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ORIGINAL PAPER

The Cenerian orogeny (early Paleozoic) from the perspective of the Alpine region

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Abstract In the Alps, relicts of pre-Variscan basement are composed of metagreywackes and metapelites (partly migmatic) with intercalated amphibolites and sheets of Cambro–Ordovician peraluminous metagranitoids. Such gneiss terranes are the result of an orogenic type, which was globally widespread in early Paleozoic times. It caused the formation of several 100 km wide cratonized subduction–accretion complexes (SACs) hosting peraluminous arcs at the periphery of Gondwana. "Cenerian orogeny" is a newly suggested term for these early Paleozoic events, which culminate in the Ordovician. The justification for a separate name is given by three characteristics, which are significantly different compared to the Cadomian, Caledonian and Variscan orogenies: the age, the paleogeographic position and the tectonic setting. Other parts of the southern and central European crust might also have been generated by the cratonization of peri-Gondwanan SACs during the Cenerian orogeny.

Keywords Cambro-Ordovician peraluminous magmatism · Cratonization of subduction-accretion complexes · Recycling of crust at periphery of Gondwana · European crust · Strona-Ceneri zone · Lachlan fold belt

Introduction

The early Paleozoic represents a plate tectonically unique era in the Earth's history. This uniqueness is portrayed by the following three aspects:

(a) Laurentia, Baltica, Siberia and Gondwana were separated by oceans (Cocks and Torsvik 2006) and no continent–continent collisions occurred. Instead pericratonic arcs of great strike-length formed along the margins of these continents (Van Staal and Hatcher 2010).
(b) Gondwana was assembled by Pan-African orogenies and was, therefore, full of intercratonic mountain belts, which became eroded and delivered extraordinary amounts of detritus.
(c) The assembly of Gondwana causes the closure of the oceans between its cratons and subductions jumped to the periphery of the supercontinent as described for East-Gondwana by Foden et al. (2006). Therefore, Gondwana was framed at the beginning of the Paleozoic by two major subduction systems (Rino et al. 2008), the Avalonian-Cadomian one facing the Celtic Ocean, and the Ross-Delamerian one facing the Paleo-Pacific Ocean (Fig. 1a).

These three aspects caused a concentric structure of Gondwana with a center characterized by a network of intercratonic Pan-African belts and a periphery composed of (1) continental arcs, (2) large accretionary complexes, which became fed by detritus from the arcs and the far hinterland (where the intercratonic belts got eroded), and (3) subduction zones of great strike-length (Fig. 1a).

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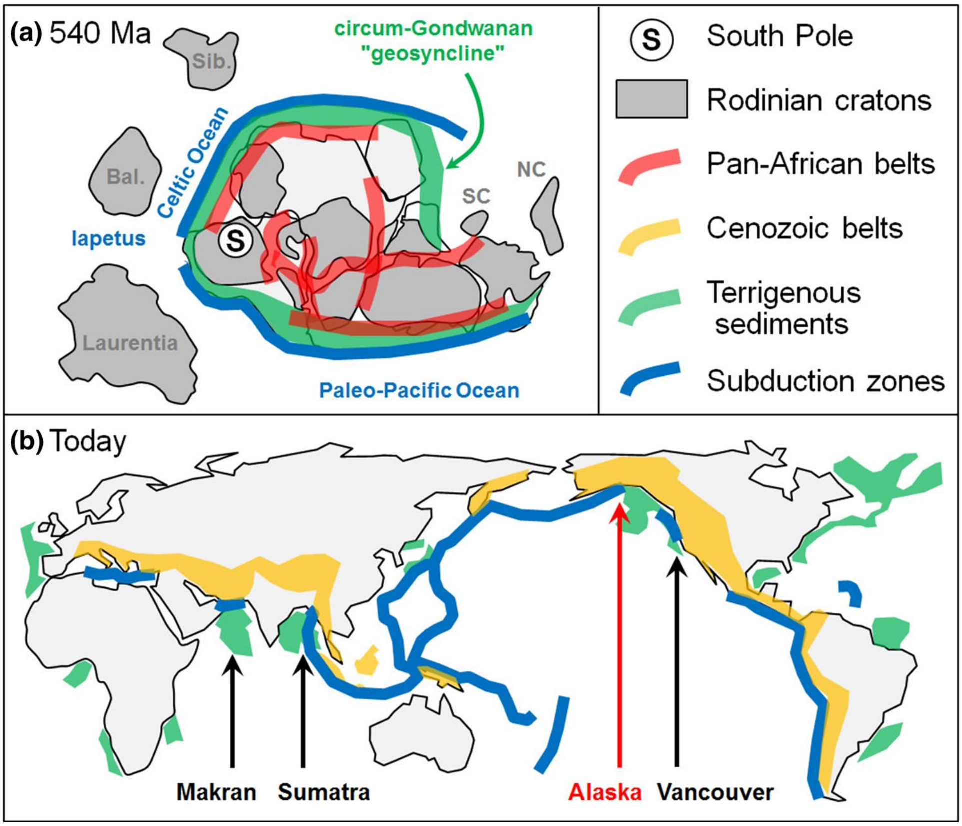

Fig. 1 Plate tectonic configurations at the beginning of the Paleozoic 540 Ma ago (**a**) and today (**b**). The reconstruction for 540 Ma refers to Cocks and Torsvik (2006), Rino et al. (2008), Linnemann et al. (2014), and Meert and Lieberman (2008). The circum-Gondwanan "geosyncline" refers to Fig. 10.28 from Seyfert and Sirkin (1973). Recent terrigenous sequences and Cenozoic belts are taken from Frisch and Meschede (2011). *SC* South China, *NC* North China

This concentric structure generated an early Paleozoic circum-Gondwanan system of subduction–accretion complexes (SACs), which recycled continental crust in dimensions never reached before or after. This global phase of crustal recycling subsequently followed a Pan-African era from 0.8 to 0.5 Ga for which Rino et al. (2008) identified the ever highest rate of crust formation.

SACs are poorly recognized orogenic systems since they are rare at present active margins. The reason for this rareness is the low overlap of subduction zones with regions of high terrigenous sediment input (Fig. 1b). Today, the subduction zones of Alaska, Makran, Sumatra, and Vancouver are potential candidates, but the sediment input into these zones is too limited to form SACs comparable to those in early Paleozoic time (Zurbriggen 2015). This could be related to the relatively short distances from the accretionary prism to the water divide of the associated mountain range, providing limited sediment supply. In contrast, during the early Paleozoic, huge hinterland areas with high sediment transport capacities (related to large river systems and/or ice shields) dominated the systems.

