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Geochronology of regional metamorphism in the Ivrea-Verbano Zone and Serie dei Laghi, Italian Alps

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Abstract

The Ivrea-Verbano, IVZ, and Serie dei Laghi (which includes the Strona-Ceneri Zone), SdL, have long been regarded as a more or less complete cross-section through the continental crust and the transition zone between crust and mantle of the Southern Alps that was tilted in its present position by ≈ 80°. As this tilting is difficult to accommodate geometrically, other models suggest that the two zones were juxtaposed late in their evolution and eventually exhumed with substantially less tilting. To resolve inconsistencies between different reconstructions of their metamorphic histories, we dated the amphibolite/greenschist facies S1 and S2 assemblages in SdL and the post-granulite evolution in IVZ using the index minerals, amphiboles, refraining from more retentive minerals and from geohygrometers in order to avoid partial isotopic inheritance and predominance of fluid flow history.

We analysed 17 amphiboles, 1 epidote and 2 micas by $^{39}Ar/^{40}Ar$ from two traverses spanning IVZ and SdL, along Val Cannobina and Valle Strona, and from rocks in which S2 is weak or absent E of Lago Maggiore. Our data together with a critique of existing age data suggest a new geochronological reconstruction. The peak (S1) amphibolite facies in SdL, at temperatures not exceeding the "closure temperature" of unrecrystallized amphiboles, occurred around 340 Ma, followed by an S2 (Schlingen-) event probably around 290 Ma. In contrast to SdL, the granulite event in the IVZ peaked in the Early Permian, rapidly followed by exhumation; the juxtaposition and welding of IVZ with the cooler, partly exhumed SdL was achieved around 270 Ma, and no significant differential exhumation occurred thereafter. The granulite facies metamorphism of the IVZ is probably connected both with the intrusion of the Main Gabbro around 285 Ma and with the generation of granitic magmas. Thus, IVZ and SdL must no longer be regarded as a tilted coherent crustal cross-section, as they are two juxtaposed terranes with partly different geological evolutions. The metamorphic history of this segment of the South Alpine basement took place entirely within the Variscan cycle.

Keywords: $^{39}Ar/^{40}Ar$ dating, amphiboles, metamorphic geochronology, isotope correlations, Ivrea Zone, Strona-Ceneri/Serie dei Laghi, Variscan orogeny.

1. Introduction

Ivrea-Verbano Zone (IVZ) and Serie dei Laghi (SdL) are two metamorphic and igneous units of the western Southern Alps (Massiccio dei Laghi). IVZ consists of high-T amphibolite and granulite metapelite, metabasite and marble with lenses of ultramafite and numerous mafic intrusions. The isograd surfaces are steep with respect to present-day surface.

The presence of spinel lherzolite lenses in the granulites near the mafic intrusion induced many authors to consider IVZ as an exhumed crust-mantle transition (MEHNERT, 1975; FOUNTAIN, 1976; ZINGG, 1983). Recently, however, QUICK et al. (1995) questioned that the crust-mantle transition is indeed exposed in the IVZ, as the peridotite lenses of the IVZ appear interfingered with the metasediments and should be better interpreted as assembled in an accretionary wedge. SdL consists of homogeneously low-T amphibolite facies metapelites (Scisti dei Laghi) and metapsammites (Strona Ceneri) separated by a continuous horizon of basaltic metatuffites with ultramafite and retrogressed eclogite lenses (GIOBBI ORIGONI et al., 1997); it also contains metagranites, with an age of intrusion of about 460 Ma and a row of post-metamorphic granitic

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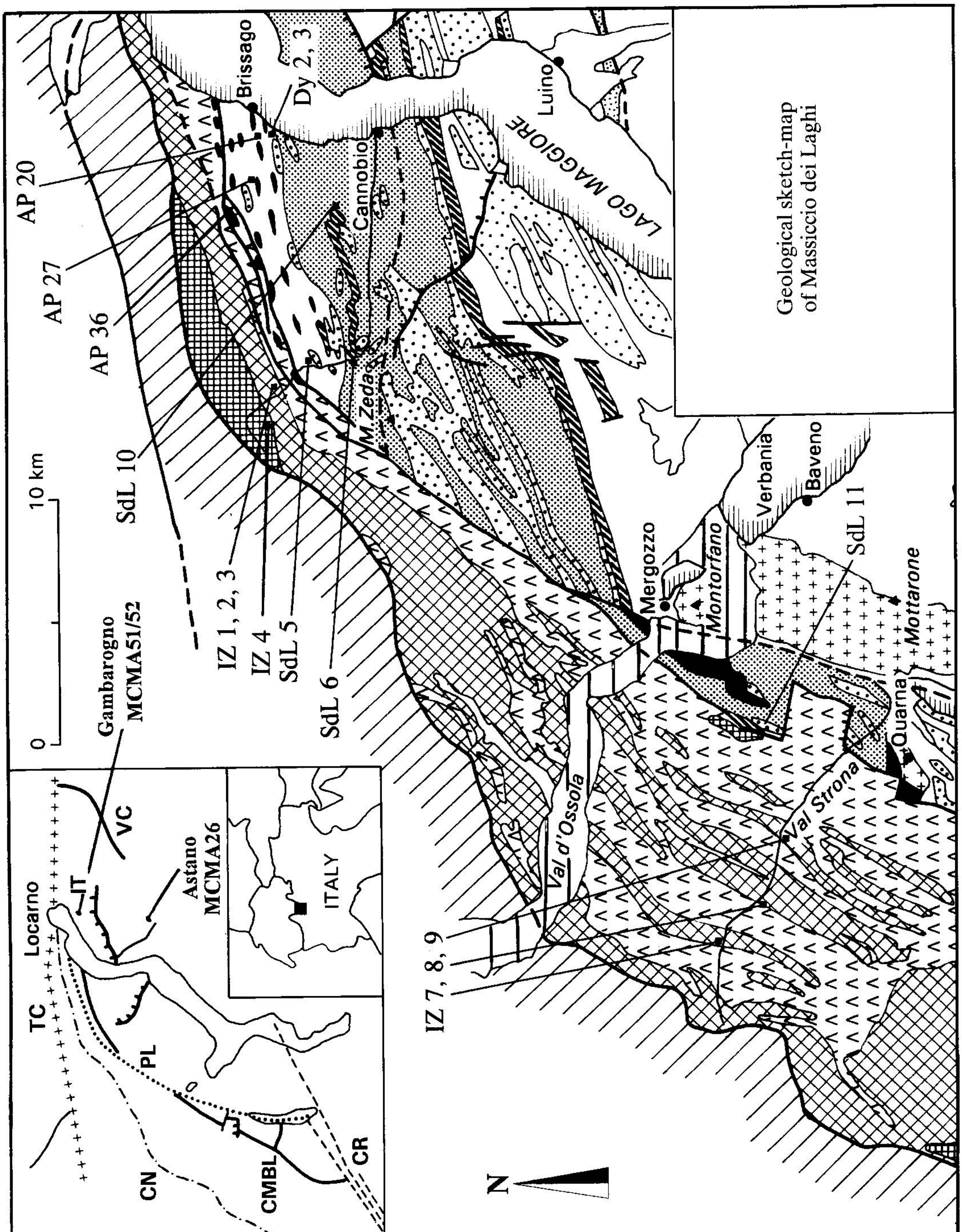

Geological sketch-map
of Massiccio dei Laghi
0
10 km
AP 20
AP 27
AP 36
SdL 10
IZ 1, 2, 3
IZ 4
SdL 5
SdL 6
Gambarogno
MCMA51/52
Brissago
Dy 2, 3
Cannobio
Luino
LAGO MAGGIORE
M.Zeda
Verbania
Baveno
Mergozzo
Montorfano
SdL 11
Mottarone
Quarna
Val Strona
Val d'Ossola
IZ 7, 8, 9
N
Locarno
TC
IT
VC
Astano
MCMA26
ITALY
PL
CN
CMBL
CR

Fig.1 Geological sketch-map of Massiccio dei Laghi with sample locations (modified after GIOBBI ORIGONI et al., 1997).

Quaternary

Sedimentary Mesozoic-Cenozoic cover

Permian granites ("Graniti dei Laghi")

Permian mafic and acidic stocks and dykes ("Appinites")

SERIE DEI LAGHI:

(a) Strona Ceneri Zone (paragneisses, including Cenerigneisses and Gneiss minuti);
(b) Strona Ceneri Border Zone (metabasites ± ultramafites)

Scisti dei Laghi (micaschists, paragneisses)

Ordovician metagranitoids

IVREA VERBANO ZONE:

(a) mafic rocks (both granulite and amphibolite facies);
(b) ultramafites

Kinzigites (pelitic and semipelitic, high-grade metasedimentary rocks, with subordinate marble and amphibolite intercalations)

ALPINE DOMAIN

FAULTS: In the inset: CN = Canavese; TC = Tonale Centovalli; VC = Val Colla; CMBL = Cossato-Mergozzo-Brissago Line; PL = Pogallo Line; CR = Cremosina.

OVERTHRUSTS: In the inset: IT = Indemini – Monte Tamaro.

plutons of Early Permian age (BORIANI et al., 1995).

The contact between IVZ and SdL occurs through an important subvertical tectonic line (BORIANI and SACCHI, 1973; BORIANI et al., 1990a), the Cossato-Mergozzo-Brissago Line (CMBL), a lineament characterized by the simultaneous occurrence of three distinctive features: high-T mylonites, basic-to-acid dykes and stocks (locally known as *appinites)* and migmatites. Lower temperature reactivations and minor later subvertical faults, among which the most important is the Pogallo Line (PL), complicate the original contact. The PL is only characterized by amphibolite to greenschist facies mylonites.

