite(f) Sharp contact between Krikov Formation and Toarcian Perbla Formation characterized by marls. Micrograph: crinoidal grainstone in topmost calciturbidites of Krikov Formation. (g) Thin ?Toarcian marl between Pliensbachian bioclastic limestone (left) and Lower Tithonian-Berriasian Biancone Limestone (right). Micrograph: mudstone with calpionellids from Biancone Limestone. (h) Sharp contact between radiolarinan cherts of the Tolmin Formation (upper member; Middle Bajocian-Lower Tithonian) and Biancone Limestone.

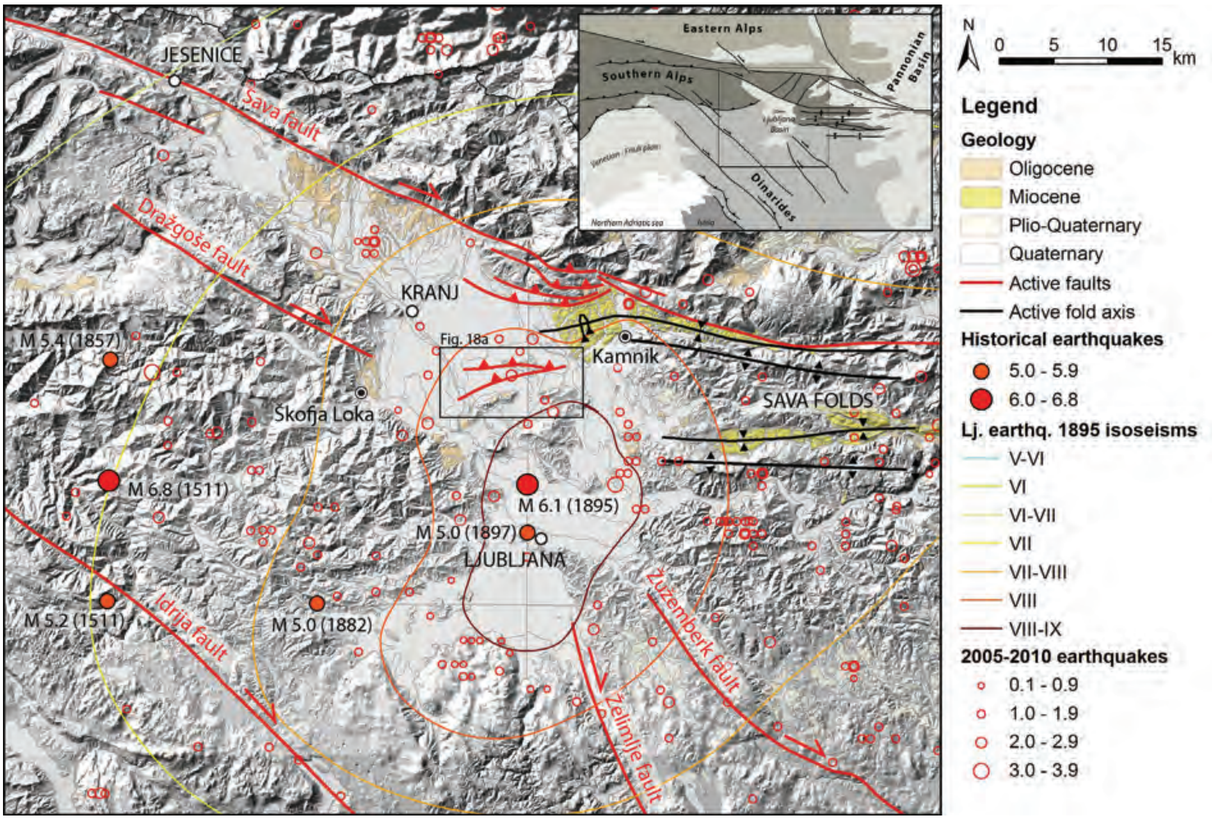

Julian Carbonate Platform
Slovenian Basin
a
b
1mm
c
1mm
d
1mm
e
1mm
f
1mm
g
0,5mm
h

Stop 5 – Hraše: Vodice fault (guided by Petra Jamšek Rupnik)

The Vodice fault is located in the Ljubljana Basin (Fig. 16) at the contact between the Southern Alps and the Dinarides (Fig. 17). The basin is bounded by two NW-SE-striking dextral faults, the Sava fault to the north and the Žužemberk fault to the south, interpreted as master faults that control the subsidence of Ljubljana basin in a releasing overstep between them (VRABEC & FODOR, 2006). Smaller ~E-W oriented reverse faults that displace Quaternary sediments in the basin (VERBIČ, 2006) may indicate a recent change in the deformational regime from transtensional subsidence to transpression. Geological and geomorphological observations, earthquake focal mechanisms, and geodetic measurements suggest that the NW-SE-striking dextral faults and ~E-W-striking reverse faults may be active in the current regional stress regime with ~N-S oriented axis of maximum horizontal compression (POLJAK et al., 2000; VRABEC & FODOR, 2006; VERBIČ, 2006; BAVEC et al, 2012; JAMŠEK RUPNIK et al., 2012).

Figure 16: Geographical location of Stop 5.

Figure 17: Seismotectonic map of the Ljubljana Basin showing main active structures, Oligocene to Quaternary geological units (BUSER, 2009), historical earthquake epicenters with magnitude above 5.0 (ŽIVČIĆ, 2009), isoseisms of the Ljubljana 1895 M=6.1 earthquake (LAPAJNE, 1989) and instrumental seismicity 2005-2010 (, 2006-2011). Inset figure: simplified tectonic map of the Alps-Dinarides junction (VRABEC & FODOR, 2006) showing the location of Fig. 17.



The Ljubljana Basin is the most densely populated and a highly urbanized region of Slovenia, experiencing continuous seismic activity with earthquake magnitudes frequently reaching 3-4 (Živčić, 2009). The largest recorded event in the basin was the destructive 1895 Ljubljana earthquake with macroseismic magnitude 6.1 (Ribarič, 1982) and maximum intensities of VIII-IX EMS-98 (Cecić, 1998). The fault responsible for this earthquake is still unknown. The seismic hazard is further increased by the unconsolidated Quaternary sedimentary infill of the basin, reaching up to 280 m of thickness, which may significantly enhance site effects during earthquakes (Gosar et al., 2010).

