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Nature and plate-tectonic significance of orogenic magmatism in the European Alps: a review

Dedicated to Professor Marc Vuagnat on the occasion of his retirement

by *Alexander Frank Waibel*[1]

Abstract

The objective of this paper is to provide a brief overview of Alpine orogenic intrusive and eruptive episodes, and to discuss their nature in relation to the plate-tectonic evolution of the European Alps. The occurrences of subduction related magmatism that remain preserved in the geological record range in age from the Late Maastrichtian to Early Miocene and are confined to three grossly concentric zones in the Western and Southern Alps. These are, structurally in successive order of occurrence: 1) an external graywacke belt containing volcaniclastic intercalations of andesitic composition in the Gurnigel-Schlieren-Wägital Flysch and Taveyanne Formation; 2) an internal array of granitic intrusive bodies and basaltic-rhyolitic, mostly andesitic dike swarms that discordantly penetrate the Alpine edifice along the Periadriatic fault system; and 3) basic, ultrabasic, and acidic lavas erupted in the Venetian volcanic province, possibly within the confines of a backarc basin. Whereas the two outer belts are predominantly calc-alkaline in composition and related to crustal compression, the innermost occurrence is mainly alkaline and appears to be related to penecontemporaneous crustal attenuation behind the exposed root of the volcano-plutonic arc and its derivative graywackes. From the pattern of intrusive and eruptive cycles, it is assumed that the entire range of orogenic magmatic activity was generated by NW-directed convergence along the northwestern edge of the Adriatic plate since at least the Maastrichtian.

Keywords: plate tectonics, orogenic magmatism, andesitic volcanism, graywacke, Taveyannaz Sandstone, flysch, Alpine arc, review.

Introduction

In spite of the scientific attention it has attracted since early investigations (DE QUERVAIN, 1928; VUAGNAT, 1952), the nature of orogenic volcanism in the Alps has remained something of a mystery, especially in terms of its temporal relationship with mountain building and the extent to which it was active. Several predicaments have widely been regarded as apparent contradictions to plate-tectonic theory: the scarcity of calc-alkaline andesitic volcanic activity, its unduly late emergence in relation to the assumed onset of continental convergence, and hence its limited duration prior to the ensuing continental collision.

The earliest manifestations of continental convergence that have been documented to date are high-P/low-T metamorphic minerals that imply that it was at least locally initiated in the earliest Cretaceous (e.g. WINKLER and BERNOULLI, 1986; WINKLER, 1987; DAL PIAZ et al., 1978; HUNZIKER and MARTINOTTI, 1987). And yet no signs indicative of associated calc-alkaline andesitic volcanism appear to have emerged until the Late Cretaceous, some 70 Ma later, as volcaniclastic intercalations in the Late Maastrichtian to Mid (Late?) Eocene Gurnigel-, Schlieren-, and Wägital Flysch (WINKLER, 1984; WINKLER et al., 1985), and possibly as dikes contained in Austroalpine nappes. One of these dikes has been dated at 89 ± 7 Ma (GATTO et al., 1976b; see also BECCALUVA et al., 1979), but this is an uncharacteristically old age in relation to associated intrusions (see below). Traces of laterally *extensive* calc-alkaline andesitic volcanic activity are not

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preserved until the latest Eocene or earliest Oligocene, i.e. not before the Penninic Ocean had been reduced to an armlet of the dwindling Tethys – by what must have been active subduction and plate consumption. This refers to the discontinuous but widespread and massive interspersal of andesitic detritus throughout several Eocene/Oligocene clastic formations of the waning Alpine foredeep, in the Taveyanne Sandstone and its lateral equivalents (VUAGNAT, 1985, and references therein). However, with minor, debatable exceptions (see VUAGNAT, 1985, for discussion), the original eruptive units that furnished these volcaniclastic graywackes have completely vanished, either by erosion or subduction, or because they now lie safely buried under a thick sedimentary cover or tectonic nappe stack (VUAGNAT, 1952). The little that remains of this volcanic material in the sands and gravels of the foreland was quickly subjected to a regional metamorphic event by thrust loading at the front of the radially vergent orogen (STALDER, 1979), making meaningful geochemical, mineralogical, or textural comparisons between outcrops or modern analogues more difficult. Whereas in the Western Alps traces of andesitic volcanism are locally preserved but somewhat altered and mostly confined to widely dispersed volcaniclastic formations, in the Eastern Alps such volcanism appears to be lacking altogether throughout most of their history, apart from late-Alpine dikes that were emplaced to the north of the Periadriatic fault system, mostly during the Oligocene (GATTO et al., 1976a, 1976b; BECCALUVA et al., 1979; DEUTSCH, 1980, 1984).

As a result of these difficulties, many divergent and sometimes unusual hypotheses have been put forward to account for various conflicting aspects of this orogenic volcanism. Amid this confusion it is nonetheless clear that in plate-tectonic terms the Alps cannot be fully understood without contending with this seemingly anomalous pattern of volcanic activity. The purpose of this paper is to provide a brief overview of known orogenic occurrences and to interpret the pattern of eruptive and intrusive cycles within the framework of plate tectonics and mountain building. Although it is predominantly concerned with the orogenic volcanism of the Alps, i.e. with what is left of it in the Western Alps and the apparent lack of it in the Eastern Alps, reference will be made in passing to other volcanogenic provinces of Alpine Europe in Italy and the Carpathians. Emphasis is on the Taveyanne Sandstone and its lateral equivalents, as these deposits contain the only calc-alkaline volcanic relics of extensive paleogeographic significance. Possible links between the parent volcanic arc and remote but penecontemporaneous igneous products in the Southern Alps are also discussed, more specifically the intrusive bodies situated along the Periadriatic fault system and the Paleogene Venetian volcanic province in northern Italy. For additional occurrences of intrusive and eruptive units, the reader is referred to compilations by DAL PIAZ and VENTURELLI (1985), DIETRICH (1976, 1979), DIETRICH et al. (1974), and the numerous references contained therein.

