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THE STRUCTURE OF THE EASTERN ALPS: FROM EDUARD SUESS TO PRESENT-DAY KNOWLEDGE

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ABSTRACT

Based on scattered earlier observations of other researchers and his own fieldwork, Eduard Suess analyzed the tectonic origin of the Alps and developed a number of basic concepts in his influential book "Die Entstehung der Alpen ("The Origin of the Alps"; published in 1875) and some concepts are still applied today. Suess based his ideas on the tectonic development of the Alps largely on the interplay between field observations and comparison with other mountain ranges. He therefore introduced and used a specific comparative methodology in the field of tectonics. The tectonic structure of the Alps, which he finally compiled in a map in year 1909, is quite similar to the present-day tectonic concept. The further development of ideas on the structure and origin of the Eastern Alps can be characterized by refinement of stratigraphic and structural observations, application of new tectonic concepts like plate tectonics since the early Seventies of the last century, by application of specific newly-developed geochronological and petrological methods mainly on metamorphic rocks, and then by increasingly detailed geophysical observations on the deep structure, and finally by application of experiments and numerical modeling. All these latter methods, specifically when validated by careful field observations and integrated into current knowledge, resulted in increasingly deeper understanding of the crustal and lithospheric-scale structure and the tectonic development of the Eastern Alpine orogen. However, the present knowledge is still far from a full three-dimensional understanding of the overall structure and of the mountain building processes behind. The main reasons for this, aside from the lack of observations, are complications resulting from the oblique convergence and plate collision as well as by the lateral retreat of the subduction acting on a remnant land-locked basin in the eastern lateral extension of the Eastern Alps.

Aufbauend auf älteren Beobachtungen anderer Forscher und auf Grund eigener Geländearbeiten analysierte Eduard Suess die tektonischen Entwicklung der Alpen und entwickelte eine Reihe von Basiskonzepten in seinem 1875 publizierten einflussreichen Buch „Die Entstehung der Alpen“. Einige der Konzepte werden immer noch angewandt. Suess baute seine Ideen über die tektonische Entwicklung der Alpen auf das Wechselspiel zwischen Geländebeobachtungen in den Alpen und den Vergleich mit anderen Gebirgsketten auf. Er führte damit eine spezifische Vergleichsmethodologie in das Feld der Tektonik ein. Die tektonische Struktur der Alpen, die er schließlich 1909 kompilierte, ist sehr ähnlich zu gegenwärtigen tektonischen Konzepten. Die weitere Entwicklung der Ideen über die Struktur und Entwicklungsmodelle der Ostalpen kann durch Verfeinerung der Stratigraphie und strukturellen Beobachtungen charakterisiert werden, durch die Anwendung der plattentektonischen Konzepte seit den siebziger Jahren des letzten Jahrhunderts, durch die Anwendung spezifischer, neu entwickelter geochronologischer und petrologischer Methoden hauptsächlich an metamorphen Gesteinen, später durch zunehmend detaillierte geophysikalische Beobachtungen zur Tiefenstruktur der Alpen und schließlich durch Analogexperimente und numerische Modellierungen. All diese genannten Methoden erlauben, besonders wenn sie durch Geländebeobachtungen getestet und in die gegenwärtige Kenntnis eingebaut wurden, resultierten zu einem tieferen Verständnis der krustalen und lithosphärischen Struktur und tektonischen Entwicklung der Ostalpen. Dennoch ist die gegenwärtige Kenntnis noch weit von einem vollen dreidimensionalen Verständnis der Gesamtstruktur der Ostalpen und der dahinterstehenden Gebirgsbildungsprozesse entfernt. Die Hauptgründe dafür sind, abgesehen von fehlenden Beobachtungen, Komplikationen durch schräge Plattenkonvergenz und Plattenkollision wie auch das seitliche Zurücktreten der Subduktion des landumschlossenen ozeanischen Restbeckens in der östlichen Fortsetzung der Ostalpen.

1. INTRODUCTION

Based on his early work on stratigraphy, geology and paleontology since ca. 1852, Eduard Suess became highly interested in the tectonic evolution of mountain ranges, particularly of the Alps. He wrote down his ideas in an influential book on the origin of the Alps (Suess, 1875). Later, he refined several aspects in his monumental volumes "Face of the Earth" (Suess, 1885 to 1909). In his initial book (Suess, 1875), he already introduced the comparative method in tectonics and was the master of this approach. He based his arguments on the comparison of distinct features of the Alps with many mountain belts worldwide (for more details, see also Erh. Suess, 1916; Şengör, 2014 and Şengör et al., 2014). Eduard Suess attained detailed knowledge of the Alps and mountains in the eastern lateral extension of the Eastern Alps, the Dinarides and Carpathians, and he compared important aspects of the internal zonation of the Alps with such of many other mountain ranges (see below) and compiled observations in his benchmark and highly influential books “Das Anlitz der Erde”. This series of books finally comprised three volumes in four books (Suess, 1885, 1888, 1901, 1909), which were eventually translated into English under the title “The Face of the Earth”.

