Oxygen isotopes in ophicalcites: an ever-lasting controversy?

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Abstract

Tectono-sedimentary breccias, known as ophicalcites, overlie serpentinised peridotites at a Jurassic ocean–continent transition along the Penninic-Austroalpine transition in the Eastern Alps of Switzerland. Deformation of the exhumed mantle rocks and breccia formation occurred under decreasing temperatures and along low-angle detachment faults exposing the mantle rocks at the sea floor and was coupled with hydrothermal activity and carbonation of the serpentinites at shallow depth and/or at the sea floor. Carbon isotopes in the ophicalcites persistently show marine values; however, the interpretation of oxygen-isotope values remained controversial: are they related to Jurassic hydrothermal activity or do they reflect Alpine metamorphic overprint? Here we discuss recent interpretations that relate oxygen isotope values measured in ophicalcites exclusively to Jurassic hydrothermal activity; to this end we use data that we earlier obtained along a north–south profile across Graubünden (eastern Switzerland). We revisited the sites of controversial interpretation along a north–south profile in eastern Switzerland. Along this profile, oxygen isotope values in ophicalcites and overlying pelagic sediments, up to 25 my younger than the ophicalcites, show identical values and become systematically lower with increasing Alpine metamorphism; they strongly deviate from values in ophicalcites and pelagic sediments measured along the Mid-Atlantic Ridge or ancient Atlantic ocean-continent transitions as e.g. in the Iberia–Newfoundland transect. The oxygen-isotope values measured in Alpine ophicarbonates thus reflect isotopic resetting during the Alpine orogeny, related to fluid-rock interaction during regional metamorphism. Hydrothermal processes that accompanied the formation of ophicalcites are not disputed; however, they cannot be traced by oxygen isotope geochemistry.

Keywords Ophicalcite · Oxygen-isotopes · Ocean–continent transition · Jurassic · Alps · Graubünden

Introduction

Ever since the pioneering work of Bärtchi (1957), a large amount of data on the stable isotope composition of Alpine carbonate rocks and minerals has been assembled. Isotope data of sedimentary, igneous or metamorphic rocks serve as proxies of past environmental and geochemical conditions, the evolution of the carbon cycle through time, the reconstruction of palaeotemperatures in marine sediments and the identification of the source of magmatic rocks or the composition and origin of fluids acting during diagenesis, and regional and contact metamorphism.

Several early oxygen isotope studies focused on carbonates derived from Jurassic tectono-sedimentary ophiolite breccias, known as ophicalcites. Oxygen isotope data from ophicalcites originally were interpreted as proxies of hydrothermal origin of the carbonate in these rocks (Barberi et al. 1979; Lemoine et al. 1983); however, other authors questioned the hydrothermal signature preserved in bulk oxygen isotope data. They interpreted oxygen isotope trends measured in Alpine ophicalcites and associated pelagic sediments as proxies of Alpine metamorphism (Weissert and Bernoulli 1984; Früh-Green et al. 1990). In a recent study, Coltat et al. (2019) rejected the proposed metamorphic origin of oxygen isotope signatures in Alpine ophicalcites. They use, in agreement with the early studies by Barberi et al. (1979) and Lemoine et al. (1983), oxygen isotope values from Alpine ophicalcites as a proxy of Jurassic oceanic hydrothermal processes.

In this short contribution we use earlier published O- and C-isotope data from tectono-sedimentary breccias
ophicalcites) and calcite veins in serpentinites formed along a Jurassic ocean-continent transition in the Alpine Tethys Ocean together with O- and C-isotope data from overlying Jurassic and Cretaceous pelagic sediments (Weissert and Bernoulli 1984; Früh-Green et al. 1990) and discuss them in their regional geological and tectonic context (Figs. 1, 2). We resume a long-lasting discussion on the significance of oxygen isotope values in both tectono-sedimentary breccias and pelagic limestones along the Penninic/Austroalpine boundary zone of the Swiss Alps. In particular, we try to answer the question whether the oxygen isotope composition in ophicalcites is a signal related to Jurassic oceanic hydrothermal processes (Coltat et al. 2019) or is, for its larger part, an Alpine metamorphic signal as postulated by us in earlier papers (Weissert and Bernoulli 1984; Früh-Green et al. 1990).

