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Eduard Suess' conception of the Alpine orogeny related to geophysical data and models

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Abstract

In his treatise „Die Entstehung der Alpen“, Eduard Suess presents a wealth of geological observations and a fascinating conception of the orogeny of the Alps and mountain chains in general. It is an inspiring task to review the state of the Physics of the Earth at the time when Suess worked on this treatise and to estimate its impact on Suess' work. We find that only seismology, a discipline to which Suess himself contributed a substantial amount of research, supported his geological work and tectonic reasoning to some extent. Since the publication of „Die Entstehung der Alpen“, Physics of the Earth has made tremendous progress and geophysical data and models have become of fundamental importance for tectonic theories. We review this evolution as well as modern geophysical data closely related to the orogeny of the Eastern Alps. We consider fundamental observations and findings of Suess and relate them to modern geophysical data on the structure and kinematics of the lithosphere. Issues we wish to highlight are the significant asymmetry and arcuate shape of mountain ranges and in particular the Alpine system. Suess related these observations to absolute movements of crustal blocks. In the case of the Alps, an Adriatic crustal block moves from south toward the axes of the mountain range. For the Himalayas, the direction is opposite and the Asian crust moves from north towards India. Suess' conception is consistent within the frame of the contraction theory, generally accepted at that time. We interpret the moving crustal block sensu Suess as the upper plate of a continent-continent collision. We show that this transformation of Suess' conception to a platetectonic frame is consistent with modern geophysical data and models of the lithosphere and upper mantle. Suess' ideas would require a uniform subduction of European continental lower lithosphere under the Adratic plate to be realizable. Suess points out that the architecture of the Southern Alps does not follow the general scheme of one-sided northward movement. We show that also a modern model of the lithospheric structure and kinematics addresses this observation and needs a minor modification of the general plate tectonic principles, i.e. some north-south oriented compression of the Adriatic plate. Finally we emphasize Suess' considerations regarding the tectonic situation south-east of the Bohemian promontory. Here the axis of the mountain range bends to the north-east and, according to Suess, the moving crustal masses are deflected to the east, thus introducing tension and forming the Vienna Basin. We value this interpretation as an ancestor of the extrusion model. We address the same issue on the basis of the modern geophysical data and present a tectonic model of the lithospheric mantle, which explains extrusion as a plate tectonic process.

In seiner Abhandlung “Die Entstehung der Alpen” präsentiert Eduard Suess eine Fülle geologischer Beobachtungen und ein faszinierendes Konzept über die Entstehung der Alpen und die Gebirgsbildung im Allgemeinen. Es erscheint als anregende Aufgabe, den Stand der Physik der Erde zurzeit, als Suess an dieser Abhandlung arbeitete zusammenzufassen und seinen Einfluss auf seine Arbeit zu bewerten. Wir finden, dass lediglich die Seismologie, eine Disziplin zu der Suess selbst als aktiver Forscher Wesentliches beitrug, seine geologische Arbeit und sein tektonisches Denken in mancher Hinsicht beeinflusste. Seit dem Erscheinen von „Die Entstehung der Alpen“ machte die Physik der Erde gewaltige Fortschritte. Geophysikalische Daten und Modelle erlangten grundlegende Bedeutung für die Entwicklung tektonischer Theorien. Wir geben einen Überblick über diese Entwicklung und fassen neue geophysikalische Daten mit einem engen Bezug zur Orogenese der Ostalpen zusammen. Wir betrachten grundlegende Beobachtungen und Erkenntnisse von Suess und stellen sie zu neuen geophysikalischen Daten über Struktur und Kinematik der Lithosphäre in Beziehung. Ein Thema, das wir besonders hervorheben wollen, ist die signifikante Asymmetrie und der bogenförmige Bau von Gebirgsketten im Allgemeinen und dem Alpinen System im Besonderen. Suess setzt diese Beobachtungen mit absoluten Bewegungen von Teilen der Erdkruste in Beziehung. Im Fall der Alpen bewegt sich ein der adriatischen Kruste zugehöriger Block von Süden her gegen die Achse des Gebirges. Beim Himalaya ist die Bewegungsrichtung umgekehrt und es bewegt sich Asien von Norden her gegen Indien im Süden. Die Vorstellung von Suess ist konsistent im Rahme der Kontraktionstheorie, welche zur dieser Zeit allgemein akzeptiert war. Wir interpretieren den Teil der bewegten Kruste sensu Suess als die Oberplatte bei einer Kontinent-Kontinent Kollision und zeigen, dass diese Transformation des Konzepts von Suess in einen plattentektonischen Rahmen konsistent mit modernen geophysikalischen Daten und Modellen der Lithosphäre und des oberen Mantels ist. Suess‘ Vorstellungen fordern demnach eine einheitliche Subduktion europäischer kontinentaler tieferer Lithosphäre unter die Adriatische Platte. Suess hält fest, dass die Architektur der Südalpen nicht dem generellen Muster der einseitigen, nach Norden gerichteten Bewegung entspricht.

Wir zeigen, dass auch ein neueres Modell der Struktur und Kinematik der Lithosphäre diesen Aspekt berücksichtigt und ein geringfügiges Abweichen von den Grundprinzipien der Plattentektonik bedingt, und zwar eine nord-süd orientierte Kompression innerhalb der adriatischen Platte. Schließlich heben wir Suess' Überlegungen zur tektonischen Situation südlich und östlich der Böhmischen Masse hervor. In diesem Bereich der Ostalpen und Überganges zu den West-Karpaten biegt der Gebirgsbogen nach Nord-Ost. Nach Suess werden die von Süden herkommenden bewegten Krustenteile hier nach Osten abgelenkt. Die hierdurch induzierten Zugspannungen sind für die Entstehung des Wiener Beckens verantwortlich. Wir bewerten diese Interpretation als einen Vorläufer des Extrusionsmodells, behandeln denselben Aspekt auf der Basis der neuen geophysikalischen Daten und zeigen ein tektonisches Modell des lithosphärischen Mantels, das die Extrusion als plattentektonischen Prozess erklärt.

1. Introduction

The treatise „Die Entstehung der Alpen“ by Eduard Suess (1875) had an extraordinary impact on geological reasoning regarding mountain building and orogeny during the decades after its publication. Even today the ideas are fascinating and challenging due to the wealth of geological observations and the admirable degree of generalization. Cooling and thermal contraction of the Earth was considered by geologists and physicists during the 19th century to be the engine driving mountain building. This continued until 1960-65 (Jeffreys, 1962, Toperczer, 1960). Eduard Suess accepted this theory as the most probable, however he put particular emphasis on geological observations and their generalization. Only at the very end of the treatise are his geological findings interpreted within the frame of the contraction theory.

Among the many interesting topics treated by Eduard Suess in "Die Entstehung der Alpen" we have selected some observations which can be related to geophysical data of the deeper crust and lithosphere. The first issue we want to highlight is Eduard Suess' observation of a significant asymmetry of mountain ranges (e.g., Sengör, 2012, 2014) and his conclusion that mountain ranges represent outer masses of our planet having moved uni-directionally toward their axes. The whole Alpine system, including the Apennines, Western Alps and Carpathians, documents movements primarily from south to north. Geological data do not suffice to derive a direction for the Dinarides, as Suess states (Suess, 1875, p 121):

„Die bisher besprochenen Gebirge stellen sich als einseitig bewegte oder sich bewegende Theile der äusseren Masse des Planeten dar und die Richtung der Bewegung lässt sich, insoweit die Beobachtungen dazu ausreichen, in jedem ein-

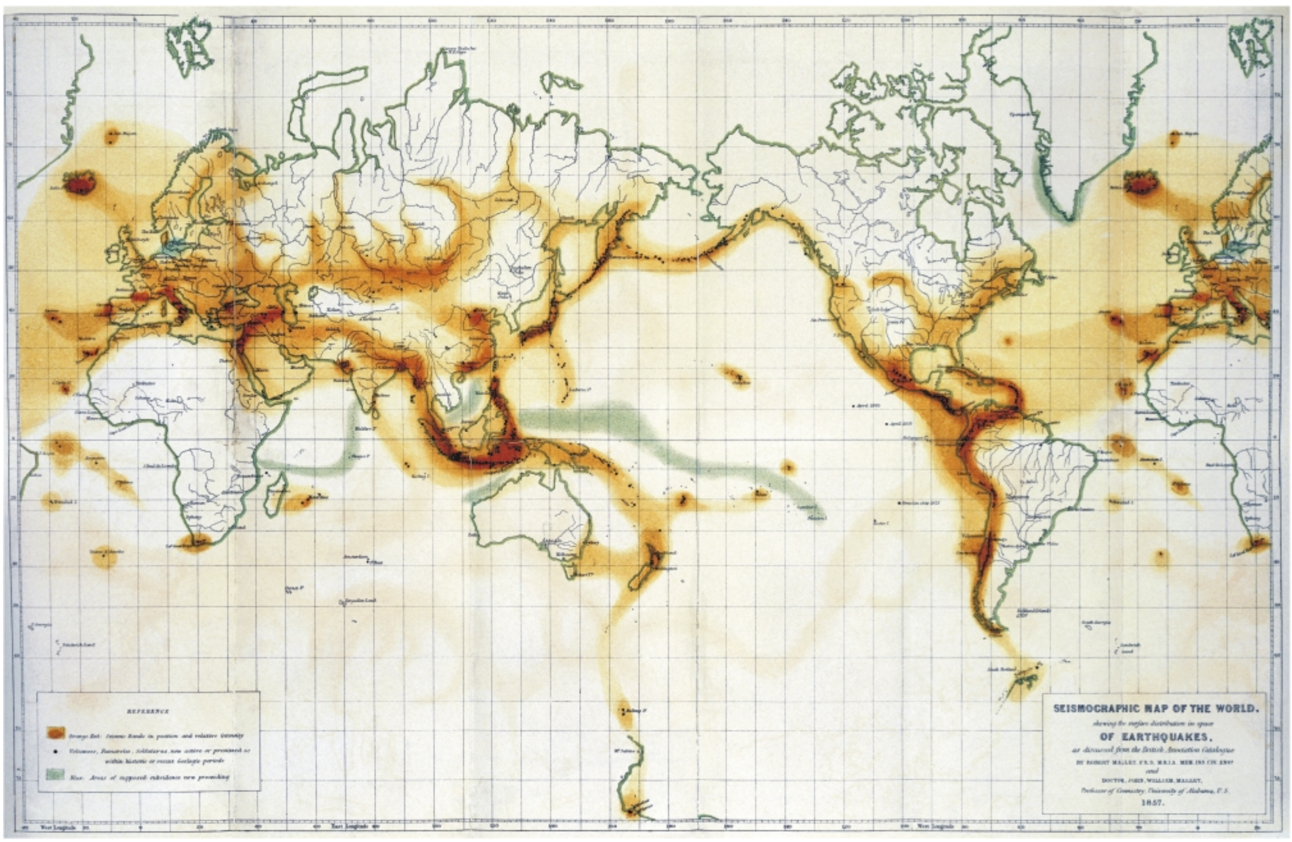

Figure 1: Robert Mallet and his son John W. Mallet published the first comprehensive earthquake catalogue of the world for the time-period 1606 B.C.-A.D. 1850. Based on this compilation they draw a "Seismographic map of the world" (Mallet et al., 1858) which shows in a fascinating way the earthquake zones along the young mountains of the Alps, the Himalaya (continent-continent collision), along the circum-Pacific seismic belt, Sumatra arc (subduction) but also the grabens of the Rhine Valley, Jordan – Dead sea, Red Sea, or hot spots on the mid-ocean ridge (e.g. Iceland).

