Article

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Adding pieces to the puzzle of the Western Tethys Oceanic Basin structure: the architecture of the Inzecca Unit in the Noceta-Vezzani area (Alpine Corsica, France)

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The Middle to Late Jurassic, high-pressure metamorphic ophiolites of Inzecca Unit are well exposed in the Noceta-Vezzani area of Alpine Corsica. These metaophiolites were studied by using a multidisciplinary approach to reconstruct the architecture of the oceanic sector from which they derived. The collected data indicate that this oceanic crust consists of a mantle metaperidotites and metaophicalcites, both covered by massive or pillow metabasalts with or without a layer of ophiolite-bearing metabreccias. The field evidence indicates that the metaperidotites were exposed at the sea bottom and then covered by metabreccias and metabasalts. The metabasalts are intruded by plagiogranite dikes representing the last magmatic event referred to by U/Pb dating at the Kimmeridgian-Oxfordian. The metaophiolites were then covered by Early Cretaceous, hemipelagic sediments represented by metaradiolarites and by the calcschists of the Erbajolo Fm. Overall, all the features of these metaophiolites suggest its origin in an ultra-slow spreading ridge. In this frame, the origin of this ophiolite sequence is discussed, and its characteristics are compared with analogous examples from other sectors of the Alpine-Apennine belt.

Introduction

Ophiolites represent fragments of the oceanic lithosphere enclosed within the collisional belt as deformed and metamorphosed bodies (Dilek and Furnes, 2011 and references therein). They originate in several geodynamic settings, such as mid-oceanic ridges, ocean islands, island arcs, each characterized by different geochemical fingerprint as well as contrasting stratigraphic architecture (Agard et al., 2023 and references therein). Understanding the stratigraphic and geochemical characteristics of exhumed ophiolitic complex means being able to reconstruct the processes of formation and the geodynamics of the oceanic basin from which the ophiolites were derived. To do this, we need to be able to "erase" the tectono-metamorphic history that allowed the emplacement of the ophiolitic bodies into the collisional belts where they crop out.

As most of the Phanerozoic collisional belts, also the Alpine-Apennine belt is characterized by good examples of ophiolites derived from the Middle to Late Jurassic northern branch of the Western Tethys Ocean, also known as Ligure-Piemontese basin (e.g., Bortolotti and Principi, 2005 and references therein). Most of the ocean-derived crustal sections experienced deformation and metamorphism related to their involvement at depth in the subduction zone and, consequently, their pristine features are obliterated, hampering the reconstruction of the original stratigraphy and architecture and the definition of the geodynamic setting of oceanic basin formation.

In Alpine Corsica, the southern branch of the Alpine collisional belt is exposed. It includes bodies of deformed and metamorphosed ophiolites preserved with continental crust slices within the Schistes Lustrés Complex (Vitale Brovarone et al., 2013 and references therein). Among these units, the Inzecca Unit is classically considered as a fragment of oceanic lithosphere that experienced a severe tectono-metamorphic imprint acquired in a subduction zone during underplating and subsequent exhumation within the accretionary wedge (Levi et al., 2007; Garfagnoli et al., 2009). Despite its tectonic history and penetrative deformation, this fragment kept its stratigraphic coherence without any evidence of recycling as tectonic mélange, similarly to what reported from many metaophiolites preserved in the worldwide collisional belts (Festa et al., 2022 and references therein).

The contribution in literature discussing the possible stratigraphic settings for the Inzecca Unit metaophiolites dates back to previous century (e.g., Ohnenstetter, 1979) and rely on integration of observations from scattered outcrops, owing its pervasive polyphase deformation history. A detailed, three-dimensional reconstruction of the architecture of the sector of the Western Tethys oceanic basin, from which these metaophiolites derived, has thus not been attempted yet.

In this paper we report a multidisciplinary study of the strongly deformed and metamorphosed Inzecca Unit in the Noceta-Vezzani area, central Corsica, that we use to reconstruct the original stratigraphy and architecture of the ophiolite sequence of the Western Tethys oceanic basin. This approach included a geological mapping at 1:10,000 scale, a detailed study of the lithological characteristics in selected outcrops, geochronological U/Pb dating of magmatic rocks, and a detailed meso- and micro-scale structural analysis, all representing the starting point for the reconstruction of the three-dimensional architecture for the ophiolite sequence. The proposed architecture is discussed in the frame of the different ophiolite sequences reconstructed in several sectors of the Alpine-Apennine belt, to provide constraints on the spreading processes and geodynamic evolution of the Western Tethys oceanic basin.

Geological Framework of the Ophiolites from Alpine Corsica

The Alpine Corsica (Figs. 1a and b) consists of a stack of continental and oceanic units deformed during the Alpine orogeny, i.e., during the Late Cretaceous-Middle Eocene closure of the Western Tethys oceanic basin and the subsequent Late Eocene - Early Oligocene collision between the Europe and Adria continental margins (Malavieille et al., 1998, Molli, 2008; Marroni et al., 2017). This pile of units is thrust over Hercynian Corsica, representing the European continental margin affected by localized Alpine deformation (Di Vincenzo et al., 2016; Di Rosa et al., 2020c). This margin includes a polymetamorphic basement recording Pan-African and Variscan orogenic events intruded by Permo-Carboniferous magmatic rocks (Ménot and Orsini, 1990; Rossi et al., 2009, 2015; Di Rosa et al., 2020a), in turn covered by sedimentary successions of Permian volcaniclastic rocks, Mesozoic carbonates and middle to late Eocene siliciclastic turbidites (e.g., Durand-Delga, 1984).

Alpine Corsica includes three groups of tectonic units, namely, from bottom to the top, Lower Units, Schistes Lustrés Complex and Upper Units, each interpreted as representative of different paleogeographic domains. The Lower Units consists of slices of the European continental crust involved in Alpine subduction (Frassi et al., 2023; Di Rosa et al., 2020b, 2023), the Upper Units mostly derived from the rim of the Western Tethys oceanic basin close to the European continental margin, whereas the Schistes Lustrés Complex comprise tectonic slices of oceanic and continental affinity representative of the internal part of the Western Tethys oceanic basin and its as transition to the European continental margin (Vitale Brovarone et al., 2011 and references therein).

The Upper Units are affected by a polyphase deformation acquired under very-low metamorphic conditions (Marroni and Pandolfi, 2003 and references therein), while the units of the Schistes Lustrés Complex range from the blueschist to eclogite facies conditions (Vitale Brovarone et al., 2013 and references therein). The oceanic units are represented by metaserpentinites, metagabbros and metabasalts topped by quarzites, marbles and calcschists, with the latter regarded as the metamorphic equivalent of the Radiolarites - Calpionella Limestone - Palombini Shale trilogy as reconstructed in the Internal Ligurian Units of Northern Apennine (Principi et al., 2004 and references therein). The

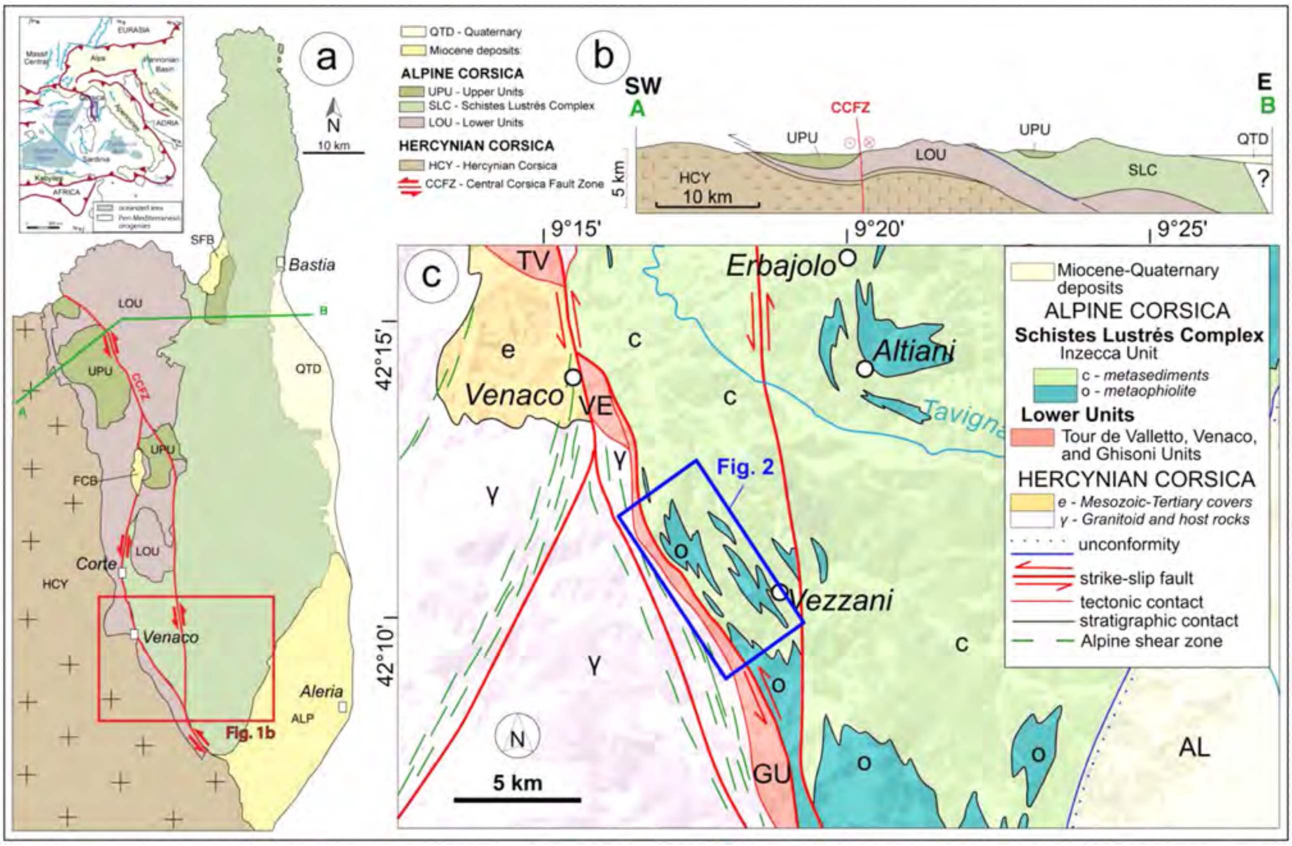

Figure 1. a) Tectonic setting of the Alpine Corsica (modified from Di Rosa et al., 2020b); b) Schematic cross section showing the tectonic stack of the Alpine Corsica; c) Tectonic sketch of the southern sector of the Alpine Corsica. The blue box indicates the study area.

units of the Schistes Lustrés Complex with continental affinity are represented by slices of upper continental crust, mainly metagranitoids, with rare remnants of its sedimentary cover, represented by quarzites, paragneisses, marbles and micaschists. As mentioned above, some of these slices have been interpreted as derived from the ocean-continent transition, thus representing former extensional allochthons inherited from the last stage of the opening of the Western Tethys oceanic basin (Meresse et al., 2012).

