Ordovician orogeny in the Alps – a reappraisal

Roger Zurbriggen

Published in: International Journal of Earth Sciences (Geologische Rundschau) (2015) 104:335–350
DOI 10.1007/s00531-014-1090-x

Abstract

An important part of the Pre-Mesozoic basement of the Alps is the product of orogenic processes occurred in Ordovician times. Most of the geological constrains for this reconstruction have been obtained by the study of the Strona-Ceneri zone in the Southern Alps, where Alpine overprint was weak.

The erosion of late Pan-African belts delivered large amounts of greywackes and pelites into subduction zones along Gondwana. The sediments were subducted and accreted to form wide complexes. As a result of the large sediment input, subduction retreated and the mantle-derived magmas intruded the base of the fertile "mud pile". This initiated substantial anatexis to produce peraluminous magmas, which intruded and extruded syntectonically. Thereby, the predominantly steeply structured subduction-accretion complex provided ideal pathways for the uprising magmas and down-thrusting host rocks to result in an isostatically stable crust.

The SE-Australian Lachlan fold belt is interpreted as an upper crustal analogue of the Strona-Ceneri zone. Based on the combination of their geology a crustal profile through an Alaskan-type of orogen is drawn.

Keywords: Ordovician forearc magmatism, cratonization, Alaskan type subduction-accretion, Ceneri gneiss, Strona-Ceneri zone, Lachlan fold belt

Address of author: roger-zurbriggen@bluewin.ch, Feldmatt 10, CH-6206 Neuenkirch, Tel.: +41 41 467 25 02, Fax: +41 41 469 69 05

1. Introduction

The Strona-Ceneri zone is located south of the Insubric line (Fig. 1), where Alpine tectono-metamorphism did not exceed subgreenschist facies conditions (Frey et al. 1974). Thus, any high-grade structures are of pre-Mesozoic origin. From a lithological point of view, the Strona-Ceneri zone is a classical gneiss terrane composed of para- and orthogneisses with intercalated banded amphibolites.

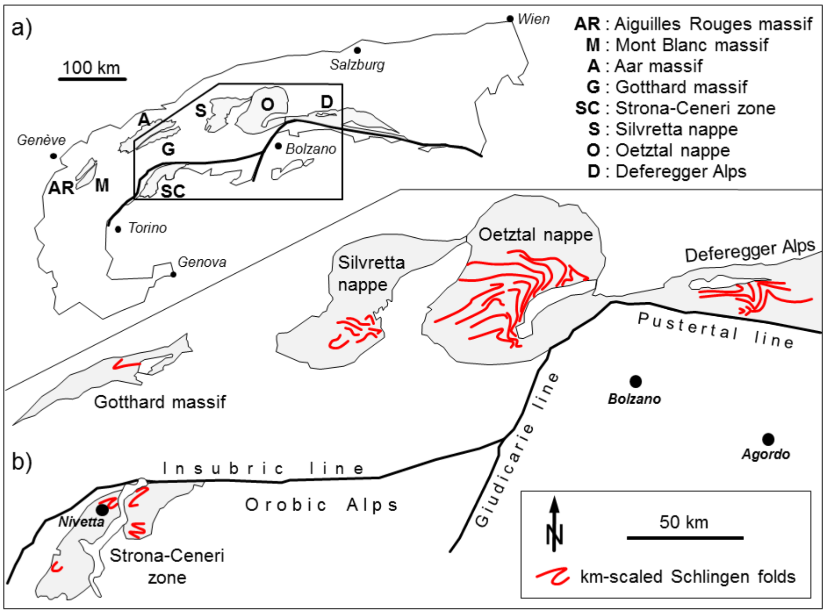
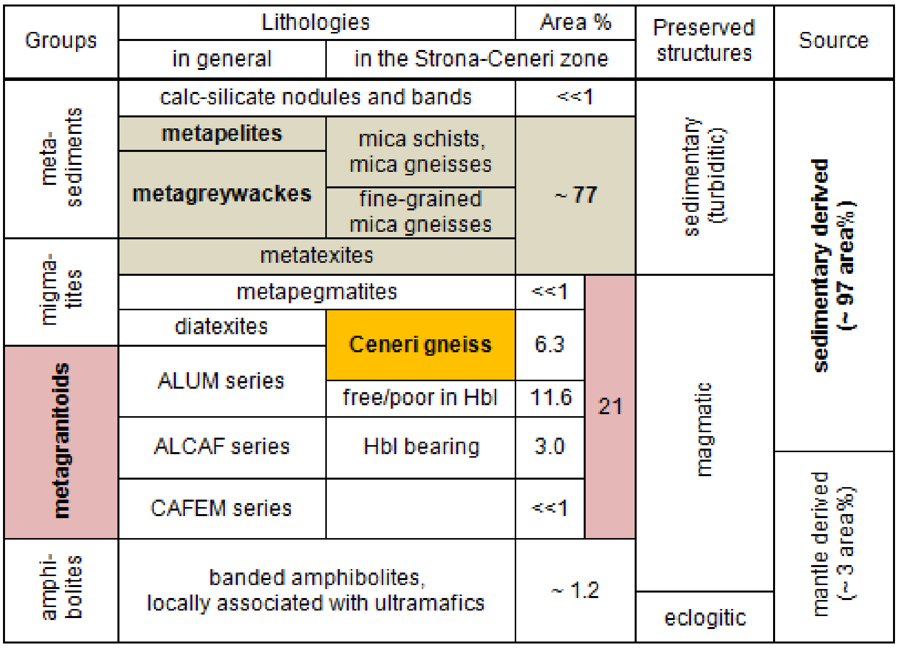


***Fig. 1**: (a) Map of Alpine belt (redrawn after von Raumer et al. 2013) with highlighted basement units for which pre-Permian Schlingen structures are described. (b) Detailed map with indicated pre-Permian km-scaled Schlingen folds. Information about Schlingen in the Austro-alpine basement units are taken from Schmidt (1965).*

The following five features are characteristic for the Strona-Ceneri zone: (i) Paragneisses derived from pelites and greywackes form the matrix (c. 77 area%, see Tab. 1) of the gneiss terrane. (ii) A continental substrate for these metasediments is not present, but amphibolites with MORB signature could represent a possible former substrate. However, the banded character of most amphibolites might indicate andesitic protoliths. (iii) Large amounts of mainly peraluminous orthogneisses (c. 21 area%, see Tab. 1) have been derived from greywacke source rocks, similar to the host rocks, the so-called paragneisses. (iv) The main structures such as the lithological contacts and the pervasive amphibolite facies main schistosity of the orthogneisses are moderately to steeply oriented (Handy et al. 1999). (v) These main structures are folded by amphibolite facies "Schlingen", which are km-scaled folds with generally steep axial planes and fold axes (Zurbriggen et al. 1998).



Groups	Lithologies		Area %		Preserved structures	Source
	in general	in the Strona-Ceneri zone				
meta-sediments	calc-silicate nodules and bands		<<1		sedimentary (turbiditic)	**sedimentary derived (~ 97 area%)**
	metapelites	mica schists, mica gneisses	~ 77			
	metagreywackes	fine-grained mica gneisses				
migma-tites	metatexites					
	metapegmatites		<<1	21	magmatic	
	diatexites	**Ceneri gneiss**	6.3			
metagranitoids	ALUM series	free/poor in Hbl	11.6			
	ALCAF series	Hbl bearing	3.0			
	CAFEM series		<<1			mantle derived (~ 3 area%)
amphi-bolites	banded amphibolites, locally associated with ultramafics		~ 1.2		eclogitic	

***Tab. 1**: Lithologies of the Strona-Ceneri zone (a typical greywacke dominated gneiss terrane rich in peraluminous metagranitoids) with estimated percentages according to Zurbriggen (1996).*

What is the tectonic scenario of such greywacke dominated gneiss terranes rich in peraluminous metagranitoids? Remarkably, today such settings are very rare, but in Ordovician time they were globally widespread.

German geologists of the 18th century created the term "Grauwacke" for Paleozoic sandstones, as they realized the vast occurrence of such rocks. In the 19th century the concept of geosynclines was developed, which later became further differentiated in order to describe large thicknesses of immature clastics, such as shales, greywackes and conglomerates, associated with volcanics, as eugeosynclines (Seyfert and Sirkin 1973). The same authors show a map of Gondwanaland (their figure 10.28), which is fully framed by early Paleozoic geosynclines, partly specified as eugeosynclines. Siever (1988) relates the abundance of early Paleozoic potassium-rich clastics to the absence of vascular plants. Therefore, chemical weathering of granites might have been different in those times. Furthermore, he mentions that unstable mineral compositions, typical for greywackes, could be linked to stream deposition during and following the intense stages of orogeny. Thus, greywackes are signs of terranes related to volcanism and perhaps to earlier stages of orogeny.

The two text books describe how the peculiar early Paleozoic circumstances were realised by sedimentologists long ago. But how can we explain the genesis of these metagreywacke dominated gneiss terranes within a plate tectonic setting? Interestingly, already Sengör and Okurogullari (1991) gave a hint, that earlier classified eugeosynclines relate to accretionary processes indicating an active margin in the context of modern plate tectonics.

This study compares different pre-Mesozoic basement units in the Alps with a focus on the Ordovician magmatism. The reason is that this type of magmatism and its structural overprint is regarded as a key for the Ordovician orogenic evolution. There is broad consensus about age, composition and its relation to anatexis. But, with respect to its structural overprint and the tectonic setting there is a controversy ranging from collisional scenarios (e.g., Franz and Romer 2007) to extensional scenarios (e.g., von Raumer et al. 2013). In order to explain the genesis and tectonic setting of the Ordovician orthogneisses a new orogenic model is described. For that purpose the author refers to two concepts, which were poorly recognized in the past: (i) the concept of forearc granitoids as defined by Barker et al. (1992), and (ii) the concept of cratonization of subduction-accretion complexes as developed by Crook (1980). Barker's concept of forearc granitoids provides a new sight on the relationship between para- and orthogneisses, and Crook's concept can explain the setting of predominantly steeply structured metapelites and metagreywackes with intercalated metagranitoids and amphibolites. To introduce these two concepts the author will compare the Strona-Ceneri zone with two other regions far away from the Alps, (i) the Alaskan forearc region and (ii) the Paleozoic Lachlan fold belt in Australia, for which Barker and Crook developed their concepts, respectively.

Three claims are made, which will be discussed in the frame of this study: (1) The Ordovician orogeny was not a continent-continent collision because of the absence of pre-Ordovician cratonic crust. (2) The Ordovician orogeny was not a rifting controlled event because of the eclogite facies metamorphism and the syn-tectonically emplaced steeply inclined sheets of orthogneisses indicating a compressional or transpressional field. (3) The Ordovician orogeny was not an Andean-type active margin because the magmatism does not indicate a dominant metaluminous chemistry typical for granites generated by fractionation of mafic magmas.

However, the MORB-signature of some amphibolites with eclogitic relics clearly indicates a subduction related scenario, and the dominance of metagreywackes clearly indicates a nearby, tectonically active, terrigeneous hinterland with high erosional rates.