Geological setting

The Penninic/Austroalpine boundary zone in the Alps of Graubünden (eastern Switzerland) preserves the remnants of a Jurassic ocean-continent transition (e.g. Froitzheim and Manatschal 1996; Manatschal and Bernoulli 1998, 1999). Alpine thrusting led to the formation of a nappe edifice (Figs. 1, 2) in which the distal continental margin units are represented by the Lower Austroalpine Err and Julier (= Bernina) nappes; the exhumed mantle rocks, by the ophiolite nappes, i.e. the Malenco Unit, the Platta and Totalp nappes with their sedimentary cover (Weissert and Bernoulli 1985). Smaller imbricates of these units occur in the so-called Arosa Zona, a complex assemblage of imbricates of continental margin and ophiolitic units. The Margna Nappe (Fig. 2) occupies an intermediate position sandwiched between the ophiolite units: the present position of this continental margin fragment might reflect its origin as an extensional allochthon (Froitzheim and Manatschal 1996). Subduction and formation of west-vergent thrust nappes began during the Late Cretaceous and was followed by extension soon after; during the Cenozoic, the Cretaceous/Paleocene nappe edifice was thrust to the north over the middle and lower Penninic units (Fig. 2; Froitzheim et al. 1994). The Alpine metamorphic zonation appears to be affected by later, post-nappe thrusting and folding (Ferrero Mählmann 1995), and subsequent extension between 45 and 30 Ma (Nievergelt et al. 1996); however, by and large, Alpine metamorphism traced in the ophiolitic nappes is of Late Cretaceous to Paleocene age (Handy et al. 1996; Ferreiro Mählmann and Giger 2012; Picazo et al. 2019) and increases along a north–south gradient in southeast Switzerland, exposing deeper units of the Cretaceous–Paleocene nappe edifice (Fig. 2). Oterdoom (1978) studied tremolite- and diopside-bearing assemblages in ultramafic rocks between Davos in the north and the Engadine Valley in the south. He arrived at metamorphic temperatures starting at 200 °C near Davos (Totalp nappe, prehnite-pumpellyite [sub-greenschist] facies) and reaching up to 400 °C in the Engadine Valley (high greenschist facies). In the Platta nappe (sample location Falotta, Fig. 2, see also Coltat et al. 2019), Alpine metamorphism reached pumpellyite to lower greenschist facies.
In spite of Alpine thrusting and imbrication, the original palinspastic sequence of the different units can be reconstructed with confidence from the distal continental margin of the Err nappe to the exhumed mantle rocks of the Platta nappe. The serpentinised mantle rocks of what is now the Platta thrust nappe were exhumed during Jurassic rifting along a system of low-angle detachments and emplaced at the seafloor before being covered by the submarine volcanics and sediments. The intrusion of gabbros into the mantle rocks and the emplacement of the volcanics at the seafloor overlapped in time with the extensional movements as shown by syn-magmatic deformation of the intrusive rocks and their tectonic exhumation at the seafloor (Desmurs et al. 2001). High-temperature deformation and subsequent hydration of the mantle and intrusive rocks was followed by low-temperature deformation, both well documented in the Falotta area of the Platta nappe (Desmurs et al. 2001). The top of the serpentinites is typically formed by tectono-sedimentary breccias, described as ophicalcites which record deformation under decreasing temperatures during ascent of the mantle rocks (Desmurs et al. 2001), hydrothermal activity (Früh-Green et al. 1990), and their final emplacement at the seafloor. The ophicalcites display different phases of carbonation and mineral formation, namely in situ-replacement of serpentine minerals by calcite (Desmurs et al. 2001: Fig. 6c), hydrothermal formation of andradite and tremolite (Früh-Green et al. 1990), cementation by drusy calcite and infill of geopetal marine and/or diagenetic sediment (Fig. 3, Bernoulli and Weissert 1985).