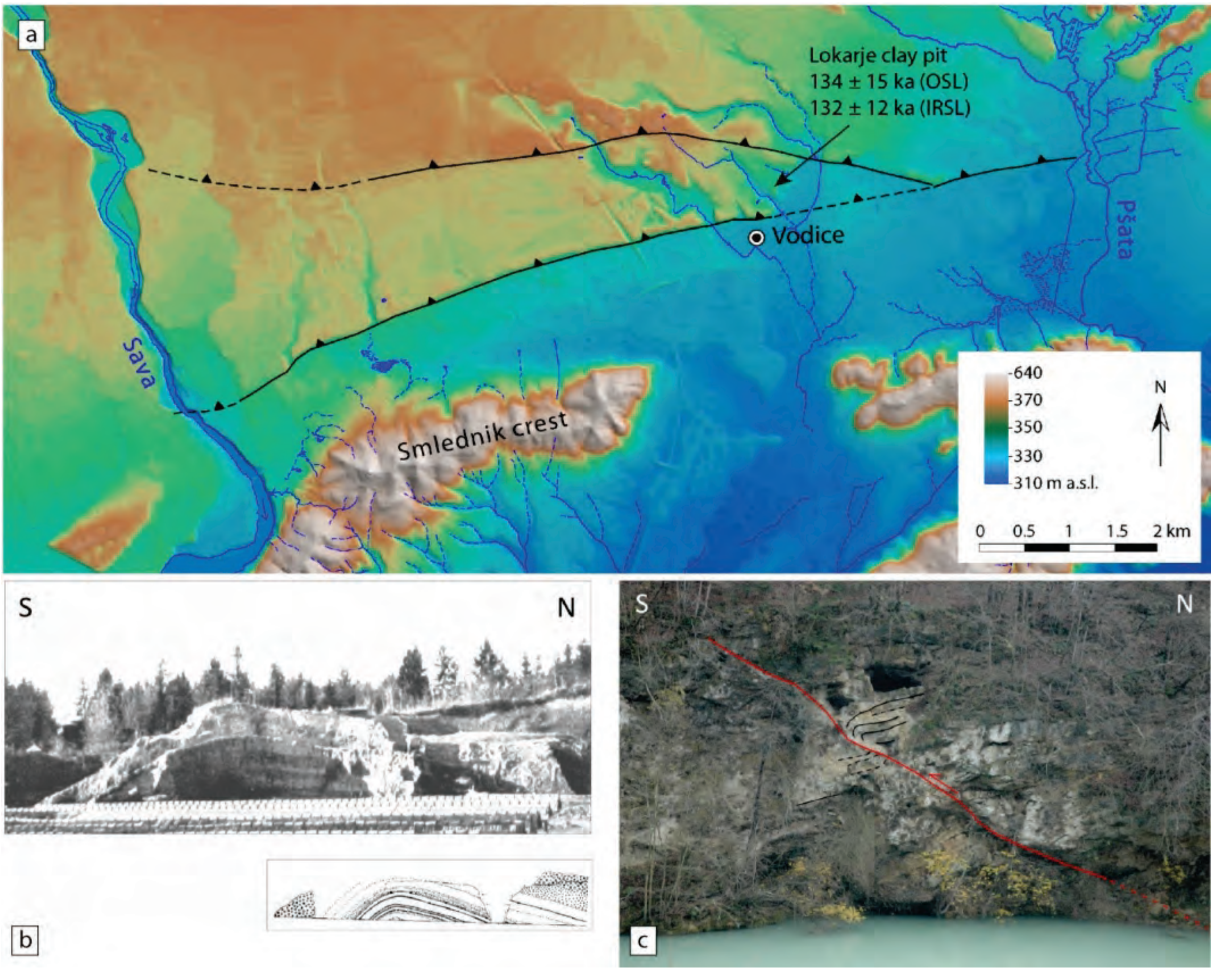


Figure 18: (a) The Vodice fault scarps as seen on the DEM 5 m (Public Information of Slovenia, the Surveying and Mapping Authority of the Republic of Slovenia, DEM 5, 2006). (b) Asymmetric anticline in Quaternary sediments in the now abandoned Lokarje clay pit (Šifrer, 1961). (c) fault plane of the southern Vodice fault and associated fault drag folds exposed on the Sava River bank.

The Vodice fault presents one of the active and possible seismogenic reverse faults in the Ljubljana Basin (Jamšek Rupnik et al., 2013a). In the area of Vodice, 15 km north of Ljubljana, two prominent fault scarps are clearly visible (Fig. 18a). Oriented in WSW-ENE direction, perpendicular to the general trend of fluvial terrace risers in the area, they displace Quaternary alluvial surface along a length of 10-11 km for 5-25 m, and 3-18 m, respectively. Both scarps are the highest in the central part with heights decreasing towards their eastern and western tips. At the top of both scarps, the alluvial surface that was originally sloping southwards is today sub-horizontal or even dipping gently to the north. The top of alluvial surface is strongly incised by recent rivers and creeks. Several dry valleys and perched valleys are observed near the scarps. Folding of Quaternary sediments was reported in the now abandoned Lokarje clay pit (Šifrer, 1961) located in between the two scarps, where an asymmetric anticline was exposed, with the southern limb dipping 40° towards SSE, the northern limb dipping around 10° towards NNW and with the ENE-WSW oriented anticline axis parallel to the strike of the scarps (Fig. 18b). Westward, where the fault cuts the N-S running Sava River, Quaternary conglomerates are also folded and offset, with a fault plane dipping 35° to the north (Fig. 18c). Drag folds in conglomerate layers indicate reverse offset along this fault plane. All geomorphic and structural observations suggest that the scarps are the surface expression of an active emergent reverse fault, which was recently confirmed also by geophysical investigations and paleoseismological trenching (BAVEC et al., 2012; ATANACKOV, 2013).

Dating using Optically Stimulated Luminescence (OSL) of quartz and Infrared Stimulated Luminescence (IRSL) of K-feldspar yielded an OSL age of 134 ± 15 ka and an IRSL age of 132 ± 12 ka for the upper alluvial surface (JAMŠEK RUPNIK et al., 2013b). By using this age, and taking into account the height of the southern scarp and the observed dip of 35°N of the fault plane, we estimate Late Quaternary slip-rate of the Vodice fault at 0.1 to 0.3 mm a^{-1} over the last 133 ka. According to empirical scaling relationships (WELLS & COPPERSMITH, 1994), 10 km long Vodice fault could trigger an earthquake of M 5.9 to 6.5 with a coseismic displacement of 0.1 to 0.9 m. In the case of constant slip-rate the recurrence time of such earthquakes could be from 300 to 9,000 a.

Day 3

Upper Oligocene Smrekovec Volcanic Complex, Periadriatic Lineament (Fig. 19) (guided by Polona Kralj)

Stop 6 – Krnes : Lithofacies architecture of volcaniclastic deposits in the Upper Oligocene Smrekovec Volcanic Complex – The secton Krnes 1

Introduction

The Upper Oligocene (28-22 Ma; HANFLAND et al., 2004) Smrekovec Volcanic Complex (SVC) occurs in a sequence of Tertiary marine silts deposited in the Smrekovec Basin (MIOČ, 1983), one of several small and marginal sub-basins in the south-west of the Pannonian back-arc realm (ROYDEN, 1988).