Gurnigel-, Schlieren- and Wägital Flysch

Due to the likelihood of incomplete preservation, it will never be known with certainty when and where the first volcanic products were generated in response to continental convergence. Apart from one questionable andesitic dike dated at 89 ± 7 Ma (GATTO et al., 1976b), the oldest such volcanics that remain preserved in the geological record are the andesite-tonalite and diorite fragments contained in the Gurnigel-, Schlieren-, and Wägital Flysch (Fig. 1). These are reported by WINKLER (1981, 1983, 1984) and by WINKLER et al. (1985) who, largely on the basis of intercalated volcanic ash layers and derivative clay minerals, assume that the activity coincided with the period of sedimentation from the Late Maastrichtian to Mid (Late?) Eocene. The turbiditic sequence comprises an association of abyssal-plain and trench-slope deposits that are inferred to have been deposited along a convergent plate boundary below the CCD. The volcanic detritus and fallout deposits are thought to have been derived from the active Austroalpine continental margin to the south of the Piedmont-Ligurian sea.

Taveyanne Sandstone and lateral equivalents

Taveyanne Sandstone *s.l.* refers to an association of volcaniclastic formations, in which calc-alkaline, basaltic andesite is more or less abundant, locally comprising up to 95% of the sedimentary rock. Some volcaniclastic formations have been thought to include volcanic remnants related directly to eruptions in or near the depositional basin, such as submarine lava flows, intrusive bodies, pyroclastic fallout deposits and the like (e.g. BEUF et al., 1961; DIDIER and LAMEYRE, 1978; GIRAUD, 1983; DOUDOUX et al., 1987). However, where the graywackes are composed almost exclusively of andesitic rock and mineral fragments, such claims must result from metamorphic transformations which apparently can mask the clastic

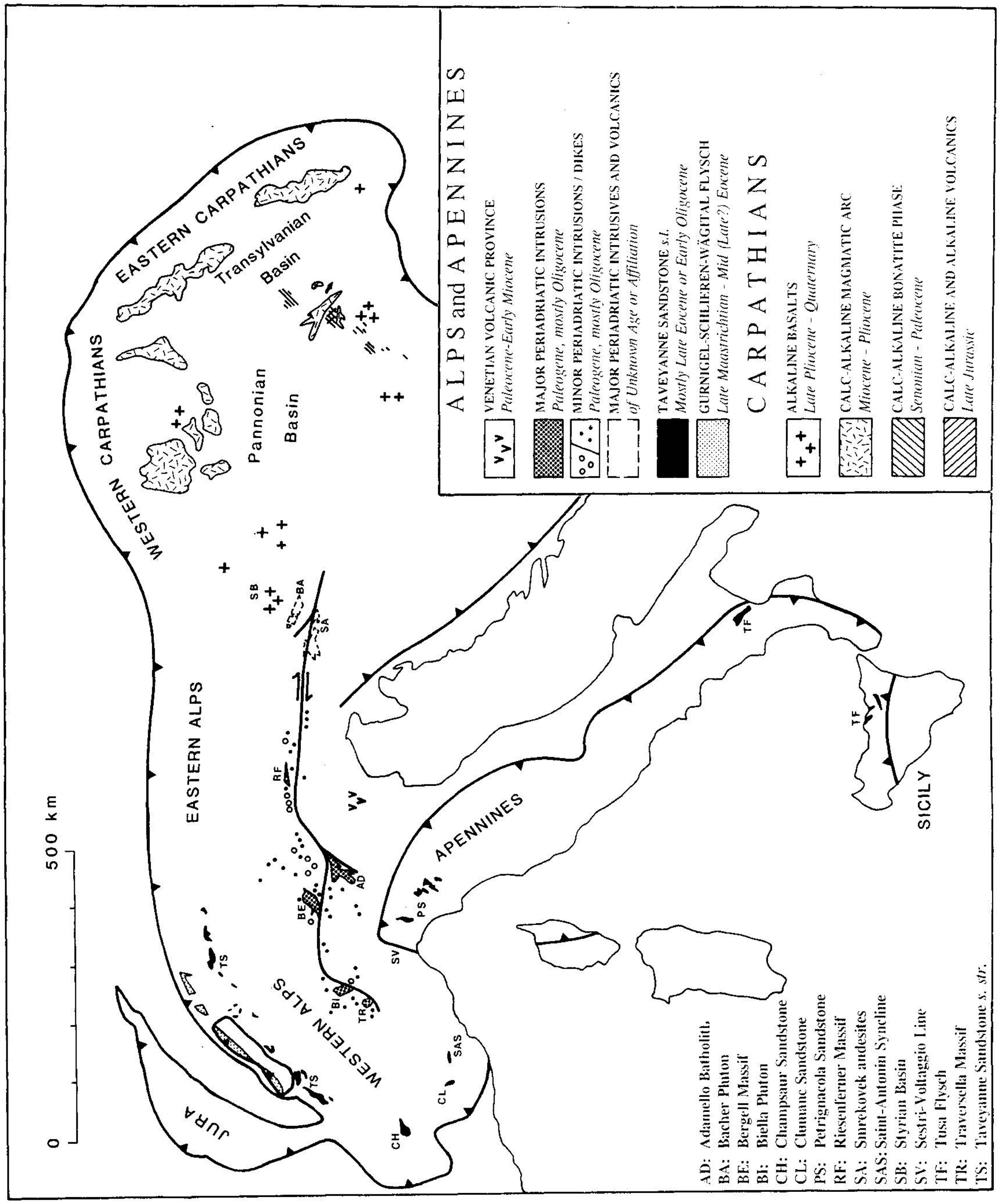

Fig. 1 Distribution of pertinent orogenic magmatic provinces in the Alps, Apennines, and Carpathians, according to authors cited in text. For the distribution of Alpine occurrences in particular, see maps by Dal Piaz and Venturelli (1985), Dietrich (1976), and Dietrich et al. (1974), which provide more geological detail. Not shown is magmatism of Maures-Esterelle, Corsica, Sardigna, etc.

Epoch	Stage	Southern French Alps ⟸	Northern French Alps ⟸	Western Swiss Alps ⟸
Oligocene	Chattian			Molasse Rouge
	Rupelian (Stampian)	Molasse Rouge	Molasse Rouge Grès de St.Didier (■)	Grès de Massongex
	Sannoisian	la Poste de Clumanc (■,•)		Grès du Val d'Illiez (■,•) Grès de Taveyannaz (•,■)
Eocene	Lattorfian	Synclinal de St.Antonin (•,■)	Grès du Champsaur (•,■)	
	Priabonian	Grès d'Annot	Flysch des Aiguilles d'Arves	Grès Ultrahelvétiques

Fig. 2 Schematic portrayal of Alpine foreland stratigraphy displaying progressive changes in relative positions of Tertiary basins and diagnostic compositional variations with age. Arrows indicate polarity of foreland basin shifts towards the more external zones of the Alps. Deposits containing andesitic debris are designated with a filled circle, those containing ophiolitic material with a filled square (based largely on VUAGNAT, 1952; PAIRIS et al., 1984; EVANS and ELLIOT, 1985; CHAUVEAU and LEMOINE, 1960; and LATELTIN and MÜLLER, 1987).

nature of the sedimentary rock (VUAGNAT, 1985). The volcanic rock material is thus for the most part, if not entirely, epiclastic, i.e. derived from erosion of older volcanoes related to previous eruptive episodes, presumably mostly lava flows with little evidence of explosive violence, such as volcanic ash, lapilli, or other ejecta.