Because of the immediate proximity of these two units from the lower (IVZ) and intermediate crust (SdL), FOUNTAIN (1976) proposed to consider this area as a complete cross section through the continental crust, and the fault that separates the two units as a tilted low angle normal fault (HODGES and FOUNTAIN, 1984; HANDY, 1987). The idea of tilting was based on the assumption that both units shared the same age of metamorphism (Caledonian, following HUNZIKER and ZINGG, 1980; Caledonian and Variscan, following ZINGG et al., 1990) and that the younger radiometric mineral ages found in the IVZ were all cooling ages and did not reflect a different age of metamorphism. The role of low angle normal fault was attributed by HANDY (1986, 1987) to the Pogallo Line, characterized by dominantly greenschist facies mylonites crosscutting a small plutonic body ("S. Rocco granite") incorrectly considered by this author a deformed relative of the Early Permian Montorfano and Baveno granites instead of an acidic differentiate of the "appinite" suite. The age of the activity of this fault should therefore be post-Permian and, on the basis of the reconstructed cooling history of the two adjacent units, probably Late-Triassic to Early-Middle Jurassic. In HANDY's opinion (1986, 1987) the tilting of the Pogallo Line and of the entire crustal section of the 60°–85° necessary to reach the present setting, occurred partly in the Early-Middle Jurassic and was completed during the Alpine orogeny. No discussion is given of the geometrical difficulties involved; HANDY (1986, p. 262) postulated an unobservable Lago Maggiore fault to remove the necessity of a sphenochasm opening to the east of the SdL-IVZ contact; the subhorizontal contact between Permian sediments and steep foliation, which could have cast doubts on the situation in the Permian, is not mentioned. These ideas, with only slight modifications, also appear in later papers by ZINGG et al. (1990) and S. SCHMID (1993).

Different views are expressed by BORIANI et al. (1990a) and PIN (1986, 1990). On the basis of geological, petrological and geochronological evidence the former authors reject the interpretation of the Pogallo fault as tilted low-angle normal fault of Mesozoic age (their fairly long discussion needs not being repeated here). SdL had already cooled down to greenschist facies conditions before the emplacement of the Early Permian granites. The adjacent Baveno pluton was intruded at depths as shallow as 1 kb, as attested by miarolitic cavities, and could not have been tilted by more than 20° after its solidification. A Triassic alkaline pipe (BIINO and MEISEL, 1995), which was intruded vertically, is still vertical today. Finally, those biotites in HUNZIKER and ZINGG (1980) that are not altered have uniform ages around 180 Ma, and their ages show no strong E–W gradient as would be required by an 80° Alpine tilting. All this means that the SdL terrane never was tilted in its entirety after the Permian (all while localized folding and tilting is likely to have occurred). The main contact between SdL and IVZ is the CMBL, whose attitude never was that of a low-angle normal fault, i.e. SdL is not necessarily the autochthonous cover of IVZ.

The structure of SdL (BORIANI et al., 1990b; BORGHI, 1989) is dominated by a huge synform (F1) with subvertical axial plane trending SW–NE with variable axial plunge: from sub-horizontal in the western part to steeply plunging in the eastern part. The main foliation S1, characterized by peak amphibolite facies metamorphic assemblages, is parallel to the axial plane of the synform. In the NW part of SdL, S1 is overprinted by F2 open subvertical folds giving a weak greenschist facies S2 ("Schlingenbau", BÄCHLIN, 1937), with edenitic-actinolitic overgrowth/replacement on S1 amphiboles. F2 folds become tighter and tighter the more we approach the CMBL, where S2 becomes a mylonitic foliation. This suggests a genetic link between S2 and CMBL. Near the CMBL S2 is overprinted by a static lower P metamorphism reaching the conditions for dehydration melting (BURLINI and CAIRONI, 1988). This static thermal event is not followed by any other important plastic deformation or foliation. SdL amphiboles formed during the S1 event; some were overprinted by S2, a weakly pervasive foliation whose grade is regionally greenschist-facies (except in the Malcantone area, where it is virtually absent), resulting in actinolite rims in some samples, but which locally reached amphibolite facies conditions near the CMBL. Samples near CMBL probably also were affected by the subsequent thermal event induced by the juxtaposition of the hot IVZ along the CMBL.

Non-isotopic age constraints for the metamorphic history of SdL and IVZ are very scarce. The oldest unambiguous marker, the Early Permian Arosio sandstone, limits the age of the S2 deformation (see § 3 below) to be older than ≈ 270 Ma. The Stephanian Manno conglomerate, on the other hand, is in fault contact with the basement and thus may be questionable in limiting the age of the S2 event as was done by ZURBRIGGEN (1996).

The aim of this paper is to put these contrasting models to the test by new radiometric data, to attempt an overall geochronological reconstruction that is able to resolve the present inconsistencies, and to reconsider the metamorphic evolution of SdL and IVZ and the history of their relationships.

2. A discussion of previous geochronology

We will mainly discuss those chronometers which have some bearing on dating the peak of metamorphism; mica and fission track data relate to the retrograde evolution and are outside the scope of this paper.

In the present critical discussion, one aspect which must be addressed is what chronometer can give what sort of information on what geological process. In view of the contrasting interpretations of the geology of the IVZ and SdL terranes, understanding the similarities and differences of their metamorphic histories can help clarify their genesis; a decisive problematic aspect is the suitability of the various geochronometers (and/or geohygrometers) to date different kinds of geological events. In the present decade our paradigms of interpreting geochronological data have undergone profound modifications. It is therefore necessary to discuss the criteria that limit the applicability of the various dating methods; for the most common ones, we can direct the readers to more or less recent literature work (e.g. HOFMANN, 1992 for the Rb/Sr method; VILLA et al., 1996b for the $^{39}Ar/^{40}Ar$ method; GEBAUER and GRÜNENFELDER, 1976 for the U/Pb method on zircons). Other, less well-documented ones, such as the U/Xe method, have never been discussed in the literature and need to be reviewed here with sufficient detail to allow readers to independently assess the reliability of the geological conclusions.

Age data on the Ivrea Zone were reported by PIN (1986) who proposed a Permian age for the mafic complex and concomitant granulite facies metamorphism, and obtained an U/Pb zircon age of 285^{+7}_{-5} Ma on the dioritic part of the complex. In contrast, VOSHAGE et al. (1987) argued, on the basis of Sm/Nd whole rock isochrons, that the age of the ultramafites of the mafic complex was Late Proterozoic (≈ 600 Ma). However, this same laboratory analysed additional samples and revised the age of the Mafic Complex to Early Permian (VOSHAGE et al., 1990). Metamorphic zircon growth was dated by VAVRA et al. (1994, 1996); TEUFEL et al. (1994) analysed monazites by U/Pb, but as they do not document the analysed grains by cathodoluminescence or BSE, and as TEUFEL and HEINRICH (1997) showed that Pb loss in monazite essentially involves fluid assisted dissolution/reprecipitation, it is straightforward to conclude that at least the youngest among their ages do not represent simple cooling but rather fluid circulation and retrogression. Both these groups independently propose Early Permian ages (≈ 296–280 Ma) for the granulite-grade episode, recorded by the oldest samples of their suites; the subsequent retrograde path was long, wet and complex, as documented by VAVRA et al. (1996) by relating ion probe dating to overgrowth morphology and petrogenetic environment. Overall, there is now very convincing evidence that the intrusion of the mafic body in the Permian and the granulite metamorphism are temporally, and probably causally, related. This was also predicted from geochemical arguments (PIN and SILLS, 1986; VOSHAGE et al., 1990; SINIGOI et al., 1994). Finally, Triassic ages were repeatedly reported (around 227 Ma: STÄHLE et al., 1990; at 217 ± 6 Ma: BIINO and MEISEL, 1995; at 207 Ma: VON QUADT et al., 1993). It is still open whether they all represent shallow-level magmatism or if the fluid circulation documented by VAVRA et al. (1996) can account for these ages.

Age data on the Serie dei Laghi were reviewed by HUNZIKER and ZINGG (1980), BORIANI et al. (1985), and ZINGG et al. (1990). We need not discuss in detail every single paper included in these reviews, but rather pont out the gist of the controversial interpretations. BORIANI et al. (1995) obtained Ordovician ages for the magmatic emplacement of the orthogneiss protolith. ZINGG and coworkers noted that Rb/Sr isochrons on whole rocks collected over a 30 km distance gave Ordovician ages and showed no evidence of the Variscan metamorphism. MCDOWELL (1970) and BORIANI and VILLA (1992), on the contrary, found Variscan amphibole ages throughout the region, substantiating the suggestion of a Carboniferous metamorphism in the SdL made by BORIANI et al. (1982–83).

The latter two observations could be reconciled as later work (HOFMANN, 1992) demonstrated that the Rb/Sr system is homogenized on the 30 km scale only during the massive fluid circulation connected with the first dehydration of sediments (cfr. also PIN, 1990, p. 94), and is thus a priori not expected to ever record a later regional higher-grade metamorphic overprint once rocks have been sufficiently dehydrated. In the WR approach, diverse lithologies are pooled into one Rb/Sr evolutionary graph; the necessary condition to interpret a correlation of the data-points as an isochron is achievement of perfect isotopic equilibrium among all analysed samples at some initial time t_0. This clearly only happens over tens of km during intense fluid circulation, as no purely diffusive process can produce diffusion lengths of that magnitude in the crust. Indeed the very persistence of mantle heterogeneities over Ga timespans means that even at T >> 1200 °C diffusion length scales are comparatively short.

Sluggish Pb diffusion in monazite (DAHL, 1997, and references therein) makes these minerals totally insensitive to amphibolite and lower grade overprints. This may imply that KÖPPEL and GRÜNENFELDER's (1971) data on Ordovician monazite have no relevance for the subsequent metamorphic evolution. The important point to notice is that KÖPPEL and GRÜNENFELDER'S (1971) Casletto locality is very close to Ordovician plutons and that the monazite was likely formed by contact metamorphism *sensu lato* rather than by regional metamorphism. On the other hand, precisely the high Pb retentivity of monazite is decisive evidence to establish that the age of the local migmatization event in the SdL near the CMBL producing monazites Stro-1 and 2 (KÖPPEL, 1974) is no earlier than 295 ± 5 Ma.

Further age data were obtained on zircons from para- and orthogneisses by conventional U/Pb multigrain analyses (KÖPPEL and GRÜNENFELDER, 1971) and by U/Xe bulk extraction (RAGETTLI, 1993). Both studies yielded Ordovician ages.

