Chapter 1: Introduction

The Alps are, in a geological sense, a collisional orogen resulting from the collision of the European continent (“Europe”) with the Adriatic continent (“Adria”, also termed “Apulia”) after the subduction of intervening ocean basins. The collision took place in the Tertiary but was preceded by other collision events in the Cretaceous period. The first overthrusting processes during the Alpine Orogeny already took place in the Jurassic, ca. 160 million years (Ma) before present. Today, the Earth’s crust is still being shortened in the eastern part of the Alps. Altogether, the Alpine Orogeny thus lasted from Jurassic until Recent. The Alps are also called a thrust belt because large parts of the Alps are formed by thrust sheets (nappes).
1.2. Plate tectonics and orogeny

Here we have to clarify some terms. A continent in a geological sense is an area underlain by continental crust. An ocean in a geological sense is an area underlain by oceanic crust. Pieces of oceanic lithosphere that are now above sea level are called ophiolites. In mountain ranges, ophiolites often form a suture. This is the interface where rocks from two former continents are in touch; in between are the ophiolites. Orogeny means mountain building. This term does not only include surface uplift but also deformation, metamorphism, erosion and other related processes. The Alpine Orogeny is the orogeny that formed the Alps. In this context, collision means that two continents collide after subduction of the lithosphere of an ocean (Fig. 1-1). Important: It’s the continents that collide, not the plates. For example, the continent Africa is not identical with the African Plate. The latter includes not only the continent but also the eastern part of the Atlantic from the continental margin to the Mid Atlantic Ridge. If the Atlantic were subducted, the African continent would collide at the end with the South American continent, not the African Plate with the South American Plate - these cannot collide because they are in touch already now. Another type of collision is the collision of a continent with an island arc (arc-continent collision). This occurs when a subduction zone lies within an ocean, not at its margin (Fig. 1-2). In the Jurassic, an arc-continent collision probably took place in the area of the Alps. A third type is the collision between two arcs (arc-arc collision) but there is no evidence that this occurred in the Alps.

1.3. Shape and boundaries of the Alps

The Alps are arc-shaped, ca. 1000 km long and between 120 and 250 km wide. The eastern end of the Alps is approximately along a line from Vienna towards south. There, the tectonic units of the Alps plunge under the sediment fill of Miocene-age basins belonging to the Pannonian basin system: the Vienna Basin to the North and the Styrian Basin to the South. Some of the tectonic units reappear in the Western Carpathians; this mountain belt represents the continuation of the northward-thrust northern part of the Alps. To the Southeast, there is no clear geological or geographic boundary between the Alps and the Dinarides. The Dinarides represent the continuation of the southward-thrust Southern Alps. South of the Alps is the Po Basin with a Cenozoic sediment fill. It is the southern foreland basin of the Alps, in front of the southward-thrust Southern Alps. It is active as a foreland basin today, i.e. it is subsiding and receiving sediments (e.g., 0.7 to 1 mm of subsidence per year during the last million years in the area of Venice). The Po Basin is closed to the West by the arc of the Western Alps. At the southern end of this arc, the Alps continue into the Appennines. A complex, nor-south trending fault zone (Sestri-Voltaggio Line) is taken as the boundary. At this line, the dominant thrusting direction changes: the main thrusts on the Alpine side are directed towards SW,
whereas the younger thrusts on the Appennine side (from late Middle Miocene onward) are directed towards NE. Thus, the Po Basin is not only the southern foreland basin of the Alps but also part of the northern foreland basin of the Appennines.

On its outer (western) side, the arc of the Western Alps abuts against the Chaines Provençales, a bundle of west-east striking mountain ridges, structurally representing the eastern continuation of the Pyrenees. North of these chains, the Alps are bordered by the sedimentary fill of the Tertiary-age Rhone-Bresse Graben. Farther north, the most frontal and youngest folds of the Alps become detached from the rest and form an arcuate, west- to north-vergent fold-and-thrust belt in front of the Alps, the Jura Mountains. Since the formation of this belt is kinematically linked to the Alps, the Jura may be seen as a part of the Alps in a structural sense. Between the Alps and the Jura is the southwestward-tapering Swiss part of the Molasse Basin, which continues eastward through Bavaria and Austria up to Vienna. The Molasse Basin is the northern foreland basin of the Alps. In contrast to the Po Basin, large parts of it are being uplifted and eroded, and are not active as a foreland basin any more.

1.4. Thrusts, nappes, and fold-and-thrust belts

A thrust is a fault where the relative motion of the upper block is opposite to the dip direction of the fault. Thrusts are shallowly dipping (0° to 45°), such faults with more than 45° dip angle are called reverse faults. Thrusts often have a staircase geometry with subhorizontal flats alternating with ca. 30° inclined ramps. Flats form where the fault follows incompetent layers, ramps where it breaks across competent layers. A nappe is a complex of rocks detached from its deeper substrate and thrust over another rock complex. A nappe is allochthonous. A rock complex still resting on its original substrate is autochthonous.

There are fold nappes and thrust nappes. Fold nappes form when the inverted limb of a recumbent anticline is progressively thinned and stretched (Fig. 1-4, 1-5). A discrete thrust fault does not necessarily exist in this case. Thrust nappes (or thrust sheets), in contrast, are floored by a thrust fault and have no inverted limb (Fig. 1-6). Both kinds of nappes may include basement and sedimentary cover (basement-cover-nappes), only basement (basement nappes), or only cover (cover nappes).


Fig. 1-4: Fold nappe and thrust nappe
During the formation of a fold-and-thrust belt, the thrusts usually form in a certain sequence (sequence of thrusting): The uppermost and most rearward thrust is the oldest and the lowermost and most forward thrust is the youngest. If a mountain range or a part of a mountain is dominated by a certain direction of thrusting, the part of the range that is located in thrusting direction is called external and the part opposite to thrusting direction internal (Fig. 1-7). Internal zones are often metamorphic and external zones unmetamorphic. Ahead of the fold- and thrust belt lies the foreland and behind lies the hinterland. If the thrusts formed in sequence, the original paleogeography may be reconstructed by restoring the uppermost nappe to the most internal position and the lowermost nappe to the most external position. If the sequence of thrusting was disturbed, however, this may lead to wrong results. The sequence may be disturbed in two ways: By out-of-sequence thrusting (Fig. 1-8) or by nappe refolding. In order to reconstruct the paleogeography in such cases, one has to restore the younger thrust first and then the older one. If nappe refolding or out-of-sequence thrusting remain unnoticed, the paleogeography is incorrectly reconstructed (e.g., two basins instead of one).
1.5. Geographic subdivision of the Alps

From a geographic point of view, the Alps are subdivided into Western, Central, Eastern and Southern Alps (Fig. 1-9). A system of E-W trending longitudinal valleys (Valtellina, Pustertal, Gailtal) defines the boundary between the Southern Alps and the rest of the Alps. These valleys are the morphological expression of a Tertiary-age fault system, the Periadriatic Line. The valleys were incised there because the rocks had been fractured by motions along the fault. Therefore, this is a geographic as well as a tectonic boundary.

The boundary between the Eastern and Central Alps runs from Bodensee along the Rhine Valley and over the Splügen Pass to Lago di Como, the boundary between Central and Western Alps from Lac Leman along the Rhone Valley to Martigny and from there over the Grand St.Bernard Pass and through Aosta Valley to Ivrea.

In the German and Austrian literature, the Central Alps are treated as part of the Western Alps. Then, the boundary between Western and Eastern Alps runs from Bodensee to Lago di Como. Also, the Eastern Alps are often divided into three E-W stripes: Northern Calcareous Alps, Central Alps, and Southern Calcareous Alps. The term “Northern Calcareous Alps” is well defined and generally used, the term “Central Alps” should not be used in this way to avoid confusion, and the term “Southern Calcareous Alps” is obsolete (most of the carbonates there are dolomite, anyway).

