The Maggia nappe: an extruding sheath fold basement nappe in the Lepontine gneiss dome of the Central Alps

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Abstract

The Lepontine gneiss dome represents a unique region of the Central Alps where Oligocene-Miocene amphibolite facies grade rocks and fold nappes of the deepest tectonic level of the Alpine orogenic belt are exposed in a tectonic window. The Cenozoic structures of the Maggia nappe reveals a giant tens of kilometre scale tubular fold structure that cross-cut through the surrounding lower Penninic nappes from its root situated in the southern steep-belt of the Alps near Bellinzona. The Mesozoic sedimentary cover of the Maggia nappe is typical for the Helvetic stratigraphic domain. The age of formation of the lower Penninic fold-nappes by ductile detachment of the upper European crust during its underthrusting below the higher Penninic and Austroalpine orogenic lid and Adriatic indenter was estimated between 40 and 30 Ma. Maximal pressures of 8-9 kbars and temperatures of 600-700 °C were attended during and after the nappe emplacement some 30-22 Ma ago. The Maggia and surrounding nappes are crosscut by the isograds of the Barrovian regional metamorphism.

Keywords Swiss Alps, Alpine tectonics, Penninic nappes, sheath fold structure

1. Introduction

The block diagram of the Central Alps of Switzerland and Italy illustrates the tectonic position of Maggia nappe in the Lepontine gneiss dome (Fig. 1, modified after Steck, 2008)). The geology of the Lepontine gneiss dome of the Central Alps of Switzerland and Italy is documented on numerous geological maps and stratigraphic studies of the twenties century (e.g. Geologische Karte und Tektonische Karte der Schweiz (2005). The here considered lower Penninic nappes are composed of polycyclic basement gneisses intruded by Permo-Carboniferous granites and overlain by their autochthonous Mesozoic-Cenozoic sedimentary cover of European affinity (Steck et al., 2013). A modern geological study of the Central Alps started with the fieldwork of Schmidt & Preiswerk (1905), Preiswerk et al. (1934) and Niggli et al. (1936) after the discovery of the lower Penninic fold nappe structures during the perforation of the Simplon railway gallery by Schardt (1903). The first description of the Antigorio fold nappe with its amplitude of 9 km by Gerlach (1869) was followed by the confirmation of the fold nappe geometry of the Simplon structures and the higher Saint Bernard and Monte Rosa nappes by Schardt (1903), Schmidt & Preiswerk (1905), Argand (1916), Milnes (1974), Steck (1984), Escher (1988) and Froitzheim (2001). Schmid et al. (2004) and Berger et al. (2005) considered the Maggia nappe as a thrust sheet situated in a high tectonic level of the lower Penninic nappe stack and attributed it to the middle Penninic Briançonnais domain as already proposed by Preiswerk et al. (1934). The high tectonic position on top of the Cimalunga unit was also formerly proposed by Steck et al. (2013). New field work and the integration of the observations of Bächlin et al. (1974) and Spicher and Wenk (1981) conducted us to the conclusion, that the Maggia nappe plunges in the southern steep belt of the Alps as a tubular fold structure below the higher Mergoscia and Cimalunga units (Fig. 2). The interpretation of the Maggia nappe as a sheath fold like tubular fold structure will be discussed in the present study. The study of the Mesozoic Cristallina sedimentary cover of the northern Sambuco lobe of the Maggia nappe similar to that of the Helvetic Gotthard massif conducted us to the conclusion that the Maggia nappe belongs to the Helvetic or European domain. Some units of the Valais suture, as the Mergoscia and Cimalunga Mélanges, possess relicts of an eclogitic late Eocene high-pressure metamorphism. The entire nappe pile was afterwards formed concomitant with and overprinted by an Oligocene-Miocene Barrovian-type orogenic regional metamorphism. The aim of this study is to describe the enigmatic Maggia nappe in the frame of the Alpine orogeny and discuss possible models of its formation.

2. Geological Setting of the Maggia and surrounding nappes.

The Lower Penninic nappe stack is composed from base to top of the Leventina, Verampio, Antigorio, Simano (the latter subdivided in Simano and Campo Tencia units, after Preiswerk, 1934), Lebendun, Maggia, Mergoscia, Cimalunga, Adula, Orselina-Bellinzona, Monte Leone and Valais calc-schist nappes that were detached from the upper European crust during its SE-directed underthrusting below the middle and higher Penninic nappes, the

Dent Blanche-Sesia thrust sheet and Adriatic indenter (Table 1). Milnes (1974; Steck, 1984; Steck et al. 2013) considered the Lower Penninic nappes of the Lepontine gneiss dome as fold-nappes. The fold-nappe geometry of the Maggia nappe is well exposed in its northern Sambuco lobe with its autochthonous Mesozoic sedimentary cover the Cristallina unit on its upper and lower fold limb (Figs. 2 and 4).

The deepest level of the Alpine nappe stack is overprinted by an amphibolite facies grade Barrovian-type regional metamorphism (e.g. Niggli & Niggli, 1965; Trommsdorff, 1966; Engi et al., 1995; Rubatto et al., 2009). An older late Eocene eclogite facies metamorphism affected the Mergoscia, Cimalunga and Adula nappes (e.g. Heinrich, 1986; Trommsdorff, 1990; Pfeifer et al. 1991; Becker, 1993; Gebauer, 1996; Brower et al. 2005; Herwartz et al. 2011; Sandmann et al. 2014). The external limit of the Oligocene-Miocene amphibolite facies grade metamorphism is indicated by the albite An0-3-hornblende = plagioclase An >17-hornblende-isograd (Wenk & Keller, 1969; the isograd position is modified in the Monte Rosa region after Steck et al., 2001, 2015). The nappe stack of the Central Lepontine gneiss dome is represented on Table 1 and the Alpine structures of the central part of the Lepontine gneiss dome are illustrated on the map and profiles of Figs. 2 and 3.

The Maggia nappe was for a first time represented on a geological map of the Lepontine gneiss dome by Preiswerk,1932 in Niggli et al. (1936) and Preiswerk et al. (1934) as a NW-SE oriented synform perpendicular to the SW-NE trend of the Central Alps. Already Preiswerk (1919), in a structural study of the Campolungo pass region recognised the superposition of the Maggia transverse synform on the deeper Antigorio nappe to the west and the Campo Tencia and Simano (=Verzasca gneiss) nappes to the east. Preiswerk's model was confirmed by our own observations (Steck, 1998; Steck et al., 2013). Grütter and Kündig considered in the same review paper of Niggli et al. (1936) the Maggia nappe as a tectonic root that separates the deeper Antigorio from the higher Campo Tencia nappe. An idea that was also suggested by other studies (Grujic & Mancktelow, 1996, Maxelon & Mancktelow, 2005, Rütti et al., 2005). The latter model is contrary to the Alpine structural data collected by Preiswerk (1919), Wenk (1955), Steck (1998) and correctly documented on Fig 12 of Maxelon & Mancktelow (2005). The superposition of the Antigorio and Campo Tencia nappes by the frontal Maggia nappe proposed by Preiswerk in Niggli et al. (1936) is confirmed by new fieldwork on the Pizzo Massari – Pizzo Prevat geological profile (Fig. 4). The frontal fold hinge of the Campo Tencia Nappe and the sedimentary syncline of the Campolungo pass transect form a down facing fold structure testifying that the Sambuco klippe is situated above the Campo Tencia nappe front. The geometry of the down facing Mogno Mesozoic sedimentary syncline was also confirmed by observations in the Prato-Camblee water gallery (personal communication by Franz Keller, Fig. 5; Steck et al. (2013).

Keller et al. (1980) separate on their 1:25’000 scale geological map “Campo Tencia” the northern Sambuco klippe from its southern continuation the Maggia synform. The Alpigia gneisses, separating the Sambuco klippe from the southern Maggia synform, were attributed by Keller et al. (1980) to the Antigorio nappe. This attribution is supported by the identical Early Permian U-Pb zircon ages of the tonalites, granodiorites and granites dated between 289 ± 2 Ma and 296 ± 2 Ma by Bergomi et al. (2007) in the Antigorio nappe and between 288 ± 2 and 294 ± 2 Ma in the Alpigia unit by Hirsiger et al. (2015). The tonalites, granodiorites and granites of the Matorello gneiss in the northern Sambuco klippe and the similar Cocco gneiss in the centre of the Maggia synform have a Late Carboniferous age dated at 300-304 ± 8 Ma for the Matorello and at 308 ± 7 Ma for the Cocco gneiss (U-Pb zircon ages, Bussien et al., 2011). The latter data corroborate the Keller et al. (1980) proposal that the Sambuco spoon and the Maggia synform belong to the same Maggia complex and not the Sambuco unit to the Helvetic and the southern Maggia synform to the Briançonnais domain as proposed by Berger et al. (2005). The Early Permian Mezzalama granite of the Monte Rosa nappe and the Randa-granite of the Briançonnais Siviez-Mischabel basement are dated at 270±4 Ma (Bussy in Steck et al. 1999; Pawlig & Baumgartner, 2001). Based on the structural study of the northern and middle part of the Maggia synform we first concluded that the Maggia synform continues to the south and superpose there the deeper Mergoscia and Cimalunga nappes (Steck et al. 2013), an idea also supported by Schmid et al. (2004, 2017), Berger et al. (2005), Berger & Mercolli (2006) and Bousquet et al. (2012). New field observations on the southern end of the Maggia nappe conducted us to a totally different model of the Maggia structure that we discuss later in this study. The Maggia nappe plunges near Bellinzona as a tubular fold below the Mergoscia nappe in the southern steep belt (Chapter 3. Alpine structures).