The interpretation of zircon U/Pb ages in metamorphic rocks should be based on GEBAUER and GRÜNENFELDER (1976). In that paper, the paramount importance of dehydration of sediments becomes apparent: rocks from a classical Variscan locality unexpectedly gave Ordovician ages without showing any evidence of the Variscan metamorphism that had obviously affected them, neither by U/Pb on zircons nor by whole-rock Rb/Sr. The behaviour of the Rb/Sr system has been discussed above. As for the zircons, GEBAUER and GRÜNENFELDER (1976) were able to demonstrate that the crystallographically observed fluid-induced recrystallization was responsible for resetting the ages of their detrital zircons during Ordovician diagenesis, and suggested that the annealed zircons were much more resistant to high-temperature dry metamorphism. In other words, KÖPPEL and GRÜNENFELDER'S (1971) data, in the light of the subsequent insights of that same group (GEBAUER and GRÜNENFELDER, 1976), may not be directly relevant for an age determination of regional metamorphism. Even if KÖPPEL and GRÜNENFELDER'S (1971) original conclusions of an Ordovician metamorphism not disturbed during the Variscan were never retracted, it is now clear that subsequent work allows to reliably re-interpret the zircon data as dating an Ordovician diagenesis; although zircons were metamorphosed in the Variscan orogeny, they could not record it. The extreme thermal stability of Pb in zircons has later been abundantly demonstrated (e.g KRÖNER et al., 1987; CHERNIAK et al., 1993); a recent review (LEE, 1993a) underlines the preponderance of fluid-induced rejuvenation with respect to thermally induced Pb loss. We may thus define zircons not as isotopic thermometers but rather as isotopic *hygrometers*.

The analytical improvement due to ion microprobe dating of zircons (e.g. VAVRA et al. [1996] and references therein) has provided important modifications to our perception of the mechanisms of "lead loss". It is now evident from the data that it is predominantly successive, heterochemical overgrowth zones that are responsible for discordant U/Pb ages, and not diffusion of Pb out of an unmodified zircon. This is very probably the case for monazite as well (cfr. TEUFEL and HEINRICH, 1997, Fig. 3). This means that only overgrowth events are amenable to dating by zircons, and not thermal overprints that leave the grain morphology unchanged; it also confirms the statement made above that, as a rule, high temperature *alone* will not change the zircons' Pb isotopic record.

RAGETTLI (1993) obtained U/Xe data on abraded zircons which are plagued by at least two artefacts: the decay constant for spontaneous fission of U is not that recommended by IUPAC (HOLDEN, 1989) but is 30% higher; abrasion of U-rich outer layers produces an apparent "excess Xe", Xe_{XS}, because the Xe that recoiled inwards from them is unsupported after abrasion (KAPUSTA et al., 1983). Indeed the only documented instance of duplicate analysis (CAS-1: RAGETTLI, 1993, p. 73) proves that the reproducibility is no better than 25%, i.e. the magnitude of the abrasion-derived Xe_{XS} is at least this high. Thus, after using the IUPAC constant and correcting back for the effects of abrasion one derives an U/Xe age of 226 Ma for the Casletto sample, in agreement with the well-known observation (GEYH and SCHLEICHER, 1990, p. 157) that U/Xe ages are lower than the corresponding U/Pb ages.

The intrusion of granitoids (Baveno, Montorfano, Mottarone) was dated using WR Rb/Sr by PINARELLI et al. (1988). Ages cluster around 280 Ma and are statistically barely distinguishable from the Orf-1 monazite age by KÖPPEL (1974), 295 ± 5 Ma.

In the compilation of ZINGG et al. (1990) it can be noted that ages E of CMBL frequently exceed 300 Ma while they are < 250 Ma to the W of it. This difference could be interpreted both as a smooth gradient (an effect of Alpine 80° tilting) and as a discrete jump due to a terrane boundary (evidence that the peak of the metamorphism in the IVZ was not coeval with that in the SdL). We performed a closely-spaced sample collection on both sides of CMBL to shed light on the controversy.

3. Sample description

Samples were collected along two traverses perpendicular to the CMBL, from both IVZ and SdL (Fig. 1). Petrographic descriptions are summarized in table 1, together with coordinates.

In the Val Cannobina traverse, three amphibolites from the IVZ were collected from the new road tunnel excavations in Creves, near Cursolo; one amphibole is from the Finero ultramafic body and three amphibolite samples between Falmenta and the Lago Maggiore derive from the SdL.

In the Valle Strona traverse, we collected three amphibolites from the IVZ and one from SdL. Especially in the polydeformational Serie dei Laghi, our sampling was aimed at resolving different generations of amphiboles, both by attempting to collect samples with a single generation of amphiboles, and by attempting to resolve mixed-generation amphiboles by means of a new isotope correlation technique. While it is true that most literature work does not report a distinction between the ages of D1 and D2 parageneses, we believe that our sample choice was appropriate as it included both rocks in which D1/S1 was never overprinted by D2 (see § 4.1) and rocks in which D2 penetratively erased every petrographic record of S1 (see § 4.2).

In order to provide a better age constraint on S1, three amphibolite samples (MCMA: cfr. GIOBBI ORIGONI et al., 1997) were collected in the SdL on the eastern side of Lago Maggiore, in Astano, where S2 is absent (as also testified by the Carboniferous mica ages by MCDOWELL, 1970) and only brittle deformation occurred, and in Gambarogno, where S2 does not form a pervasive foliation.

In addition, we sampled four mafic magmatic rocks ("appinites"), which only grew syn- to post-D2, to constrain the Permian vertical movements; however, owing to their close spatial association with the CMBL, all amphiboles were overprinted during the hydrothermal activity associated with late reactivation of CMBL and PL. A muscovite-bearing pegmatitic differentiate from Brissago, Dy3, was collected in order to examine its relation to the close-by mafic dyke, Dy2, which is characterized by very minute (< 10 μm) biotite-amphibole intergrowths.

Amphiboles were separated from the 100–160 μm sieve fraction magnetically, then by heavy liquids; finally, about 10 mg were further purified by handpicking. Irradiation and Ar analyses follow VILLA et al. (1996b). The results of the analysed samples are summarized in table 2, and plotted in figures 2 (Malcantone), 3 (western Serie dei Laghi) and 4 (Ivrea-Verbano zone). The complete data can be obtained from the authors. Errors are quoted at the 1σ-level.

4. Geochronology of regional metamorphism

In order to date the regional amphibolite metamorphism, it is first necessary to assess what chronometer is suitable for dating it. From the more recent literature mentioned in § 2 it is clear that highly retentive minerals (zircon, monazite) are not appreciably rejuvenated under amphibolite facies, and are thus *a priori* unable to provide a meaningful chronological framework in the polyphase SdL. Other minerals such as micas are all too easily altered and rejuvenated, besides violating the requirement of complete isotopic closure for Ar and Sr under amphibolite facies conditions. Amphiboles, on the other hand, are index minerals of the amphibolite facies; chemically different amphiboles are formed at different PT, and they are isotopically closed systems ever since the majority of formation conditions (unless they are recrystallized during alteration or retrogression, in which case different PT conditions are easily resolved chemically). Thus, dating amphiboles by $^{39}Ar/^{40}Ar$ is a very reliable way to reconstruct the geochronology of an amphibolite facies metamorphism.

It is now clear that in samples free from recrystallisation texturally older amphiboles retain Ar at temperatures near or higher than 600 °C as a function of their crystal chemistry (KAMBER et al., 1995; VILLA et al., 1996 a, b), so that the amphiboles of the SdL should be considered formation ages dating the metamorphic peak, which slightly if at all exceeded 550 °C. From the chemical compositions and site occupations we calculated values for Z (as defined by DAHL, 1996) be-

Tab. 1 Sample description

Sample	Locality	Coordinates	Rock name	Texture	Association	Remarks
Malcantone-Gambarogno area						
MCMA 26	Astano mine	706.9, 96.1	amphibolite	granoblastic	gr.Hbl, Pl, Bt, Grt	
MCMA 51	Monti di Agra	708.8, 108.8	id.	id.	gr.Hbl, Pl, Grt, Rt	Hbl-Pl sympl./keliph.
MCMA 52	ibid.	709.0, 108.9	id.	id.	gr.Hbl, Pl, Grt, Rt	id.
Val Cannobina section						
IZ 1	Finero-Creves tunnel	686.0, 106.4	Hbl granulite	mylonitic	brown Hbl, Pl, Cpx	new green Hbl
IZ 2	ibid.	id.	Hbl-Grt granulite	mortar	br.Hbl, Grt, Pl, Cpx	new gr.Hbl + keliph.Grt
IZ 3	ibid.	id.	Hbl-Ep fels	mortar	br.Hbl, Ep, Cpx	gr.Hbl replacing Cpx
IZ 4	Finero	685.5, 106.7	Grt gabbro cumulate	granoblastic	Ol, Cpx, Opx, br.Hbl	
SdL 5	jct. Spoccia road	689.6, 104.9	amphibolite	grano-nematobl.	gr.Hbl, Pl, Chl, Bt	Hbl poik.
SdL 6	Ponte Falmenta	690.0, 103.5	id.	id.	gr.Hbl, Pl, Bt	id.
SdL 10	Cavaglio/P.te Gana	693.5, 103.6	id.	id.	br.Hbl, Pl, Bt	id.
Val Strona section						
IZ 7	Forno-Campello rd, bridge	661.6, 89.9	Hbl-Grt granul.	granoblastic	br.Hbl, Grt, Pl, Cpx	gr.Hbl repl.Cpx
IZ 8	Val Strona road, km 13.5	664.5, 89.4	Hbl granul./amphibolite	id.	br.Hbl, Pl, Cpx	unaltered
IZ 9	same road, km. 11.2	666.0, 87.8	id.	id.	br.Hbl, Pl, Cpx, Czo	gr.Hbl repl.Cpx
SdL 11	Spanero-Alpe Morello road	671.1, 87.5	spotted amphibolite	granoblastic	gr.Hbl, Pl, Bt	unaltered
Appinites and dykes						
Dy 2	end of Piodina road	697.3, 107.4	mafic dyke	ophitic	gr.Hbl, Pl, Bt	Hbl with Bt incl.
Dy 3	ibid.	id.	felsic dyke	aplitic	Kfs, Qtz, Pl, Ms, Bt	fine grain size
AP 20	Piodina road	698.1, 109.2	mafic pegmatite	cumulitic	gr.Hbl, Pl, Bt	Hbl poik., Bt chlor.
AP 27	Alpe Cortaccio	696.0, 108.6	chill.marg. of maf.dyke	ophitic	gr.Hbl, Pl, Bt	Bt strongly chlor.
AP 36	Alpe Arolgia	696.4, 110.1	coarse-gr. hornblendite	poikilitic	gr.Hbl, Pl, Chl	Bt totally chlor.

tween 37.7 and 38.4%. The corresponding "closure temperatures" are based on the upper limit for amphibole diffusivity in VILLA et al. (1996b) and are therefore lower limits. Following DAHL (1996, p. 3693) the lower limit for the "closure temperature" of a recrystallization-free amphibole with $Z = 38.1\%$ is ≥ 550 °C.