The subduction–accretion complex (SAC) of the Gulf of Alaska is the only recent example, where magmatic rocks (Moore et al. 1991) indicate that the arc started to intrude the own sediments accreted shortly before the intrusions. Therefore, the recycling of eroding mountain belts by the formation of SACs is also referred as Alaskan-type orogeny (Zurbriggen 2015). However, the SAC of the Gulf of Alaska represents an embryonic stage compared to the mature stage of SACs of early Paleozoic times.

This paper will discuss two major aspects, the dynamics of growth of SACs (Chap. 2), and the justification to define a new orogeny, namely the "Cenerian" orogeny, responsible for the generation of relevant portions of the southern and central European crust (Chap. 3).

The main goal of this paper is to inspire geoscientists working in similar pre-Variscan gneiss terranes by the concept of cratonizing SACs hosting a peraluminous arc. The term "cratonizing" is used according to Crook (1980), for processes of subduction and accretion, which generate a 25–30 km thick SAC.

Dynamics of early Paleozoic cratonizing subduction-accretion complexes

The dynamics of cratonizing SACs will be discussed along seven aspects: (1) stages of growth, (2) age of formation, (3) sedimentation and the role of ice shields, (4) orientation of main structures, (5), subduction and mantle dynamics, (6) plate tectonic setting, and (7) influencing parameters of cratonizing SACs.

Stages of growth

Figure 2 illustrates the dynamics of a growing subduction–accretion complex (SAC). In analogy to existing arcs at the periphery of Gondwana, such as the Cadomian arc (Linnemann et al. 2014) and the Ross-Delamerian arc (Rino et al. 2008), the model starts with the standard setting of a continental arc (Fig. 2a). An increase in the sediment input causes the formation of an accretionary prism, which grows oceanwards. As a result, the arc starts entering the landward edge of the accretionary prism and imports additional heat into the subducted and accreted fertile flyschoid sediments. As described by Barker et al. (1992) for the Gulf of Alaska, "forearc" granitoids are generated by the melting of flyschoid sediments in the accretionary prism (Fig. 2b).

Due to the large sediment input and the resulting vertical load, the oceanic crust reacts elastically inducing the trench to retreat further oceanwards and the mantle-derived magmas fully intrude the accreted greywackes and pelites. This initiates large-scale anatexis. The basaltic magmas solidify at these temperatures and mixing with the anatectically derived magmas occurs to a limited degree, only (Zurbriggen 2015). Thus, the magmatism changes from metaluminous, typical for a continental arc (Fig. 2a) to peraluminous, typical for early Paleozoic SACs (Fig. 2c).

In the region of the peraluminous arc a SAC undergoes processes of cratonization, which generate a crustal thickness of approximately 30 km. Therefore, the back-arc part of a SAC behaves like an isostatically stable cratonic crust (Figs. 2d, 3), while the front-arc part becomes tectonically structured by processes of subduction and accretion. According to D'Lemos et al. (1992) strike-slip faults (as indicated in Fig. 3) provide an important mechanism for the syn-kinematic emplacement of S-type granites. In the ductile lower crust strongly sheared sheets of orthogneisses are generated, while in the brittle upper crust the granites still follow the fault system, but develop increasingly discordant contacts.

SACs can grow hundreds of kilometers oceanwards, and with that, the locations of near-trench subduction and arc magmatism migrate oceanwards, too. Synmagmatic

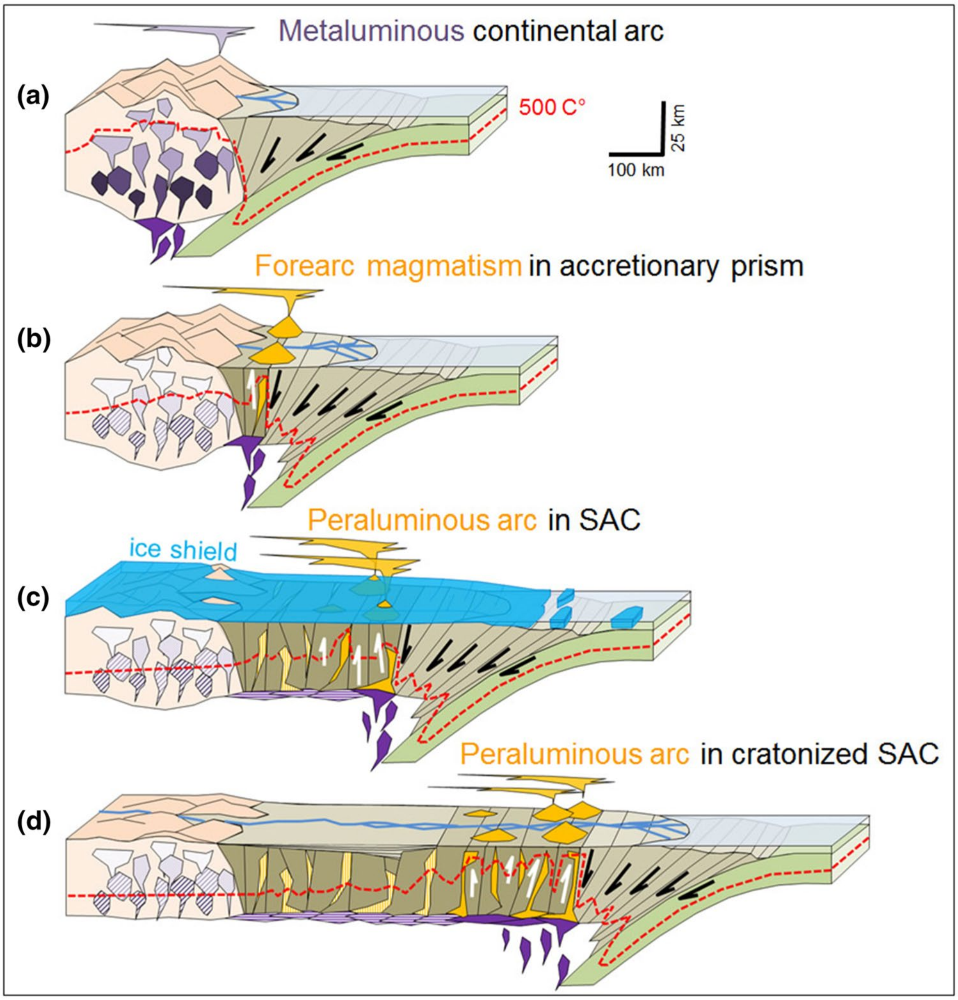

Fig. 2 Evolution of a subduction-accretion complex (SAC) from stages a-d: **a** Metaluminous continental arc with small and cold accretionary prism, e.g., Andean arc. **b** S-type forearc granitoids intruding the accretionary prism, e.g., Gulf of Alaska. **c** Peraluminous arc in a SAC during Ordovician glaciation. An ice shield can overflow passes of a coastal range and deliver large quantities of detritus from the continent behind the water divide. **d** Cratonized SAC partly covered by syn- to post-orogenic sediments. (Note the 500 °C isotherm in all block diagrams)