2. Discussion of geology and plate tectonics

The Strona-Ceneri zone comprises the deformed and metamorphosed remains of an early Paleozoic subduction-accretion complex with relicts of eclogite facies assemblages that became re-equilibrated under amphibolite facies conditions during the intrusion of peraluminous Ordovician granitoids (Zurbriggen et al. 1997). One of these metagranitoids, namely the Ceneri gneiss, is controversially discussed in the literature because it has the same chemistry as the metagreywacke host rocks, but in the core regions of the bodies it displays isotropic magmatic structures with xenoliths (Zurbriggen et al. 1997). Although Pinarelli et al. (2008) interpret the Ceneri gneiss as a metasedimentary rock, the comparison with other Ceneri gneiss-like lithologies of the pre-Mesozoic basement units will demonstrate that these peculiar inclusion-rich S-type metagranitoids link the metasediments with the widespread anatexis and related metagranitoids (see chapter 3). The main schistosity of these gneisses was generated under amphibolite facies conditions in the range of 570-630°C and 7-9 kbar (Zurbriggen et al. 1997). Pinarelli and Boriani (2007) attribute the main structural overprint of the orthogneisses to Variscan tectonics, and, conclusively, interpret the Ordovician magmatism as an atectonic thermal event with totally different implications for the Ordovician setting. On the other hand, new age data of Franz and Romer (2007) confirm that accretion, eclogitization, anatexis and pre- to synmagmatic deformation occurred in a remarkable short time interval of 12 Ma (462-450 Ma), and clearly indicate an Ordovician orogenic evolution for the Strona-Ceneri zone.

A similar geology is reported for other pre-Mesozoic basement units in the Alps: Schaltegger et al. (2003) indicate a time span of 35 Ma (480-445 Ma) including gabbroic intrusion (478 ± 5 Ma), its HP overprint followed by anatexis between 456 and 450 Ma in the Aar massif. Ordovician ages of 460-470 Ma for eclogite metamorphism subsequently followed by anatexis and magmatism are also reported for the Gotthard massif (Oberli et al. 1994, Mercolli et al. 1994) and for the Oetztal-Stubai complex (Hoinkes and Thöni 1993, Thöny et al. 2008). The Silvretta nappe shows similar rock associations (Schaltegger et al. 2003). But in addition to the late Ordovician metagranitoids (“Flüelagranitic gneisses”) a series of late Cambrian to early Ordovician “Older Orthogneisses” (including the Mönchalp granite, metagabbros, metadiorites, metatonalites and metagranitoids) indicates a more complex magmatic evolution associated with anatexis in several pulses (Poller et al. 1997). Von Raumer et al. (2003) mention that in the Aiguilles Rouges/Mont-Blanc area c. 450 Ma magmatic ages have been obtained for both, eclogitized MORB-like basic rocks and for S- and I-type orthogneisses.

In the Strona-Ceneri zone the main schistosity of the orthogneisses is deformed by km-scaled folds with steep axial planes and fold axes ("Schlingen", Schmidegg 1936), which were dated Variscan (Zurbriggen et al. 1998, 321 Ma, Locality Nivetta, Fig. 1). Comparable structures have been recognized in the External massifs (Gotthard massif: Huber 1943; Aiguilles Rouges-Mont Blanc: von Raumer and Bussy, 2004) and in the Austroalpine domain (Silvretta nappe: Wenk 1934, Maggetti and Flysch, 1993; Oetztal-Stubai complex: Schmidegg 1936, Schmidt 1965; and in the Deferegger Alps: Schulz 1988; Fig. 1).

Already Wenk (1934) and Schmidegg (1936) have interpreted the Schlingen as folding of steep schistose rocks around steep axes. Therefore, the occurrence of amphibolite facies Variscan Schlingen folds indicates the pre-existence of a steeply structured gneiss terrane, which generated, in this case, c. 130 Ma earlier in Ordovician time. In fact, von Raumer et al. (2013) describe large-scale strike slip tectonics at about 330 Ma (see their Fig. 6D), which would deliver the right scenario leading to the formation of Schlingen.

Altogether there is clear evidence that the Ordovician orogenic evolution and the Variscan formation of Schlingen occurred regionally and affected all pre-Mesozoic basement units of the Alps. However, for the reconstruction of the Ordovician evolution it is fundamentally important if the main schistosity of the orthogneisses is related to synmagmatic Ordovician tectonics or to a post-magmatic Variscan overprint. The former would indicate a convergent setting in Ordovician time. The latter would leave the Ordovician anatexis and cogenetic magmatism as a thermal event related to extensional tectonics and decompression. Therefore, we have to consider this aspect in more detail.

It is known that the structural relationships between pluton and host rock is dependent on the crustal level. As illustrated in Fig. 2c, a pluton can be concordant and pervasively sheared in the lower crust, and will be interpreted as syn-tectonic, while with decreasing metamorphic grade in the upper crust, the same pluton develops a contact aureole and discordant contacts, and will be interpreted as post-tectonic. Because Austroalpine basement units indicate a low pressure (e.g., Thöny et al. 2008 indicate less than 2.8 kbar for the Ordovician event in the Oetztal nappe), the Ordovician granitoids might be interpreted as post-tectonic or atectonic, simply due to their position in the upper crust. In addition, the pre-Mesozoic basement units north of the Insubric line suffered an Alpine overprint of their Variscan and pre-Variscan structures, which makes their identification even more difficult. Therefore, the Strona-Ceneri zone offers a unique example of a pre-Mesozoic basement unit, which preserved the Paleozoic high-grade structures of the lower crust.

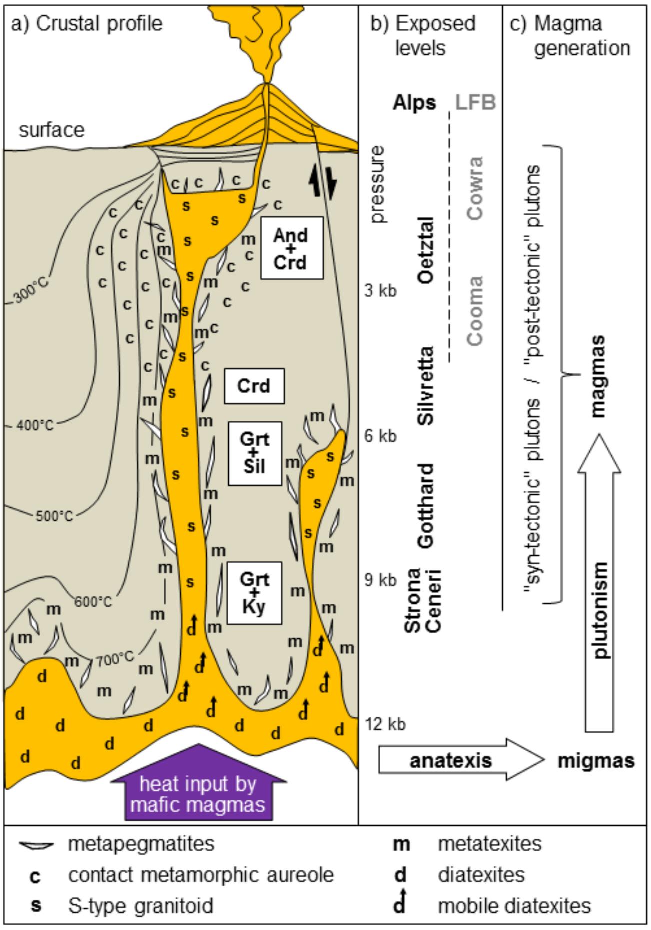


***Fig. 2**: Petrogenetic model for the Ceneri gneiss and similar inclusion-rich S-type granitoids. (a) Hypothetical cross section through the crust at the time of Ceneri gneiss magmatism. For location of the cross section see figure 6. (b) Different basement units of the Alps (and the Lachlan fold belt, LFB) are located according to the pressure indicators in the Ceneri-gneiss-like granitoids. (c) "Per migma ad magma" and the structural relationships of plutons as a function of crustal depth. For explanations see text. The author was inspired by figures of Flood and Vernon (1978), D'Lemos et al. (1992), and Brown (1994).*

Zurbriggen et al. (1997) argue for a syntectonic emplacement of the Ordovician granitoids as follows: (1) Relics of magmatic foliation are concordant with intrusive contacts and main schistosity in the country rocks, which is a reliable argument for syn-tectonic intrusions. (2) The high aspect ratio of the plutons and their orientation parallel to the main schistosity indicates a tectonically controlled emplacement. Zurbriggen (1996) provides an example of an approximately 20 km long Ceneri gneiss body ranging from Cannobio (Italy) across Lago Maggiore into the Gambarogno area (Switzerland) and back into the Lago Delio area (Italy). It has an aspect ratio of 1:45. In contrast, the aspect ratios of its inclusions are mainly in the range of 1:5 – 1:25, indicating a synmagmatic shearing component, which did affect the pluton but not its inclusions. (3) The Ordovician lower intercept ages of the metasediments date a severe isotopic disturbance that is reasonably inferred to be the age of the main tectono-metamorphic event, which caused the main schistosity under amphibolite facies conditions.

Schaltegger and Gebauer (1999) concluded that the major pre-Alpine tectono-metamorphic event was the Ordovician orogenic cycle. Based on the age records of detrical zircons from the metasediments these authors infer the Brasilian and/or Guyana shield as provenance area for metasediments rather than the West African Craton. Other studies favor a position of the Ordovician orogenic belt north of Gondwana (Torsvik and Cocks 2011, Meinhold et al. 2013, and Figs 12.2 and 12.3 of Frisch and Meschede 2011) or at the periphery of the South China Craton (Stampfli et al. 2013). Wherever the position was (see Fig. 3b), the sediment input from the corresponding hinterland must have been extraordinary high, which relates to the erosion of the global network of Pan-African belts (Fig. 3a).