As practically all samples have internally discordant age spectra (as expected from a polyphase metamorphism), age assignments are made on the basis of those portions of the spectra that can be diagnosed to represent a pure end-member in isotope correlation diagrams. The Cl/Ca/K three-element plot (Fig. 2a; cfr. EVERARD and VILLA, 1994; VILLA et al., 1996b) has the diagnostic purpose of identifying chemically distinct Ar reservoirs, i.e. distinct mineral phases. The fact that variable ratios of Ca, Cl and K are present in most but not all amphiboles forces the conclusion that most amphiboles which look homogeneous under the binocular microscope are petrologically complex entities, likely to be zoned at a scale escaping optical detection (< 10 µm). As the Ar release of amphiboles occurs during discrete breakdown reactions (LEE, 1993b), it is to be expected that only a few heating steps will coincide with the breakdown reactions of one end-member, amphibole 1, without attending breakdown of the other intergrown amphibole 2, and that some of the steps dominated by amphibole 1 will be separated from each other by steps that represent degassing from amphibole 2 (cfr. VILLA et al., 1996a, Fig. 4). In most samples of the present study the end-member composition is only approached by one isolated step, and its age is taken as that of the end-member. In a few samples several steps form a tight cluster around a possible end-member; in these cases, an isochron through these steps gives the best option to control the trapped Ar composition (this approach is precluded if only one step identifies the end-member composition, as the trapped Ar composition could have been variable during heterochemical growth of more than one generation of amphibole, and an isochron is therefore arbitrary). We observe that the trapped Ar calculated from these isochrons is atmospheric. Only in the case of IZ-3 and IZ-4 (see § 4.3) there is clear evidence of a substantially non-atmospheric trapped Ar.

4.1. THE AGE OF THE S1-FORMING METAMORPHISM IN THE SERIE DEI LAGHI

The three MCMA samples were collected E of Lago Maggiore, an area where the S2 overprint was weak or absent, in order to most closely ascertain the age of the S1. Comparison with samples W of Lago Maggiore, with a stronger S2 overprint, shows indeed excellent isotopic evidence of different degrees of preservation of the same geological events (see § 4.2).

Samples MCMA 26 and 51 (Fig. 2 a–c) have age spectra featuring broad, flat portions around 330–340 Ma. In both samples, most of the gas corresponds to typical amphibole compositions (Ca/K > 20). In figure 2a, we identify 7 points from MCMA 51 with a high Ca/K ratio that are spread out along a mixing line, whose end-members are labelled M (Ca/K = 22.5, Cl/K = 0.021) and N (Ca/K = 19.7, Cl/K = 0.006). In figure 2b, these same 7 steps have ages between 326 ± 3 and 341 ± 6 Ma. The simplest interpretation is that the amphibole *sensu stricto* in our separate MCMA 51 grew (in discrete episodes, or continuously) between 341 and 326 Ma under changing chemical conditions (slightly decreasing Ca/K and markedly decreasing Cl/K). Similar observations apply to MCMA 26, whose high-Ca/K points define a mixing line PQ. Point Q has an age indistinguishable from that of point M; amphibole MCMA 26 grew between 342 ± 2 and 321 ± 3 Ma (with point P indicating an age as young as 310 ± 8 Ma). It is also possible to control the implicit assumption that ages of isolated steps are not grossly incorrect due to excess Ar (Ar_{XS}): in figure 2a, four steps of MCMA 26 define a tight cluster near point Q and can be therefore assumed as almost cogenetic. The isochron through these four points has an age of 339 ± 36 Ma and an atmospheric trapped Ar composition of 263 ± 92. The atmospheric intercept encourages the view that individual step ages are not substantially affected by Ar_{XS} and can be used at face value in the interpretation of the age-chemistry correlation diagrams.

As both MCMA 26 and 51 have a simple, near-ideal behaviour (reflecting their almost monometamorphic history), their common age ≈ 340 Ma reliably dates the S1 amphibolite facies event.

Sample MCMA 52 is not useful from a geochronological point of view, but rather from a systematic one, as it didactically illustrates the pitfalls of amphibole dating. Following conventional interpretation, the flat portion of the spectrum (Fig. 2d) containing ≈ 50% of the gas and averaging ≈ 300 Ma would be considered a "plateau" dating some geological event. However, figure 2e clearly shows that the mineral separate consists of a two-component mixture, and figure 2f identifies their ages as ≤ 228 and ≥ 326 Ma. Thus, the 300 Ma step ages are an artefact caused by the binary mixing, while the truly relevant information is provided by the end-members of the mixing trends of

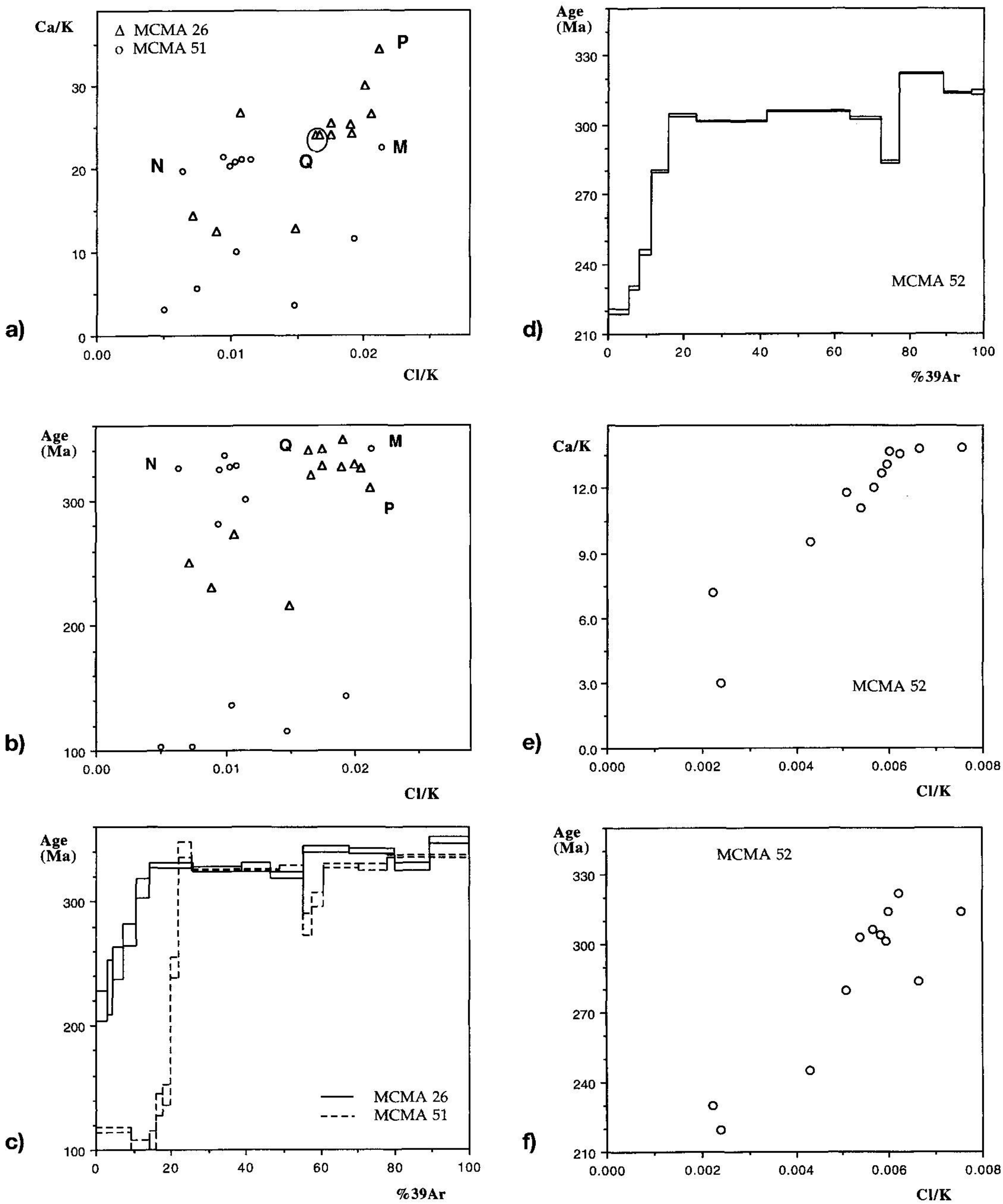


Fig. 2 Stepwise heating results for Serie dei Laghi amphiboles E of Lago Maggiore. (a) Chemical correlation diagram, derived from the ^{37}Ar, ^{38}Ar and ^{39}Ar measured in each step (VILLA et al., 1996b). Linear trends correspond to a binary mixing whose end-members represent different amphibole generations. The letters identify steps that most closely approach the end-members. (b) Age-chemistry correlation diagram; note that the ordinate is equivalent to an $^{40}Ar^{*}/K$ element ratio. Symbols as in a). The end-members M and Q recognized in a) can be assigned an age around 340 Ma in this diagram, which represents the age of the S1 metamorphic event. (c) Age spectra of samples MCMA 26 and 51. This traditional data presentation is less rigorous than the combination of a) and b). (d) Age spectrum; (e) chemical, and (f) age-chemistry correlation plots for MCMA 52. The existence of a "plateau" in d) is an artefact of mixing the two amphibole generations clearly visible in e) and f).

figures 2 e–f: this amphibole also was formed during S1 around 340 Ma, but later (only partly) recrystallized with a different chemistry from its predecessor during a local fluid infiltration. The second-generation amphibole has a Cl-, Ca-poorer chemical composition and is younger than 228 Ma.