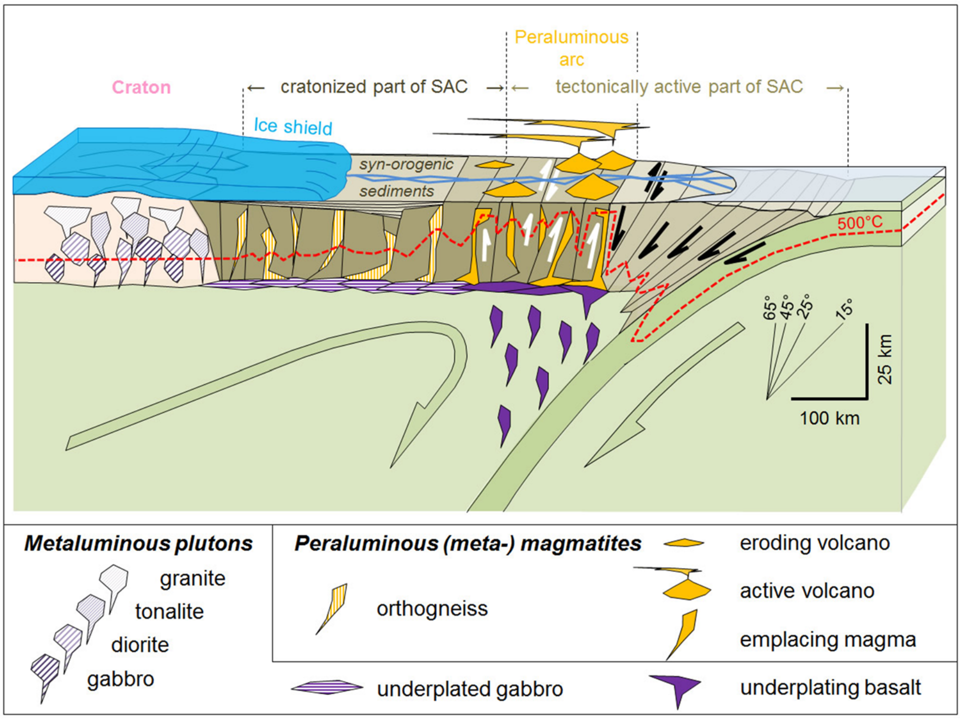

Fig. 3 Dynamics of cratonization of a subduction-accretion complex (SAC). The growth of an entire SAC can extend over more than 100 Ma, but the cratonization of a specific part can occur within a short period of c. 10 Ma. (Note that *horizontal* scale is four times shorter than *vertical* scale, and structures are virtually steepened in the scheme. The indicated angles are calculated for the shortened scheme)

cratonization will occur with a delay of 10–15 Ma (age constraints for this delay come from the Strona-Ceneri zone, where accretion, eclogitization, anatexis and pre- to syn-magmatic deformation occurred in a time interval of 12 Ma; Franz and Romer 2007) after subduction and accretion, but all three processes migrate with a similar velocity away from the cratonic hinterland. This increases first, the distance of transport for the craton-deriving sediments, and second, the type of sediments will change also, because volcanic rocks and low-grade metamorphic sediments from exposed parts of the SAC become eroded and recycled again as they are deposited in the trench. However, the key mechanism of a mature SAC is its cratonization. Figure 3 illustrates the aspects of cratonization based on studies of the Strona-Ceneri zone in the Southern Alps and comparative studies of other pre-Mesozoic basement units of the Alps and the Australian Lachlan fold belt (Zurbriggen 2015).

With respect to the latter, processes of cratonization are constantly discussed since Crook (1980) by many studies. However, Cawood et al. (2009) state that processes of cratonization and the formation of most pre-Mesozoic accretionary orogens still are not fully understood. Foster and Goscombe (2013), a recent review on the Lachlan fold belt, interpret its cratonization by the closure of a back-arc basin in which a large turbidite fan was deposited previously. The lower crust is formed by imbrication of the basaltic substrate, while the turbidite sequences are folded, thrusted and intruded by plutons, composing together the upper crust. The author criticizes this model of a closing back-arc basin, where the basaltic crust is not subducted (to initiate arc magmatism), but should be imbricated to build-up the lower crust, because it cannot explain the large volume of granitoids. More than 20% of the outcrop area are composed of granitoids (Foster and Goscombe 2013 and references therein), and 90% of which represent S-types (Chappell and White 2001). The peraluminous S-type magmatism in cratonizing SACs, such as the Strona-Ceneri zone or the Lachlan fold belt, is so dominant, that any tectonic model must first account for the heat source necessary to generate the corresponding volumes of anatectical melts.

Volume estimations indicate (1) that 97% of the outcrop area of the Strona-Ceneri zone (sum of metapelites, metagreywackes, migmatites and the majority of metagranitoids as described by Boriani et al. 1983, 1990, 1995; Zurbriggen et al. 1997; Pinarelli and Boriani 2007; Franz and Romer 2007) consist of recycled crustal material, and (2) that about the lower fifth of that SAC melted away and either intruded into higher crustal levels or even partly extruded as volcanics (Zurbriggen 2015). These sheet-like syntectonic intrusions along the moderately to steeply plunging main structures provide the main mechanism for cratonization. Where a magmatic body intrudes, frictional forces are reduced owing to the lubrication effect of the melts, and rock packages (host rocks and magmas) can relocate in the SAC. The tectonics will focus to such sheet-like magma intrusions and cause a strain partitioning on a crustal scale. The products are highly strained orthogneiss bodies with aspect ratios till 1:45 (Zurbriggen 2015). The syn-magmatic tectonics along moderately to steeply inclined structures allow for a re-organization of the entire SAC (from surface to its base at the Moho) within relatively short periods. Unlike collisional orogens, which are subhorizontally structured by nappes, moderately to steeply structured SACs need short slip distances to redistribute rock packages in the vertical direction, to achieve an isostatically stable crust of about 30 km thickness. Therefore, SACs do not develop an over-thickened crust with a topographically high mountain range. Zurbriggen (2015) sees the evidence in the lack of a late- to post-orogenic exhumation of the Ordovician amphibolite facies gneisses of the Strona-Ceneri zone. In fact, their exhumation occurs c. 150 Ma later at the end of the Variscan orogeny, which created an over-thickened crust. Further evidence derives from the Australian Lachlan fold belt, which he interprets as an upper crustal analogue of the Strona-Ceneri zone. If so, the Lachlan fold belt represents a preserved SAC at the other side of Gondwana, which did not suffer any younger orogenic overprint. There the sub-volcanic character of many granitoids and the lower greenschist facies metamorphism in the cleaved turbiditic sequences indicate a shallow crustal level. Even in the Wagga–Omeo and the Cooma–Cambalong metamorphic belts which contain the highest metamorphic rocks of the Lachlan fold belt, 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.