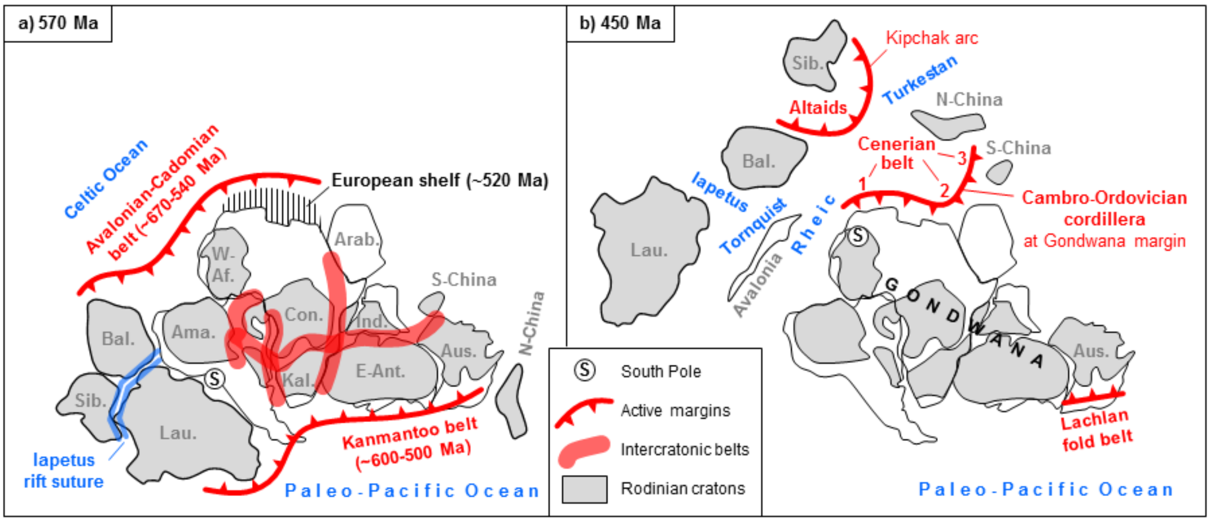


Fig. 3*: (a) Neoproterozoic supercontinent Vendia (c. 570 Ma) with peripheral and intercratonic Pan-African belts redrawn after Murphy and Nance (1989), Powell et al. (1990), Dalziel et al. (1994) and Meert & Lieberman (2008). (b) Late Ordovician (c. 450 Ma) configuration of continents redrawn after Dalziel et al. (1994) and Jurdy et al. (1995). Localization of the Lachlan fold belt and Altaids after Powell et al. (1990) and Sengör et al. (1993), respectively. The Cenerian belt (as part of a much larger Cambro-Ordovician cordillera along the Gondwana margin) is localized at [1], [2], or [3] according to different reconstructions of Torsvik and Cocks (2011), Stampfli (2000), or Stampfli et al. (2013), respectively.*

Von Raumer and Stampfli (2008) relate the large thicknesses of early Paleozoic sedimentary sequences to a rifting scenario with high subsidence rates in combination with an uplift of the Gondwana passive margin (shoulder uplift). Furthermore they relate this scenario to the opening of the Rheic Ocean as a back-arc basin. However, large sedimentary thicknesses can also be the result of lateral accretion in a convergent tectonic setting like it will be discussed in the context of subduction-accretion complexes.
Fig. 4 is a schematic visualization of global plate tectonics during Neoproterozoic and Paleozoic times. Four supercontinents have been formed: Rodinia, Vendia (or Panafrica), Gondwana and Pangea. Note that Pangea was open to its east side (Paleo-Tethys), and was therefore much less compact than Vendia with its widely abundant intercratonic and peripheral Pan-African orogens (Fig. 3a).

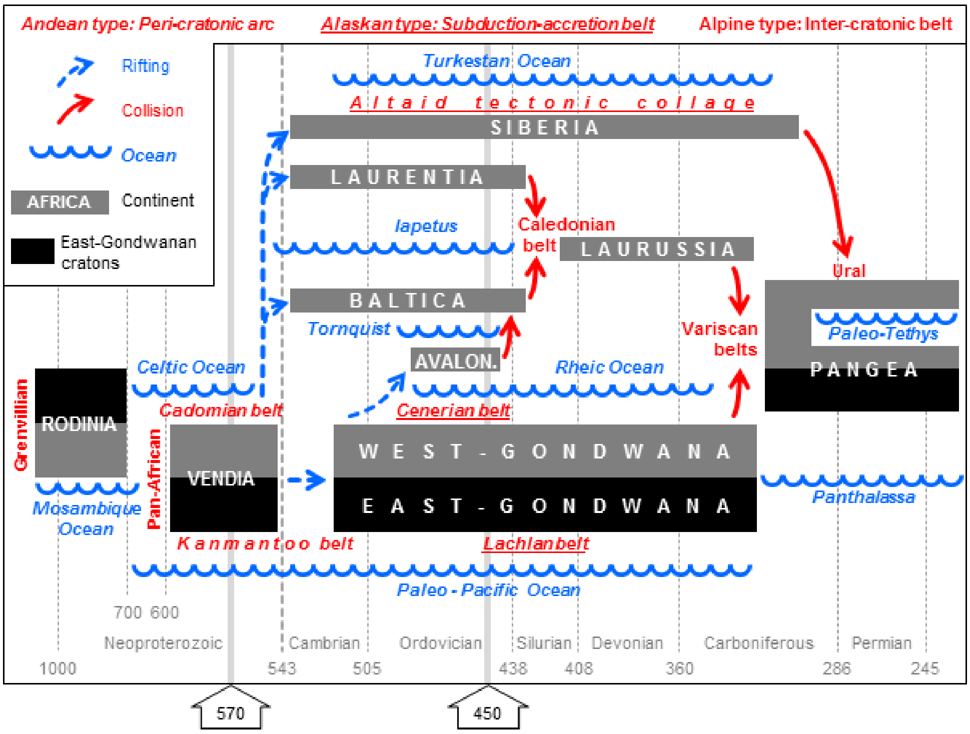


Fig. 4*: Flow chart of Neoproterozoic and Paleozoic plate tectonics. Chinese cratons and minor terranes are not considered. The two arrows at the base of the scheme correspond to the snapshots shown in Fig. 3a and b. (Redrawn after Zurbriggen 1996.)*

Jurdy et al. (1995) suggest that in a time span of about 150 Ma (from 750 until 600 Ma) the continents split from Rodinia and were rearranged in a second Neoproterozoic supercontinent called Vendia or Panafrica (Fig. 3a). Thereby, East-Antarctica, Madagascar, India and Australia (the later East-Gondwanan cratons) rotated from the west side of Rodinia to the east side of Vendia (Fig. 4) and the East African orogen formed (Meert and Lieberman 2008, Meinhold et al. 2013). In addition, Vendia was bordered by two active margins, (i) the Avalonian-Cadomian belt (670-540 Ma) and (ii) the Kanmantoo belt (Powell et al. 1990), also called the Ross-Delamerian belt (Dalziel 1992).

The world-wide orogenic activities between 750 and 520 Ma represent an important part of the Pan-African episode, at the end of which the European shelf (Dalziel et al. 1994) began to develop at the northern margin of Gondwana (Fig. 3a). There, the protoliths of the metagreywackes and metapelites of the pre-Variscan basement units of the Alps were deposited. In fact, the youngest detrital zircons in metasediments from the Central- and Southern Alps are 570 Ma old (Schaltegger and Gebauer 1999). This configuration is consistent with above mentioned recent plate tectonic reconstructions for Ordovician times showing corresponding south European terranes at the northern or north-eastern rim of Gondwana. In addition, Torsvik and Cocks (2011) indicate a sediment delivery from northern Gondwana by the northward flowing South Polar ice shield.

The Cadomian orogeny included a sinistrally oblique subduction (Linnemann et al. 2014), which might have caused an eastwards migration of the subduction zone into the European shelf**,** an area of high sediment input (Fig. 3a). The critical combination of subduction of oceanic crust and large sediment input into the trench region triggered the development of subduction-accretion complexes with forearc magmatism at the periphery of northern Gondwana or further eastwards near to the South China Craton (Fig. 3b).

Sengör et al. (1993) interpret the whole Altaid tectonic collage in the middle of Asia as an assemblage of various, mainly Paleozoic subduction-accretion complexes. The large amounts of clastic sediments derived from Baltica and Siberia, a self-consistent configuration of continents which was plate-tectonically decoupled from Gondwana (Fig. 3b). However, the configuration is similar to that of Gondwana including the same type of peri-cratonic orogens such as the Cenerian belt and the Lachlan fold belt are.

3. Characteristics of Ordovician magmatites

Ordovician metagranitoids are abundant in pre-Mesozoic basement units of the Alps. The comparison of these metagranitoids is focussed in a first step on the main types, namely the orthogneisses or metagranitoids of the Strona-Ceneri zone, the Streifen gneisses of the Gotthard massif, the Flüelagranitic gneisses of the Silvretta nappe and the ortho-, augen-, and granitic gneisses of the Oetztal-Stubai complex.

Fig. 5 shows that these metagranitoids are very similar in their peraluminous composition, plotting remarkably near the mean compositions of pelites or shales (P), and greywackes (G), after Pettijohn (1963). Except for some hornblende-bearing metatonalites from the Strona-Ceneri zone (compare Fig. 7 in Zurbriggen et al. 1997) the majority of metagranitoids plots far away from a mantle-derived basaltic source.

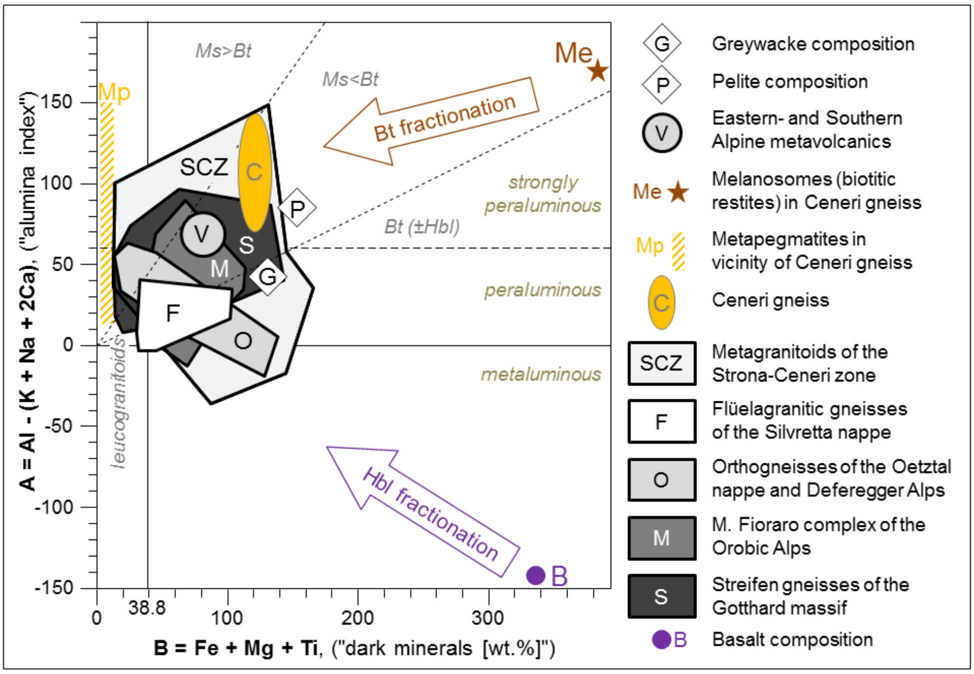


***Fig.** 5: Debon-Le Fort diagram for various Ordovician (meta-) magmatites in the Alps. For references of data see table 2. Data from Ceneri gneiss, its melanosome and metapegmatites are taken from Zurbriggen et al. (1997). (The mean composition of common basalts after Le Maitre 1976, is denoted with a "B".)*

Rock type and tectonic unit	Reference of data
Metavolcanics (porphyroids) (Eastern and Southern Alps)	- Mean of 255 analyses (Heinisch 1981)
Metagranitoids (Strona-Ceneri zone)	- 69 analyses (Boriani et al. 1983, Boriani et al. 1995)
Flüelagranitic gneisses (Silvretta nappe)	- 11 means of 335 analyses (without aplitic dykes) of Liebetrau (1996)
Ortho-, augen-, and granitic gneisses (Oetztal-Stubai complex and Deferegger Alps)	- 4 means of 41 analyses (Peccerillo et al. 1979) - 13 analyses of Borsi et al. (1980) - Mean of 16 analyses (Heinisch 1981) - 2 means of 187 analyses (Heinisch & Schmidt 1982)
M. Fioraro magmatic complex (Orobic Alps)	- 20 analyses of Colombo et al. (1994)
Streifen gneiss (Gotthard massif)	- 1 analysis of Oberholzer (1955) - 7 analyses (without sample TPG) of Pettke (1991) - 24 analyses (without samples 58, 129B; Häusler 1993)

***Tab. 2**: References of the geochemical data base for Fig. 5.*

The mean composition of 255 Ordovician metavolcanics (porphyroids) from the Eastern and Southern Alps is very similar to that of the Ordovician metagranitoids supposing that both can be regarded as volcanic and plutonic equivalents of the same magmatic event as already mentioned by Peccerillo et al. (1979) and Heinisch and Schmidt (1982).