zelnen Falle ermitteln. …In dem appeninischen Zweige des Alpensystems ist sie nach Norden gerichtet, in den Westalpen nach West, nach Nordwest, dann nach Nord, im Juragebirge nach Nordwest, in den Ostalpen nach Nord, in dem karpathischen Zweige nach Nordwest, nach Nord und endlich nach Nordost, am äussersten Ende nach Ost, im ungarischen Mittelgebirge nach Nordwest. In den croatisch-syrmischen Höhenzügen ist sie wegen der Mangelhaftigkeit der Ausbildung kaum erkennbar: für die dinarischen Alpen mangeln hinreichende Angaben.“

The direction of the movement is, according to Eduard Suess, quite similar for Europe and North America. However, in Asia, for the Himalayas in particular, he derives movements in the opposite direction (Suess, 1875, p 131):

„Nur eine einseitige horizontale Verschiebung der Masse des Gebirges (remark: Swiss molasse) kann diess hervorbringen; die gleiche Ueberschiebung der subhimalayaschen Molasse ist ein Zeichen, dass hier die allgemeine Bewegung gegen Süd gerichtet ist.“

Most mountain chains, especially the Alpine-Himalaya system, show a succession of arcs. Eduard Suess relates the curvature of the individual chains to the direction of the unidirectional movement. The Alps are convex to the north and the movement comes from the south. The opposite is true for the Himalayas (Suess, 1875, p 126):

“Alpen, Jura und Karpathen beschreiben in Europa von den nach West gedrängten Massen der Westalpen bei Lyon bis zu den nach Ost geschobenen äussersten Ketten der Karpathen an der Grenze der Moldau, grosse Bogenlinien, deren Convexität nach Nord gerichtet ist ; mit Ausnahme der Beugung der Alpen bei Wien kennt man überhaupt in Europa keine grössere Gebirgslinie, welche nach Süd convex wäre. In Asien ist diess nicht so. Der Himalaya beschreibt mit seinen Hauptketten eine nach Südwest gewölbte Curve …“

The dominance of the asymmetry and unidirectionality of mountain chains and the elegance of this conception does not mislead Eduard Suess to oversimplify. For example, he recognizes clearly that the architecture of the Southern Alps does not follow the general scheme of one-sided northward movement (Suess, 1875, p 86):

„Im Widerspruche mit Allem bisher Gesagten bemerkt man im mittleren Europa auch da und dort einzelne Gebirgstheile oder längere Streifen, welche gegen Süd oder Südwest überschoben oder überbogen sind.“

Eduard Suess describes the situation in the Val Sugana (Trentino, Italy) and derives a southward-oriented movement in the Southern Alps. However, he deems this reversal a subordinate feature which does not bring into question the general polarity.

The Eastern Alps at their transition to the Carpathians show convex curvature to the south as an exception. Eduard Suess does not interpret this observation as a reversal of the general trend of motion. He interprets the Bohemian Massif as a buttress against the masses approaching from the south. The masses are deflected to the east, thus introducing tension and forming the Vienna Basin (Suess, 1875, p 37):

„An der Südspitze der böhmischen Gebirgsmasse stauen sich, wie wir oben sahen, die nördlichen Zonen der Ostalpen; sobald sie dieses Hinderniss umgangen haben, schwenken sie nach Nordost ab und bilden weiterhin in grosse, regelmässige Bogen über das galizische Plateau ausgebreitet, den westlichen Theil des karpathischen Gebirges. Wo die Ablenkung am stärksten ist, entsteht wie durch Zerrung ein gewaltiger Riss, eine Lücke in der Gebirgskette, welche den Wässern der Nordabhänge ihren Abfluss gegen Süd öffnet und welche wir als die inneralpine Niederung von Wien zu bezeichnen pflegen.“

In the following chapters we describe the state of Physics of the Earth including Geodesy at the time of Eduard Suess' “Die Entstehung der Alpen”. We anticipate that the state of Physics of the Earth during Eduard Suess' work on this treatise with the seismology as an exception provided no essential constraints on his conception of the origin of the Alps and comparable mountain ranges. We review milestones in the geophysical sciences since 1875 and address large-scale geophysical experiments that yielded substantial information on transects or profiles crossing the Alpine system as well as structural models of the Moho and the upper mantle. Quantitative data on crustal movements in the past and at present are supplied by paleomagnetic studies and geodetic campaigns, especially by GPS. On the occasion of the 100th anniversary of the death of Eduard Suess we relate his ideas on mountain building to modern geophysical data and models.

2. Physics of the Earth at 1875

2.1 Geomagnetism

Navigation using a magnetic compass for purposes of orientation was first used around 1000 AD in China (Needham, 1971) and later in Western Europe. In the 19th Century geomagnetics was already highly developed and of fundamental importance for navigation.

In 1797 the Prussian geographer Alexander von Humboldt (1769-1848) led a magnetic expedition to the Palatinate (Pfalz, Germany), where he attributed the many anomalies he noticed in the direction of his compass to the rocks near the summit. He coined the terms “isodynamics” (lines of equal magnetic intensity), “isoclines” (lines of equal magnetic dip), and “magnetic storm” (Courtillot et al., 2007).

During the late eighteenth and early nineteenth centuries, the construction of non-magnetic huts for geomagnetic observation began. Early observations were carried out in many places across and outside Europe, for example by the British military engineer and cartographer John Macdonald (1759–1831) in Fort Marlborough on Sumatra/Indonesia. At Greenwich Observatory from 1818 to 1820 the magnetic declination was read thrice daily by the French astronomer François Arago (1786-1853). Observations of the declination were recorded at the Paris Astronomical Observatory from 1820 to 1835, as well as at Kremsmünster Abbey (Upper Austria) from 1832, to name just a few.

In the acquisition of measurements of the geomagnetic properties Humboldt saw a global task. After his trip to Russia in 1829, Humboldt established a geomagnetic observation network in Europe. It was in 1834 that German mathematician Carl Friedrich Gauss (1777-1855) and the physicist Wilhelm Eduard Weber (1804-1891) decided to participate in Humboldt's scheme of simultaneous observations at the new Göttingen observatory. A number of other observatories associated themselves with this proposal in what became known as the "Göttinger Magnetischer Verein". The goal of the association was essentially to measure the variations of the geomagnetic field simultaneously at stations distributed across the world. From 1836 to 1841 the measurements were carried out on 28 certain days, or "Termintagen," each for 24 hours at intervals of five minutes. Thirty-five of the participating observatories, including the Kremsmünster Abbey in Upper Austria, were located in Europe, six in Asia, two in Africa, three in North America and four in the South Pacific (Courtillot et al., 2007). The results were sent to Göttingen and interpreted by Gauss and Weber. Gauss developed a method of measuring the horizontal intensity of the magnetic field and worked out the mathematical theory for separating the inner and outer sources of Earth's geomagnetic field. The simultaneity of magnetic disturbances over large areas was confirmed by this method. Gauss went on to develop the general theory of geomagnetism and showed that the magnetic field observed at the Earth's surface originated almost entirely inside the Earth (Gauss, 1839).

Irregular geomagnetic measurements in Austria recorded at Kremsmünster Abbey date back to 1815. Regular recordings started in the Abbey in 1832 and an official geomagnetic observatory was established in 1839. National observations have been carried out since 1851 by the "k.k. Centralanstalt für Meteorologie und Erdmagnetismus," today the Zentralanstalt für Meteorologie and Geodynamik (ZAMG). The first director of the institute, the Austrian astronomer and meteorologist Karl Kreil (1798-1862), conducted the first geomagnetic survey for the Austro-Hungarian Empire, the Adria coast, Asia minor and the Black sea. The results were published in geomagnetic maps of the epoch 1850.0. The ZAMG established its first geomagnetic observatory in 1852 in Vienna in the garden of the "Theresianum.", where declination, inclination and intensity of the Earth's magnetic field were measured. (Hammerl et al., 2001).

2.2 Contraction theory

Contraction theory dominated tectonic reasoning at the time of Suess formulating his concepts on the Alpine orogeny. The German mathematician and philosopher Gottfried Wilhelm Leibniz (1646-1716) addressed the idea of the Earth's crust as a "shrinking tree bark" in his posthumously published work Protogaea on the figure of the Earth. He explained the mountainous shape of the surface as the cooling and shrinking of an originally regular round and red-hot molten Earth (Engelhardt, 1949). The French geologist Elie de Beaumont (1798-1874), who was one of the representatives of the catastrophism theory, argued in his treatise "Recherches sure quelques-unes des révolutions de la surface de globe" (Paris 1829-30) that the unequally distributed cooling of the Earth leads the crust to constant constriction so that the contact is not lost to the

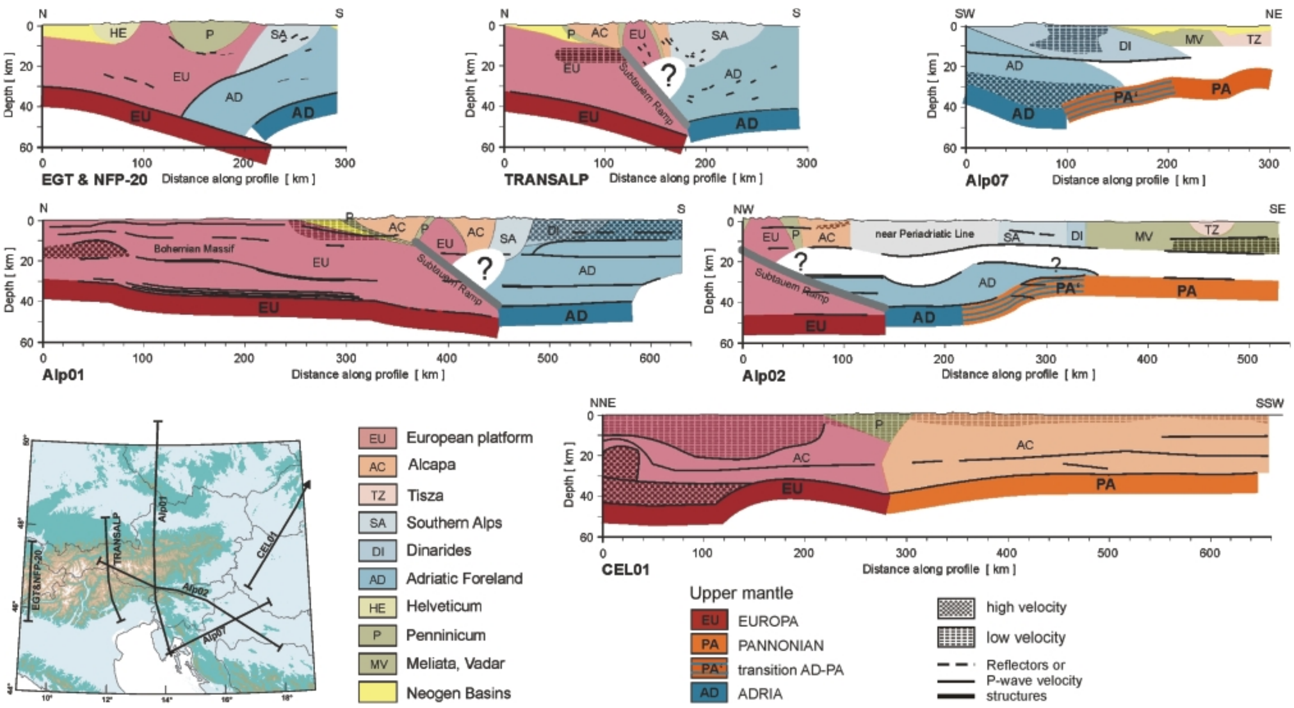

Figure 2: Modern seismic cross sections in the wider Eastern Alps area (modified after Brückl, 2010). The cross sections show the major seismic structures, the geological units of the upper crust, and a tentative attribution of the middle and lower crust to the major tectonic plates or blocks (Adria, Europe, Pannonian domain). For references and particulars please see chapter: Geophysical traverses across the Eastern Alps and the surrounding areas.

diminishing interior mass. Another prominent representative of the contraction theory was Alexander v. Humboldt (1769-1859). In his work the "Kosmos" he depicted the origin of mountains caused by folding of the crust due to the shrinking Earth (Ette and Lubrich, 2004). Eduard Suess (1892) summarized the results of his concept of the Shrinking Earth theory in his main publication "Das Antlitz der Erde" as follows: "*Der Zusammenbruch des Erdballes ist es, dem wir beiwohnen…* " (we observe the collapse of our planet).