Conclusively, SACs are directly cratonized during the main tectono-magmatic events and form a peraluminous arc consisting of single volcanoes, which are footed on sea level and become relatively rapidly eroded (Fig. 3).

The model of cratonizing SACs delivers a concept for a continental crust entirely composed of subducted and accreted rocks. Thus, no assumption for a putative Proterozoic lower crust is needed, which would serve as a hypothetical substrate for metasediments. Consequently, the model interprets crustal signatures of the metagranitoids not by a hypothetical Proterozoic lower crust. Instead, chemical and isotopic signatures in the metasediments are interpreted to be inherited from the eroded hinterland, and by the melting of these metasediments their signatures are inherited further to the peraluminous metagranitoids. Even I-type signatures can be inherited from metasediments, which derived from an eroded arc in the hinterland, as described by Barker et al. (1992) for the Gulf of Alaska.

As a consequence the model suggests that the primary subduction-related mafic magmas largely underplate the base of the SAC, because (1) of higher densities compared to the metasediments, and (2) viscosity contrasts between them and the anatectic melts avoiding magma mixing on a larger scale. Thus, the metasediments of a SAC suffer gradually higher metamorphic conditions with increasing depth. Figure 2 of Zurbriggen (2015) provides a hypothetical cross-section through a SAC with andalusite bearing schists in the uppermost part, garnet-sillimanite gneisses in the middle, and garnet-kyanite gneisses, metatexites and diatexites in successively deeper parts. The latter are generated by advanced partial melting of greywacke-pelitic metasediments in the temperature range between 850 and 875 °C. Such conditions are supposed to be given in the contact to crystallizing basaltic melts, related to the subduction of oceanic crust underneath the SAC.

Age of formation

According to Schaltegger and Gebauer (1999) the youngest detrital zircons in the pre-Variscan metasediments of the Alps are 570 Ma old. Scheiber et al. (2014) indicate a maximum age of 490 Ma for the sedimentation in Penninic units. Manzotti et al. (2015, 2016) made several statistical detrital zircon studies in the Western Alps. Apart from dominant Carboniferous ages (Dora-Maira, Zone Houillère) relating to the Variscan magmatism, they report a main population of Ordovician and Cambrian ages (Money Complex) relating to an early Paleozoic orogeny. For the Strona-Ceneri zone (Southern Alps) Pinarelli et al. (2008) show a distribution of zircon ages with different peaks. The highest at c. 480 Ma refers to the Ordovician magmatism. The next elderly peaks indicate Cadomian ages ranging from 550 to 700 Ma. Thus, sedimentation in the Strona-Ceneri zone must have occurred between 550 and 480 Ma. Taking the youngest Cadomian ages as maximum detritic ages and assuming 10 Ma for their exhumation, sedimentation must have started earliest at 540 Ma. However, the earliest magmatic zircons (long prismatic zircons of "type 2" in Table 2 of Pinarelli et al. 2008) have ages of 547 ± 22 Ma, and the latest have ages of 410 ± 18 Ma.

Important to note is that the majority of these magmatites is peraluminous with a dominant crustal signature. For example, in the Strona-Ceneri zone 90% are peraluminous to strongly peraluminous and only 10% are metaluminous including some rare (c. 1%) mafic end-members.

To summarize, the age of the early Paleozoic SACs in the Alps can be restricted to a time span from 540 to 410 Ma, from sedimentation of the greywackes and pelites until the peraluminous magmatism, respectively, and even more closely from 490 to 440 Ma, mainly during the Ordovician.

The time period during which a SAC is generated can extend over tens of Ma to even more than 100 Ma, depending on how long the two external parameters are lasting, (1) the delivery of large amounts of sediments into (2) an operating subduction zone. The cratonization of a SAC occurs from the craton towards the ocean. At a given location the cratonization (including accretion, eclogitization, anatexis and pre- to syn-magmatic deformation) can occur relatively fast within 12 Ma as shown by Franz and Romer (2007) for the Strona-Ceneri zone. In fact, this is fast if one considers that the cratonization represents petrogenetic cycles including (1) the subduction of oceanic crust to the eclogite facies and their integration into the SAC, where they are overprinted in amphibolite facies, (2) the burial of sediments to the lower crust, where under granulite facies conditions peraluminous magmas are generated, which intrude at higher levels and extrude, and (3) the tectonic re-equilibration of the entire SAC resulting in an isostatically stable crust, which behaves like a craton.

Sedimentation and the role of ice shields

The super-large early Paleozoic peri-Gondwanan greywacke-pelite series (Fig. 1a) must be caused by the uplift and erosion of large areas related to different scenarios or combinations of them: (1) The erosion of Pan-African and Cadomian belts by rivers and/or glaciers, (2) the ongoing erosion of cratonizing SACs by rivers and/or glaciers, and (3) the fast uplift of intra-continental basins and/or orogens by the break-off of oceanic slabs as remnants of intercratonic oceans closed by Pan-African collisions. The latter might have caused mega-earthquakes giving rise to global mass wasting, another unique feature of the Ordovician (Meinhold et al. 2011).

The abundance of early Paleozoic potassium-rich sediments indicates a predominance of active margins and is related to the absence of vascular plants (Zurbriggen 2015). The global high flux of immature clastics into the oceans triggered the formation of extended shelf regions and modified sea water compositions in favor of GOBE, the Great Ordovician Biodiversification Event (Servais et al. 2009), yet another feature of the Ordovician era.

