Ocean Subduction Dynamics in the Alps

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The Alps preserve abundant oceanic blueschists and eclogites that exemplify the selective preservation of fragments of relatively short-lived, small, slow-spreading North Atlantic–type ocean basins whose subducting slabs reach down to the Mantle Transition Zone at most. Whereas no subducted fragments were returned during the first half of the subduction history, those exhumed afterwards experienced conditions typical of mature subduction zones worldwide. Sedimentary-dominated units were underplated intermittently, mostly at ~30–40 km depth. Some mafic–ultramafic-dominated units formed close to the continent were subducted to ~80 km and offscraped from the slab only a few million years before continental subduction. Spatiotemporal contrasts in burial and preservation of the fragments reveal how along-strike segmentation of the continental margin affects ocean subduction dynamics.

Keywords: subduction; Alps; rock record; slab dynamics; oceanic lithosphere

WHAT SORT OF OCEANIC SUBDUCTION IN THE ALPS?

Subduction of oceanic lithosphere is a key driver of plate tectonics and a major seismic and volcanic hazard. Remnants of subducted rocks, such as blueschists and eclogites, provide a window on the physical and chemical processes operating at depths beyond direct observation (~20–100 km). Subducted remnants abound in the Alps. The Alps were the original natural laboratory where the concept of subduction first emerged (Ampferer and Hammer 1911) and where the relationship between high-pressure–low-temperature (HP–LT) metamorphism and subduction was first discerned (Ernst 1971; Chopin 1984).

But to what extent is Alpine subduction representative of subduction dynamics worldwide? The Alpine Ocean (or Alpine Tethys) is special in several ways: it was characterized by ~400–700 km wide Atlantic-type, slow-spreading oceanic lithosphere, with no associated volcanic arc and with trench sediments quite different from those in peri-Pacific subduction zones today (Lemoine et al. 1986).

How much and what sort of oceanic subduction prevailed in the Alps? Are there major differences along the belt? What role did inherited tectonic features play? Here, we focus on the subduction of oceanic lithosphere, discuss its implications for subduction processes and address some points of contention that have recently emerged.

SMALL OCEAN(S) MADE OF DISCONTINUOUS LITHOSPHERE

Subducted Remnants Scattered Throughout the Alpine Orogen

Fragments of oceanic lithosphere subducted prior to collision of the Eurasian and Adriatic plates are exposed in the Alpine orogenic core in the two sutures of the Alps: the Liguro–Piemont and Valais domains (Fig. 1A) (Schmid et al. 2004). These were small oceanic basins floored by heterogeneous oceanic lithosphere (mostly pelagic sediments, altered basalts and serpentinized peridotites) (Lemoine et al. 1986) and characterized by broad ocean–continent transitional domains and small continental fragments (Fig. 1B).

The Alpine fragments of subducted oceanic lithosphere show diagnostic HP–LT minerals: lawsonite, omphacite, blue amphibole, garnet (in metamafic rocks); Fe–Mg-carpholite, lawsonite, chloritoid, garnet, talc, coesite (in metasedimentary rocks); antigorite and titano-clinohumite/chondrodite (in metaperidotites). The metamorphic gradient from blueschist to transitional blueschist–eclogite to eclogite facies, which is best preserved in the Western Alps (Fig. 1C), is consistent with southeast-directed subduction of oceanic and European lithosphere below the Adriatic plate (Handy and Oberhänsli 2004). In the Eastern Alps, the same fossil subduction zone is exposed in the Engadine, Tauern and Rechnitz Windows (Fig. 1). The overlying Austroalpine nappes also contain HP–LT remnants, but these are related to the older closure of a northwestern branch of the Neotethys Ocean (Fig. 1B) (Froitzheim et al. 1996).

Geodynamic Setting: Boundary Conditions for Oceanic Subduction

Kinematic reconstructions (Handy et al. 2010; Vissers et al. 2013) indicate that the Alpine Ocean was ~400–700 km wide and comprised, in its southern part (Fig. 1B), the ~300–400 km wide Liguro–Piemont Ocean, the ~100–150 km wide continental fragment of the Briançonnais Domain and, in the southwest, the 50–200 km wide Valais Ocean.

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Slow opening of the Liguro–Piemont Ocean (<2 cm/y) occurred between 170 Ma and 120 Ma. The age range of gabbros (~165–150 Ma) (Fig. 2A), which are the remnants of the Liguro–Piemont crust, shows that subsequent magmatism was either insignificant and/or that the entire oceanic lithosphere that had formed between ~150 Ma and 120 Ma was subducted without a trace.

The locus (and mechanism) of subduction initiation beneath Adria is not well constrained, but likely started to the east of the Sesia Zone for the Liguro–Piemont Ocean (Fig. 1B). Orogenic flysch deposits constrain the onset of subduction to around 100–95 Ma, but no later than 84–86 Ma (Handy et al. 2010). Subducted oceanic fragments yield peak burial ages mostly between 60 Ma and 35 Ma (Fig. 2C) (Berger and Bousquet 2008). Continental subduction affected the Sesia Zone (75–65 Ma), the Briançonnais Domain, including the Internal Basement Complexes of the Monte Rosa, Gran Paradiso, and Dora Maira massifs (~42–35 Ma), and the European margin (e.g., Adula) at 38–35 Ma. Collision between Europe and Adria started at 34–32 Ma in the Western Alps. Given that 400–700 km of lithosphere (including the Briançonnais Domain) was subducted within ~60 Ma, the inferred subduction rate from 100–95 Ma to 40–35 Ma was ~1 cm/y. A minimum of ~200–300 km of this subduction was truly oceanic in the Liguro–Piemont Ocean (Handy et al. 2010). In the Central and Western Alps, the largely detached Alpine slab possibly reached down to the Mantle Transition Zone, suggesting that slab dynamics were confined to upper mantle convection.