Following the Subalpine Chains of the Western Alps from N to S, the clastic formations that have been shown to contain andesitic rock fragments in variable amounts are the Val d'Illiez Sandstone and Taveyanne Sandstone *s. str.* of the Swiss and northernmost French Alps (VUAGNAT, 1952; MARTINI, 1968; MARTINI and VUAGNAT, 1970; SAWATZKI, 1975), the Champsaur Sandstone of the northern French Alps (WAIBEL, 1990; BERTRAND et al., 1991), the Clumanc Sandstone of the southern French Alps (BODELLE, 1971), the sandstones in the Barrême Basin (EVANS and MANGE-RAJETZKY, 1991) and the St. Antonin Syncline of the Maritime Alps (ALSAC et al., 1969; BOUCARUT and BODELLE, 1969; LE GUERN, 1979, 1981). Farther south, in Italy, volcaniclastic intercalations of similar composition, age, and metamorphic grade are known from the Petrignacola Sandstone of the northern Apennines (ELTER et al., 1964, 1969; ABBATE and SAGRI, 1970; VALLONI and ZUFFA, 1984), which reappear in the Tusa Facies of southern Italy (OGNIBEN, 1969) and Sicily (OGNIBEN, 1964; WEZEL, 1973).

Either a Late Eocene or Early Oligocene age has been assumed for each of these occurrences but has commonly been a matter of uncertainty, due to the characteristic deficiency of diagnostic fossil associations. For the Western Alps in general, the latter is more likely, considering that the base of the Taveyanne Sandstone has recently been dated as Lower Oligocene (LATELTIN and MÜLLER, 1987). Potassium-argon age determinations on some andesite cobbles have yielded apparent ages that are usually close to the stratigraphic age or somewhat older, suggesting that the lava flows were originally erupted during the Late Eocene or Early Oligocene (FONTIGNIE, 1980, 1981; FONTIGNIE et al., 1987), in relatively close succession to the deposition of the Gurnigel-, Schlieren-, and Wägital Flysch. Doubts concerning the lateral equivalence of the Tusa Flysch in Sicily have been raised by WEZEL (1973) who determined a Late Oligocene to Early Aquitanian age for this formation.

Whereas the volcaniclastic graywackes in the Alps invariably occur in shallow water basins, the Italian occurrences are thought to have been deposited in deeper active margin settings (ABBATE and SAGRI, 1970). WEZEL (1973) assumes a deep-sea trench environment for the Tusa Flysch in Sicily. In the Western Alps, the entire spectrum of volcaniclastic formations was deposited in a network of migrating peripheral foreland basins (Fig. 2), in a fault- and fold controlled foredeep adjacent and parallel to the orogenic belt (e.g. SINCLAIR, 1989; SINCLAIR, 1992). Here, it has been shown that, in a given cross-section, the depositional environment shifts outward and becomes progressively shallower and younger towards the more external zones of the Alps (VUAGNAT, 1952; ELLIOT and GRAHAM, 1985; APPS and GUIBAUDO, 1985). The outward transition is from open-marine, deep-water turbidite basins, through shallow-water sandstones deposited in near-shore environments, to the alluvial red-beds of the Molasse Rouge (ELLIOT et al., 1985). The introduction of andesitic detritus to the outward propagating structural depressions occurred mostly through prograding turbidites, the greater part of which was shed laterally into the basins from their inner flanks, i.e. from the deformation front of the Mesoalpine fold- and thrust belt.

Figure 1 portrays the sporadic distribution of volcaniclastic outcrops which crudely outline the western perimeter of the Adriatic plate. Major assumptions are that, along a given plate boundary segment, polarity of thrusting and folding was inherited from subduction, and that basin migration occurred in the same sense. The volcaniclastic sequences under discussion are thus located on both sides of a major tectonic boundary in northern Italy, the Sestri-Voltaggio Line, where regional vergence is reversed. This zone of tectonic divergence has been assumed to mark the site of a former transform fault, along which the direction of subduction was in the opposite sense (SCHOLLE, 1970). One may thus define the most recent orogenic events as two colliding mountain belts, in which flysch troughs ultimately migrate past each other in opposite directions before coming to a final standstill. The magmatic arc in the Apennines could nevertheless have been associated with subduction in the same sense as in the Western Alps because the inversion is assumed by some geologists to have occurred thereafter, during the Late Oligocene (BOCCALETTI et al., 1971; see also BOCCALETTI and GUAZZONE, 1972, 1974). It is nonetheless surprising that the volcaniclastic formations on both sides of the former transform fault agree so closely in terms of gross lithological composition, age, and ultimate structural position within the mountain belt. It is also astonishing that both trough segments share the virtual lack of voluminous andesitic parent outcrops to which their origin could conceivably be traced – and that both migrating foredeeps were subjected to the same effects of subsequent burial metamorphism by thrust loading (STALDER, 1979; ELTER et al., 1969) due to the arrival of their respective fold-and thrust belt.