The oxygen isotope composition of ophicalcites and associated sediments

For the ophicalcites underlying the metabasalts at Falotta, Coltat et al. (2019) claim a Jurassic high-temperature origin. The Jurassic origin of the ophicalcites is beyond doubt as they are overlain stratigraphically by Middle to Upper Jurassic radiolarites that also include re-sediments yielding clasts of ophicalcite (Desmurs et al. 2001: Fig. 6d). Coltat et al. (2019) measured oxygen and carbon isotope compositions of calcite in veins and fractures and found very uniform O- and C-isotope patterns. All C-isotope values are marine values (0.5–2‰ \(\delta^{13}C\)) corresponding to the values measured in other ophicalcites of the Alpine–Mediterranean orogenic belt (e.g. Barberi et al. 1979; Weissert and Bernoulli 1984; Früh-Green et al. 1990; Pozzorini and Früh-Green 1996; Schwarzenbach et al. 2013, Clerc et al. 2014). This is not
surprising because the carbon isotope signature in carbonate of the ophicalcite is rock-dominated, and the carbonate in the ophicalcite is ultimately derived from seawater circulating in the mantle rocks driving serpentinisation. Weissert and Bernoulli (1984) measured like Coltat et al. (2019) exclusively marine carbon isotope values in ophicalcites and, also, in associated Jurassic-Cretaceous pelagic rocks along the described metamorphic gradient.

The interpretation of the O-isotope values has been discussed more controversially (Fig. 4). Whereas Coltat et al. (2019) interpreted their data as a proxy for a Jurassic hydrothermal origin of the calcites in the ophicalcites, we interpreted these values in our earlier papers as an Alpine-metamorphic signal (Weissert and Bernoulli, 1984; Früh-Green et al. 1990). To test the hypothesis that not hydrothermal activity but Alpine metamorphism caused the resetting of the O-isotope composition in ophicalcites, Weissert and Bernoulli (1984) and Früh-Green et al. (1990) measured the O-isotope composition of the overlying pelagic limestones (Calpionella Limestone [Maiolica] and Palombini Formations, uppermost Jurassic and Lower Cretaceous) along a north–south running profile. Indeed, if the O-isotopes in the ophicalcites were an original signature reflecting primarily hydrothermal activity and/or a thermal imprint caused by the overlying basalts, we would expect the O-isotope signatures of overlying oceanic sediments, radiolarites (Middle to Upper Jurassic) and pelagic limestones (Calpionella Limestone and Palombini Formation) to be different from those of the ophicalcites, i.e. showing low-temperature values corresponding to Jurassic–early Cretaceous seawater.