Furthermore, the abundance of potassium-rich clastics can be related to glaciations. Glaciers cause mechanical erosion in the source region, but during transportation the debris is preserved from further physical and chemical weathering. Thus, unlike river sediments, ice debris does not undergo a maturization during transportation on account of an immature greywacke composition. An ice shield erodes a continent more homogeneously, can carry more sediments and deposits them well distributed along the shoreline, where it calves and melts in the trench region (Fig. 2c). A key aspect of an ice shield is that it can overflow topographic heights, such as mountain passes of a coastal range (Figs. 2c, 3), and transport detritus from the entire continental hinterland.

If an ice shield covers the peraluminous arc of a SAC, then subglacial eruptions can lead to the formation of sandurs (Magilligan et al. 2002), which transport the eruptive materials right into the trench without creating any topography, accelerating the recycling of continental crust once more.

The role of ice shields in the formation of rapidly growing SACs remains speculative. However, ice shields can accelerate the growth of SACs as discussed above, but they do not represent a precondition because the Lachlan fold belt, which shows a similar geology, formed in equatorial latitudes free of glaciers.

Another aspect is that earlier ice shields (including the "Snowball Events", Hoffman et al. 1998, Stern et al. 2006) might have eroded Gondwana and deposited sediments well before subduction entered these shelf regions. This addresses a general aspect of SACs, that sedimentation can have occurred long before subduction started or entered the region to start accretion.

Orientation of main structures

Seismic investigations of the Gulf of Alaska (Moore et al. 1991) indicate that the accretionary prism is structured by flat-lying and moderately to steeply inclined structures. This must also have been the case in the SACs of the early Paleozoic, for example, the Strona-Ceneri zone (Handy et al. 1999) and other pre-Mesozoic basement units in the Alps (Zurbriggen 2015).

Moderate to steep structures are the result of accretionary tectonics in a convergent regime. Anatectical magmas use such tectonic structures, especially in transpressional orogens (Fig. 3) and syn-kinematically intrude higher crustal levels (D'Lemos et al. 1992). Simultaneously, the uprising plutons create themselves emplacement-controlled steep structures along the conduits. Conclusively, both mechanisms mutually enhance each other and create steeply structured parts in a progressively cratonizing SAC.

Sub-horizontal structures can be the result of syn- to post-orogenic sedimentation (Figs. 2d, 3), or being caused by a later tectonic overprint, in the case of pre-Mesozoic basements of the Alps by the Variscan event. If Variscan compressions (or compressional components) are subparallel to the strike of pre-existing steeply to moderately inclined structures, then folds with steeply to moderately inclined axes, the so-called "Schlingen" will form (Zurbriggen 2015). But, if Variscan compressions (or compressional components) are roughly perpendicular to the strike of pre-existing steeply to moderately inclined structures, then reverse faulting and nappe tectonics can produce subhorizontal structures.

The pre-Mesozoic basements of the Strona-Ceneri zone (Southern Alps), the Eastern Alps and External Massifs are mainly steeply structured and show Variscan Schlingen folds with steep axes. Also the Australian Lachlan fold belt, which did not suffer any younger orogenic overprint is mainly steeply structured (Zurbriggen 2015).

The Orobic Alps (Southern Alps; Feijth 2002) and other pre-Mesozoic basements outside the Alps show mixed orientations without a predominance of steep structures such as lithological contacts, main schistosity and fold axes.

Subduction and mantle dynamics

The duration of subduction must have been in the time span between the oldest and youngest magmatic activities. For the Alpine region the early Paleozoic magmatism lasted over a period of c. 140 Ma, from 550 to 410 Ma, with the most intense phase during the Ordovician. The rate of subduction was probably similar to today's rates of several cm/year.

A key question is: Which kind of mechanism allowed increasing the space between the former craton and the trench without drastically changing the overall tectonic setting and stopping the growth of the SAC? This problem addresses the mantle dynamics below the SAC (Fig. 4).

In the scope of the new model, the initial entering of the arc into the prism (Fig. 4a) is interpreted to be related to a delamination of the subducting slab from the base of the prism. This brings mantle material or mantle-derived melts in contact to the base of the prism and initiates anatexis ("A" in Fig. 4) and forearc magmatism ("F" in Fig. 4a). The Gulf of Alaska might represent such an initial stage of an evolving SAC. Barker et al. (1992) estimate the volume ratio of crystallizing basalt to melting flysch in the order of 1:1, depending on different factors such as pre-existing partial crystallization or heat dissipation into the prism. However, the tectonic setting providing the necessary volumes of basalts to generate the Alaskan forearc granitoids is of debate (see Barker et al. 1992 and references therein).

A delamination of the dense subducting slab would let the specifically lighter accretionary prism to buoy up. Simultaneous with the production of anatectical melts such vertical tectonics provide another mechanism to produce steep synmagmatic structures within the SAC.

Subduction zones with high sediment input form accretionary complexes with a seaward retreating trench (Clift and Vannucchi 2004). In the early Paleozoic the continued accretion of sediments caused a growth of the SAC, which was pushing the trench ("T" in Fig. 4) oceanwards. As delamination of the subducting slab from the growing SAC proceeded, the delamination point ("D" in Fig. 4) migrated oceanwards too, and inflowing mantle could access more distal parts of the SAC. Decompression melting in the inflowing mantle and/or subduction related water induced melting in the mantle wedge supplied large amounts of basaltic melts ponding and crystallizing at the base of the SAC, which in turn furnished heat to sustain melting the metagreywackes and metapelites. As a result the magmatism changed from metaluminous ("M" in Fig. 4a) to peraluminous ("P" in Fig. 4b).

So far, we can only speculate on the mantle dynamics, because modern accretionary wedges are much smaller and numeric modelling on SACs of early Paleozoic dimensions must be done yet to verify such scenarios.