The main characteristics of the Ordovician plutonic suites are: (i) large volumes (e.g., 21 area% of the Strona-Ceneri zone; Tab. 1); (ii) sheet-like concordant bodies (typical for syntectonic intrusions); (iii) xenoliths are identical to the country rocks (metasediments and amphibolites); (iv) cogenetic mafic enclaves are rare or absent; (v) mafic end members are rare or absent; (vi) association with inclusion-rich S-types; (vii) mainly potassium-dominated, peraluminous granitic to granodioritic suites; (viii) mainly ALUM- (generated by biotite fractionation of sedimentary protoliths) and ALCAF-suites; (ix) real CAFEM-suites (generated by hornblende fractionation of mafics) are rare or absent (Fig. 5).

According to Debon and Le Fort (1988) ALUM- and CAFEM-suites correspond in a descriptive sense to Chappell and White's (1974) S- and I-types, respectively. ALUM-, ALCAF-, and CAFEM-suites further correspond to the S-, H-, and M-type granitoids of Castro et al. (1991), standing for sedimentary-derived, hybrids and mantle-derived granitoids, respectively. Furthermore, Castro et al. (2009) describe ALUM-suites as ferrosilicic granitoids, which reflects their metagreywacke source rock.

The above list of characteristics of the Ordovician metagranitoids, their association with metaturbidites (flyschoid metapelites and metagreywackes) and banded amphibolites (partly with MORB signature), the steep structures, and the apparent absence of pre-Ordovician cratonic crust suggest a geodynamic setting similar to that found in a forearc accretionary complex. Barker et al. (1992) give a case study (Gulf of Alaska) of such an accretionary prism and the forearc granitoids occurring therein (note that the term "forearc granitoids" is taken from their publication). They show that melting of flyschoid sediments, and especially greywackes which are fertile in granitoid melts, is a major process in the generation of such granitoids. Forearc granitoids reflect compositions and isotopic signatures of their sedimentary source rocks, which themselves have inherited compositions and signatures of the hinterland they are derived from. Therefore, common tectonic-discrimination diagrams for granitic rocks may misinterpret forearc granitoids, in that they interpret their source rocks rather than the tectonic setting of the magmatism (Barker et al. 1992). For example, according to the dominant granite-forming process of melting sediments, the Alaskan forearc granitoids should be labelled with an "S". But the inherited I-type signature of the greywacke-source rocks remains preserved in the granitoids, which therefore still have I-type compositions. Or, according to the granite classification scheme of Pearce et al. (1984) the Alaskan forearc granitoids are of the volcanic arc type. But Barker and co-workers note that Pearce et al. (1984) have no category for forearc magmatism, instead typical forearc intrusives were included by Pearce's team with their volcanic arc granitoids. Conclusively, it can be a misleading practice to apply genetically pre-interpreted tectonic discrimination diagrams to forearc granitoids. Therefore, in this study the chemically descriptive diagram of Debon and Le Fort (1988) is applied to the Ordovician magmatites (Fig. 5). As shown by Zurbriggen et al. (1997) the metagranitoids of the Strona-Ceneri zone show a Rb-(Y+Nb) pattern (Pearce et al. 1984) identical to the inherited volcanic arc signatures of their metasedimentary host rocks.

Of specific interest are the inclusion-rich S-type metagranitoids like the Ceneri gneiss (Flasergneiss is similar) of the Strona-Ceneri zone, and comparable rock-types from the Gotthard massif (Paradis gneiss and similar Schmitzen gneiss), the Silvretta nappe (Mönchalp granite), and the Oetztal nappe (Winnebach granite and similar Sulztaler, Inziger and Schlosskopf granites). Such inclusion-rich S-type granitoids (Tab. 3) bear many similarities to the Ordovician Cooma granodiorite, the type locality of Chappell and White's (1974) S-type of the SE-Australian Lachlan fold belt. In all those regions these inclusion-rich peraluminous granitoids represent key-lithologies linking the metasedimentary pile with volumetrically abundant magmatism in their areas.

		Ceneri gneiss	Paradis gneiss	Winnebach granite	Mönchalp granite	Cooma granodiorite
Mineralogy	Quartz	19-37	25-30	~40	26	48
	Oligoclase	31-58	15-40	~30	32	19
	K-Feldspar	0-22	-	-	15	9
	Muscovite	4-24	5-20	~10	-	4
	Biotite	4-22	15-25	15-20	18	17.5
	Andalusite					+
	Pinite				Pinite pseudo-morph after Cordierite	+
	Cordierite			+		+
	Sillimanite	±				+
	Garnet	+	+			
	Kyanite	±				
Inclusions	Calc-silic. nodules	+	+		+	
	Mica gneisses	+	+	+	+	+
	Amphibolites	+	+		+	
	Bt-rich enclaves	+	+	+	+	+
	Quartz lumps	+	+			+
Ref.	Petrography	*Boriani '70 Zurbriggen '96*	*Huber '43 Arnold '70*	*Hammer '25 Hoinkes et al. '72*	*Streckeisen '28 Wenk '34*	*Chappell et al. '91*
	Ordovician isotopic age	*Zurbriggen et al. (1997)*	*Mercolli et al. (1994)**	*Thöny et al. (2008)*	*Poller et al. (1997)***	*Chappell et al. (1991)*

***Tab. 3**: Petrographic data for Ordovician inclusion-rich S-type granitoids. (*The Paradis gneiss was not isotopically dated, but according to Mercolli et al. (1994) it associates with migmatites post-dating granulite facies at 470 Ma, and pre-dating Streifen gneiss intrusion at 440 Ma. **Poller et al. (1997) mention late Cambrian to early Ordovician isotopic ages for the Mönchalp gneiss/Mönchalp granite.)*

In anatectically derived granitoids the formation of retrograde muscovite can reduce the mode of K-feldspar producing a shift in the QAP diagram towards the tonalite field (White and Chappell 1990). Therefore, Ceneri gneiss-like lithologies (Tab. 3), which are very similar in chemical composition, can vary mineralogically from the granite to the tonalite field simply due to retrograde rehydration reactions. This could also explain the clusters of tiny oligoclase crystals with interstitial muscovite, the typical microstructure of the Ceneri gneiss (Boriani 1970), which is typical for all inclusion-rich S-type granitoids in the Alps! Their origin could be caused by decompression related to the mobilization and emplacement of the melts. Thereby water deliberated from the melt and reacted with K-feldspar and alumosilicates to form clusters of oligoclase and muscovite.

The Ceneri gneiss, the Paradis gneiss and the Winnebach granite are tonalites. The latter is quite rich in quartz. The Cooma granodiorite plots into the field of quartz-rich granitoids, and the Mönchalp granite is much more granitic in composition and except for the lower content in quartz similar to the Cooma granodiorite. High modes of quartz are very typical for S-type granitoids which derived from quartz-rich source rocks. Most of these Ceneri gneiss-like lithologies fall within the S-type field of Lewis et al. (1994).

The Cooma granodiorite is partly foliated and partly massive and contains various metasedimentary xenoliths, such as metagreywacke-gneiss xenoliths, sillimanite and/or biotite-rich enclaves or schlieren, and feldspar and quartz xenocrysts or so-called quartz lumps (Tab. 3). Feldspar xenocrysts originate from early formed pegmatites which in a later advanced stage of anatexis become disrupted. Quartz lumps may have the same origin or they can derive from vein quartz in the protolith. They are clearly restitic and very typical for S-type granitoids (Chappell et al. 1987).

Ceneri gneiss-like lithologies are strongly peraluminous. In the case of the Ceneri gneiss the percentage of normative corundum ranges from 1.5 to 8.1%, typically around 5%. Consequently they bear Al-silicates according to the attained P-T conditions. Kyanite, sillimanite, and garnet in the Ceneri gneiss (Tab. 3) indicate pressures around 10 kb (Zurbriggen et al. 1997). The abundance of garnet and the lack of cordierite in the Paradis gneiss indicate pressures between 6 and 9 kb (Vielzeuf and Holloway 1988). The classical cordierite granites of the Silvretta and Oetztal nappes (Mönchalp granite and Winnebach granite/migmatite) indicate pressures around 5 kbars (Söllner et al. 1982), but Thöny et al. (2008) provide geobarometric data for the latter to be less than 2.8 kb.

The andalusite and cordierite bearing Cooma granodiorite of the SE-Australian Lachlan fold belt crystallized at pressures between 3.5 and 4 kb (Ellis and Obata 1992) and the Cowra granodiorite (about 200 km west of Sydney) has a very limited aureole and is associated with volcanics of the same composition, and is therefore classified as a subvolcanic granitoid (Wyborn et al. 1991).

Based on these pressure indicators a petrogenetic model, shown in Fig. 2, can be drawn: Granulite facies temperatures in the lowermost crust produce migmatites and progressively diatexites. Driven by buoyancy and simultaneous tectonics, these migmas became isostatically unstable and tended to rise, preferentially along pre-existing steep structures and deep-reaching active faults zones. In an early stage of anatexis pegmatites were produced. Evidence for an anatectic origin of these leucotonaltic metapegmatites is provided by their chemical composition (Fig. 5) plotting on a line with the Ceneri gneiss and its melanosomes (biotitic restites). This explains why metapegmatites and metatexites predominantly occur in the vicinity of Ceneri gneiss bodies, and why metapegmatites are cut by the subsequently emplaced Ceneri gneiss pluton as drawn in Fig. 2 (see also photo 2e in Zurbriggen et al. 1997).

The reason why the Strona-Ceneri zone is relatively rich in Ceneri gneisses is its position in the lower crust. Due to the relative high viscosity of deep-seated water-under-saturated magmas such plutons tend to accumulate in the lower to middle crust rather than intruding shallow crustal levels. One of the most important consequences of this model (Fig. 2) is that together with the uprising S-type granitoids the isotherms and the migmatic aureole become flexed upwards and narrowed, producing steeply inclined isograds, large lateral gradients, and high T/low P metamorphism at shallow crustal levels. However, to understand the causes for such intensive deep-crustal anatexis of metasediments we have to look at the tectonic setting discussed in the next chapter.