In view of (1) the calc-alkaline nature of the andesite fragments, (2) their widespread curvilinear occurrence adjacent and parallel to a sutured plate boundary, and (3) their appearance during a convergent episode, there is ample justification for relating their origin to a subduction zone and associated magmatic arc, and not to local graben-like fractures in the autochthonous foreland as some geologists are inclined to believe (HOMEWOOD and CARON, 1982). Though in the Western Alps synsedimentary normal faulting was apparently active in the underlying platform of the foreland (see Fig. 4 by PFIFFNER, 1986), it is possible that these axes of tension and related grabens or half-grabens were formed where the downgoing lithospheric slab was suddenly bent by the load of the adjacent nappes. For instance, similar graben-like structures and associated extensional zones have been delineated by fault-plane solutions in the axes of some modern deep-sea trenches, and have been linked to the sudden downward movement of the underlying plate (ISACKS et al., 1968). Because the initiation of normal faulting immediately predated or coincided with the appearance of andesites in the Western Alps (the generation of which should have corresponded to a stronger compressive resultant between the converging plates), fracturing might have occurred in response to the higher strain rate at shallow structural levels in the downgoing plate. On the other hand, if the convergence rate was high but strongly oblique, block-and-basin topography might also have been formed by a network of transcurrent faults in the underlying continental platform, similar to the Continental Borderland Province of Southern California within the tectonic regime of the San Andreas Fault (cf. CROWELL, 1974). The point to be emphasized here is that the localized presence of extensional grabens at any particular time and place in the foreland, or elsewhere in Europe (cf. LAUBSCHER, 1985), does little to cast doubt on the association of andesitic volcanism with the overall scenario of compression at the Eocene/Oligocene boundary, which can safely be assigned to the main meso-Alpine period of nappe formation.

It is therefore plausible that the andesitic volcanism was generated along a convergent plate boundary in the vicinity of a subduction zone, and that the volcanic rock masses that were ultimately eroded in the foreland originated from the adjacent magmatic arc. The provenance of the volcaniclastic sands and gravels, however, remains somewhat unclear, given the virtual lack of eruptive analogues from which they could have been derived. Nevertheless, numerous lines of evidence suggest that the volcanic fragments were derived from internal terranes (DE QUERVAIN, 1928; VUAGNAT, 1952). The strongest indication in favor of this hypothesis stems from the associated ophiolite debris, the mafic cobbles of which retain a high-P/low-T, subduction related overprint with lawsonite and blue amphibole (DE GRACIANSKY et al., 1971; SAWATZKI, 1975; EVANS and MANGE-RAJETZKY, 1991). The fact that no ophiolitic outcrops are currently exposed on the external side of the basin remnants also strongly suggests that terrigenous materials were derived internally from accreted terranes at the front of the rising orogen. It is hardly possible, then, that the vast volcanic occurrences in the more external zones of southeastern France (Massif Central, etc.) contributed as a major source, the greater part of which is younger (Miocene-Pliocene) and predominantly alkaline (see BAUBRON, 1984).

The interpretation that the magmatic arc was situated on the internal side of the basins in the foreland is fully compatible with the polarity of thrusting within the mountain belt. The magmatic arc is thought to have originally occupied a position near the boundary between the Penninic and Austroalpine facies belts (VUAGNAT, 1985), i.e. at the paleogeographic limit between the oceanic and continental domains. It is still a matter of speculation, however, whether the parent volcanoes formed part of an intraoceanic or continental arc. The first Sr^{87}/Sr^{86} whole-rock ratios that have been determined for a suite of andesite cobbles taken from several volcaniclastic formations in the Western Alps are consistently high and fall in the range that is suggestive of crustal contamination (FONTIGNIE and WAIBEL, in prep.). A likely position of the original volcanoes is on top of the Austroalpine nappes, more specifically, above the granitic intrusive bodies situated along the Periadriatic fault system, which are locally associated with andesitic dikes, tuffs, and flows (see below).

If this assumption is correct, then the andesitic volcanoes must have been far removed from their foundation by the time they reached the autochthonous foreland. It has been thought that once the parent volcanoes were erected in the vicinity of a subduction zone, they were detached from their foundation in the course of continental collision, incorporated into one or several nappes, then transported to the basin margin in the foreland, away from the orogenic belt (VUAGNAT, 1952). During the onlap of the volcaniclastic turbidites onto the *external* basin margin platform, the greater part of coarse parent rock materials was derived from an *internal*, predominantly andesitic source at the opposite shore. The fact that the parent andesitic rock units were mechanically disintegrated and redeposited with negligible dilution by other sediments or alteration implies a local source. It may be assumed that the depositional basin was narrow and that the andesitic rock masses were exposed somewhere in the immediate hinterland and along the length of the internal coast. In that the andesitic rock masses were in an internal position at or near sea level, they must have been at a structural level directly above the external autochthonous foreland platform, because the depth of the migrating foredeep at this stage of basin evolution cannot have been particularly deep, perhaps only one or two thousand meters (WAIBEL, 1990). Therefore – during the deposition of the volcaniclastic sandstones – the parent rock units cannot have occupied a structural position above the entire pile of accreted Penninic sediments, much less above the Austroalpine nappes. So if, originally, the volcanoes were truly situated somewhere near the Penninic/Austroalpine plate boundary, they must have been thrust over this edifice before sliding down to their frontal position in the foreland. Emplacement of andesitic nappes by long-distance overthrusting and/or gravity sliding is not required if, alternatively, eruption of the andesitic flows initially occurred closer to the depositional basin, i.e. directly in the foreland. In either circumstance, omission of the parent rock units from the geological record could have taken place by subsequent underthrusting or total erosion between the internal basin margin and the front of the approaching nappes.

Periadriatic dikes and intrusions

The late-Alpine, mostly Oligocene Periadriatic plutons comprise an array of granitic intrusive bodies which, irrespective of regional Alpine structures, discordantly penetrate the Penninic-Austroalpine nappe edifice along the Periadriatic fault system (EXNER, 1976; AHRENDT, 1980; DAL PIAZ and VENTURELLI, 1985; LAUBSCHER, 1985). Radiometric age determinations cluster around 30–31 Ma, so they were intruded subsequent to the thermal peak of the Lepontine metamorphic event at 38 Ma; emplacement during the cooling period (GULSON, 1973) appears to have been facilitated by the residual thermal dome (DAL PIAZ and VENTURELLI, 1985, and references therein; DAL PIAZ et al., 1979; VENTURELLI et al., 1984). Only the southern portions of the Adamello batholith yield older ages (42–35 Ma, DEL MORO et al., 1985).