Material Types: Ultramafic, Mafic and Sedimentary

The Alpine Ocean lithosphere comprised extensive, partly refertilized, exhumed mantle that was directly overlain by deep-sea sediments and ophicarbonates, plus discontinuous patches of gabbroic or basaltic bodies and limited ridge-type magmatism (Manatschal and Müntener 2009). Pelagic sediments deposited on the seafloor (typically ~200–400 m thick) exhibit syntectonic centimetre-to-metre scale ophiolitic or continental detritus (Fig. 2B) and, in places, kilometre-sized carbonate or continental fragments (e.g., Tasna, Err–Platta) that are interpreted as extensional allochthons (Fig. 1B).

Late Cretaceous to Paleocene flysch sequences interpreted as trench sediments mark the former accretionary margin during oceanic subduction. Tethyan sediments dominated by carbonates and organic-rich pelites (the future "calcschists") contrast with the more mafic graywackes of the circum-Pacific trench fills. The Alpine Tethyan seafloor, thus, did not resemble the thick, stratified Pacific-type crust but rather, in terms of size and constitution, parts of the North Atlantic, such as along a NW–SE transect between Greenland and Norway.

SEDIMENTARY VERSUS MAFIC–ULTRAMAFIC-DOMINATED TECTONIC UNITS

Tectonic units are dominated by two types of rock (Agard et al. 2009). First, the metamorphosed pelagic sediments that were to become the calcschists of the Schistes Lustrés and Bündnerschiefer, herein termed the S (sedimentary) units. Second, the MUM (mafic and ultramafic) units, which contain only minor calcschists.

In the Western Alps, the S units are dominantly blueschist facies and are located in the west, whereas the large, mainly eclogitic mafic and ultramafic bodies crop out structurally below and to the east (Fig. 1D and Fig. 2D). The consistency of structural and metamorphic patterns within the various units (either S or MUM) suggests that they were exhumed as individual tectonic slices and nappes along the subduction interface, and not as a kilometre-scale mélange. Both types were largely exhumed by 35 Ma (Agard et al. 2002), before collision.

Metasedimentary-Dominated Units from the Western Alps

The S units comprise intensely folded calcschists, rare marbles and minor fragments of other oceanic rocks (Fig. 2B). These can be distinguished using lithostratigraphy and metamorphic grade (Plunder et al. 2012; Lagabrielle et al. 2015) and divided into three broad units. First, chloritoid ± garnet ± epidote–bearing lower S units formed at 2.0–2.3 GPa and 470–550 °C. Second, more calcareous, chloritoid + lawsonite or epidote–bearing middle S units formed at 1.5–2.0 GPa and 370–450 °C. Third, lawsonite- and/or Fe–Mg-carpholite–bearing upper S units formed at 1.1 GPa and 330 °C and at 1.4 GPa and 350 °C.

A continuous evolution of *P–T* conditions is observed in the southwestern Alps, from 1.2 to 1.3 GPa and 350 °C to ~2.0 GPa and 500 °C (Fig. 2F). These metasediments were scraped off the underlying oceanic crust/mantle during subduction, then underplated at depths between ~30 km and 60 km from ~62 Ma to ~50–45 Ma (in the Cottian Alps) and at 40–36 Ma (in the Combin Zone). Exhumation rates were on the order of 1–2 mm/y (Fig. 2C) (Agard et al. 2002).

Mafic/Ultramafic Dominated Units from the Western Alps

Large, 1–10 km long eclogitized MUM fragments with subordinate metasediments are found in the Liguro–Piemont Ocean, but not in the Valais Ocean (Fig. 1D). Although strongly deformed and crosscut by shear zones, they are continuous over kilometre lengths and hectometre- to kilometre thick domains. These eclogitized MUM fragments preserve coherent "slab" structures, including sedimentary and/or magmatic features partly reworked during subduction and exhumation (Balestro et al. 2015). Two examples can be given:

(i) Zermatt–Saas, where tectonic slices are variably retrogressed garnet–clinopyroxene ± glaucophane–talc–chloritoid–lawsonite metabasalts (Fig. 2E). The *P–T* conditions are relatively constant at ~2.5–2.8 GPa and 550 °C (Angiboust et al. 2009), with the exception of one small, hm-thick, 2 km^2 locality hosting coesite-bearing ultra-high pressure (UHP) metasediments (Cignana, ~2.8–3.2 GPa, 600 °C). Age constraints for peak burial cluster are at 43 ± 4 Ma, with indications for prograde growth at 49–48 Ma (Fig. 2C).

(2) In the Monviso area, the ~15 km long, 2–3 km thick Lago Superiore Unit is the most intact eclogitized slab fragment recognized worldwide, with serpentinized ultramafics, Mg-rich metagabbros, Fe–Ti metagabbros capped by metabasalts and metre-thick calcschist horizons. Peak burial at ~2.6–2.7 GPa and 550–580 °C was attained at 46 ± 3 Ma, following prograde mineral growth at 49 Ma (Fig. 2C). Its detachment from the slab at ~80 km depth was promoted by extensive fracturing, as recorded by eclogite breccia preserved in shear zones (Fig. 2E) (Locatelli et al. 2018).

