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Data Repository

APPENDIX A

In this section we accurately describe the geology of the Alps. Considering the different paleogeographic domains, the Alps could be subdivided into different tectonic units (Dal Piaz et al., 2003; Schmid et al., 2004; Pfiffner, 2014), as shown in Figure A1. In the North-Western bound, it is located the Helvetic-Dauphinois domain (HD), constituted by crystalline duplexes, sedimentary cover units, and décollement nappes belonging to the European continental plate (Dal Piaz et al., 2003; Pfiffner, 2014). The Penninic domain (P) is located in the central portion of the Alpine region and is constituted by Mesozoic sediments deposited in marine basins between the European and the Adriatic plates (Pfiffner, 2014). It includes oceanic crust in the form of ophiolites (O), continental nappes, and turbiditic rocks (from flysch to silico-clastic and carbonate turbidites) (Dal Piaz et al., 2003). In the South-Eastern portion of Alpine chain, the Western and Eastern Austroalpine domains (respectively WA and EA) and the Southern Alps (SA) are constituted by rocks belonging to the Adriatic continental margin (Dal Piaz et al., 2003; Pfiffner, 2014) mainly grew during the Cretaceous orogenesis (Dal Piaz et al., 2003). The WA and EA domains are characterized by heterogeneous geo-lithological composition (Schmid et al., 2004) non or weakly metamorphosed sedimentary rocks (Northern Calcareous Alps and Grauwackenzone, roughly located in the northern portion of EA) to metamorphosed basement nappes (both in EA and in WE) (Schmid et al., 2004; Pfiffner, 2014). The SA domain includes mainly carbonates and secondly crystalline rocks (Schmid et al., 2004; Pfiffner, 2014; Dal Piaz et al., 2003).

From the bottom to the top, the tectonic units are ordered as follows: Helvetic (HD), Penninic (P), and Austroalpine domains (WA and EA) (Pfiffner, 2014). The Austroalpine nappe is eroded at the Engadine and Tauern tectonic windows (respectively EW, and TW) where the Penninic domain (P) outcrops (Dal Piaz et al., 2003; Pfiffner, 2014). P outcrops also in Ossola-Ticino tectonic windows (OTW) and in the Prealpine klippen (PK) on the Northern margin of the Alps (Dal Piaz et al., 2003; Pfiffner, 2014).

The SA and the external Dinarides (DI) are separated from the WA and EA domains by the Periadriatic Line (PL), a major fault system of Oligocene-Neogene age (Dal Piaz et al., 2003; Pfiffner, 2014). The Adamello batholith, the largest of the numerous Periadriatic intrusions (PI) that occurred in the eastern Alps along with the tectonic boundary between the WE and EA domains and the SA (Martin et al., 1993), is located at the Northern border of SA. The PI were emplaced during the late Oligocene, when extensional/transtensive conditions were active in the suprastructure of the Alpine chain near the border between the Austroalpine domains (WA and EA) and the SA (Dal Piaz and Venturelli, 1985; Laubscher, 1985; 1988), and are mainly quartz-diorite/quartz-gabbro in composition (Martin et al., 1993).

In the following, the geology of the Alps is described as highlighted by the Alpine Geo-LiM (Fig. 2).

The Western and Eastern Australpine Domains

Figure 2 confirms the heterogeneity of the Western and Eastern Australpine domains (respectively WA and EA), since they include: (1) the Northern Calcareous Alps and the Grauwackenzone (Janák et al., 2004; Pfiffner, 2014); (2) the Australpine complexes such as Altkristallin, Schladming and Bundschuh complexes (Janoschek and Matura, 1980); and (3) the Sesia Zone and the Dent Blanche Klippe (Manzotti et al., 2014; Pfiffner, 2014).