The geothermal gradient played an important role in contraction theory. The first geothermal temperature measurements with a thermometer were likely carried out around 1740 by the French engineer Antoine de Gensanne (?-1780) in a mine near Belfort in France. In 1791 Alexander von Humboldt determined for the first time in history a temperature increase with depth of 3.8 ° C per 100 m in the Freiberg mining district; the geothermal gradient had been discovered. Confirmations in Central and South America soon followed. During 1831 and 1863 temperature measurements were performed in deep boreholes of up to 1000 m depth in Germany. A few years later first results with a depth of up to 1700 m were available. An average temperature increase of 3 ° C per 100 meters was observed, which we know today to be the normal temperature gradient (Stober et al., 2012).

2.3 Geosynclines, isostasy and gravity

A concept that played an important role in classical orogenesis was that of "geosyncline", introduced by the American geologists James Hall (1811-1898) in 1859 and James Dwight Dana (1813–1895), representative of the principle of uniformitarianism, in 1873. It was believed that sedimentary layers were formed along with subsidence of long narrow zones where various orogenic activities, including igneous and metamorphic processes, would eventually occur. The strata would then be deformed, elevated and would finally create the great mountain ranges (Lee et al., 2002).

In 1873 Dana attributed the sinking of the oceanic basins between the continental blocks to differential regional cooling, caused by different thermal conductivities of the rocks. This method allowed for the creation of mountains and also the origin of earthquakes (Dana, 1873). Dana's geosynclinal theory remained the relevant tectonic explanation model until well into the 20th century. It was Eduard Suess with his work "Entstehung der Alpen" who helped to get such ideas accepted in Europe, but not without critical examination.

Hall's idea of the development of geosynclines was only reasonable if one could imagine a viscous or liquid subsurface instead of a cooling rigid bedrock, from which magma would rise into the bottom of the geosyncline. In a letter to the geologist Charles Lyell (1797-1875) the astronomer John Herschel (1792-1871) speculated that the outermost layer of crust of the Earth was in a form of dynamic equilibrium with its underlying substratum or sea of lava (e.g., Watts, 2001), thus anticipating the idea of isostasy. This idea was cast into a physical model by the British astronomer George Biddell Airy (1801-1892). According to this model, parts of the thickened earth's crust are immersed like floating trunks or sheets of ice in the water (Airy, 1855).

Before Airy first developed his ideas the French mathematician, geophysicist, geodesist, and astronomer Pierre Bouguer (1698-1758) led an expedition in 1738 to Peru, where in the vicinity of Mount Chimborazo (6250 m) he investigated the vertical deflection. Bouguer and de La Condamine (1749) published their research on the expedition in "La figure de la terre". In the last part of the book Bouguer dealt with gravity measurements. In order to process the data from the summit of Pichincha, Quito and the coast he applied for the first time two reductions, which are today known as the Free-air and Bouguer reductions.

Airy built his thesis on the results of gravity measurements made with a plumb-line, which were carried out south of the Himalayas in the same year by the English clergyman and mathematician John Henry Pratt (1809-1871). These measurements did not show significant gravitational pull of the mountains, which had initially been expected due to the height difference between the mountains and surroundings (Hölder, 1989). Pratt developed an alternative model for isostatic compensation, widely used in Geodesy.

2.4 Seismology

One fundamental achievement of seismology was to resolve the shell structure of the Earth and the structure of the crust and lithosphere. These findings, however, only became possible with the development of effective seismographs. At the time of Eduard Suess' "Entstehung der Alpen" (1875), such instruments were only in use in testing or development and none of the instruments provided the required sensitivity, time stamp or continuous recording. According to Dewey and Byerly (1969), the first "true" seismograph, i.e. a device that recorded the relative motion of an inertial mass and the Earth as a function of time, was the instrument built in 1875 by the Italian seismologist P. F. Cecchi.

Many myths, legends and theories arose around historical earthquake disasters. Various attempts were made to develop plausible theories to explain the processes in the earth. Influenced by zeitgeist and culture, diverse concepts emerged. The strongest earthquake of the 18th Century on 1st November 1755 in Lisbon/Portugal forced the discussion regarding the causes of earthquakes. Not only the German philosopher Immanuel Kant (1724-1804) published his treatise on the causes of earthquakes (Kant, 1756), but also many other authors like Voltaire (1694-1778) and Jean-Jacques Rousseau (1712-1778) dealt with the disaster. Additionally, numerous reports in newspapers, sermons and poems were issued in the following years (Oeser, 2003). Kant contradicted in his work the then common view that earthquakes were caused by certain planetary constellations and thus denied any mystical or religious explanation. Instead, he gave a chemical explanation.

John Winthrop (1714-1779), professor of mathematics and natural philosophy in Harvard, and the English natural philosopher and geologist John Michell (1724-1793) were both strongly influenced by the Lisbon earthquake of 1755. They published their ideas, which significantly encouraged research into finding the answer to the question of the cause of the earthquakes. Although still influenced by Aristotelian thoughts, the two scientists dealt not only with the cause but also with the effects of earthquakes. After the Cape Ann, Massachusetts earthquake of November 18th 1755, which caused considerable damage in Boston, Winthrop made the important discovery that earthquakes exhibit wave characteristics, "*As it is certain, that in the great shock, the earth had an horizontal motion; so it appears with the most sensible evidence to me, that in the shock we felt the Saturday evening following, at 27' after 8, there was a perpendicular motion of the earth. I was then sitting on a brick hearth, and felt not a motion of the whole hearth together, either from side to side, or up and down; but of each brick separately by itself. Now as the bricks were contiguous, the only motion, which could be communicated to them separately, was in a perpendicular direction; and the sensation excited in me was exactly the same, as if some small solid body, by moving along under the hearth, had raised up the bricks successively, which immediately settled down again. The motion of the earth in this instance plainly appeared undulatory to me; and this shock, I apprehend, was occasioned by one small wave of earth rolling along, but not with a very swift motion…*" (Winthrop, 1755).

In 1760, five years after the Lisbon earthquake, John Michell, then lecturer at Cambridge University, published a treatise discussing a comprehensive earthquake theory. Michell also recognized the undulating motion of the ground during an earthquake: "*The motion of the earth in earthquakes is partly tremulous, and partly propagated by waves, which succeed one another sometimes at larger and sometimes at smaller distances; and this latter motion is generally propagated much farther than the former*" (Michell, 1760). He anticipated findings that led later to the understanding of the causes of earthquakes (Hammerl et al., 1997).

During the Age of Enlightenment, the reception of earthquake disasters changed in a socio-economic and administrative as well as a scientific sense. The earthquake of the 27th February 1768 is probably the strongest to ever have affected Wiener Neustadt in Lower Austria. The Empress Maria Theresia commissioned her court mathematician Joseph Anton Nagel (1717–1794) to survey the effects of the earthquake in Lower Austria (Hammerl, 2000). Nagel's enterprise was more or less the first "macroseismic expedition". Nagel dealt not only with the effects of an earthquake, but he also developed his own ideas about the possible causes of an earthquake (Nagel, 1768; Aric, 1990). He found a relation between the felt area and focal depth and the intensity decrease with distance. However, Nagel's achievements were not appropriately recognized at the time.

When the British geologist Charles Lyell (1797-1875), one of the representatives of uniformitarianism theory, published his first volume of "Principles of Geology" (1830), Robert Mallet

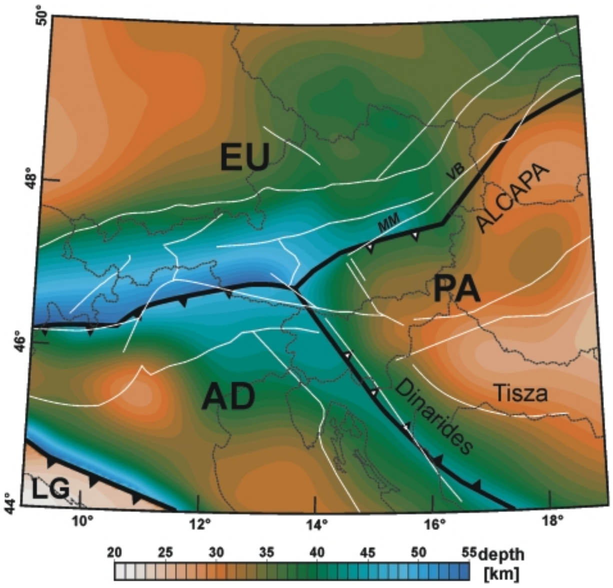

Figure 3: Moho depth and structure. Destructive and transform plate boundaries have been inferred partitioning the Moho and upper mantle into separate plates: LI – Liguris, AD - Adria, EU – Europe, and PA –the Pannonian domain comprising ALCAPA, Tisza, and the Dinarides). For references and particulars please see chapter: Moho structure and plate boundaries. White lines are the main faults. MM and VB mark the Mur-Mürz and the Vienna Basin fault system.

was greatly impressed. Mallet applied his knowledge of mechanics to the interpretation of Earth movements and their propagation. The papers that Mallet read to the Royal Irish Academy between 1842 and 1846, published as "On the dynamics of earthquakes" (Mallet, 1848), are considered unique in their field. Mallet believed he was founding a true science of seismology, a term first coined by him and first used in 1858 (Blake, 2010).