Our profile across eastern Switzerland between Davos and the Engadine includes tectonic units of different Alpine-metamorphic grade (Oterdoom 1978; Bousquet et al. 2012). It definitely displays a parallel trend in O-isotope composition of calcite in ophicalcites and of bulk carbonate of overlying Jurassic-Cretaceous oceanic sediments. Pelagic bulk carbonate values near Davos are up to 5‰ lower than in their equivalent non-metamorphic rocks in the Southern Alps, known as Maiolica Limestones (e.g. Weissert et al. 1985). An oxygen isotope gradient can be drawn starting from the non-metamorphic Southern Alps to prehnite–pumpellyite facies in more external units (Totalp–Davos, Arosa) and finally ending in higher greenschist facies in the south-Penninic and Austroalpine nappes in the Engadine. In the Southern Alps (shallow burial diagenesis, <100 °C), δ^{18}O_{V-PDB} values of −3 to 0‰, corresponding to δ^{18}O_{V-SMOW} values of 28–31‰ were measured in Lower Cretaceous pelagic limestones (Maiolica Lombarda Formation); at Totalp (Davos, Totalp Nappe) and Arosa (Arosa Zone) (prehnite–pumpellyite facies) values of 19–24‰ δ^{18}O_{V-SMOW} (δ^{18}O_{V-PDB} = −7 to −10‰) in the ophicalcites and the overlying sediments. At Falotta, all values measured by Coltat et al. (2019) fall around +16‰ δ^{18}O_{V-SMOW} (−14.5‰ δ^{18}O_{V-PDB}) (Fig. 4).
These values are in perfect agreement with oxygen isotope compositions measured by Weissert and Bernoulli (1984) and by Früh-Green et al. (1990) at the same location in calcite veins cutting serpentinites and in ophioclites. $\delta^{18}O_{\text{V-PDB}}$ values in pelagic sediments (Palombini Formation, Lower Cretaceous) of the same area are around $-10.5\%e$ $\delta^{18}O_{\text{V-PDB}}$ ($20\%e$ $\delta^{18}O_{\text{V-SMOW}}$) with lowest values near $-16\%e$ $\delta^{18}O_{\text{V-PDB}}$ ($14\%e$ $\delta^{18}O_{\text{V-SMOW}}$) along lithological boundaries testifying to post-Jurassic isotope fractionation during recrystallization of calcite (Eppel and Abart 1997). Further to the south, near the contact aureole of the Oligocene Bregaglia (Bergell) intrusion (Fig. 1), the O-isotope values in Jurassic-age ophioclites of the Malenco complex range from 8 to $13\%e$ $\delta^{18}O_{\text{V-SMOW}}$ ($-22$ to $-17\%e$ $\delta^{18}O_{\text{V-PDB}}$) whereby the range decreases with distance from the intrusive contact to $11-12\%e$ $\delta^{18}O_{\text{V-SMOW}}$ ($-19$ to $-18\%e$ $\delta^{18}O_{\text{V-PDB}}$; Pozzorini and Früh-Green 1996).

The oxygen isotope compositions in both ophioclites and pelagic limestones show exactly the same trend of decreasing oxygen isotope values starting from Davos in the north and ending south of the Engadine valley. The same trend in O-isotope values has been recognized long ago in ophioclites and overlying oceanic sediments in the Apennines where the O-isotope values become more negative from the more metamorphic Ligurian units in the north to their less metamorphic counterparts in the south (Bonatti et al. 1974; Barberi et al. 1979). The ultramafic carbonate breccias from the Mid-Atlantic Ridge vary from 2.5 to $5\%e$ $\delta^{18}O_{\text{V-PDB}}$ or $33.5-36\%e$ $\delta^{18}O_{\text{V-SMOW}}$ (Bonatti et al. 1974); fracture-filling calcites from the Iberian distal margin from $-0.8$ to $1\%e$ $\delta^{18}O_{\text{V-PDB}}$ or around $30\%e$ $\delta^{18}O_{\text{V-SMOW}}$ (Millikan and
Morgan (1996), and oxygen isotope values of calcites from Cretaceous ophicalcites of the Newfoundland Margin cluster in a relatively restricted range of 30.8 to 32.6‰ $\delta^{18}O_{\text{VSMOW}}$ for replacive calcite grains and at 28‰ $\delta^{18}O_{\text{VSMOW}}$ in calcite veins (Picazo et al. 2020). Indeed, all cited examples from the Atlantic Ocean formed near or at the sea floor and at low temperatures (< 20 °C), even where syn- and post-rift magmatism occurs as in the Platta unit. By contrast, the uniform low O-isotope values of the ophicalcites at Falotta argue for a late, metamorphic origin of the O-isotope composition. Indeed, we would expect that the different generations of calcite observed in ophicalcite would display more widely varying O-isotope signatures if they formed at different depth below the Jurassic seafloor, but they do not; all lie slightly above − 14‰ $\delta^{18}O_{\text{V-PDB}}$ (16.5‰ $\delta^{18}O_{\text{V-SMOW}}$), in the range that also the overlying oceanic sediments display. No low-temperature ophicalcites have been found yet in the Alps, suggesting that their original low-temperature signatures have been obliterated by Alpine metamorphism.