Preiswerk in Niggli et al. (1936) considered the Maggia nappe as a synformal klippe situated on top of the Lower Penninic nappes and as a lateral equivalent of the Middle Penninic Sankt-Bernhard nappe of the Briançonnais domain. This attribution to the Briançonnais domain was later adopted by Schmid et al. (2004; 2017), Berger et al. (2005) and Bousquet et al. (2012). It is in agreement with Preiswerk’s idea based on the high level tectonic position of the Maggia nappe. New stratigraphic studies of the Mesozoic cover sediments suggest an attribution of the Maggia nappe to the Helvetic palaeographic domain (Masson & Steck, 2015). The Sambuco klippe of the northern Maggia nappe retains its autochthonous stratigraphic cover, the Cristallina Mesozoic sediments of a typical Helvetic affinity, similar to the autochthonous cover of the Gotthard massif (Liszkay-Nagy, 1965). The Triassic starts with a thin band of 30-50 cm of quartzose and arkosic sandstone overlain by a band of < 2 m of white dolomite. The latter dolomite is followed by the Naret Formation, a series of 100 m of heterogeneous, garnet, staurolite and kyanite bearing sandstones with some thin layers of yellow calcite and dolomite marbles similar to the Rhaetian of the Gotthard cover, the lower and upper garnet schists of Liszkay-Nagy (1965). The Lower and Middle Jurassic is composed of variable types of some garnet, kyanite and staurolite bearing graphitic sandstones and conglomerates, gritty and banded marbles, overlain by pure Upper Jurassic white calcite marble on top. The Pertusio zone, at the limit of the Maggia and Campo Tencia nappes, is composed of complex refolded centimetre-decimetre slices of quartzite and white calcite marble of a probable middle and upper Jurassic age respectively and the up to ten metre white marbles of the Someo zone at the limit between the Maggia and Mergoscia nappes of a probable Upper Jurassic age are interpreted as the reduced Mesozoic cover of the Maggia nappe forming the southern Helvetic continental margin. The fossil-free and strong deformation of these sedimentary slices makes their stratigraphic interpretation questionable and open. Never the less it is herein suggested that the Sambuco-Maggia nappe belongs together with the Antigorio and the Gotthard fold nappe to the Helvetic stratigraphic domain. The Campolungo Triassic sedimentary cover of the Campo Tencia nappe is characterized by its huge over 300m wide zone of banded black and white dolomitic marbles overlying a thin band of basal quartzite. It may be attributed to a transition zone between the Helvetic and Briançonnais domains. A similar large series of Triassic dolomitic marbles characterize the units of the Briançonnais domain (Ellenberger, 1953; Escher, 1988)

The Mergoscia and Cimalunga nappes are composed of tectonic mélanges of polycyclic basement gneisses, Meso-Cenozoic continental and marine sediments and oceanic ophiolites, successively overprinted by an approximate Late Eocene eclogite and Oligocene-Early Miocene amphibolite facies regional metamorphism (Engi et al. 1995; Rubatto et al. 2009; Sandmann et al. 2014). The Orselina nappe is a similar tectonic mélange overprinted by the Oligocene-Early Miocene amphibolite facies metamorphism but without eclogite facies relicts (Fig. 2; Steck et al., 2013; Pfeifer et al. 2018). The Mergoscia and Cimalunga tectonic mélanges and the Adula nappe with their Late Eocene eclogite facies metamorphism (Becker, 1993; Brouwer et al. 2005; Herwartz et al. 2011; Sandmann et al. 2014), the Bosco and Bombogno-Orselina-Bellinzona mélanges, the Monte Leone and Valais calc-schist nappes mark a major zone of deep subduction and accretion in the Nappe stack of the Lepontine Alps situated below the middle Penninic nappes of the Briançonnais paleogeographic domain. This Late Eocene zone of deep subduction and accretion in the Alpine thrust belt is named Valais suture on Table 1 (Engi et al. 1995; 2001; Gebauer, 1996; Cavargna-Sani et al. 2014).

3. Alpine structures of the Sambuco – Maggia nappe

The decode of the Alpine structure and history of the Maggia nappe was a main subject of the present field work. The Maggia unit forms a high Alpine nappe of the Lepontine gneiss dome. It overlies the deeper Antigorio nappe to the west and Campo Tencia and Verzasca nappes to the east. The measured fold axis and stretching lineations of this study corroborate the data of the structural map of the Ticino Alps by Wenk (1955). The gneiss structures result from multiple ductile folding during and after the nappe emplacement. The unequivocal distinction of the successive formed folds and their axial surface schistosities was established in the Helvetic Aar and Gotthard F2 basement folds and in the frontal parts of the lower Penninic F2-F3 Verampio, Antigorio, Maggia and higher basement fold nappes (Liszkay-Nagy, 1965; Masson et al. 1980; Steck, 1984, 1987, 1990, 1998, 2011). Four schistosities S1-S4 and six phases of folding F1-F6 are distinguished in the Maggia and surrounding nappes. Late crenulation folds F7 with a sub-horizontal to low-angle west dipping axial surface were formed during a phase of vertical shortening below the Simplon normal fault (Table 2, Steck, 1987). Note that the first alpine schistosity S1, sub-parallel to the lithologic banding observed by Liszkay-Nagy (1965 and this study) in the Nufenen-pass region is missing in many descriptions (Huber et al. 1980; Huber, 1981; Maxelon & Mancktelow, 2005). This early first schistosity is also clearly observable in the Mesozoic sediments of the autochthonous cover of the Aar and Gotthard massifs F2 basement folds. But first folds F1 are infrequent and rarely demonstrable (Steck, 1984, 1987, 2011).

Early schistosites S1-S3 and a SE-plunging stretching lineation L1-L3 were developed in the gneiss fold nappes during their NW-directed ductile shear décollement from the upper European crust during its underthrusting below the middle and higher Penninic nappes, the Dent Blanche-Sesia thrust sheet and Adriatic indenter. A dominant and late axial surface schistosity S4, post nappe folds F4 and an associated SE-plunging stretching lineation L4 were developed after the NW-directed nappe emplacement, creating the southwest-verging Verzasca antiform and Sambuco-Maggia synform during a phase of dextral shear in the zone of Alpine collision between the European plate and the Adriatic indenter (Fig. 2 and 3). The pre-existing NW-directed S1-S3-related sense-of-shear structures were inverted by rotation around the axis and stretching lineation of the younger Verzasca F4-antiform (Allaz et al., 2005; Steck et al., 2013). The unequivocal discernment of the different phases of schistosities and stretching lineations is difficult and in many places impossible. The final planar and linear gneiss structures result from internal rotation and transposition by continuous ductile deformation (Figs. 2 and 3). The post-nappe steepening of the southern Alpine belt with the formation of the

Vanzone and Cressim F5 backfolds occurred during the so-called Argand's phase of backfolding (Fig. 1 and Table 2; Argand, 1911; Milnes, 1974).

The northern end of the SE-plunging Maggia F4-synform was later overprinted by younger NE-trending Foroglio and Cristallina F6 folds creating a type 2-fold interference pattern after Ramsay (1967). The Neogene uplift of the Lepontine gneiss dome since over 18 Ma (Steck & Hunziker, 1994) accompanied by its erosion were responsible for the separation of the Sambuco lobe from its southern continuation the Maggia synform (Figs. 1 and 2).

The fold axes and parallel stretching lineations of the synformal Maggia nappe plunge from north to south, between the Val Lavizzara, Peccia, Bignasco and the Verzasca reservoir, over a distance of 30 km with a regular low angle of 0-10° to the SE. To the south-east of the Verzasca reservoir the fold axes plunge increases rapidly from 10° to 70°, ending in an east closing steep plunging F5 antiform of the Mergoscia nappe (Fig. 2). New detailed field work in the Sementina and upper Gorduno valleys confirm the geological observations of Bächlin et al. (1974): The Ruscada- and Cocco-gneisses of the Maggia nappe dip to the SE with a steep angle of over 75° in a tubular fold structure below the eclogitic Mergoscia mélange nappe (Fig. 2). It is "der schlundartige Wirbel von Bellinzona", the gorge like whirl of Bellinzona represented by Wenk (1955) on his map of Alpine fold axes. Spicher & Wenk (1981) describe the steep converging structure near Bellinzona as a late vortex-like root zone, in a neutral sense of the term, formed under highly ductile conditions in Oligocene-Early Miocene time, after the nappe emplacement and during a late orogenic phase of folding and re-crystallisation in the deep mobile belt (Read 1955) of the Alps. It is herein considered that the on the geological map established sheath fold like tubular structure originate from the overprint and squeeze of the Maggia F1-F3 thrust root during the late F4-F5 folding phases related to dextral shear in the southern steep belt of the Alps (Figs. 2, 3 and 6). The southern root of the Maggia nappe possesses the geometry of a tubular sheath fold like structure surrounded by the Antigorio and Campo Tencia-Verzasca nappes at its base and the eclogitic Mergoscia and Cimalunga mélanges on the top (Fig. 2 and 6). The geometry of this sheath fold like tubular structure results from multiple folding and not from the mechanism of simple shear alone proposed by the Cobbold & Quinquins (1980) model. Sheath folds or sheath fold like structures of centimetre- to metre-dimension are common in other Alpine ductile thrust zones, for instance at the base of the Helvetic Doldenhorn thrust fold (Krayenbühl & Steck, 2009), there characterised by multiple ductile folding. Lacassin and Mattauer (1985) described a kilometre-scale sheath fold in the Mattmark region on top of the NW-directed Monte Rosa nappe thrust. The pictures of fold interference patterns published by these authors suggest also a zone of multiple shear folding. Cobbold and Quinquins (1980) discussed and studied experimentally a sheath fold model as a mechanism of simple shear affecting a pre-existing deflection of an irregular surface. The formation of the Maggia sheath fold like tubular structure results not from the process of simple shear alone described in the Cobbold and Quinquins (1980) model, but probably by a more complex process of multiple shear folding in a thrust zone. The intersection of folds of successive generations may be an ideal site for the formation of a sheath fold like structure.

4. Age and pressure-temperature conditions of the ductile Lower Penninic nappe detachment zone

The ductile detachment of the Lower Penninic nappes from the upper European crust started at the base of the Alpine Middle and Upper Penninic nappe stack, an overburden of 25 km, after its emplacement dated between 52-35 Ma (Markley et al., 1998; Skora et al., 2015) and after or synchronous of the 40-35 Ma of the Paleocene-Eocene planktonic foraminifera in the Sion-Courmayeur zone, Valais flysch (or contourite) nappe near Sion (Bagnoud et al., 1998) and before the formation of the Vanzone and Cressim back folds and the Southern Steep belt of the Central Alps since about 30 Ma (Milnes, 1974; Berger et al., 1996; Steck and Hunziker, 1994; Schmid et al., 1996; Steck et al., 2013). The detachment of the Lower Penninic nappes in the zone of underthrusting of the European crust below the higher Alpine orogenic lid occurred consequently in the Early Oligocene between 40 and 30 Ma by ductile shear under increasing greenschist to amphibolite facies metamorphic conditions and this before reaching the thermal peak. Stable assemblages of kyanite-staurolite-garnet-biotite crystallised during the formation of the main S3 schistosity and the NW-directed L3 shear and remained stable during the W-verging Verzasca and Maggia F4 folding. Most of the acicular or prismatic hornblende, staurolite and kyanite synkinematic crystals are oriented parallel to L2-3 stretching lineations, others postkinematic are non-oriented (Allaz et al. 2005). Maximum pressures reaching 8-9 kbars and temperatures of 600-700°C where attended in the Maggia region (Todd & Engi, 1997; Allaz et al., 2005; Brower et al., 2005; Burri et al. 2005; Boston et al. 2017). The isograds of the Barrovian regional metamorphism cut through the nappe limits (Fig. 7, e.g. Niggli & Niggli, 1965; Trommsdorff, 1966; Wenk & Keller, 1969; Burri et al. 2005). The northern limit of the over 6 km wide Tertiary migmatite zone cross the southern root of the Maggia nappe to the south of the village of Maggia and occupies the southern steep belt of the Alps from the entrance of the Valle Onsernone and Locarno to the west to the Bergell intrusion to the east (Fig. 7, Burri et al., 2005; Steck et al., 2013). In situ migmatites were dated in the Bellinzona region by the age of Cenozoic synkinematic leucosome veins of the high amphibolite facies grade metamorphism of the K-feldspar-silimanite zone at 32-22 Ma with U-Pb SHRIMP zircon ages by Rubatto et al. (2009), allanite U-Pb ages by Gregory et al. (2012) and U-Pb monazite ages by Boston et al. (2017). These Cenozoic migmatites are of the same age as cross cutting crustal derived pegmatites and aplites (Romer et al., 1996; Schärer et al., 1996). The concentration of Tertiary migmatite and discordant aplites and pegmatites in the southern steep belt and the geometry of the Andesine An >40 amphibolite-isograd around the southern Maggia-root suggest a greater terrestrial heat flow in vertical zones of the Lepontine gneiss dome (Fig. 7, Wenk & Keller, 1969). Schärer et al. (1996) suggest that frictional heating in the dextral shear zone of the southern steep belt of the Alps may also be responsible for this phase of post-nappe heating. This signifies that the up heating to thermal peak conditions of the southern steep belt outlast the pre-existing extrusion and emplacement of the Maggia nappe. Thermal peak conditions and emplacement of crustal derived aplites and pegmatites are coeval to a Late Oligocene to Miocene incipient phase of vertical shortening and lateral, mainly SW-NE directed extension of the Alpine nappe stack, dextral shear in the southern steep belt of the Alps and the formation of the Simplon low-angle detachment of the Lepontine dome and Dent Blanche depression pull-apart structure (Fig. 1; Steck, 1990; Steck & Hunziker, 1994; Steck et al., 2013).