It has long been speculated that, in spite of departures in mineralogical and chemical composition, the Taveyanne volcanism might somehow be related to these intrusions situated along the Periadriatic fault system (DE QUERVAIN, 1928). The notion is similar to present-day orogenic belts where granitic batholiths were emplaced at the base of compound volcano-plutonic arcs, beneath and contemporaneous with andesite suites situated behind and on the high-T/low-P side of the associated trench graywackes (DICKINSON, 1970a, 1970b). Similarities to the present configuration of Alpine outcrops are unmistakable, and the possibility of such a genetic linkage has been addressed before (HSÜ and SCHLANGER, 1971). In the Alps the granitic rock bodies are accompanied by numerous porphyritic dikes and laterally extensive swarms of dikes (Fig. 3), which are calc-alkaline and locally ultrapotassic in composition (DAL PIAZ et al., 1979; NIEVERGELT and DIETRICH, 1977; GAUTSCHI and MONTRASIO, 1979; GATTO et al., 1976a, 1976b; BECCALUVA et al., 1979, 1985; SCOLARI and ZIRPOLI, 1972; DEUTSCH, 1980, 1984; WENK, 1980; TROMMSDORFF and NIEVERGELT,

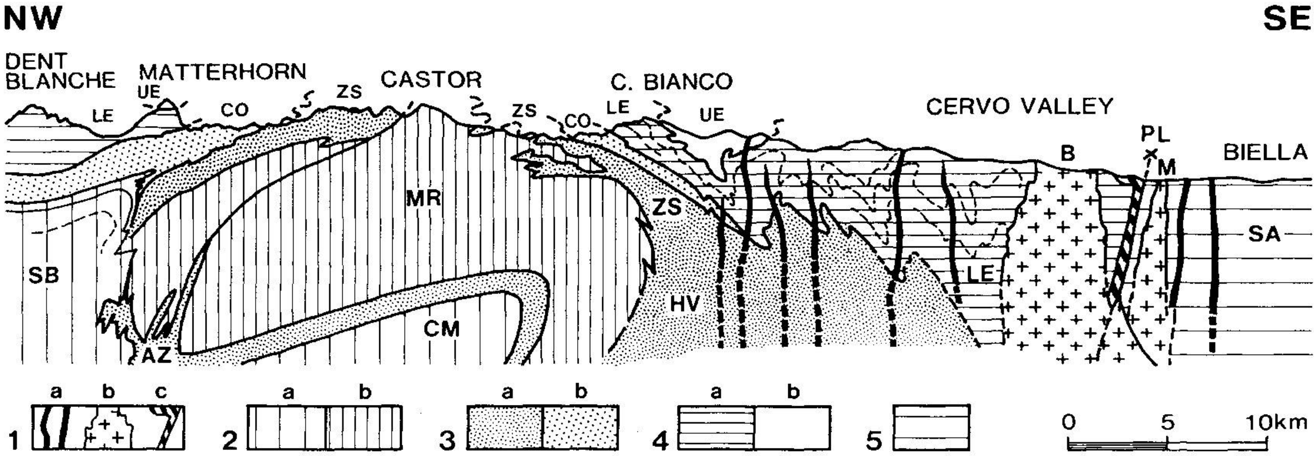

Fig. 3 Cross section through the internal Northwestern Alps between Biella and Southern Valais (after DAL PIAZ et al. (1979) and references therein). 1) late-Alpine magmatic bodies: a) dikes; b) intrusives (B: Biella; M: Miagliano); c) volcanic and volcaniclastic cover of the internal Sesia-Lanzo zone. 2) The Penninic nappes: a) Gd St Bernard nappe (SB) and Camughera-Moncucco units (CM); b) Monte Rosa nappe (MR). 3) The Piemonte ophiolite nappe (Tethyan suture): a) the underlying Zermatt-Saas unit (ZS), grading into undifferentiated high-velocity body (HV); the Antrona Zone (AN); b) the overlying Combin unit (CO). 4) The Austroalpine Dent Blanche and Sesia-Lanzo composite nappe: a) the lower tectonic element (LE), including the Gneiss minuti (= Arolla series) and the eclogitic micaschist complexes; b) the upper tectonic element (UE), including the II Diorito-kinzigitica zone (Sesia-Lanzo) and the Valpelline series (Dent Blanche nappe). 5) The Southern Alps (SA): Ivrea zone, Laghi series and Triassic-Liassic sedimentary cover. PL: Periadriatic (Canavese) Line.

1985). Moreover, well preserved andesitic flows and tuffs of comparable age and composition are known to occur in proximity to the Biella intrusion (SCHEURING et al., 1974; AHRENDT, 1980). Furthermore, andesitic tuffs, flows, and sills of Miocene age are widespread at the other extremity of the Periadriatic fault system, close to its termination in Slovenia (Smrekovek-andesites, EXNER, 1976; and Lavanttal-andesites, LIPPOLT et al., 1975). However, due to the uncharacteristically young, Miocene age of these occurrences, they should perhaps more appropriately be assigned to the Styrian Basin (HAUSER, 1954; HERITSCH, 1967) which, in turn, is transitional to the Pannonian alkaline province in the east (DIETRICH, 1976).

As reasonable as the DICKINSON (1970a, 1970b) model may seem in terms of defining the spatial distribution and mutual relationships of outcrops, it cannot be adopted without reservations (cf. DAL PIAZ et al., 1979). One problem is the difference in age between the external volcaniclastic graywackes and the remnants of the internal magmatic arc, the greater part of which is somewhat younger (see below). An additional problem is that the graywackes predate the episode of intense deformation associated with continental collision (cf. GILL, 1982) in this external part of the orogen, while the arc rocks are conspicuously post-kinematic with respect to their ambient structures and the Lepontine regional metamorphism.

Concerning the first problem, coincident radiometric age determinations are emerging that are nevertheless suggestive of some temporal overlap within one and the same evolving magmatic arc. Andesitic cobbles in the St. Antonin Syncline have recently been dated at 33.9 ± 1.5 Ma (BAUBRON and CAVELIER, 1982, in PAIRIS et al., 1984) and 31.7 ± 0.8 Ma (FONTIGNIE and WAIBEL, in prep.). Excluding the occurrences that have been appreciably rejuvenated by subsequent burial metamorphism (FONTIGNIE, 1981), these are the youngest K/Ar whole-rock isochron datings that have been determined in Taveyanne-type rocks so far. The ages fall close to the cluster of cooling ages at 30–31 Ma in the Periadriatic intrusives (DAL PIAZ and VENTURELLI, 1985, and references therein) and their associated andesitic tuffs and flows (29–33 Ma, SCHEURING et al., 1974). The ages are younger than parts of the Adamello batholith, the oldest portions of which cooled at 42 Ma (DEL MORO et al., 1985); even more so than one andesitic dike which has been dated at 89 ± 7 Ma (GATTO et al., 1976b), an uncharacteristically old age for a Periadriatic intrusive body.