When were the isotope compositions in the pelagic sediments and the ophicalcites homogenized? Subduction of the “South Penninic” Ocean with its ophiolites started in the Late Cretaceous. Pelagic oozes of latest Jurassic and Early Cretaceous age entered the accretionary wedge as a fluid-rich stiff carbonate oozes at the sea floor and at low temperatures (< 20 °C), even where syn- and post-rift magmatism occurs as in the Platta unit. By contrast, the uniform low O-isotope values of the ophicalcites at Falotta argue for a late, metamorphic origin of the O-isotope composition. Indeed, we would expect that the different generations of calcite observed in ophicalcite would display more widely varying O-isotope signatures if they formed at different depth below the Jurassic seafloor, but they do not; all lie slightly above − 14‰ $\delta^{18}O_{\text{V-PDB}}$ (16.5‰ $\delta^{18}O_{\text{V-SMOW}}$), in the range that also the overlying oceanic sediments display. No low-temperature ophicalcites have been found yet in the Alps, suggesting that their original low-temperature signatures have been obliterated by Alpine metamorphism.

Interestingly, Jurassic carbonated fault rocks and ophicalcites of the Bracco-Val Graveglia Unit of the Liguride nappes in the Northern Apennines showed $\delta^{18}O$ values of 19.8 to 20‰ $\delta^{18}O_{\text{V-SMOW}}$ for the fault rocks (Alt et al. 2018), and between 13 and 20‰ $\delta^{18}O_{\text{V-SMOW}}$ for the ophicalcites (Schwarzenbach et al. 2013). These values are in the range of those of ophicalcites of the Platta nappe and the Arosa...
Zone in Graubünden. In fact, Lucchetti et al. (1990) and Leoni et al. (1996) established, based on mineral assemblages in the ophiolites and ililitic/chlorite crystallinity in the sediments overlying them, prehnite-pumpellyite facies and low-grade metamorphic (anchizone) conditions for the Bracco-Val Graveglia Unit. Also, in these cases Alpine isotopic exchange is probable.

Conclusion

We do not doubt the importance of hydrothermal activity, accompanying serpentinisation and fracturing for the carbonation of the ophicalcites that we documented in an earlier paper (Früh-Green et al. 1990). Hydrothermal activity is testified to in the mineralogy, in cathode luminescence analysis of calcite veins (Fig. 5) but not in the measured oxygen isotope values of ophicalcites that follow a regional metamorphic trend (Früh-Green et al. 1990). All the oxygen isotope values measured in Alpine ophicarbonates reflect isotopic resetting during Alpine orogeny, related to fluid-rock interaction during regional metamorphism and show that pervasive metamorphic fluids, derived from metamorphic fluids, derived from metamorphic rock interaction during regional metamorphism and show isotopic resetting during Alpine orogeny, related to fluid-rock interaction during regional metamorphism and show that pervasive metamorphic fluids, derived from metamorphic reactions caused local or regional widespread homogenization of the O-isotope compositions. C-isotope values were not affected because the C-isotope system was rock-dominated during the Alpine metamorphic event.