5. Discussion of models for the extrusion structures in fold nappes.

A fundamental question exists in the interpretation of the Penninic nappes, are they simple thrust sheets as the Sesia-Dent Blanche (Salassic) and Australpine thrust sheets, are they folds deforming crustal sheets or are they nappes formed by a mechanism of ductile folding alone. The question is still discussed. Froitzheim et al. (1996) and Schmid et al. (2004) consider the Maggia nappe as a thrust sheet. In contrast, Wenk (1955), Milnes (1974), Maxelon & Mancktelow (2005), Steck (1984, 2008) and Steck et al. (2013) interpreted the Lower Penninic nappes of the Lepontine gneiss dome as fold-nappes formed by multiple ductile shear folding and decollement of the upper European crust under greenschist to amphibolite facies metamorphic conditions during its south directed underthrusting below the higher Penninic and Salassic orogenic lid and Adriatic indenter. The geometry and penetrative texture of the gneiss fold nappes suggest a mechanism of ductile folding under greenschist to amphibolite facies conditions. The study of Cenozoic deformed granitic basement rocks of the Alpine Aar massif – Leventina nappe transect by Voll (1976) reveal their ductile behaviour related to the quartz synkinematic crystallisation at temperatures over 300°C and feldspar crystallization at amphibolite facies conditions. Early brittle thrusting under lower temperature conditions cannot completely be excluded. A model for fold nappe extrusion by ductile squeezing of the deep zone of the Europe-Adria collision is suggested by Merle & Guillier (1989). A more realistic mechanism of ductile detachment of basement gneiss folds by pure and simple shear from the under-thrust European crust was proposed by Epard & Escher (1996), Escher & Beaumont (1997) and Pfiffner et al. (2000). Field data confirm the fold nappe geometry of the Maggia nappe front. The northern Sambuco lobe of the Maggia nappe possess slices of its autochthonous Mesozoic sedimentary cover on its upper and lower fold limb. The sedimentary cover is farther south reduced and strongly deformed to thin quartzite and limestone bands of the Pertusio and Someo cover series (Fig. 2 and 4). The question of the autochthony of these sediments is open. It is herein suggested that these slices of Mesozoic sediments represent a reduced autochthonous cover of the Maggia nappe and the southern border of the European continental margin. The Maggia nappe roots in the southern steep belt of the Alps in direct contact with the eclogitc Mergoscia and Cimalunga mélanges units (Fig. 2 and Table 1; Bächlin et al.1974). It is probable that the Maggia nappe emplacement is related to the deep subduction and later extrusion and accretion of these ultra-high pressure units in the Valais suture (Table 1). The action of strong buoyancy and diapirism of deep subducted and later extruded and accreted upper crustal slabs was suggested in the model of Chemenda et al. (1995). A vertical pull and imbrication of the Maggia fold nappe by the deep subducted high pressure rocks of the Valais suture during their extrusion is probable. Engi et al. (2001) suggest the notion of tectonic accretionary channel (TAC) for such enigmatic zones of deep subduction, extrusion and accretion of the Alps.

6. Conclusions

The tectonic window of the Central Alps allows the study of the structural variation through superposed tectonic levels of the orogenic belt. It permits a modern image of the so-called “Stockwerk Tektonik” of Wegmann (1953). NW-directed thrusting and multiple ductile folding of detached European crustal rocks characterise the deepest exposed tectonic level of the Central Alpine nappe stack. The Maggia nappe represents a north-directed pipe-like extruding fold-nappe structure. It has the geometry of a tubular sheath fold like structure that roots in the southern steep belt of the Central Alps (Figs.2 and 6). Its Mesozoic stratigraphic cover assigns the Maggia fold nappe to the Helvetic paleogeographic domain. It is bordered by the higher tectonic units of the Valais suture composed of the high pressure Mergoscia and Cimalunga mélanges, the Adula high pressure nappe, the medium pressure Orselina mélange and the Valais calc-schist nappe situated below the Middle

Penninic nappes of the Briançonnais domain and the Monte Rosa nappe. The formation of the Lower Penninic nappe pile occurred between some 40 and 30 Ma ago by ductile detachment of the upper European crust starting with high-pressure conditions in the Mergoscia and Cimalunga mélanges followed by increasing greenschist and amphibolite facies conditions in the zone of underthrusting below the higher orogenic lid and Adriatic indenter. The thermal peak of the Tertiary Barrovian regional metamorphism was attended between 30 and 22 Ma after the Alpine nappe emplacement and related to the uplift and E-W extension of the Oligocene-Miocene Lepontine gneiss dome structure.

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References

Allaz, J., Maeder, X., Vannay, J.-C. & Steck, A. (2005). Formation of alumosilicate-bearing quartz veins in the Simano nappe (Central Alps): structural, thermobarometric and oxygen isotope constraints. *Schweizerische Mineralogische und Petrographische Mitteilungen 85*, 191-214.

Argand, E. (1911). Les nappes de recouvrement des Alpes Pennines et leurs prologements structuraux. *Beiträge zur Geologischen Karte der Schweiz [N.F.] 31*, 26.

Bächlin, R., Bianconi, F., Codoni, A., Dal Vesco, E., Knoblauch, P., Kündig, E., Reinhard, M., Spänhauer, F., Spicher, A., Trommsdorff, V. & Wenk, E. (1974). Blatt 1313 Bellinzona. *Geologischer Atlas der Schweiz 1:25'000, Federal Office of Topography, Ch-3084 Wabern.*

Bagnoud, A., Wernli, R., Sartori, M. (1998). Découverte de foraminifères planctoniques paléogènes dans la zone de Sion-Courmayeur à Sion (Valais, Suisse). *Eclogae geologicae Helvetiae 91/3*, 421-429.

Becker, H. (1993). Garnet peridotite and eclogite Sm-Nd mineral ages from the Lepontine dome (swiss Alps): New evidence for Eocene High-pressure metamorphism in the central Alps. *Geology 21*, 599-602.

Berger, A. & Mercolli, I. (2006). Tectonic and petrographic map of the Central Lepontine Alps. *Carte geologica speziale N. 127, 1:100'000, Federal Office of Topography, Ch-3084 Wabern.*

Berger, A., Mercolli, I. & Engi, M. (2005). The central Lepontine Alps: Notes accompanying the tectonic and petrographic map sheet Sopra Ceneri (1:100'000). *Schweizerische Mineralogische und Petrographische Mitteilungen 85*, 109-146.

Berger, A., Rosenberg, C. & Schmid, S.M. (1996). Ascent, emplacement and exhumation of the Bergell pluton within the Southern Steep Belt of the central Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen 76*, 357-382.

Bergomi, M.A., Tunesi, A., Shi, Y.-R., Colombi, A. & Liu, D.-Y. (2007). SHRIMPH U-Pb geochronical constraints of pre-Alpine magmatism in the Lower Penninic units of the Ossola Valley (Western Alps, Italy), *Geochronological Research Abstracts, 9*, 07780, European geosciences Union.

Bianconi, F. (1971). Geologia e petrografia delle regione del Campolungo. *Materiali per la Carta Geologica della Svizzera N.S. 142*, 238 p.

Bianconi, F., Beffa, F.A., Steiger, R.H., Günthert, A., Hasler, P., Baumer, P. & Huber, C.W. (2014). Foglio 1252 Ambri-Piotta.- *Atlante geologico della Svizzera 1:25 000, Carta 138, Federal Office of Topography, Ch-3084 Wabern*.

Bianconi, F. & Strasky, S. (2015). Foglio 1252 Ambri-Piota. *Atlante geologico della Svizzera 1:25 000, Note explicative 138, Federal Office of Topography, Ch-3084 Wabern*.

Boston, K.R., Rubatto, D., Hermann, J., Engi, M. & Amelin, Y. (2017). Geochronology of accessory allanite and monazite in the Barrovian metamorphic sequence of the Central Alps, Switzerland. *Lithos 286-287*, 502-518.

Bousquet, R., Goffé, B., Vidal, O., Patriat, M. & Oberhänsli, R. (2002). The tectono-metamorphic history of the valaisan dmain from the Western to the Central Alps: New constraints for the evolution of the Alps. *Bulletin of the Geological Society of America114,* 207-225.

Bousquet, R., Schmid, S.M., Zeitlinger, G., Oberhänsli, R., Rosenberg, C., Molli, G., Robert, C., Wiederkehr, M. & Rossi, Ph. (2012). Tectonic framework of the Alps. Map 1: 1 000 000. *Commission for the Geological Map of the World. Subkommission for Magmatic and Metamorphic Maps. IUGS and IUGG, Paris. http://www.cegm.org.*

Brower, F.M., Burri, T., Engi, M. & Berger, A. (2005). Eclogite relics in the Central Alps: PT-evolution, Lu-Hf ages and implications for formation of tectonic mélange zones. *Schweizerische Mineralogische und Petrographische Mitteilungen 85*, 147-174.

Burri, T., Berger, A. & Engi, M. (2005). Tertiary migmatites in the Central Alps: regional distribution, field relations, conditions of formation, and tectonic implications. *Schweizerische Mineralogische und Petrographische Mitteilungen 85*, 215-232.

Bussien, D., Bussy, F., Magna, T.& Masson, H. (2011). Timing of Palaeozoic magmatism in the Maggia and Sambuco nappes and paleogeographic implications (Central Lepontine Alps). *Swiss Journal of Geosciences 104,* 1-29.

Cavargna-Sani, M., Epard, J.-L., Bussy, F. & Ulianov, A. (2014a). Basement lithostratigraphy of the Adula nappe: implications of Palaeozoic evolution and Alpine kinematics. *International Journal of Earth Sciences 103*, 61-82.