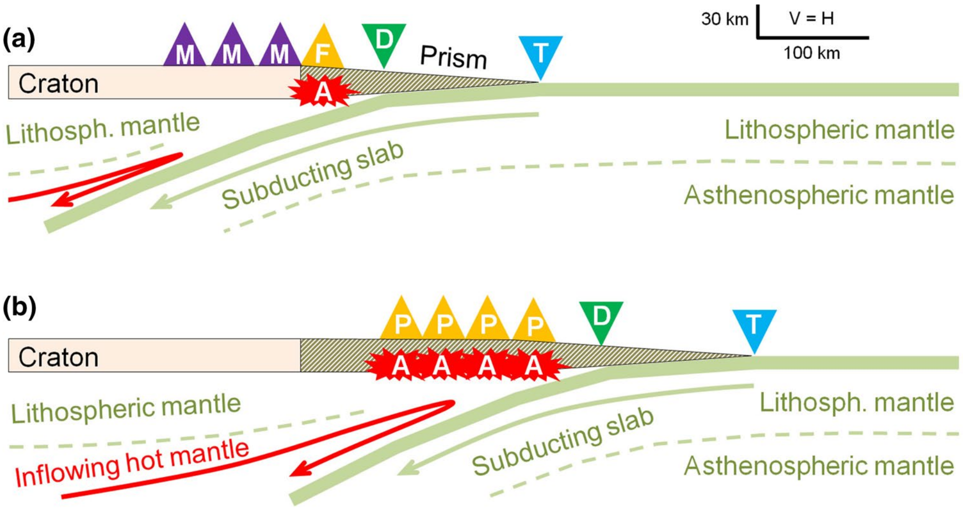

Fig. 4 Subducting oceanic slab with growing accretionary prism on top. **a** Delamination of the slab from the prism let the arc entering the accretionary prism where forearc magmatism develops (e.g., Gulf of Alaska). The geometric dimensions of the prism are taken from Moore et al. (1991). **b** In the early Paleozoic, delamination proceeded and hot mantle could access more distal parts of the rapidly growing SACs, where large-scale anatexis and related peraluminous magmatism developed. (*M* metaluminous magmatism, *A* anatexis, *F* forearc magmatism, *P* peraluminous magmatism, *D* tip of delamination, *T* trench.)

Plate tectonic setting

The key features of SACs are metagreywacke-pelite sequences (paragneisses) with intercalated amphibolites, all together intruded by syn-tectonic peraluminous granitoids (orthogneisses). The origin of the amphibolites can principally be related to MORB (wedged into the SAC from the subducted oceanic slab), arc or back-arc related mafic intrusiva (meta-gabbros) or extrusiva (meta-andesites). The banded amphibolites of the Strona-Ceneri zone were interpreted by Giobbi Mancini et al. (2003) as a bimodal back-arc volcanic sequence. However, it is important to put their volume (<1 area% of the map) versus the large volume (21 area% of the map) of metagranitoids, 90% of which are peraluminous or even strongly peraluminous in chemistry. Thus, the main tectonic scenario, which will be discussed in the following must account first for the dominant peraluminous magmatism.

The deposition of super-large sequences of greywackes and pelites and the tectonic setting of peraluminous S-type suites are often interpreted in the context of extensional tectonics in relation to the break-up of Gondwana and the opening of the Rheic Ocean (e.g., Von Raumer et al. 2013). This widespread interpretation is questionable at least in the context of actual rifts and ocean formations. In fact, there are no greywacke-pelite sequences hosting S-type granitoids generated at today's passive margins and former rifts, like the Atlantic coastlines. The reason is that greywackes primarily indicate an active margin scenario as stated by Sengör and Okurogullari (1991) who remind, that earlier classified "eugeosynclines" (rich in greywackes) relate to accretionary processes in the context of modern plate tectonics.

With respect to the peraluminous granitoid suites, large-scale anatexis and S-type magmatism are often interpreted to be collisional or rifting related. The latter seems to confirm the interpretation that their greywacke-pelitic host rocks were deposited during the break-up of Gondwana. But the reason for such interpretations is that peraluminous (meta-) granitoids are widely classified by standard discrimination diagrams in their tectonic setting, which can be problematic. In this regard, Barker et al. (1992) made an important statement: "Furthermore, many prisms, especially those bearing high proportions of quartzofeldspathic graywacke, are fertile in granitic melts. These Alaskan granodiorites do not fit into the alphabetical classification of Australian workers. Being melts of sedimentary rocks, they should have S-type character. Because, the source flysch is quartzofeldspathic and of arc origin, however, the granodiorite shows I-type character. Our results also highlight a problem with Pearce et al.'s (1984) and Harris et al.'s (1986) purportedly tectonic-discriminant plots for granitic rocks. These diagrams classify our granodiorites as "volcanic arc granite" and reflect their source rocks rather than their tectonic environment of origin."

Conclusively, peraluminous granitoids should not be classified by standard tectonic discrimination diagrams, because those diagrams do not account for the complexity of multiple inherited signatures from the greywacke-pelitic source rocks, which themselves have inherited signatures from the hinterland they derived from.

In the light of this study, large greywacke-pelite series hosting a peraluminous arc with great strike-length imply the tectonic setting of a SAC at an active margin. However, extensional tectonics can always be a regional option, for example in the back-arc of a peraluminous arc, but the emplacement structures of the early Paleozoic metagranitoids in the Alpine region clearly indicate a synmagmatic convergent tectonic scenario. Thus, the model of cratonizing SACs describes the basic mechanism, which in reality can be further complicated by (1) the accretion of terranes, (2) changes in velocity and angle of subduction, and (3) changes in amount and types of terrigenous sediments. Therefore, beside the majority of peraluminous granitoids, metaluminous magmatites can be present in SACs and indicate that not all mantle-derived melts underplate the anatectical horizon, especially in periods when the sedimentary flux decreases and/or the subduction accelerates. But all these complications are options and not principal characteristics of SACs.

Influencing parameters of cratonizing subduction-accretion complexes

Cratonizing SACs are hitherto poorly recognized orogenic systems and their local descriptions and understanding in a regional and global context of early Paleozoic plate tectonics stands yet at the beginning. An identification of the influencing parameters and an estimation of their significance (Table 1) might be helpful for future studies including numeric modeling approaches.

Conclusions for the Cenerian orogeny

The tectonic model of an early Paleozoic SAC hosting a peraluminous arc was first applied to the Strona-Ceneri zone and related pre-Mesozoic basement units of the Alps by Zurbriggen (2015). That study put a strong focus on the widespread peraluminous arc magmatism and its structural relationships, which were regarded as key for the understanding of the early Paleozoic orogenic evolution.