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References

Alt J, Crispi L, Gaggero L, Levine D, Lavagnino G, Shanks P, Gubbranson C (2018) Normal faulting and evolution of fluid discharge in a Jurassic seafloor ultramafic-hosted hydrothermal system. Geology 45:523–526

Barberi M, Masi U, Tolomeo L (1979) Stable isotope evidence for a marine origin of ophicalcites from the north-central Apennines (Italy). Mar Geology 30:193–204

Bärtchi P (1957) Messung und Deutung relativer Häufigkeitsvariationen von O18 und C13 in Karbonatgesteinen und Mineralien. Schweiz Mineral Petrogr Mitt 37:73–152

Bernoulli D (1972) North Atlantic and Mediterranean Mesozoic facies, a comparison. In: Hollister CD, Ewing JT et al. (eds) Init. Rep Deep Sea Drilling Proj 11:801–871

Bernoulli D, Jenkyns HC (2009) Ophiolites in ocean–continent transitions: From the Steinmann Trinity to sea-floor spreading. C.R Géosci 341:363–381

Bernoulli D, Weisset H (1985) Sedimentary fabrics in Alpine ophicarbonates, South-Pennine Arosa zone, Switzerland. Geology 13:755–758

Bonatti E, Emiliani C, Ferrara G, Honnorez J, Rydell H (1974) Utramafic-carbonate breccias from the equatorial Mid Atlantic Ridge. Mar Geol 17:83–102

Bousquet R, Oberhansli S, Schmid SM, Berger A, Wiederkahr M, Robert Ch, Moller A, Rosenberg C, Zeilinger G, Molli G, Koller F (2012) Metamorphic Framework of the Alps. Map 1:1’000’000. CCGM/CGMW (Commission for the Geological Map of the World, Paris)

Clerc C, Boulvais P, Lagabrielle Y, de Saint Blanquat M (2014) Ophiolites from the northern Pyrenean belt: a field, petrographic and stable isotope study. Int J Earth Sci 103:141–163

Coltart R, Boulvais P, Branquet Y, Collot J, Epin ME, Manatschal G (2019) Syntectonic carbonation during syn-magmatic mantle exhumation at an ocean–continent transition. Geology 47:183–187

Desmurs L, Manatschal G, Bernoulli D (2001) The Steinmann Trinity revisited: mantle exhumation and magmatism along an ocean-continent transition, the Platta nappe, eastern Switzerland. In: Wilson RCL, Whitmarsh RB, Taylor B, Froitzheim N (eds) Non-volcanic rifting of continental margins: a comparison of evidence from land and sea. Geol Soc (London) Spec Publ 187:235–266

Eppel H, Abart R (1997) Grain-scale isotope disequilibrium during fluid-rock interaction. 2: An example from the Penninic-Austroalpine contact in eastern Switzerland. Am J Sci 297:707–728

Ferrero Mählmann R (1995) Das Diagenese-Metamorphose-Muster von Vitrinit-Refllexion und Illit-„Kristallinität“ in Mittelbünden und im Oberhalbstein. Teil I: Bezüge zur Stockwerktektonik. Schweiz Mineral Petrogr Mitt 75:85–122

Ferrero Mählmann R, Giger M (2012) The Arosa zone in Eastern Switzerland: oceanic, sedimentary burial, accretional and orogenic very low- to low-grade patterns in a tectono-metamorphic mélangé. Swiss J Geosci 105:203–233

Froitzheim N, Manatschal G (1996) Kinematics of Jurassic rifting, mantle exhumation, and passive-margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). Geol Soc Am Bull 108:1120–1133

Froitzheim N, Schmid SM, Conț P (1994) Repeated change from crustal shortening to orogeny-parallel extension in the Austroalpine units of Graubünden. Eclogae Geol Helv 87:559–612

Früh-Green GL, Weisset H, Bernoulli D (1990) A multiple fluid history recorded in Alpine ophicarbonites. J Geol Soc (London) 147:959–970

Handy MR, Herwegh H, Kamber BS, Tietz R, Villa IM (1996) Geochronologic, petrologic and kinematic constraints on the evolution of the Err-Platta boundary, part of a fossil continent-ocean suture in the Alps (eastern Switzerland). Schweiz Mineral Petrogr Mitt 76:453–474