The structurally highest units of the Schistes Lustrés Complex (Figs. 1 a and b) includes the Inzecca (Padoa, 1999), Casaluna (Lahondère and Lahondère, 1988) and Lento (Levi et al., 2007) units. All these units consist of metaophiolites and associated metasediments affected by a metamorphism not exceeding the blueschist facies.

The tectono-metamorphic history of the Schistes Lustrés Complex started with the Middle to Late Jurassic spreading of the Western Tethys oceanic basin and proceeded throughout the Late Cretaceous - middle Eocene, with East-dipping subduction and closure of the oceanic lithosphere and the development of an accretionary wedge and the associated trench-slope system. During subduction, the fragments of the oceanic lithosphere were transferred to the accretionary wedge as slices deformed and metamorphosed under eclogite and blueschist facies P-T conditions. Subsequently, the metaophiolites and associated metasediment recorded a retrograde metamorphic path in the greenschist facies during exhumation (Vitale Brovarone et al., 2013 and references therein). The exhumation process comprises several deformation events that testify the progressive rise to shallow structural levels of the metaophiolites. The timing of this evolution is not well constrained, with scarce geochronological ages spanning from 65 (Brunet at al., 2000) to 34-37 Ma (Brunet et al., 2000; Vitale Brovarone and Herwatz, 2013) for the blueschist facies metamorphism, and a single and debated dating of 83.8±4.9 Ma for the eclogite metamorphism (Lahondère and Guerrot, 1997). The exhumation ended in the Burdigalian as constrained by the Early Miocene to Quaternary deposits of Francardo, Saint-Florent and Aleria basins that unconformably seal the structures related to underplating and exhumation of the Schistes Lustrés Complex.

Methods

The Inzecca unit has been mapped at 1:10,000 scale (Fig. 2). During mapping, a detailed, meso-scale lithological description of all the outcropping rock types and their mutual relationships, have been performed in selected outcrops where key samples have also been collected. The geological mapping also comprised a detailed structural study of the most significant outcrops where samples have been collected and subsequently studied to outline the microscale features of the deformations. Four deformation phases, from D1 to D4 phase, have been identified in the field: each phase includes a set of deformations developed as result of a geodynamic event at the same P-T conditions. The results of the structural analyses were used to carry out detailed geological cross sections parallel and perpendicular to the strike of prevalent mineral lineation. These cross sections, associated with the details from the key-areas, have provided a clear 3D picture of the present structural setting, a necessary base to reconstruct the pristine architecture of the fragment oceanic crust preserved in these units.

In addition, a selected sample of plagiogranites has been collected for geochronology. This sample was crushed and sieved at the Università di Pisa. Zircon grains were then concentrated using batea and a Frantz magnetic separator. Approximately 50 crystals were hand-picked and mounted in epoxy resin and the interiors were imaged by cathodoluminescence (CL) using a Zeiss EVO101 scanning electron microscope at the INGV Pisa. In-situ U/Pb isotope analysis was performed at the CISUP (Università di Pisa) using a PerkinElmer NexION 2000 ICP-MS coupled with an NWR-193 AR_F 193 nm excimer laser. Data were acquired in time-resolved, peak-jumping, pulse-counting mode with a routine of 30 s of background measured alternated to 30 s of sample ablation. The analyses were performed at 10 Hz and an energy density of 3.5 J/cm^3 per pulse. The laser spot analysis was set to 25 µm. The data acquired were corrected by normalization to the zircon 91500 reference material (Wiedenbeck et al., 1995). Plešovice zircon were used as a secondary standard (Sláma et al., 2008). The data processing was performed with the Iolite software (Paton et al., 2011).

Results

Overview of the Geology of the Study Area

The study area (Fig. 1c) extends between the Vezzani and Noceta villages in the Central Corsica, immediately south of Corte town. This area is characterized by the good exposures of metaophiolites and associated metasediments belonging to the Inzecca Unit. The mapping show that this area is characterized by several meso-scale folds with the metaophiolites at the core that are folded together with the pelagic, deep-sea metasediments covering the ophiolitic section. This unit is thrust over the Lower Units by a high-angle shear zone. In the study area, the Lower Units are represented by Late Carboniferous to Permian metagranitoids, deformed and metamorphosed during the Alpine tectonics (Di Rosa et al., 2023 and references therein). Westward, the boundary between the Lower Units and Hercynian Corsica occurs by a N-S-trending strike-slip fault belonging to the Central Corsica Fault Zone (Waters, 1990). Out of the study area, the Inzecca Unit is thrust over the Castagniccia and Morteda-Farinole Units, still part of the Schistes Lustrés Complex (Caron, 1977; Amaudric du Chaffaut et al., 1985).

Lithostratigraphy

In the study area, the Inzecca Unit is characterized by a succession that includes metaophiolites and metasediments, both deformed and metamorphosed by different tectonic phases (Fig. 2). As assessed for the other oceanic units from the Schistes Lustrés Complex (e.g., Vitale Brovarone et al., 2013), the metaophiolites are regarded as Middle to Late Jurassic in age whereas the metasediments are probably ranging in age from Early to Late Cretaceous. Despite its complex tectonic setting, a reconstruction of the stratigraphic log of the ophiolite sequence can be attempted. Ohnenstetter (1979) first provided a stratigraphic section for the metaophiolites from Noceta-Vezzani area based on the observations of several key-outcrops. This author interpreted the metaophiolites as representative of a Jurassic oceanic transform fault segment of the Western Tethys oceanic basin. According to what observed

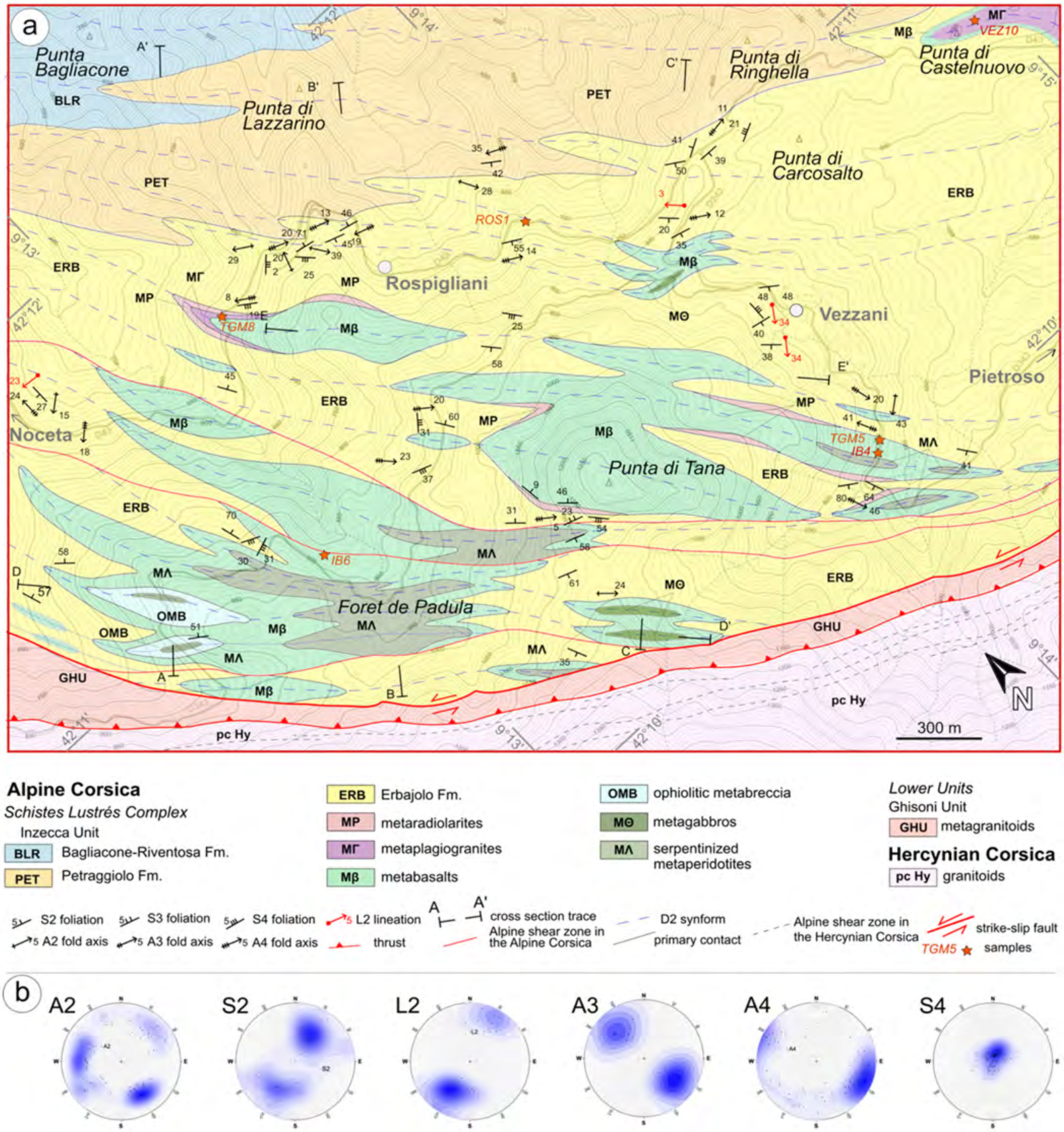

Figure 2. a) Geologic map of the study area. The traces of the cross sections (A-E) presented in Fig. 9 are also indicate; b) stereographic projections (Schmid net, lower hemisphere) related to the D2-D4 deformation phases.