Figure 19: Geographic location of Stops 6, 7 and 8.

Volcanic activity that created the Smrekovec Volcanic Complex (SVC) is considered to be post-collisional and related to slab breakoff processes (VON BLANCKENBURG & DAVIS, 1995). It occurred in the initial stage of extensional evolution of the Pannonian Basin, particularly during the activation of the Periadriatic Line. Magmas erupted in the SVC show calc-alkaline and medium-K affinity, and produced a suite ranging in composition from basaltic andesite to dacite (KRALJ, 1996; ALTHERR et al., 1995).

The SVC forms a part of a wider, approximately 70 km long belt of Upper Oligocene and Lower Miocene (Lower Egerian) volcanic deposits (Fig. 20) that outcrop south of the Smrekovec Fault and the Šoštanj Fault. This belt is locally termed the Smrekovec Series and mainly consists of volcaniclastic deposits (MIOČ, 1983).

The SVC is the lower (Upper Oligocene) unit of the Smrekovec Series, and belongs to the remains of a former submarine stratovolcano edifice. Today, the SVC extends in an area of about 200 km^2 and its maximum thickness ranges from about 800 m to 1100 m (MIOČ, 1983). Lavas and shallow intrusive bodies are subordinate in occurrence and mainly outcrop along the mountain range encompassing Mt. Komen, Mt. Krnes, Veliki Travnik and Mt. Smrekovec. The most widespread are volcaniclastic deposits, and they show a diverse and complex development. Lithofacies classification and initiation processes are shown in Table 1. The complexity of lithofacies architecture is shown in a simplified section Krnes 1, sub-section Vodnik (Fig. 21).

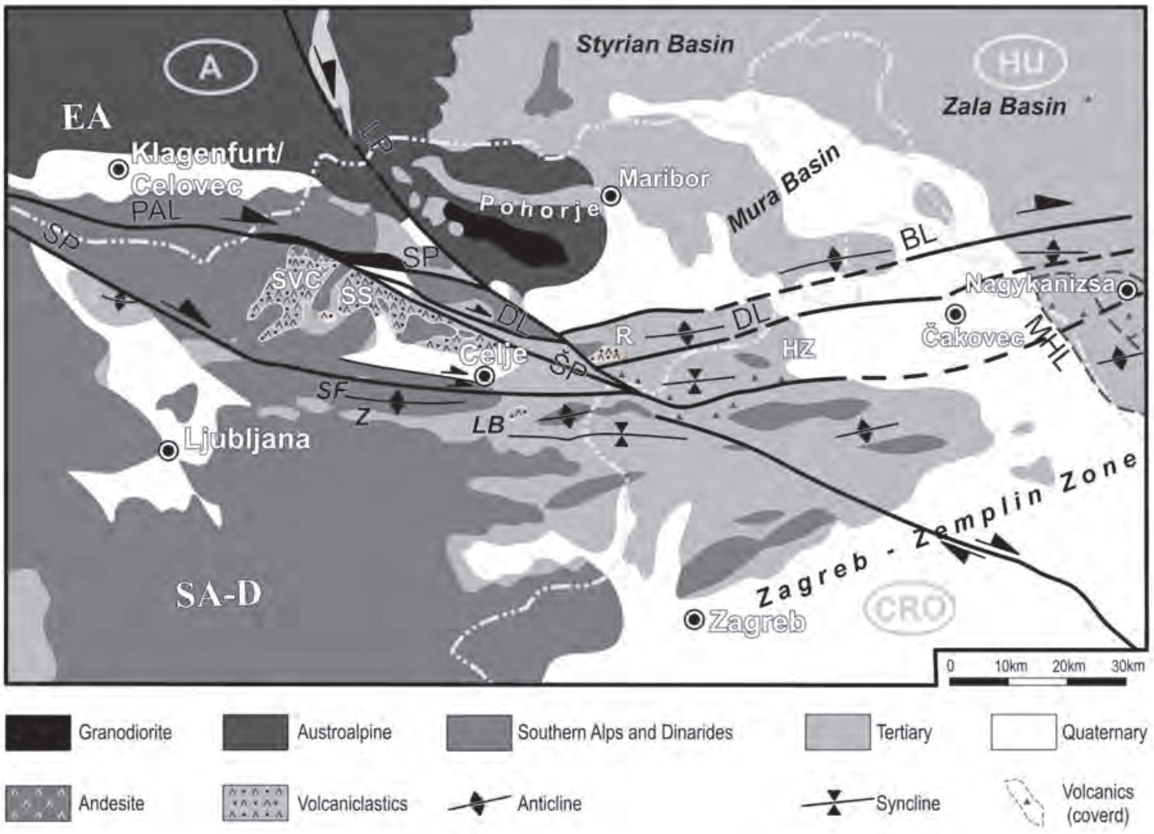


Figure 20: Simplified geological map of north Slovenia (after MIOČ, 1978; FODOR et al., 1998; JELEN & RIFELJ, 2002). EA—Eastern Alps; SA-D—Southern Alps and Dinarides; PAL—Periadriatic Line; BL — Balaton Line; MHL — Mid-Hungarian Line; DL — Donat Line; LP — Lavanttal Fault; SF — Sava Fault; SP — Smrekovec Fault; ŠP — Šoštanj Fault; SVC — Smrekovec Volcanic Complex; SS — Smrekovec Series; LB — Trobni Dol; Z — Zasavje; R — Rogaška Slatina; HZ — Hrvatsko Zagorje (Croatian Zagorje).

Lithofacies Group	Lithofacies	Thickness	Initiation process
Autoclastic deposits (A)	Autobreccia (AB)	1-5 m	*Quench fragmentation*
	Hyaloclastite breccia (HB)	1-5 m	*Quench fragmentation*
	Hyaloclastite (mH)	several dm - 3 m	*Quench fragmentation, phreatic explosions*
	Peperite (P)	0.5-3 m	*Quench fragmentation and mixing and mingling with the enclosing wet sediment*
	Blocky peperite (PB)	< 1 mm - 1m	
	Fluidal peperite (P)		*Mixing and mingling of lava or magma and the enclosing wet sediment*
Resedimented hyaloclastite deposits (Hr)	Horizontally bedded lapilli-sized hyaloclastite(sHL)	1-10 cm	*Resedimentation of mH by grain flows and small debris flows*
	Horizontally bedded ash-sized hyaloclastite (sHT)	thick lamination-thin bedding	
	Crudely bedded hyaloclastite [s(c)HT]	thick lamination-thin bedding, bed-sets up to 12 cm	
	Massive resedimented hyaloclastite [s(m) HT]	5–15 cm	
	Chaotic hyaloclastite [s(x)HT]	1-5 dm	
Pyroclastic deposits (Py)	Massive pumice lapilli tuff [mLT(p)]	several dm–several m	*Gas- and water-supported eruption-fed density flows*
	Massive coarse- to fine-grained tuff [mT(p)]	3-20 cm	
	Massive to diffusely bedded tuff [dT(p)]	2-5 m	
	Horizontally bedded tuff [sT(p)]	very thin to medium-thick beds	
	Horizontally laminated fine-grained tuff [sF(p)]	laminae, in 1-20 cm thick unit	
	Cross-laminated fine-grained tuff [xF(p)]	laminae, in 1-5 dm thick unit	
	Subtly lenticular fine-grained tuff [cF(p)]	laminae, in 1-5 dm thick unit	
	Wavy laminated fine-grained tuff [vF(p)]	laminae, in several cm thick unit	
Volcaniclastic debris	Polymict volcaniclastic	2-15 m	*Debris flows*