Many aspects of the contributions of Eduard Suess to the field of tectonics, particularly to nappe tectonics (e.g. Pilger, 1974; Tollmann, 1981, 1986), and on the origin of mountain belts were already highlighted in a number of papers (e.g. Şengör, 2000, 2009). Consequently, although it is quite important, no attempt is made here to repeat and further refine this historical knowledge of the early evolution of ideas on structure and evolution of the Alps. Here, the development of ideas on the formation of the Eastern Alpine orogen is traced from the initial benchmark book of Suess (1875) up to recent times. At the time of Suess, sedimentary rocks and its fossil contents in combination with observations on the structure were mainly used to infer the tectonic evolution of a mountain belt as well as its overall structure. Of course, other rocks such as granites and their relationships to sedimentary and metamorphic rock sequences got a lot of attention (e.g., Şengör et al., this volume). Aside from refined and detailed field observations, the concepts of the new global tectonics/plate tectonics, the application of new techniques such as geochronology in combination with metamorphic petrology led to significant steps in the understanding of the formation of the Eastern Alpine mountain range. These methods and the observations of geophysical sounding on the deep structure as well as modeling work allow a more coherent model although the present state of knowledge is still not sufficient for a full understanding. These new observations allowed inferences on a real 3D-structure and its development through time.

This contribution is aimed to demonstrate how new observational techniques contribute to the structure and interpretation of mountain building processes since the initial work of Eduard Suess (1875). This approach demonstrates that not only classical concepts on scientific progress including changes of paradigms (e.g., Kuhn, 1970) or the verification or falsification of concepts, hypotheses and theories (e.g., Popper, 1935) influence the scientific progress but also new technologies. Looking back on the last ca. 140 years of research reveals that the application of new observational techniques adds new dimensions and allows in particular the recognition of physical parameters to mountain building processes.

2. WHAT GUIDES THE DEVELOPMENT OF KNOWLEDGE?

Research fields like mineralogy, petrology, geochronology and geophysics, all disciplines of Earth sciences, initially developed with totally different approaches as compared to classical geology. The emerging knowledge provided new data that upon integration into the already known geological data gave new insights and deepened our knowledge considerably.

Many fields of natural sciences progress from initial basic observations and the development of concepts based on the interpretation of these observations to a more process oriented science. However, there is also another path, namely new observational techniques, which may potentially allow determination of physical and chemical parameters, which then may allow qualitative and quantitative assessment of geological processes, in our case that of mountain building. Initially, such new techniques are often developed for entirely different purposes but eventually reach the Earth sciences. Observations based on such new innovative methodologies can poten-

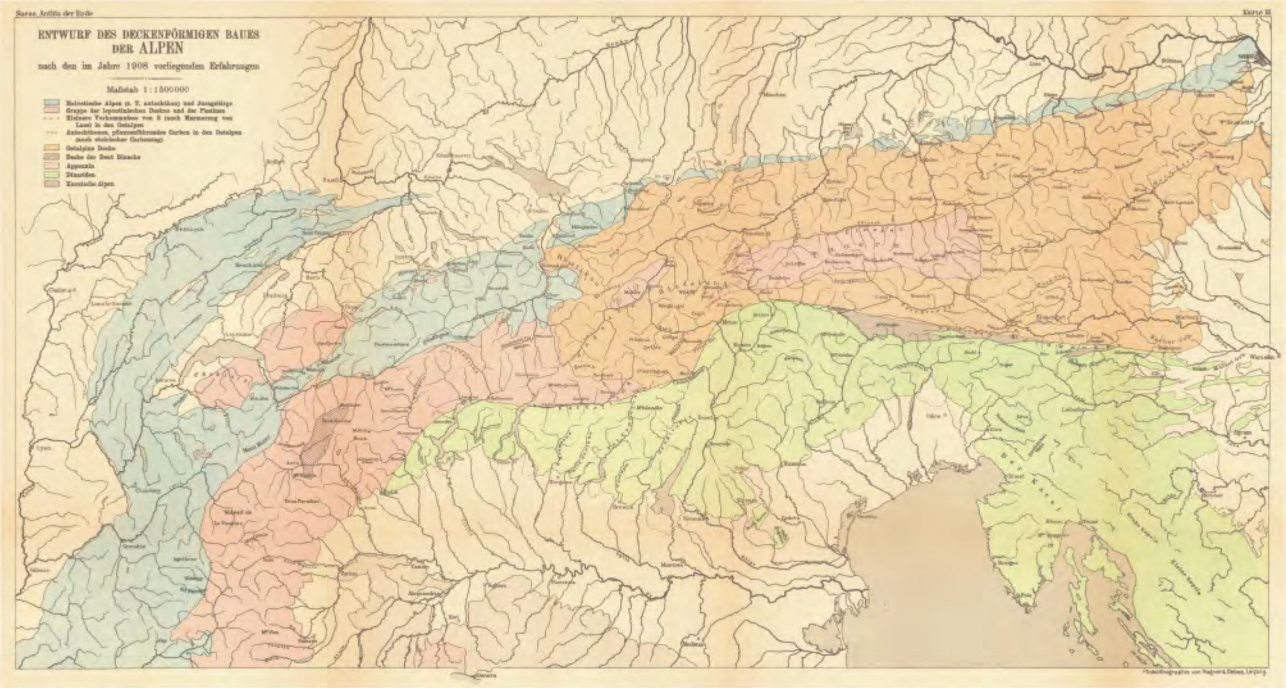

FIGURE 1: Simplified tectonic map of the Alps from Suess (1909).