4. New model for the Ordovician orogeny in the Alps

The model of cratonization of subduction-accretion complexes can explain the genesis of metagreywacke dominated gneiss terranes such as the Strona-Ceneri zone and similar basement units. In order to describe the many details of these highly dynamic petrogenetic processes, the model will be discussed along seven aspects which are located with corresponding numbers in Fig. 6.

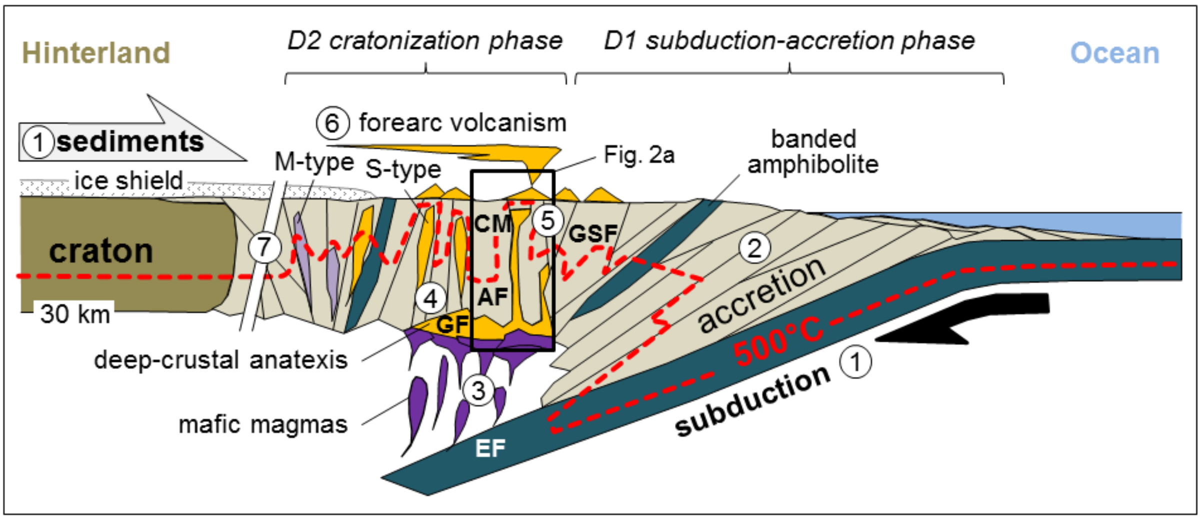


***Fig. 6**: Tectonic model of the Cenerian belt at the periphery of northern Gondwana or the South China Craton in Ordovician time. Possible paleogeographic positions of the Cenerian belt are indicated in Fig. 3b. The numbers 1-7 are described in the text. (EG: eclogite facies, GF: granulite facies, AF: amphibolite facies, GSF: greenschist facies, CM: contact metamorphism; simplified and redrawn after Zurbriggen 1996.)*

Point #1 in Fig. 6: Geodynamic setting: large input of detritus into subduction trench

The cratonization of forearc subduction-accretion complexes is a fast, highly dynamic and self-sustaining process (Crook 1980), needing (i) long lasting subduction and (ii) a high sedimentary flux from a craton. (i) Van Staal and Hatcher (2010) notify that the Ordovician is marked by the formation of peri-cratonic arcs of great strike-length along the margins of Laurentia, Baltica, Siberia, and Gondwana, which were separated by wide oceans. (ii) In case of the Lachlan fold belt, the sediments derived from the Kanmantoo belt (600-500 Ma), whereas the sedimentary input for the Strona-Ceneri zone (as part of the Cenerian belt) probably have been derived from the Cadomian belt (670-540 Ma) and/or intercratonic late Pan-African belts of northern Africa (e.g., Meinhold et al. 2013). Von Raumer et al. (2013) mention additional sedimentary sources in north-eastern Gondwana and the South China Craton. The Ordovician South Polar ice shield accelerated the rates of erosion and caused a sediment transport in direction to the shorelines (e.g., Torsvik and Cocks 2011), where the deposition of sediments was localised at the sites of calving and melting, right in the trench area!

Point #2 in Fig. 6: Accretionary tectonics

Subduction zones with high sediment input form accretionary complexes with a seaward retreating trench (Clift and Vannucchi 2003). With the addition of new wedge-shaped sedimentary packages at the base of the prism, older thrust wedges are gradually moved upwards and rotated with their top to the arc. The continuous (trans-) pressional tectonics cause a progressive steepening of the main structures of the accretionary prism with increasing distance from the trench. Both, subduction and accretion tectonics predate the forearc magmatism creating pre-magmatic structures in the metasediments.

Point #3 in Fig. 6: Development of forearc granitoids

The Strona-Ceneri zone consists of 21 area% of metagranitoids (Tab. 1), 85% representing crustal-derived S-type granitoids. Taking into account the extruded equivalents, about the lower fifth of the accretionary complex melted and intruded higher crustal levels. Assuming an approximate thickness of 30 km of the accretionary complex, this means, that the lowermost 6 km were melted away. What was the heat source for such a substantial anatexis?

Mantle-derived mafic magmas are generally hotter than 1000°C and have solidi above 900°C. As they come in contact with the cooler accretionary complex they cool, rheologically thicken, and start crystallizing releasing cooling and crystallization heat. According to Vielzeuf and Holloway (1988), in the metapelite-greywacke system large amounts of anatectical melts are generated in a narrow temperature range between 850 and 875°C. This will have an important buffering effect on metamorphic temperatures in the lowermost crust, because temperatures cannot further rise until melting reactions, such as biotite-dehydration is completed. Due to these processes the lowermost parts of the accretionary wedge reach temperatures between 850 and 900°C. Exactly in this temperature range crustal derived melts are near their liquidi. On the other hand, mantle-derived mafic magmas begin to solidify at 900°C, and thus, will have increased viscosities. These viscosity contrasts reduces magma interaction and the formation of hybrid magmas. Due to their higher density, mafic rocks tend to remain at depth where they underplate the anatectic horizon of the lowermost accretionary wedge.

During the initial stage of the development of a subduction-accretion complex, the accretionary prism is small and the subduction-related mantle-derived magmas intrude the margin of the craton. The input of crustal-derived magmas will, therefore, be minor and the magmatism will be of the Andean-type (Tab. 4). As the sediment input increases due to increased erosion rates in the hinterland, the accretionary prism grows ocean-wards. As a result, the subduction zone retreats, and from a certain point, the subduction-related mantle-deriving magmas intrude directly the accreted and fertile “mud-pile” instead of the former sterile cratonic crust, and the magmatism changes from an initial volcanic arc of the Andean-type to a forearc magmatism of the Alaskan-type.

Beside the majority of crustal-derived S-type granitoids, M-type granitoids and hybrids (nomenclature according to Castro et al. 1991) can be present in cratonized subduction-accretion complexes, too, indicating that not all mantle-derived melts underplate the anatectical horizon, especially in periods when the sedimentary flux decreases and/or the subduction accelerates.

Barker et al. (1992) list many options for basaltic magma sources including the subduction of a spreading ridge. In fact, the plate tectonic reconstructions of Stampfli (2000) indicate the subduction of the fast-spreading Rheic Ocean. However, the widespread occurrence of forearc granitoids over geographically large areas all along Gondwana and over chronologically long periods during the Paleozoic era would favour a long lasting standard subduction scenario as suggested by the model.

With respect to the tectonic setting and the location where the basaltic magmas underplate the prism (as inferred by the model), this peraluminous magmatism represents the arc itself, instead of being in the forearc region. Therefore, from a model’s perspective this type of magmatism should be called for example “peraluminous arc” rather than “forearc”. However, in this study the term “forearc granitoids” from Barker et al. (1992) was applied to the peraluminous Ordovician granitoids because of their concept of inherited signatures.

Point #4 in Fig. 6: Processes in the lower crust as represented in the Strona-Ceneri zone

The steep structures provide an ideal framework for the syntectonic emplacement of magmas. This upwards mass flow must be compensated by a downwards flow of country rocks, causing a major reorganization into a stable cratonic crust. This would explain the juxtaposition of eclogite facies rocks next to lower grade rocks in the Strona-Ceneri zone, all overprinted in amphibolite facies grade (Zurbriggen et al. 1997).

From a geodynamic point of view, all deformation phases can be regarded as one continuous tectonic event during which the Ordovician magmas were generated, successively emplaced, and subsequently deformed under amphibolite facies conditions. However, from a geometric point of view, there are still two deformation phases: the pre-intrusive D1 subduction-accretion phase, and the syn- to subsequent post-intrusive D2 cratonization phase.

Point #5 in Fig. 6: Processes in the upper crust with reference to shallow crustal analogues

In the same way as mantle-derived mafic magmas bring advective heat into the lowermost crust, heat is transferred by the plutons to the upper crust. As a result the isotherms become narrowed inducing high thermal gradients and associated high T/low P metamorphism in the upper crust, as can be observed in the Lachlan fold belt. The cratonization processes do not form an over-thickened crust. Therefore no late to post-orogenic exhumation of the deeper crust occurs. At this point the comparison to the Lachlan fold belt becomes most interesting because it might represent a shallow crustal analogue of a cratonized subduction-accretion complex (Crook 1980). Because no Variscan and Alpine tectonics overprinted the Lachlan fold belt, its original configuration was preserved. In contrast, late and post-Variscan tectonics have uplifted the Strona-Ceneri zone and exposed the Ordovician amphibolite facies levels.

Point #6 in Fig. 6: Volcanism in the forearc

As discussed in chapter 3, the metavolcanics (porphyroids) of the Eastern and Southern Alps can be regarded as extruded equivalent of the coeval plutons. Together they belong to the Ordovician forearc magmatism in the Alps. Boriani and Colombo (1979) investigated the "Gneiss Chiari" from the Val Colla zone (which is located between the Strona-Ceneri zone and the Orobic Alps in Fig. 1) concluding that it might represent the metamorphic product of a pre-Variscan alkali rhyolite, thus, representing a volcanic member of the Ordovician magmatism, too.

Heinisch (1981) showed that the Ordovician metavolcanics of the Eastern and Southern Alps have ignimbrite characteristics, supposed to be accompanied by a large amount of emplacing granitoids. His volume estimations indicate that the Late Ordovician volcanism in the Alps is comparable to any of the known major ignimbrite eruptions in the earth's history!

Ordovician volcanics do also occur on Sardinia, where they discordantly truncate already deformed Cambrian and Early Ordovician strata (Eltrudis et al. 1995). Evidence for a possible existence of an equivalent discordance to the so-called "Sardic Unconformity" is discussed by Poli and Zanferrari (1992) for the Agordo basement in the eastern Southern Alps (see Fig. 1 for location of Agordo).