Cavargna-Sani, M., Epard, J.-L. & Steck, A. (2014b). Structure, geometry and kinematics of the northern Adula nappe (Central Alps). *Swiss Journal of Geosciences 107,* 135-156.

Chemenda, A.I., Mattauer, M., Malavieille, J. & Bocun, A.N. (1995). A mechanism for syn-collisional rock exhumation and associated mormal faulting: Results from physical modelling. *Earth and planetary Sciences letters 132,* 225-232.

Cobbold, P.R. & Quinquins, H. (1980). Development of sheath folds in shear regimes. *Journal of Structural Geology 2,* 119-126.

Ellenberger, F. (1953). La série du Barrhorn et les rétrocharriages penniques. *C.R. Académie des Sciences (Paris) 236,* 218-220.

Engi, M., Berger, A. & Roselle, G.T. (2001). Role of the tectonic accretion channel in collisional orogeny. *Geology 29,* 1143-1146

Engi, M., Todd, C.S. & Schmatz, D.R. (1995). Tertiary metamorphic conditions in the eastern Lepontine Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen 75*, 347-369.

Epard, J.-L., Escher, A. (1996). Transition from basement to cover: a geometric model. *Journal of Structural Geology, 18,* 533-548.

Escher, A. (1988). Structure de la nappe du Grand Saint-Bernard entre le val de Bagnes et les Mischabel. *Rapports géologique du Service hydrologique et géologique national 7*.

Escher, A. & Beaumont, C., 1997. Formation, burial and exhumation of basement nappes at crustal scale: a geometric model based on the western Swiss-Italian Alps. *Journal of Structural Geology, 19*, 955-974.

Froitzheim, N. (2001). Origin of the Monte Rosa nappe in the Pennine Alps – A new working hypothesis. Bulletin of the Geological Society of America, 113/5, 604-614.

Froitzheim, N., Schmid, S.M. & Frey, M. (1996). Mesozoic palaeography and the timing of eclogite facies metamorphism in the Alps: A working hypothesis. *Eclogae Geologicae Helvetiae 89*, 81-110.

Galster, F., Cavargna-Sani, M., Epard, J.-L. & Masson, H. (2012). New stratigraphic data from the lower Penninic between the Adula nappe and the Gotthard massif and consequences for the tectonics and the paleogeography of the Central Alps. *Tectonophysics 579*, 37-55.

Gebauer, D. (1996). A P-T-t path for an (ultra?-) high pressure ultramafic/mafic rock association and its felsic country-rocks based on SHRIMP-dating of magmatic and metamorphic zircon domains. Example: Alpe Arami (Central Swiss Alps). In: Basu, A. and Hart, S. (eds): *Earth processes: Reading the isotopic code, Geophysical Monograph 95,* American Geophysical Union, Washington, 307-330.

Gregory, J.C., Rubatto, D., Hermann, J., Berger, A. & Engi, M. (2012). Allanite behaviour during incipient melting in the southern Central Alps. *Geochimica et Cosmochimica Acta 84*, 433-458.

Grond, R., Wahl, F. & Pfiffner, M. (1995). Poly-phase Alpine deformation and metamorphism in the northern Cima Lunga unit, Central Alps (Switzerland). *Schweizerische Mineralogische und Petrographische Mitteilungen 75(3)*, 371-386.

Grujic, D. & Mancktelow, N.S. (1996). Structure of the northern Maggia and Lebendun nappes, Central Alps, Switzerland. *Eclogae Geologicae Helvetiae 89*, 461–504.

Heinrich, C.A. (1986). Eclogite facies regional metamorphism of hydrous mafic rocks in the Central Alpine Adula nappe. *Journal of Petrology 27,* 123-154.

Herwartz, D., Nagel, T.J., Munker, C., Scherrer, E.E. &Froitzheim, N. (2011). Tracing two orogenic cycles in one eclogite sample by Lu-Hf garnet chronometry. *Nature Geoscience 4*, 178-183.

Hirsiger, C., Bussy, F., Epard, J.-L., Masson, H., Steck, A. & Ulianov, A. (2015). The Lower Permian Alpigia magmatic complex and its country rock (Upper Maggia Valley, Central Alps): petrology, geochronology and structural position. *13th Swiss Geoscience Meeting, Basel 2015, Abstracte volume 54*.

Huber, M.L. (1981). Geologisch-strukturelle Untersuchungen im oberen Maggiagebiet (Tessin, Schweiz). *Ph.D. dissertation, ETH Zürich*, 221 p.

Huber, M.L., Ramsay, J. & Simpson, C. (1980). Deformation in the Maggia and Antigorio nappes, Lepontine Alps. *Eclogae Geologicae Helveltiae 73,* 593-606.

Keller, F., Wenk, E., Bianconi, F. & Hasler, P. (1980). Blatt 1272 P. Campo Tencia, *Geologischer Atlas der Schweiz, 1: 25'000, Atlasblatt 73, Federal Office of Topography, Ch-3084 Wabern*.

Krayenbuhl, T. & Steck, A. (2009). Structure and kinematics of the Jungfrau syncline, Faflertal (Vais, Alps), and its regional significance. *Swiss Journal of Geosciences 102*, 441-456.

Lacassin, R. & Mattauer, M. (1985). Kilometer scale sheath fold at Mattmark and implications for transport direction in the Alps. *Nature 316(6022)*, 739-724.

Liszkay-Nagy, M. (1965). Geologie der Sedimentbedeckung des südwestlichen Gotthard-Massivs im Oberwallis. *Ecloge geologicae Helveticae 58*, 901-965.

Markley, M.J., Teyssier, C., Cosca, M.A., Caby, M.A., Hunziker, J.C. & Sartori, M. (1998). Alpine deformation and 40Ar/39Ar geochronology of synkinematic white mica in the Siviez-Mischabel Nappe, western Pennine Alps, Switzerland. *Tectonics 17*, 407–425.

Masson, H., Herb, R. & Steck, A. (1980). Helvetic Alps of Western Switzerland. *Excursion No I in Geology of Switzerland a guide-book by Trümpy, R.* edited by Schweizerische Geologische Kommission, Wepf & Co, Basel, NewYork.

Masson, H. & Steck, A., 2015. The Maggia-Sambuco nappe: stratigraphy, correlations and tectonic consequences (Central Alps). *13th Swiss Geosciences Meeting, Basel 2015, Abstract Volume 1,* 16-17.

Maxelon, M. & Mancktelow, N.S. (2005). Three-dimensional geometry and tectonostratigraphy of the

Pennine zone, Central Alps, Switzerland and Northern Italy. *Earth-Sciences Reviews 71*, 171–227.

Milnes, A. G. (1974). Post-nappe folding in the western Lepontine Alps. *Eclogae Geologicae Helveltiae 67,* 333-348.

Niggli, E. & Niggli, C. (1965). Karten der Verbreitung einiger Mineralien der Alpidischen Metamorphose in den Schweizeralpen (Stilpnomelan, Alkali-Amphibol, Chloritoid, Staurolith, Disthen, Sillimanit). *Eclogae Geologicae Helveltiae 58,* 335-368.

Niggli, P., Preiswerk, H., Grütter, O., Bossard, L. & Kündig, E. (1936). Geologische Beschreibung der Tessineralpen zwischen Maggia und Bleniotal. *Beiträge zur Geologischen Karte der Schweiz N.F. 71. Lieferu*ng.

Pfeifer, H.R., Colombi. A., Ganguin, J., Hunziker, J.C., Oberhansli, R. & Santini, L. (1991). Relics of high-pressure metamorphism in different lithologies of the Central Alpa, an updating inventory. *Schweizerische Mineralogische und Petrographische Mitteilungen 71,* 441-451.

Pfeifer, H.R., Kobe Huldrich †, Colombi, A., Steck, A., Pozzorini, D. & Gouffon, Y. (2019). Map sheet 1312: Atlante geologico et Note esplicative, *Ufficio federale di topografia,Wabern, Svizzera.*

Pfiffner, M.A., Ellis, S. & Beaumont, C. (2000). Collision tectonics in the Swiss Alps: Insight from geodynamic modelling. *Tectonics 19,* 1065-1094.

Preiswerk, H. (1919). Die überkippte Tauchfalte am Campolungopass und ihre früheren Deutungen. "Heim-Festschrift", *Vierteljahresschrift Naturforschende Gesellschaft Zürich, LXIV*, 1–15.

Preiswerk, H., Bossard, L., Grütter, O., Niggli, P., Kündig, E. & Ambühl, E. (1934). Geologische Karte der Tessineralpen zwischen Maggia- und Bleniotal. *Geologische Spezialkarte Nr. 116. Bern: Schweizerische Geologische Kommission.*

Ramsey, J. (1967). Folding and fracturing of rocks. *London: McGraw-Hill.*

Read, H.H. (1955). Granite series in mobile belts. *Special Publication of geological Society of America 62*, 409-430.

Romer, R., Schärer, U. & Steck, A. (1996). Alpine and pre-Alpine magmatism in the root zone of the western Alps. *Contribution to Mineralogy and Petrography 123,* 138-158.

Rubatto, D., Herrmann, J., Berger, A. & Engi, M. (2009). Protracted fluid-induced melting during Barrovian metamorphism in the Central Alps. *Contributions to Mineralogy and Petrology, 158*, 703-722.

Rütti, R., Maxelon, M. & Mancktelow, N.S. (2005). Structure and kinematics of the northern Simano nappe, Central Alps, Switzerland. *Eclogae Geologicae Helveltiae 98*, 63-81.

Sandmann, S., Nagel, T.J., Herwartz, D., Fonseca, R.O.C. & Kursawski, R.M. (2014). Lu-Hf garnet systematics of a polymetamorphic basement unit: new evidence for coherent exhumation of the Adula Nappe (Central Alps) from eclogite facies conditions. *Contributions to Mineralogy and Petrology, 168: 1075.*

Schärer, U., Cosca, M., Hunziker, J. & Steck, A. (1996). Termination of major ductile strike-slip shear and differential cooling along the Insubric Line (Central Alps). *Earth and Planetary Sciences letters 142*, 331-351.

Schardt, H. (1903). Note sur le profil géologique et la tectonique du massif du Simlon compares au travaux antérieurs. *Eclogae Geologicae Helvetiae 8*, 173-200.

Schmid, S.M., Berger, A., Davidson, C., Giere, R., Hermann, J., Nievergelt, P., Puschnig, A.R. & Rosenberg, C. (1996). The Bergell pluton (southern Switzerland, northern Italy): overview accompanying a geological-tectonic map of the intrusion and surrounding country rocks. *Schweizerische Mineralogische und Petrographische Mitteilungen 76,* 329-355.

Schmid, S.M., Fügenschuh, B., Kissling, E. & Schuster, R. (2004). Tectonic map and overall architecture of the Alpine orogeny. *Eclogae Geologicae Helveticae 97,* 93-117.