by Ohnenstetter (1979), the base of the section is characterized by strongly serpentinized metaperidotites (Fig. 3). The metaperidotites derived from mantle rocks, probably lherzolites and hazburgites, with pyroxenite and dunite layers. Locally, the metaperidotites are associated with small bodies of metagabbros, cut by mylonitic shear zones that do not affect the overlying metasediments. The original metaperidotites-metagabbros relationships are obliterated by the subduction-related deformations, but an occurrence of the gabbros as intrusive bodies within the metaperidotites can be suggested, by comparison with ophiolite sequences from the Northern Apennines (e.g., Menna, 2009) and elsewhere in Alpine Corsica (e.g., Sanfilippo and Tribuzio, 2013). A few metres thick level of metaophicalcites cover the metaperidotites in several outcrops (Fig. 3), probably making a continuous level at the top of the mantle rocks before the deformation. The metaperidotites and metaophicalcites are covered either by ophiolitic metabreccias or directly by metabasalts. The metabreccias are about 50 metres thick (Fig. 3) and consist of subangular fragments of gabbro, mylonitic gabbro, serpentinite and basalt set in a fine-grained matrix. The

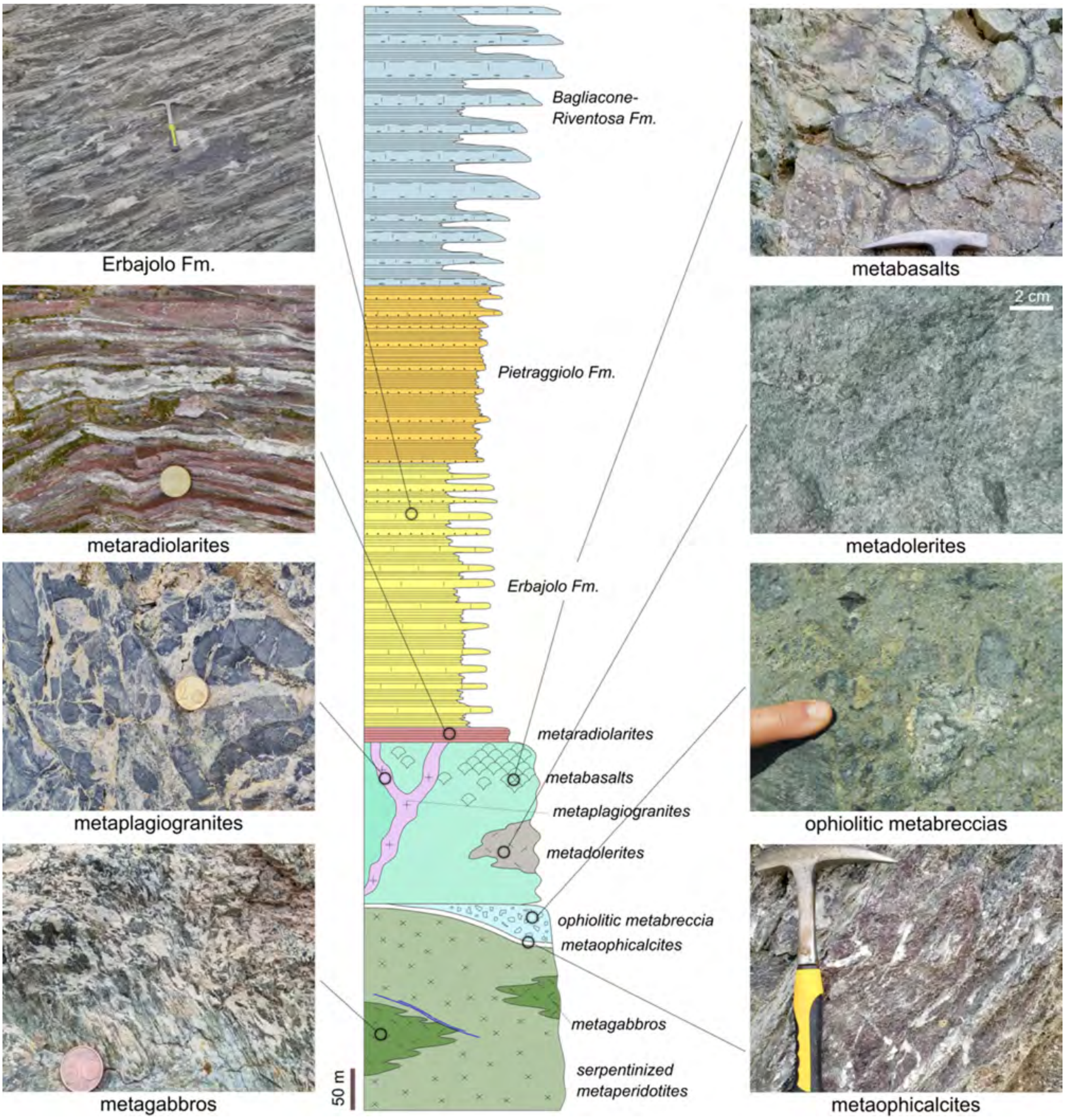

Figure 3. Lithostratigraphic log of the Inzecca Unit reconstructed on the base of the field mapping performed in this work and the field pictures of selected rock types. Blue lines indicate the shear zones localized in the ophiolite sequence.

metabasalt layer, comprises pillow metabasalts (Fig. 3) and pillow metabreccias, cropping out for a thickness of about 200 metres. Locally, massive metabasalts representing former metadolerite sills are recognized. When metabasalts are directly overlying the metaperidotites or the metaophicalcites, the boundary is marked by very thin levels of ophiolitic metasandstones. The metabasalts show a MORB geochemical fingerprint that indicates their origin by melting from an oceanic mantle not modified by fluids derived from a subduction zone (Saccani et al. 2008). In some places the basalts show a pervasive alteration with sulphides and copper mineralization. In addition, the metabasalts are intruded by several generations of cm to dm-thick dikes of metaplagiogranites representing the last magmatic events detected in the metaophiolites. The emplacement of these dikes led to a magmatic metabreccia made of angular fragments of metabasalts in a matrix of metaplagiogranites (Fig. 3). The sedimentary cover, lying on top of the metabasalts, consists of a discontinuous level of metaradiolarites (Late Jurassic) and by the Erbajolo Fm. (Early Cretaceous?). The metaradiolarites are made of cm-thick layers of siliceous metapelites and quarzites (Fig. 3) showing at its base ophiolite-bearing, fine-grained sandstones. The metaradiolarites pass stratigraphically to the Erbajolo Fm., composed of thick layers of schists alternating with thin layers of impure marble (Fig. 3). At the Eastern rim of the study area, the Erbajolo Fm. shows a stratigraphic transition to Petraggiolo and Bagliacone-Riventosa Fms., a sequence of metamorphic, siliciclastic and carbonate turbidites, as described by De Cesari et al. (2024).

U-Pb Dating of Plagiogranites

The system of metaplagiogranite dykes of the study area have been previously studied by Ohnenstetter et al. (1981) and Li et al. (2015). For this study, a sample (VEZ10) of metaplagiogranite has been taken from an outcrop not studied before located in the Punta di Castelnuovo area, by selecting a dike from the latest stage of plagiogranite intrusion. The mineral assemblage of the sampled metaplagiogranites is made of albite (40%), quartz (30%), K-feldspar (10%), chlorite (10%) and titanite (5%). The remaining 5 vol% includes white mica, epidote, lawsonite, apatite and zircon. Albite shows a "dirty" inner portion enriched in lawsonite and white mica inclusions. Chlorite has a metamorphic origin and replaces the original biotite. Zircon crystals were extracted by crushing about 7 kg of sample VEZ10. They range in size from 70 to 250 μm and appear colorless, euhedral, and stubby in shape (Fig. 4). Under CL, grains show a large homogeneous, faintly zoned, or patchy interiors, either bright or dark and sometimes zoned. The rims are usually darker than the cores and show in few cases an oscillatory zoning. Small inclusions are sometimes placed along a narrow band close to the crystal edges (Fig. 4).

Thirty-one spot analyses were performed on zircon interiors from the sample VEZ10 (Table 1). These analyses yielded U-Pb dates ranging between 160 and 150 Ma (Fig. 5a). Thirteen spot analyses did not pass the discordancy test (Table 1). The U/Pb weighted mean performed on the sample VEZ10 gave an age of 157.2 ± 2.2 Ma (1, n = 28, MSWD = 3.8, Fig. 5b), which is interpreted as the crystallization age of the metaplagiogranite.

Mesoscopic Structural Analysis

In the field, the remnants of the first event of deformation D1 are rare. In the siliceous metapelites an S1 foliation has been recognized as a relic foliation within the microlithons of the S2 foliation. In the Erbajolo Fm. intrafoliar, isoclinal F1 fold with acute hinges are visible, as well as calcite and quartz-filled veins deformed by the S2 foliation (Fig. 6a).

The D2 phase is the most pervasive deformation event in the field.