Point #7 in Fig. 6: Lateral trench-ward growth of accretionary complexes

Crook (1980) suggests that cratonization of accretionary complexes caused the formation of a c. 1000 km wide tract of continental crust which was accreted to the Australian craton over a 250-300 Ma long period. Sengör et al. (1993) did an estimation of a similar dimension for the Altaid tectonic collage (Fig. 3b). They calculated that c. 5.2 million square km of subduction-accretion complexes were accreted within 350 Ma to Eurasian cratons. These two examples show that the process of frontal accretion and subsequent stabilization of accretionary complexes as cratonic crust is, on one hand, very fast, and on the other hand, can last over geologically long periods. Thereby, accretionary complexes can grow hundreds of kilometers ocean-wards, and with that, the locations of near-trench subduction and forearc magmatism migrate ocean-wards, too. Cratonization will occur with a certain delay after subduction and accretion, but all three major processes migrate with a similar velocity away from the cratonic hinterland. This increases firstly, the distance of transport for the craton-deriving sediments, and secondly, the type of sediments will change also, because volcanic rocks and low-grade metamorphic metasediments from exposed parts of the accretionary complex itself get eroded and recycled again as they become deposited in the trench.

The model of subduction-accretion complexes at the periphery of a craton does explain why pre-accretionary cratonic basement units cannot be found in the accretionary complexes themselves. For this reason Precambrian crystalline basement units cannot be found in the Alps. Apart from the few ophiolitic rocks and a minor amount of mantle-derived igneous rocks, an accretionary complex such as the Strona-Ceneri zone can consist of 97% of recycled cratonic crust (Tab. 1). Evidence for this can be found in inherited ages and chemical signatures of the metasediments.

The model of cratonizing subduction accretion complexes describes the basic mechanism, which in reality can be further complicated by (i) the accretion of terranes, (ii) changes in velocity and angle of subduction, and (iii) changes in amount and types of terrigeneous sediments. But these complications are options and not principal characteristic of this type of orogeny.

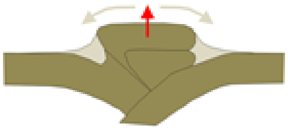
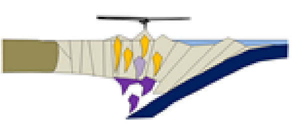
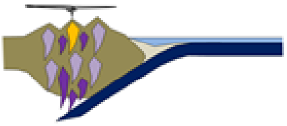
Zurbriggen (1996, pp. 170-179) did a detailed comparison between the Ordovician Strona-Ceneri zone (SCZ) and the Ordovician-Devonian SE-Australian Lachlan fold belt (LFB) and showed that both orogens are of the same type with respect to the following aspects: (i) peri-cratonic setting at South-East-Gondwana (LFB) and North-Gondwana (SCZ); (ii) Gondwana-derived clastic sediments; (iii) Neoproterozoic to early Paleozoic age of turbiditic sediments; (iv) wedged slices of oceanic lithosphere; (v) vast syntectonic magmatism with a dominant crustal component; (vi) mobilized diatexites which rise as plutons and intrude metasediments of the same greywacke-pelitic composition, namely the Cooma granodiorite (LFB) and the Ceneri gneiss (SCZ); (vii) no exposure of Precambrian cratons; (viii) predominant steep structures; (ix) no exhumation of the lower crust.

The last aspect will be discussed in more detail because it targets a key aspect of cratonized subduction-accretion complexes. The subvolcanic character of many granitoids like the very limited contact aureoles and the close spatial association with coeval volcanics (e.g. Cowra granodiorite, Wyborn et al. 1991) indicate a shallow erosional level of the LFB. Often only graphite and sericite indicate lower greenschist facies metamorphism in the cleaved turbiditic sequences. Even in the Wagga-Omeo and the Cooma-Cambalong metamorphic belts which contain the highest metamorphic rocks of the LFB, pressure indicators hardly exceed depths of more than 10 km (Johnson and Vernon 1995). Isobaric cooling at the end of their anticlockwise PTt-paths is consistent with a general lack of late to post-orogenic exhumation of lower crustal metamorphic rocks.

In the Strona-Ceneri zone, there is evidence for a limited uplift of the amphibolite facies gneisses into the stability field of andalusite in late Ordovician time (Zurbriggen et al. 1997). However, an exhumation of the amphibolite facies gneisses did not occur until the end of the Variscan orogeny. Such a scenario would explain the strong age contrast between the high-grade events during which the crust was generated (i.e. Ordovician U-Pb zircon and monazite ages as mentioned in Zurbriggen et al. 1997) and the 140-160 Ma younger cooling ages indicating uplift events (i.e. Permo-Carboniferous K-Ar and Rb-Sr mica ages, McDowell 1970, and Hunziker 1974). These contrasting age patterns are also typical for other pre-Mesozoic basement units in the Alps. Based on these considerations there are two distinct orogenic cycles, (i) the Ordovician cratonization of a subduction-accretion complex after which no exhumation of the lower crust occurred, and (ii) the middle Carboniferous formation of amphibolite facies Schlingen (corresponding to the Variscan collision of Gondwana and Laurussia). The Variscan orogeny caused (at least regionally) a crustal over-thickening and resulted in a late to post-orogenic exhumation of the lower crust as indicated by late Carboniferous cooling ages (Zurbriggen et al. 1998) and the exposure of Schlingen structures, which are unconformably overlaid by the non-metamorphosed conglomerates of Manno (c. 310 Ma).

In order to emphasize the characteristics of cratonizing subduction-accretion complexes table 4 compares three idealized types of orogens: Alpine-type continent-continent collision, Alaskan-type subduction-accretion complex and Andean-type continental arc. The listed criteria are strongly generalized and, thus, denote typical situations. It is clear, that these three types of orogens represent end members, or even only single stages in a more complex orogenic history. This is probably best explained by the Caledonian fold belt, which is listed as an example for the Alpine-type continent-continent collision. In the standard Alpine-type, namely the Alps, the subducted ocean was small, so that typical subduction-related magmatism could not develop on a larger scale. In contrast to this, the subducted lapetus was much bigger, and therefore, in an early stage of the Caledonian orogeny subduction-related processes played a dominant role. But even though, the final continent-continent collision produced the dominant imprint, and allows classifying the Caledonian fold belt as such.

The Cadomian belt resembles very much to an Andean-type continental arc that changed into an orogenic system of a Western Pacific style with a continental arc and a back-arc basin (Linnemann et al. 2014), whereas the Cenerian belt shows all characteristics of a typical subduction-accretion complex. This is important to highlight because Alaskan-type subduction-accretion complexes with forearc magmatism are nowadays rare and poorly recognized orogenic systems as stated by Barker et al. (1992), Sengör and Natal'in (1996), and Van Staal and Hatcher (2010). The reason for this rareness is the low overlap of subduction zones with regions of high terrigeneous sediment input (compare Fig. 4.12 in Frisch and Meschede 2011). The subduction zones of Alaska, Makran, Sumatra and Vancouver are potential candidates, but the sediment input into these zones is not high enough to form subduction-accretion complexes comparable to those in Ordovician time. However, the subduction-accretion complex of the Gulf of Alaska (Moore et al. 1991) is the most similar recent example.

			
	Alpine type continent-continent collision	**Alaskan type** subduction-accretion complex	**Andean type** continental magmatic arc
External sediment supply	Not necessary	Essentially necessary	Not necessary
Involvement of crystalline basement	Yes	No	Yes
Predominant structures	Subhorizontal nappes	By accretionary tectonics verticalized structures	Emplacement related structures of any orientation
Igneous rocks	Very few	Very rich in crustal-dominated, K-rich forearc granitoids	Very rich in tonalites with abundant mafics
Main type of metamorphism	Burial type	High T – various P	Emplacement-related contact metamorphism
Isostacy	Isostatically metastable over-thickened nappe stack	Isostatically stable due to direct cratonization	Isostatically metastable over-thickened continental magmatic arc
Topography	Steep mountains of thrusted metamorphics	Forearc regions on sea level	Steep volcanic-plutonic mountain ranges
Typical syn-orogenic sediments	Thick molasse sequences in foreland depression	Forearc basin and trench sediments (turbidites)	Volcano-clastic sediments
Exhumation of the middle to lower crust	Exhumation in late to post orogenic stage	No exhumation of lower crust	Exhumation in late to post orogenic stage
Production of new continental crust	New continental crust is generally not produced (mainly stacking of pre-orogenic sterile continental crust)	Recycling of craton-derived fertile sediments (some accreted oceanic material; minor juvenile mantle-derived magmas)	High production of new continental crust by juvenile mantle-derived magmas
Examples of Neoproterozoic and Paleozoic orogenic belts	**Caledonian fold belt** (Silurian)	**Cenerian belt** (Ordovician)	**Cadomian belt** (Vendian – Cambrian)

Tab. 4: *Comparison of the three orogenic types, Alpine, Alaskan and Andean.*

A surprising aspect of subduction-accretion complexes are their fast dynamics which make them so efficient in recycling sediments into stable cratonic crust. Barker et al. (1992) have shown that in the forearc of the Gulf of Alaska, 50 Ma old sedimentary-derived granodiorites postdate their source rocks of the Paleocene to Eocene flyschoid Orca Group by just a few million years. Sample and Moore (1987) describe another example from the same region with a very short time interval of only 12 Ma between deposition of the sedimentary country rocks and the emplacement of the plutons. In this context it is interesting to note that Fernández-Suárez et al. (2014) relate Iberian Ediacaran-Early Cambrian sediments to an active margin due to the short time gap between sedimentation and magmatism, which might indicate a similar orogenic scenario.

Another astonishing feature of cratonizing subduction-accretion complexes is the occurrence of an anatectical granite kitchen at depth, whereas at the surface the erosion of corresponding forearc volcanics and the transportation and sedimentation of greywackes continues to form a shallow coastal range mostly eroded to sea level. In the Eastern Alps more than 1000 m thick sequences of Ordovician sediments of the Grauwacke Zone do not show any sign indicating an Ordovician orogeny (Schönlaub and Heinisch 1993). But in the light of the new model these Ordovician sequences represent the ongoing sedimentation during the cratonization of the subduction-accretion complex as confirmed by the intercalated volcanics.

Here, the term "Alaskan-type" is applied to subduction-accretion type of orogens because the Alaskan forearc complex represents a today's active orogenic system, which is in analogy to the Alpine and Andean types. Sengör and Natal'in (1996) suggested an alternative term: "Turkic-type". However, the cratonization of subduction-accretion complexes was first described by Crook (1980) for the Lachlan fold belt.

Note the three idealized types of active margins localized in Fig. 4: continent-continent collisional belts of the Alpine type, peri-cratonic continental arcs of the Andean type (in italic font), and Alaskan type subduction-accretion complexes with forearc magmatism (in italic and underlined).