tially change the respective field by providing access to important physical parameters such as absolute time, temperature and pressure of rock formation, e.g. of metamorphic rocks and intrusives, which were previously unknown. This is particularly true for large objects such as mountain ranges, which expose rocks at the surface, which were formed at a wide range of distinct structural levels – as we now know – of the crust and lithosphere. Application of novel analytical methods potentially allows determination of physical and chemical conditions, particularly the recognition of timing, duration and rate of processes. This change in methodologies and the impact is shown using the example of the development of ideas on the origin and formation of the Eastern Alps.

3. The ideas of Eduard Suess on the origin of the Eastern Alps

As stated before, Eduard Suess was a master of the comparative methodology in tectonics. With the concept of comparative tectonics, Suess considered the development of distinct stratigraphic successions and the distribution of tectonostratigraphic units of various mountain belts and tried to deduce general principles. His merits in tectonics and in particular for shortening tectonics by folding were already described in several contributions, from which some are mentioned here including those of Tollmann (1981, 1986) and Şengör (2000, 2009). Eduard Suess observed many features which are still fundamental in field geology and discussed distinct features of many orogenic belts. Through contact with many researchers worldwide he learned much about mountain belts he never visited.

In his book on the origin of Alps, Suess in 1875 already described a great number of characteristics, e.g. nature and relationships between various sedimentary units, and processes responsible for the origin of mountain belts. The focus of his work was clearly on sedimentary rocks and the fact that various distinct units formed approximately at the same time. In other cases, he discussed particular rock successions, e.g. the presence of pelagic above shallow water sediments, resulting from a process which is now known as basement subsidence of a sedimentary basin. A fundamental observation was that mountain ranges incorporate thick sedimentary deposits of margins of seas and that the central zone contains mainly plutonic rocks, which were considered to be older than the marine sediments along margins of the future mountain range (for a recent discussion on the development of the geosyncline concept, see Mahlburg Kay, 2014). He discovered that mountain ranges extend laterally over large distance with rocks, which are similar in composition and stratigraphic age. He discussed the presence of mountain-parallel folds as the result of horizontal ("transversal") shortening, which is directed towards the foreland. He introduced the aspect of foreland-directed vergence of motion within mountain belts. He also found that earthquakes are sometimes the expression of horizontal motion, e.g. citing the Calabrian earthquake of 1783 (Suess, 1875, p. 168). Intuitively, he also recognized that basement massifs like the Bohemian Massif in the front of the