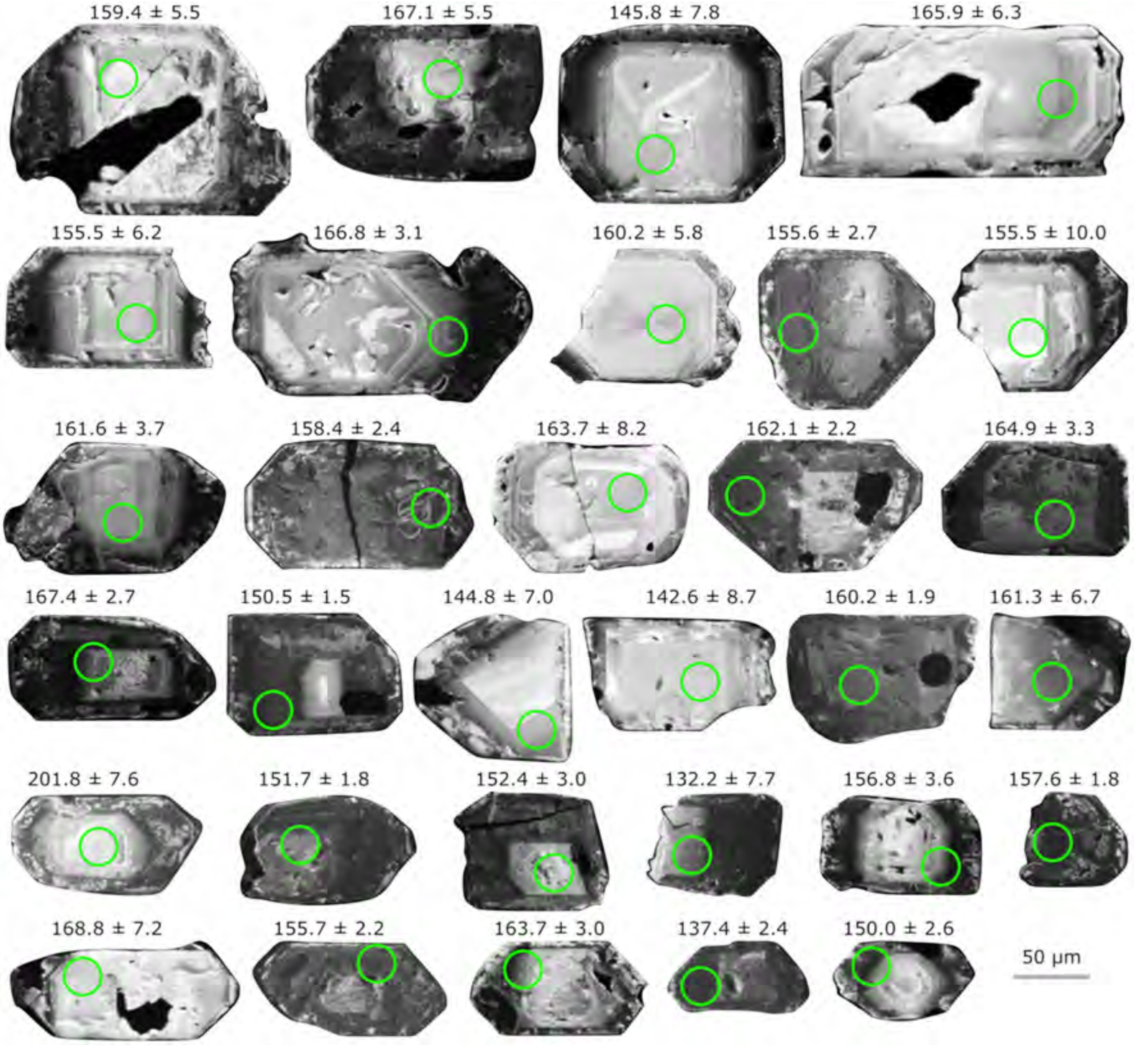

Figure 4. Zircons CL images and dated spots of the metaplagiogranite (sample VEZ10).

Table 1. Zircon LA-ICP-MS U/Pb Dates of Sample VEZ10

	Isotopic ratios						Dates (Ma)		Apparent dates (Ma)			
	$^{206}\text{Pb}/^{238}\text{U}$	2σ	$^{207}\text{Pb}/^{235}\text{U}$	2σ	$^{207}\text{Pb}/^{206}\text{Pb}$	2σ	$^{206}\text{Pb}/^{238}\text{U}$	2σ	$^{207}\text{Pb}/^{235}\text{U}$	2σ	$^{207}\text{Pb}/^{206}\text{Pb}$	2σ
VEZ10_1	0.0250	0.0009	0.1768	0.0292	0.0558	0.0089	159.4030	5.5381	159.2090	24.5516	416.6894	337.3445
VEZ10_2	0.0244	0.0010	0.1630	0.0310	0.0533	0.0099	155.5438	6.2485	146.1152	26.5400	117.1271	398.1151
VEZ10_3	0.0263	0.0009	0.3171	0.0369	0.0947	0.0102	167.0748	5.5489	271.7624	27.9831	1275.5624	224.3792
VEZ10_4	0.0252	0.0009	0.1261	0.0251	0.0418	0.0086	160.2127	5.7913	115.5167	22.4700	-348.7387	475.0351
VEZ10_5	0.0261	0.0010	0.2799	0.0647	0.0832	0.0178	165.8760	6.2637	238.8156	47.1161	555.4342	456.7753
VEZ10_6	0.0229	0.0012	0.1542	0.0382	0.0556	0.0139	145.8383	7.7631	134.5453	33.1497	974.4840	362.9017
VEZ10_7	0.0262	0.0005	0.1777	0.0146	0.0529	0.0042	166.8195	3.1350	164.5081	12.6603	276.7139	178.4439
VEZ10_8	0.0254	0.0006	0.1553	0.0178	0.0475	0.0054	161.6188	3.6616	144.0880	15.6219	-18.2334	268.8664
VEZ10_9	0.0263	0.0004	0.2000	0.0145	0.0580	0.0038	167.3892	2.6668	185.8328	11.5541	423.3284	142.7085
VEZ10_10	0.0259	0.0005	0.2235	0.0241	0.0638	0.0065	164.8973	3.2961	200.9857	19.4918	592.4654	231.1007
VEZ10_11	0.0257	0.0013	0.2011	0.0484	0.0588	0.0143	163.6545	8.2402	170.4514	38.9176	531.9970	416.2383
VEZ10_12	0.0249	0.0004	0.1933	0.0098	0.0557	0.0027	158.4127	2.3599	178.7230	8.3359	378.1172	113.6993
VEZ10_13	0.0255	0.0003	0.3059	0.0271	0.0854	0.0067	162.1047	2.1597	266.5472	21.1038	1178.4583	163.7676
VEZ10_14	0.0244	0.0004	0.1833	0.0155	0.0526	0.0039	155.6074	2.6706	169.1429	13.0740	181.9914	173.7705
VEZ10_15	0.0244	0.0016	0.2492	0.0740	0.0738	0.0205	155.5223	10.0479	194.8647	53.6517	1465.7769	370.1717
VEZ10_16	0.0236	0.0002	0.1619	0.0069	0.0487	0.0021	150.4934	1.5006	152.0410	6.0559	83.8862	102.7957
VEZ10_17	0.0238	0.0003	0.1732	0.0075	0.0513	0.0021	151.7129	1.8176	161.7457	6.4799	196.7758	98.9754
VEZ10_18	0.0227	0.0011	0.1637	0.0221	0.0526	0.0071	144.8027	7.0649	150.2213	19.1951	3.7870	365.7346
VEZ10_19	0.0224	0.0014	0.1544	0.0370	0.0506	0.0123	142.5922	8.6987	140.6667	33.0885	662.6521	367.2046
VEZ10_20	0.0246	0.0006	0.2283	0.0154	0.0669	0.0049	156.7789	3.5907	207.1678	12.6987	661.3616	175.0647
VEZ10_21	0.0257	0.0005	0.2215	0.0147	0.0617	0.0041	163.7068	2.9887	201.6997	12.1141	548.9904	149.8124
VEZ10_22	0.0239	0.0005	0.1795	0.0138	0.0548	0.0043	152.3842	2.9824	168.2135	11.2567	269.9007	174.5554
VEZ10_23	0.0236	0.0004	0.1844	0.0088	0.0561	0.0027	150.0496	2.5563	171.2925	7.5041	417.7303	107.1322
VEZ10_24	0.0215	0.0004	0.1586	0.0080	0.0524	0.0028	137.3746	2.3898	148.9614	7.0093	380.6551	101.1867
VEZ10_25	0.0244	0.0004	0.2459	0.0109	0.0735	0.0038	155.7098	2.2482	222.4216	8.8499	957.1968	103.1335
VEZ10_26	0.0318	0.0012	0.5740	0.0706	0.1312	0.0150	201.8071	7.6367	440.9671	43.9717	1824.6218	225.6038
VEZ10_27	0.0266	0.0011	0.2740	0.0438	0.0765	0.0122	168.8408	7.2194	233.6026	35.2536	1078.9780	294.0820
VEZ10_28	0.0248	0.0003	0.1778	0.0068	0.0515	0.0018	157.6142	1.7565	165.8039	5.8433	221.0368	81.5485
VEZ10_29	0.0207	0.0012	0.1557	0.0201	0.0597	0.0077	132.1892	7.7306	147.4745	19.1417	298.2255	355.0810
VEZ10_30	0.0253	0.0011	0.2422	0.0447	0.0666	0.0114	161.2802	6.6947	207.4393	35.1251	684.8558	334.6240
VEZ10_31	0.0252	0.0003	0.1900	0.0078	0.0541	0.0021	160.1705	1.8504	176.2142	6.6123	341.6618	85.9521
Ples_2	0.0511	0.0007	0.3634	0.0189	0.0544	0.0028	321.1023	4.2573	312.7669	14.1290	317.1913	122.4786
Ples_13	0.0535	0.0006	0.3687	0.0193	0.0535	0.0028	336.8296	3.2774	316.6951	14.1347	278.6817	121.0850
Ples_3	0.0540	0.0007	0.4695	0.0262	0.0626	0.0032	339.2373	4.1078	387.6522	17.7553	619.1036	108.2653
Ples_4	0.0531	0.0010	0.3939	0.0268	0.0538	0.0039	333.7451	6.0487	333.3604	19.6358	240.5351	172.5706
Ples_5	0.0562	0.0010	0.4003	0.0233	0.0526	0.0032	352.6222	6.0903	339.0542	16.8693	204.4543	150.1614
Ples_6	0.0569	0.0009	0.4076	0.0244	0.0530	0.0031	356.8344	5.5160	347.3467	18.5776	248.7772	148.5942

The F2 folds are widespread in the Erbajolo Fm., where strongly non-cylindrical, tight to isoclinal folds associated to a well-developed axial plane foliation can be observed (Fig. 6b). The thickened hinges of the F2 folds range from subangular to sub-rounded, whereas the limbs are usually thinned with well-developed boudinage and/or pinch and swell structures. The axis shows variable random strikes due to the non-cylindric geometry of the F2 folds and to their interaction with the D3 phase (A2 from Fig. 2b). The axial planes of the F2 folds and the associated S2 foliation show a prevalent NW-SE strike with a dip both toward W and E (S2 from Fig. 2b). L2 lineation with a N30 strike direction can be identified on the foliation plane (L2 from Fig. 2b). The main feature of the D2 phase is the strong partition of the defor-