So even though the bulk of the Taveyanne volcanism may appear to be somewhat older than the Periadriatic intrusions on the basis of radiometric datings, it is possible that both events formed part of the same orogenic episode, in which andesitic surface flows preceded the emplacement of granitic intrusive bodies below (VUAGNAT, 1985). The present state of knowledge does not preclude the existence of older intrusions at greater depths beneath those currently exposed. Intrusive contacts are generally sharp, often with well defined thermal contact aureoles, and the plutons locally occur in association with contemporaneous andesitic *surface* flows, suggesting that the current level of erosion is shallow. It is conceivable that incremental crustal heating by successive intrusive cycles resulted in progressively higher levels of magma penetration and cooling, with the consequence that ultimately the youngest intrusions were on average the most shallow. The Lepontine thermal dome is perhaps the manifestation of such subcrustal heating by one or several precursor diapirs remaining at depth below. Alternatively, the initiation or reactivation of the Periadriatic Fault might merely have facilitated the ascent of buoyant magmas to higher crustal levels at this particular time and location (DIETRICH, 1976; DAL PIAZ et al., 1985; BECCALUVA et al., 1985).

The problem still exists of why the Periadriatic dikes and plutons were intruded subsequent to the regional episodes of nappe formation, rock deformation, and recrystallization, a relationship which appears to be post-collisional in origin (DAL PIAZ et al., 1979). Even though this interpretation holds with respect to the country rocks present, the intrusive bodies are in turn deformed by neo-Alpine compressive to transpressive events, which supplied a further shortening of the mountain chain. The intrusive bodies are not entirely post-collisional with regard to the crustal shortening that was to affect the Subalpine Molasse. In fact, compressional movements continued intermittently up into the Late Miocene and Early Pliocene, as shown by the décollement and folding of the adjacent Jura Mountains. So whereas the innermost Western Alps had essentially assumed their basic tectonic and metamorphic signatures prior to the emplacement of the Periadriatic intrusions in the Oligocene, deformation continued some 25 Ma thereafter and was transmitted to progressively deeper levels in the Alpine edifice by underthrusting, while gradually shifting outward during the continent-continent collision. The uppermost Penninic sequences were already accreted to the Austroalpine continental margin during the Cretaceous, and the successive underthrusting of Penninic wedges was essentially completed by the Eocene, when the encroaching passive European continental margin was finally intercepted in the north and for the first time subjected to compressional deformation and underthrusting (WAIBEL and FRISCH, 1989). The Periadriatic dikes and plutons were thus intruded into the base of the Austroalpine continental crust and often into the highest, earliest, and most tightly packed Penninic wedges, where in the Oligocene the activity of thrusting would have tended to be the least active, if not nonexistent, while allowing for extensive underthrusting at the base of the accretionary succession in the foreland (cf. SEELY, 1974). The inception of continental collision does not rule out the generation of calc-alkaline magmas by subduction of lithospheric material, which may have persisted at depth in more internal regions underlying the Periadriatic Fault system.

Venetian volcanic province

Of less obvious concern to Alpine geologists is the Venetian volcanic province on the perimeter of the Po Plain in Northern Italy. Yet the Paleocene to Late Oligocene, partly Early Miocene (PICCOLI and ZANCHE, 1968; DE PIERI et al., 1985) age of the eruptive sequences and their occurrence near the physiographical limit of the Southern Alps attest to their close association in space and time with the Alpine orogeny (DIETRICH, 1976). For that reason they are included in this study even though they are not, strictly speaking, orogenic rocks. They are neither calc-alkaline nor do they display any *immediate* connection to episodes of crustal compression in the Alps.

Comprehensive reviews of the Venetian province are given by DE VECCHI et al. (1976) and BARBIERI et al. (1978). The greater part of the igneous activity comprises basic and ultrabasic products, to the virtual exclusion of intermediate and acid rock types, except for the Colli Euganei where they abound. Chemical affinities are mildly alkaline throughout the entire volcanic province, with tholeiitic tendencies solely during the most recent eruptive stages. Volcanic activity took place in a region that was affected by extensional block-faulting.

The Venetian volcanic province has thus been shown to be genetically related to anorogenic rifting by DE VECCHI et al. (1976), much like the East African Rift System, which they believe was caused by anomalous geothermal gradients in response to an unspecified process of Alpine subduction. One mechanism that could maintain the supply of such magmas over prolonged periods under predominantly marine conditions (PICCOLI, 1966; BARBIERI et al., 1991) is the development of a marginal basin by backarc spreading (BOCCALETTI and GUAZZONE, 1974), or rather an aborted attempt thereof. This model requires a tensile stress pattern and crustal attenuation behind, i.e. to the continental side of the associated trench. Given the present configuration of plate boundary segments, polarities of tectonic vergence, and relative motions between the interacting plates (see below), it follows that the underlying convective motion may have been generated by subduction-related processes in the Western Alps.

One could interpret the episodic extrusion of predominantly alkaline magmas in the southernmost realm of the Southern Alps to have been induced by convection currents beneath the overriding continental plate. Crustal attenuation was initiated during the Early Paleocene, once the asthenospheric flow pattern had been established by the onset of subduction sometime prior to the deposition of the lower, i.e. Late Maastrichtian Gurnigel-, Schlieren-, and Wägital Flysch. From then onwards, the duration of this volcanism grossly overlapped and slightly outlasted the various magmatic activities associated with crustal compression in the Western and Southern Alps, partly until the Early Miocene. The essentially coincident ages are an indication that the generation of alkaline magmas occurred in response to the same mechanism that gave rise to the calc-alkaline magmatic arc situated closer to the trench, which requires a stable convective pattern over a period of at least 30 Ma in the asthenosphere. The appearance of tholeiitic magmas during the latest eruptive stages suggests that the marginal basin was at the verge of becoming oceanic in character, when incipient back-arc spreading was finally arrested. The induced flow pattern was suddenly weakened and perturbed in the wake of collisional events occurring in the adjacent mountain belt and its foreland, when convergent plate motions were slowly declining and continental collision was nearing completion.