In 1858 Robert Mallet and his son John W. Mallet published the first comprehensive earthquake catalogue of the world for the period 1606 B.C. to A.D. 1850. Based on this compilation they drew a "Seismographic map of the world" (Mallet et al., 1858) (Fig.1). The map shows in a fascinating manner the zones known today as earthquake zones along the young mountains of the Alps, the Himalayas (continent-continent collision), the circum-Pacific seismic belt, the Sumatra arc (subduction), and also the grabens of the Rhine Valley, Jordan and the Dead sea, Red Sea, or hot spots on the mid-ocean ridge (e.g. Iceland). Since Mallet got his information for the world map on earthquakes from descriptive historical sources, the map shows the earthquake belts only on inhabited land, which of course leads to parts missing in the oceanic areas. Mallet commented on his map, "*I therefore venture to present this map as more than a mere picture – as being, in fact, a first approximation to a true representation of the distribution of earthquake forces, so far as they are yet known, over the surface of our world.*" (Mallet et al., 1858).

Eduard Suess himself contributed actively to seismology. In 1874 he published a treatise on "Earthquakes in Lower Austria" (Suess, 1874). Suess devoted the first three chapters to a comprehensive study of one small and two strong earthquakes in Lower Austria in 1873, 1590 and 1768. In the fourth chapter, earthquakes in Lower Austria from 1021 to 1873 were abridged, citing literature as well as original sources. In the fifth chapter Suess described "*seismische Stoßpunkte und Linien*" and a supposed relation between earthquakes and the geological structure of the region. In his treatise "*Die Entstehung der Alpen*" Suess again discussed earthquake lines not only in the Eastern Alps but also the southern Apennines, the Aeolian islands, and the Aetna. The terms "*Thermenlinie*" (southern Vienna Basin, SW-NE strike) and "*Kamplinie*" (south-eastern Bohemian Massif, S-N strike) defined by Suess are still in use today, although their meanings have changed. Most probably seismology around 1875 was the only discipline of the Physics of the Earth which had an impact on Eduard Suess's conceptions of Alpine orogenesis. Seismic activity indicated that mountain building is a long lasting and ongoing process.

3. Milestones of geophysical sciences since 1875

Physics of the Earth has made tremendous progress since the publication of "Die Entstehung der Alpen" by Eduard Suess. In the following we highlight some milestones relevant to the development of tectonic hypotheses and models.

3.1 Seismic observatories and structure of the Earth

In 1898 the German seismologist Reinhold Ehlert (1871-1899) published a "Summary, explanation and critical examination of the most important seismometers with special regard to their practical applicability" (Ehlert, 1898). This comprehensive synopsis gave a description of the principles – devices with inertial masses moving on ball bearings on horizontal plates, instruments indicating or recording surface motions of heavy fluids/mercury, and simple as well as astatized horizontal and vertical pendulums with mechanical/smoked paper or optical/photographic paper recording – of over seventy different types of seismographs and seismoscopes. The instruments were invented during the 19th century by many designers in Europe and Japan, among them the very well known names Agamennone, Cancani, Cavalleri, Cecchi, Darwin, Davison, Ehlert, Ewing, Forster, Galli, Grablovitz, Mallet, Milne, Palmierei, Schmidt, Stevenson, von Rebeur-Paschwitz, Vicentini and Wagener. Very popular among the category of mechanically recording horizontal seismographs were the Wiechert inverted vertical pendulum, the Omori/Bosch (Strassburg) heavy pendulums and the Rebeur-Ehlert triple pendulum. Another representative of a vertical seismograph was Vicentini's vertical pendulum around the turn of the penultimate century (Plešinger, 2003).

Shortly after the strong Ljubljana, Slovenia earthquake of 14th March 1895, the "Commission for the purpose of promotion of a more intensive study of seismic phenomena in the Austrian countries" – the "Erdbebenkommission" – was established by the Academy of Sciences in Vienna. The most important task of this commission was the establishment of seismographic stations equipped with autonomously recording seismographs. The astronomical and physical observatories at Trieste, Vienna, Lemberg, Lvov and Kremsmünster were proposed as locations for seismic stations. Regular recordings have been carried out since 1898 (Mojsisovics, 1897). This data and the development of theory (e.g., inversion of travel time data by the Wiechert-Herglotz-Bateman integral) initiated a tremendous increase of our knowledge of the structure of the Earth.

A. Mohorovičić (1910), while studying seismograms of the Kulpa valley earthquake on the 8th October 1909, observed two distinct pairs of seismic waves and related these phases

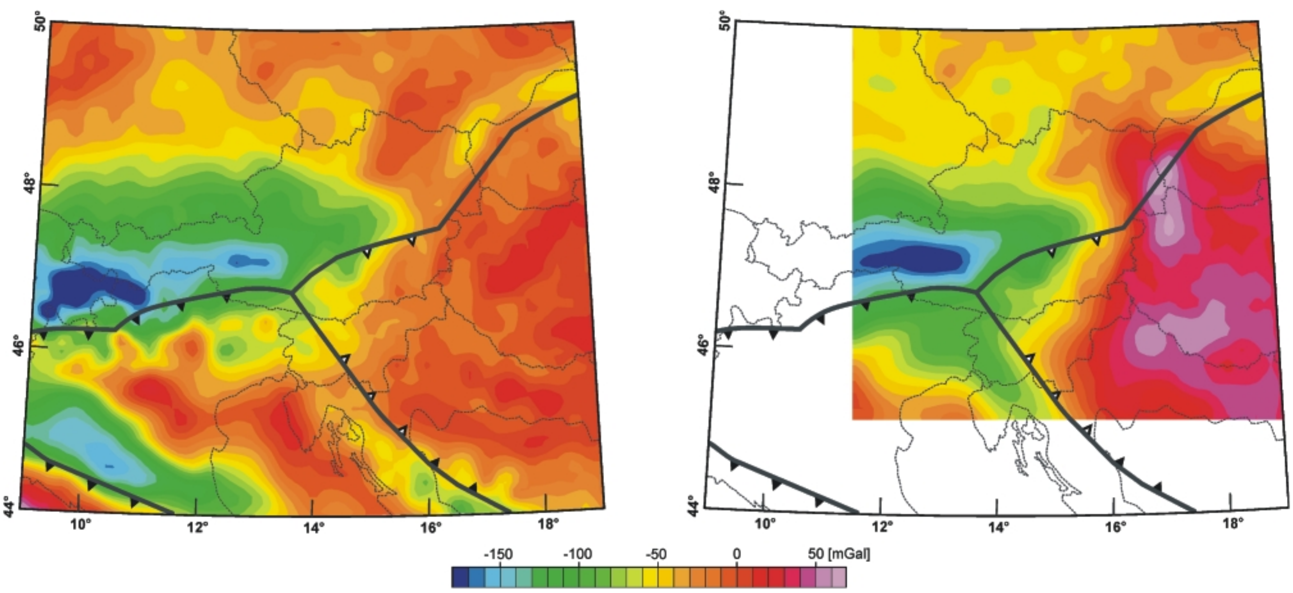

Figure 4: (a) Bouguer gravity (BA) compiled from Bielik et al. (2006) and from data supplied by the West_East Europe gravity project (http://www.getech.com); (b) BAC, the gravity effect of density variations in the upper crust stripped (Simeoni and Brückl, 2009); the plate and country borders are superimposed on both maps for orientation.

to ray paths through the crust and the uppermost mantle. From this data he determined the depth of the crust-mantle boundary to be approximately 50 km. S. Mohorovičić (1914) and A. Mohorovičić (1916) confirmed the existence of this discontinuity, later named the Mohorovičić discontinuity or Moho.

Further progress into resolving the structure of uppermost layers of the Earth was made by V. Conrad (1925, 1927) during studies of the Tauern (28th November, 1923) and the Schwadorf (8th October, 1927) earthquakes in Austria. He observed additional seismic phases, which revealed an intermediate discontinuity in the crust. This discontinuity divides the crust into an upper crust and a lower crust. Comparable observations of Jeffreys (1927) supported Conrad's discovery. In his book "The Earth – Its Origin, History and Physical Constitution" (Jeffreys, 1962) he expresses his astonishment that the ideas of SAL (SIAL) and SIMA introduced by Eduard Suess had not received notice by the geophysicists at the time.

Studies on deep and intermediate focus earthquakes near the Pacific trenches, independently carried out by Wadati (1928) and Benioff (1954) led to the discovery of narrow zones of high seismicity dipping from the oceanic trenches under the continents or islands. These zones were later named Wadati-Benioff zones and supplied the first information on subducting lithospheric slabs.

After World War II, the largest non-nuclear explosion ever ignited, Helgoland on the 18th April, 1947, was used as a controlled source seismic experiment by scientists from the former allied nations and Germany to improve travel time data necessary for earthquake location and to resolve structural features of the earth's crust. (e.g., Schulze, 1974). The exploration of the lithosphere of the Eastern Alps and the surrounding area by wide angle seismic reflection/refraction experiments started around the Eschenlohe quarry, southern Germany, roughly 50 years ago (Giese and Prodehl, 1976). The Alpine longitudinal profile (ALP'75) extended along the axis of the Western and Eastern Alps to the Pannonian Basin (e.g., Yan and Mechie, 1989; Scarascia and Cassinis, 1997) and improved our knowledge of the Alpine crust considerably.

3.2 Gravity and isostasy

Improvement of instrumentation has been a necessary prerequisite to mapping Earth's gravitational field. L. Eötvös carried out the first field campaign with his innovative instrument, the torsion balance, in 1891 (e.g., Szabó, 1998). In the year 1887 Sterneck constructed a pendulum instrument capable of field data acquisition (e.g., Toperczer, 1960). A first gravity gradient map was obtained from the data of the torsion balance survey on Lake Balaton 1901-1903 (Szabó, 1998).

Gravity data acquisition in the field was substantially facilitated by the development of gravimeters based on astatic spring systems. The development of the LaCoste-Romberg gravity meter dates back to 1939, and the subsequent Worden gravity meter was developed in the 1940s. Both systems, complemented these days by electronic components, are still state of the art. With the use of gravity meters gravity mapping started in Austria in the 1960s. E. Senftl (1965) published the first Bouguer gravity map of Austria.

Isostasy has always been an important issue of gravity research and posed constraints on tectonic theories. The advancement of the Airy model (e.g., Watts, 2001) by the consideration of the lithosphere bearing capacity as an elastic plate by Vening-Meinesz (1931) may be seen as a substantial step forward.

3.3 Age, magnetism, and plate tectonics

The first attempts to determine the age of the Earth were closely connected to the theory of contraction due to cooling. The English physicist W. Thomson (later Lord Kelvin, 1824-1907) calculated the age of the Earth, taking into account cooling and solar radiation for a given age of 100 million years, later with only 20-40 million years. During Suess´ lifetime Lord Kelvin's data were physically incontrovertible. However, Kelvin himself admitted some uncertainty of the age determination because, as he thought, unknown heat sources could affect his calculations. In 1904 Kelvin's successor Ernest Rutherford (1871 - 1937), nuclear physicist, gave a lecture on radioactive heat production in the Earth and in 1913 the British geologist Sir Arthur Holmes (1890-1965) published his book "The Age of the Earth" where he introduced new calculations: "*…With these discoveries the long controversy was finally buried, and Kelvin's treatment of the problem was proved to have been fallacious. …Indeed, if our interpretation is correct, some of the oldest Archean rocks must date back 1600 million years…*" (Holmes, 1913). The correct quantitative estimation of the age of rock samples has been of fundamental importance to the interpretation of geo- or paleomagnetic data.