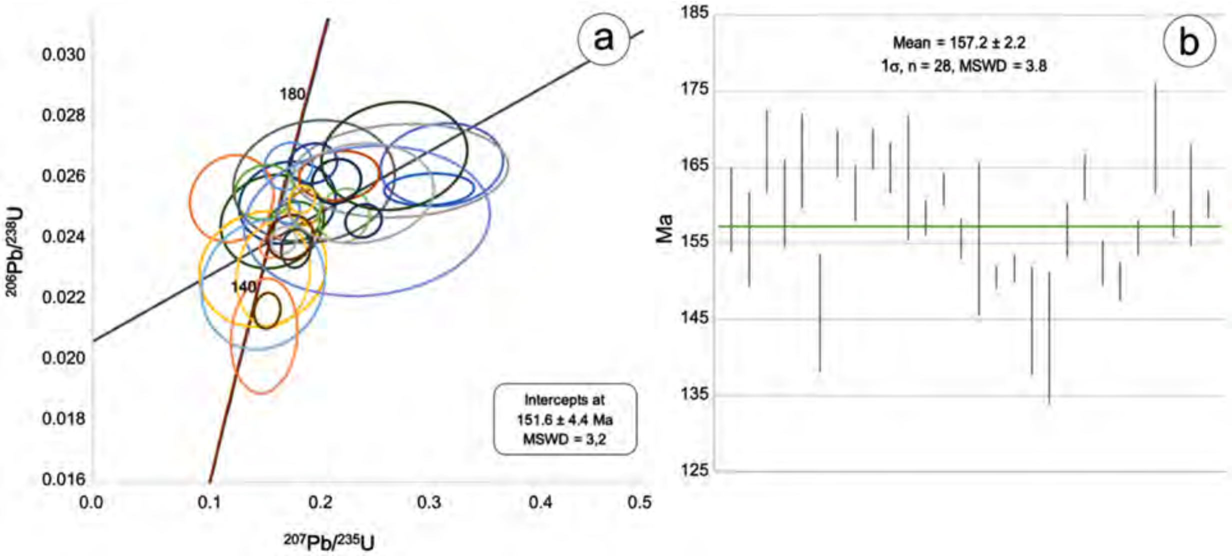

***Figure 5.** a) Concordia diagram and b) weighted average diagram related to the metaplagiogranite (sample VEZ10).*

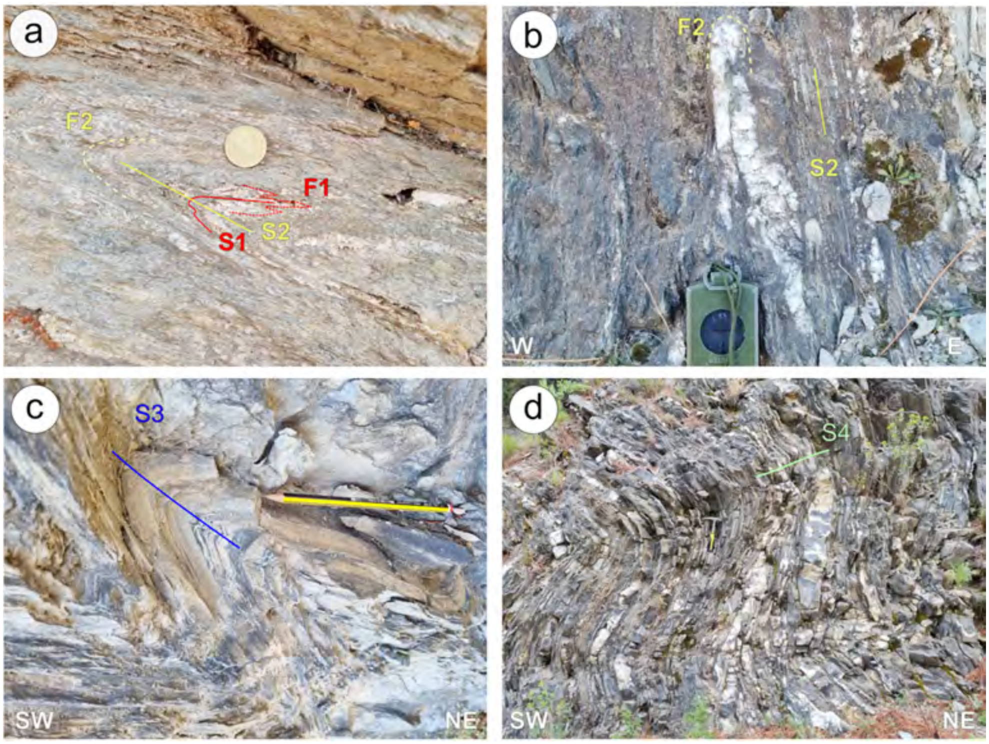

***Figure 6.** Mesoscale features of the D1-D4 deformation phases in the Inzecca Unit. a) Relations between the F1 and F2 folds in the Erbajolo Fm.; b) F2 fold and S2 foliation in the Erbajolo Fm.; c) F3 fold and related S3 foliation in the Petraggiolo Fm.; d) F4 fold and related S4 foliation in the Bagliacone-Riventosa Fm.*

mation at out-crop scale. In less competent lithologies, the S2 foliation obliterates the previous D1 phase structures as well the stratigraphic features, whereas the more competent lithologies are not affected by the S2 foliation and, consequently, the magmatic and sedimentary characteristics of both metaophiolites and metasediments can be fully detected. For instance, the metabasalts locally show well-preserved pillow-lava or pillow-breccia textures, whereas in other outcrops appear as well-foliated rocks without any record of the magmatic structures. Parallel to the S2 foliation are also several shear zones, ranging in thickness from 10 m to 60 m, characterized by core zones with a well-preserved mylonitic fabric. The core zones develop preferentially within a single rock type (e.g., the metabasalts) or even more frequently at the boundary of two different lithologies, such as along the contact between ophicalcites and metabreccias or between metaserpentinites and metagabbros. Along the mylonitic foliation, top-to-W kinematic indicators such as d-type porphyroclasts are observed (Fig. micro).

The D3 phase is characterized by tight to close, asymmetric F3 folds showing high-angle, east-dipping axial planes (Fig. 6c) and NW-SE striking A3 axes (A3 from Fig. 2b). The limbs are unaffected by boudinage, and the hinges are not thickened. The asymmetric shape of the F3 folds indicate a W-vergence of these folds. The S3 foliation is represented by a steep crenulation cleavage that can be observed only in the less competent lithologies. During this phase the shear zones developed during the D2 phase are locally overprinted by brittle deformations producing cataclasite bands made up of mylonite fragments.

The D4 phase is characterized by close to open folds with rounded hinges. The F4 folds show a low-angle axial plane (Fig. 6d), whereas the A3 axes show a main NW-SE trend that changes to NE-SW to the north of the mapped area (A4 from Fig. 2b). At the outcrop scale, the S4 foliation is represented by a low-dipping (S4 from Fig. 2b) and well-spaced crenulation cleavage.

Microscopic Structural Analysis

The foliations associated with the deformation phases show different micro-scale characteristics based on the mechanical properties of the lithotypes. More competent lithologies show a static recrystallization of metamorphic minerals during the D1 and D2 phases, so that no preferred orientation is visible at this scale. Less competent lithotypes show on the contrary a dynamic recrystallization associated with deformation, with development of distinct compositional domains characterized by a preferred minerals orientation.

At microscale, the remnants of the D1 phase are better preserved than at mesoscale. The S1 foliation (Fig. 7a) can be observed in the calcschists of the Erbajolo Fm., in the microlithons along the S2 folia-