Schmid, S.M., Kissling, E., Diehl, T., van Hinsbergen, D.J.J. & Molli, G. (2017). Ivrea mantle wedge, arc of Western Alps, and kinematic evolution of the Alps-Apennines orogenic system. *Swiss Journal of Geosciences 110,* 581-612.

Schmidt, C. & Preiswerk, H. (1905). Geologische Karte der Simplongruppe. *Beiträge zur Geologischen Karte der Schweiz. 26,* Spezialkarte No 48.

Schmidt, M.W. (1989). Petrography and structural evolution of ophiolitic remnants in the Bellinzona Zone, Southern Steep Belt, Central Alps (CH/I). *Schweizerische Mineralogische und Petrographische Mitteilungen 69*, 393-405.

Simpson, C. (1982). The structure of the northern lobe of the Maggia nappe, Ticino, Switzerland. *Eclogae Geologicae Helvetiae 75*, 495-516.

Skora, S., Mahlen, N.J., Johnson, C.M., Baumgartner, L.P., Lapen T.J., Beard, B.L. & Szilvagyi, E.T. (2015). Evidence for protracted prograde metamorphism followed by rapid exhumatio oft he Zermatt-Saas Fee ophiolite. *Journal of metamorphic Geology 33*, 711-734.

Spicher, A. & Wenk, E. (1981). Blatt 1313 Bellinzona. *Geologischer Atlas der Schweiz 1:25'000, Erläuterungen, Federal Office of Topography, Ch-3084 Wabern*.

Steck, A. (1984). Structures de déformation tertiaries dans les Alpes centrales (transversal Aar-Simplon-Ossola). *Eclogae Geologicae Helveltiae 77*, 55-100.

Steck, A. (1987). Le massif du Simplon – Réflexions sur la cinématique des nappes de gneiss. *Schweizerische Mineralogische und Petrographische Mitteilungen 67,* 27-45

Steck, A. (1990). Une cartes des zones de cisaillement ductile des Alpes centrales. *Eclogae Geologicae Helvetiae 83,* 603-627.

Steck, A. (1998). The Maggia cross-fold: An enigmatic structure of the Lower Penninic nappes of the Lepontine Alps. *Eclogae Geologicae Helvetiae 91*, 333–343.

Steck, A. (2011). Blatt 1269 Aletschgletscher und Erläuterungen. *Geologischer Atlas Schweiz 1:25'000, Karte 131, Federal Office of Topography, Ch-3084 Wabern.*

Steck, A., Della Torre, F., Keller, F., Pfeifer, H.R., Hunziker, J. & Masson. H. (2013). Tectonics of the Lepontine Alps: ductile thrusting and folding in the deepest tectonic levels of the Central Alps. *Swiss Journal of Geosiences 106*, 427-450.

Steck, A., Epard, J.L., Escher, A., Gouffon, Y. & Masson, H. (2001). Notice explicative de la carte géologique de Suisse occidentale 1:100'000. *Carte géologique special N°123, Office fédérale des Eaux et de la Géologie, (Berne).*

Steck, A. & Hunziker, J. (1994). The Tertiary structural and thermal evolution of the Central Alps – compressional and extensional structures in an orogenic belt. *Tectonophysics 238,* 229-254.

Steck, A., Masson, H. & Robyr, M. (2015). Tectonics of the Monte Rosa and surrounding nappes (Switzerland and Italy): Tertiary phases of subduction, thrusting and folding in the Pennine Alps. *Swiss Journal of Geosiences 108*, 3-34.

Tektonische Karte der Schweiz, 1:500'000, 2005. *Federal Office for Water and Geology. Bern.*

Todd, C.S. & Engi, M. (1997). Metamorphic field gradients in the Central Alps. *Journal of Metamorphic Geology 15,* 513-530.

Trommsdorff, V. (1966). Progressive Metamorphose kieseliger Karbonatgesteine in den Zentraalpen zwischen Bernina und Simplon. *Schweizerische Mineralogische und Petrographische Mitteilungen, 46,* 431-460.

Trommsdorff, V. (1990). Metamorphism and tectonics in the central Alps: the Alpine evolution lithospheric mélange of the Cimalunga and Adula. *Memorie della Socita Geologica Italiana 45,* 39-49.

Voll, G. (1976). Recrystallisation of quartz, biotite and feldspars from Erstfeld to the Leventina nappe, Swiss Alps and its geological significance. *Schweizerische Mineralogische und Petrographische Mitteilungen, 56,* 641-647.

Wegmann, E. (1953). Über gleichzeitige Bewegungsbilder verschiedener Stockwerke. *Geologische Rundschau 41*, 21-33.

Wenk, E. (1955). Eine Strukturkarte der Tessineralpen. *Schweizerische Mineralogische und Petrographische Mitteilungen, 35,* 311-319.

Wenk, E. & Keller, F. (1969). Isograden in Amphibolitseries der Zentraalpen. *Schweizerische Mineralogische und Petrographische Mitteilungen, 49,* 157-191.

Zingg, A., Handy, M.R., Hunziker, J.C. & Schmid, S.M. (1990). Tectonometamorphic history of the Ivrea zone and its relationship to the crustal evolution of the Southern Alps. *Tectonophysics, 182,* 169-192.

Zingg, A. & Hunziker, J.C. (1990). The age of movements along the Insubric line west of Locarno (Northern Italy and southern Switzerland)., 83/3 *Eclogae Geologicae Helveltiae,* 629-644.

Table and figure captions

Table 1: Tectonic units of the Central Alps of Switzerland and Italy enumerated from north to south and bottom to top. The radiometric ages of the phases of high pressure metamorphism suggest a displacement of the zones of deep subduction and accretion from south to north in the Alpine nappe stack: the Senonian Canavese, Eocene Piemont and Late Eocene - Oligocene Valais sutures (Zingg & Hunziker, 1990; Zingg et al. 1990; Brower et al. 2005; Sandmann et al. 2014; Skora et al. 2015).

Table 2: Comparison of models of the Cenozoic structural evolution of the lower Penninic nappes published by Huber et al. (1980), Huber (1981), Simpson (1982), Grujic & Mancktelow (1996), Maxelon & Mancktelow (2005) and this study.

Fig. 1: Blockdiagram of the Central Alps, modified after Steck et al. (2008). The Maggia-Sambuco nappe is situated in the centre of the Lepontine gneiss dome. CT = Campo Tencia nappe, GN = Gurnigel flysch, 2DK = Seconda zona diorito-kinzigitica, UH = Ultrahelvetic, ZH = Zone Houillère. Campo Tencia and Simano nappes of Preiswerk (1934) form a composite nappe designated as Simano nappe on the Tectonic map of Switzerland (2005) and on Figs. 2 and 3.

Fig. 2: Tectonic and structural map of the central Lepontine gneiss dome. A-E indicate the positons of the geological profiles through the Maggia nappe of Fig. 3. Abbreviations: Cr = Cristallina Mesozoic cover, H = Helvetic nappes, ML = Monte Leone nappe, Pe = Pertusio Meszoic cover, P.d.L. = Poncione dei Laghetti Klippe (Maggia nappe), PV = Pizzo del Vallone nappe, So = Someo Mesozoic cover, VALAIS CALC-SCHISTS designates a complex zone, the eastern continuation of the Sion-Courmayeur zone composed of the Bedretto zone of Bianconi & Starsky (2015). Fig. 2 is based on the 1:25 000 Geologischer Atlas der Schweiz 1313 Bellinzona (Bächlin et al. 1974), 73 Campo Tencia (Keller et al. 1980), 1262 Ambri-Piota (Bianconi & Strasky, 2015), 1291 Bosco/Gurin (Della Torre et al. 2015), 1312 Locarno (Pfeifer et al. 2018), unpublished originals of Eduard Wenk and Paul Graeter of 1292 Maggia and our one new structural data.

Fig. 3: Geological profiles A-E (on Fig. 2) and representation of Alpine deformational structures on Schmidt net, lower hemisphere. The Maggia nappe forms a F4-synform to the north in the profiles B – E and plunges to the

west of Bellinzona in a steep structure (profile A). The late steepening of the fold axis is related to back folding and designated F5. Note the frontal down facing fold of the Campo Tencia nappe (profile E).

Fig. 4: Tectonic map and geological Pizzo Massari-Pizzo Prevat profile through the frontal down facing Campo Tencia nappe F2-fold and its autochthonous Campolungo Triassic sedimentary cover, the Bedretto calc-schist nappe (Bianconi, 1971; Bianconi & Starsky, 2015) and the Sambuco gneisses with its autochthonous Cristallina Mesozoic sedimentary cover in an inverted position at the nappe base and an upper normal position in the syncline to the west of the Pizzo Massari.

Fig. 5: The cut out of the geological map of Keller et al. (1980) illustrates the uniform about 20° S-plunging axis of the Mogno F2 down facing syncline. The southern and deeper continuation of the Triassic dolomite and calc-schist, observed by Dazio Dal Vesco in the Prato-Camblee water gallery confirms the geometry of the down facing Mogno syncline (oral communication by Franz Keller).

Fig. 6: Block diagram of the Sambuco – Maggia sheath fold like structure.

Fig. 7: Map of isograds of the Cenozoic Barrovian amphibolite facies metamorphism of the Central Alps. The limits of the Lower Penninic nappes are crosscut by the isograds of the amphibolite facies metamorphism. Highest temperature where attended at 30-22 Ma after the nappe emplacement. Isograds of metapelites after Niggli & Niggli (1965), siliceous dolomites after Trommsdorff (1966), metabasites after Wenk & Keller (1969), Steck et al. (2001) and migmatites after Burri et al. (2005) are represented.