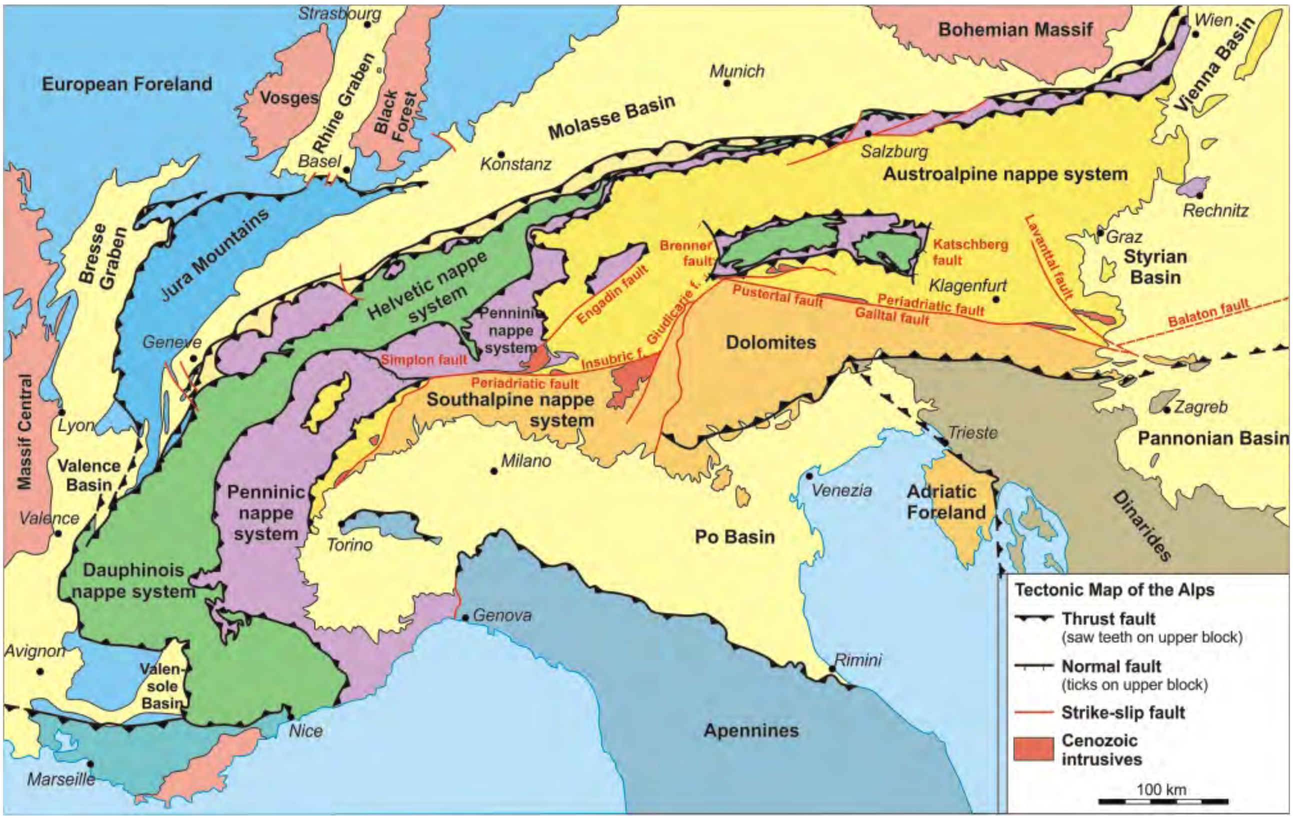

Figure 2: Geological map of the Alps (modified after Pfiffner, 2014). Abbreviation: f., fault.-

Eastern Alps are somehow related to shortening processes in the adjacent mountain range. All these observations are still correct and were refined by many subsequent researchers. Left entirely open were indications on the duration and timing of geological processes, although a long duration of such processes was generally assumed.

In his first volume of “Das Anlitz der Erde” (Suess, 1883), he further developed many aspects already mentioned in the book “Die Entstehung der Alpen" (Suess, 1875). Among these aspects is the extensive continuity of folds along the strike of mountain ranges but also the presence of late-stage sedimentary basins, such as the Pannonian Basin, post-dating orogenic motion. In particular, he described the importance of stratigraphy for the recognition of a schuppen or imbricate of sedimentary units implying significant subhorizontal shortening within the mountain range.

In the second volume of “Das Anlitz der Erde” (Suess, 1888), he discussed the difficulty of correlating sedimentary units in the Alps by applying stratigraphy developed in other regions, e.g. England, as well as the origin of basement uplifts outside of the Alps as a result of orogenic motion. In the Eighties of the Nineteenth century, based on work of Escher, Schardt and Lugeon discussed in Bertrand (1884), Suess reinterpreted the Glarner double fold as a north-directed thrust, basically as it is still interpreted now (for further details, see Tollmann, 1981 and Letsch, 2014). After the recognition of the large-scale nappe structure and the nature of the Tauern Window (Termier, 1903, 1904), he re-assessed the knowledge on the Eastern Alps in his final work (Suess, 1909) and gave an interpretation of the structure of the Eastern Alps, which is still valid today (Figs. 1, 2), as can be seen when comparing his tectonic map shown in Fig. 1 with a modern equivalent by Schmid et al. (2004, 2008) or Pfiffner (2014) shown in Fig. 2.

4. POST-SUESS DEVELOPMENT OF KNOWLEDGE ON THE ORIGIN OF THE EASTERN ALPS

4.1 REFINEMENT OF STRATIGRAPHY AND STRUCTURE

In the aftermath of the tectonic work of Eduard Suess, refinements of observations on stratigraphy and structure were undertaken (Pilger, 1974 for review). The observation that Permotriassic cover sediments are overlain by older subparallel, sometimes crystalline basement successions finally led to the recognition of nappes within the Austroalpine nappe system (Tollmann, 1959; Flügel, 1960) although many of these observations were made much earlier (e.g., Holdhaus, 1921). Despite a long-lasting heated debate, some details of the overall nappe structure are still not fully resolved and many controversial models were proposed (e.g., Schmid et al., 2004).

Ampferer (1906) was the first to recognize the disappearance of foreland rock successions underneath mountain belts and founded the theory of subfluence (Verschluckung), which is still valid today (concept of [continental] A-subduction, A for Ampferer). Trümpy (1958, 1960) was the first to give a detailed paleogeography of the Western Alps with some notes on the Eastern Alps. The integration of the concept of paleogeography with plate tectonics deepened our understanding of the evolution of the Alps.