1.6. Types of rock complexes in the Alps

The rock complexes that are involved in the building of the Alps fall into six categories with respect to their age and evolution:

1. Former Variscan basement: Rocks that have been deformed and/or metamorphosed during the Variscan Orogeny in the Carboniferous, and plutonic rocks that intruded during and in the aftermath of this orogeny. The grade of Variscan metamorphism ranges from unmetamorphic to eclogite and granulite facies.


3. Mesozoic ophiolites, that is, former ocean floor (serpentine, gabbro, basalt).
4. Former sedimentary cover of the Mesozoic ocean floor.

5. Tertiary intrusive rocks, in particular, tonalite and granodiorite.

6. Post-tectonic sediment cover with subordinate volcanic rocks (mainly Tertiary).

Rocks of categories (1) to (4) may or may not show Alpine metamorphism (“Alpine” meaning that the metamorphism took place during the Alpine Orogeny, that is, since Late Jurassic). Former Variscan basement may thus be polymetamorphic, that is, have experienced more than one cycle of metamorphism.

1.7 Tectonic superunits

The Alps are traditionally subdivided into the Helvetic, Penninic, Austroalpine and South Alpine superunits (Fig. 1-3, 1-10). Helvetic, Penninic and Austroalpine lie north of the Periadriatic Line. All three superunits themselves comprise a multitude of nappes which have been thrust towards the European foreland, that is, towards north and west. The South Alpine superunit forms the Southern Alps, south of the Periadriatic Line, and is characterized by south-directed reverse faults and thrust.

Fig. 1-10: Schematic profile of the Alps along the boundary between Eastern and Central Alps. Blue: Helvetic; green: Penninic; light brown: Austroalpine; dark brown: South Alpine; orange: Tertiary-age Bergell pluton. AA: Aare Massif; AM: Permo-Mesozoic cover of the Aare Massif and the Molasse Basin substratum; B: Bergell; G: Gotthard Massif; EL: Engadine Line; HD: Helvetic and Ultrahelvetic Nappes; Penn.: Lower, Middle and Upper Penninic Nappes; SG: basement of the Southern Alps; SM: Permo-Mesozoic cover of the Southern Alps; SP: Subpenninic Nappes.

The Helvetic

The Helvetic is the most external and lowermost of the superunits. With respect to the paleogeography in the Early Cretaceous, the Helvetic represents the southern shelf and proximal, i.e. continentward, part of the European continental margin (Fig. 1-11). The Helvetic in a wider sense comprises from base to top (1) the Variscan basement cropping out in the External Massives (Argentera, Pelvoux, Belledonne, Montblanc, Aiguilles Rouges, Aare and Gotthard massives), (2) the autochthonous Permian-Mesozoic-Paleogene sediment cover of the External Massives, (3) the northward-overthrust Helvetic Nappes which are also formed by Permian to Paleogene sedimentary rocks, overlain by (4) the thin and discontinuous Ultrahelvetic Nappes. The latter are derived from Mesozoic to Paleogene sediments of the continental slope. In the Western Alps, the tectonic units equivalent to the Helvetic are called Dauphinois. Mesozoic sediments in the Helvetic are generally non-metamorphic.
The Penninic

The Penninic superunit comprises ophiolite-bearing nappes derived from two Mesozoic-age ocean basins (the Valais Ocean to the North and the Piemont-Ligurian Ocean to the South) as well as nappes consisting of continental crust. The Penninic is subdivided into Subpenninic, Lower, Middle, and Upper Penninic nappes. The Subpenninic nappes are derived from the distal European continental margin (in terms of Early Cretaceous paleogeography), the Lower Penninic ones from the Valais Ocean, the Middle Penninic nappes from continental crust of the Briançonnais (a spur of the Iberian continent), and the Upper Penninic Nappes from the Piemont-Liguria Ocean. A continental fragment or microcontinent, Cervinia, existed in this ocean. In consequence, there are both oceanic and continental, i.e. Cervinia-derived, Upper Penninic nappes. The latter (Sesia and Dent Blanche Nappes) are often regarded as Austroalpine, which is, however, wrong in my opinion.

The Penninic nappes occur in a coherent outcrop area in the Western and Central Alps and, additionally, in outliers isolated by erosion (Klippen) along the northwestern boundary of the Alps. By far the largest of these is the Préalpes outlier. In the Eastern Alps, The Penninic is largely covered by the Austroalpine nappes and is only exposed in a narrow zone along the northern front of the Alps (the Rhenodanubian Flysch Zone) and in two tectonic windows in the interior of the Alps, the Engadine Window and the Tauern Window. Another window (Rechnitz Window or Window Group) occurs east of the Alps at the rim of the Pannonian Basin. Here, Penninic units are exposed in the position of a tectonic window but framed by Tertiary-age sediment cover.

The Penninic is partly unmetamorphic (Klippen and Rhenodanubian Flysch Zone), partly shows Alpine metamorphism up to eclogite facies. The age of the Alpine metamorphism in the Penninic is Tertiary, with the exception of the Sesia Nappe (Cervinia microcontinent) where eclogite-facies overprint began already at the end of the Cretaceous.
The Austroalpine

This is the uppermost superunit, widely exposed in the Eastern Alps. The Austroalpine nappes are derived from the Adria continent. The Penninic/Austroalpine boundary coincides with the formed ocean-continent boundary between the Piemont-Ligurian ocean and the continental margin of Adria. In Jurassic times, ophiolites from the Meliata Ocean, a marginal basin of Tethys, were thrust from the Southeast onto the continental crust of the Austroalpine, in the course of an arc-continent collision. Such ophiolites occur in the Western Carpathians (Meliaticum) and their southward extension in the internal Dinarides; in the Eastern Alps, only redeposited relics of the Meliaticum are found. Tectonic structures formed during the arc-continent collision, however, can also be seen here.

The Austroalpine is subdivided into Lower and Upper Austroalpine. The Lower Austroalpine nappes occur discontinuously along the base of the Austroalpine. The Upper Austroalpine form two complexes, (1) the Northern Calcareous Alps, built mostly by Permo-Mesozoic sediments, and (2) the Central Austroalpine further south, an area of nappes dominated by Variscan basement with minor Permo-Mesozoic sedimentary rocks. The Northern Calcareous Alps have almost no Alpine metamorphism, the Central Austroalpine has been metamorphosed to various degrees up to eclogite facies. Nappe stacking and Alpine metamorphism of the Austroalpine are generally Cretaceous in age.

The South Alpine

Like the Austroalpine, the South Alpine superunit comprises continental crust of Adria. At no time existed an oceanic basin between Austroalpine and South Alpine. The South Alpine represents a more southerly part of Adria, the Austroalpine a more northerly part. In contrast to the Austroalpine, there is no Cretaceous nappe thrusting and (almost) no Alpine metamorphism in the South Alpine. South-directed reverse faults and thrusts in the South Alpine are Tertiary in age. In the eastern part of the Southern Alps, the most external thrusts at the margin of the Po Basin are still active today.

Chapter 2: Overview of the paleogeographic evolution

2.1. Opening and closure of the Meliata Ocean

During the Triassic, the Penninic oceans did not yet exist. Europe, Iberia-Briançonnais and Adria together formed a coherent continental area (Fig. 2-1 to 2-4). The Meliata Ocean, a marginal basin of Tethys, opened in the early Middle Triassic (Anisian). From then on, the Austroalpine and South Alpine formed the northwestern continental margin of the Meliata Ocean. Consequently, the Middle and Upper Triassic successions in these superunits are characterized by a transition from a generally marine (“Alpine”) facies in the Southeast to a more continentally influenced facies (“Germanic”) in
the Northwest. The facies boundaries have been disrupted and displaced by later thrust and strike-slip faults. The trend from marine to continental continues towards northwest in the Penninic (that is, in the continental units of the Penninic because the oceanic units did not yet exist) and in the Helvetic.