flow deposits (Vd)	breccia (Bx) Massive coarse-grained tuff (Sx)	0.3-5 m	*Sandy debris flows*
Volcaniclastic turbidite deposits (Vt)	Volcaniclastic tuff-breccia (Bt) Massive lapilli tuff [mLT(v)] Horizontally bedded coarse-grained tuff [hsT(v)] Horizontally bedded fine-grained tuff [hlF(v)] Vaguely laminated fine-grained tuff [vlF(v)] Cross-bedded coarse- to fine-grained tuff [xF(v)] Massive fine-grained tuff [mF(v)]	0.1-3 m several cm – 0.5 m thin to medium thick beds laminae, in 1-20 cm thick unit laminae, in several cm thick unit laminae, in 5-15 cm thick unit 1-25 cm	*Low-density turbidity currents and settling from suspension clouds*
Mixed volcaniclastic-siliciclastic deposits (M)	Massive tuffaceous sandstone [mS(v)] Horizontally laminated tuffaceous sandstone [hS(v)] Cross-bedded tuffaceous sandstone [tS(v)] Massive tuffaceous mudstone [mM(v)]	several mm – several cm laminae several mm – several cm several mm – several cm	*Settling from suspension clouds, reworking by oceanic bottom currents*

Table 1: Synopsis of the characteristics for the SVC volcaniclastic deposits (from KRALJ, 2012).

Lithofacies encountered in the section Krnes-1 (Fig. 21)

Autoclastic deposits (A): autobreccia (AB) and fluidal peperite (P): Lithofacies AB consists of blocky, angular, subangular or subrounded, essentially non-vesicular clasts attaining 1-50 cm in size. Fluidal peperite occurs at the bottom division of autobrecciated lava flows along the contacts with the underlying fine-grained sediment. Peperite forms globular or semi-globular granules or pillows, attaining < 1mm to 1m in diameter.

Pyroclastic deposit units (PDUs): Two varieties of pyroclastic deposit units, Type 1 PDU and Type 2 PDU, have been distinguished on the basis of lithofacies architecture.Type 1 PDU is more common in occurrence, and the architecture resembles that of volcaniclastic turbidite deposits. The thickest units attain up to 5 m. Lithofacies $mL_1T(p)$ occurs at the base, and is overlain by the intermediate, horizontally bedded division, composed of lithofacies sT(p), which becomes upward more thinly bedded and finer-grained. Some coarser lithofacies sT(p) occurring at the base of thicker bedded divisions are amalgamated. Thicker Type 1 PDUs are commonly topped by [sF(p)] or [vF(p)] and [sF(p)]. In thicker units, massive division predominates and forms from 60-80 % of the bulk pyroclastic depositional unit.

The Type 2 PDU is less abundant in occurrence. Thicker units attain several metres and are composed of lithofacies $mL_2T(p)$ at the base. Transition into the overlying lithofacies dT(p) is indistinct and gradual. Lithofacies dT(p) may show indistinct grading from somewhat coarser ash-sized tuff at the base and somewhat finer ash-sized tuff at the top. Lithofacies dT(p) is overlain by sF(p), and there is a sharp distinction in the degree of lithification, colour and internal structure. Whilst $mL_2T(p)$ and dT(p) are very well lithified and dark-green, the overlying sF(p) is much softer and brownish, and columnar jointing never continues from $mL_2T(p)$ and dT(p) to sF(p). The Type 2 PDU has been interpreted to be settled from hot, gas-supported pyroclastic flows, with internal organization that resembles thin and mainly non-welded ignimbrite facies (MANDEVILLE et al., 1996; WHITE, 2000).

Volcaniclastic debris flow deposits (Vd): In the section Krnes-1, volcaniclastic debris flow deposits occur as lithofacies Bx (volcaniclastic breccia). It is massive, ungraded and extremely poorly sorted. The lower boundary is erosive. The formation of Bx is possibly related to a laminar, volacniclastic debris flow.

Volcaniclastic turbidites (Vt) and internal organisation of a turbidite sedimentation unit (TSU): An ideal turbidite sedimentation unit (TSU) is typically 1-5 m thick and consists of lithofacies Bt or mLT(v) at the base, hsT(v), or interlayered hsT(v) and hlF(v) in the intermediate division, hlF(v), xT(v), and more rarely, vlF(v) in the upper division, and mF(v) at the top, and is the deposit of a single flow event.

Lithofacies thickness obtained by field measurements of several TSUs was calculated as lithofacies abundance in a single TSU, and is given as percents by volume (%) of the bulk lithofacies. Based on the calculated lithofacies abundance, three TSU subgroups, Type 1, Type 2 and Type 3, respectively, have been recognised. In Type 1 TSU, the lower, intermediate and upper divisions amount to 50-75 %, 20-35 % and 5-15 % of the bulk lithofacies, respectively. The lower division consists of Bt and mLT(v) is absent. The intermediate division consists of hsT(v) which may show bed amalgamation. In the upper division hlF(v) is common, mF(v) may occur but is thin and attains less than one centimetre. Type 1 TSU ranges in thickness from about 2-5 m.

In Type 2 TSU, the lower, intermediate and upper divisions amount to 30-50 %, 35-45 % and 15-25 % of the bulk lithofacies, respectively. In the lower division Bt very seldom occurs; far more abundant is mLT(v). The intermediate division shows general upward grain-size fining and bed-thinning. Amalgamation is common in the lower- and middle portion of the bedded division, and it gradually changes into distinct bedding of hsT(v) and interlayering of hsT(v) and hlF(v). The upper division consists of hlF(v) and sometimes xT(v), and the upperost positioned mF(v). Type 2 TSU ranges in thickness from about 0.7-3.5 m.