4.2 IMPACT OF THE PLATE TECTONIC CONCEPT

After the foundation of the plate tectonic concept of the opening and closure of oceans (Wilson, 1966), mountain ranges became the focus of structural geologists as the sites of collision of continents after subduction and final consumption of oceans between the continents. The initial research focus was on the recognition of oceanic sutures as the sites of lost oceans between continents and the recognition of high-pressure metamorphic remnants as the potential sites of former subduction zones. Suddenly, eclogites, which were initially described from the Saualpe region of the Eastern Alps (Haüy, 1822) received much attention (see below). However, the main focus during that period was to revise the well-known lithostratigraphic units and paleographic domains in regard to their significance in a plate tectonic framework. Based on Trümpy´s work (e.g., Trümpy, 1960, 1971), the first models applying the plate tectonic concept to the Eastern Alps are those of Hawkesworth et al. (1975) and Frisch (1977) (see also Trümpy, 2001). They recognized major rifts separating the Austroalpine continental microplate from stable Europe, the formation and consumption of one respectively two Penninic oceans, and the evidence (e.g. timing of metamorphism) for units transformed during subduction. Interestingly, although dealing with lithospheric-scale plate processes, all the concepts were still essentially based on supracrustal rock successions and on processes visible in the upper crust without the involvement of lower crustal units and mantle lithosphere.

4.3 IMPACT OF GEOCHRONOLOGY AND PETROLOGY

The accurate absolute timing of geological processes is of prime importance to linking plate tectonic processes to the formation of a mountain range in time and space. Biostratigraphy provides detailed knowledge on the timeframe of geological processes in the sedimentary realm on Earth´s surface. However, biostratigraphy alone does not allow determining geological rates. The introduction of the absolute time scale was possible by the emerging field of geochronology after the detection of radioactivity and its application to the geological time-scale (Holmes, 1913). For the first time, geologists realized the duration and rates of geological processes including plate tectonic processes, although the long duration of geological processes was already considered before the detection of radioactivity.

The age of protolith formation of magmatic rocks and the age and degree of metamorphism did not play a major role in the early discussion of the origin of mountain ranges or in the considerations of Suess. In the Eastern Alps, most amphibolite-grade metamorphic rocks – except those of the Tauern Window – were until quite recently considered as Altkristallin with inferred Precambrian age. The application of geochronology brought significant new insights, both in discussion on the age and the tectonic significance of metamorphism. Suddenly, it appeared that metamorphic rocks have the same age as sedimentary units in their neighborhood. This was, e.g., the discussion on the Late Cretaceous age of metamorphism in the Koralpe and the nearby Upper Cretaceous Kainach Gosau basin (Kantor and Flügel, 1964; Flügel, 1964). About two decades ago, the well-known eclogites of the Koralpe and Saualpe (Haüy, 1822) were dated and it was revealed that their high-pressure imprint within eclogite metamorphism was caused by the subduction of Permian rift-generated gabbros embedded within a passive continental margin during late Early Cretaceous (Thöni and Jagoutz, 1992). Application of experimental results to metamorphic mineral parageneses showed the high temperatures and (increasingly higher estimates of) pressures during peak conditions of metamorphism to be related to subduction processes. These studies also revealed the final juxtaposition of distinct metamorphic rocks units, which formed at different structural levels and in part at different times. These studies also allowed inferences on the mode of exhumation of previously buried rock successions. The metamorphic map of Frey et al. (1999; Fig. 2) is a good example for showing the fourth dimension (time) of the Alpine mountain range now frozen at the Earth´s surface (Fig. 3). Major orogen-parallel extensional structures within the convergent orogen were also revealed (Selverstone, 1988; Ratschbacher et al., 1989). Another important discovery was the detection of rift-related Permian high temperature/low-pressure metamorphism (Schuster et al., 2001).

4.4 Impact of geophysics on recognition of the deep structure of the Eastern Alps

Some geophysical characteristics of mountain belts like a negative gravity anomaly were already considered in the Nineteenth century. On a larger scale, since the Sixties of last century, geophysical methods were applied to reveal the deep structure beneath the Alps. Initially, geophysics established the negative gravity anomaly along the central axis of the Alps, implying a deep mountain root below the Alps. Later, first some commercial reflection seismic lines of oil companies reached the geology community in the Seventies of the last century. Then, in the aftermath of many short and detailed sections in the French-Italian (ECORS-CROP; Nicolas et al., 1989) and Swiss Western and Central Alps (NRP20; Pfiffner et al., 1997), the TRANSALP cross-section across the central Eastern Alps revealed details of the internal structure of the Eastern Alps (TRANSALP Working Group, 2002). The most important first order features were the Moho dipping towards the center of the orogen, the different thicknesses of lower and upper crust of the stable European plate and the indenting Adriatic microplate as well as the detection of deep-