The remanent magnetization discovered in rock samples contains information about the location and orientation of the sample at the time of the magnetization. In 1906 B. Brunhes (Brunhes, 1905, 1906; Laj and Kissel, 2002) published his discovery of the reversed polarisation of basalts in the Massif Central (France). The observations of P-L. Mercanton (1926) and M. Matuyama (1929) revealed that Brunhes' discovery was not only local but a world-wide phenomenon. The development of modern paleomagnetic methods for the determination of rock magnetizations was initiated by S.K. Runcorn. A comparison of paleomagnetic orientations between Europe and North America supplied substantial evidence for polar wandering and continental drift (Runcorn, 1956, 1960).

The development of the proton precession magnetometer as an instrument capable of determining the total intensity of the earth's magnetic field absolutely, accurately, and with a high sample rate pushed magnetic mapping forward. Marine surveys revealed the magnetic anomaly lineation in the northeastern Pacific (Menard, 1964) and around the mid-Atlantic ridge south of Iceland (Pitman and Heirtzler, 1966; Heirtzler et al., 1966; Vine and Matthews, 1963; Vine, 1966). This data gave evidence for the spreading of ocean floor at mid-ocean ridges. On the basis of these observations the plate tectonic theory was developed, which disproved and replaced the contraction theory that had been accepted by the majority of the geoscientific community for more than a century.

4. Modern geophysical traverses across the Eastern Alps and adjacent orogens

Since the year 1980 the geoscientific community has been undertaking integrated large-scale experiments. Controlled source seismic investigations built the backbone of these campaigns, and complementary geophysical methods as well as geological and petrologic studies completed the seismic data. In the following we concentrate on 6 profiles across the Eastern Alps and the adjacent tectonic units (Fig. 2).

The EGT&NFP-20 traverse provided a detailed crustal image along an approximately north-south oriented profile near the western border of the Eastern Alps. The cross-section shown in Fig. 2 is based on near-vertical and wide angle reflection and refraction (WARR) data (Valasek et al., 1991, Ye et al., 1995, Pfiffner et al., 1997, Kissling et al., 2006). The near-vertical reflection data allow for the delineation of the Helvetic and Penninic nappes and the basal decollement, a reflective European lower crust and the Moho boundary. The WARR data reveal the seismic velocity structure of the crust and upper mantle and the Moho depth. The geological/tectonic interpretation of Schmid et al. (2004) is adopted in Fig. 2. Structures of particular interest for this article concern the distinct jump of the Moho boundary from Europe to Adria, the indenting Adriatic lower crust, the Helvetic and Penninic nappes over-thrusted to the north, and the seismic signature of back-thrusting in the Southern Alps.

The TRANSALP geoscientific traverse crosses the central part of the Eastern Alps from Munich to Venice (e.g., Gebrande et al. 2006 and references therein). Similar to the study of the EGT&NFP-20, steep angle high resolution reflection seismic profiling was combined with wide angle reflection and refraction. Seismic tomography (Bleibinhaus and Gebrande, 2006), receiver functions (Kummerov et al., 2004), and gravimetric studies (Ebbing et al., 2006; Zanolla et al., 2006) supplemented the seismic transect. The profile shown in Fig. 2 is based on the seismic data of Lüschen et al. (2006), Kummerov et al. (2004), and the interpretations of Castellarin et al. (2006) and Lammerer et al. (2008). The north-vergent Austro-Alpine nappes and the south-vergent South-Alpine thrust faults and nappe decollements are well imaged down to a depth of 15 - 20 km. A seismic low-velocity zone below the Eastern

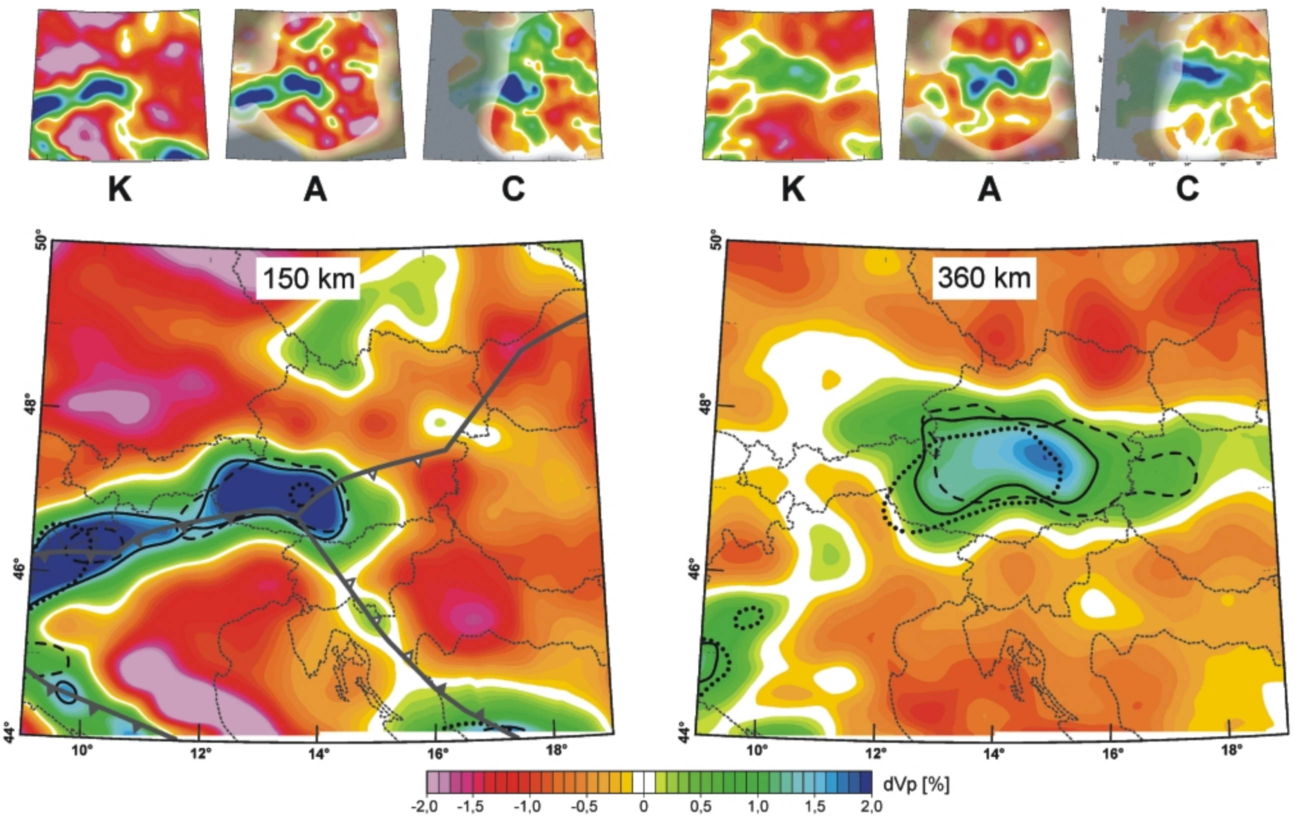

Figure 5: The P-wave velocity structure of the upper mantle derived from teleseismic data. Depth slices at 150 km and 360 km of the models K (Koulakov, 2009), A (ALPASS, Mitterbauer et al., 2011), and C (Carpathian Basin Project, Dando et al., 2011) are shown on top. The areas of reduced resolution of the A- and C-models are greyed. The K-, A-, and C-models were averaged with equal weights within the high resolution areas to create a combined model. Outside the high resolution areas of the A- and C-models their weights were set to zero with a smooth transition from full weights. The sum of all weights was normalized to keep the amplitudes of the individual models and the combined model comparable. Depth slices at 150 km and 360 km of the combined model are shown below the K-, A-, and C-models.The positive P-wave velocity anomaly at 150 km depth delineates the "shallow slab" (subducted continental lower lithosphere), and at 360 km depth the "deep slab" (subducted Penninic Ocean). Contours of dVp = 1.5% and dV = 1.0% are shown black for the depths 150 km and 360 km. Additional contours of dVp = 1.5% and dV = 1.0% at the depth levels 90, 150, 210 km and 300, 360, 410 are superimposed in grey to show the +/- vertical dip of the slabs.

Alps thrust belt was revealed by tomographic studies (Bleibinhaus and Gebrande, 2006). A roughly 30° south dipping reflective zone, the Subtauern ramp, has been interpreted as a crustal scale fault zone, over which the Tauern Window was exhumed by thrusting and folding. Under the Southern Alps a reflective lower crust indicates crustal thickening. The Moho boundary is constrained by steep and wide angle reflections and by receiver functions (Kummerov et al., 2004). The latter data in particular indicate an upward jump from the European to the Adriatic Moho.

The CELEBRATION 2000 and the ALP 2002 projects covered the wider Alpine area east of the TRANSALP transect by many seismic wide angle reflection and refraction profiles. Seismic shots were ignited along these profiles and simultaneous recording along all profiles of one deployment made definition of the 3-D field geometry possible (Guterch et al., 2003a, 2003b; Brückl et al., 2003). Here we concentrate on the most representative profiles (Fig. 2) evaluated by the method of interactive ray-tracing.

Alp01 (Brückl et al., 2007) extends from the Bohemian Massif to the Adriatic foreland (Istria). The topography of the Moho and the velocity structure of the crust supplied constraints to transfer the tectonic style of the collision between Europe and Adria (especially the Subtauern ramp) from TRANSALP to Alp01. The shape of the gneiss core of the Tauern Window is based on the "lateral extrusion model" proposed for the TRANSALP profile (TRANSALP Working Group, 2002; Castellarin et al., 2006). Evidence is given for mid- or lower crustal thickening under the Southern Alps and low deformation of the Adriatic foreland.

Alp02 (Brückl et al., 2007) extends from the western end of the Tauern Window along the Periadriatic line into the Pannonian Basin and further south-east to the Tisza unit. Like Alp01, the interpretation in the area of the Tauern Window follows TRANSALP. The Moho is fragmented into Europe (EU) and Adria (AD) and separated by a transition zone, the Pannonian domain (PA). It is most probably the case that the lower Adriatic crust thrusts widely over the PA mantle, however there are too few constraints to correlate mid-crustal layers with the geological units.

Alp07 (Šumanovac et al., 2009; Šumanovac, 2010) traverses the Dinarides from the Adriatic Sea to the Pannonian Basin at the latitude of Istria. Adriatic lower crust, identified by high seismic velocities, thrusts over the Pannonian mantle (PA) under the Dinarides. An extended lower velocity zone marks the transition from the Adriatic to the Pannonian domain in the upper crust. Too few constraints exist for a geological correlation of the mid-crust.

CEL01 (Sroda et al., 2006) crosses the Western Carpathians from the European platform to the Pannonian Basin. Near surface low velocity zones mark basins in the Paleozoic of the European plate, the West Carpathian Flysch trough and the Pannonian Basin. A wide indentation of PA mantle under EU crust into the European domain was interpreted by Sroda et al. (2006). Here we follow the interpretation of Brückl (2011) with little indentation of the extended and rather "weak" ALCAPA lithosphere.