While MUM units show variations – in internal structure and crustal components that can be attributed to complex ocean–continent transitional domains and/or magmatic processes – all record strikingly similar *P–T–t* conditions, with peak burial near ~2.6 ± 0.2 GPa, at 550 °C, and taking place at 45 ± 5 Ma (Figs. 2C and 2F). The MUM units were, therefore, metamorphosed and detached from the top of the slab at the same ~80 km depth late in the

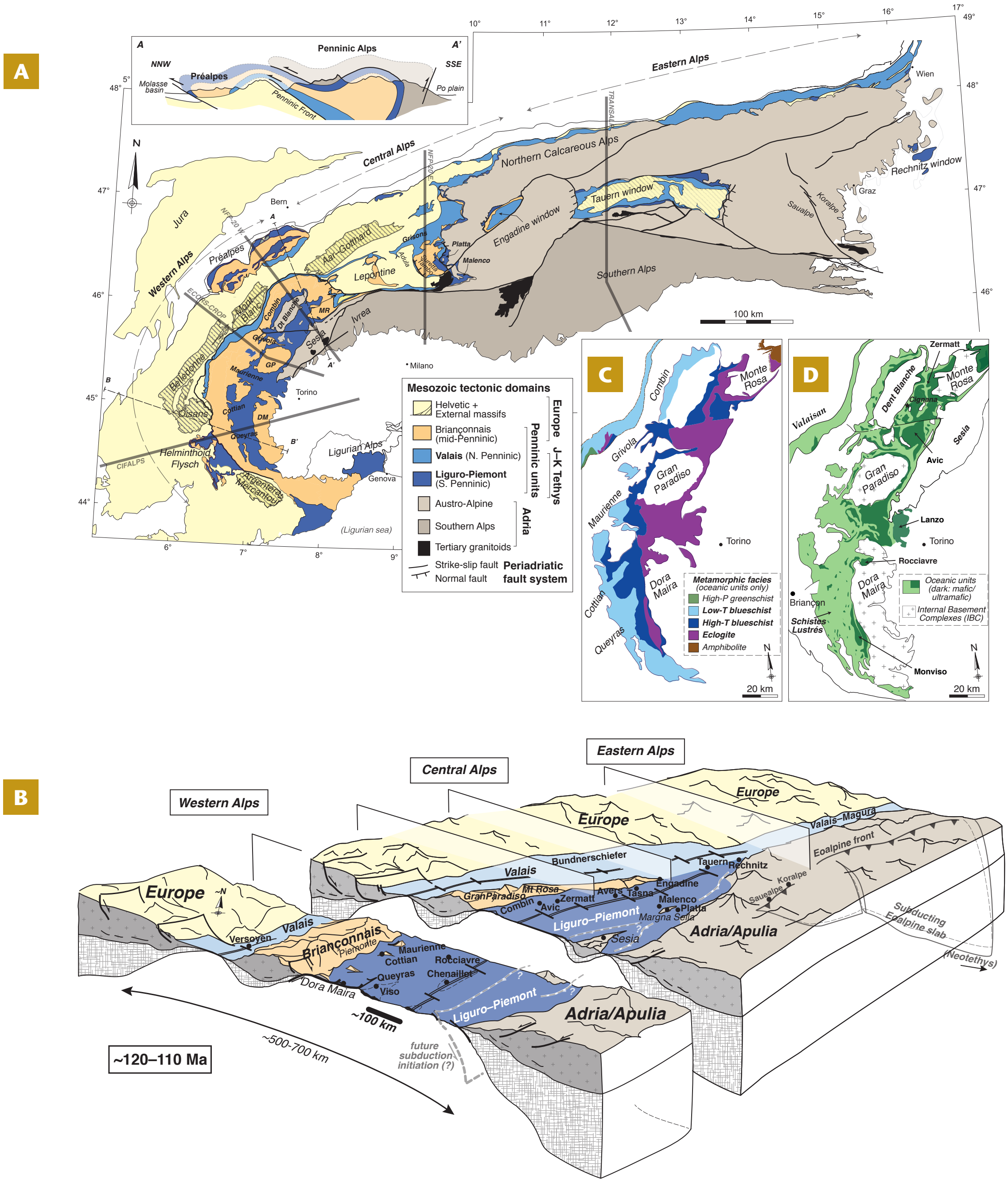

FIGURE 1 (**A**) Structural map of the Alps, showing the two oceanic domains of the Alpine Ocean/Tethys: the Valais Ocean and the Liguro–Piemont Ocean. INSET Schematic cross section A–A´ [point A is just SW of Bern] shows the simple organization of the major palaeogeographic domains, from the Austro-/South-Alpine units on top to the European units below. Abbreviations for Western Alps: DM = Dora Maira ; GP = Gran Paradiso ; MR = Monte Rosa. Cross section labelled B–B´, see FIGURE 2B. The five grey lines labeled with acronyms/initialisms are seismic transect lines. AFTER HANDY AND OBERHÄNSLI (2004). (**B**) A 3-D view of the Alpine domain at ~120–110 Ma (compare with FIG. 1A), showing the broad ocean–continent transition, micro-continental blocks and localities discussed in the text. The Eoalpine subduction zone is depicted schematically. (**C**) Distribution of metamorphic facies across the Western Alps. (**D**) Distribution of sedimentary- and mafic–ultramafic-dominated units.

oceanic subduction history (FIG. 2C). Subsequent deformation and slicing along the plate interface occurred during syn-convergent exhumation at ~42–36 Ma at a rate of ~1 cm/y. Unlike the S units, the MUM units are closely associated with the Internal Basement Complexes: they are always tectonically underlain by them, share similarly oriented high-pressure stretching lineations, and have only slightly older peak burial ages (FIG. 2C) (Gran Paradiso and Monte Rosa: 42–43 Ma; Dora Maira: 40–35 Ma).