In Type 3 TSU, the lower, intermediate and upper division amount to 0-30 %, 50-60 %, and 20-40 % of the bulk lithofacies, respectively. The lower division, if present, consists of lithofacies mLT(v). The intermediate division is well developed and shows general upward grain-size fining and bed-thinning, and bed amalgamation is rather uncommon. The upper division consists of low- and high-angle cross-laminated and thinly bedded tuffs, vaguely laminated tuffs, horizontally laminated tuffs and massive fine-grained tuffs. Type 3 TSU ranges in thickness from about 0.1-1.5 m.

Sedimentation units recognised in the sequence of volcaniclastic turbidites in the Smrekovec Volcanic Complex can be compared with turbidites emplaced from low-density currents (LOWE, 1982; MCPHIE et al., 1993). The Bouma a, b, c, d and e divisions (BOUMA, 1962) correspond to Bt and/or mLT(v), hsT(v), xF(v) and/or vlF(v), hlF(v), and mF(v), respectively. The change of TSUs from the Type 1 to Type 2, and from Type 2 to Type 3 can be related to the evolution of turbidity currents along the flow length, from the initiation of deposition to the final settling.

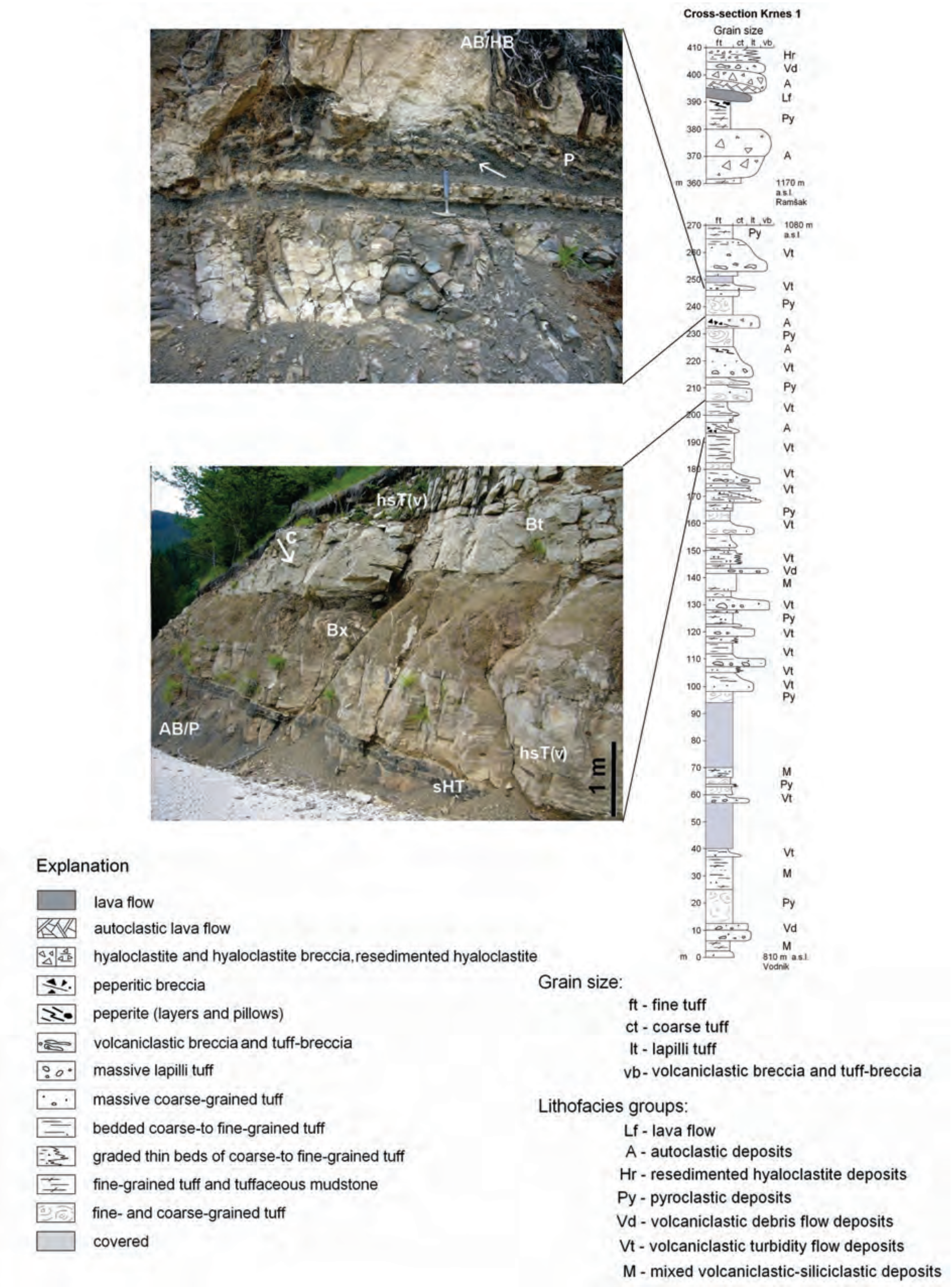


Figure 21: Cross-section Krnes 1 with the sub-sections Vodnik and Ramšak (from KRALJ, 2012). Upper photography: autoclastic breccia and hyaloclastite breccia (AB/HB) with a peperite layer (P) at the base. Hammer (33 cm) is for scale. The position is in the sub-section Vodnik at 237–247 m. Lower photography: a succession of volcaniclastic debris flow (Bx) and turbidite deposits showing a Type 2 TSU with the massive (Bt) and bedded [hsT(v)] divisions. Note large intraclasts (c) of fine-grained tuff in Bt. The position is in the sub-section Vodnik, at 193–205.

Periadriatic Line (guided by Marko Vrabec)

Stop 7 – Bistra valley: outcrop of Oligocene tonalite (Fig. 19)
Stop 8 – Quarry on the northern slope of Smrekovec: brittle Periadriatic fault (Fig. 19)

Introduction

The Periadriatic fault system (PFS) is a major Oligocene-Miocene tectonic feature of the Alps. The main segments along its strike of more than 700 km are the Canavese line, the Insubric/Tonale fault, the Giudicarie fault system, and the Pustertal-Gailtail fault (Fig. 22). The fault kinematics is both dip-slip north-side-up (particularly in the Central Alps, where the faults accomodated northward underthrusting of the South Alpine units) and dextral strike-slip, which mainly overprints earlier dip-slip movement (e.g. SCHMID et al., 1989). In the Eastern Alps, the Tertiary collisional shortening was to a large degree facilitated by lateral extrusion of the central eastalpine domain (also known as the "ALCAPA unit", see Fig. 22) towards the east (RATSCHBACHER et al., 1991; FRISCH et al., 1998). Dextral motion on the eastern part of the PFS accomodated these large-scale orogen-parallel displacements, and the PFS is commonly regarded as the discrete southern boundary of the extruding unit.