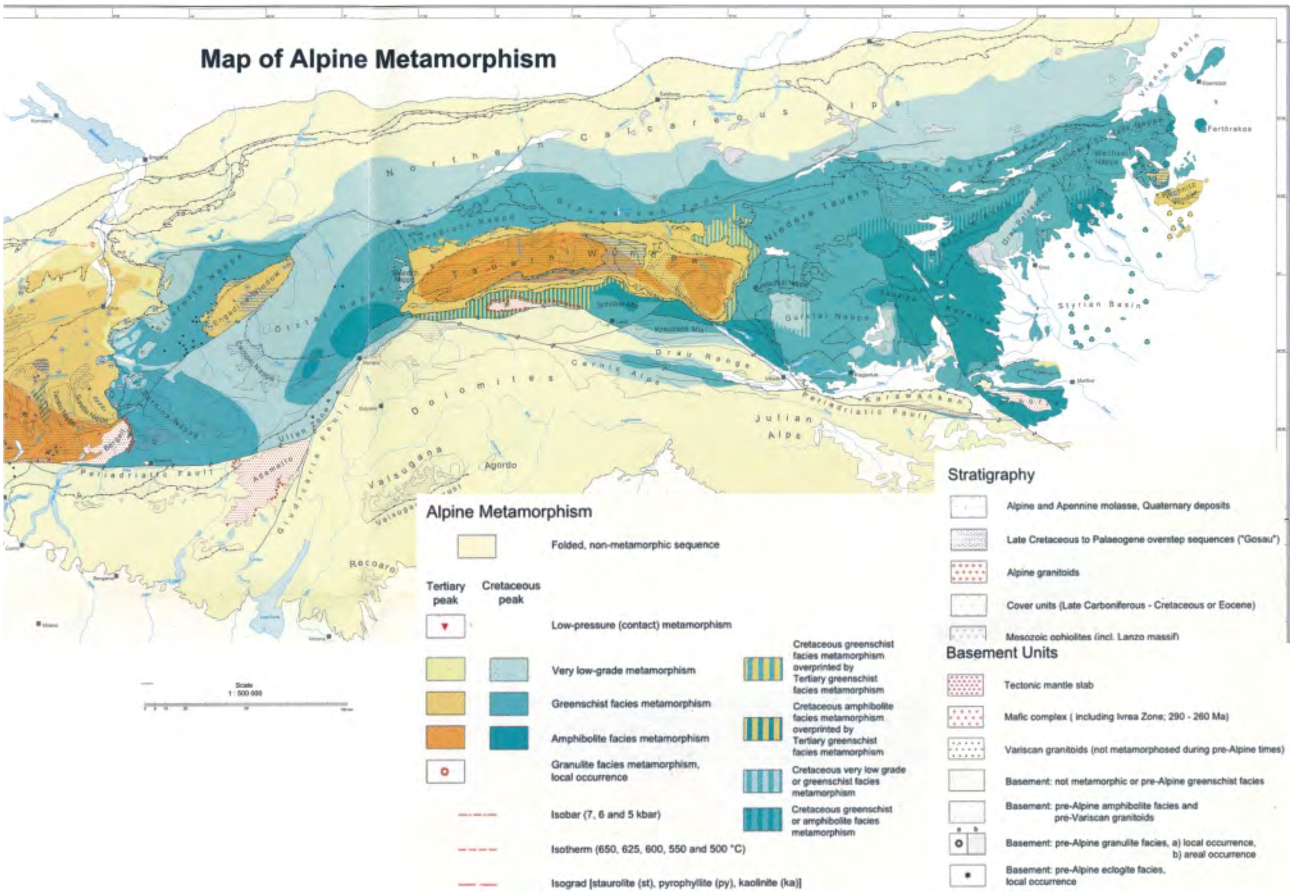

Figure 3: Simplified map of metamorphism in the Eastern Alps (slightly adapted from Frey et al., 1999).

seated sub-Tauern reflectors under the Hohe Tauern area, which is interpreted as the major preserved thrust formed during continent-continent collision (TRANSALP Working Group, 2002; Diehl et al., 2009; see Pfiffner, 2014 for a full discussion for crustal and lithospheric thicknesses).

The lithospheric structure of the Alpine orogeny was revealedby mantle tomography, a piece of information previously unavailable (e.g., Wortel and Spakman, 2000; Lippitsch et al., 2003), and resulted in the recognition of subducted lithosphere underneath the present-day Pannonian basin and of microplate interaction. A polarity flip of the late-stage of subduction was also postulated (Lippitsch et al., 2003). More recent images of the upper mantle show a +/- vertically dipping slab to a depth of 200 – 250 km under the Eastern Alps (Koulakov et al., 2009; Dando et al., 2011; Mitterbauer et al., 2011). This shape of the slab neither directly supports nor contradicts the idea of a subduction polarity flip. Future work, including modelling and 3D plate tectonic reconstructions might have the potential to resolve this issue. Further work resulted in the recognition of several lithospheric plates, which interacted in the eastern part of the Eastern Alps (e.g., Brückl et al., 2010). Based on shear wave splitting of earthquake seismic waves, Bokelmann et al. (2013) recognized the orientation of the fastest direction of seismic waves within deep levels of the lithosphere subparallel to the Alpine orogen. This is consistent with the model of lateral eastwards extrusion within the uppermost crust (Ratschbacher et al., 1989, 1991a, b).