5. Moho structure and plate boundaries

Several Moho maps covering parts of the Alps have been generated (e.g. Waldhauser et al. 1998, Ziegler and Dèzes, 2006). The map shown in Fig. 3 is based on the European Moho map of Grad et al. (2009) as a backbone with higher resolution maps of Waldhauser et al. (1998) and Behm et al. (2007) integrated. The Moho depth fits the values determined along the profiles shown in Fig. 2. Šumanovac (2010) derived Moho depth data using gravity modelling at profiles across the Dinarides south of about 45°N. The data were also integrated into the Moho map in Fig. 3. Data from Di Stefano et al. (2009) were used to refine the Ligurian area.

Moho troughs down to 55 km depth follow mountain ranges of the Apennines, the Central and Eastern Alps, and the Dinarides. Significant Moho highs up to 25-20 km depth are observed below the area around the Rhine Graben, the Po Plain, and the Pannonian Basin.

Information about the plate tectonic setting is gained from the interpretation of the Moho topography. Destructive plate boundaries or subduction zones can be identified by offsets of an otherwise smooth Moho boundary (Zhao et al., 2001; Thybo et al., 2003; Weber et al., 2009). Waldhauser et al. (1998) approximated the Moho boundary with smooth surfaces and inferred plate boundaries with Moho jumps, when otherwise only a rough surface could approximate the depth. Plate boundaries between Europe and Adria and Adria and Liguria were derived according to this method and integrated into the map (Fig. 3). In the area of the Eastern Alps and Dinarides Brückl et al. (2010) applied 2D elastic plate modelling of the lithosphere to determine if a continuous plate is an appropriate model or if the introduction of a plate boundary (where no bending moment is transferred across the plate boundary) yields a better fit. Both methods, Waldhauser et al., (1998) and Brückl et al. (2010), postulate the smoothness of the Moho boundary within one lithospheric block or plate. Destructive plate boundaries were clearly identified along the Apennines, the Central and Eastern Alps and the southern Dinarides. The decision which plate is the subducting one can be taken from the polarity of the Moho jump. The plate boundary in the areas of the Mur-Mürz fault and the Dinarides are probably transpressional. The plate boundary east of the Mur-Mürz fault across the Vienna Basin fault to the Western Carpathians is not well constrained and most likely transform or transfer. The locations of the Mur-Mürz and the Vienna Basin faults are marked in Figure 3.

The plate boundaries separate the European (EU) and Adriatic (AD) mantle lithospheres from each other and from the mantle lithosphere of the Pannonian domain. They form a triple junction near the south-eastern border of the Tauern Window at about 46.6°N and 13.7°E. The Pannonian domain (PA) is an accretion of ALCAPA, Tisza, the Dinarides, and probably the Dacia unit. According to our interpretation Adria

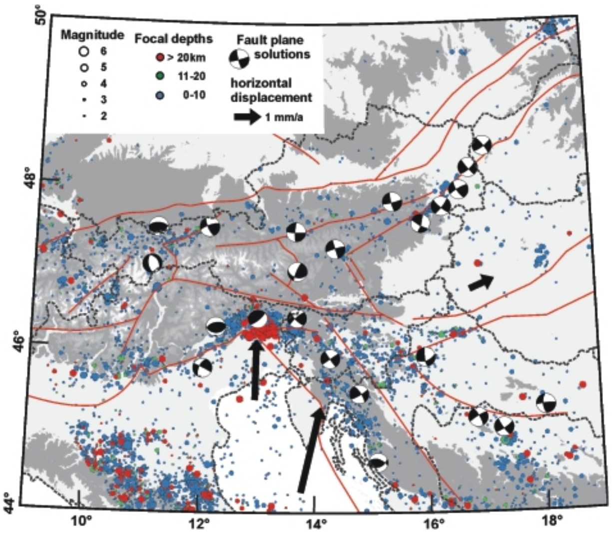

Figure 6: Active tectonics documented by seismicity and plate velocities. Major faults, seismicity (NEIC, 1973-2008), and representative focal plane solutions (see Brückl et al., 2010 for references) are superimposed on digital terrain model. Arrows show horizontal plate velocities derived from GPS-data (Grenerczy and Kenyeres, 2006; Weber et al., 2006) relative to Europe.

represents the lower plate with respect to Liguria and the Pannonian domain and the upper plate with respect to Europe. This scheme was earlier inferred by Doglioni and Carminati (2002).

6. Gravity

Within the TRANSALP project the latest regional gravity data were compiled (Zanolla et al., 2006), and gravimetric modelling and isostasy studies were carried out (e.g., Ebbing, 2004; Ebbing et al., 2006). Studies on the integration of gravity data into the seismic models derived from the CELEBRATION 2000 and ALP 2002 data were carried out by Brückl et al. (2006) and Simeoni and Brückl (2009). Accurate Bouguer gravity data was provided by Bielik et al. (2006) and Meurers and Ruess (2007) for the Alpine-Carpathian area. Regional Bouguer gravity data were supplied by the West-East Europe Project (http://www.getech.com). A Bouguer gravity map compiled from this data is shown in Fig. 4a.

The Bouguer anomaly (BA) shows clear negative correlation with topographic height and the Moho depth. This correlation has to be expected in the case of the Airy isostasy (or Vening-Meinesz isostasy) being approximately fulfilled. Detailed studies on isostasy in the Eastern Alps were carried out by e.g., Wagini (1988), Ebbing (2004), Ebbing et al. (2006), and Zanolla et al. (2006). In the wider area of the Tauern Window the isostatic anomaly is slightly negative, a result which corresponds to the uplift (~1 mm/year) observed in this area by GPS (Höggerl, 1989, Haslinger, 2006). Zanolla et al. (2006) detected a local positive isostatic anomaly in the area of the Monti Lessini and Colli Euganei, where magmatic activity took place during the Paleogene.

The correlation between BA and Moho depth can be improved if the gravity effect of density variations in the crust is removed. A density model of the upper crust (0-10 km depth) was derived by Simeoni and Brückl (2009) from the seismic model of Behm et al. (2007) along with density-depth relations for the sedimentary basins. A Bouguer anomaly gravity map, stripped of the effect of upper crust density anomalies (BAC), is shown in Fig. 4b. The correlation with the gravity effect of the varying Moho depth has been significantly enhanced and a 1:1 relation has been established by this processing assuming a density contrast of 300 kg/m^3 between lower crust and upper mantle (Simeoni and Brückl, 2009). The effect of the root of northern Dinarides on the gravity data can be seen much more clearly.

7. Upper mantle structure and subducting slabs

Key information on subduction and other processes related to mantle convection and plate tectonic processes can be derived from the seismic velocity structure of the upper mantle. Bodies of relatively high seismic velocity bodies can represent down-moving slabs of low temperature oceanic lithosphere or continental lower lithosphere. Areas of low seismic velocity may indicate lithospheric thinning and upwelling asthenosphere, mantle plumes or local mantle convections. Large-scale tomographic studies covering the Eastern Alps are mainly based on travel time data provided by the International Seismological Centre (e.g. Bijwaard and Spakman, 1998; Wortel and Spakman, 2000; Piromallo and Morelli, 2003; Koulakov et al., 2009). High resolution teleseismic investigations in the east alpine area (e.g. Lippitsch et al., 2003; Dando et al., 2011; Mitterbauer et al., 2011) include data from temporary networks. Results from all these tomographic studies are presented as deviations of the seismic wave velocities from a reference model (e.g., ak135: Kennett, et al., 1995).

The models of Dando et al. (2011), Mitterbauer et al. (2011) and Koulakov et al. (2009) reveal similar resolution and resolve the upper mantle structure down to the 670 km discontinuity. A weighted average of these models was constructed, with equal weights of the three models in their area of high resolution (Brückl et al., 2012). The following main structures were identified (Fig. 5):

- high velocity bodies below the Alps, Apennines, and Dinarides down to a depth of 200 – 250 km. These bodies are interpreted as subducting continental lower lithosphere. We refer to the slab under the Eastern Alps as "shallow slab". An important coincidence is that the extent of the shallow slab to the east terminates near the triple junction and no comparable structure can be found along the EU-PA plate boundary further to the east. Fig. 5a shows a depth slice through the model at 150 km depth. Contours of dVp=1.5% at the depth levels 90, 150 and 210 km are superimposed. These contours show that the dip of the shallow slab is approximately vertical in the depth interval 90 – 210 km.
- at greater depth another high velocity body between 47°N and 48°N and east of about 13°E. We name this body "deep

slab" and interpret it as subducted and detached oceanic lithosphere of the Penninic Ocean (Alpine Tethys) sinking down to the 670 km mantle discontinuity (Dando et al, 2011). Fig. 5b shows a depth slice through the model at 360 km depth. Contours of dVp=1.0% at the depth levels 300, 360, and 410 km are superimposed. These contours show that the deep slab dips also subvertically in the depth interval 300 – 410 km and extends to the east with increasing depth. Synthetic tests with the ALPASS data set show that separated shallow and deep slabs appear connected because of the limited vertical resolution (Mitterbauer, pers. communication).

The shape of the shallow slab as determined by the models of Dando et al. (2011), Mitterbauer et al. (2011) and Koulakov et al. (2009) agrees with the model of Lippitsch et al. (2003), west of about 13°E. Further to the east the model of Lippitsch shows the shallow slab dipping about 60° to the north-east. A change of subduction polarity has been inferred by Lippitsch et al. (2003) from this image of the slab. The model of Lippitsch et al. (2003) ends at 400 km depth and does not resolve the deep slab under the Eastern Alps. We prefer the models of Dando et al. (2011), Mitterbauer et al. (2011) and Koulakov et al. (2009) and their combination because they have denser coverage of ray-paths in this area and extend down to the 670 km discontinuity. The idea of a subduction polarity reversal is not supported by these models.

8. Plate movements

The evolution of the Alpine mountain system is closely related to the opening of the Atlantic Ocean since the Jurassic period. The magnetic anomaly patterns east and west of the Mid Atlantic ridge constrain the relative plate motions between North and South America and Europe and Africa. Based on this evidence, plate motions since the breakup of Pangaea were reconstructed in the area of the Alpine mountain system (e.g., Dewey, et al., 1989). Oceanic crust also constitutes major parts of the Mediterranean Sea and the Black Sea. However, seafloor spreading ceased in this area in Cretaceous times. Furthermore, several micro-plates split off of Africa and Europe (e.g. Iberia, Apulia, Dacia, Tisza, etc.) and started to move independently. The magnetic anomaly pattern is therefore complex and incomplete (Bayer et al., 1973) and not enough to constrain the motions of smaller lithospheric blocks or micro-plates like Iberia, Apulia, or Adria relative to Europe.

Paleomagnetic investigations provided additional constraints for the reconstruction of plate motions. Changes of latitude and rotations since the time of the magnetization can be uniquely derived from this data. Since Cretaceous times the difference in latitude of EU and the African domain was reduced by about 10°, indicating the NS component of the movement of Africa versus EU (Besse and Courtillot, 1991; Mauritsch and Márton, 1995).

The 20° CW rotation of Adria (northern part of Apulia) relative to Africa during the Late Cretaceous (Maastrichtian, 70 Ma) and Mid Eocene (40Ma) indicates its separation from the main African plate (Márton et al., 2010). Jurassic and Cretaceous poles within the Eastern Alps show different schemes. Apparent polar wander paths of the Northern Calcareous Alps (NCA) east of 12°E follow the European trend (CW rotation), whereas the western region of the NCA and some locations of the Styrian Basin rotate CCW and follow the African trend (Mauritsch and Becke , 1978).