The closure of the Meliata Ocean began at the end of the Triassic, probably through subduction in a southeast-dipping, intra-oceanic subduction zone southeast of the present Alps (Fig. 2-1). Oceanic spreading in the back-arc basin above the subduction zone produced Jurassic-age oceanic crust of the Vardar Ocean which persisted until Late Cretaceous. In the Late Jurassic, the collision of the Adriatic continental margin with the island arc above the subduction zone led to the obduction of ophiolites onto the margin of Adria. Such ophiolites crop out in the Dinarides; in the Austroalpine, they have been eroded away already during the Cretaceous, but detritus from them is found in Cretaceous sediments (Gosau Group) of the Austroalpine.

![Fig. 2-1: Paleogeographic evolution of the Alpine area](image1)

![Fig. 2-2: The paleogeographic situation at the beginning of the Late Cretaceous. Same picture as Fig. 2-1 c but colour-coded in the same way as Figs. 2-3 and 2-4](image2)
2.2. The Piemont-Ligurian Ocean and the Cretaceous orogeny in the Eastern Alps

After a phase of crustal extension in the Liassic to Lower Middle Jurassic, spreading of the Piemont-Ligurian Ocean started in the Middle Jurassic (Bathonian), which separated Adria from Europe. Therefore, the ophiolites of the Piemont-Ligurian Ocean are generally covered by Late Jurassic radiolarite (Fig. 2-5). This oceanic spreading was linked to the opening of the middle Atlantic: During the Jurassic, the Atlantic opened from south to north only up to the latitude of Gibraltar, from where a sinistral transform fault between Iberia and North Africa transferred spreading towards east into the
Piemont-Ligurian Ocean. It is still not completely clear how the Piemont-Ligurian Ocean linked up towards east with the remaining ocean basins in the Tethys area. The microcontinent Cervinia in the Piemont-Ligurian Ocean was either independent or represented an extension of Alcapeca, a ribbon continent in a similar position whose remnants are spread out over the Western Mediterranean (Alboran, Cabylie, Peloritani, Calabria).

After the Jurassic arc-continent collision, thrust tectonics propagated into the foreland (Austroalpine) during the Cretaceous, and a west- to northwest-vergent fold-and-thrust belt evolved. In this process, an intracontinental, southeast-dipping subduction zone formed within the Austroalpine, in which Austroalpine units were buried to eclogite-facies metamorphism at about 95 Ma. Subduction of the Piemont-Ligurian Ocean towards southeast under the Austroalpine continental margin started at about the same time. At the end of the Cretaceous, the Cervinia microcontinent entered this subduction zone (first eclogite-facies metamorphism in the Sesia Nappe at about 78 Ma). In the following, the subduction zone rolled back towards northwest whereby the Austroalpine nappe stack was stretched during the later part of the Late Cretaceous (80-67 Ma). The extension was mostly accommodated by east- to southeast-dipping normal faults, partly low-angle detachment faults, and produced a basin within the Austroalpine area which became deep-marine towards the end of the Cretaceous. The sediments of the Gosau Group were deposited in this basin.

During these tectonic processes, the Austroalpine was decoupled from the South Alpine by a sinistral strike-slip fault which approximately coincides with the later, Tertiary-age, Periadriatic Line (“Paleo-Periadriatic” or “Paleo-Insbruck” Line). Such a fault must have existed because the Southern Alps were neither affected by the west-directed nappe stacking nor by the later rifting event.
2.3. The Valais Ocean

During the Early Cretaceous the opening of the Atlantic propagated west of Iberia towards north up to the Bay of Biscay. Thereby Iberia broke away from Europe and moved southeast relative to Europe, leading to the opening of a system of oceanic basins including the Bay of Biscay, a basin in the area of the present-day Pyrenees, and the Valais Ocean in the Alpine area. The Early-Cretaceous break-up is particularly well documented in the Tasna Nappe of the Engadine Window, where serpentinized peridotite of the subcontinental mantle was exposed at the seafloor by the breaking-apart of the continental crust and was covered by deep-marine sediments of Early Cretaceous age (Fig. 2-7). The Tasna Nappe belongs to the transition area between the continental crust of the Briançonnais and the Valais Ocean.

Towards east, the Cretaceous spreading axis of the Valais Ocean probably merged into the “old” spreading axis of the Piemont-Ligurian Ocean. This required re-rifting and break-up of the Jurassic-age oceanic lithosphere between the European continental margin and the “old” mid-ocean ridge. As a result of the oblique sinistral opening, a part of the Jurassic-age lithosphere came to lie within the Valais Basin (Fig. 2-1). In two places (Chiavenna Ophiolite at the western boundary of the Eastern Alps and Balma Unit in the Monte Rosa area) ca. 93 Ma old oceanic gabbros of the Valais Ocean have been dated; it follows that at this time (Cenomanian) oceanic spreading still took place, contemporaneously with the intracontinental subduction in the Austroalpine (see above). It is not clear if the subduction of the Valais Ocean began already during the Cretaceous or started only in the Paleogene.

2.4. Closure of the oceans and continent collision

In the Tertiary, the Penninic oceans were closed by subduction in south- to southeast-dipping subduction zones. Two separate subduction zones probably existed during the Paleocene and Early Eocene: the one at the southern margin of the Valais Ocean continued through the Pyrenees to the southern margin of the Bay of Biscay, and the one at the southeast margin of the Piemont-Ligurian Ocean continued south to Corsica. Oceanic and continental rock complexes were subducted and metamorphosed to eclogite facies. The age of eclogite-facies metamorphism decreases from more southeasterly-located paleogeographic areas to more northwestern ones (Fig. 2-8) which reflects the northwestward propagation of orogeny. The temporal overlap of eclogite metamorphism in the Piemont-Ligurian and Valais Ocean units (Fig. 2-8) indicates that the two subduction zones were partly active at the same time. The last parts of the oceans were closed in the Eocene (ca. 40 Ma) but subduction of continental lithosphere of the European continental margin went on. The youngest eclogites of the European margin, which are exposed in the Tauern Window, are only about 32 Ma
old. After the continent collision, the further tectonic evolution was characterized by extensional
tectonics in the interior of the Alps, outward-propagating thrust belts at the margins of the Alps, and
important strike-slip faults.

Chapter 3: The Northern Calcareous Alps

As already mentioned in chapter 2, the Austroalpine is subdivided into Lower and Upper
Austroalpine. The Lower Austroalpine occurs discontinuously. The Upper Austroalpine makes up the
bulk of the Austroalpine nappes. It comprises the Northern Calcareous Alps and the Central
Austroalpine further south. We first deal with the Northern Calcareous Alps. This complex extends
over 500 km length from the Rhine Valley to Vienna. At the eastern end, the nappes of the Northern
Calcareous Alps are downthrown by a system of east-dipping Miocene normal faults and disappear
under the fill of the Vienna Basin. The western prolongation has been eroded away with the
exception of small relics, the westernmost ones being the Iberger Klippen in Central Switzerland. The
Northern Calcareous Alps are completely allochthonous and their origin is south of the Tauern
Window. The nappes comprise Permian to Eocene rocks. However, the stacking of the nappes took
place mainly in the Cretaceous until Turonian; the sediments of the Gosau Group (Turonian to Early
Eocene) discordantly cover most of the thrusts.

3.1. Nappes of the Northern Calcareous Alps

The Northern Calcareous Alps comprise a deeper group of nappes, the Bajuvaric nappes, and a higher
group, the Tirolic Nappes. An uppermost group, the Juvavic nappes, occurs in the eastern part of the
Northern Calcareous Alps (Fig. 3-1).
The Bajuvaric nappes cover a large area in the western part of the Northern Calcareous Alps. In this area, they comprise at the base, i.e. at the border of the Alps, a thin sheet called “Cenoman-Randschuppe” (Cenomanian marginal sliver), overlain by the Allgäu Nappe, and at the top the Lechtal Nappe. Further east, near Kufstein, the Tirolic advances north to the border of the Alps, so that the Bajuvaric Nappes do not crop out in the middle part of the Northern Calcareous Alps. Further east the front of the Tirolic swings back towards south and the Bajuvaric reappears with the deeper Frankenfels Nappe (equivalent to the Allgäu Nappe in the West) and the higher Lunz Nappe (equivalent to the Lechtal Nappe).