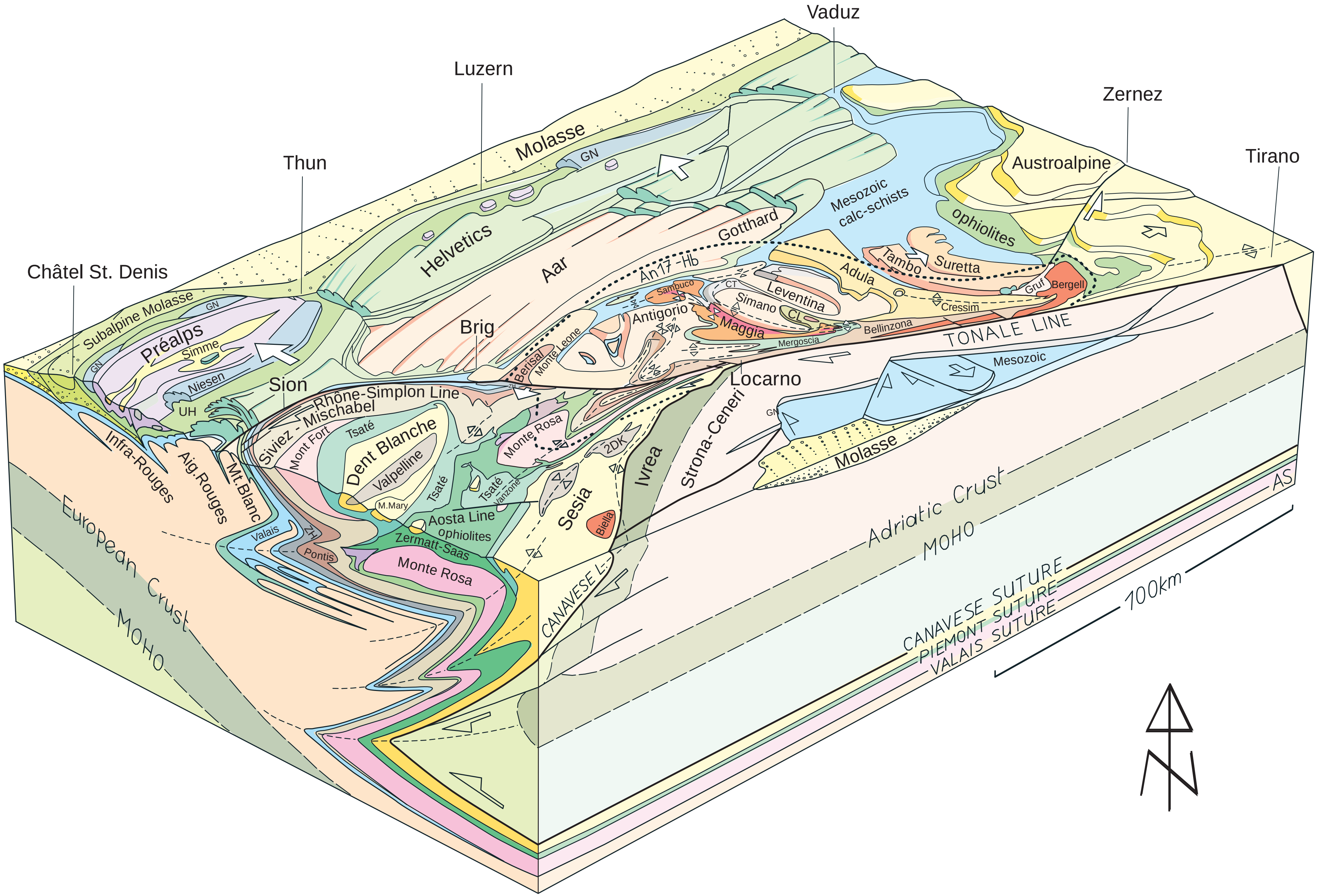
TECTONIC DIVISION	ALPINE NAPPES: CRYSTALLINE BASEMENT	ALPINE NAPPES: MESO-CENOZOIC SEDIMENTARY COVER	METAMORPHISM AGE (Ma)	CENOZOIC METAMORPHISM
HELVETIC	AAR MASSIF FOLD	LOWER HELVETIC NAPPES	~32-15	ZEOLITE FACIES
	GOTTHARD NAPPE	WILDHORN NAPPE		GREENSCHIST FACIES
ULTRAHELVETIC	LUCOMAGNO-LEVENTINA NAPPE	PIORA SYNCLINE		
LOWER PENNINIC	VERAMPIO NAPPE	TEGGIOLO SYNCLINE	~38-30	AMPHIBOLITE FACIES
	ANTIGORIO NAPPE	TEGGIOLO COVER		
	SIMANO NAPPE	FRASCO COVER		
	CAMPO TENCIA NAPPE	CAMPOLUNGO COVER		
		LEBENDUN NAPPE		
	OSBARINO-VALGRANDE NAPPE	PIZZO DEL VALLONE NAPPE		
	MAGGIA (-SAMBUCO) NAPPE	CRISTALLINA-PERTUSIO-SOMEO COVER		
	ADULA NAPPE		≥38	ECLOGITE→ AMPHIBOLITE FACIES
	MERGOSCIA-CIMALUNGA TECTONIC MELANGES			
	ORSELINA-BELLINZONA TECTONIC MELANGES	VALAIS SUTURE		AMPHIBOLITE FACIES
	MONTE LEONE NAPPE	HOLZERSPITZ COVER		GREENSCHIST FACIES
		VALAIS CALC-SCHIST NAPPE		BLUESCHIST FACIES
MIDDLE PENNINIC	SIVIEZ-MISCHABEL NAPPE (BRIANÇONNAIS)	BARRHORN COVER	40-35	
	MONTE ROSA NAPPE	FURGG COVER		
UPPER PENNINIC	ANTRONA - ZERMATT-SAAS FEE OPHIOLITIC NAPPES	PIEMONT SUTURE	~50-38	ECLOGITE→ AMPHIBOLITE FACIES
TERTIARY MAGMATISM	BERGELL TONALITE		30	NON METAMORPHIC
SALASSIC	SESIA ZONE	CANAVESE SUTURE	≥70-65	ECLOGITE→ AMPHIBOLITE FACIES
SOUTHERN ALPS	IVREA ZONE	CANAVESE COVER		GREENSCHIST FACIES BORDER
	STRONA-CENERI ZONE	LOMBARDIAN COVER		NON METAMORPHIC

N bottom — top S

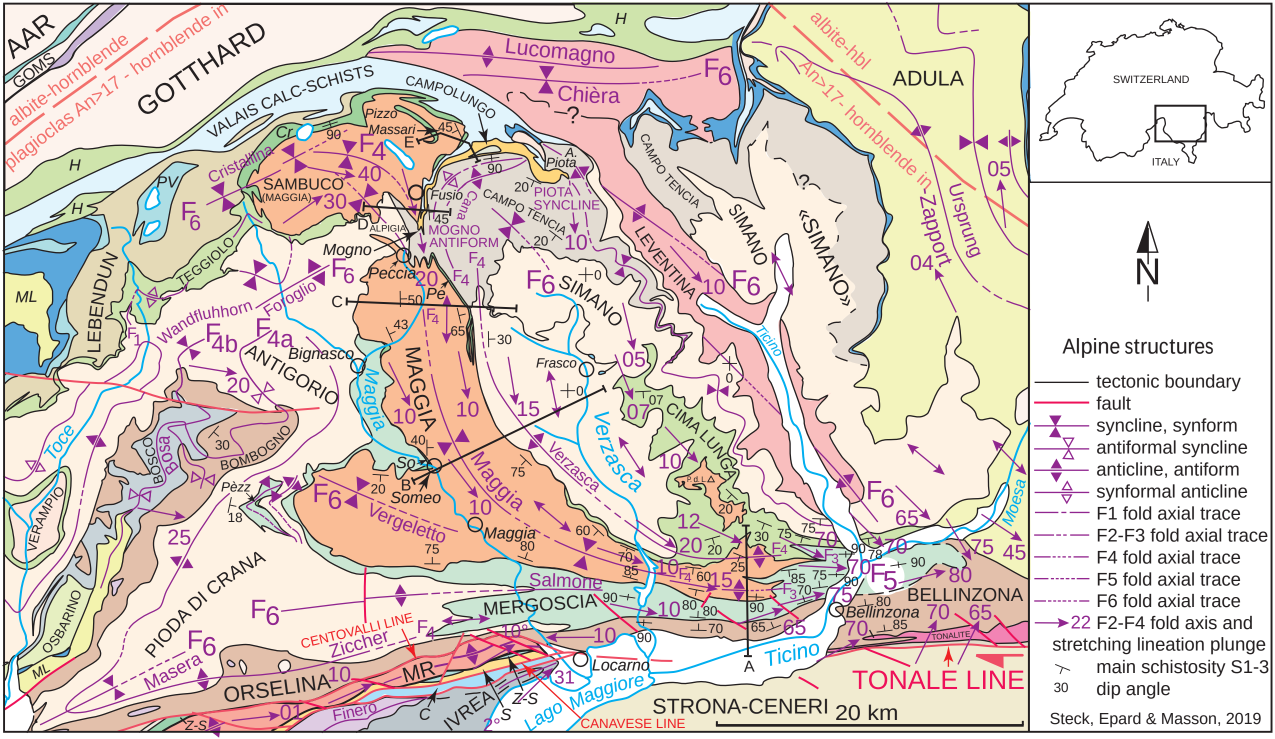
European crust

Steck, Epard & Masson (this study) and Liszkay-Nagy (1965), Steck (1987, 1998), Steck et al. (2013)					
Main deformational phases	early deformation in Mesozoic sediments S1, F1	NW-directed main nappe emplacement S2-S3, F2-F3	W-verging recumbent-folds S4, F4	Southern steep belt F5	late backfolds F6 vertical shortening F7
Main structures	first schistosity and rare early folds	Maggia and Lower Penninic nappes Gotthard fold	Verzasa antiform Maggia synform Ziccher fold Bosa and Wandfluhhorn antiform	Vanzone antiform Cressim antiform verticalisation of Maggia root to the W of Bellinzona	Chièra synform Cristallina synform Foroglio antiform Salmone antiform Masera synform Simplon fault
Metamorphic grade	greenschist facies →	amphibolite pfacies prograde →			retrograde
Age of deformation and metamorphism	~Late Eocene →	Oligocene →	~ 32-30 Ma temperature culmination at 30-22Ma Late Oligocene-Early Miocene		18 Ma - present

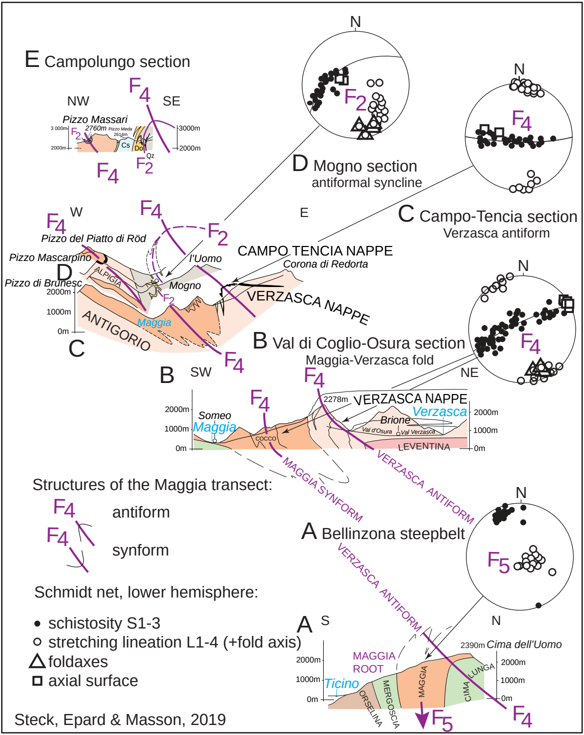
Huber, Ramsay & Simpson (1980), Grujic & Mancktelow (1996), Maxelon & Mancktelow (2005)					
Main deformational phases	D1 thrusting and isoclinal folding	D2 main post-nappe folding	D3 transverse folds	D4 Northern Backfolds Southern Steep Belt	D5 vertical shortening
Main structures	Teggiolo zone	Antigorio antiform (-nappe) Ledendun synform Campolungo synform	Peccia-Basodino synform Campo Tencia synform Maggia steep zone Wandfluhhorn antiform	Cristallina synform Chièra synform Southern Steep Belt	Simplon fault
Metamorphic grade	prograde	amphibolite facies	amphibolite facies	retrograde	
Age	Late Eocene-Oligocene	Oligocene (pre-Bergell)	Late Oligocene	Neogene	