The same type of magmatism with respect to (1) the timing (496–457 Ma), (2) the predominance of (strongly) peraluminous S-type plutons and volcanics, (3) the large volumes of plutons and volcanics (namely the Ollo de

Table 1 Description of parameters influencing the formation of cratonizing SACs in the early Paleozoic

Erosion of Pan-African and Cadomian orogens	Gondwana was crisscrossed by Pan-African and framed by Cadomian orogens, which eroded and provided large quantities of sediments
Ice shields	Acquisition of sediments from large parts of Gondwana behind a water divide
Sedimentary flux	Assumed to have been a magnitude higher than in modern accretionary prisms
Subduction rate	Assumed to have been similar than today (<10 cm /year)
Subduction period	In the order of 140 Ma, from 550 to 410 Ma in the region of the Alps
Dimensions of SAC	Low topography, 25–30 km thick, several 100 km wide (from craton to trench), >1000 km along coastline of Gondwana
Accretionary thrusting	Steepened sedimentary structures and thrusts
Large scale anatexis to initiate peraluminous arc	S-type plutons and volcanics forming a peraluminous arc required the melting of equivalent volumes of sediments corresponding to the lowermost 5–6 km of the SAC (Zurbriggen 2015)
Heat transfer at Moho	Capacity to heat the lowermost 5–6 km of the SAC by 250 °C, from c. 600 to at least 850 °C (Zurbriggen 2015)
Heat transfer within SAC, from lower to upper crust	Uprising magmas initiated high T/low P metamorphism in upper parts of SAC (e.g., Australian Lachlan fold belt)
Magma emplacement	Magmas emplaced preferentially along moderately to steeply inclined active fault zones
Synmagmatic tectonics	Magma emplacements caused strain localization in SAC and concordant sheets of mylonitic orthogneisses have been formed

Sapo volcanics with a total thickness of at least 2000 m), (4) the richness in metasedimentary inclusions (which reflect the lithological spectra from pelites to greywackes of the host rocks) and restites such as quartz lumps, calc-silicate nodules, and biotite-rich enclaves, (5) the rareness of gabbroic end-members and enclaves, and (6) the inherited chemical and isotopic signatures and zircon ages, which overlay with those of the metasedimentary host rocks are also reported for the Variscan terranes of France and Spain (Díez Montes et al. 2010; Ballèvre et al. 2012; Rubio-Ordóñez et al. 2012; Lopez-Sanchez et al. 2015; Díaz-Alvarado et al. 2016; Pouclet et al. 2017; Villaseca et al. 2016).

There is consensus that this magmatism was widespread over large parts of southern and central Europe as illustrated by Ballèvre et al. (2012), Von Raumer et al. (2013), and Villaseca et al. (2016). But regarding the tectonic setting, there is a large controversy as portrayed by Villaseca et al. (2016). The different models envisage either (1) subduction and back-arc rifting, (2) continental rifting and break-up, (3) crustal thickening, or (4) the formation of forearc accretionary complexes.

Ballèvre et al. (2012) and Von Raumer et al. (2013) represent the widely accepted interpretation that the Cambro–Ordovician peraluminous magmatism of Europe is related to extensional tectonics, more specifically to the opening of the Rheic Ocean. The author opposes the geodynamic setting of an extensional regime, whether back-arc or the opening of an oceanic basin. The main arguments are given in the rock assemblage indicating an accretionary environment of an active margin setting (as previously discussed) and the synmagmatic shearing of the Cambro–Ordovician orthogneisses in the lower crust indicating convergent tectonics (Zurbriggen 2015).

Crustal thickening (collisional) settings are not compatible with plate tectonic reconstructions of Van Staal and Hatcher (2010), who conclude in their abstract: “The global distribution, setting, and dynamic implications of Ordovician orogenesis are reviewed. Evidence for true Ordovician continent–continent collision is absent.”

In accordance with this statement and in the light of the model of a cratonizing SAC, Fig. 5 visualizes that the Cambrian and Ordovician were free of collisional orogens (Alpine type).

SACs do not form mountain belts of high altitude. Therefore, the term “orogen” is not appropriate with respect to the topographic profile. However, SACs can be regarded as orogenic systems, because they recycle continental crust by tectono-metamorphic and magmatic processes, which in principle are the same as for magmatic arcs or collisional orogens producing high altitude topographies.

Despite the fact, that large parts of the Central European Variscan basement (as defined in Fig. 1 of Von Raumer et al. 2013) were generated during the early Paleozoic, so far no specific term was dedicated to this orogenic phase. Instead existing terms like “Pan-African”, “Cadomian”, “Caledonian”, “Sardic”, “Eo-Variscan” or “Variscan” were applied. This praxis did not favor the development of a clear view of the early Paleozoic orogeny, because neither the timing, nor the paleogeographic position and tectonic setting of all these events apply to the early Paleozoic orogeny (Fig. 5).

Zurbriggen (2015) suggested a new term for this orogenic system, namely the Cenerian belt. The term

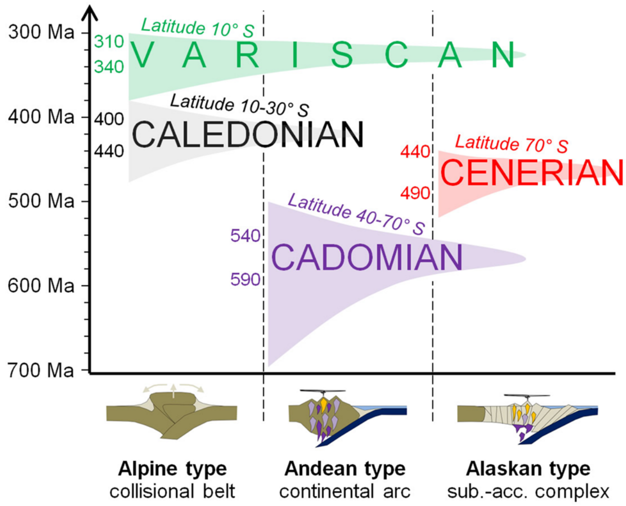

Fig. 5 Timing versus tectonic setting of the Cenerian in contrast to the Cadomian, Caledonian and Variscan events. The indicated ages in Ma, e.g., 490 and 440 for the Cenerian, mark begin and end of the most intense stage during the corresponding orogeny. According to Cocks and Torsvik (2006, 2011) and Torsvik and Cocks (2011) the four orogenies were located at different paleo-latitudes as indicated. See Zurbriggen (2015) for a detailed comparison of the Alpine, the Andean and the Alaskan type orogenies