Asthenospheric convection cells beneath marginal basins may apparently persist for quite a while once the opposing continental margin is intercepted. This is illustrated in Alpine Europe by analogous occurrences of predominantly alkaline basalts in the Pannonian and Transylvanian basins, which occupy a similar, more internal position with respect to their related calc-alkaline arc and associated trench sediments (Fig. 1). These basins are distinctly extensional in origin (ROYDEN et al., 1983a, 1983b) and have been interpreted as retroarc basins that were formed during the Late Tertiary and Quaternary (BLEAHU et al., 1973; BOCCALETTI et al., 1976). Whereas in the course of continental collision the volcanic feeders of the outer, calc-alkaline arc were the first to be intercepted and obstructed in the Pliocene, eruption of the internal alkaline magmas was not impeded until well into the Quaternary. The fact that, in both the Venetian volcanic province and inner Carpathians, the inception of continental collision did not immediately disrupt the pattern of tensile stresses and associated volcanism suggests that the underlying asthenospheric convective motion continued thereafter, either by a gradual slowdown of the descending lithospheric slab and its drag, or by residual motions of thermal inertia following the final standstill.

Plate-tectonic interpretation

The following is an attempt to document and clarify the temporal and spatial occurrences of the various magmatic provinces as a function of the relative motions between the Adriatic and European plates (DEWEY et al., 1973; BIJU-DUVAL et al., 1977; OLIVET et al., 1982; SAVOSTIN et al., 1986; PLATT et al., 1989). A major assumption in this discussion is that orogenic magmatic provinces are indicative of strong compressive resultants between the converging plates, and that their occurrence may thus be used as a measure of the convergence transmitted, at least to a first approximation.

The geometric outline of the Adriatic plate (Fig. 1) is such that its initial eastward drift relative to Europe during the Jurassic and much of the Cretaceous (Fig. 4) must have resulted in active sea-floor spreading behind its trailing edge in the Western Alps, mostly left-lateral transcurrent motion along its margin in the Eastern Alps and Western Carpathians, and continental convergence in the Eastern Carpathians. Upper Jurassic volcanic activity (BURCHFIEL and BLEAHU, 1976; BURCHFIEL, 1980) and deformation of the adjacent flysch trough from at least the Albian onwards attest to the significant compressive resultant at its leading edge in the Eastern Carpathians (HESSE, 1981, 1982).

During the Late Cretaceous, the original W–E directed motion of the Adriatic plate relative to Europe was abruptly reversed (Fig. 4). Consequently, in the Eastern Alps and Western Carpathians, the dominant strike-slip motion was largely maintained but in the opposite sense, whereby local compressive resultants and associated eo-Alpine metamorphic events were concentrated along irregular protrusions of its northern edge (WAIBEL and FRISCH, 1989). Subduction was initiated at its formerly passive margin in the west, which, by no later than the Late Maastrich-

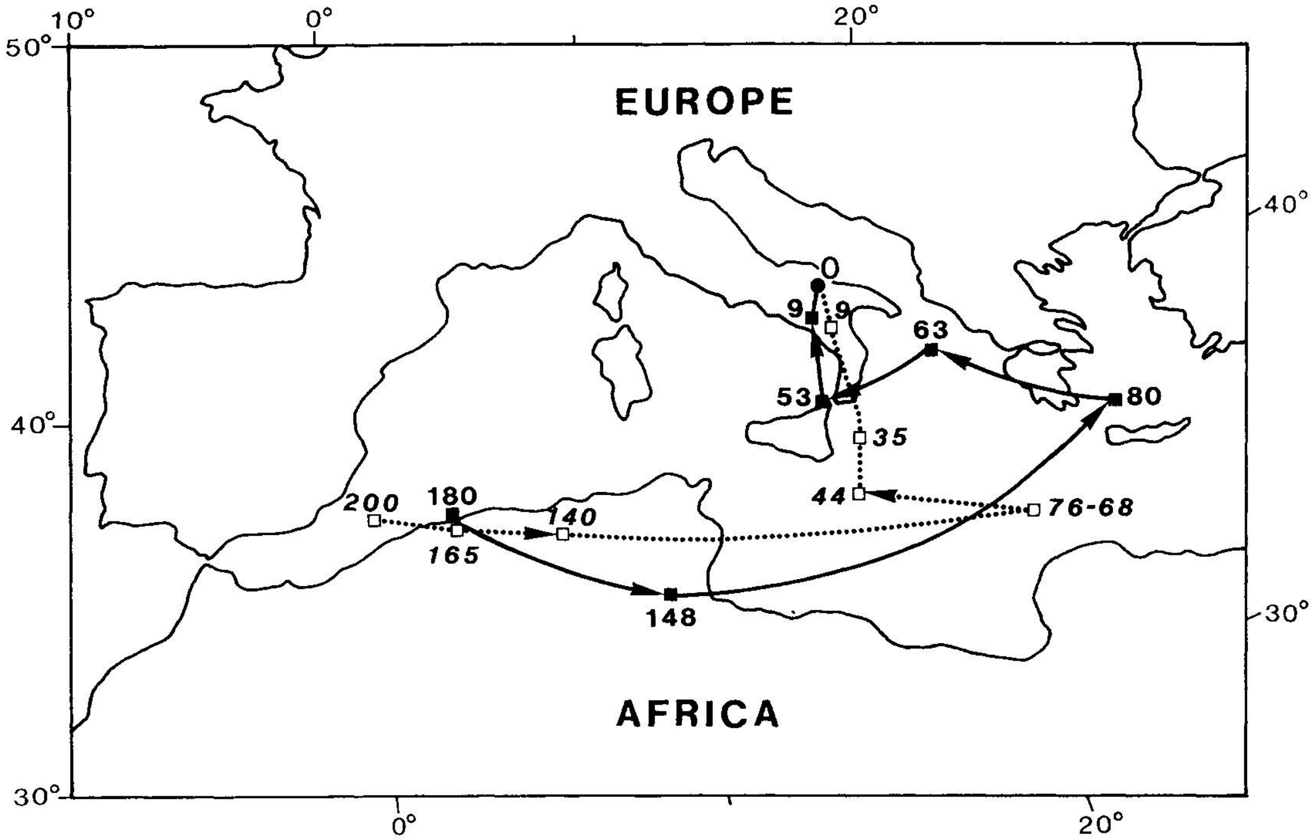

Fig. 4 Movement of Africa and therefore Adria relative to Europe since the Early Mesozoic, derived from Atlantic anomaly data, as depicted by CHANNELL et al. (1979). Full line: according to PITMAN and TALWANI (1972) and DEWEY et al. (1973). Dotted line: modification made by BIJU-DUVAL et al. (1977). Numbers represent ages in millions of years.