In the West, the Tirolic is represented by the Inntal Nappe and the still higher Krabachjoch Nappe. In the middle part, the most important subunit of the Tirolic is the Staufen-Höllengebirge Nappe.

The Juvavic comprises Lower and Upper Juvavic. The Lower Juvavic does not consist of coherent nappes but is a rather chaotic complex of slivers, the Hallstatt Nappes. These slivers contain, among other rocks, thick Permian-age evaporites, in particular, rock salt (“Haselgebirge” with salt mines, e.g. in Hallstatt). The upper Middle and Upper Triassic of these slivers is represented by pelagic limestones (Hallstatt Limestones), in contrast to the rocks of the same age in the Tirolic nappes which are platform carbonates (e.g., Norian Dachstein Limestone). According to the presently prevailing interpretation, the Hallstatt Nappes were not imbricated by thrusting but were emplaced as olistoliths, that is, by gravity sliding, from the southeast into basins on top of the Tirolic nappes. This took place in the Middle to Late Jurassic. These olistoliths are embedded in a matrix of silicious shales of late Middle and early Late Jurassic age. After the gravity sliding there was again relative tectonic quiescence and Late Jurassic platform carbonates were deposited on top of the olistolith complexes. According to this interpretation, the Lower Juvavic is not a nappe complex but an extremely coarse-grained clastic “sediment” belonging to the sediment succession of the Tirolic nappes. Thrusted over this are the Upper Juvavic Nappes in which the Norian is again represented by thick platform-type Dachstein Limestone (Berchtesgaden Nappe, Dachstein Nappe, Mürzalpen-Hohe Wand Nappe). In the Dachstein Nappe as well, the Triassic is overlain by a Middle to Late Jurassic complex with Hallstatt olistoliths (at Salzberg near Hallstatt). This demonstrates that the Hallstatt Nappes were emplaced in a first step on the Tirolic and its southern extension, the Dachstein Nappe, before the Dachstein Nappe was thrust northward “out of sequence”.

Fig. 3-1: Nappes of the Northern Calcareous Alps
3.2. Stratigraphy of the Northern Calcareous Alps

Three facies areas are distinguished in the sediment succession of the Northern Calcareous Alps. From NW to SE, that is, from the continent towards the Meliata Ocean, these are the areas of the Bavarian-North Tyrol Facies, the Berchtesgaden Facies, and the Hallstatt Facies (Fig. 3.2).

**Fig. 3-2:** Permian and Triassic of the Northern Calcareous Alps. abs: “Alpine Buntsandstein”, dkl: Dachstein Limestone - lagoonal facies; dkr: Dachstein Limestone - reef facies; gk: Gutenstein Limestone; hd: Hauptdolomit; hk: Hallstatt Limestones; hs: Haselgebirge; kó: Kössen Formation; kp: shale layers in the Hauptdolomit (“Keuper”); ork: Upper Rhaetian limestone; ps: Partnach Formation; ra: Ramsau Dolomite; rb: North-Alpine Raibl Group; rk: Reifling Limestone; rs: Reingraben Shale; sk: Steinalm Limestone; vc: “Verrucano”; vk: volcanic rocks; wkl: Wetterstein Limestone - lagoonal facies; wkr: Wetterstein Limestone – reef facies; ws: Werfen Formation; zb: Zlambach Formation.

In the Bavarian-North Tyrol Facies, the Permian sediments are terrestrial conglomerates and sandstones (“Verrucano”) associated with volcanic rocks (mainly rhyolite). In the Hallstatt Facies, the Permian comprises thick salt layers (“Haselgebirge”) which have been strongly deformed and mixed with pelites. Permian-age volcanic rocks are also present. The Scythian is represented by sandstone (“Alpiner Buntsandstein”) in the Bavarian-North Tyrol Facies; towards East, marine influence becomes increasingly stronger in the Berchtesgaden Facies and the Hallstatt Facies (mixed clastic-carbonatic Werfen Formation). In the Early and Middle Anisian, marginal-marine Gutenstein and Steinalm limestones were deposited in all facies areas. A marked phase of subsidence, related to the break-up of the Meliata Ocean, occurred in the Late Anisian when relatively deep-water Reifling Limestone was deposited in the Bavarian-North Tyrol and Berchtesgaden Facies and the deposition of pelagic Hallstatt Limestone started in the Hallstatt Facies. Neptunian dykes filled with Hallstatt Limestone indicate that subsidence was associated with crustal extension (Fig. 3-3).

**Fig. 3-3:** Reddish, Upper Anisian Schreieralm Limestone fills a neptunian dyke in light grey, Middle Anisian Steinalm Limestone. The Steinalm Limestone consists of Dasycladaceans (calcareous algae) and was deposited in very shallow sea water. The Schreieralm Limestone belongs to the pelagic Hallstatt Limestones which were deposited in open marine, considerably deeper water. This outcrop at Hoher Schreieralmkogel near Hallstatt documents a strong subsidence phase in the Anisian, which was associated with crustal stretching and dyking.
The Ladinian is developed in different facies. In the westernmost part of the Northern Calcareous Alps (not shown in Fig. 3-2) the Ladinian is represented by limestones alternating with shale (Arlberg Formation) and contains mafic volcanic rocks (Lech Melaphyr). In the Bavarian-North Tyrol and Berchtesgaden Facies, the Wetterstein Limestone forms atoll-like carbonate platforms with unbedded, reef-facies Wetterstein Limestone on the outside and well-bedded, lagoonal Wetterstein Limestone or Ramsau Dolomite in the interior (Fig. 3-4). Between the carbonate platforms, marls of the Partnach Formation are deposited in deeper water. Progradation of the carbonate platforms leads to a gradual decrease of the size of the Partnach basins. In the Hallstatt Facies, deposition of pelagic Hallstatt Limestones continues during the Ladinian.

The reef development ends in the Carian and the North-Alpine Raibl Group is deposited on top, comprising evaporites (anhydrite/gypsum, today mostly occurring as Rauhwacke, a porous calcite rock), shale, sandstone, limestone, and dolomite. In the Hallstatt Facies, the deposition of Hallstatt Limestones is only temporarily replaced by shale (Reingraben Shale).

A large carbonate platform developed in the Norian which included almost the entire Northern Calcareous Alps and wide areas beyond. Intra- to supra-tidal Hauptdolomit was deposited in the Bavarian-North Tyrol Facies, characterized by algal laminites. It grades into the bedded variety of the Dachstein Limestone towards southeast (Berchtesgaden Facies), consisting of the Lofer Cyclothems, rhythmic successions of (from base to top) dolomitic breccias, dolomitic or calcareous algal laminites, and megalodon limestone (Fig. 3-7). Above follows an erosional surface and on top the next cyclothem. The cyclothems result from eustatic sea-level oscillations, the megalodon limestones representing the sea-level high-stand. Towards southeast, a barrier reef of unbedded Dachstein Limestone separates the bedded Dachstein Limestone from the open sea where the deposition of pelagic Hallstatt Limestone...
continues. The Dachstein Limestone is often, particularly in its lower part, replaced by dolomite (Dachstein Dolomite).

In the Rhaetian, the carbonate platform development came to an end over wide areas, giving way to the deposition of shales with fossiliferous limestone layers (Kössen Formation, Fig. 3-8). Only in part of the Berchtesgaden Facies area, the deposition of Dachstein Limestone continued. Towards the end of the Rhaetian, reefs prograded again for some time (Upper Rhaetian Limestone). In the Hallstatt Facies, marls were deposited in the Rhaetian (Zlambach Formation).