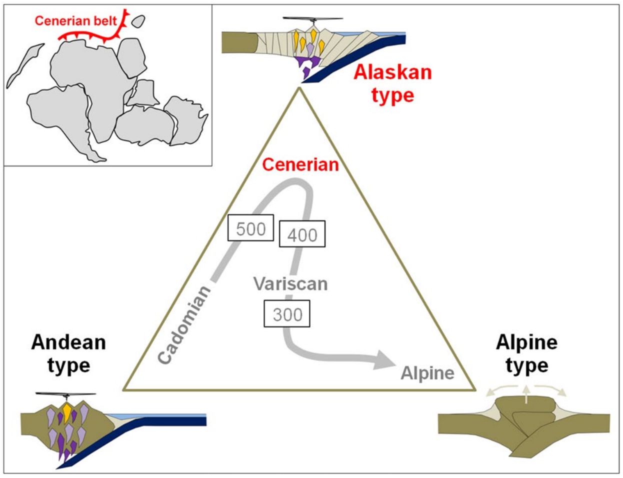

Fig. 6 Growth of central and southern European crust during different orogenies. For explanations see text. *Numbers* indicate ages in Ma

“Cenerian” originates from the “Ceneri gneiss” - a key lithology in the Southern Alps. It is an anatectically derived peraluminous metagranitoid rich in (1) metasedimentary inclusions such as calc-silicate nodules, gneisses and schists of greywacke-pelitic compositions, and (2) restites such as biotite-rich selvedges and quartz lumps. Ceneri gneiss-like lithologies are typical for early Paleozoic gneiss terranes in the Alps and they are characteristic for the Cenerian orogeny. In general, Ceneri gneiss-like lithologies, i.e., inclusion-rich peraluminous S-type granitoids intruding metagreywackes and metapelites, are elsewhere characteristic for the recycling of continental crust by the formation of cratonizing SACs. For example, the nodular granites, nebulites and orthogneisses of the Spanish Central System (as illustrated in Fig. 2 of Díaz-Alvarado et al. 2016 and Fig. 2 of Villaseca et al. 2016) represent such Ceneri gneiss-like lithologies, and indicate, according to this study, the tectonic setting of a cratonizing SAC. In fact, Villaseca et al. (2016) correlate the Cambro-Ordovician S-type orthogneisses of Spain, France and the Alps to one magmatic belt. The orthogneisses from central Spain to Galicia mark a total length of 650 km (Villaseca et al. 2016). Together with equivalent rocks in France Pouclet et al. (2017) estimate an approximate length of the so-called “Tremadocian Volcanic Chain” in the order of 1300 km. About the same length was reconstructed by Von Raumer (1998; see his Fig. 5) for a complex Cambro–Ordovician suture zone hidden in the Alpine basement areas, comprising a Gondwana-directed subduction zone with stages of accretion. Zurbriggen (2015) concluded that this suture zone and possibly further parts of a much larger “Cambro–Ordovician cordillera” (Von Raumer et al. 2013) can be identified with the Cenerian belt. Given by the strong similarities described in this study, the “Tremadocian Volcanic Chain” (Pouclet et al. 2017) might represent the western part of the early Paleozoic Cenerian belt with a total length of at least 2500 km along the northern periphery of Gondwana (Fig. 6).

To give the early Paleozoic orogeny an own new term, namely the “Cenerian orogeny”, is justified by three characteristics, which are significantly different compared to the Cadomian, Caledonian and Variscan orogenies: (1) the age, (2) the latitude, and (3) the tectonic setting (type of orogeny), as illustrated in Figs. 5 and 6, and described in the following. Linnemann et al. (2014) interpret the Cadomian orogeny as an Andean-type continental arc. They describe large occurrences of late Cadomian (c. 540 Ma) anatectical granitoid series in the Saxo-Thuringian Zone. From the perspective of this study, these S-type series might indicate that the transition from an Andean-type metaluminous arc to an Alaskan-type peraluminous arc of a SAC might have occurred already at the beginning of the Cambrian.

The Cadomian is the oldest orogeny in the Central European Variscan basement. It is followed by the formation of early Paleozoic SACs. In the region of the Alps these SACs are mainly Ordovician in age and mark the generation of continental crust by the Cenerian orogeny. Thereby, the northern rim of Gondwana grew until the facing ocean closed and the Variscan collision with Laurussia started. New crust was also formed by Variscan arc systems. Thus, the Variscan orogeny can regionally be characterized as magmatic arcs (Andean-type) and in other regions SACs

(Alaskan type) and collisional belts with nappe tectonics (Alpine type) prevail (Fig. 6). As stated by Zurbriggen (2015) the three types of orogens represent end members, or even only single stages in a more complex orogenic history. Even though collisional orogens have an active margin pre-history, their dominant tectonic imprint is related to the final collision, which allows to classify them as such, like in the case of the Alps.

As already mentioned, SACs do not form cordilleras of high altitudes. They reach thicknesses of approximately 30 km, which are directly isostatically stable. Therefore, no over-thickened crust forms and no late to post-orogenic exhumation of the deep crust occurs. The lack of exhumation leaves the high-grade rocks at mid-crustal levels until they become involved in the Variscan collision. This explains why isotopic dating of the Cenerian orogeny can be disturbed by Variscan events.

This study does not aim to reconstruct the plate tectonics and paleogeographic distribution of the early Paleozoic basement units, because the author identifies a lack of systematic analysis regarding two aspects in each of these terranes: first, the predominant type of magmatism (metaluminous versus peraluminous), and second, the provenance of the detritus with respect to the different Precambrian cratons. Knowing that an anatectical peraluminous arc (early leucotonalitic pegmatites followed by peraluminous plutons with associated volcanics) indicates the setting of a SAC, and a metaluminous differentiation suite (diorite-tonalite-granodiorite-granite with late pegmatites) indicates a continental or island arc setting (Zurbriggen 2015), allows to classify each terrane with respect to its orthogneisses. Combining this information with the provenance of the protoliths of the paragneisses, would allow reconstructing age and paleogeographic position of the different metaluminous arcs, the shelves, and when the latter became accreted and intruded by peraluminous granitoids to form cratonized SACs.

This study makes four contributions:

1. It provides fundamental characteristics of cratonizing subduction–accretion complexes (SACs), an orogenic type quasi unique for early Paleozoic times.
2. It uses these characteristics to interpret Cambro–Ordovician metasedimentary and metamagmatic rocks occurring in the Alpine domain in terms of a newly defined orogeny: the Cenerian orogeny.
3. It highlights the central role of recycling Proterozoic continental crust by the cratonization of SACs at the periphery of Gondwana in the formation of Proto-European continental crust.
4. It points to a not yet fully understood role of Gondwanan ice shields (including Neoproterozoic "Snowball Events") with respect to Gondwana's erosion, high sediment flux and the rapid growth and cratonization of early Paleozoic SACs.

The author is deeply convinced that future studies with a focus on early Paleozoic rock associations in central and southern Europe will deliver more exhaustive evidence for the Cenerian orogeny along the northern periphery of Gondwana.

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