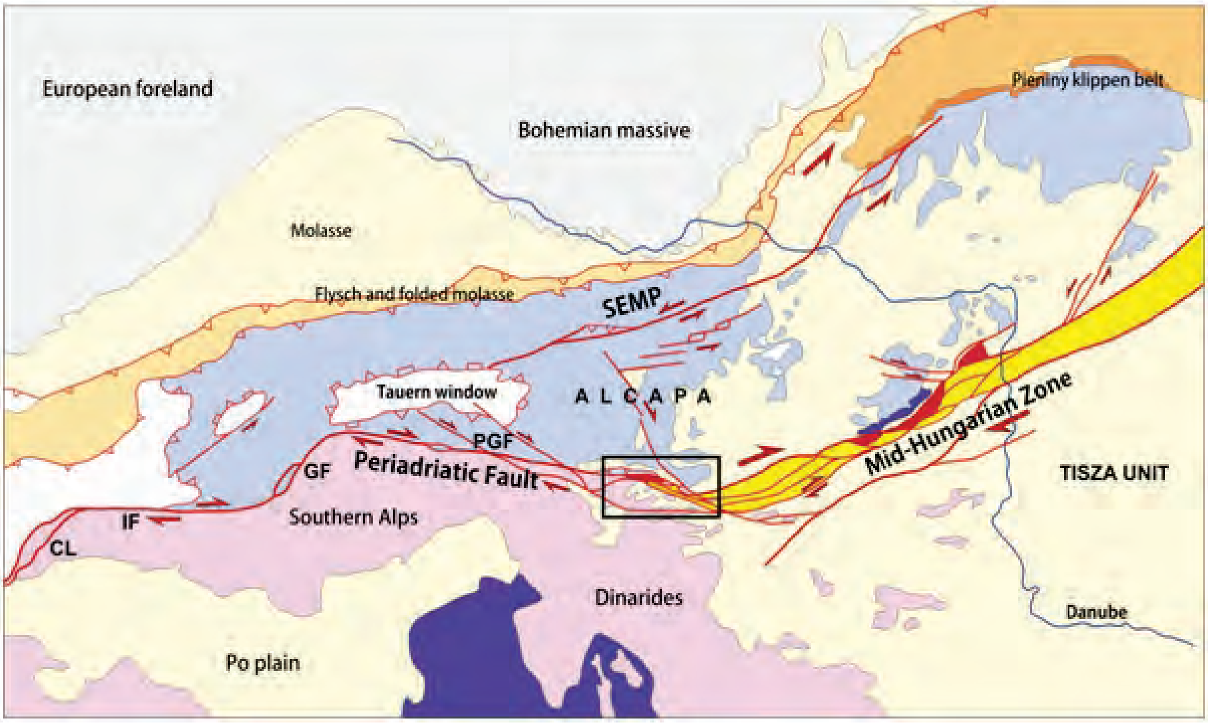


Figure 22: Simplified tectonic map of the Alps, highlighting the faults of the Periadriatic fault system and its proposed eastward continuation, the Mid-Hungarian Zone (from FODOR et al., 1998). The inset box shows the position of map presented in Fig 24. CL – Canavese line; IF – Insubric fault; GF – Giudicarie fault; PGF – Pustertal-Gailtal fault; SEMP - Salzachtal-Ennstal-Mariazell-Puchberg fault.

The magnitude of dextral slip on the eastern PFS is a matter of controversy, which is complicated by the fact that the northern side of the fault was extended both synchronously with and after the main slip episode. In the kinematic reconstruction of FRISCH et al. (1998) the amount of slip on the main Periadriatic fault (Pustertal-Gailtal segment) is estimated to ~100 km. FODOR et al. (1998) used displaced parts of the formerly united Hungarian-Slovenian Paleogene basin, occuring today in central Slovenia and in central Hungary, to argue for ~300 km of dextral separation (Fig. 23). This value, however, is to a large part produced by significant mid-Miocene extension of the area during the Pannonian basin subsidence, which postdated the main (Oligocene-Early Miocene) slip episode on the PFS.

The same paleogeographical argument was also used to propose that the PFS formerly continued into the Mid-Hungarian Zone (MHZ), which bounds the northern displaced part of the Paleogene basin, and contains isolated occurences of those Paleogene sediments inside the fault zone between the displaced parts (Fodor et al., 1998; Fig. 23).