The Liassic and Early Dogger are characterized by extensional tectonics and strong subsidence; normal faults subdivided the depositional area of the Northern Calcareous Alps into submarine highs and basins (Fig. 3-9). The marls and silicious limestones of the Allgäu Formation, with turbidites and breccias, were deposited in the basins, thin, often reddish limestones on the highs (crinoidal Hierlatz Limestone and ammonite-bearing, nodular Adnet Limestone, Fig. 3-10). Crustal extension led to the break-up of the Piemont-Ligurian Ocean northwest of the Austroalpine.
The Austroalpine itself subsided to deep-marine conditions as well: In large parts of the Northern Calcareous Alps, the uppermost Callovian and Oxfordian are represented by radiolarite, a calcite-poor to calcite-free silicious sediment deposited below the calcite compensation depth (Fig. 3-11). At the same time, up to kilometer-scale packages of sediments (olistoliths) from the Hallstatt Facies area – the Hallstatt Nappes – glided into the radiolarite basin, in the area which later formed the Juvavic Nappes. They probably originated from a thrust front located more to the southeast and caused by the Meliata arc-continent collision (see chapter 2.1). The Hallstatt olistoliths represent a convincing example of gravitational napp emplacement. (For other Alpine nappes, e.g. the Helvetic Nappes, gravitational transport has been suggested as well; this, however, is not accepted any more). After the gliding event, tectonic processes came to a rest and “neo-autochthonous” carbonate platforms of the Plassen Limestone developed on top of the olistolith complexes (Fig. 3-12). In northwestern parts of the depositional area of the Northern Calcareous Alps, pelagic Aptychus Limestone was deposited in a deep marine environment.

During the Cretaceous, thrust tectonics propagated from southeast to northwest; ahead of the thrust fronts, turbidite-rich successions like the Roßfeld Formation (Valanginian to Barremian) were deposited. From Southeast to Northwest, deposition of this type of sediments started later and went on longer. The Lech Formation (“Lechtaler Kreideschiefer”), in the westernmost part of the Northern Calcareous Alps, reaches into the Early Turonian. After a great unconformity related to the “Pre-Gosauic” or Trupchun Phase, the Gosau Group was deposited from Late Turonian to Eocene. This starts with terrestrial alluvial fans, followed by shallow-marine limestones, typically with rudists, that is, sessile gastropods (Fig. 3-13), and finally deep-marine marly sediments with turbidites and debris flows (Fig. 3-14).
3.3. Tectonics of the Northern Calcareous Alps

The Northern Calcareous Alps represent a typical fold-and-thrust belt (Fig. 3-15). Most folds result from processes along thrust faults (fault bend folds, fault propagation folds). On the other hand, folding also leads to the formation of thrust (“out-of-syncline thrusts”). The tectonic style is influenced by sediment facies (“facies tectonics”): In the West, in the area of the Bavarian-North Tyrol Facies, the Triassic is often deformed into large-scale folds, whereas in the East (Berchtesgaden Facies), the thick Triassic carbonate platforms mostly form flat-lying thrust blocks. Incompetent formations, like the shaly Partnach Formation and the evaporite-bearing Raibl Group, form décollement horizons in which thrusts are horizontal over longer distances. These are repeatedly reactivated; therefore, the kinematic reconstruction is difficult in many cases.

The nappes of the Northern Calcareous Alps were imbricated during the Cretaceous by mostly northwest-directed thrusting. In most cases, higher thrust faults are older than deeper ones (in-sequence thrusting). As a result, higher thrusts are often folded during the formation of lower thrusts, by fault-bend and fault-propagation folding (e.g., the basal thrust of the Lechtal Nappe is folded during the formation of the Allgäu Nappe, see Fig. 3-15). On the other hand, the basal thrust of the Inntal Nappe in the western part of the Northern Calcareous Alps is younger (Albian-Cenomanian) than the structurally deeper basal thrust of the Lechtal Nappe (Aptian-Albian), i.e. the Inntal thrust is out of sequence.
Fig. 3-15: Profile through the western part of the Northern Calcareous Alps, approximately along a line Pfronten-Ims, from Eibacher et al. (1990). In the upper panel, the nappes are colour-coded, in the lower one, the stratigraphic units. Note the folding of the Lechtal Nappe basal thrust by fault-propagation folds in the Allgäu Nappe (northwest part of the profile) and the occurrence of foeward thrusts and backthrusts nucleating in synclines ("out-of-syncline thrusts", particularly in the middle and to the right).

The Gosau basins of the Northern Calcareous Alps, which formed and subsided from Late Turonian onward, are interpreted as rift-like extensional basins by some authors but as thrust-related by others. In the western Northern Calcareous Alps, there is evidence for an extensional phase with normal faulting in the Late Cretaceous, lending support to the rift model. Not before Tertiary (Eocene) was the entire nappe stack of the Northern Calcareous Alps, together with the rest of the Austroalpine, thrust over the Penninic units and folded, as can be seen from the folding of the Gosau sediments themselves (Fig. 3-16). In the Oligocene and Miocene, the Northern Calcareous Alps were mainly affected by strike-slip faults.

Fig. 3-16: Synformally folded strata of the Upper Gosau Group (Santonian and younger) at Roßkopf near Muttekopf in the Inntal Nappe, showing that the units Northern Calcareous Alps were folded once more when they were thrust over the Penninic units in Tertiary time. North is to the right.
Chapter 4: The Central Austroalpine

The Austroalpine south of the Northern Calcareous Alps is subdivided into three nappe complexes, from base to top: the Lower Austroalpine, the Lower Central Austroalpine (formerly known as Middle Austroalpine), and the Upper Central Austroalpine (Fig. 4-1). In contrast to the Northern Calcareous Alps, these complexes comprise Variscan basement rocks volumetrically dominating over Permo-Mesozoic cover rocks. Another important difference is that the Lower and Central Austroalpine units, in contrast to the Northern Calcareous Alps, partly show Alpine (Cretaceous) metamorphism, which is particularly strong in the Lower Central Austroalpine.

![Fig. 4-1: Subdivision of the Austroalpine nappes according to Janak et al. (2004). B: Bajuvaric; BM: Brenner Mesozoic; C: Campo Nappe; D: Drauzug; EB: Err and Bernina Nappes; ED: Engadine Dolomites, EF: Engadine Window; GN: Gurktal Nappe; GP: Graz Paleozoic; IQ: Innsbruck Quartz Phyllite; K: Koralpe; KA: Karawanken; NGZ: Northern Grauwackenzone; Ö: Ötztal Nappe; P: Pohorje Massif; R: Radstadt Nappes; S: Sausalpe; SA: Stangalm Mesozoic; SI: Silvretta Nappe; ST: Steinach Nappe; SW: Semmering and Wechsel nappes; T: Tirol; TO: Tonale Nappe.]