4.2. SERIE DEI LAGHI TRAVERSES

The westernmost among the three Val Cannobina samples (SdL 5) has a very discordant age spectrum with several step ages exceeding 1 Ga (Fig. 3d); no isochron can be calculated. This is likely caused by its proximity to the CMBL and consequent high-grade overprint, accompanied by uptake of $^{40}Ar_{XS}$ from the fluid, during the earliest time the CMBL was active, i.e. the Permian.

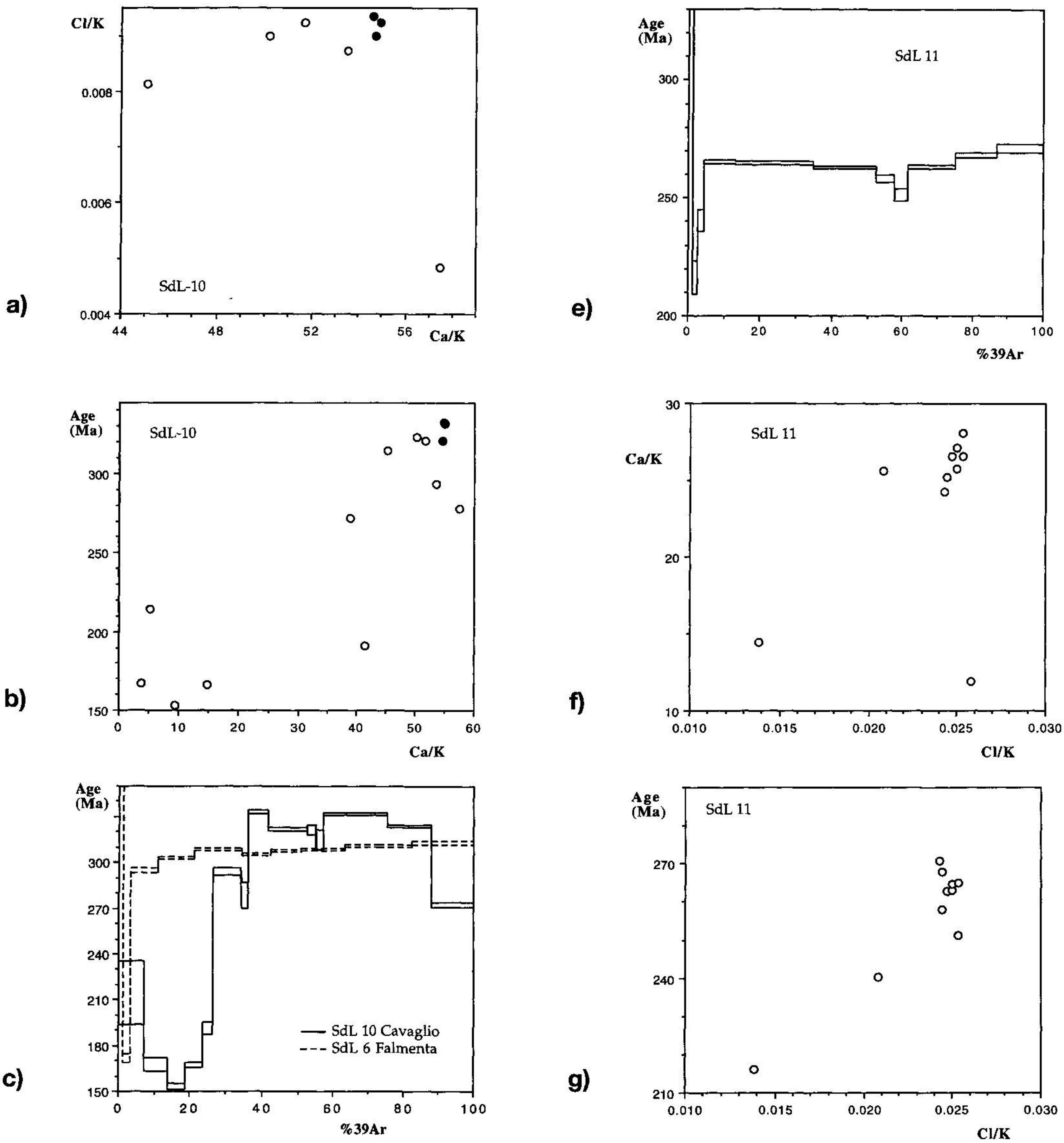
Sample SdL 6.1 km to the SE, has a fairly regular age spectrum (Fig. 3c) suggesting a mixture between one Cl-rich amphibole < 300 Ma and an older one ≥ 310 Ma. A better age estimate of the S1 event is provided by sample SdL 10, which only underwent greenschist-facies S2 overprint. In order to maximize the age information despite the discordant age spectrum (Fig. 3c), we are again resorting to the Cl–Ca–K correlation diagram (Fig. 3a). The trajectory is complex and some points likely represent minute amounts of alteration phases, revealed by the high Ca/K and low Cl/K ratio. Three points cluster around values likely to be closest to an amphibole end-member, and are highlighted by filled symbols. Comparison with figure 3b, the age-chemistry correlation, shows that these three data points also cluster, and supports the idea that they represent the degassing of the oldest preserved phase, i.e. the S1 amphibole. Note that the fact that these three steps are not contiguous does not conflict with their interpretation as being the pure representatives of the S1 amphibole.

The age of the S1 metamorphism at Cavaglio is thus given by the three high-Ca/Cl steps which average 329 Ma. The isochron through these three steps has a scatter exceeding the purely statistical one (MSWD = 6.8), an obvious effect of the complex mineralogy of this sample, but as it has an atmospheric intercept we consider the "isochron" age of 333 Ma as significant.

The Cavaglio age is coincident with that obtained from the Malcantone samples and we consider this terrane-wide concordance an additional proof that it represents amphibole growth during S1. If both were cooling ages following an Ordovician formation (HUNZIKER and ZINGG, 1980), it would be necessary to explain how two occurrences 30 km apart, on opposite shores of Lago Maggiore, can have recorded the same Carboniferous exhumation history. As already noted, regional metamorphic temperatures were slightly if at all higher than 550 °C both during S1 and S2. This means that any pre-S2 amphibole relic was at most only partly (if at all) outgassed during S2 even in the highest-grade area W of Lago Maggiore. The existence of petrographic S1 amphibole relics is therefore a guarantee of finding isotopic inheritance; more importantly, the degree of inheritance should be strongly dependent on sample chemistry. This effect would be most pronounced if S1 had been substantially older than S2, e.g. Ordovician (HUNZIKER and ZINGG, 1980): variable mixed ages between Ordovician and Carboniferous should be observed in chemically different amphiboles that underwent an amphibolite-facies S2 overprint without undergoing complete recrystallization. This is not observed, and it provides independent strong support for a Carboniferous age assignment for S1.

From geological arguments, the age of the S2-forming event ("Schlingenbau", BÄCHLIN, 1937) is only constrained by the age of the Arosio conglomerate to be ≥ 270 Ma (see § 1) and the age of the S1 phase to be ≤ 340 Ma. ZURBRIGGEN (1996, p. 134) and ZURBRIGGEN et al. (1997) report a Pb–Pb stepwise leaching experiment, from which a 321 Ma formation age for an S2 garnet is inferred. While this age does not *per se* conflict with the age constraints just mentioned, we note that the Pb isotope data treatment is not satisfactory, as the chemical diagnostic properties of that method (cfr. FREI et al., 1997) were not considered. If the information on Th/U contained in the stepwise leaching data is made explicit, the chemical signature of zircons becomes obvious, meaning that the Pb results do not date the formation of the garnet but that of its xenocrystic zircon inclusions. Further Rb/Sr data on three muscovites (ZURBRIGGEN, 1996, p. 136; ZURBRIGGEN et al., 1997) also may not have been relevant for the dating of S2, as the temperature conditions during the latter were insufficient to reset even the K/Ar clock of white mica (HAMMERSCHMIDT and FRANK, 1991) so that inherited Sr from S1 precursor material is almost certainly an explanation for the lack of geologically meaningful reproducible ages.

Another possibility is that the Schlingen structures, which become tighter near the CMBL but are not discordantly cut by it, are causally related to the Earliest Permian movement on the CMBL (which is dated by the synkinematic appinites around 290 Ma, slightly older than the Baveno-type granitic intrusions around 280 Ma, see § 2).



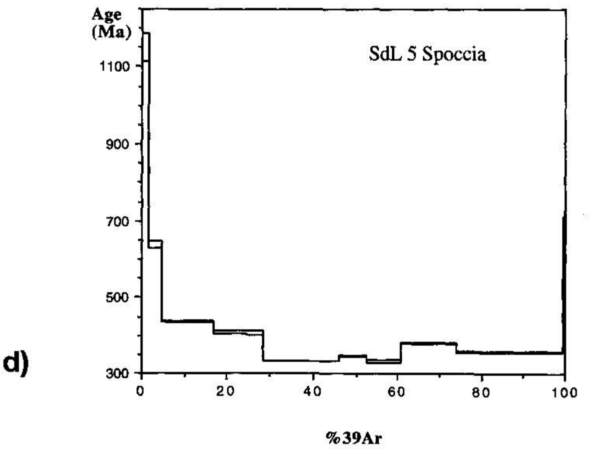


Fig. 3 Stepwise heating results of Serie dei Laghi amphiboles W of Lago Maggiore. (a) Chemical correlation diagram for SdL 10. The three points closest to the "S1 amphibole" end-member composition (see text) are shown as filled symbols. (b) Age-chemistry correlation diagram; the age of the older end-member (filled symbols) is ≈ 330 Ma, very close to the age of the S1 event determined from figure 2b. (c) Age spectra of Val Cannobina samples SdL 6 and SdL 10. (d) Age spectrum of SdL 5, from Val Cannobina very close to CMBL. (e) Age spectrum, (f) chemical, and (g) age-chemistry correlation plots for SdL 11 from Valle Strona.