Recent investigations in the central NCA reveal two remagnetization events during the Jurassic and Cretaceous periods, which may be associated with the end of NCA thrust system configuration and the Austro-Alpine units stacking and thrusting over the Rhenodanubian Flysch. Major CW rotations of about 86° occurred since the last event. These rotations are very inhomogeneous, presumably due to rearrangements of individual blocks (Pueyo et al., 2007).

We may summarize that ocean magnetic anomalies and paleomagnetic records of continental rocks are important constraints but not sufficient to reconstruct plate or microplate tectonic movements in the Alpine area. The most reliable solutions have been achieved using the integration of structure geological data (e.g., Ustaszewski, 2008), reconstruction of basin geometry and subsidence history from stratigraphic data, petrological and geochronological information, and the consideration of the upper mantle structure, especially the geometry of subducting slabs (Handy et al., 2010).

Further support of plate tectonic reconstruction yields data on active tectonics. The data may be interpreted as a boundary condition to which all models of movements in the past should converge at geological age 0 Ma. The spatial distribution of seismicity, solutions of the focal mechanisms and especially plate motions observed by GPS draw a clear picture of active tectonics in the Alpine mountain system (Fig. 6).

From all these data and methods we may summarize that a CCW rotation of Adria with respect to EU around an Euler pole west of Torino by an amount of 20 – 25° since Oligocene is a reasonable description of the convergence between the EU and AD domain in the area of the EA.

9. Eduard Suess' conception of the evolution of the Alps and modern geophysical data

Eduard Suess (Suess, 1875) derived a general northward movement of the crust from south against the Alps from geological and geomorphological observations. More specifically he postulated movements to the north in the northern Apennines, westward in the Western Alps, north in the Central and Eastern Alps and the Western Carpathians. Following the Carpathians to the east the direction of the movement turns to east. He derived no direction for the Dinarides due to lack of evidence. He treated these movements as absolute movements. At that time considerable horizontal movements were seen as an exception because of the general acceptance of the contraction theory. An absolute geological reference frame was not an issue as long as fixism dominated tectonic reasoning.

Modern magnetic and paleomagnetic evidence and the pattern of active tectonics strongly support Eduard Suess' observations in the Alpine mountain system. For the Himalayas Eduard Suess postulated a general movement of Asia from north to south against India. However, modern geophysical and geodetic evidence is clear enough to allow for full accordance in the scientific community that India moved and still moves from the south against Asia and the Himalayas.

Thus, if we want to further apply Eduard Suess' scheme of crustal movements to modern geophysical data we must treat them as relative movements and interpret the moving crustal block (sensu Eduard Suess) as the upper plate of a collisional orogen. This transformation of Eduard Suess' original scheme to a plate tectonic reasoning can be applied successfully to the Himalayas, the Apennines, the Western and Central Alps and the Carpathians. In the following we argue on the base of modern geophysical data that Eduard Suess' postulated movements define the upper plate along the whole Alpine system.

We recognize a significant pattern concerning the course and polarity of the convergent plate boundaries derived from seismic data (Fig. 3) and the location of relative Bouguer gravity lows (Fig. 4). The axes of the Bouguer gravity lows follow roughly the course of the convergent plate boundaries, but they are shifted to the side of the lower, subducting plate. In order to make this systematic pattern clearer, we compiled the topographic elevation, the Moho depth, and the Bouguer anomalies along 5 profiles over the LG (Liguria)-AD (Adria), AD-EU (Europe), PA (Pannonian domain)-EU, and AD-PA plate boundaries (Fig. 7). The profiles run from the lower plate to the upper plate and they are centered on the plate boundary. Keeping the polarity of subduction shown on the Moho map (Fig. 3), the Moho depth and the BA confirm the pattern identifiable in Figure 4. Profiles 1 – 4 show clear upward steps of the Moho from the lower to the upper plate. At profile 5 no step could be identified, but the general asymmetric pattern of the Moho depth profiles from the lower to the upper plate is maintained. The minima of the Bouguer anomaly (BA) or the Bouguer anomaly stripped of the density variations in the upper crust (BAC) are 25-45 km shifted to the lower plate along the profiles 1, 2, 3, and 5 (Fig. 7). The shift of the BAC minimum to the lower plate at profile 4 (EU-PA) is less, an issue we will address later. As mentioned before, subduction polarity is a matter of discussion in the area of profile 3, the area of the Tauern Window. However, in this case we postulate subduction of EU under AD along this section of the AD-EU plate boundary. Without this, the otherwise systematic pattern of Moho depth and BA (or BAC) across the plate boundaries would be destroyed. Keeping the subduction polarities as shown in Figures 3, 4, 5, 7 they correspond completely to the crustal movements observed by Eduard Suess (1875).

Subduction of lithospheric mantle of the lower plate below the upper plate or subvertical down is not the only geodynamic conception that explains the accommodation of ongoing convergence after continent - continent collision. Ren et al. (2012) propose a symmetrical down-welling of both European and Adriatic mantle lithosphere due to a gravitational (Rayleigh-Taylor) instability (Houseman and Molnar, 1997). E. g., Lorinczi and Houseman (2009) applied this conception to the near vertical and drop-shaped slab below the Vrancea area in the Southeast Carpathians. They were able to explain the present distribution of deformation and the extent of the seismically active zone. Applying this conception to the Alps would make the discussion about upper and lower plate obsolete and we would lose the connection to the principle of uni-directionality of mountain building introduced by Eduard Suess. In the following, we therefore only consider the plate tectonic conception of upper - lower plate and subduction and show if and

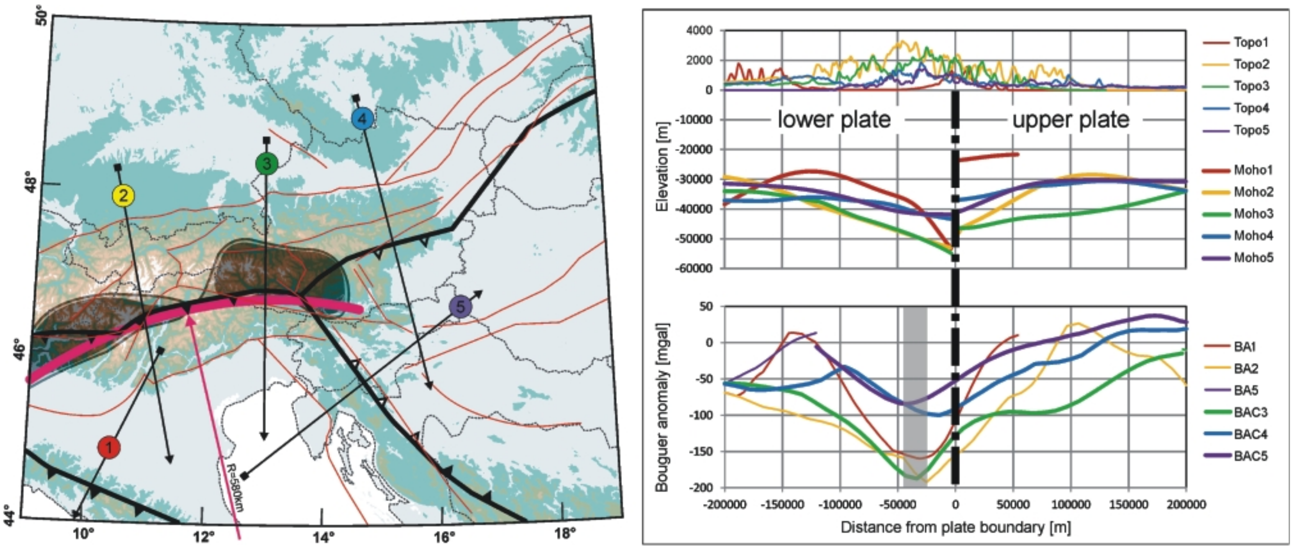

Figure 7: Asymmetric pattern at destructive plate boundaries. (a) contours of Alpine slab(s) (dVp = 1.4 % and 1.6%), plate boundaries, major faults and location of profiles 1 – 5 are superimposed on digital terrain model; profiles are N to S, except for profile 5; arrows point from lower to upper plate; (b) surface elevation, Moho depth, and Bouguer anomaly (BA, BAC, see Fig. 4) along profiles 1 – 5; profiles are centred at plate boundaries; grey bar highlights systematic offset of Bouguer gravity minimum from plate boundary.

how the observed structure of the East Alpine lithosphere and slab can be explained by applying these principles.

Eduard Suess emphasized the arcuate alignment of mountain ranges within orogenic systems. The concave sides of the mountains' arcs are oriented against the approaching crustal blocks according to his observations. This means that the concave sides of mountain arcs are generally oriented toward the upper plate of subduction zones or collisional orogens. This conception fits the situation in the Alpine system perfectly. The subducting (shallow) slabs under the Central and Eastern Alps form an arc with a radius of about 580 km (Fig. 7) with the concave side pointing to the south, i. e. towards the Adriatic plate. The ping pong ball model (e.g., Moores and Twiss, 1995) explains the arcuate shape of trenches and subducting lithosphere by an analogy to a dent in a ping pong ball. This analogy supports the interpretation that the concave side of a subducting slab points toward the upper plate. The ping pong model assumes further conservation of the area of the subducting slab. The radius of the arc and the dip of the slab are connected by a simple relation. A dip of 12° follows from this relation for the shallow slab. Tomographic images reveal a near vertical dip of the shallow slab in the Central and Eastern Alps. The consequence of this greater dip is lateral tension. We may speculate that the partition of the slab into apparently separate parts near the Brenner normal fault (~12°E) is a consequence of this tension. However, we have to bear in mind that geological factors initiating and accompanying subduction and physical processes controlling the subduction of a slab may be the dominant reasons for the partition.

Eduard Suess drew our attention to the one-sided nature of Alpine mountain systems and related it to the direction of crustal movements. Vergence of large folds and the dip of major thrusts primarily follow this conception in the Eastern Alps. However, Eduard Suess did not oversimplify, and he admits that nature does not always follow generalized conceptions in all details. This is the case for the Southern Alps, where he describes geologic structures that indicate crustal movements in the opposite direction. However, he interprets these structures as features of secondary order (Suess, 1875).