4.5 Integration of the Eastern Alps into the Alpine-Mediterranean mountain belt

Eduard Suess already integrated the geology of the Alps into a larger framework of Alpine Mediterranean mountain belts. The major difference to other straight mountain ranges is (1) the arcuate shape of the Alpine belt (e.g., in Western Alps and Carpathians) and (2) the presence of the Neogene Pannonian basin on top of the mountain range. Both observations call for additional geological processes, which are not dominant in straight mountain belts. In contrast to the eastern extensions, the Eastern Alps continue straight to the Central Alps, although the predominance of deeper tectonic units indicate a stronger exhumation of Central-Alpine units resulting in eroding away of the higher, Austroalpine tectonic unit. This is particularly well visible in a metamorphic map of the Alps (Fig. 3), which shows the younger Oligocene-Neogene age of metamorphism in the Central and Western Alps.

Towards the Carpathians and Dinarides in the east, units of the Eastern Alps diverge, and the northern orogenic front is concave towards the foreland. The greatest degree of curvature (ca. 60°) is found adjacent to the Bohemian massif. A similar change of strike is visible along the southern front, in the Friuli area. Three competing processes were proposed to be responsible for the particular Neogene curved structure, which is superimposed on earlier Cretaceous to Paleogene structures: (1) Closure of a land-locked oceanic basin driven by Late Eocene-Miocene (Kázmer et al., 2003) slab-rollback beneath the Carpathians and eastward retreat of the trench triggering extension and eastward motion of upper plate units (e.g., ALCAPA - Alpine-Carpathian-Pannonian - and Tisia blocks) (Royden, 1988, 1993; Wortel and Spakman, 2000). This was paralleled by an Oligocene to Pliocene shift of depocenters in the peripheral foreland basin all around the Alpine-Carpathian front. Slab break-off triggered magmatism, which also migrated along the strike of the Carpathian orogen from ca. 18 Ma in the west to a Pleistocene age (70 ka) in the SE Carpathian bend zone (Wortel and Spakmann, 2000). (2) The ca. NNW-ward motion of the Adriatic indenter resulted in eastward extrusion of the ALCAPA block, which is confined by a northern sinistral and a southern dextral wrench corridor (Ratschbacher et al., 1991a, b). (3) Bending around the Bohemian promontory resulted in bending and rotation of blocks around promontories and counter-clockwise and clockwise rotation of the eastern part of these blocks.

4.6 Impact of modeling of tectonic processes

Geological processes must be considered to be influenced by many parameters, making it impossible to model all parameters using numerical modeling techniques. Since the increasing power of computers, more and more programs are in use, which are often specifically developed for revealing distinct geological processes. Numerical models include physical and chemical parameters and allow sensitive analyses on how parameters influence the development of a distinct geological structure. Modeling cannot always portray a geological situation explicitly but rather potentially allows recognizing the principal parameters controlling a specific geological process. Consequently, validation of results is of prime importance. In this sense, subsidence modeling of the Austroalpine passive continental margins was likely one of the first applications of numerical modeling (Hsü, 1982). Modeling of the thermal evolution of metamorphic terrains allowed limiting possible evolutionary paths (Oxburgh and Turcotte, 1974; Genser et al., 1996). A good example of application of timing and degree of metamorphic P-T conditions on rheological properties and density parameters is the study of Stüwe and Schuster (2010) on potential controls of the site of subduction initiation in the Alpine orogen, which, however, still needs to be validated. Further numerical modeling studies revealed the dependence of nappe-internal structures from the stratigraphic successions (Wissing and Pfiffner, 2003; Wissing et al., 2003), the influence of erosion on the structure of the orogen formed in continental collision (Pfiffner et al., 2000) or mantle scale modeling on exhumation of high-pressure assemblages (Stöckhert and Geryas, 2005). Other numerical studies demonstrated the control of only a few parameters on the final overall structure of the orogen (Robl and Stüwe, 2005).

4.7 Earth´s surface processes

Over a long period of research, Earth´s surface and morphology of mountain ranges were not in the focus of structural geologists, but of geomorphology housed within geography. In my personal opinion, this suddenly changed as a result of several factors: (1) the recognition in the Eighties of last century that the Earth´s surface is incompletely known and detection of high mountains in remote areas (e.g., Burchfiel et al., 1989); (2) the availability of high-resolution topographic data covering most of the Earth´s surface (http://srtm.usgs.gov/index.php), and (3) application of numerical modeling on mountain belts, which show the effects of changing isostasy, subsidence and explanation of stratigraphy. Although some effects such as isostasy were already known at the time of Eduard Suess the increasing integration into geological models is new; and (4) the availability of digital elevation models allows the study of mountain belts at the orogen scale and even of its surface changes with a high precision (e.g., Frisch et al., 2000). Previous geodetic surveys yielded precise determinations of vertical motions since the Nineteenth century (see compilation in Pfiffner, 2014). Global position surveys (GPS) allow precise horizontal measurements and the integration into geological models (e.g., Grenerczy et al., 2000 for the Eastern Alps). Numerical models combined with field observations revealed the significance of erosion and climate for the internal structure of mountain belts. Although many precursor observations were available for the Eastern Alps (Winkler-Hermaden, 1957) and the geogenic hazard by earth surface processes was always in the focus of both geologists and geomorphologists, the latter in geography departments, basic work on the evolution of the overall morphology of the Eastern Alps came into focus again by the working group of Wolfgang Frisch (Tübingen) who showed the significant difference between western and eastern parts of the Eastern Alps (Frisch et al., 2000). Kühni and Pfiffner (2001) studied the evolution of the drainage pattern as a function of bedrock geology and orogenscale uplift patterns of the Swiss Central Alps by a numerical model. Robl et al. (2008) modeled the geomorphological evolution of the Eastern Alps and are able to reasonably reproduce the lateral extrusion-related nature of the formation of the present-day morphology of the Eastern Alps (Ratschbacher et al., 1989).