An age estimate of ≈ 290–300 Ma for S2 is more attractive because it also agrees with KÖPPEL's (1974) monazite growth ages from D2 migmatites (see § 2).

Two amphiboles from Val Cannobina were sampled in the area where S2 is associated to the highest grade (i.e. the inherited S1 component is most thoroughly recrystallized). While the most pervasively recrystallized one, SdL 5, contains Ar_{XS}, resulting in step ages exceeding 1 Ga (Fig. 3d), the other one, SdL 6, shows several step ages close to 300 Ma. If the partial rejuvenation of amphibole SdL 6 truly only reflects recrystallization during the Schlingen phase, the age of S2 is confirmed to be Permian.

From the Valle Strona traverse we analysed one amphibole, SdL 11, from a spotted amphibolite about 500 m east of CMBL (Fig. 3e). This amphibolite is included in a migmatitic orthogneiss; it was statically recrystallized and we believe it dates the thermal anomaly caused by the rising IVZ rocks. Eight steps (accounting for 95% of the Ar release) correlate in a chemical correlation diagram (Fig. 3f) and anticorrelate in an age-chemistry correlation diagram (Fig. 3g). The step ages vary in a narrow but significant time interval between 251 ± 2 and 271 ± 2 Ma. We interpret the pattern of figures 3 f–g to mean that the amphibole started growing around 270 Ma; growth proceeded in a slightly changing environment until 258 Ma (with minor overgrowth as late as 251 Ma). We propose that the amphibole growth age interval of 260–270 Ma dates the welding of the two terranes in the Valle Strona area.

4.3. IVREA-VERBANO ZONE

The three Val Cannobina samples IZ-1, -2, -3 were collected within a few metres from each other. Their age and Ca/K spectra are shown in figures 4 a–b. They all show amphibolite facies mylonitization; newly formed mylonitic hornblendes have very similar chemical compositions and natural grain sizes around 100 µm. Thus any age difference must be interpreted as a reflection of the chemical history of the samples, as the thermal histories are identical and retentivities quite similar.

This is best exemplified by sample IZ-3, from which we obtained both a pure epidote separate and a brown mylonitic hornblende pervasively intergrown with epidote. The pure epidote fraction released the bulk of its Ar around 1000 °C. Its apparent age spectrum has the shape of a steep saddle, from extremely high ages > 4 Ga down to a minimum of 224 Ma. Amphibole step ages show a minimum at 204 Ma. While the epidote points do not align on a statistically acceptable isochron, Ar correlation diagrams show a comparatively simple behaviour (Figs 4 c–e). In order to exploit the epidote-amphibole association, the data from both minerals are presented together. The amphibole separate clearly reveals the admixture of epidote in the first three steps having high $^{37}Ar/^{39}Ar$ ratios, but over the remaining 93% of the gas release the Ca/K and the Cl/K ratios vary little, indicating that a mineralogically pure amphibole was degassed. In figure 4c all points are contained in a triangle, therefore the identification of the end-member reservoirs as the vertices of the minimum triangle, ACE, is straightforward. In the first step of the epidote analysis a volumetrically minor, Cl-rich phase is degassed (open and symbols labelled "1"); it represents a contaminant phase C whose exact composition is not decisive. The bulk of epidote release occurs at 1000 °C and results in a cluster of points close to E. The gas release of the amphibole can be interpreted as initially dominated by C and E (open circles labelled "1,2,3"). At higher temperatures (7 steps between 1030 and 1300 °C) the amphibole data points all lie near point A. Traces of epidote probably affect all steps, visible as displacements of the data points away from end-member A towards E. It must be stressed that the existence of a single linear A–E trend is evidence of a simple binary mixing. The epidote release mirrors that of amphibole: steps obtained at higher temperature than pure end-member E trend towards A, likely reflecting percent intergrowths of amphibole.

After identifying the amphibole release steps *sensu stricto* as the points closest to A, we regressed them in an isochron diagram (Fig. 4d) and obtained 183.3 ± 1.9 Ma, and an acceptable MSWD of 1.2. It may be noted that the epidote points plot in close proximity to the amphibole isochron.

Finally, we addressed the possible correlation of Ar_{XS} with Ca-derived ^{37}Ar in epidote by means of an age-chemistry correlation diagram (Fig. 4e). The epidote points define an alignment which intercepts the ordinate axis at 182.7 Ma. This age is remarkably similar to the amphibole isochron age and we interpret it as dating the epidote formation.

In summary, our ability to date the mylonitic hornblende at 183 Ma and the coincidence of epidote and amphibole age leads us to propose that amphibolite facies mylonitization took place in Early to Middle Jurassic; IZ-3 records no further chemical/thermal/deformational overprints.

Comparing the behaviour of very epidote-rich amphibole IZ-3 with epidote-poor IZ-2 and epi-

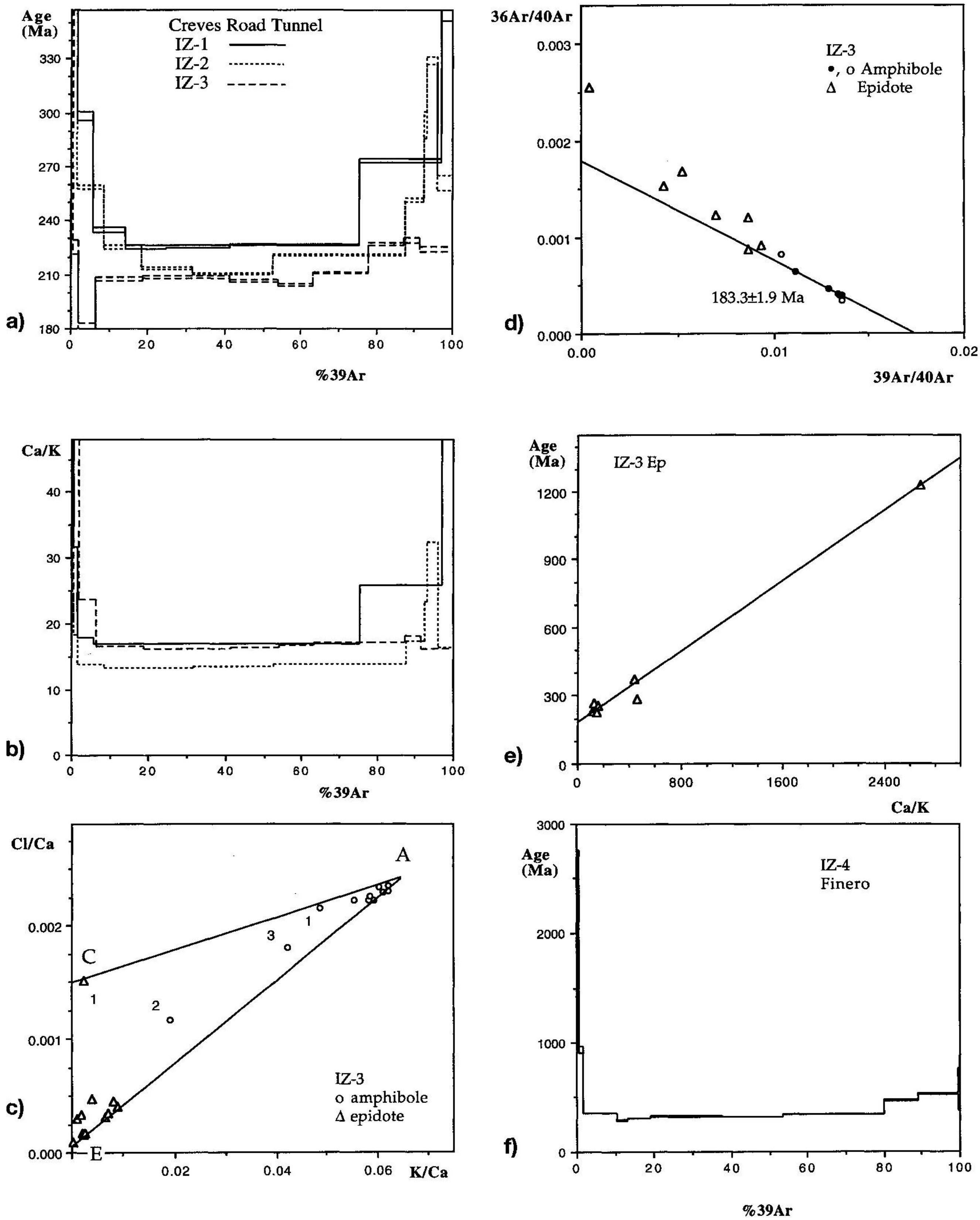
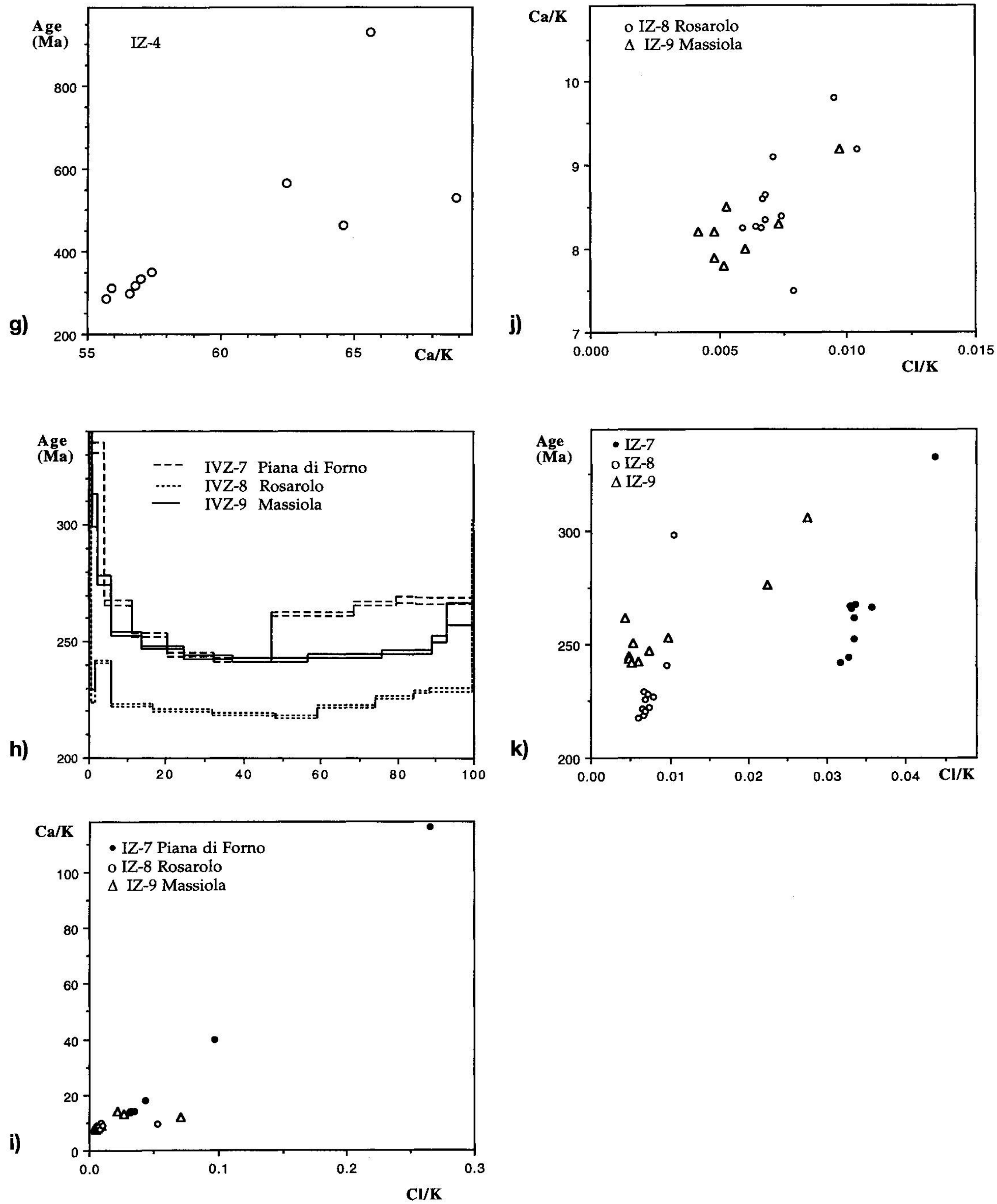