Subducted Fragments from the Central and Eastern Alps

The S-type Valais Units are largely exposed as a ~10 km thick tectonic pile in the eastern part of Switzerland, in the Grisons (FIG. 1A) (Frey and Ferreiro Mählmann 1999). These metasediments contain blueschist facies lawsonite-, Fe–Mg-carpholite– or chloritoid-bearing assemblages. Similar *P–T* estimates (0.9–1.4 GPa, 350–400 °C) are obtained as in the upper S units of the Western Alps (FIG. 2C). They provide evidence for tectonic underplating at ~30–40 km depth (FIG. 2G), which is close to the Moho depth of the

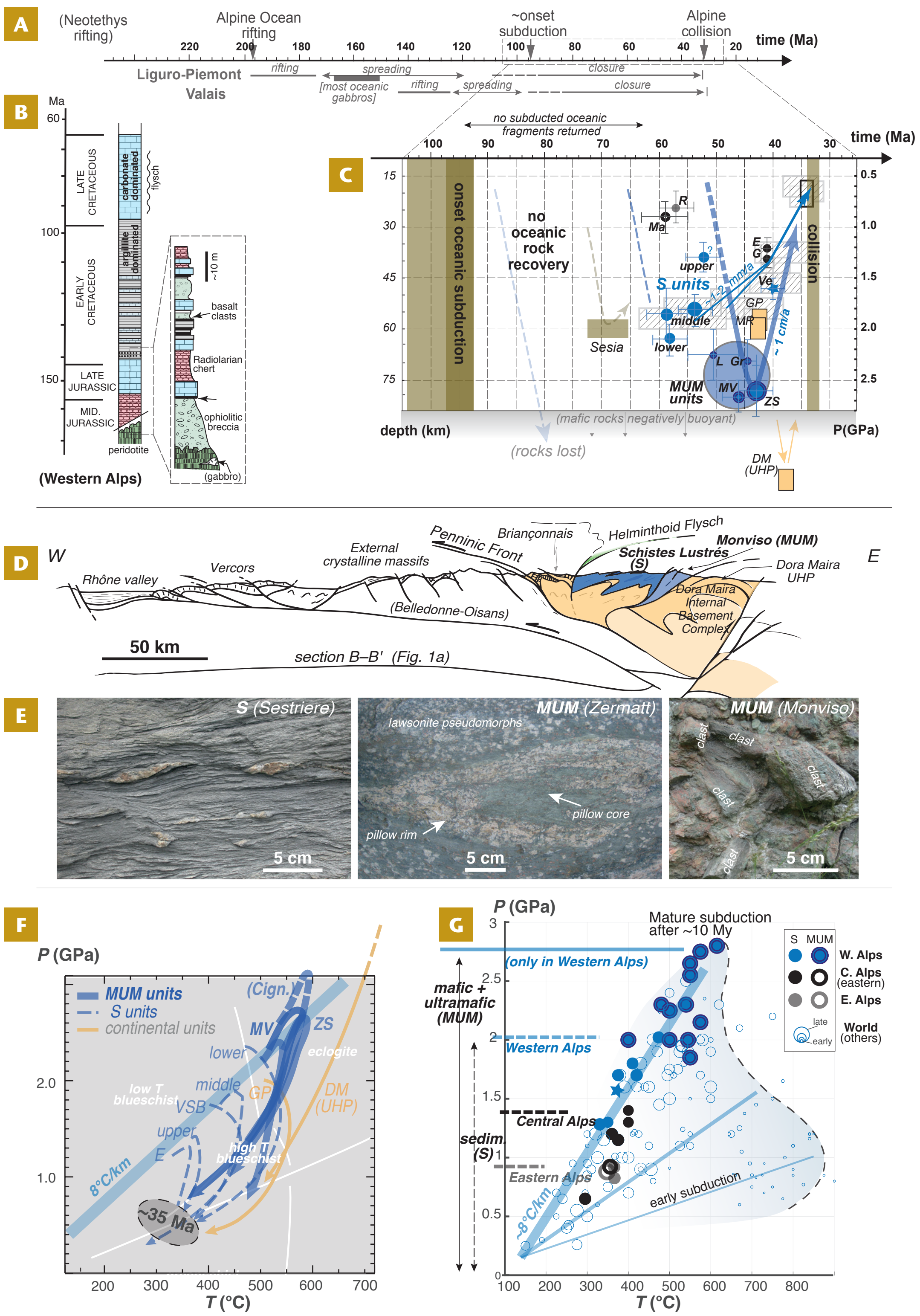

FIGURE 2 (**A**) A chronology of major Alpine geodynamic events. (**B**) Representative lithostratigraphic column for the Liguro–Piemont domain (Queyras area, Western Alps). (**C**) Pressure–time paths of subducted Alpine fragments. Note the contrast between the early (no rock recovery) and late subduction period. Abbreviations: S units = sedimentary units (divided into lower, middle, upper); MUM units = mafic- and ultramafic-dominated units; Ma = Malenco; R = Rechnitz; E = Engadine; G = Grisons ; Ve = Versoyen; GP = Gran Paradiso ; MR = Monte Rosa; L = Lanzo ; Gr = Grivola; MV = Monviso; ZS = Zermatt–Saas; DM = Dora Maira; UHP = ultrahigh pressure. (**D**) Schematic crustal-scale cross section across the Western Alps (located as section B–B´ on FIG. 1A). Abbreviations as for FIGURE 1 and FIGURE 2A. (**E**) Characteristic sedimentary (S) and mafic/ultramafic (MUM) rocks. (LEFT) Blueschist facies lawsonite-bearing calcschist with quartz ± calcite veins. From Sestriere (Italy, Western Alps). (CENTRE) Eclogitized pillow lava, with lawsonite pseudomorph-rich rim and dry garnet–omphacite-bearing core (white arrow). From Zermatt–Saas (Western Alps). (RIGHT) Brecciated eclogite facies Fe-Ti-rich metagabbro, with angular fragments dispersed in an eclogite-facies cement. From Monviso (Cottian Alps, Italy). (**F**) Characteristic *P–T* paths of subducted Alpine fragments, both oceanic [Engadine (E); Monviso (MV)]; lower, middle and upper S(edimentary) units from the Western Alps; Zermatt–Saas (ZS) and Cignana (Cign.); Valaisan Pt. St. Bernard (VSB)] and continental [Dora–Maira (DM); Gran Paradiso (GP)]. (**G**) Comparison between *P–T* estimates of Alpine subducted fragments and other diagnostic fossil oceanic subduction zones worldwide. Note the alignment along the *P–T* gradient for mature subduction, and differences in maximum pressures along strike. AFTER AGARD ET AL. (2018).