The Northern Calcareous Alps and the Grauwackenzone constitute a belt in the upper part of WA mainly composed of calcareous rocks ("pure carbonate" and "mixed carbonate") and secondly of "sandstone." The Australpine complexes are a mélange of outcrops, ranked by abundance, composed by "claystone" (micascists, paragneiss, and phyllites), "mixed carbonate," "acid rocks" (orthogneiss, and granites), and "mafic rocks" (basalts, amphibolites) (Schuster and Frank, 1999; Janoschek and Matura, 1980; Mählmann and Giger, 2012; Schmid et al., 2013) and occupy the rest of WE. The Sesia Zone and the Dent Blanche Klippe represent a portion of continental crust formed by metasediments, granitoids and gabbroic bodies (Dal Piaz, 1972; Compagnoni, 1977; Manzotti et al., 2014) defined in the map as "claystone," "acid rocks" and "mafic rocks," respectively. The outcrops of continental crust are surrounded by oceanic units (ophiolites) (Dal Piaz et al., 2003; Schmid et al., 2004; Manzotti et al., 2014) classified in Figure 2 as "mafic rocks."

The Penninic Domain

Figure 2 highlights the complexity of the Penninic domain (P) associated with (1) ophiolitic deposits (O) in the Piedmont zone (Dal Piaz et al., 2003; Pfiffner, 2014) constituted by "mafic rocks," (2) the crystalline complexes of Dora Maira, Gran Paradiso, and Monte Rosa, (3) the Prealpine klippen (PK), (4) the Ossola-Ticino and (5) the Tauern tectonic windows (respectively OTW, and TW). The Dora Maira, Gran Paradiso, and Monte Rosa complexes are made up of continental basement nappes, mainly composed of crystalline (granitic) deposits (Dal Piaz et al., 2003; Pfiffner, 2014) represented in Figure 2 by "acid rocks." PK is constituted roughly by carbonates sediments associated with marls and shale deposits (Wissing and Pfiffner, 2002) classified in the figure as carbonate rocks (in the forms of "pure carbonate" and "mixed carbonate") and "claystone," respectively.

The Ossola-Ticino window (OTW), also named Lepontine dome, is composed of continental basement units mainly constituted by gneiss with granitoid protoliths (classified in Figure 2 as "acid rocks"), secondly of metapelitic sediments with small marble and amphibolite layers (classified in the map by "pure carbonate," "mixed carbonate," "claystone" and "sandstone"), and finally of a small presence of meta-serpentinites (in the map as "mafic rocks") (Merle et al., 1989; Bergomi et al., 2009; Steck et al., 2013).

TW is made up of a granitic metamorphosed core (Pfiffner, 2014; Pennacchioni et al., 2016) (in Figure 2 as "acid rocks") surrounded by a mix of rocks composed by ophiolites (represented in Figure 2 by "mafic rocks"), mafic and acidic rocks, paragneiss, schists, shales, amphibolites, greywackes, and quartzite (in Figure 2 as a mix of "pure carbonate," "mixed carbonate," "claystone" and "sandstone") (Pfiffner, 2014; Höck, 1993).

The Helvetic-Dauphinois Domain

The Helvetic-Dauphinois domain (HD) is composed by the Helvetic domain (H) in its northern sector and by the Dauphinois domain (D) in the southern sector (Pfiffner, 2014). H is made up of sedimentary cover (mainly marine carbonates and shales, classified in Figure 2 as "pure carbonate," "mixed carbonate" and "sandstone") deposited on a basement constituted by siliciclastic and volcanic (mainly gneisses and granites, represented in the map by "acid rocks") deposits. The basement is exposed in the Aar, Gotthard, Aiguilles Rouges and Mont Blanc massifs (Kempf and Pfiffner, 2004; Pfiffner, 2014). D is composed by deep-marine facies deposits (Arnaud-Vanneau and Arnaud, 1990) made up of shales, siliciclastics deposits and dolomitic limestones (Barale et al., 2013, 2016, 2017) defined in Figure 2 by "sandstone" and carbonates classes ("pure carbonate" and "mixed carbonate"). In this sector of Alpine chain, the basement is visible in the Argentera, Belledonne, Pelvoux massifs. Argentera is mainly made up of granitoid rocks and orthogneiss (represented in Figure 2 by "acid rocks") and amphibolites ("mafic rocks" in Fig. 2) (Pfiffner, 2014). Belledonne is mainly constituted by granitoid rocks (classified as "acid rocks" in Fig. 2) and ophiolites ("mafic rocks" in Fig. 2) (Pfiffner, 2014). Pelvoux is mainly composed of granitoid rocks (Beucher et al., 2012).