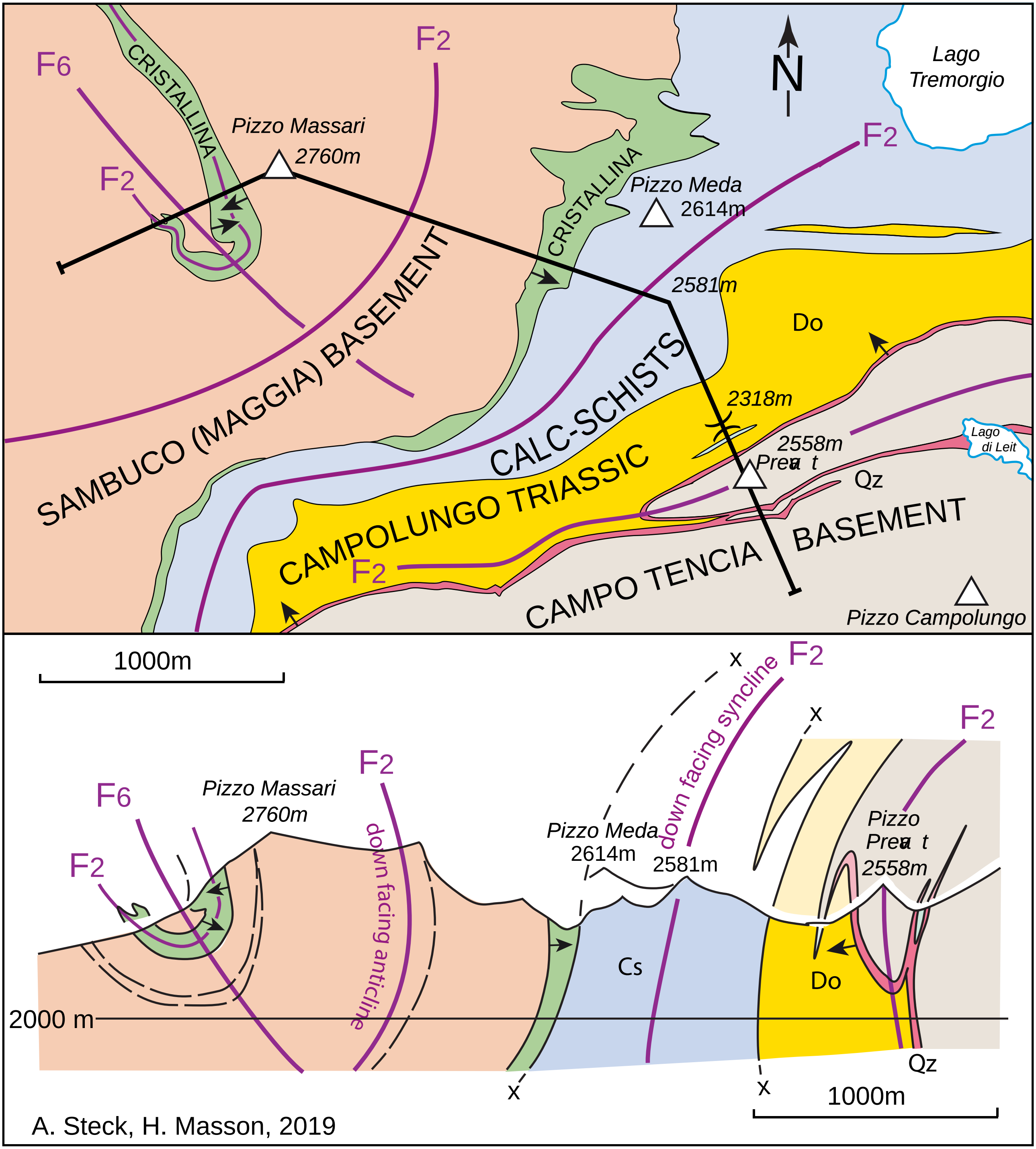
Vaduz
Luzern
Zernez
Tirano
Thun
Châtel St. Denis
Molasse
GN
Helvetics
Aar
Gotthard
Mesozoic calc-schists
Austroalpine
ophiolites
Subalpine Molasse
Préalps
Simme
Niesen
UH
Sion
Brig
Tambo
Suretta
Adula
Leventina
Simano
Antigorio
Sambuco
Maggia
Bergell
Gruf
Cressim
Bellinzona
Mergoscia
TONALE LINE
Mesozoic
Locarno
Rhône-Simplon Line
Mischabel
Siviez
Mont Fort
Tsaté
Dent Blanche
Valpelline
M.Mary
Monte Rosa
Monte Leone
Berisal
2DK
Sesia
Biella
Ivrea
Strona-Ceneri
Infra-Rouges
Aig.Rouges
Mt.Blanc
Valais
Pontis
Aosta Line
ophiolites
Zermatt-Saas
Monte Rosa
European Crust
MOHO
CANAVESE L.
Adriatic Crust
MOHO
AS
CANAVESE SUTURE
PIEMONT SUTURE
VALAIS SUTURE
100km
N



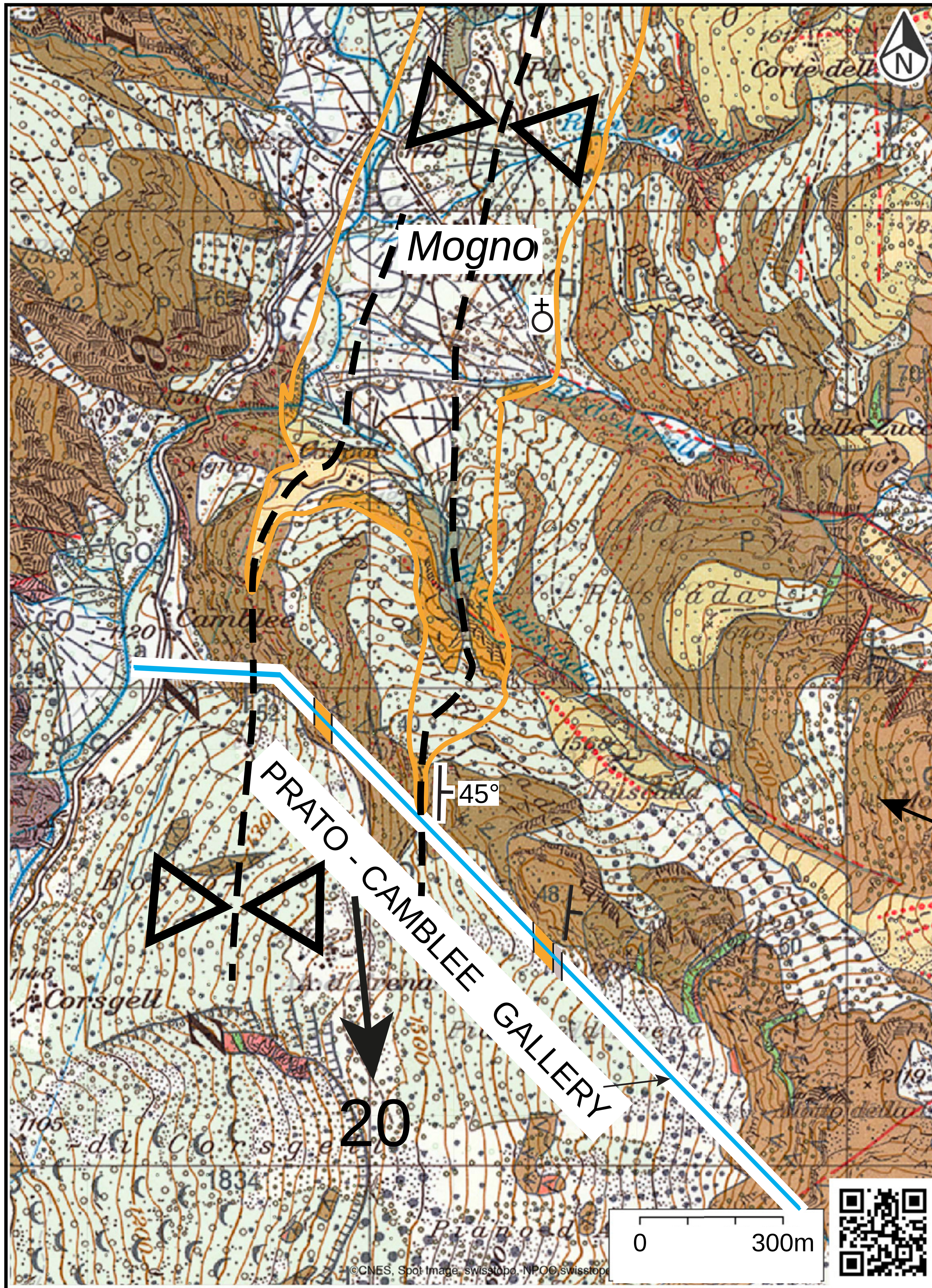
AAR
GOMS
GOTTHARD
albite-hornblende
plagioclas An>17 - hornblende in
VALAIS CALC-SCHISTS
CAMPOLUNGO
Lucomagno
Chièra
ADULA
albite-hbl
An>17- hornblende in
Zapport
Ursprung
SAMBUCO (MAGGIA)
Cristallina
Pizzo Massari
Fusio
PIOTA SYNCLINE
A. Piota
CAMPO TENCIA
MOGNO ANTIFORM
Mogno
Peccia
LEBENDUN
TEGGIOLO
Wandfluhhorn
Foroglio
ANTIGORIO
Bignasco
MAGGIA
SIMANO
«SIMANO»
LEVENTINA
CAMPO TENCIA
Frasco
CIMA LUNGA
Verzasca
Ticino
Maggia
Toce
BOSCO
Bosa
BOMBOGNO
VERAMPIO
OSBARINO
Pèzz
Someo
Vergeletto
Maggia
PIODA DI CRANA
Salmone
MERGOSCIA
CENTOVALLI LINE
Ziccher
Masera
ORSELINA
MR
Finero
IVREA
Locarno
Lago Maggiore
CANAVESE LINE
STRONA-CENERI
20 km
Bellinzona
BELLINZONA
TONALITE
TONALE LINE
Moesa
SWITZERLAND
ITALY
N
Alpine structures
tectonic boundary
fault
syncline, synform
antiformal syncline
anticline, antiform
synformal anticline
F1 fold axial trace
F2-F3 fold axial trace
F4 fold axial trace
F5 fold axial trace
F6 fold axial trace
22 F2-F4 fold axis and stretching lineation plunge
main schistosity S1-3
30 dip angle
Steck, Epard & Masson, 2019