adjacent upper Adriatic Plate, at 42–40 Ma (Wiederkehr et al. 2009). The more deeply buried slices of oceanic metasediments of the lower Glockner Unit of the Tauern Window (~2 GPa, 500 °C) (Groß et al. 2020) represent fragments entrained by continental subduction and then exhumed as part of the distal European margin.

The Liguro–Piemont units of the Central Alps comprise three units (Fig. 1B) (Froitzheim et al. 1996). (1) The lower unit is the metasedimentary Avers S unit (1.1–1.3 GPa, 350–400 °C). (2) The middle unit comprises the MUM units of Malenco (an exhumed sub-continental mantle fragment later subducted to temperatures around 400 °C between 63 and 55 Ma) and Platta (a high-pressure greenschist-facies metamorphosed ocean–continent transitional domains) (Handy et al. 1996). These units lie structurally below and above, respectively, the high-pressure, greenschist-to-blueschist facies Margna–Sella extensional allochthon, a palaeogeographic equivalent of the Sesia Zone (Fig. 1B). (3) The upper unit made up of the ~1–2 km thick Arosa Zone, which was interpreted as the fossil subduction plate interface between ~58 Ma and 47 Ma (Bachmann et al. 2009). Syn-subduction deformation immediately above the subduction thrust, together with upper plate extension recorded by the deposition of the Gosau basins between ~80 Ma and 55 Ma, may reflect a switch from subduction erosion to accretion ~10–15 My before ocean closure (Wagreich 1995). Further east, subducted fragments record low-grade blueschist facies conditions both in the Tauern Window (~1 GPa; 350–400 °C; ~50 Ma) and the Rechnitz Window (0.9–1.0 GPa; 370 °C; 57 ± 3 Ma).

SUBDUCTION DYNAMICS THROUGH SPACE AND TIME

Data constraining *P–T–t* paths and lithostratigraphy of Alpine metamorphic rocks reveal a marked contrast between the S and the MUM units (Fig. 2C), particularly in the Western Alps. The MUM units there exhibit larger coherent fragments and/or features attributable to ocean–continent transitional domains. They reached higher peak pressures and temperatures, underwent faster exhumation rates, and were buried (and exhumed) during the final stages of oceanic subduction.

While the record of subduction in the Central and Eastern Alps often lacks the spectacular eclogites of the Western Alps, all S and MUM units share the same metamorphic gradient of ~8–10 °C/km, which is diagnostic of mature subduction (Fig. 2G) (Agard et al. 2018) and consistent with rocks formed in the same subduction zone. Maximum pressures differ along strike: no deeply buried oceanic rocks are recovered east of the Simplon and Lepontine Units of the Central Alps (i.e., >1.5 GPa) (Fig. 2G), with the exception of the lower Glockner Unit. The fact that metamorphic pressures vary with temperatures consistently along a common metamorphic gradient, irrespective of location in the Alps, rules out significant overpressure, which would lead to a large scatter in pressure at a given temperature. The same cut-off in maximum pressure (~2.8–3.0 GPa) is observed in the Alps as in other comparable orogens worldwide (Agard et al. 2009, 2018), beyond which mafic rocks ± serpentinites become negatively buoyant (Fig. 2C). The 100 m thick Cignana ultra-high-pressure sub-unit could reflect minor overpressure of at most ~10% (3.2 GPa vs 2.8 GPa) (Fig. 2F) or might represent a deeper thin strip of slab.

Neither older high-pressure metamorphic rocks nor rocks that reached higher temperatures at a given pressure – both traits typical of early subduction (Fig. 2G) – exist along the Alps. Thus, no slab fragments are preserved from subduction between 100–95 Ma and 65 Ma (Fig. 2C). All subducted fragments of the Liguro–Piemont Ocean and the Valais Ocean are younger than ~60–65 Ma, i.e., these fragments post-date the subduction and exhumation of the Sesia Zone.

Offscraping of the S units from the underlying MUM portion of the slab (Fig. 3A), and partial exhumation along the plate interface, is documented in the Valais and Liguro-Piemont Oceans between ~60 Ma and 35 Ma. Most S units experienced peak metamorphic pressures and temperatures of ~1.0–1.3 GPa and ~350–400 °C (~30–40 km depth) which is consistent with most HP–LT rocks worldwide (Agard et al. 2018). The amount of underplated rock varies along strike, from 100 metres to several kilometres thick, in both the Valais and Liguro–Piemont Oceans. But underplating at distinct depths only occurred in the Southwestern Alps.