The Upper Central Austroalpine

This comprises a stripe of tectonic units along the Periadriatic Line and three groups of nappes further north: The Northern Grauwackenzone, the Graz Paleozoic, and the Gurktal Nappe (Fig. 4-1). Finally, there is the small Steinach Nappe west of the Tauern Window. All these units have in common that the grade of their Alpine (Cretaceous) metamorphism is significantly lower than in the directly subjacent Lower Central Austroalpine units.
The Northern Grauwackenzone, the Graz Paleozoic, and the Gurktal Nappe are very similar to each other. All three consist of several individual nappes. The thrust faults separating these are partly Variscan, partly Alpine. The three complexes are formed by Paleozoic sediment successions (Ordovician to early Late Carboniferous) showing low-grade Variscan metamorphism (greenschist facies) and Variscan deformation (folds and thrusts). The Ordovician is represented by pelitic-psammitic series with oceanic basalts and subaerially erupted rhyolites (Blasseneck Porphyroid), the Silurian occurs in two different facies, a pelitic and a carbonatic one, and the Devonian is predominantly carbonatic. The Devonian carbonates are often ore-bearing, e.g. the Devonian Limestone of the Styrian Erzberg (Fig. 4-2; iron carbonates) and the Schwaz Dolomite (Ag-tetraedrite). The Lower Carboniferous and the lower part of the Upper Carboniferous are partly calcareous, partly pelitic-psammitic. The main phase of Variscan deformation took place in the middle Late Carboniferous; in the Gurktal Nappe, the uppermost Carboniferous (Stephanian), represented by conglomerate, sandstone, and slate, rests unconformably on the older formations. Permian sediments occur along the northern boundary of the Northern Grauwackenzone; these are regarded as part of the Northern Calcareous Alps (Tirolic). The Permian rests with an unconformable sedimentary contact on different older formations, showing that the Northern Grauwackenzone is the basement on which the sediments of the Tirolic Nappes were deposited (Fig. 4-3). The Gurktal Nappe and the Graz Paleozoic are devoid of Permo-Mesozoic cover, with the exception of the Gosau Group (Late Cretaceous to Paleogene) which rests unconformably on the SW part of the Graz Paleozoic (Kainach) and on the eastern part of the Gurktal Nappe (Krappfeld and Lavanttal). These Gosau successions were deposited during the Late Cretaceous phase of crustal extension; they are partly linked to east- to northeast-dipping extensional detachment faults. This is particularly clear in the case of the Kainach Gosau. The Alpine metamorphism of the Northern Grauwackenzone, the Gurktal Nappe, and the Graz Paleozoic is generally even lower in grade than their Variscan metamorphism (diagenesis to greenschist facies).

The Upper Central Austroalpine units adjacent to the Periadriatic Line are also distinguished by their low Alpine metamorphic grade from the subjacent Lower Central Austroalpine units following to the north. Partly, however,
drawing a boundary is difficult. These units comprise Variscan basement, partly with low-grade Variscan metamorphism (e.g. the Eisenkappel Diabase unit in the Northern Karawanken mountains, with Paleozoic pillow basalts and deep sea sediments), partly, however, high-grade, e.g. the Ulten Zone in the Tonale Nappe (Fig. 4-1) which includes Variscan high-pressure rocks (garnet peridotite). Together with these basement units, Permo-Mesozoic cover units occur in the same zone north of the Periadriatic Line, in particular the Drauzug (Fig. 4-4) and the Mesozoic of the Northern Karawanken mountains.

Today, the contacts between the Upper and Lower Central Austroalpine are often low-angle normal faults of Late Cretaceous age (ca. 80 to 67 Ma). The transport direction of these normal faults is mostly east to southeast.

The Lower Central Austroalpine

This comprises nappes with a Variscan and/or Permian metamorphic basement, like the Silvretta, Campo and Ötztal nappes to the West and the Saualpe, Koralpe and Pohorje units to the East. In part, this basement carries relics of Permo-Mesozoic sediment cover: the Triassic of the Ducan - Landwasser area on the southwestern part of the Silvretta Nappe; the Engadine Dolomites between the Silvretta, Campo, and Ötztal nappes; the Brenner Mesozoic, a relic of the cover of the Ötztal Nappe close to its eastern border; the Stangalm Mesozoic southeast of the Tauern Window. In part, however, the Permo-Mesozoic cover has been stripped off from the basement during the Cretaceous subduction; this is the case for the deeply subducted Saualpe, Koralpe and Pohorje units which are devoid of cover rocks. The facies of the Lower Central Austroalpine Permo-Mesozoic is similar to the one of the Bajuaric nappes in the westernmost Northern Calcareous Alps, in particular, the Lechtal Nappe. As an example, Fig. 4-5 shows the Triassic of the Ortler Nappe, a subunit of the Engadine Dolomites. In contrast to the Northern Calcareous Alps, the Anisian in the Lower Austroalpine often contains sandstone. For example, the clastic-carbonatic Fuorn Formation in the Engadine Dolomites (Fig. 4-5) represents not only the Scythian but also parts of the Anisian.
The Variscan metamorphism in the basement of the Lower Central Austroalpine is mostly of relatively high grade, often amphibolite facies with relics of ca. 350 Ma old eclogite facies. This is the case, for example, in the Ötztal and Silvretta nappes. Other units – often units with rather high-grade Cretaceous metamorphism – have hardly any relics of Variscan metamorphism, e.g., the Schneeberg Zone in the southern Ötztal Nappe. Possibly, these units have experienced little or no Variscan metamorphism. Other units like the Koralpe and the Sausalpe show relics of a Permian-age high-T-low-P metamorphism in the amphibolites facies (Fig. 4-6), connected with the intrusion of Permian gabbros (partly eclogitised during the Cretaceous metamorphism) and of granitic pegmatites. This Permian metamorphism, which is also known from the South Alpine and parts of the Penninic, is explained by extensional tectonics and the advection of heat and magma from rising asthenosphere.

The grade of Cretaceous metamorphism in the Lower Central Austroalpine increases from north or northwest to south or southeast. As an example, the NW parts of the Ötztal and Silvretta nappes are only ancinizational whereas increasingly higher metamorphism occurs towards south and southeast, eventually reaching the amphibolite facies with Cretaceous eclogite relics in the southernmost Ötztal Nappe (Texelgruppe). These eclogites belong to an W-E trending belt extending from the Texelgruppe towards east over the Kreuzberggruppe south of the Tauern Window to the Sausalpe, Koralpe and Pohorje massives. The highest pressures of the Cretaceous metamorphism are reached in eclogites of the Pohorje massif (3.0 to 3.1 GPa, 760-825°C).

The Lower Central Austroalpine was formerly known as the Middle Austroalpine and was, in particular by Austrian geologist Alexander Tollmann, regarded as being structurally lower than the nappes of the Northern Calcareous Alps. The latter were correlated with our Upper Central Austroalpine, and together these were termed Upper Austroalpine. This correlation gave rise to much debate; in particular, it was repeatedly emphasized that the Mesozoic sediments of the Lechtal Nappe (Bajuvaric, Northern Calcareous Alps) are connected by depositional contacts – albeit locally faulted – with the Variscan basement of the Silvretta Nappe, and that therefore, the “Upper Austroalpine” Lechtal Nappe is connected with the “Middle Austroalpine” Silvretta Nappe, and consequently these two nappes are one and the same structural level. We solve this problem by correlating the lower nappes
of the Northern Calcareous Alps (Bajuvaric) with the Lower Central Austroalpine, and the higher nappes (Tirolic) with the Upper Central Austroalpine (Fig. 4-7). This view is supported by depositional contacts between the Tirolic and the Northern Grauwackenzone (Fig. 4-3). The thrusts climb in the stratigraphy from south to north; therefore, the southern part of the Lower Central Austroalpine (e.g., Pohorje) may well be the basement on which the northern part of the Tirolic nappes was originally deposited. This correlation, however, neglects east-west-trending strike-slip faults. Such faults played an important role in the Cretaceous and possibly already in the Jurassic.

The tectonics of the Central Austroalpine units will be considered in more detail in a later chapter, together with the tectonics of the other Austroalpine units.