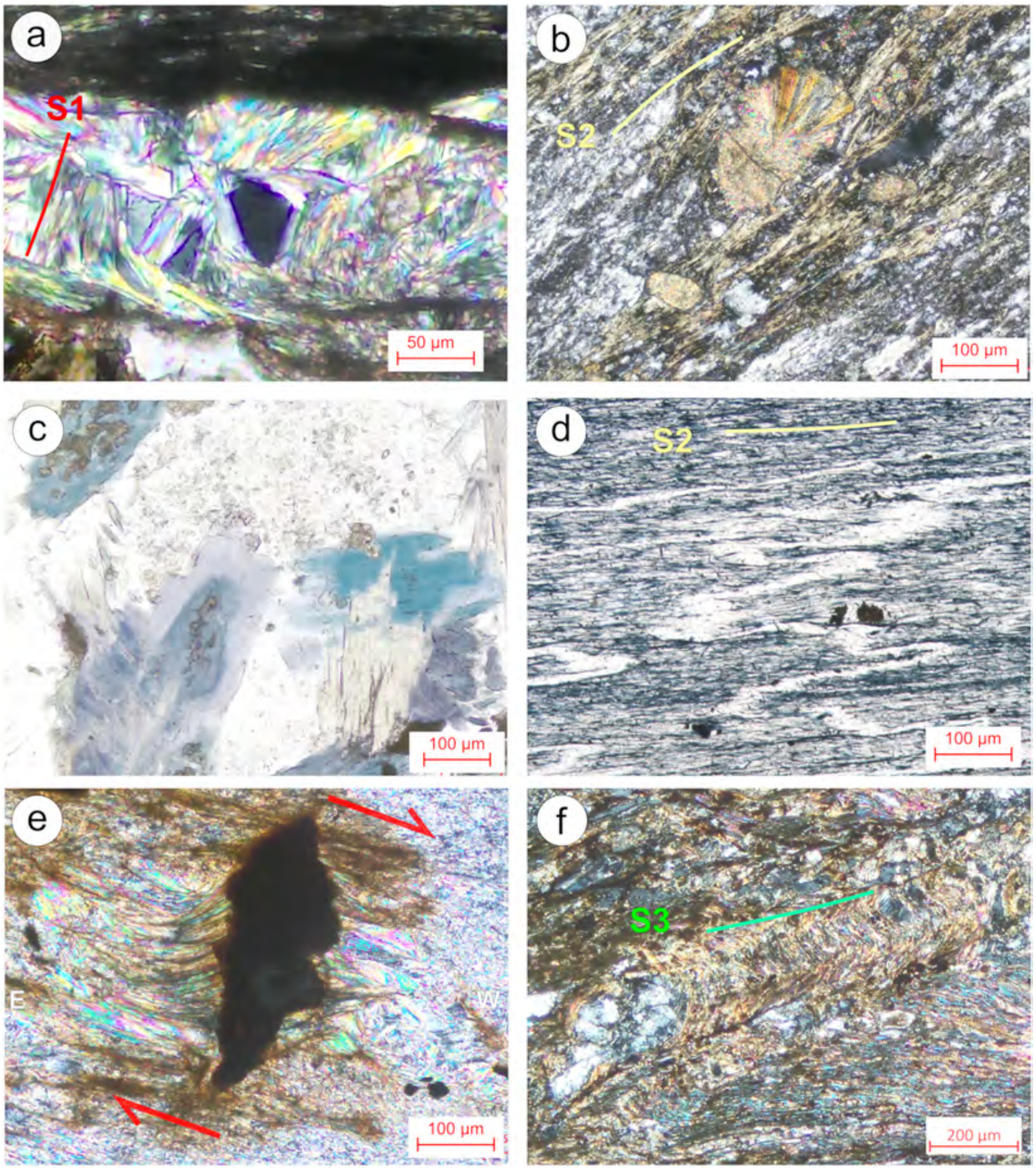

Figure 7. Microphotographs showing the D1-D3 deformation phases. a) S1 foliation made of white mica and chlorite into microlithons in the F2 hinge zone, Erbajolo Fm., sample ROS1 (cross-polarized Nicols); b) the S2 foliation in the metabasalts, sample IB4b (cross-polarized Nicols); c) static recrystallization of amphibole in the metaplagiogranite, sample TGM8 (parallel-polarized Nicols); d) F2 isoclinal folds and S2 foliation in the metaradiolarites, sample TGM5 (parallel-polarized Nicols); e) strain shadows wrapping a iron oxide aggregate in the metagabbro, sample IB6 (cross-polarized Nicols) and f) S3 foliation in the Erbajolo Fm., sample ROS1 (cross-polarized Nicols).

tion, as a schistosity with alternating granoblastic levels of quartz-albite aggregates and lepidoblastic levels with elongated chlorite-white minerals. The remnants of the D1 phase can be identified also in the more competent lithologies where the S2 foliation is not developed.

In the metabreccias and metagabbro (Fig. 7b) blue-amphiboles arranged in a radial pattern are very common. Zonate amphiboles are common in thin sections, with cores showing blue pleochroism surrounded by lilac rims (Fig. 7c). This variation is caused by a compositional variation during the retrograde metamorphic path from blueschist to greenschist facies. In the metabasalts, the relics of the D1 phase are instead represented by the blue amphiboles grown around the pyroxene crystals.

The S2 foliation is the most penetrative surface at microscale (Fig. 7d). In the calcschists of the Erbajolo Fm., this foliation shows a different texture along the hinge and the limbs of the F2 folds. Along the limbs, the S2 foliation is continuous and represented by a composite layering defined by the minerals grown during the D2 phase, i.e., chlorite, white mica, calcite and quartz, that overprinted on pre-existing ones. In the hinge, the S2 foliation can be instead classified as crenulation cleavage, characterized by smooth lepidoblastic domains consisting of chlorite and white mica that show a gradational to discrete transition to the granoblastic microlithons made up of quartz, albite, and calcite aggregates. Quartz veins are also present as tension gashes. In these lithotypes, the kinematic indicators suggest a top-to-W sense of shear (Fig. 7e). In the metabasalts, the S2 foliation consists of oriented chlorite, quartz, albite, epidote and sphene minerals that recrystallized around the relics of the magmatic paragenesis, such as oxides and pyroxenes, or around relics of blue amphibole reoriented along the S2 foliation. The oxides are altered to pyrites and show epidote asymmetric tails. In the siliceous metapelites from the metaradiolarites, the S2 foliation is represented by alternating lepidoblastic levels made of green-blue amphibole and mica, and granoblastic levels with a polygonal texture made of quartz and feldspar.

De Cesari et al. (2024) provide an accurate estimate of the P-T path for the Erbajolo Fm. by multiequilibrium approach. The P-T equilibrium of the S1 chlorite-white mica couples was estimated by these authors at 245-275 ℃ and 1.2-1.0 GPa. The P-T conditions related to the S2 foliation were instead estimated at 270-320 ℃ and 0.8-0.7 GPa.

At microscopic scale, the D3 and D4 phases are mainly registered in the less competent lithotypes, such as the calcschists from Erbajolo Fm. It can be described as a discrete and spaced millimetric crenulation cleavage without any metamorphic recrystallization (Fig. 7f).

Map-scale Structures

The geological mapping at 1:10000 scale has allowed identifying the map-scale structures, that have been assigned to the different deformation events recognized with the structural analysis. This is crucial for a correct reconstruction of the original stratigraphy of the Inzecca Unit in this sector of the belt.

The mapping shows that the folds of the D1 phase are lacking at all at meso-scale, whereas those of D2 phase are widespread and represent the main structural element in the map (Fig. 2). The lack of D1 phase structures can possibly indicate that in the study area only limbs of F1 folds are cropping out. In contrast, D2 phase produces structures that are represented by trains of alternating antiforms and synforms with the metaophiolites and the metasediments at the core, respectively (Fig. 2). The antiforms and the synforms show their closure downward and upward, respectively. These folds show subvertical axial plane and low- to medium-dipping axes whose strike progressively change from NW-SE to NNE-SSW moving from S to N in the mapped area. The interference of D2 phase folds with the topography indicate that A2 axes change not only their strike but also their plunge over short distance indicating a strongly non-cylindrical geometry of F2 folds at map scale. According to the microstructural evidence, the hinge zones of these structures show the S2 foliation overprinting at high angle the relics of S1 foliation. In the study area, the Inzecca Unit is tectonically dismembered in several slices, each bounded by D2 phase shear zones, everywhere striking parallel to the S2 foliation (Fig. 2). Four slices have been identified during mapping, each internally characterized by the same structural “antiforms and synforms” setting. Most of the folds show metabasalts at the core, sometimes surrounded by thin levels of metaradiolarites. Two outcrops show antiforms with metaperidotites at the core: one in the area of Punta di Tana along the road Vezzani – Pietroso (Fig. 2); and a bigger structure mapped in the area of the Foret de Padula (Fig. 2). In the northern rim of this bigger structure, metabreccias have been recognized between the metaperidotites and metabasalts, while they are absent in the southward prolongation of the fold core. Southeast of this structure, two small antiforms show metagabbros at the core. During D3 and D4 phase, the F3 and F4 folds deformed these antiforms and synforms without strong modification of the tectonic setting of the Inzecca Unit acquired during D2 phase. The most evident deformation at the map scale of D2 phase structures seems to be achieved during D4 phase, as suggested by the deformation of F2 folds axial planes by F4 folds characterized by low-angle axial planes.

Discussion

Reconstruction of the Oceanic Architecture

The stratigraphy and structure of the oceanic basin from which the Noceta-Vezzani metaophiolites derived has been reconstructed with the aid of several geological cross sections traced both parallel and perpendicular to the strike of the L2 mineral lineation, that allow a 3D view of the deformation structures at map-scale (Fig. 8). This, integrated with the detailed structural observations, allow a retro deformation of the structures to depict the original stratigraphic setting of the unit. This reconstruction indicates the occurrence of two different stratigraphic settings in the study area, as also detected in the southernmost outcropping area of the Inzecca Unit (Padoa, 1999).

The first representative stratigraphy, that characterizes the easternmost outcrops, shows metaperidotites directly covered by metabasalts, that pass to the Erbajolo Fm, with a discontinuous level of metaradiolarites at its base. Metaophicalcites are frequently found at the top of the metaperidotites at the boundary with the metabasalts. The primary stratigraphic relationships between metaperidotites and metabasalts is testified locally by very thin levels of ophiolitic metasandstones between them,. The plagiogranites dykes represent the last magmatic event recorded in this stratigraphic setting, that has been estimated to be 157.2 ± 2.2 Ma in age. This result is coherent with previous estimates by zircon geo-

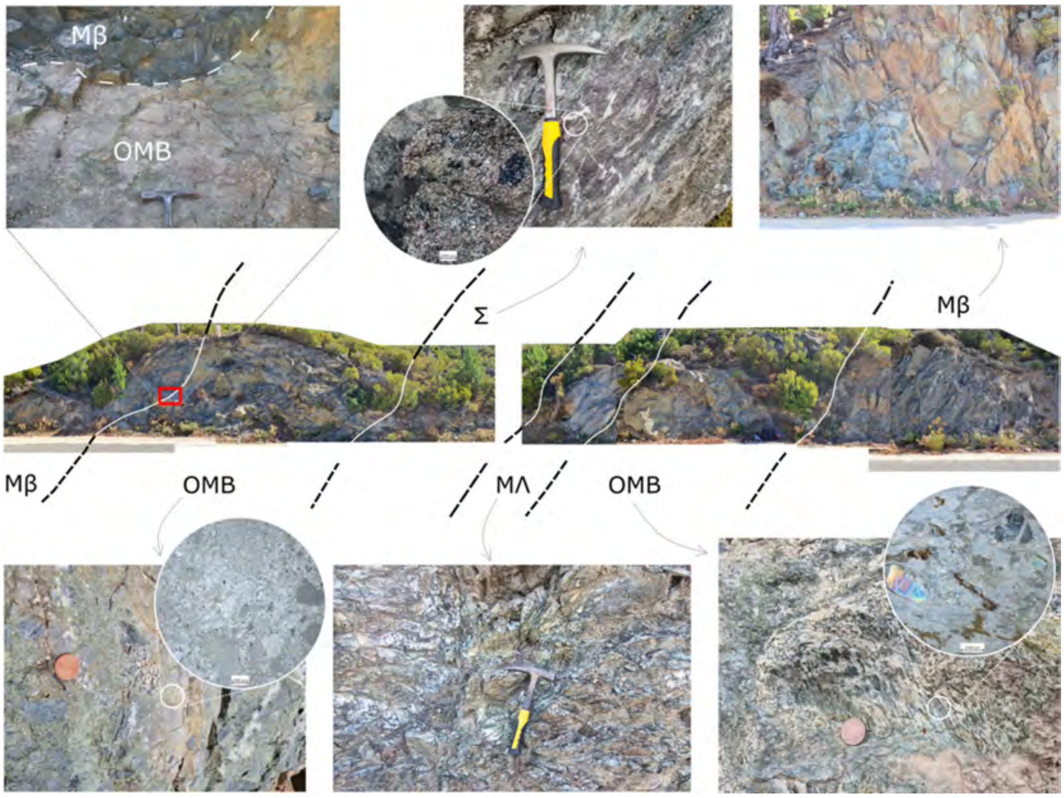

Figure 8. ***Meso-to microscopic characterization of the lithostratigraphy along a well exposed transect of the ophiolitic sequence northward of Foret de Padula on the D343 road.***