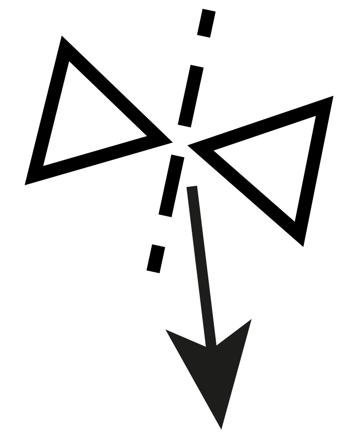
E Campolungo section
NW
SE
Pizzo Massari
2760m
Pizzo Meda
2614m
3 000m
2000m
3000m
2000m
Cs
Do
Qz
F2
F4
D Mogno section
antiformal syncline
N
C Campo-Tencia section
Verzasca antiform
W
E
Pizzo del Piatto di Röd
Pizzo Mascarpino
D
Pizzo di Brunesc
l'Uomo
Mogno
ALPIGIA
2000m
1000m
0m
Maggia
ANTIGORIO
C
CAMPO TENCIA NAPPE
Corona di Redorta
VERZASCA NAPPE
B Val di Coglio-Osura section
Maggia-Verzasca fold
B
SW
NE
2278m
VERZASCA NAPPE
Someo
Maggia
COCCO
Brione
Verzasca
Val d'Osura
Val Verzasca
LEVENTINA
2000m
1000m
0m
MAGGIA SYNFORM
VERZASCA ANTIFORM
Structures of the Maggia transect:
antiform
synform
Schmidt net, lower hemisphere:
schistosity S1-3
stretching lineation L1-4 (+fold axis)
foldaxes
axial surface
A Bellinzona steepbelt
VERZASCA ANTIFORM
F5
A
S
N
2390m Cima dell'Uomo
MAGGIA ROOT
Ticino
ORSELINA
MERGOSCIA
MAGGIA
CIMA LUNGA
Steck, Epard & Masson, 2019



F6
F2
F2
F2
F2
CRISTALLINA
CRISTALLINA
Pizzo Massari
2760m
Pizzo Meda
2614m
Lago
Tremorgio
N
2581m
Do
SAMBUCO (MAGGIA) BASEMENT
CALC-SCHISTS
CAMPOLUNGO TRIASSIC
2318m
2558m
Prea t
Qz
Lago
di Leit
BASEMENT
CAMPO TENCIA
Pizzo Campolungo
1000m
x
F2
down facing syncline
x
F2
F2
F6
Pizzo Massari
2760m
down facing anticline
F2
Pizzo Meda
2614m
2581m
Pizzo
Prea t
2558m
Cs
Do
2000 m
Qz
x
x
1000m
A. Steck, H. Masson, 2019



The Mogno down facing syncline

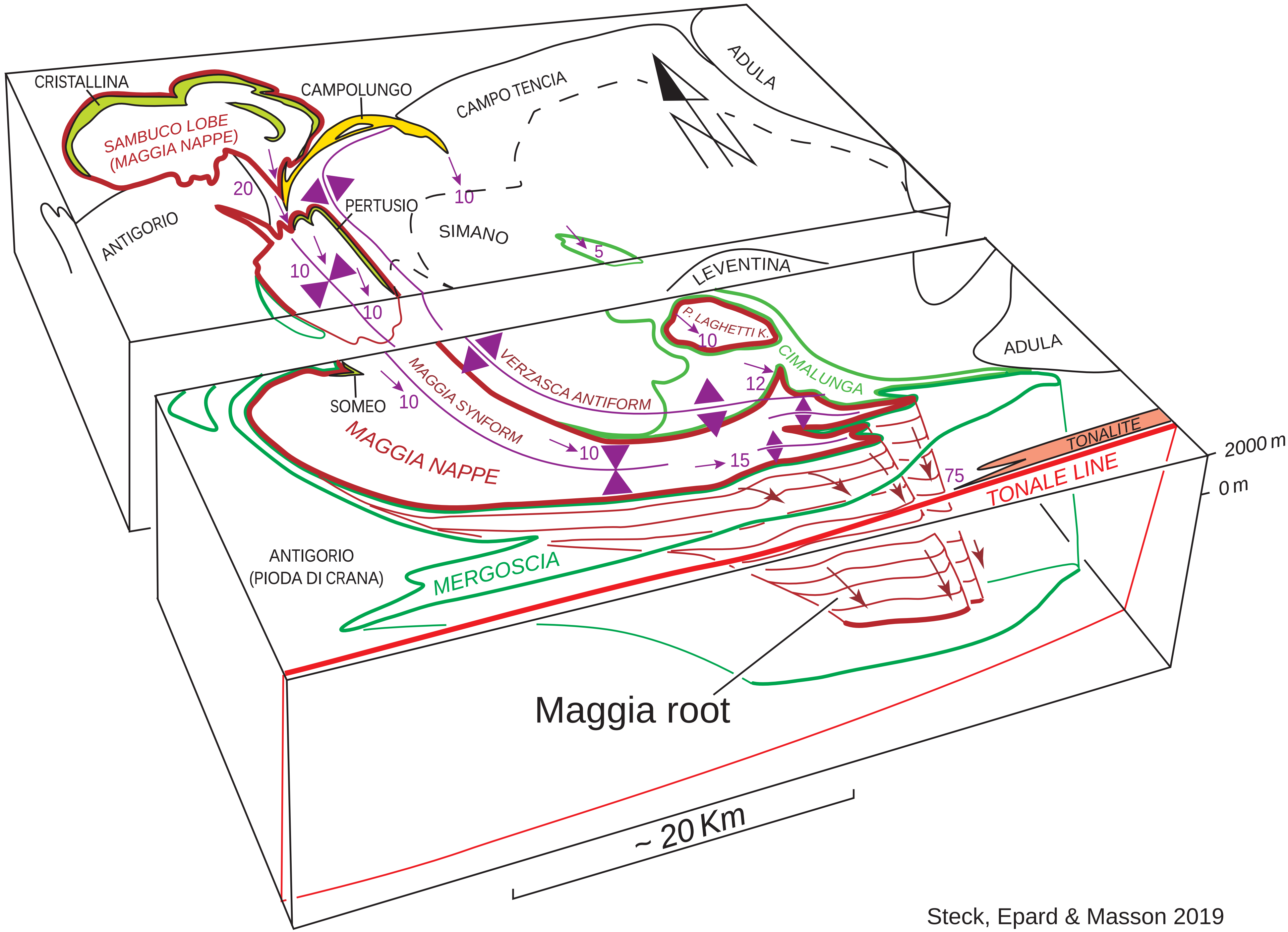


20 axial plunge

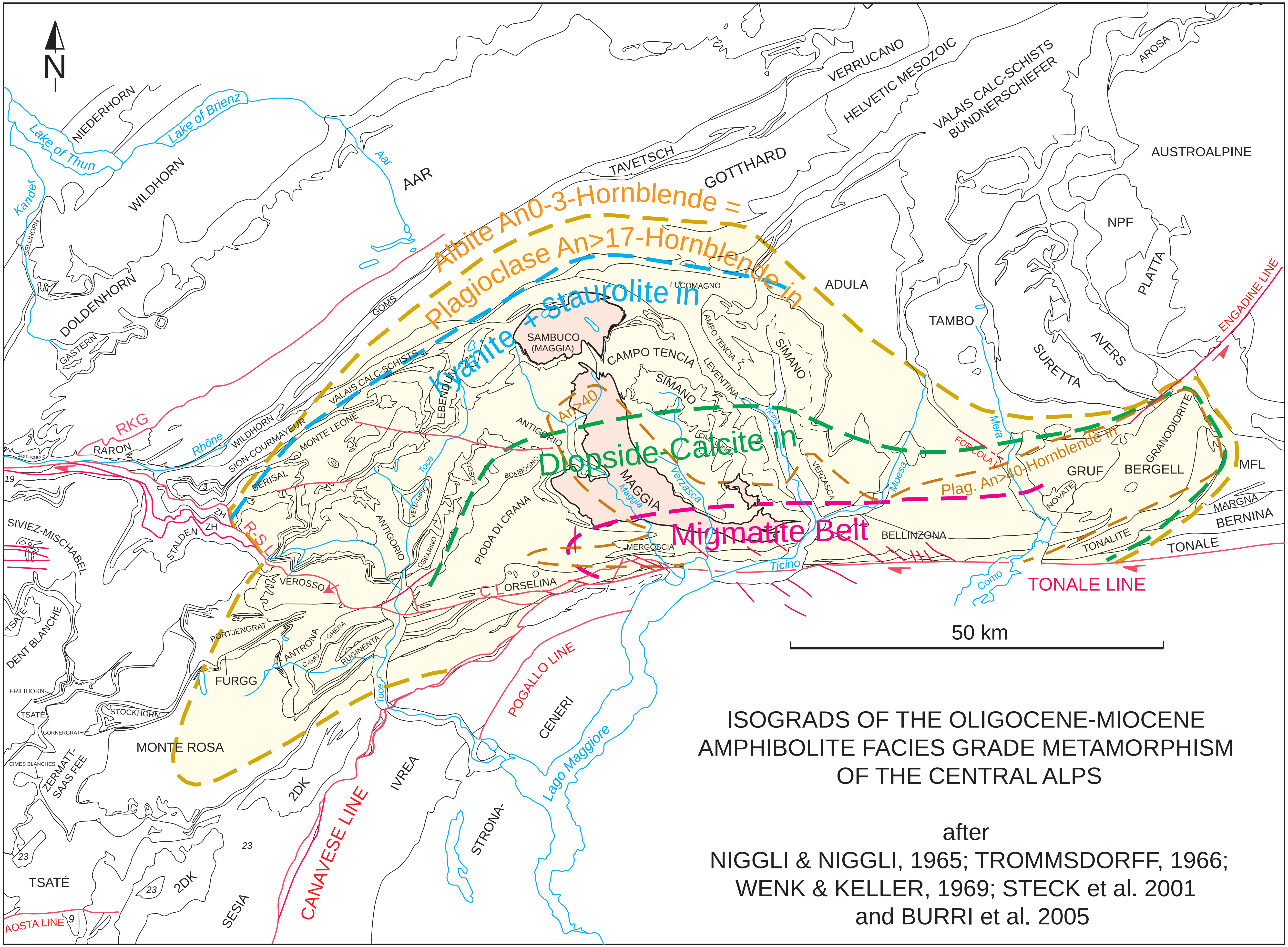
Triassic dolomite and Valais calc-schist outcrops in Prato-Camblee water gallery (alt. 1135m), after Ezio Dal Vesco, personal communication by Franz Keller

staurolite and kyanite bearing garnet micaschists of Campo Tencia nappe

cut out of map sheet 1272 P. Campo Tencia by Keller et al. (1980)



Steck, Epard & Masson 2019



ISOGRADS OF THE OLIGOCENE-MIOCENE AMPHIBOLITE FACIES GRADE METAMORPHISM OF THE CENTRAL ALPS

after

NIGGLI & NIGGLI, 1965; TROMMSDORFF, 1966; WENK & KELLER, 1969; STECK et al. 2001 and BURRI et al. 2005