tian, ultimately led to the generation of the andesitic volcanism that remains preserved in the Gurnigel-, Schlieren-, and Wägital Flysch. Here, convergent motion continued and, by the latest Eocene or earliest Oligocene, finally resulted in the emergence of the Taveyanne *s.l.* volcanoes in the Western Alps, the Northern Apennines, Southern Italy and Sicily. The sporadic but widespread occurrence of this volcanism along approximately 1,800 km of the western edge of the Adriatic plate strongly suggests that – irrespective of paleomagnetic or other considerations – it was generated in response to convergence transmitted by Adria's drift towards the west. Considering the orientation of the two loop structures in the Western Alps and in Southern Italy and Sicily, it follows that the main compressional component was in all likelihood directed more towards the NW, which is similar to the convergence vector inferred by PLATT et al. (1989) for the same time period. This direction is roughly consistent with the pattern of divergent motion that in the meantime was induced in the Venetian volcanic province, behind and to the SE of the leading edge. In that the Periadriatic intrusive bodies occupy a similar position with respect to the derivative graywacke arc in the Western Alps, they too may have been generated by subduction in the same southeasterly direction.

Whereas the ensuing N–S directed compressional component between Europe and Africa (Fig. 4) resulted in the formation of abundant Neogene volcanic activity in the Carpathians (BLEAHU et al., 1973; RADULESCU and SANDULESCU, 1973), no such volcanism was generated in the Eastern Alps, where subduction perhaps did not reach big enough depths (HESSE, 1982). This seems possible in view of the strike-slip motion that prevailed throughout most of the prior history of the Eastern Alps. Once a strong compressive resultant was finally established, the initial width of the basin could have fallen short of the minimum value the oceanic lithosphere would have required to reach the critical depth. The lack of sufficient depth is not necessarily due to low-angle subduction because sea-floor spreading is assumed to have commenced in the Lias, leading to an old and therefore cold and dense oceanic lithosphere in the Paleogene, which in any case should have ensured a steep dip for the Benioff plane. In the Western Carpathians, by contrast, the width of the oceanic lithosphere was presumably larger to begin with due to the greater initial intervention of the adjacent Paleotethys, in addition to the modest width subsequently created by oblique Alpine sea-floor spreading from the Jurassic onwards. Similarly, in that the initial, exceedingly long-lived eastward movement of the Adriatic plate must have left a sizeable ocean basin in its wake, large volumes of lithospheric material were potentially available for subduction and magma generation, and this ultimately led to the laterally most extensively preserved volcanic activity along its western edge. So even if in the Eastern Alps volcanic products were once generated but subsequently eliminated once and for all from the geological record by underthrusting (HESSE, 1982), the apparent lack of this volcanism could nonetheless reflect the restricted width of the adjacent ocean basin, which inherently determines the volumes and preservation potential of the magmas generated.

Whereas the production of andesitic magmas requires subduction to depths of at least 80 km (HATHERTON and DICKINSON, 1969), high-P/low-T lawsonite- or garnet bearing assemblages, for instance, are formed at depths in excess of only 10 km (3 Kb) or 20 km (6 Kb), respectively. This might explain why in the Eastern Alps there is an apparent lack of the former but not of the latter. Though high-P/low-T assemblages are indicative of subduction *per se*, it is of fundamental importance to realize that they are not necessarily suggestive of the *exhaustive* plate consumption with which they are intuitively thought to be associated.

Conclusions

The occurrences of orogenic magmatic activity that remain preserved in the geologic record range in age from the Late Maastrichtian to Early Miocene. In the outermost graywacke belt, volcaniclastic detritus and pyroclastic fallout deposits were initially introduced laterally into an active deep-sea trench environment from the southern, Austroalpine continental margin during the deposition of the Late Maastrichtian to Mid (Late?) Eocene Gurnigel-, Schlieren-, and Wägital Flysch. In the latest Eocene or Early Oligocene, this was succeeded by the massive introduction of volcaniclastic rock materials to the Taveyanne Sandstone and lateral equivalents, which, by contrast, were deposited in a migrating peripheral basin, in comparatively shallow water at the front of an active fold- and thrust belt, where the opposing European passive continental margin was being intercepted and subjected to underthrusting at the base of the accretionary succession in the foreland. The Periadriatic intrusions are mainly Oligocene in age and in all likelihood comprise the very last, high-level magma chambers and feeder dikes that were intruded after the initiation of continental collision, but *prior* to the cessation of continental convergence and therefore subduction, into fairly stable bedrock of the active continental margin and underlying accretionary prism. It is reasonable to assume that they were emplaced at the base of the same volcano-plutonic arc that had previously supplied abundant volcaniclastic detritus to the Gurnigel-Schlieren-Wägital Flysch and Taveyanne Formation. The presence of older plutons contemporaneous with these turbidite sequences at greater depths than those currently exposed along the Periadriatic fault system is likely but remains speculative. What is left of the original volcano-plutonic arc in the inner Alps is *in situ* and is currently exposed 150–350 km behind the derivative graywackes. Some 500 km behind this graywacke belt, crustal attenuation was initiated in the Venetian volcanic province during the Paleocene, whereafter the development of alkaline magmas was possibly coupled by way of asthenospheric convection with that of the calc-alkaline arc situated closer to the collisional foredeep, partly until the Early Miocene.

Even when poorly preserved, orogenic volcanism appears to be an effective kinematic indicator of strong compressive resultants between converging plates – more so than high-P/low-T metamorphic assemblages – and should be taken into consideration along with other methods in order to determine the plate-tectonic history of collisional mountain belts. In the Alps the general pattern of eruptive and intrusive episodes is consistent with current assumptions (especially those by PLATT et al., 1989) regarding the directions and rates of motion of the Adriatic plate – if generous allowances are made for inprecisions in dating and notably incomplete preservation. The entire range of magmatic activity that remains preserved in the European Alps appears to have been generated by subduction in a southeasterly direction along the northwestern edge of the Adriatic plate and is therefore largely restricted in space to the Western and Southern Alps, with some minor occurrences in the Eastern Alps. Though the appearance of this magmatic activity would at first thought seem to have occurred excessively late, it coincides in time with the earliest *significant* compressive resultant that is geometrically predictable on the basis of the shape, direction, and rates of motion of the Adriatic plate. A major controlling factor for the preservation of these magmas appears to have been the initial width of the adjacent oceanic basin, which ultimately governs the volumes of magma generated and, hence, its preservation potential in the aftermath of a continent-continent collision.

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