Fig. 4 Stepwise heating results of Ivrea-Verbano amphiboles. (a) Age, and (b) Ca/K spectra of IZ-1, IZ-2 and IZ-3; samples were collected < 100 m from each other. (c) Chemical correlation diagram for amphibole and epidote IZ-3. (d) Isochron of steps representing amphibole IZ-3 *sensu stricto* (filled symbols). These give an age of 183.3 ± 1.9 Ma. Note proximity of most other amphibole and epidote steps (open symbols) to isochron line. (e) Age-chemistry correlation for epidote IZ-3. The amphibole (not visible at this scale) lies on the same trend, i.e. the trajectories in figures 4 c–d must indeed be viewed as the result of binary amphibole-epidote phase mixing. (f) Age spectrum of am-



phibole IZ-4 from the Finero peridotite body. Excess Ar is indicated by step ages > 1 Ga. (g) Age-chemistry correlation for IZ-4. (h) Age spectra of Valle Strona amphiboles IZ-7, IZ-8, and IZ-9. (i) Chemical correlation diagram for IZ-7, IZ-8, and IZ-9. All three samples show linear mixing trends diagnostic of two or more generations of amphiboles. (j) Detail of figure 4i. Sample IZ-7 plots off scale along the trend defined by the points shown. (k) Age-chemistry correlation diagram for IZ-7, IZ-8, and IZ-9.

dote-free IZ-1 one clearly recognizes that Ca/K ratios (Fig. 4b) do not, and ages (Fig. 4a) do inversely, correlate with the degree of alteration. The latter is not an effect of different amphibole retentivity, as all three samples have the same composition within analytical resolution of the electron microprobe. Rather, it may date the patchy fluid-assisted mylonitization, thereby confirming an old conjecture by ARNOLD and JÄGER (1965) that temperature is *not* a rate-limiting factor in promoting isotope transport when faster transport (such as fluids or pervasive deformation) is available. It is also noteworthy that IZ-1 began retaining Ar all while amphibolite facies conditions lasted for almost 40 Ma longer.

An amphibole from a garnet-bearing gabbro cumulate in Finero, IZ-4, is presented in figure 4f. The age spectrum shows step ages > 1 Ga, an effect of Ar_{XS}. This Ar_{XS} is correlated to Ca-derived ^{37}Ar (Fig. 4g); in order to correct for Ar_{XS} and to estimate the age, a diagram such as figure 4e is impractical in the case of IZ-4 because the spread in the Ca/K ratio is too small (with the added difficulty that the extreme values are both close to the microprobe value for the pure amphibole), and the dependence of Ar_{XS} on ^{37}Ar too strong, to allow a reliable correction. Instead, we used a three-dimensional fit (KENT et al., 1990), with axes $^{36}Ar/^{40}Ar$, $^{37}Ar/^{40}Ar$ and $^{39}Ar/^{40}Ar$. The intercept of the best-fit plane with the $^{39}Ar/^{40}Ar$ axis defines an age of 282 ± 8 Ma. The age of the Finero amphibole is thus remarkably close to that of the emplacement of the Mafic Complex, or at least one of its subdivisions, the Lower Layered Group, dated at ≈ 270 Ma by VOSHAGE et al. (1990). We note that the age of 191 ± 5 Ma obtained by LU (1994) on a hornblende from the Finero amphibole peridotite unit, 3 km away from Creves, is almost 100 Ma younger than our own sample IZ-4 and can only be interpreted as an alteration age.

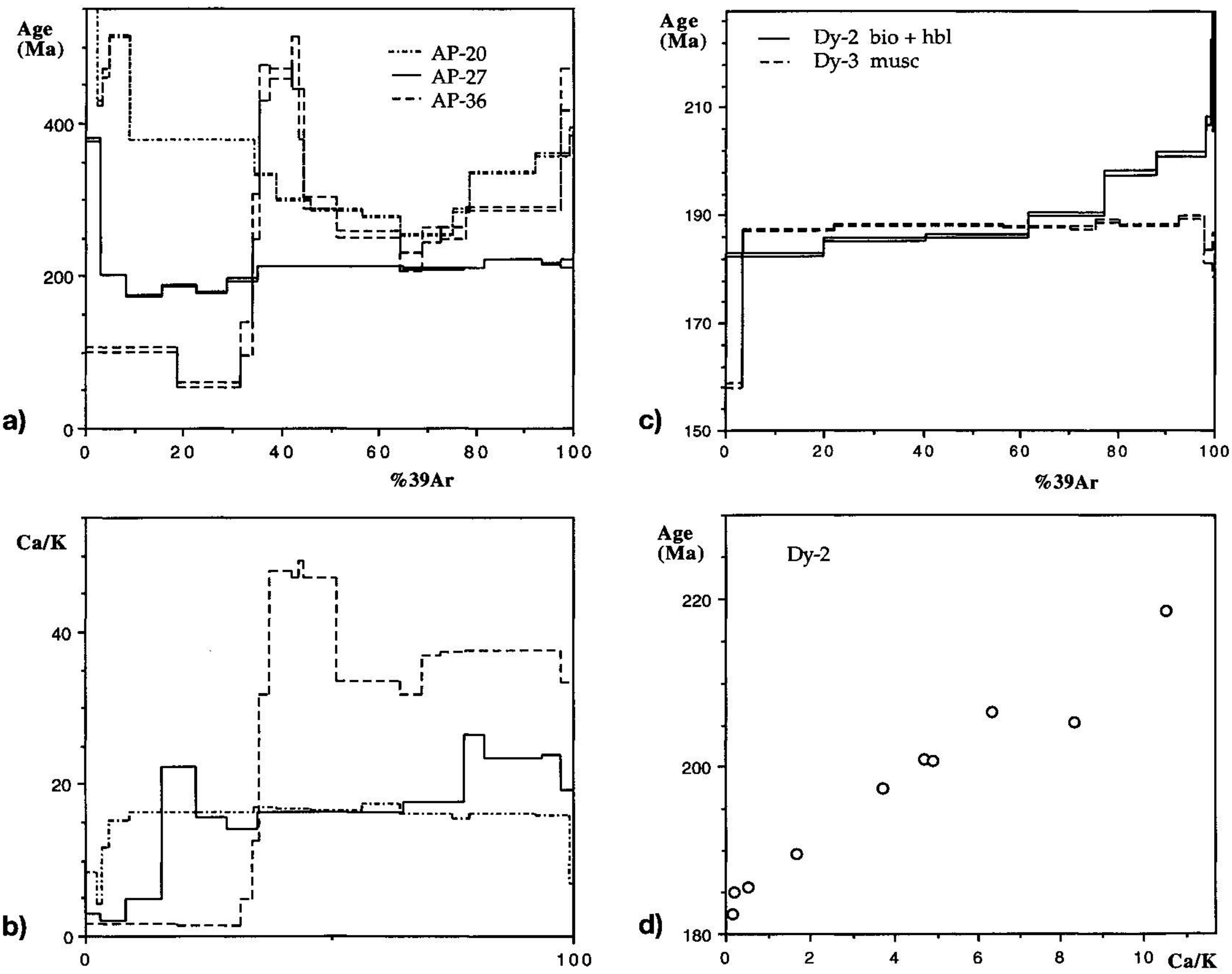


Fig. 5 (a) Age, and (b) Ca/K spectra of "appinites". (c) Age spectra of two dykes near Brissago. Dy-2 is a fine-grained biotite-amphibole intergrowth, Dy-3 a pure muscovite. (d) Age-chemistry correlation for Dy-2.

Tab. 2 Summary of $^{39}Ar/^{40}Ar$ data. Ar* is the radiogenic ^{40}Ar concentration (in nl/g), with the usual convention that the trapped $^{40}Ar/^{36}Ar$ ratio is 295.5, the atmospheric value. Concentrations of K (in ‰), Cl (in ppm) and Ca (in %) were calculated from the ^{39}Ar, ^{38}Ar and ^{37}Ar production during irradiation, respectively. t_A is the age of the amphibole end-member identified from chemical correlation diagrams. n is the number of steps that can be attributed to the amphibole end-member; if n > 1, t_A is calculated from the isochron through these n points, and the last two columns refer to that case only. f is the percentage of the total gas the n steps contain. The trapped Ar composition is that of the calculated isochron. The MSWD parameter indicates the goodness of fit and should be approximately 1 for an acceptable isochron. Errors are 1σ throughout.