Figure 8 shows a N-S oriented cross section through the Eastern Alps at 13°E, which combines the results from the TRANSALP and Alp01 profiles (Fig. 2) and the teleseismic upper mantle models (Fig. 5). The geophysical data demonstrate the one-sided nature of this mountain range at a lithospheric scale. The boundary between the Eastern and Southern Alps (the PAL) at the surface almost coincides with the plate boundary between AD and EU at Moho level. The thrust of Rhenodanubian Flysch and Austro-Alpine units over EU basement and Molasse amounts to about 120 km. Thrust faults in the Southern Alps dip to the north and upper crustal shortening of 35 - 50 km has to be inferred (Castellarin et al., 2006). We speculate that indentation and Adriatic lower crustal and lithospheric thickening accommodates for this compression. Low P-wave velocities (Figs. 5, 8) in the upper mantle under the Southern Alps and the Adriatic foreland may support thermal

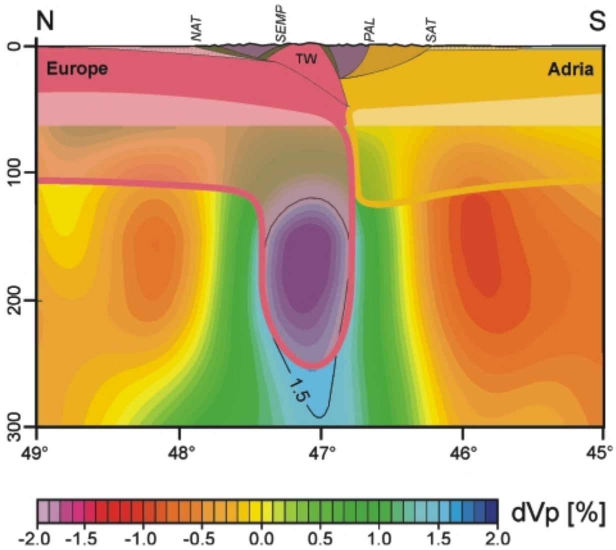

Figure 8: N-S oriented cross section through the lithosphere and upper mantle at 13°E (profile 3 in Figure 7). Schematic geological profile, crustal basement (red for Europe and yellow for Adria), tentative LAB, and EU continental slab are superimposed on cross section through the combined tomographic model of the upper mantle; arrows highlight that the amount of thrust of Rhenodanubian Flysch and Austro-Alpine units over European basement agrees approximately with the length of the subducted slab (~120 km).

erosion of the lower lithosphere and facilitate this process.

Eduard Suess addressed also the only exception of the direction of crustal movement and the curvature of the Alpine system mountain. This concerns the Eastern Alps near the southern corner of the Bohemian Massif and the Vienna Basin. The convex side of the Alpine mountain range points to the south in this section. This observation would indicate a reversed direction of crustal movements and, according to our interpretation of Eduard Suess' conception, a subduction polarity reversal. However, Suess explained this situation as the effect of the Bohemian Massif as a buttress. The crustal block approaching from the south was diverted to the east and bent around this buttress. Tensile stress was induced by this mechanism resulting in the generation of the Vienna Basin. We may estimate Eduard Suess' interpretation as a first step in the conception of lateral tectonic extrusion (e.g. Ratschbacher et al., 1991).

Extrusion of parts of the Eastern Alps to the east is still an issue in tectonic interpretation of geophysical data. In our opinion, the essential geophysical constraints on tectonic models of the eastern Eastern Alps are as follows:

- the geometry of the Moho fragmentation (Fig. 3), including the existence of the triple junction and the new micro-plate named the Pannonian domain;
- the termination of the shallow slab near the triple junction; no or only minor amounts of continental lower lithosphere was subducted along the Alpine arc east of the triple junction and under the Western Carpathians after consumption of the lithosphere of the Penninic Ocean by subduction.

A plate tectonic model of the lithospheric mantle to meet these two constraints was proposed. The absence of shallow slabs east of the triple junction was explained by the transition from subduction in the west to transform (strike-slip) in the east (Brückl et al., 2013). An additional assumption was that the Periadriatic line (PAL) east of the triple junction and the Mid-Hungarian line corresponds to a plate boundary separating ALCAPA in the north from Tisza and the Dinarides in the south. So far geophysical data is insufficient to reveal the plate boundary distinctly. Figure 9 shows three constitutive stages of the collision between the Adriatic domain and Europe. The extent of the European plates before subduction of continental lithosphere was tentatively reconstructed by flipping the vertically dipping shallow slab to the horizontal in the southward direction. The paleogeographic locations of main Austro-Alpine units according to Frisch et al. (2000) and Linzer et al. (2002) are superimposed on the tectonic blocks. These blocks represent the tectonic plates at the level of the Moho and upper mantle.

30 Ma: This stage characterizes the situation during the Oligocene period. The Adriatic domain comprising the Adriatic foreland, the Dinarides, Tisza, and ALCAPA converges to EU by rotation around an Euler pole at approximately 7°E, 45°N (e.g., Ustaszewski et al., 2008). The northern border of the Adriatic domain represents an active continental margin throughout. European lithosphere (which corresponds now to the shallow slab) in the west and lithosphere of the Penninic Ocean in the east are subducted to the south or south-east at this plate boundary.

25 Ma: Convergence and subduction along the whole active continental margin of the Adriatic domain continued. The Penninic Ocean subducted completely beforehand and breakoff had already occurred. At this stage – Late Oligocene or Early Miocene – the plate tectonic scenario changed significantly. The EU-ALCAPA plate boundary changed from subduction to transform or strike slip, thus avoiding subduction of continental lithosphere in this area. The boundary between ALCAPA and the rest of the Adriatic domain, the Periadriatic line (PAL), also became a transform boundary, generating a triple junction together with the AD-EU and EU-ALCAPA plate boundaries. Ongoing convergence of Adria, the Dinarides, and Tisza forced ALCAPA to escape to the east, and this escape was supported by slab roll-back of the Carpathian arc and extensional processes in the Pannonian Basin (e.g., Royden et al., 1983; Horváth et al., 2006). The triple junction moved along the PAL (AD-ALCAPA plate boundary) to the east. West of the triple junction the PAL line became an active margin and EU continental lower lithosphere started to subduct at this portion of it.

5-0 Ma: Convergence between AD and EU nearly reached the current state. The triple junction moved along the PAL more than 100km to the east, thus supporting lateral extrusion of East Alpine crust to the east significantly. The angle between the strike-slip boundaries confining ALCAPA became more oblique because of the CCW rotation of AD versus EU, forcing a west-east-oriented extension of ALCAPA. Due to this acute angle strike-slip at the PAL decayed and the tectonic activity predominantly moved to the plate boundary between Adria and the Dinarides, thus forming the Pannonian Domain (ALCAPA, Tisza, Dinarides, Dacia ?) into a new "soft" plate. Henceforward the triple junction may have moved along the Adria–Dinarides plate boundary transforming this boundary from strike-slip to subduction behind itself. These movements of the lithospheric mantle would offset the otherwise straight line of the PAL. However, we expect an offset in the range of 5 -10 km, an amount which is below the resolution of the Moho map (Fig. 3) and indiscernible in new surface structures.

10. Conclusion

Eduard Suess accepted in his treatise "Die Entstehung der Alpen" (Suess, 1875) continuous contraction of the Earth as the primary cause of mountain building. Contraction caused by cooling primarily affects vertical movements. Therefore, inhomogeneity of thermal properties must be induced to achieve vary-

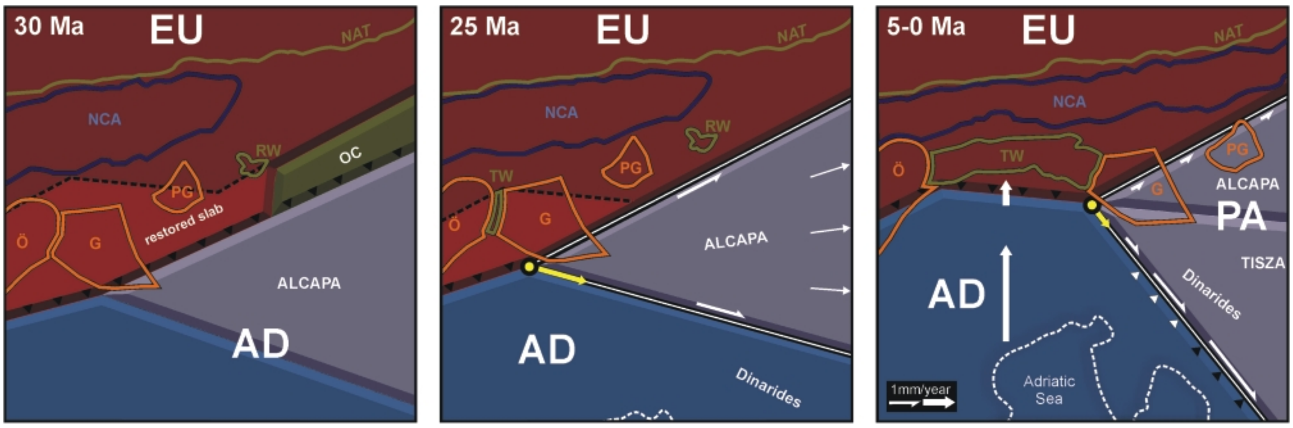

Figure 9: Plate tectonic model of the evolution of the eastern Alps since Oligocene. AD (Adria), EU (Europe), and PA (Pannonian domain, comprising ALCAPA, Tisza, and Dinarides) represent the lithospheric mantle of the major plates; plate boundary types (subduction, transform or transfer) are indicated by correspondent signatures; black circle with yellow fill marks triple junction AD-EU-PA; NAT is the North Alpine thrust fault in its current position; paleo-geographic locations of major geologic units (NCA – Northern Calcareous Alps, Ö – Ötztal nappe, TW – Tauern Window, G – Gurktal Nappe, PG- Graz Paleozoic, RW – Rechnitz Window) are superimposed on maps after Frisch et al. (2000) and Linzer et al. (2002); left map (30 Ma): OC represents the rest of the Penninic Ocean before complete subduction; central map (25 Ma): arrows on the east side of the ALCAPA unit symbolize extension toward the Pannonian Basin; right map (5 – 0 Ma): arrows represent a model of actual relative plate velocities.

ing lateral contraction of the uppermost layers of the Earth. Beside this deficiency of the contraction theory, Eduard Suess emphasized the existence of considerable horizontal movements.

Another physical theory concerning vertical movements is isostasy. The isostatic model presented by Airy could have provided constraints on the generation of sedimentary basins and especially the development of geosynclines. However, Eduard Suess did not include isostasy quantitatively into his considerations regarding these processes and mountain building in general.

Eduard Suess was actively working on seismology and provided major contributions to this discipline. At the time, only macro-seismic studies were carried out due to the lack of powerful seismographs. These studies provided valuable information about the distribution and effect of earthquakes. Eduard Suess correctly related the occurrence of earthquakes to active tectonic processes and the stress field (Fig. 1) induced thereby. A today's look at Mallet's world seismicity map instantaneously highlights the close relationship between seismic zones and plate boundaries. However, such associations are only pos-sible within the frame of the modern plate tectonic theory. Eduard Suess could not decipher this information, hidden at that time, from Mallet's map.

While studying "Die Entstehung der Alpen", it is intriguing to note that Eduard Suess abstracted fundamental observations on mountain building, which can be validly related to modern plate tectonic models based on geophysical data. The erroneous confinement to the contraction theory was no barrier to him generalizing his geological observations in a forward-looking conception. In our study we were able to show that Eduard Suess' observations on the direction of crustal movements and the asymmetry and arcuate form of mountain ranges correspond to subduction polarities at continent-continent collisions like the Alps and the Himalaya derived from modern geophysical data. Eduard Suess also addressed local deviations from the general scheme of mountain building. These exceptions are thrusting in a direction opposite to the general trend in the Southern Alps and the bending of the Eastern Alps in a "wrong" direction around the southern border of the Bohemian Massif. Eduard Suess supplied explanations, which are in principle still valid and do not question his general conception. These issues can also be addressed by tectonic models of the lithosphere, which take into consideration constraints provided by modern geophysical data and maintain the correspondence between Eduard Suess' observations and the general plate tectonic concept of the Alps.

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