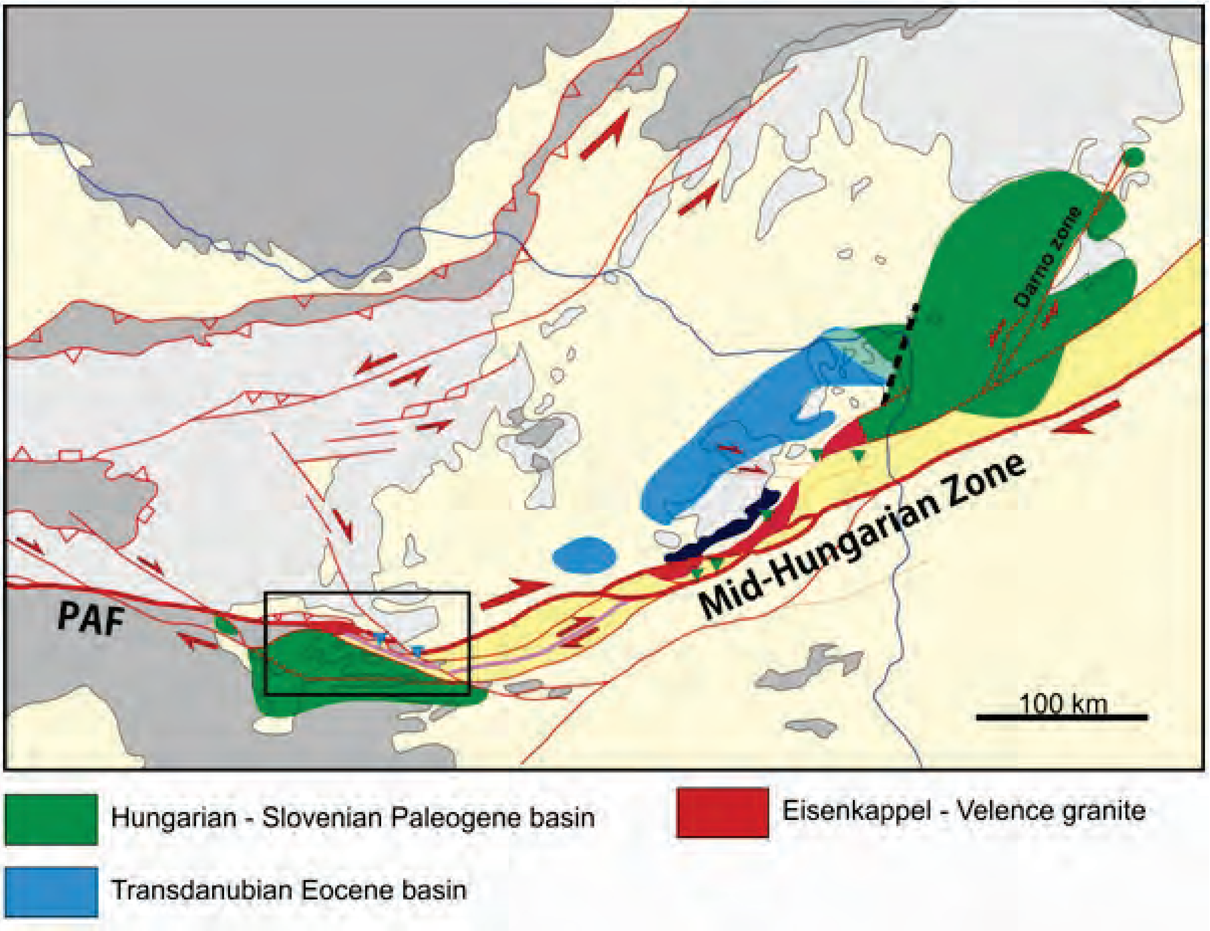


Figure 23: Present-day position of Paleogene sedimentary basins along the Periadriatic fault – Mid-Hungarian Zone corridor, implying ~300 km of dextral separation (from Fodor et al., 1998). The inset box shows the position of map presented in Fig. 24.

The easternmost outcrops of the Periadriatic fault occur in northern Slovenia, where the fault zone eventually disappears below mid-Miocene and younger sediments of the Pannonian basin (Fig. 24). The geometry of the PFS in this structurally complex region, the inferred fault kinematics, and timing of deformation as constrained by Tertiary to Quaternary sediments, provide valuable insights into Oligocene to present-day tectonic history of the eastern PFS.

The Periadriatic fault proper is a highly deformed, up to 5 km wide fault zone, consisting of lenses of various magmatic and metamorphic rocks, which are interpreted as strike-slip duplexes (Fodor et al., 1998). Their dextral separation is clearly visible in map view (Fig. 24). The synkinematic tonalite intrusion (the Karawanken pluton) of Oligocene age, which is the easternmost outcropping Periadriatic intrusive, was emplaced along the fault and was subsequently cut by late brittle faults. The narrow and subvertical magmatic body continues westward into Austria along the strike of the Periadriatic fault for about 40 km.

North of the Periadriatic fault, the Mesozoic carbonates of the Northern Karawanken are thrust northward over the Miocene sediments. This structural unit is a part of the Karawanken transpressional flower structure, which in Klagenfurt basin (Austria) overthrusts Quaternary deposits (Polinski & Eisbacher, 1992; Nemes et al., 1997), indicating that dextral wrenching along the eastern PFS persisted into Quaternary times. In fact, a regional study of active deformation in the Central European GPS network (GRENERCZY, 2002) suggests that eastward extrusion in the Eastern Alps is still active, and GPS measurments of active displacements in the Slovenian part of the PFS confirm that the Periadriatic fault is the southern boundary of the extruding unit with a slip rate of ~ 1 mm/yr (VRABEC et al., 2006).

Eastward, the Periadriatic fault is sealed by 17 Ma old syn-rift sediments of the Pannonian basin (Fig. 24), which mark the end of the main slip episode on the fault, dated to 24 – 18.5 Ma (FODOR et al., 1998; see also Fig. 25a). At that time, the amalgamation of the extruding ALCAPA unit with the Tisza block along the MHZ, and coeval rotational disintegration of the ALCAPA, documented by paleomagnetic data, prevented further dextral motion along the PFS-MHZ corridor (Fig. 25b). Throughout the mid-Miocene period, the deposition of sediments that occur today between the Labot (Lavanttal) fault and the Šoštanj fault (Fig. 24) was uninterrupted, and no evidence was found for significant mid-Miocene slip on the faults of the PFS (Fig. 25b). However, those mid-Miocene sediments are faulted and tighty folded inside the dextrally sheared zone betwen the Periadriatic fault proper and the Šoštanj fault (Fig. 24). Pliocene and Quaternary age of deformation is implied from youngest deformed sediments, occuring in the strike-slip Velenje basin along the dextral Šoštanj fault (e.g. VRABEC, 1999). This evidence is interpreted as post-12 Ma transpressional reactivation of the PFS (FODOR et al., 1998; Fig. 25c), when in northern Slovenia the dextral slip in the PFS was transferred from the immobilised Periadriatic fault proper to southward-lying segments like the Šoštanj fault (Fig. 24).