Sample	Min	Ar*	K	Ca	Cl	t_A	n(f)	$^{40}Ar/^{36}Ar$	MSWD
Malcantone-Gambarogno area									
MCMA 26	hbl	4.37	3.2	7.3	57	342 ± 2	1 (13)		
MCMA 51	hbl	4.62	3.9	6.3	43	341 ± 6	1 (4)		
MCMA 52	hbl	8.95	7.2	7.9	40	> 326	1 (12)		
Val Cannobina section									
IZ 1	hbl	3.51	3.0	6.1	58	–			
IZ 2	hbl	4.43	4.3	6.3	88	–			
IZ 3	hbl	3.34	3.8	6.5	97	183 ± 2	4 (46)	560 ± 22	1.2
IZ 3	ep	0.83	0.4	12.1	20	see text			
IZ 4	hbl	2.36	1.0	6.0	140	285 ± 8	6 (78)	see text	
SdL 5	hbl	1.85	0.7	5.3	18	–			
SdL 6	hbl	4.44	3.4	6.0	16	–			
SdL 10	hbl	2.08	1.8	6.6	13	333 ± 26	3 (35)	287 ± 71	6.8
Val Strona section									
IZ 7	hbl	4.92	3.9	5.7	98	242 ± 1	1 (15)		
IZ 8	hbl	6.67	7.0	5.9	37	217 ± 1	1 (11)		
IZ 9	hbl	9.21	7.0	6.0	37	243 ± 1	4 (59)	302 ± 12	1.2
SdL 11	hbl	2.54	2.3	5.8	41	271 ± 2	1 (13)		
Appinites and dykes									
Dy 2	bt + hbl	19.02	24.6	3.6	121	–			
Dy 3	ms	66.27	86.8	0.2	4	187.8 ±.5	7 (71)	302 ± 13	0.96
AP 20	hbl	6.71	4.4	6.5	123	–			
AP 27	hbl	5.32	6.1	9.2	55	–			
AP 36	hbl	2.72	2.8	6.6	57	–			

The age spectra of the three Valle Strona samples IZ-7, -8 and -9 are shown in figure 4h. The chemical correlation plot (Figs 4i–j) shows the features typical of mixing of different amphibole generations. The age spectra of IZ-7 and IZ-9 suggest similar ages; IZ-9, which has the most regular spectrum, gives an isochron age of 242.7 ± 0.9 Ma on the 4 steps having the lowest Cl/K ratio, with an atmospheric intercept. An age of 241.8 ± 0.8 Ma for IZ-7, indistinguishable from that of IZ-9, is indicated by the step with the lowest Cl/K ratio (Fig. 4k). In contrast to the westernmost and easternmost samples, IZ-8 (collected in an intermediate locality) gives a significantly younger age of 217.4 ± 0.6 Ma, suggesting a local recrystallization event.

We also point out that the ages of our Valle Strona samples are identical to an $^{39}Ar/^{40}Ar$ amphibole age obtained on the Val Mastallone diorite, 243 Ma (R. SCHMID, pers. comm.), 10 km S of IZ-7 and ≈ 10 km W of CMBL.

The absence of a regular E–W trend in amphibole closure ages in the Valle Strona traverse can be explained by the interplay of a local fluid circulation, which affected IZ-8 more than the other two samples, with a regional exhumation pattern with no E–W difference at all. This argues against a large differential exhumation across the ≈ 10 km traverse later than 240 Ma.

4.4. "APPINITES"

As discussed above, the intrusion of hydrous mafic dykes and stocks in both IVZ and SdL in a narrow belt along the CMBL is causally related to its activity as a high-grade shear zone. In an attempt to examine the duration of the CMBL activity, we analysed three massive appinites (AP 20, 27, 36). All amphibole spectra are discordant (Figs 5 a–b), and multiphase intergrowths are indicated by complex trajectories in the correlation diagrams. AP 27 yields ages similar to those of the Creves mylonites (see § 4.3) which may relate to widespread fluid circulation along the CMBL.

Finally, the micas from the two dykes near the Italian-Swiss border, Dy 2 and Dy 3, both give ages in the vicinity of 180 Ma (Fig. 5c). The age spectrum of Dy 2 is dominated by biotite in the early part of the release; the amphibole, monitored by rising Ca/K ratios (Fig. 5d), is never resolved from the biotite, even at high degassing temperatures. We can only set a lower limit of ≥ 220 Ma for the Dy 2 amphibole. In this area, McDowell (1970) had obtained mica ages between 200 and 240 Ma.

5. Regional implications

Many observations that were made over the past decades and appeared to be in mutual contradiction can be incorporated in an organic model, which derives its time-frame from the present work. The individual observations were not all made by us; thanks to a critical assessment of the available geochronology and to the incorporation of the new interpretive paradigms that have been evolving over the last 5 years, the present interpretation in a self-consistent perspective differs, sometimes substantially, from that originally proposed.

The Serie dei Laghi acquired its S1 foliation during amphibolite facies metamorphism in the Carboniferous around 340 Ma, and thus at a different time from the Permian age of granulitic metamorphism in the Ivrea-Verbano Zone.

This conclusion confirms ideas already proposed by Boriani et al. (1990 a, b) and Pin (1990): for the first part of their history until the Permo-Triassic, the two units do not have a documented common evolution. As testified by their different metamorphic history, these two units must be no longer considered parts of a coherent section of continental crust. Thus, the hypothesis that the IVZ-SdL represent a crust-mantle cross-section tilted as a block during the Alpine orogeny should be abandoned.

SdL can be envisaged as an accretionary prism (continental scarp sequence containing siliciclastics), which underwent Lower Paleozoic diagenesis/anchimetamorphism, and locally shows remnants of HP metamorphism (Giobbi Origoni et al., 1997), followed by intrusion of Ordovician granitoids and a stasis at shallow level. Zircons described in the literature studies quoted above were obtained from orthogneisses, in which case they date granitoid intrusion, and from paragneisses, in which case their recrystallization dates the sediment dehydration during the Ordovician; both zircon types are *a priori* unable to record the overprint due to the S1-forming metamorphic event. The metasediments of the IVZ derive from distal sediments (of unknown age), platform carbonates, abyssal tholeiites (N-MORB and E-MORB: Pin, 1990, and references therein) that later were incorporated in the accretionary prism. These two allochthons were finally brought together during the Hercynian orogeny. Welding of the two units was completed by ≈ 260–270 Ma.

The Carboniferous ensialic convergence produced a barrovian metamorphism that can be observed today in SdL (Matte, 1991). During the ensuing extension, a mafic underplate was emplaced under the IVZ, causing overstepping of the solidus curve in the IVZ protolith and resulting in extensive melt extraction and formation of restites under granulite facies PT conditions (e.g. Pin, 1990; Schnetger, 1994; Vavra et al., 1996). Age data concordantly indicate the Early Permian for the mafic underplate and the restitic granulites. It is possible that at this time the two terranes were already close to their present-day relative position.

Vertical movement (down-to-the-east, with a sinistral strike-slip component) along the CMBL during the Permian favoured rapid exhumation of the IVZ granulites and amphibolites, accompanied by "appinitic" dykes and stocks, and eventually by granites. It juxtaposed hot IVZ rocks to cooler ones in the present-day SdL, causing amphibole recrystallization in the latter (SdL 11) at ≈ 260–270 Ma, significantly later than the ≈ 290 Ma age we have proposed for the regional S2 event. During this period of exhumation, dehydration melting triggered by decompression produced overgrowths on zircons from IVZ; this event was dated at ≈ 260–270 Ma by Vavra et al. (1996). We interpret the cooling after the "wet pressing-iron effect" on SdL 11 as the end of the thermal overprint due to thrusting. Then IVZ and SdL, joined almost in their present-day relative positions, underwent brittle fracturing until the Jurassic, during which the fluid flow was channelled along the fractures.

The timing of the subsequent retrograde evolution does not have strong independent geological constraints and is usually only reconstructed from geochronology. Mylonitization within the IVZ took place from 220 to 180 Ma in Creves, S of the Finero peridotite body (see above). Local fluid infiltration occurred at the same time (samples IVZ 1–3; cfr. also VAVRA et al., 1996). The biotite ages of the appinite bodies are Jurassic (PINARELLI et al., 1988; this work, sample Dy 2); in the whole area N of Cannero, the age distribution (HUNZIKER and ZINGG, 1980) suggests a widespread Jurassic hydrothermalism accompanied by alteration events (cfr. sample IZ-3 above).

6. Conclusions

1. The dating of regional amphibolite-facies metamorphism is possible using appropriate geochronometers (e.g. amphiboles by $^{39}Ar/^{40}Ar$). Geohygrometers such as WR systems or zircons fail to give information relevant to the chronology of multiphase regional metamorphism unless microprobe dating is performed under close control by microprobe chemical analysis.

2. Use of $^{39}Ar/^{40}Ar$ stepwise heating in connection with diagnostic correlation diagrams allows unravelling the multistage history of mineralogically complex samples.

3. SdL consists of an accretionary prism which underwent diagenesis and dehydration during the Ordovician. It experienced an amphibolite-facies S1 at ≈ 340 Ma, and an amphibolite-to-greenschist-facies S2 ("Schlingentektonik") very probably around 290 Ma. IVZ, whose granulite-facies metamorphism is known from literature to be closely connected to intrusion of the Mafic Complex at ≈ 285 Ma, gives amphibole ages that show little or no E–W gradient away from the contact with the SdL, implying no substantial differential exhumation within IVZ later than ≈ 240 Ma. The welding of SdL and IVZ was completed around 270 Ma.

4. As the metamorphic evolution in SdL and IVZ was different, it is no longer acceptable to consider them as a coherent crustal cross-section that was rigidly rotated in its present attitude.

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