The MUM units are volumetrically insignificant in the Central and Eastern Alps. They experienced peak *P–T* conditions from unmetamorphosed to blueschist facies <~1 GPa and were subducted between 60 Ma and 50 Ma. In the Western Alps, all MUM units show comparable eclogitic conditions and reached peak burial late in the oceanic subduction history at ~45 Ma, at most a few million years before continental subduction. Assuming convergence velocities around 1–2 cm/y, burial of these MUM eclogitic units to 80 km depth must have started near 50 Ma (Fig. 2C). The ~5 My difference in peak burial between the MUM and the Internal Basement Complexes (45 Ma versus 38–42 Ma) shows that they were located 50–100 km apart, i.e., that MUM units were located close to the continent (Figs. 1D and 3A). It also suggests that the entrance of the continental margin into the subduction zone at ~45 Ma triggered the detachment of MUM units from the slab, possibly facilitated by lateral discontinuities in the heterogeneous oceanic lithosphere (Fig. 3B). The continental Internal Basement Complexes later accompanied the MUM units along the plate interface during part of their return path, as shown by their spatial association, their commonly fast exhumation rates and their tight *P–T* paths.

The present location of the MUM units coincides with the areal extent of the subducted Briançonnais, Sesia and Margna–Sella continental fragments (Fig. 3C). This suggests a strong influence of both initial margin architecture and continental subduction. More MUM units are found near the Gran Paradiso, Monte Rosa and Sesia Units (Fig. 1D) than near Dora Maira. The latter is, in fact, the only Internal Basement Complex subdivided into five or six hectometre- to kilometre thick slices, with one slice recording higher pressures than its adjacent MUMs. The extensively thinned continental crust near Dora–Maira may have been more readily subducted to great depth, yet not buoyant enough to help exhume dense MUM units. Maximum continental subduction, however, was to about the same depths in the Western Alps (~3.5 GPa for Dora–Maira) as for the Central Alps (4–5 GPa for the Alpe Arami distal European margin) and was approximately coeval at ~40–35 Ma.

ALONG-STRIKE SEGMENTATION, SUBDUCTION ACCRETION/EROSION

First-order contrasts in the oceanic subduction record along strike are summarized in map view in Figure 3C and depicted as a snapshot of the Alpine subduction at ~40 Ma in Figure 4A. Four sectors, termed A, B, C and D, can be defined.

Sector A. The least affected by collisional overprinting, Sector A is characterized by S units subducted and returned from a range of depths during a relatively long period of about 25 My (i.e., ~65–40 Ma). The MUM units include gabbroic bodies several kilometres long (Rocciavre, Monviso). The Briançonnais margin was hyperextended (Fig. 3A), as reflected by the numerous crustal sub-massifs such as Ambin, Acceglio, and the Dora Maira slices (including one ultra-high-pressure slice). The Valais Ocean was narrow and with subordinate oceanic crust.

Sector B. This sector includes the major MUM massifs and the Sesia Zone. The S units are less abundant than in Sector A, no older than ~45 Ma (so far) and have experienced less variable maximum pressures. Internal Basement Complexes record peak *P*–*T* conditions similar to, or slightly lower than, those recorded by metamorphic assemblages in the MUM units. This sector also hosts the very low-grade nappes of the Préalpes, which preserve a record of accretionary wedge formation, and the Ivrea body, interpreted as a shallow piece of upper plate mantle (Fig. 3C).

Sector C. This sector is generally dominated by metasediments, but locally shows well-preserved fragments of the ocean–continent transitional domains in the vicinity of the Margna–Sella continental sliver. All reached maximum pressures of 1.2–1.3 GPa. The Briançonnais Domain is much narrower than in sectors A and B. Units representing the distal European margin experienced continental subduction down to 4–5 GPa.

Sector D. This sector preserves only volumetrically small subducted oceanic fragments. The Valais and Liguro–Piemont oceanic domains are in direct tectonic contact, because the Briançonnais Domain did not extend this far east.

These along-strike contrasts in subduction dynamics impacted on later continental subduction and collision (Fig. 3C) and likely reflect the irregular palaeogeography