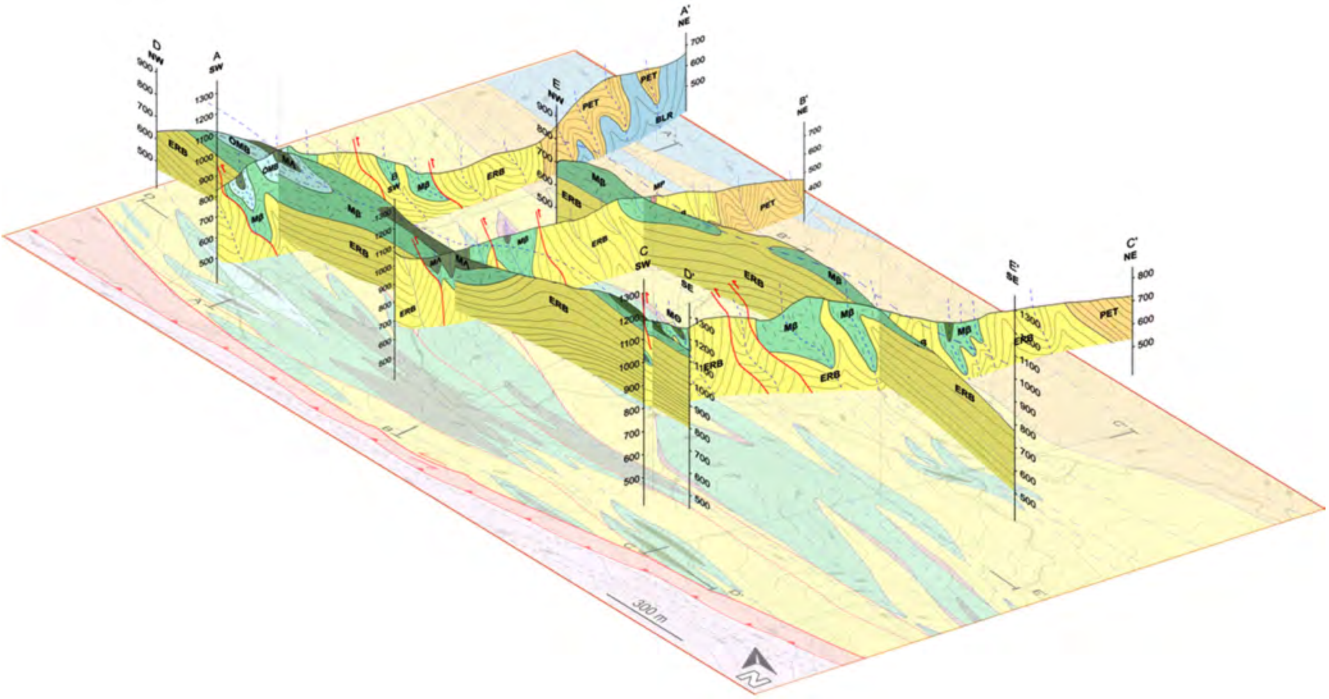

Figure 9. ***3D geological setting related to the area shown in Fig. 2 reconstructed by N-S and E-W trending cross sections.***

chronology at 161 ± 3 by Ohnenstetter et al. (1981) and at 159 ± 2 Ma by Li et al. (2015). Overall, these data indicate that the last magmatic stage in the Inzecca metaophiolites occurred in the Kimmeridgian-Oxfordian time (Cohen et al., 2023).

The second stratigraphic setting, typical of the westernmost outcrops, is instead characterized by metaperidotites covered by metabreccias that are in turn topped by metabasalts. A well-exposed section can be seen along the roadcut immediately northwest of Foret de Padula area (Fig. 2), where a D2 phase synform with a core of metaperidotites passing along the limbs to metaophicalcites, metabreccias and metabasalts, crops out (Fig. 9). The angular shape of the fragments, the lack of grading, and the very poorly sorting indicate that metabreccias can be regarded as proximal deposits sedimented at the base of oceanic scarps. Along these scarps both the mantle peridotites and gabbros were exposed, as suggested by the fragments recognized in the metabreccias. In addition, the occurrence of basalt fragments suggest the occurrence of a volcanic sequence older than that recognized at the top of the metabreccias and not preserved in the sequence of the Inzecca Unit.

The relationships between these two settings are now obliterated by the subduction-related tectonic, and only some hypotheses can be made. First, a laterally discontinuous distribution of the metabreccias layer, progressively thinning and pinching out along a slope, can be supposed. Alternatively, the boundary between the two settings could be represented by a fault that originated in the oceanic setting during the Middle to Late Jurassic spreading phase and was subsequently reworked during the subduction-related deformations. Unfortunately, no clear evidence in the field has allowed discriminating between these two hypotheses.

Another important feature of the Noceta-Vezzani metaophiolites is the occurrence of copper sulphides deposits, as described by El Gadarri (1995). These deposits are interpreted as connected to fluid circulation within the oceanic crust driven by fault zones that represented important pathways for seawater. The seawater was thus able to penetrate in the deeper crustal levels or into the mantle section, to metasomatize the fractured rocks and rise to the surface as hot mineralized fluids throughout the oceanic fault zones. The oceanic section, therefore, was dissected by a system of fault zones that enhanced fluid circulation and related mineralization.

A tentative reconstruction of the ocean architecture is proposed in Fig. 10a, where the pinch-out of the metabreccias is depicted, to show the two different stratigraphic sections.

Geodynamic Setting of Origin for the Reconstructed Architecture

The proposed architecture indicates that the remnant of the oceanic basin preserved in the Noceta-Vezzani metaophiolites was characterized by a basement made up of serpentinized mantle peridotites, probably intruded by small gabbro bodies. This basement was locally exposed at sea bottom, as testified by the occurrence of ophicalcites (e.g., Treves & Harper, 1994), in part topped by ophiolite-bearing breccias and then everywhere covered by basalts, that were in turn intruded by metaplagiogranites (Fig. 10).

In contrast to the previous interpretation by Ohnenstetter (1979), and according to the modern examples from Indian (Searle and Bralee, 2007; Boulanger et al., 2020) and Atlantic Oceans (Dick et al., 2008; Momoh et al., 2020). these characteristics unambiguously indicate that these ophiolites originated in an ultra-slow spreading ridge. following these models, the ultra-slow spreading ridge was characterized by alternation in time and space of volcanic events, with a reduced amount of magmatism, and tectonic events, dominated by extension achieved by normal faults. The extensional tectonics resulted in the exhumation of oceanic mantle and/or lower crust along structural highs, i.e. the non-volcanic oceanic sections, bounded by basins where the basaltic flows and/or sedimentary breccias accumulated, i.e., volcanic sections. According to these models, we can interpret the ophiolite sequence from the Noceta-Vezzani area as representative of a volcanic section, where evidence of several magmatic- and tectonic-dominated events are recorded.

The older magmatic event is poorly represented in the study area. The gabbros as well as the clasts of gabbro and basalt found in the ophiolitic metabreccias are the remnants of this magmatic-dominated event that probably originated a very thin oceanic crust.

This crust was destroyed by the subsequent tectonic-dominated event that resulted in the mantle exhumation and consequent wide exposure of the peridotites and the gabbros at the sea bottom by low-angle detachment faulting. The occurrence of metaophicalcites, representative of a hydrothermally weathered cataclastic shear zone, found at the top of the metaperidotites is the main evidence for mantle exposure. The detachment faulting occurred by localized deformation represented at depth by ductile, low-angle shear zone characterized by mylonites, as those recognized in the metagabbros. The mylonites were originated at depth under P-T conditions pertaining to amphibolite facies metamorphism, and then were progressively exhumed and affected by a cataclastic deformation at the uppermost structural level. This history is well-testified by the mylonitic gabbros preserved into the clasts of metabreccias. The main result of this extensional tectonics is well visible in active divergent margins, where domed, foot-wall massif comprising lower crust and upper mantle peridotite are described (e.g., Blackman et al., 2002; Dick et al., 2008). Accordingly, ophiolite-bearing breccias were supplied by the fault scarps and accumulated in the throughs.

The tectonic-dominated event was followed by a younger magmatic-dominated event represented first by the basaltic flows and then by the emplacement of the metaplagiogranites. The basalts, originated by a neo-volcanic zone, were emplaced on an ocean floor characterized by rugged morphology inherited by the previous extensional tectonics and still able to provide coarse-grained debris.

After these complex magmatism-tectonics interactions, the ocean floor of the Western Tethys oceanic basin, characterized by the exposure of oceanic mantle and/or gabbros along the structural highs and by small areas showing volcanic rocks, was subsequently covered by oceanic sediments, represented by metaradiolarites and calcschists. It is noteworthy that the calcschist lacks ophiolite-bearing breccias and sandstones, thus suggesting that in the Early Cretaceous the structural highs were totally covered by the oceanic sediments and did not function as sources of ophiolitic debris anymore.

Comparison with Analogous Examples from Northern Apennine, Alpine Corsica, and Western Alps

The reconstructed architecture of the Noceta-Vezzani metaophiolites is directly comparable with other examples of Middle to Late Jurassic, metamorphic ophiolites from Northern Apennine, Alpine Corsica, and Western Alps (e.g., Amaudric du Chaffaut et al., 1972), and then helps a more detailed reconstruction of the structure and architecture of the Western Tethys oceanic basin.