Chapter 5: The Lower Austroalpine

The Lower Austroalpine occurs mainly in four complexes: (1) the Err and Bernina nappes in Graubünden (Eastern Switzerland) and adjacent Italy, (2) the Innsbruck Quartz Phyllite and the Tarntal Mesozoics at the northwestern border of the Tauern Window, (3) the Radstadt Nappes at the northeastern border of the Tauern Window, and (4) the Semmering and Wechsel nappes in the easternmost part of the Alps (Fig. 4-1). The Lower Austroalpine Nappes originate from the former northwestern continental margin of Adria against the Piemont-Ligurian Ocean. Therefore, these units have been strongly affected by extensional tectonics during the Liassic and Early Dogger, preceding the opening of this ocean. Testimonies of this extension are Jurassic sedimentary breccias, shed from submarine fault scarps, but also the normal faults themselves which have been preserved in some areas, more or less overprinted by Alpine tectonics. The best examples are found in the Lower Austroalpine of Graubünden. The boundary between Lower Austroalpine and Penninic coincides with the former boundary between the continental crust of Adria and the oceanic crust of the Piemont-Ligurian Ocean. It is not everywhere easy to define: Slivers of Lower Austroalpine rocks are mixed with oceanic sediments and fragments of oceanic crust in the boundary zone between Penninic and Austroalpine; e.g. in the Matrei Zone of the Tauern Window and the Arosa Zone. These mixed zones are generally denoted as Penninic. The occurrence of Austroalpine slivers in these zones may be explained by gliding from the continental slope down into the trench (olistoliths), by tectonic mixing during subduction and accretion, or by emplacement of extensional allochthons, that is, klippen on top of low-angle detachments already during the break-up phase of the ocean in the Jurassic.

The Variscan basement of the Lower Austroalpine units is characterized, on one hand, by greenschist-facies metasediments, in particular, quartz phyllites from Early Paleozoic protoliths (e.g., the Innsbruck Quartz Phyllite and the Radstadt Quartz Phyllite Nappe). On the other hand, Late Variscan Granitoids are typical (e.g., the Err Granite in Graubünden or the “Grobgneis” of the Semmering Nappe System), as well as higher-grade metamorphic rock intruded by these granitoids. The Permian sediments are associated in some areas with thick bimodal volcanic rocks. The Lower and Middle Triassic is lithologically similar to other Austroalpine units, but often relatively thin. The
Upper Triassic shows the transition from the Alpine facies (Hauptdolomit) to the Germanic facies (Keuper), exemplified by the intercalation of red shale layers in the Hauptdolomit. This reflects the fact that the Lower Austroalpine represents the northwesternmost part of the Autroalpine deposition area, most distant from the Meliata Ocean. The most “Germanic” Norian is found in the Semmering area, where it is developed mainly in a terrigeneous-clastic Keuper facies. In the Liassic and Dogger, sedimentary breccias are widespread. Differently from the Upper Austroalpine (Northern Calcareous Alps and Central Austroalpine), where the breccias of the Allgäu Formation only contain reworked Mesozoic sediments, the Jurassic breccias of the Lower Austroalpine often contain basement clasts. The sediment succession reaches up into the early Late Cretaceous (flysch). The Gosau Group does not occur in the Lower Austroalpine.

Lower Austroalpine in Graubünden (Err and Bernina Nappes)

The Graubünden Lower Austroalpine is dissected by the Engadine Line, an Oligo- to Miocene strike-slip fault with variable vertical offset. The Lower Austroalpine forms two nappes, each of them subdivided into several sub-nappes divided by minor thrusts: the Err Nappe and the Bernina Nappe (Fig. 5-1). The Err Nappe is structurally deeper. Northwest of the Engadine Line, it forms the mountains around Piz d’Err. Southeast of the Engadine Line, the Err Nappe is represented by the Corvatsch Nappe and the units in the Piz Murtriröl half window. The Err Nappe comprises Variscan metamorphic basement with Late Variscan granites, the latter typically green-coloured through saussuritic alteration of feldspar (Err Granite), clastic sediments and bimodal volcanic of Permian age, a relatively thin Triassic succession, and breccia-rich Jurassic. An example of the latter is the basement-clast-dominated Saluver Breccia at Piz Nair near St.Moritz, of Latest Liassic (Toarcian) to Middle Jurassic age, erroneously attributed to the Cretaceous in earlier years. This breccia prism was shed from a normal fault scarp by submarine land slide and rock fall of the tectonically fractured footwall rocks. The series is completed by radiolarite of uppermost Dogger to Late Jurassic age, Aptychus Limestone of Latest Jurassic age, shale with turbidite layers (Lower Cretaceous), black shale (Aptian-Albian), and flysch of early Late Cretaceous age.
Although the Err Nappe was deformed during the Alpine orogeny and became a recumbent fold with a strongly thinned inverted limb, the upright sediment succession and the underlying basement in the uppermost part of the nappe, in the area around Piz d’Err, Piz Jenatsch, and Piz Laviner, remained almost undeformed. A flat-lying normal fault of Early to Middle Jurassic age, the Err Detachment, characterizes this area (Fig. 5-2 to 5-4). The uppermost crust was dismembered into tilted blocks which were displaced towards west over a fault plane which had a subhorizontal orientation at least at the end of the fault movement. The Err Detachment is partly accompanied by another detachment at a higher structural level (Jenatsch Detachment). The fault planes are marked by characteristic fault rocks, a chloritic breccias and a...
conglomerate-like cataclasite with rounded clasts in a dark grey matrix, erroneously interpreted as a carboniferous conglomerate in earlier times (“Pseudokarbon”). Findings of “Pseudokarbon” as clasts in Jurassic sedimentary breccias confirm the pre-Alpine age of the detachment faults.

![Profile through Piz Laverne, from Froitzheim & Manatschal (1996).](image1)

![Reconstruction of tectonic processes in the Late Liassic and Early Dogger which have resulted in the structural relations shown in Fig. 5-2 and 5-3. Left: Situation before formation of the Err Detachment; traces of future normal faults are dashed. Right: Final geometry of the normal fault system. From Froitzheim & Eberli (1990).](image2)

The Upper Penninic Platta Nappe (see part 2, chapter 10) underlies the Err Nappe and crops out to the West of it. It contains, in addition to the dominant ophiolites, also small slivers of Lower Austroalpine basement and sediments, sandwiched between imbricated ophiolite sheets. The typical Jurassic cataclasites of the Err Nappe also occur in these slivers. Therefore it may be assumed that the Err Detachment or a similar fault extended from the area of the Err Nappe into the Platta area. Below this fault were by mantle rocks, exhumed by tectonic unroofing and serpentinized by circulating sea water; above were “stranded” extensional allochthons of Austroalpine rocks. This allows the conclusion that the opening of the Piemont-Ligurian Ocean was accommodated by thinning of the continental crust to zero, and the resulting exhumation of the subcontinental mantle.

The Bernina Nappe reaches maximum thickness southeast of the Engadine Line. A sheet of Mesozoic sediments separates the Bernina Nappe sensu strict from the overlying Stretta Sub-Nappe. Northwest of the Engadine Line, the Bernina Nappe is represented by the granite-dominated Julier Nappe and the Ela Nappe, a detached and folded sediment succession. Like the Err Nappe, the Bernina Nappe comprises well-preserved Jurassic normal faults and the associated breccia prisms, shed from submarine fault scarps (Fig. 5-5). The normal faults within the Bernina Nappe and at the eastern border of this nappe originally dipped east, in contrast to the west-dipping normal faults along the western border of the Bernina Nappe and in the Err Nappe (Fig. 5-1).
The Alpine deformation of the Lower Austroalpine in Graubünden (Fig. 5-6) started in the Turonian with generally northwest- to west-directed thrusting and tight to isoclinal folding (Trupchun Phase), followed by extensional tectonics with southeast-dipping normal faults in the later Late Cretaceous (Ducan-Ela Phase). Where the sedimentary bedding had been steepened by sinistral transpression at the end of the Trupchun Phase, e.g. in the Albula Steep Zone along the northern boundary of the Err Nappe, extension in the Ducan-Ela Phase resulted in the formation of recumbent “collapse folds” (Fig. 5-7 and 5-8). These deformation phases affected the Lower Austroalpine together with the underlying, Upper Penninic Platta Nappe. In the Paleogene, these units were shortened in a N-S direction (upright, often south-vergent folds of the Blaisun Phase). They were affected by renewed east-west-directed extension in the Late Eocene (before intrusion of the Bergell Granodiorite at 30 Ma), leading to the formation of a shallowy east-dipping, major normal fault, the Turba Mylonite Zone. The Lower Austroalpine units are in the hanging wall of this normal fault and are cut by the associated high-angle normal faults. SW-NE-trending, NW-vergent folds formed after 30 Ma (Domlesch Phase) but these only locally affected the basal parts of the Lower Austroalpine. They are mainly found in the underlying Penninic and Helvetic units.