The Southern Alps

The Southern Alps (SA) could be roughly divided by the Giudicarie Line (GL) in two major paleogeographic and paleo-structural domains: the Trento Platform to the East and the Lombard Basin to the West (Doglioni and Bosellini, 1987; Castellarin et al., 2006). In the Trento Platform, the Dolomites (Doglioni and Bosellini, 1987) are predominantly constituted by carbonates (Pfiffner, 2014). They are classified in Figure 2 as "pure carbonate" and "mixed carbonate" and secondly as granitoids and ryolitics deposits (Castellarin et al., 2006) represented in figure by "acid rocks." In the east of the Dolomites, there is a transition between SA and DI (Pfiffner, 2014). To the West of the GL the Adamello Batholith and the Lombard Basin, mainly filled up with pelagic carbonates (Bersezio et al., 2002), represented in figure by "pure carbonate" and "mixed carbonate." In the upper part of the Lombard Basin, north-bounded by the Periadriatic Line, the Orobic Alps are located, mainly constituted of orthogneiss (represented in Figure 2 by "acid rocks"), micashists and quartzitic and pelitic layers ("claystone" in Fig. 2) (Blom and Passchier, 1997). In the Western sector of the Lombard Basin, the "Serie dei Laghi," including also the Ivrea zona (Boriani et al., 1990) is constituted by mafic rocks such as amphibolites, greenshists ("mafic rocks" in Fig. 2), greywackes and arenaceous rocks (represented in Figure 2 by "sandstone" and "claystone"), and orthogneisses ("acid rocks" in Fig. 2) (Boriani et al., 1990; Vavra et al., 1996).

The Periadriatic Inclusions

Along the Periadriatic line, a series of plutons and dykes have intruded the rocks in the nearby of the faults (Pfiffner, 2014). The magma melt is a mixture of mantle and crustal inputs and is composed of partially melted mafic lower crust contributions, dioritic, tonalitic (both classified in Figure 2 as "intermediate rocks"), granodioritic and granitic melts (represented in Figure 2 by "acid rocks"), and finally, in a less proportion, gabbros ("mafic rocks" in Fig. 2), diorites (“intermediate rocks” in Fig. 2) and granites (represented in Figure 2 by “acid rocks”) (Rosenberg, 2004).

Geological Units External to the Alps

External to the Alps, the Jura mountains (J) in the North-Western bound and the Dinarides (DI) in the South-Eastern bound are located. J is made up of shallow-marine facies deposits (Arnaud-Vanneau and Arnaud, 1990) mainly composed of limestones (in Figure 2 as “pure carbonate” and “mixed carbonate”) and sandstone (represented in Figure 2 by “sandstone”) and DI is composed of carbonate platform deposits (Velić 2007).

The Alps are bounded to the North by the Molasse basin (M), to the East by the Pannonian basin (PB) and to the south by the Po Valley and Adriatic foreland (PA). M is composed of conglomerates, sandstones, marls and siltstones (Janoschek and Matura, 1980) represented in Figure 2 by “sandstone” and “carbonate.” PB is filled by marine sedimentary rocks such as flysch, sandstone, shale and claystone with some marl and limestone deposits (Royden et al., 1983), identified in Figure 2 by the “sandstone,” “claystone” and carbonate rocks (“pure carbonate” and “mixed carbonate”) classes. Moreover, PB was interested by volcanism (Royden et al., 1983), as confirmed by “mafic rocks” and “acid rocks” in Figure 2. The Po basin is mainly filled by fluvial deposits (Amorosi et al., 1996) classified in the figure as “sandstone.”

In the Central-Southern sector of Alps, the four volcanic districts of the Lessini Mountains, the Marostica Hills, the Berici Hills and the Euganean Hills are located. The magma type of the first three districts is mainly mafic (Fig. 2), whereas the magma type of the Euganean Hills ranges from subordinate basalts (represented in the figure by “mafic rocks”) to prevalently acid (in the figure as “acid rocks”) (Milani et al., 1999).