Lemoine M, Bourbon M, de Graciansky P-C, Létolle R (1983) Isotopes in the sediments overlying them, prehnite-pumpellyite facies and low-grade metamorphic (anchizone) conditions for the Bracco-Val Graveglia Unit. Also, in these cases Alpine isotopic exchange is probable.
Leoni L, Marroni M, Sartori F, Tamponi M (1996) Metamorphic grade in metapelites of the Internal Liguride Units (Northern Apennines). Eur J Mineral 8:35–50
Lucchetti G, Cabella R, Cortesogno L (1990) Pumpellyite and coexisting minerals in different low-grade metamorphic facies of Liguria, Italy. J Metamorph Geol 8:539–550
Manatschal G, Bernoulli D (1998) Rifting and early evolution of ocean basins: the record of the Mesozoic Tethys and of the Galicia-Newfoundland margins. Mar Geophys Res 20:371–381
Manatschal G, Bernoulli D (1999) Architecture and tectonic evolution of nonvolcanic margins: present-day Galicia and ancient Adria. Tectonics 18:1099–1119
Matter A, Douglas RG, Perch-Nielsen K (1975) Fossil preservation, geochemistry and diagenesis of pelagic carbonates from Shatsky Rise, northwest Pacific. Init Rep Deep Sea Drilling Proj 32:891–921
Millikan KL, Morgan JK (1996) Chemical evidence for near-seafloor precipitation of calcite in serpentinites (Site 876) and serpentinite breccias (Site 899), Iberia Abyssal Plain. In: Whitmarsh RB, Sawyer DS, Klaus A, Masson DG (eds) Proc Ocean Drilling Program, Scientific Results 149:553–558
Nievergelt P, Liniger M, Froitzheim N, Ferreiro Mählmann R (1996) Early to mid tertiary crustal extension in the Central Alps: the Turba Mylonite Zone (Eastern Switzerland). Tectonics 15:329–340
Oterdoom WH (1978) Tremolite and diopside-bearing serpentine assemblages in the CaO–MgO–SiO2–H2O multisystem. Schweiz Mineral Petrogr Mitt 58:127–139
Picazo S, Ewing T, Münstener O (2019) Paleocene metamorphism along the Pennine-Austroalpine suture constrained by U-Pb dating of titanite and rutile (Malenco, Alps). Swiss J Geosci 112:512–542
Picazo S, Malvoisin B, Baumgartner L, Bouvier AS (2020) Low temperature serpentinite replacement by carbonates during seawater influx in the Newfoundland Margin. Minerals 10:184. https://doi.org/10.3390/min10020184
Pozzorini D, Frih-Green G (1996) Stable isotope systematics of the Ventina Ophicarbonate Zone, Bergell contact aureole. Schweiz Mineral Petrogr Mitt 76:549–564
Schwarzenbach EM, Frii-Green GL, Bernasconi SM, Alt JC, Plas A (2013) Serpentization and carbon sequestration: a study of two ancient peridotite-hosted hydrothermal systems. Chem Geol 351:115–133
Spicher A (1980) Tektonische Karte der Schweiz, 1:25 000. Schweiz Geol Komm. Bern
Trümpy R (1975) Penninic-Austroalpine boundary in the Swiss Alps: a presumed former continental margin and its problems. Am J Sci 275-A:209–238
Weissert H, Bernoulli D (1984) Oxygen isotope composition of calcite in Alpine ophicarbonates: a hydrothermal or Alpine metamorphic signal? Eclogae Geol Helv 77:29–43
Weissert H, Bernoulli D (1985) A transform margin in the Mesozoic Tethys: evidence from the Swiss Alps. Geol Rdsch 74:665–679
Weissert H, McKenzie JA, Channell JET (1985) Natural variations in the carbon cycle during the Early Cretaceous. In: Sundquist ET, Broecker WS (eds) The carbon cycle and atmospheric CO2: natural variations archean to the present. Geophys Monogr Ser 32:531–545