The studied sequence can be correlated with those of the Internal Ligurian Units (Fig. 10) of the Northern Apennines, more precisely in the Bracco-Val Graveglia Unit, where the ophiolites are affected by deformation and metamorphism acquired during Alpine subduction

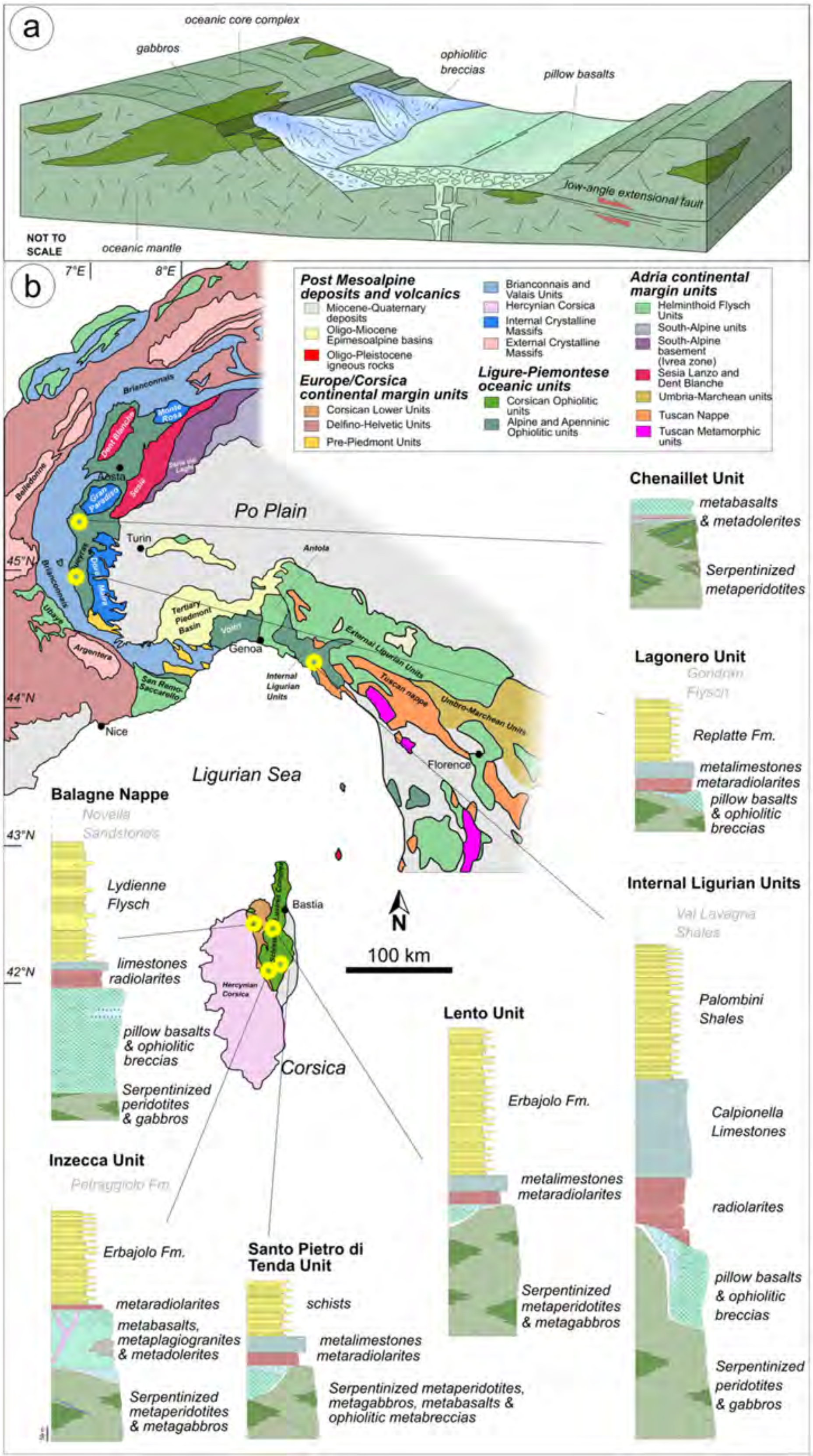

Figure 10. a) 3D reconstruction of the sector of the Western Tethys from which the metaophiolites of the study area derived. b) Tectonic setting of the Western Alps, Northern Apennines and Alpine Corsica (modified from Di Rosa et al., 2023). The lithostratigraphic logs of the Western Tethys- derived units is also shown: Chenaillet (from Manatschal et al., 2011), Lago Nero (from Burroni et al., 2003), Internal Ligurian (from Marroni et al., 2017), Lento (from Levi et al., 2007), Balagne (from Marroni and Pandolfi, 2003) and, Santo Pietro di Tenda (Filimon et al., submitted) Units.

(Marroni, 1991; Meneghini et al., 2007), although at shallower prehnite-pumpellyite facies metamorphic condition (Sanità et al., 2024) compared to the Noceta-Vezzani metaophiolites. The ophiolite sequence from the Internal Ligurian Units (Decandia & Elter, 1972; Cortesogno et al., 1987; Principi et al, 2004) are unambiguously interpreted originated in an ultra-slow spreading ridge (Donatio et al., 2013; Saccani & Principi, 2016; Festa et al., 2021), where the extensional tectonics played a major role in producing the exposure at sea bottom of the deep portions of oceanic lithosphere, such as mantle rocks or gabbros. The Internal Ligurian ophiolites also include both non-volcanic (Bracco and Scogna areas) and volcanic (Val Graveglia area) sections (Sanfilippo and Tribuzio, 2011 and references therein). The volcanic section is characterized by mantle rocks intruded by km-sized bodies of gabbros that are covered by basaltic flows interfingering with ophiolite-bearing breccias and then directly by oceanic sediments. The composition of ophiolite-bearing breccias, up to 200 m thick, strictly reflect the composition of the source areas (Cortesogno et al., 1987; Principi et al., 2004).

The same picture arises from the metamorphic ophiolites of Western Alps (Festa et al., 2015; Lagabrielle et al., 2015; Balestro et al., 2019; De Togni et al., 2021). The blueschist facies Queyras metaophiolites (Fig. 10b), for example, display several volcanic sections, where a basement consisting of metaperidotites and metagabbros is covered by ophiolite-bearing metabreccias interfingering with pillow and pillow-breccia metabasalts, up to 200 metres thick. Between these metaophiolites, Burroni et al. (2003) have reconstructed in the Lago Nero area (Fig. 10b) an ophiolite sequence where the metaperidotites, with a level of metaophicalcites at their top, are covered by metabreccias and metabasalts. The eclogite-facies metamorphic ophiolites of the Monviso area (Fig. 10b) also show sequences where the metaperidotites are locally covered by metabasalts without an intervening level of metabreccias (Festa et al., 2015; Balestro et al., 2019). The occurrence of a non-volcanic section, where the metaperidotites with metaophicalcites at their top are covered by metabreccias, have been instead described in eclogite facies metamorphic ophiolites from the Stura di Viù valley (Fig. 10b) by De Togni et al. (2021). Moreover, the low-grade blueschist Chenaillet ophiolites (Corno et al., 2023), show metaperidotites intruded by gabbros (Fig. 10b), partly topped by 200 meters thick sequence of pillow and pillow-breccia basalts (Chalot-Pra, 2005; Tribuzio et al., 2019).

In Alpine Corsica, several examples of ophiolites with a comparable stratigraphic setting can be also observed (Lagabrielle and Lemoine, 1997; Vitale Brovarone et al., 2013). The Balagne Nappe (Fig. 10b), belonging to Upper Units, are regarded as slices derived from an oceanic crust sector very close to the European continental margin and affected by very low-grade metamorphism during subduction-related deformations (Marroni and Pandolfi, 2003). These ophiolites include a basement, whose remnants include both peridotites and gabbros, covered by a thin level of ophiolite-bearing breccias and by a very thick volcanic sequence consisting of pillow and pillow breccia basalts with local sills of dolerites. Within the Schistes Lustrés Complex, the Lento Unit (Fig. 10b) displays an ophiolite sequence that includes a basement consisting of mantle metaperidotites intruded by metagabbros and covered by metaophicalcites. The basement is topped by metabasalts covered in turn by metaradiolarites and by metasediments of the Erbajolo Fm., as detected in the Golo Valley (Rossi et al., 2001; Levi et al., 2007). Within the same unit, the volcanic sequence shows a transition to non-volcanic one where the metaperidotites and the metaophicalcites are directly covered by metasediments devoid from any ophiolite-bearing debris. A similar ophiolitic sequence is also documented east of Vezzani in the Matra area, where the Santo Pietro di Tenda Unit is exposed (Caron et al., 1990; Filimon et al., submitted). The latter is one of the oceanic-bearing units located in the lowermost position of the Schistes Lustrés Complex which registered the eclogite facies metamorphism during the Alpine orogeny (Vitale Brovarone et al., 2013).

Overall, the reconstructed ophiolite sequence in Noceta-Vezzani area can be correlated with the oceanic volcanic sections from the Northern Apennines, Alpine Corsica, and the Western Alps which, in association with non-volcanic sequences, seems to characterize the crustal structure of the entire Western Tethys basin as originated in an ultra-slow spreading ridge.

Conclusions

The Noceta-Vezzani metaophiolites represent a slice of the oceanic crust derived from the Western Tethys basin and deformed in a subduction zone at high-pressure metamorphic P-T conditions. Despite their complex structural setting, the primary lithostratigraphic framework of the metaophiolites has been reconstructed by a multidisciplinary approach at different scales, from map- to microscale. These metaophiolites consist of a basement made up of metaperidotites intruded by small bodies of gabbros and topped by metaophicalcites. This basement is partly covered by ophiolite-bearing metabreccias and then by metabasalts that are in turn intruded by metaplagiogranites of Kimmeridgian-Oxfordian age by U/Pb zircon dating. The metabasalts are topped by metaradiolarites and by the metasediments belonging to the Erbajolo, Petraggiolo and Bagliacone-Riventosa Fms. The characteristics of the ophiolite sequence indicate its origin in an ultra-slow spreading ridge by interaction of several magmatic and tectonic events, as recognized in the present-day oceanic basins. In this frame, the Noceta-Vezzani metaophiolites represent a volcanic section, i.e., a sequence characterized by two, subsequent magmatic events interspersed by an extension tectonics, which is similarly recognized in the ophiolites from thenNorthern Apennines, Western Alps and Alpine Corsica.

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