APPENDIX B

Names of the attribute fields, of the different national geological maps, used for the elaboration of the Alpine Geo-LiM::

(1) for Italy: in *DESCR* field;

(2) for Switzerland: in *LITH_PET*, *LITHO*, and *LEG_GEOL* fields;

(3) for Germany: in *EN_PETROG*, *EN_PET*, *URN_LITH_1*, *URN_LITH_2*, *URN_LITH_3*, *URN_LITH_4*, and *URN_LITH_5* fields;

(4) for Austria: in *LEGTEXT_EN*, and *LITHOL_EN* fields;

(5) for France: in *urn_litho1*, *urn_litho2*, *urn_litho3*, *urn_litho4*, and *urn_litho5* fields;

(6) for Slovenia: in *urn_litho1*, *urn_litho2*, *urn_litho3*, *urn_litho4*, and *urn_litho5* fields.

The languages of the geological information contained in the aforementioned fields are Italian for Italy, French for Switzerland, and English for France, Slovenia, Germany, and Austria.

APPENDIX C

An in-depth study of alpine geology has been carried out to classify specific geological units. This is the case, for example, of several geological units in Austria that are reported it the text with single bracket. We classified the ‘Schladming complex’ as “claystone” since it is composed mainly of phyllites and sericitic quartzites (Schmid et al., 2013). The ‘Post-Variscian clastic rocks' were classified as "sandstone" as they are mainly made up of conglomerates, sandstones, and arkoses (Janoschek and Matura, 1980). The 'tectonic mélange of austroalpine and penninic rocks; Permo-Mesozoic' was considered as "metamorphic rocks" (Mählmann and Giger, 2012), as well as the 'Bundschuh complex' which is constituted of paragneiss with intercalations of felsic orthogneiss and micashists with intercalations of amphibolites (Schuster and Frank, 1999). The 'Liebenstein and Feuerstatt nappe', made up of a series of limestones, marls and sandstones (Janoschek and Matura, 1980), was considered as "mixed carbonate rocks," as well as the 'Upper Jurassic-Paleogene klippen' that is constituted of organic rich marls (Picha et al., 2006). The rocks of the Gosau Group ('mainly clastic rocks (Gosau Group); Upper Cretaceous - Eocene') were considered as "mixed carbonate rocks" since, as highlighted by Janoschek and Matura (1980), they are composed of coarse and variegated conglomerates and breccias. We considered that the composition of the gravels of the Gosau Group derives by the surrounding rocks of the Northern Calcareous Alps and by the far crystalline rocks. The molasse deposits ('Molasse-Zone; late Eocene - Miocene; intramontane basins; Neogene' and 'allochthonous and parautochthonous molasse; late Eocene - Miocene') were classified as "mixed carbonate rocks" (Pettijohn, 1957; Friebe, 1993; Goldscheider et al., 2002; Reuter et al., 2012), as well as the 'Rhenodanubian Flysch; Lower Cretaceous - Eocene', since they are composed of various layers of sandstones, marly shales, calcareous marls, and clay shists (Terhorst et al., 2009). Finally, the 'Quaternary i.g. (Alluvium, Pleistocene along main drainage systems, moraines)' was classified as "sandstone" considering the rivers transport energy (see e.g., Hjulstrom diagram, Hjulstrom, 1935).

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Figure A1. Tectonic map of Alps (modified from Dal Piaz et al. (2003) and Schmid et al. (2004), copyright by Swiss Geological Science). WA—Western Austroalpine domain; EA—Eastern Austroalpine domain; P—Penninic domain; O—ophiolites; HD—Helvetic-Dauphinois domain; OTW—Ossola-Ticino tectonic window; EW—Engadine tectonic window; TW—Tauern tectonic window; PK—Prealpine klippen; PL—Periadriatic Line; PI—Periadriatic intrusions M—Molasse foredeep; J—Jura belt; SA—Southern Alps; PB—Pannonian basin; PA—Po Valley and Adriatic foreland; DI—Dinarides; AP—Apennines; EF—European Foreland. The black line encompasses the study area of the present manuscript and represents the area of the main Alpine river basins sampled in 2011 and 2012 by Donnini et al., 2016.

10°E
15°E
48°N
46°N
44°N
EF
M
EA
TW
PB
J
HD
PK
EW
PL
PI
OTW
SA
E
WA
P
Milan
Venice
O
PL
PA
DI
Adriatic Sea
HD
O
P
AP
Tyrrhenian Sea
0
100
200 km
N