5. Discussion

5.1 Revolutionary steps in the growth of knowledge

With his benchmark work on the origin of the Alps, Suess (1875) made many statements and asked many questions on several aspects of mountain building processes, which were impossible to fully answer at that time. The driving plate boundary forces of mountain building processes, such as the sinking mantle-lithosphere slab, and three-dimensional structure of a mountain range were entirely unknown. At that time, there was no quantitative framework of geological time, which could allow determining the rate and duration of geological processes. The large progress was achieved by the combination of basic principles of comparative tectonics initially developed by Eduard Suess since 1875 with new observational techniques including geochronology, metamorphic petrology and geophysical deep sounding. Nevertheless, stratigraphic and facies observations had already allowed significant refinement of the tectonic evolution. Large steps were the application of plate tectonic concepts, the detection and refinement of the deep structure of the mountain belts, refined absolute timescale regarding geological processes in the Alps and the detection of the significance of metamorphism for the understanding of burial and exhumation.

5.2 Future directions of research

It is inherently interesting to have a look into the future development of geological research in the Eastern Alps. Kuhn (1970) divides research into gradual and revolutionary, the later involving a change of paradigms. Several trends are easily recognizable because these are in line with ongoing “gradual” research. For the Eastern Alps, these include a trend (1) to quantification of all sorts of mountain building processes (e.g., overall shortening of the mountain belt done by Lüschen et al., 2004), (2) refinement of the lithospheric-scale structure of the whole mountain belt (e.g., Lippitsch et al., 2003; Brückl et al., 2010; Brückl and Hammer, 2014, this volume), (3) integration and visualization of all sorts of data on the mountain belt within geographic information systems, the later well done by the Austrian Geological Survey and those of neighboring countries, (4) increasing application of inexpensive geochronological dating processes to all sorts of plutonic and metamorphic rocks, (5) refinement of surface processes and recognition of the relative role of climate and tectonics on the surface structure of the Eastern Alps. As can be seen in other parts of the orogen such as the Swiss Central Alps, a dense set of accurate geochronological age data removes many uncertainties on the tectonic evolution. On the other hand, the quantitative role of the competing tectonic forces in the east of the present-day Eastern Alps is still largely unknown. Work on the somehow unique transition of the Eastern Alps to the Carpathians, the Dinarides and the Pannonian basin is expected to bring new insights into the mountain building processes which have formed the Eastern Alps.

The rate of deformation processes is now considered to result from plate tectonic processes. However, the distribution of such rates over the whole lithosphere is largely unknown. In this respect, entirely new information is expected to be acquired by nanoscale investigations of geological processes in solid rocks, which will likely allow determining the role and significance of fluid transfer through deep-seated rocks. Not much is known on the role of fluids during mountain building processes although fluids are known to influence the deformation mechanisms of rock-constituting minerals at nappe contacts or within nappes within the orogen. Fluids significantly influence the duration of velocity of mountain building processes (e.g., Mahlburg-Kay, 2014). Investigations on the role of fluids might have a potential for a sort of scientific revolution. This is obviously one particular feature of the Alpine mountain range that has been left entirely out of discussion.

Another less well constrained aspect of subduction is the occurrence of only rare magmatic rocks constraining the long-lasting subduction of the Penninic oceanic lithosphere as well as of continent-continent collision. The andesitic components in the Eocene Taveyannaz Sandstones of the Western and Central Alps (e.g. Boyet et al., 2001) are an exception to such volcanism and are more synchronous with initial steps of collision than long-lasting Late Cretaceous to Middle Eocene subduction. The Late Eocene to Oligocene plutonic belt along the Periadriatic fault (Rosenberg, 2004 for a recent summary) is explained as slab break-off magmatism rather than subduction (von Blanckenburg and Davies, 1995).

A further characteristic of the progress of science is to learn that many ideas have precursor observations, which are often neglected by subsequent researchers. An example of the time of Eduard Suess is the observation of a large-scale potential nappe-structure of Richthofen (1859) and many others can be found up to recent times. Richthofen (1859) found and displayed a thrust of Northern Calcareous Alps over Eocene Flysch (see Tollmann, 1981 for further details). Other aspects with many precursor observations include the vergence of nappe transport (Ratschbacher, 1986), the role of extension (e.g., Clar, 1973 vs. Tollmann, 1977) within mountain belts or the role of large-scale orogen-parallel strike-slip faults.

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