5. Conclusions

These investigations indicate that the pre-Mesozoic crust of the Alps was mainly generated in the Ordovician by the cratonization of subduction-accretion complexes and related forearc magmatism. These Alaskan-type orogens were the dominant orogenic type in Ordovician times, but today such tectonic settings are rare. The reason is the unique plate tectonic history in Neoproterozoic and early Paleozoic times. According to Rino et al. (2008) and Van Kranendonk and Kirkland (2013) the global rate of crust formation was ever highest during the Grenvillian (1.3-1.0 Ga) and at the dawn of the Pan-African orogenies (0.8-0.6 Ga), at the end of which the supercontinents Rodinia and Vendia assembled, respectively (Fig. 4). The collision of all cratons to form the supercontinents closed all oceans in between and subduction tectonics jumped to the periphery of the supercontinent. Simultaneously, the ongoing erosion of all the intercratonic collisional belts delivered large amounts of detritus into the peripheral subduction zones along the coastline. Thus, Gondwana (major part of Vendia) was full of Pan-African belts between its cratons and at its periphery (Fig. 3a), which became successively eroded and delivered extraordinary amounts of detritus, which in Ordovician time became accreted forming the Cenerian and Lachlan fold belts (Fig. 3b). In both fold belts, special inclusion-rich strongly peraluminous (meta-) granitoids (namely the Ceneri gneiss and the Cooma granodiorite with the same composition and signature as their metasedimentary host rocks) represent the key lithologies, which link the metasedimentary sequences ("paragneisses") with the anatectically derived metagranitoids ("orthogneisses").

The Cenerian belt might correlate (at least in part) to the early–Paleozoic Gondwana-directed subduction zone with an approximate strike length of 1300 km as shown in Fig. 5 of von Raumer (1998). This suture zone was part of the much larger Cambro-Ordovician cordillera all along northern and northeastern Gondwana with a more complex evolution (Stampfli et al. 2013). However, other parts of this cordillera might have had an Alaskan-type evolution like the Cenerian belt, too.

In case of the Cenerian belt, Variscan tectonics overprinted the predominantly steeply structured subduction-accretion complex. Thereby km-scaled Schlingen folds with typically steeply plunging fold axes were formed under amphibolite facies conditions. The mid-Carboniferous Schlingen phase caused an over-thickened crust, as a result of which late to post-orogenic uplift and exhumation of the lower crust occurred. Later, Alpine tectonics disrupted these pre-Mesozoic basement units into several pieces which became part of the Alpine chain, recognized as External massifs, and Eastern and Southern Alpine crystalline basement units.

Acknowledgements

I want to thank Ivan Mercolli, my teacher who became the most important colleague for these works. His profound knowledge and enthusiasm for granites and gneisses allowed us to plunge deep into the crust and far back in time. I also thank Jürgen von Raumer, Leander Franz and Cees van Staal for critical reading and valuable discussions. Many thanks belong to the members of the Institute of Geological Sciences of the University of Bern where I enjoyed my studies. I am thankful for the travel grant of the Swiss Academy of Sciences for academic studies and field excursions in Down Under during April and May of 1995. In the person of Erwin Scheibner I had my base contact in Sydney. From there I could join geologists from the Australian Geological Survey on their field trips, namely Richard Glen, Elisabeth Morgan and Alice Warren. Ulricke Troitzsch guided me to the Cooma granodiorite. They and many more geologists at the universities between Sydney and Melbourne took their time to meet and were so kind to provide me with excursion guides, maps and papers, and most valuable hints for the best outcrops in the Lachlan fold belt.

I am glad for the unforgettable meetings with Albert Streckeisen, Paul Greater, Tjerk Peters, Fred Barker, Keith Crook, Bruce Chappell and Allan White. Their advice and support was greatest motivation.

References

Arnold A (1970) Die Gesteine der Region Nalps-Curnera im nordöstlichen Gotthardmassiv, ihre Metamorphose und ihre Kalksilikatfels-Einschlüsse (Petrographische Untersuchungen im Bereich der Anlagen der Kraftwerke Vorderrhein). Beiträge zur geologischen Karte der Schweiz. Neue Folge 138

Barker F, Farmer GL, Ayuso RA, Plafker G, Lull JS (1992) The 50 Ma granodiorite of the Eastern Gulf of Alaska: melting in an accretionary prism in the forearc. Journal of Geophysical Research 97(B5):6757-6778

Boriani A, Colombo A (1979) Gli "Gneiss chiari" tra la Valsesia e il Lago di Como. Rend. Soc. It. Min. Petr. 35 (1):299-312

Boriani A (1970) The microstructure of "Cenerigneiss". Rend. Soc. It. Min. Petr. 26:487-501

Boriani A, Giobbi Origoni E, Pinarelli L (1995) Paleozoic evolution of southern Alpine crust (northern Italy) as indicated by contrasting granitoid suites. Lithos 35:47-63

Boriani A, Origoni Giobbi E, Del Moro A (1983) Composition, level of intrusion and age of the 'Serie dei Laghi' orthogneisses (Northern Italy - Ticino, Switzerland). Rend. Soc. It. Min. Petr. 38 (1):191-205

Borsi S, Del Moro A, Sassi FP, Zirpoli G (1980) New petrographic and radiometric data on the Oetztal and Stubai orthogneisses (Eastern Alps). Neues Jahrbuch für Mineralogie. Monatshefte 1980 (2):75-87

Brown M. (1994) The generation, segregation, ascent and emplacement of granite magma: the migmatite-to-crustally-derived granite connection in thickened orogens. Earth Science Reviews 36:83-130

Castro A, Moreno-Ventas I, De la Rosa JD (1991) H-type (hybrid) granitoids: a proposed revision of the granite-type classification and nomenclature. Earth Science Reviews 31:237-253

Castro A, Garcia-Casco A, Fernandez C, Corretgé LG, Moreno-Ventas I, Gerya T., Löw I (2009) Ordovician ferrosilicic magmas: Experimental evidence for ultrahigh temperatures affecting a metagreywacke source. Gondwana Research 16: 622-632

Chappell BW, White AJR (1974) Two contrasting granite types. Pacific Geology 8:173-174

Chappell BW, White AJR, Williams IS (1991) A traverse section through granites of the Lachlan Fold Belt. Excursion guide, Second Hutton symposium on granites and related rocks, Canberra, 15-21 September 1991, Bureau of Mineral Resources, Geology and Geophysics, Record 1991/22.

Chappell BW, White AJR, Wyborn D (1987) The importance of residual source material (restite) in granite petrogenesis. Journal of Petrology 28 (6):1111-1138

Clift P, Vannucchi P (2003) Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust. Review of Geophysics 42:1-31

Colombo A, Siletto GB, Tunesi A (1994) Pre-Variscan magmatism in the central Southern Alps: the Monte Fioraro magmatic complex. Schweizerische Mineralogische und Petrographische Mitteilungen 74:127-135

Crook KAW (1980) Fore-arc evolution and continental growth: a general model. Journal of Structural Geology 2 (3):289-303

D'Lemos RS, Brown M, Strachan, RA (1992) Granite magma generation, ascent and emplacement within a transpressive orogen. Journal of the Geological Society, London 149:487-490

Dalziel IWD (1992) Antarctica; a tale of two super-continents? Ann. Rev. Earth Planet. Sci. 20:501-526

Dalziel IWD, Dalla Salda LH, Gahagan LM (1994) Paleozoic Laurentia-Gondwana interaction and the origin of the Appalachian-Andean mountain system. Geological Society of America Bulletin 106:243-252

Debon F, Le Fort P (1988) A cationic classification of common plutonic rocks and their magmatic associations: principles, method, applications. Bulletin de minéralogie 111:493-510

Ellis DJ, Obata M (1992) Migmatite and melt segregation at Cooma, New South Wales. Transactions of the Royal Society of Edinburgh: Earth Sciences 83:95-106

Eltrudis A, Franceschelli M, Gattiglio M, Porcu R (1995) Discontinuous metamorphic zonation in the Paleozoic units of the Hercynian chain of SW Sardinia, Italy: evidence from structural and illite crystallinity data. Schweizerische Mineralogische und Petrographische Mitteilungen 75:201-211

Fernández-Suárez J, Guitiérrez-Alonso G, Pastor-Galán D, Hofmann M, Murphy JB, Linnemann U (2014) The Ediacaran-Early Cambrian detrital zircon record of NW Iberia: possible sources and paleogeographic constraints. International Journal of Earth Sciences 103:1335-1357

Flood RH, Vernon RH (1978) The Cooma Granodiorite, Australia: An example of in situ crustal anatexis? Geology 6:81-84

Franz L, Romer RL (2007) Caledonian high-pressure metamorphism in the Strona-Ceneri Zone (Southern Alps of southern Switzerland and northern Italy). Swiss Journal of Geosciences 100 (3):457-467

Frey M, Hunziker JC, Frank W, Bocquet J, Dal Piaz GV, Jäger E, Niggli E (1974): Alpine metamorphism of pelitic and marly rocks of the central Alps. Schweizerische Mineralogische und Petrographische Mitteilungen 54:489-506

Frisch W, Meschede M (2011) Plattentektonik: Kontinentverschiebung und Gebirgsbildung. Primus Verlag, 4. Auflage

Hammer W (1925) Cordieritführende metamorphe Granite aus den Oetztaler Alpen. Tschermaks Mineralogische und Petrographische Mitteilungen 38:67-87

Handy MR, Franz L, Heller F, Janott B, Zurbriggen R (1999) Multistage accretion and exhumation of the continental crust (Ivrea crustal section, Italy and Switzerland). Tectonophysics 18:1154-1177

Häusler S (1993) Zu den Gesteinen im Gebiet der Greina-Hochebene / GR (Südostende des Gotthardmassivs). Unpubl. M.Sc. thesis, University of Bern, Switzerland

Heinisch H, Schmidt K (1982) Zur Genese der Augengneise im Altkristallin der Ostalpen. Neues Jahrbuch für Geologie und Paläontologie. Monatshefte, 4:211-239

Heinisch H (1981) Zum ordovizischen „Porphyroid"-Vulkanismus der Ost- und Südalpen, Stratigraphie, Petrographie, Geochemie. Jahrbuch der Geologischen Bundesanstalt 124 (1):1-109

Hoinkes G, Purtscheller F, Schantl J (1972) Zur Petrographie und Genese des Winnebachgranites (Oetztaler Alpen, Tirol). Tschermaks Mineralogische und Petrographische Mitteilungen 18:292-311

Hoinkes G, Thöni M (1993) Evolution of the Ötztal-Stubai, Scarl-Campo and Ulten basement units. In: Von Raumer JF, Neubauer F (eds) Pre-Mesozoic geology in the Alps. Springer, Heidelberg, 485-494

Huber HM (1943) Physiographie und Genesis der Gesteine im südöstlichen Gotthardmassiv. Schweizerische Mineralogische und Petrographische Mitteilungen 23:72-260

Hunziker JC (1974) Rb-Sr and K-Ar age determination and the Alpine tectonic history of the Western Alps. Mem. Ist. Geol. Min. Univ. Padova 31:1-55

Johnson SE, Vernon RH (1995) Stepping stones and pitfall in the determination of an anticlockwise P-T-t deformation path: the low-P, high-T Cooma Complex, Australia. Journal of Metamorphic Geology 13:165-183

Jurdy DM, Stefanick M, Scotese CR (1995) Paleozoic plate dynamics. Journal of Geophysical Research 100 (B9):17965-17975

Le Maitre RW (1976) The chemical variability of some common igneous rocks. Journal of Petrology 17:589-637

Lewis PC, Glen RA, Pratt GW, Clarke I (1994) Explanatory notes of the Bega-Mallacoota 1:250 000 geological sheet. Geological Survey of New South Wales, Sydney.