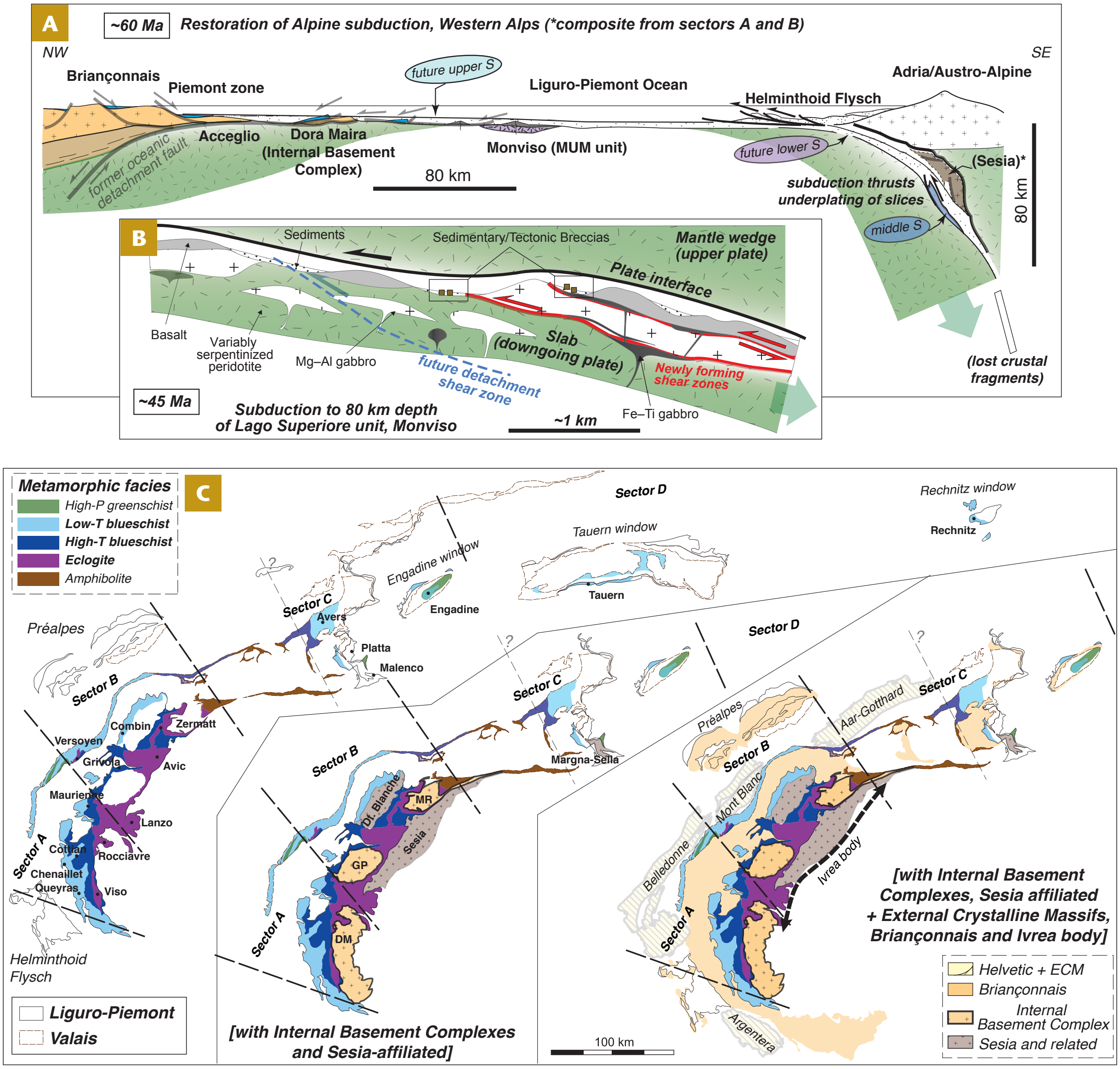

Figure 3 (**A**) Subduction configuration in the Western Alps at ~60 Ma. This section combines the characteristics of sector A (deep underplating, hyperextended margin) with those of sector B (e.g., subduction and partial exhumation of the Sesia Zone). Tectonic contacts either formed during subduction (black) or ocean formation (grey). Abbreviations: S = sedimentary units; MUM = mafic- and ultramafic-dominant rocks. (**B**) Close-up of the MUM Lago Superiore Unit of Monviso at peak burial (~80 km depth, 45 Ma), during brecciation and before detachment from the slab. Note the heterogeneous character of the oceanic lithosphere, and the combination of newly formed tectonics contacts and reworked sedimentary/magmatic contacts. After Locatelli et al. (2018). (**C**) Along-strike contrasts in ocean subduction dynamics allow us to define four distinct sectors: A, B, C and D (left). Note correlations with some major Alpine features: the Internal Basement Complexes and Sesia Zone (center), or the Briançonnais, External Crystalline Massifs (ECM), Préalpes and Ivrea body (right).

of the early-mid Jurassic transform margins formed during the opening of the Alpine Tethys. They may be controlled by former Variscan structures; by lateral variations in magmatic production, kinematics, nature and proportions of incoming sedimentary material; and/or by contrasting mechanical behaviour or fluid liberation during subduction. Subduction accretion, marked by deep underplating (Fig. 3A), prevailed along Sector A after 65 Ma. Subduction erosion, marked by basal deformation of the upper Adria plate, may have occurred along Sectors B, C, and D between ~80 Ma and 55 Ma (Fig. 4A) (Wagreich 1995; Bachmann et al. 2009).

Initial teleseismic P-wave tomography from the AlpArray seismic experiment shows that most of the subducted Alpine Tethyan lithosphere is now detached and lies partly in the Mantle Transition Zone (Fig. 4B). However, some of the first-order contrasts in the structure of the lithosphere imaged by geophysics spatially overlap with the segmentation outlined by Sectors A to D.

A FRAGMENTARY YET FAITHFUL RECORD OF SUBDUCTION

Structural relationships and petrologic constraints on *P–T–t* paths experienced by Alpine metamorphic rocks indicate that the Alpine record is representative of mature subduction processes and can be used as a reliable proxy for the pressure and temperature regime of subduction. The Alpine record precludes the existence of significant tectonic overpressure in this subduction zone, because, if it existed, it would have resulted in variable peak pressures at a given peak temperature and disparate pressure estimates in rocks with contrasting viscous strengths, such as the weak metasediments or strong mafic rocks.

Subduction of the oceanic lithosphere of the Alpine Ocean varied in time and space. This is reflected by extensive periods of metasedimentary underplating compared to short intervals of offscraping of MUM units from the slab. No fragments of subducted oceanic lithosphere were returned during the first ~30 My of subduction, until the