Fig. 5-5: Liassic breccia at Piz Mezzaun, Bernina Nappe. The breccia is composed of Triassic clasts, mainly carbonates, deposited at the foot of a normal-fault scarp by submarine rockfall and land slide. The belemnite rostrum testifies for marine deposition.

Fig. 5-6: Sequence of Alpine deformation phases (Trupchun, Ducan-Ela, Blaisun, Turba, Domlesch) in the Lower and Central Austroalpine nappes in Graubünden. From Froitzheim et al. (1997).
Innsbruck Quartz Phyllite and Tarntal Mesozoics

This complex comprises four nappes (Fig. 5-9). The lowermost Hippold Nappe rests directly on the calcareous mica schists (“Bündnerschiefer”) of the Tauern Window. It is formed by quartz phyllite at the base, followed by thin Permo-Triassic, a large volume of sedimentary breccias (Tarntal Breccia, Liassic and Dogger), and radiolarite. The overlying Reckner Nappe comprises a more complete succession of Triassic and Jurassic sediments which again include breccias in the Liassic and Dogger, but less thick than in the Hippold Nappe. Above follows the Reckner Ophiolite Complex, former oceanic basement with serpentinite and subordinate basic rocks, including blueschists. At the top is the Innsbruck Quartz Phyllite Nappe, formed by thick Early Paleozoic, greenschist-facies metamorphic pelites and minor volcanic rocks and carbonates. At the base of this nappe are Permo-Mesozoic sediments in an inverted position, in depositional contact with the quartz phyllite.

The Hippold Nappe, the Reckner Nappe, and the Reckner Ophiolite Complex were metamorphosed at high P and low T (0.8 to 10.5 GPa, 350°C: blueschist facies), whereas the Quartz Phyllite Nappe

Fig. 5-7: Recumbent folds in the Kössen Formation (Rhaetian) of the Lower Austroalpine Ela Nappe, at the Albula Pass road between Bergün and Preda. These “collapse folds” were formed by vertical shortening of steeply oriented beds during crustal extension in the Ducan-Ela Phase.

Fig. 5-8: Principle of collapse folding in the Lower Austroalpine in Graubünden. Beds which have been verticalized during the Trupchun Phase (left) are folded during the Ducan-Ela Phase (right). From Froitzheim (1992).

Fig. 5-9: Profile through the Tarntal Mesozoics and the southern part of the Innsbruck Quartz Phyllite, from Thiele (1976).
experienced only about 0.4 GPa. The position of the Reckner Ophiolite Complex above the Reckner and Hippold nappes, that is, within the Lower Austroalpine nappe stack, may be explained in the way that the Reckner and Hippold nappes originate from an extensional allochthon broken away from the Austroalpine continental margin during Jurassic rifting, so that a stripe of mantle rocks was tectonically exhumed between the allochthon and the continental margin. The Reckner Ophiolite Complex could be derived from this “mantle window”, in a similar way as described above for the Err and Platta Nappes.

To the North, a chain of gneiss lenses overlies the Quartz Phyllite Nappe. These are rocks with a higher grade of Variscan metamorphism as compared to the Quartz Phyllite (e.g., Patscherkofel Gneiss near Innsbruck, Kellerjoch Gneis near Schwaz). They are interpreted as equivalents of the Ötztal Nappe, that is “Middle Austroalpine” or, in our terminology, Lower Central Austroalpine. Above follows the Northern Grauwackenzone (Upper Central Austroalpine).

**Radstadt Nappes**

These units form the eastern continuation of the Innsbruck Quartz Phyllite and Tarntal Mesozoics, separated from these by Oligo- to Miocene activity of the SEMP Fault (=Salzach-Ennstal-Mariazell-Puchberg Fault). This is a sinistral strike-slip fault with an important vertical offset at the northern border of the Tauern Window. The Austroalpine units north of the fault are downthrown relative to the Penninic units on the southern side so that Lower Austroalpine is in the subsurface north of the fault and has already been eroded south of the fault. Further west, the SEMP Fault turns into a ductile shear zone in the Penninic units and becomes less important; to the East, it leaves the Penninic-Austroalpine boundary and trends northeast through the Austroalpine.

The Radstadt Nappes are strongly folded, the folds also affecting the boundaries between the individual nappes. Altogether, the nappes dip north and represent a foreland-dipping duplex (**Fig. 5-10**). The contact with the overlying Lower Central Austroalpine is folded as well. The following nappes are distinguished from base to top: Speiereck, Hochfeind, Lantschfeld, Pleisling, Kesselspitz, and Radstadt Quartz Phyllite Nappe. The Speiereck and Hochfeind nappes are partly enclosed in Penninic “Bündnerschiefer” of the Tauern Window (**Fig. 5-11**). This may be explained in different ways, as usual in such cases: by

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**Fig. 5-10:** Profile through the Radstadt Nappes, from Tollmann (1977).

**Fig. 5-11:** Riedlingspitze in the Zederhaus Valley, seen from northeast. Riedlingspitze is formed by Triassic dolomite of the Hochfeind Nappe, embedded as a steeply dipping sliver in Penninic “Bündnerschiefer” (background left and right).
gravitational gliding into a trench or by tectonic mixture. The pre-Mesozoic parts of the nappes are partly quartz phyllite (like in the Radstadt Quartz Phyllite Nappe), partly higher-grade basement ("Twenger Kristallin": orthogneiss, paragneiss, and amphibolite). Like in the case of the Tarntal Mesozoics, the structurally lower and originally more oceanward located nappes are characterized by large volumes of Jurassic breccias (Hochfeind Facies, analogous to the Hippold Nappe), whereas the higher nappes have a more complete Triassic succession (Pleisling Facies, analogous to the Reckner Nappe). For part of the breccias in the Hochfeind Facies, i.e. the basement-clast-rich Schwarzeck Breccia, a Late Jurassic to Early Cretaceous age is assumed because they lie on radiolarite (late MiddleDogger to early Malm). This position, however, could also result from isoclinal folding in which case the Schwarzeck Breccia could be Lower to Middle Jurassic as well. The Alpine metamorphism of the Radstadt Nappes is of greenschist-facies grade.

The Semmering and Wechsel nappes

The third large occurrence of Lower Austroalpine Nappes in Austria lies at the eastern border of the Alps. It is subdivided in two nappe systems: The Wechsel Nappe System at the base and the Semmering Nappe System at the top. The Wechsel nappes comprise basement (Wechsel Gneisses and Schists) and a relic cover of Alpine Verrucano (Permian clastics), Semmering Quartzite (Scythian), and some rauhwacke and carbonates of Middle Triassic age. The Wechsel nappes occur in a dome-like antiform beneath the Semmering nappes. The basement of the latter comprises "Grobgneis" (coarse gneiss: deformed Variscan granite) and "Hülschiefer" (enveloping schists: Variscan metamorphic country rocks of the granite). The Permo-Mesozoic of the Semmering Nappes is characterized by Keuper Facies (red and green shales, evaporites) instead of Hauptdolomit in the Late Triassic. This is because the Keuper-Hauptdolomit facies boundary is oblique to the trace along which the Penninic oceans will open in the Jurassic: Further west, it lies on the European side; here, it lies on the Adria side. The latter situation is also found in the Western Carpathians, where the Tatic units (equivalent to the Lower Austroalpine) have clastic-evaporitic "Carpathian Keuper" (Norian).
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