Liebetrau V (1996) Petrographie, Geochemie und Datierung der "Flüelagranitischen Assoziation" (sog. Jüngere Orthogneise) des Sivrettakristallins, Graubünden - Schweiz. Unpubl. Ph.D. thesis, University of Fribourg, Switzerland

Linnemann U, Gerdes A, Hofmann M., Marko L (2014) Neoproterozoic to Early Cambrian crustal growth and orogenic zoning along the periphery of the West African Craton-Constraints from U-Pb zircon ages and Hf isotopes (Schwarzburg Antiform, Germany). Precambrian Research 244:236-278

Maggetti M, Flisch M (1993) Evolution of the Silvretta nappe. In: von Raumer JF, Neubauer F (eds) Pre-Mesozoic Geology in the Alps. Springer-Verlag, Berlin, Heidelberg, pp 469-484

McDowell FW (1970) Potassium-argon ages from the Ceneri zone, southern Swiss Alps. Contributions to Mineralogy and Petrology 28:165-182

Meert JG, Lieberman BS (2008) The Neoproterozoic assembly of Gondwana and its relationship to the Ediacaran-Cambrian radiation. Gondwana Research 14:5-21

Meinhold G, Morton AC, Avigad D (2013) New insights into peri-Gondwana paleogeography and the Gondwana super-fan system from detrital zircon U–Pb ages. Gondwana Research 23:661–665

Mercolli I, Biino GG, Abrecht J (1994) The lithostratigraphy of the pre-Mesozoic basement of the Gotthard massif: a review. Schweizerische Mineralogische und Petrographische Mitteilungen 74:29-40

Moore JC, Diebold J, Fisher MA, Sample J, Brocher T, Talwani M, Ewing J, von Huene R, Rowe C, Stone D, Stevens C, Sawyer D (1991) EDGE deep seismic reflection transect of the eastern Aleutian arc-trench layered lower crust reveals underplating and continental growth. Geology 19:420-424

Murphy BJ, Nance DR (1989) Model for the evolution of the Avalonian-Cadomian belt. Geology 17:735-738

Oberholzer W (1955) Geologie und Petrographie des westlichen Gotthardmassivs. Schweizerische Mineralogische und Petrographische Mitteilungen 35:320-409

Oberli F, Meier M, Biino GG (1994) Time constraints on the pre-Varsican magmatic/metamorphic evolution of the Gotthard and Tavetsch units derived from single-zircon U-Pb results. Schweiz. Mineral. Petrogr. Mitt. 74:483-488.

Pearce JA, Harris NBW, Tindle AG (1984) Trace element discrimination for the tectonic interpretation of granitic rocks. Journal of Petrology 25 (4):956-983

Peccerillo A, Poli G, Sassi FP, Zirpoli G, Mezzacasa G (1979) New data on the upper Ordovician acid plutonism in the Eastern Alps. Neues Jahrbuch für Mineralogie. Abhandlungen 137 (2):16-183

Pettijohn FJ (1963) Chemical composition of sandstones - excluding carbonate and volcanic sands. U. S. Geological Survey Professional Paper 440-S

Pettke T (1991) Zur Geologie im oberen Val Camadra (südöstliches Gotthardmassiv, Tessin). Unpubl. M.Sc. thesis, University of Bern, Switzerland

Pinarelli L, Boriani A (2007) Tracing metamorphism, magmatism and tectonics in the southern Alps (Italy): constraints from Rb-Sr and Pb-Pb geochronology, and isotope geochemistry. Periodico di Mineralogia 76:5-24

Pinarelli L, Bergomi MA, Boriani A, Giobbi E (2008) Pre-metamorphic melt infiltration in metasediments: geochemical, isotopic (Sr, Nd, and Pb), and field evidence from Serie dei Laghi (Southern Alps, Italy). Mineralogy and Petrology 93:213-242

Poli ME, Zanferrari A (1992) The Agordo basement (NE Italy): A 500 Ma-long geological record in the Southalpine crust. IGCP No. 276, Newsletter 5:283-296

Poller U, Nägler TF, Liebetrau V, Galetti G (1997). The Mönchalpgneiss - geochemical characteristics and Sm–Nd data of a polymetamorphic S-type granitoid (Silvretta nappe/Switzerland). European Journal of Mineralogy 9:411-422

Powell CM, Li ZX, Thrupp GA, Schmidt PW (1990) Australian Palaeozoic palaeomagnetism and tectonics - I. Tectonostratigraphic terrane constraints from the Tasman Fold Belt. Journal of Structural Geology 12 (5/6):553-565

Rino S, Kon Y, Sato W, Maruyama S, Santosh M, Zhao D (2008) The Grenvillian and Pan-African orogens: World's largest orogenies through geologic time, and their implications on the origin of superplume. Gondwana Research 14:51-72

Sample JC, Moore CJ (1987) Structural style and kinematics of an underplated slate belt, Kodiak and adjacent islands, Alaska. Geological Society of America Bulletin 99:7-20

Schaltegger U, Gebauer D (1999) Pre-Alpine geochronology of the Central, Western and Southern Alps. Schweizerische Mineralogische und Petrographische Mitteilungen 79:79-87

Schaltegger U, Abrecht J, Corfu F (2003) The Ordovician orogeny in the Alpine basement: constraints from geochronology and geochemistry in the Aar Massif (Central Alps). Schweizerische Mineralogische und Petrographische Mitteilungen 83:183-195

Schmidegg O (1936) Steilachsige Tektonik und Schlingenbau auf der Südseite der Tiroler Zentralalpen. Jahrbuch der Geologischen Bundesanstalt 86:141-149

Schmidt K (1965) Zum Schlingenbau tiefer Gebirgsetagen. Krystallinikum 3:133-156

Schönlaub HP, Heinisch H (1993) The classic fossiliferous Palaeozoic units of the Eastern and Southern Alps. In: von Raumer JF, Neubauer F (eds) Pre-Mesozoic geology in the Alps, Springer-Verlag, Berlin, Heidelberg, pp 395-422

Schulz B (1988) Deformation und Metamorphose im ostalpinen Altkristallin südlich des Tauernfensters (südliche Deferegger Alpen, Oesterreich). Schweizerische Mineralogische und Petrographische Mitteilungen 68:397-406

Sengör AMC, Okurogullari AH (1991) The role of accretionary wedges in the growth of continents. Asiatic examples from Argand to plate tectonics. Eclogae Geol. Helv. 84:535-597.

Sengör AMC, Natal'in BA., Burtman VS (1993) Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. Nature 364:299-307

Sengör AMC, Natal'in BA (1996) Turkic-type orogeny and its role in the making of the continental crust. Annu. Rev. Earth Planet. Sci. 24:263-337

Seyfert CK, Sirkin LA (1973) Earth history and plate tectonics, an introduction to historical geology. Harper & Row, Publishers, New York.

Siever R (1988) Sand. Scientific American Library.

Söllner F, Schmidt K, Baumann A (1982) Zur Altersstellung des Winnebach-Migmatits im Oetztal (Ostalpen). Verhandlungen der Geologischen Bundesanstalt 1982 (2):95-106

Stampfli G (2000) Tethyan oceans. In: Bozkurt F, Winchester JA, Piper IDA (eds) Tectonics and magmatism in Turkey and the surrounding area. Geological Society, London, Special Publications 173:1-25

Stampfli GM, Hochard C, Vérard C, Wilhem C, von Raumer J (2013) The formation of Pangea. Tectonophysics, 593:1-19

Streckeisen A (1928) Geologie und Petrographie der Flüelagruppe (Graubünden). Schweizerische Mineralogische und Petrographische Mitteilungen 8:87-239

Thöny WF, Tropper P, Schennach F, Krenn E, Finger F, Kaindl R, Bernhard F, Hoinkes G (2008) The metamorphic evolution of migmatites from the Ötztal Complex (Tyrol, Austria) and constraints on the timing of the pre-Variscan high-T event in the Eastern Alps. Swiss Journal of Geosciences 101(1):111-126

Torsvik TH, Cocks RM (2011) The Paleozoic paleogeography of central Gondwana. In: Van Hinsbergen DJJ, Buiter SJH, Torsvik TH, Gaina G, Webb SJ (2011) The formation and evolution of Africa. Geological Society, London, Special Publications 357:137-166

Van Kranendonk MJ, Kirkland CL (2013) Orogenic climax of earth: The 1.2-1.1 Ga Grenvillian superevent. Geology 41:735-738

Van Staal CR, Hatcher RDJr (2010) Global setting of Ordovician orogenies. In: Finney SC, Berry WBN (eds) The Ordovician earth system. Geological Society of America Special Paper 466:1-11

Vielzeuf D, Holloway JR (1988) Experimental determination of the fluid-absent melting relations in the pelitic system. Consequences for crustal differentiation. Contributions to Mineralogy and Petrology 98:257-276

Von Raumer JF (1998) The Paleozoic evolution in the Alps: from Gondwana to Pangea. Geologische Rundschau 87:407-435

Von Raumer JF, Stampfli GM (2008) The birth of the Rheic Ocean – early Paleozoic subsidence patterns and subsequent tectonic plate scenarios. Tectonophysics 461:9-20

Von Raumer JF, Stampfli GM, Bussy F (2003) Gondwana-derived microcontinents – the constituents of the Variscan and Alpine collisional orogens. Tectonophysics 365:7-22

Von Raumer JF, Bussy F (2004) Mont-Blanc and Aiguilles-Rouges: geology of their polymetamorphic basement (External massifs, France-Switzerland): Mémoires de Géologie (Lausanne) 42:1-203

Von Raumer JF, Bussy F, Schaltegger U, Schulz B, Stampfli GM (2013) Pre-Mesozoic Alpine basements - Their place in the European Paleozoic framework. Bulletin of the Geological Society of America 125 (1-2):89-108

Wenk E (1934) Beiträge zur Petrographie und Geologie des Silvrettakristallins. Schweizerische Mineralogische und Petrographische Mitteilungen 14:196-278

White AJR, Chappell BW (1990) Per migma ad magma downunder. Geological Journal 25:221-225

Wyborn D, White AJR, Chappell BW (1991) Enclaves in the S-type Cowra granodiorite. Excursion guide, Second Hutton symposium on granites and related rocks, Canberra, 25 September 1991, Bureau of Mineral Resources, Geology and Geophysics, Record 1991/24

Zurbriggen R (1996) Crustal genesis and uplift history of the Strona-Ceneri zone (Southern Alps). Unpubl. PhD thesis, University of Bern, Switzerland

Zurbriggen R, Franz L, Handy MR (1997) Pre-Variscan deformation, metamorphism and magmatism in the Strona-Ceneri Zone (southern Alps of northern Italy and southern Switzerland). Schweiz. Minerl. Petrogr. Mitt. 77:361-380

Zurbriggen R, Kamber BS, Handy MR, Nägler TF (1998) Dating synmagmatic folds: a case study of Schlingen structures in the Strona-Ceneri Zone (Southern Alps, northern Italy). J. of metamorphic Geol. 16:403-414