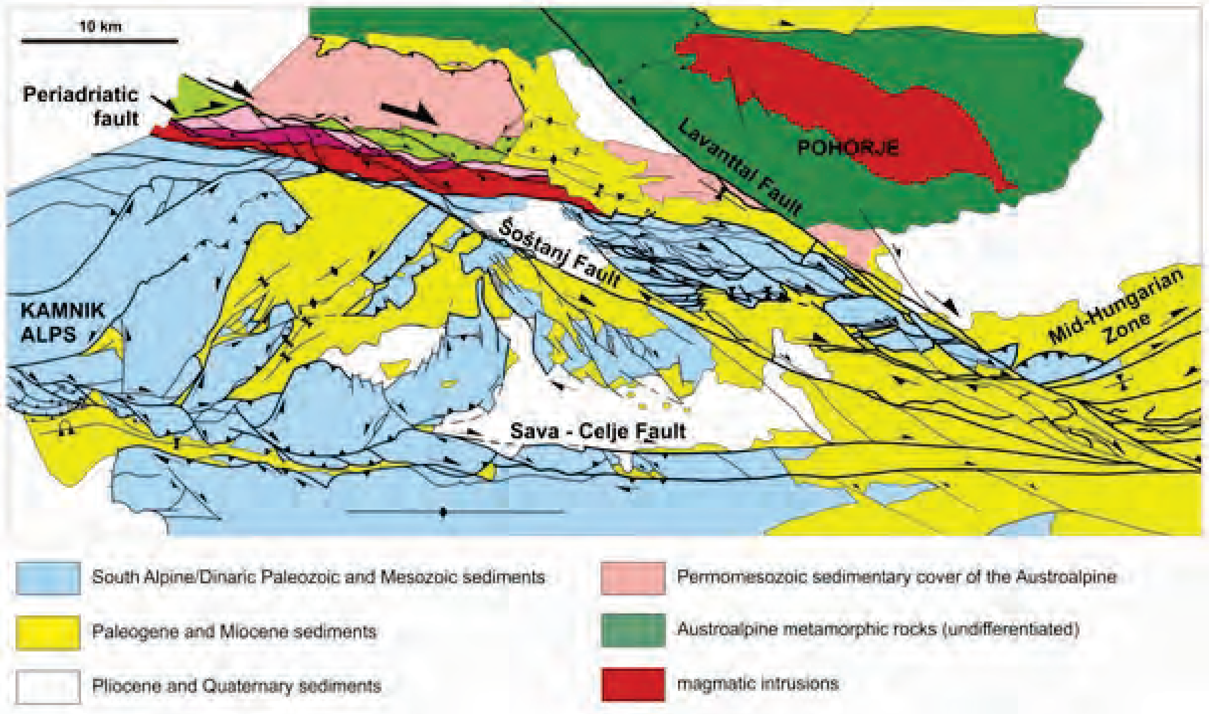


Figure 24: Tectonic map of northern Slovenia, showing the easternmost outcrop of the Periadriatic fault and associated faults of the Periadriatic fault system. From FODOR et al. (1998), based on 1: 100.000 regional geological maps (BUSER, 1978; MIOČ & ŽNIDARČIČ, 1977, 1983; PREMRU, 1983). See Fig. 22 for location.

Stop 7 – Bistra valley: outcrop of Oligocene tonalite

The tonalitic Karawanken pluton is a ~40 km long and extremely elongate intrusion, which runs parallel to the Periadriatic fault, on the northern side of the fault. Excellent outcrops of tonalite can be found in creeks and roadcuts south of the town of Črna na Koroškem. A subvertical, fault-parallel foliation is clearly expressed in the rocks. The fabric formed in the

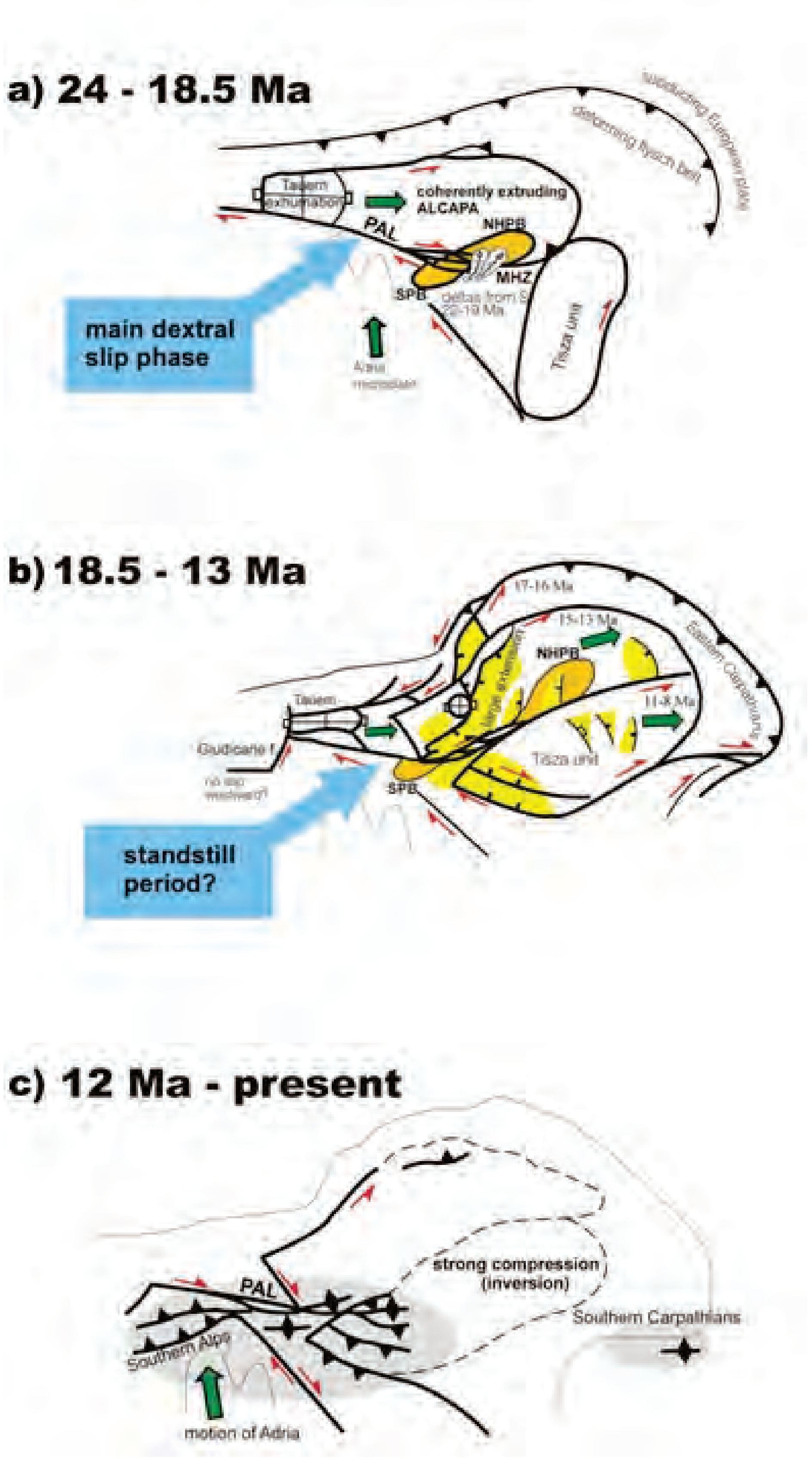


Figure 25: Summary of the evolution of the eastern Periadriatic fault system (from FODOR et al., 1998). See text for further discussion. PAL – Periadriatic line; MHZ – Mid-Hungarian Zone; SPB – Slovenian Paleogene basin; NHPB – North-Hungarian Paleogene basin.

magmatic state and was latter overprinted by greenschist facies deformation (e.g. ROSENBERG, 2004). The aspect ratio of flattened mafic enclaves suggests nearly plane-strain deformation (VON GOSEN, 1989) which is interpreted as indicative of transpressive conditions (ROSENBERG, 2004).

Stop 8 – Quarry on the northern slope of Smrekovec: brittle Periadriatic fault

The southern contact of the tonalite intrusion is a brittle fault, which is locally known as the Smrekovec fault. The fault zone is up to several 100s of m wide and may contain narrow slivers of Permian and Mesozoic carbonates (see Fig. 24). Excursion will visit a small quarry along the forest road, where the incohesive cataclastic rocks of the fault core are exposed. Slickensides on weakly preserved small secondary fault planes exhibit subhorizontal slip direction.

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