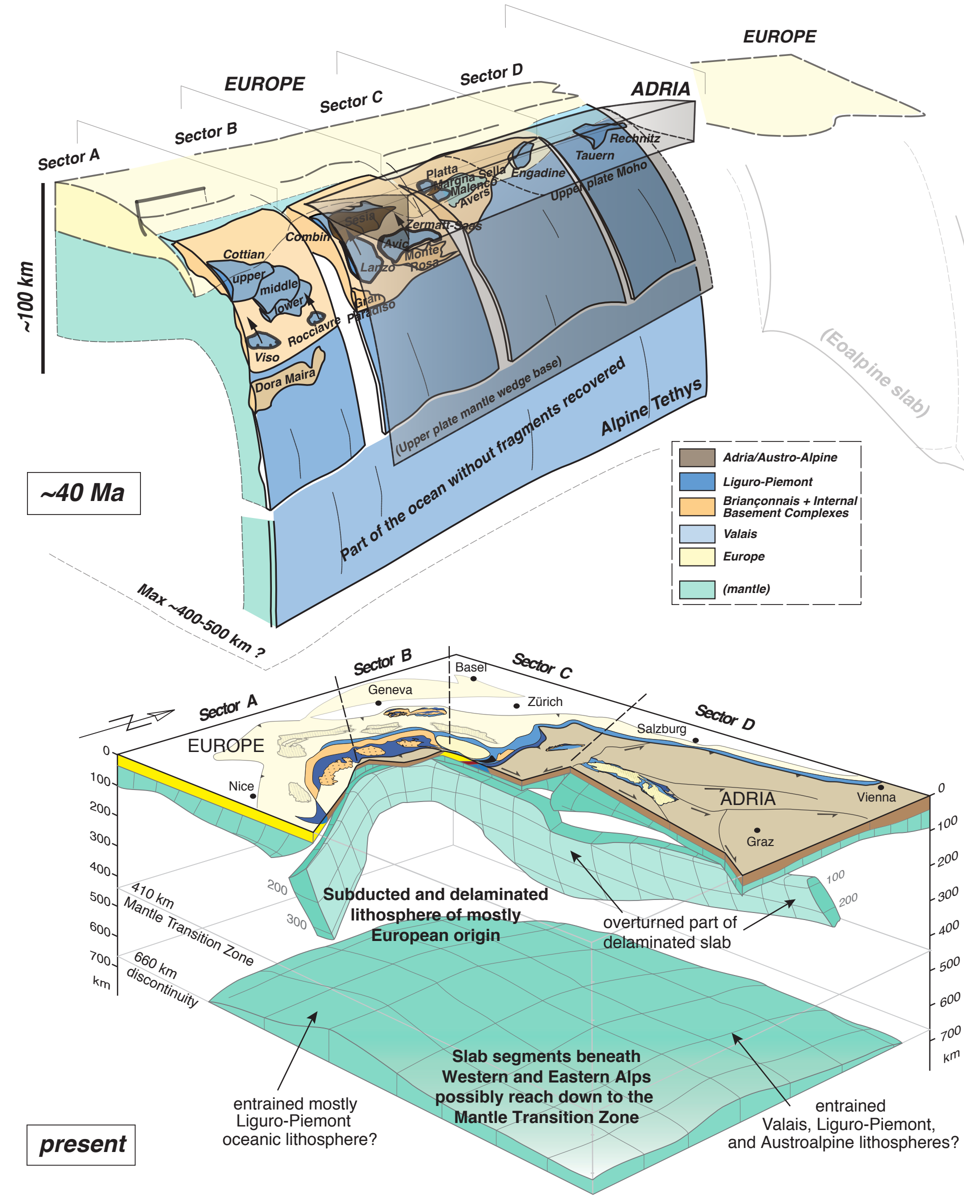

Figure 4 (**A**) Idealized view of the Alpine subduction zone at ~40 Ma, showing the relative location of subducted fragments discussed in the text (Figs. 1D and 4B). (**B**) Slab configuration based on geophysical profiles (the grey transect line in Fig. 1A) and preliminary interpretations of teleseismic tomography of the AlpArray working group by M. Paffrath, M. Handy and others.

subduction of the Sesia Zone (Fig. 2C). The greater occurrence of MUM remnants next to micro-continental slivers (Briançonnais, Sesia) demonstrates the influence of margin segmentation (Sectors A–D) (Fig. 3C): only oceanic domains close to the continental margin and/or ocean–continent transition (i.e., ~165–150 Ma MUM units) were recovered from great depths (~80 km), while all other domains formed between ~150 Ma and 120 Ma were irreversibly buried during the first 30 My of subduction. Before 65 Ma, the Alpine subduction was, therefore, erosive, sediment starved and/or sufficiently mechanically decoupled that rock recovery was impeded, as is commonly the case during oceanic subduction (see Agard et al. 2018). After ~65 Ma, subduction accretion prevailed in the Western Alps, while subduction erosion probably did so in the Eastern Alps until 55–50 Ma, reminiscent of contrasts observed along the Chilean subduction zone today.

Preservation of the Alpine subduction record is neither exceptional nor atypical but is a reflection of the slow closure over ~60 My of a short-lived, slow-spreading ocean. In contrast with the thick, continuous ocean plate stratigraphy that is going down the trenches of Chile or Japan today, the mechanically weak, heterogeneous and relatively buoyant Alpine seafloor (i.e., serpentinized mantle, irregularly distributed magmatic rocks and pelagic sediments, transitional to broad ocean–continent transition) facilitated strain localization and offscraping along the plate interface during subduction. Inherited structures and petrological constrasts, in addition to plate boundary rheology and kinematics, affected the mechanical behaviour of the subduction interface and, in particular, the potential for rock recovery. The Alpine record exemplifies the preferential recovery of portions of slow-spreading oceans near hyperextended margins, similar to the spectacular Cycladic blueschists and eclogites of the Eastern Mediterranean. Given the modest dimensions of the Liguro–Piemont and Valais Oceans, their largely detached slabs reached the Mantle Transition Zone but never crossed its 660 km lower limit (Fig. 4B) – another difference with the large-scale subduction zones, which penetrate the lower mantle and participate in wholesale mantle convection. The absence of a magmatic arc in the Alps may have resulted from insufficient water transfer from the slab to the upper plate mantle, the infertility of the upper plate (i.e., Adria) mantle, or slabs too short to trigger large-scale mantle upwelling.

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