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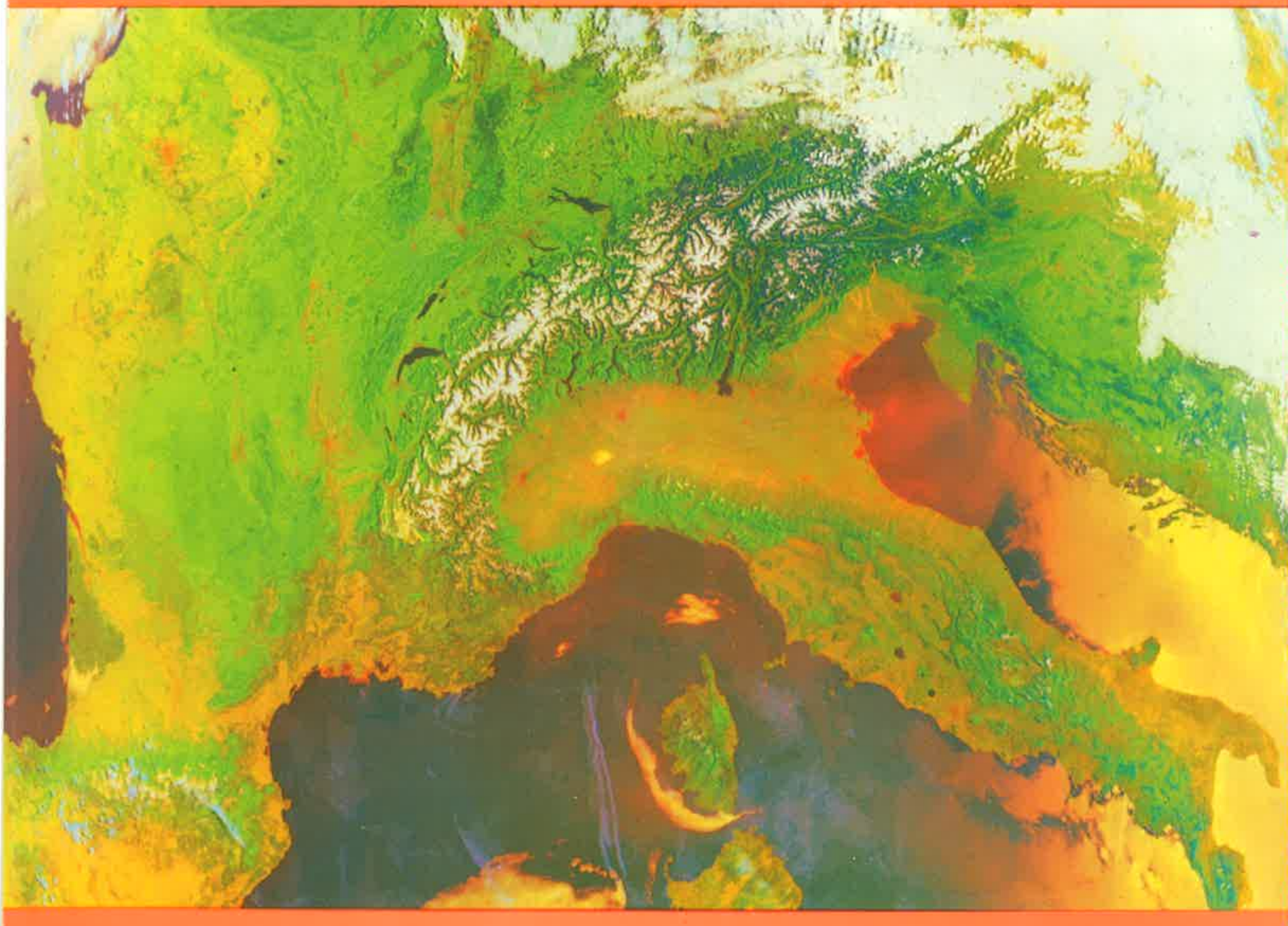
J.C. Hunziker, J. Desmons, and A.J. Hurford



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Forword

This work has been initiated as part of the new editon of the metamorphic map of the Alps (Frey, 1987a, Frey et al., in prep.). It grew to become a paper including seven maps (insets) and is published independently.

Cover Figure: Satellite photo of the Alps. NOAA-6 Weathersatellite. 15.6.81.07:30 GMT.
Source: NOAA National Oceanic and Atmospheric Administration, Washington, DC/USA.
Receiving station: CMS Centre d'Etudes Metéorologiques Spatiales, Lannion/France.
Technical details: AVHRR Advanced Very High Resolution Radiometer with 4 channels.
Flight altitude of satellite: 833 km, Revolution time: 101 min.
Image treatment and courtesy of: Institut für Kommunikationstechnik ETHZ.

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Thirty-two years of geochronological work in the Central and Western Alps: a review on seven maps

Abstract

This paper represents a review of the last 32 years of geochronological work in the Central and Western Alps. Some of these data, distributed in over 240 papers, are poorly accessible, thus starting to fade away from the view of Alpine geologists. The data have been represented on 7 maps, 3 of which, at a scale of 1:800'000, cover the area from the Alpine/Apennine boundary near Genova, through to the western Silvretta. Map I contains Rb-Sr data, map II summarizes the K-Ar and Ar-Ar mineral data. Map III shows U-Pb and whole rock data, and therefore represents our knowledge of the pre-Alpine history. The ages on maps I and II are represented by a colour code, the symbol on the maps represents the mineral concerned. A number, printed near the symbol leads to the references, which are given both in numerical and alphabetical order. 4 maps of the Central Alps are at a scale of 1:635 000, Maps IV and V give the fission track data for apatite and zircon respectively. On maps VI and VII, the K-Ar and Rb-Sr data are given respectively at the same scale for direct comparison. The interpretation of the mineral data is presented in the light of the cooling and blocking temperature concept, which is discussed in detail. All ages are calculated using the IUGS recommended constants.

The present compilation of joint geochronological research in the Central and Western Alps reveals surprising inhomogenieties both in regional and temporal distribution. The Western Alps contain practically no Rb-Sr and U-Pb data. A majority of the data deals with the Alpine metamorphism and with the cooling after the Alpine orogeny. From pre-Variscan times, only little can be said with certainty, no pre-Variscan mica ages having been found so far. Widespread Variscan granitoids (360-280 Ma) which become more acidic with time, intruded a pre-Variscan polymetamorphic basement of generally lower crustal origin, with maximum sedimentation ages between 1000 and 500 Ma. Around 300 Ma before present calcalkaline magmatism, both intrusive and effusive started, and lasted until mid Permian, the onset of Verrucano sedimentation. These late Variscan magmatic phases mark the onset of continental thinning and rifting, with high heat flow and concomitant hydrothermalism along preferred lystric planes geochemically completely altering the adjacent rocks and thus lowering their radiometric ages. In the Austroalpine/Southalpine units, mica ages between 240 and 140 Ma mark the slow uplift and cooling of these zones, from lower to upper crustal conditions.

The Eoalpine orogeny has been subdivided into an early eclogitic stage (140-85 Ma) and a later blueschist and cooling stage (85-60 Ma). The coincidence of two or more different chronometers facilitates the interpretation of the Eoalpine age data.

The Tertiary has been subdivided into 4 phases, the ±30 Ma calcalkaline magmatism subdividing the Cenozoic era into the Mesoalpine and Neoalpine.

1) The period between 60 and 45 Ma is characterized by relative quiescence (Trümpy's 1961 restoration phase). These ages can be interpreted in different ways. For example, as mixed pre-Alpine/Tertiary ages, mixed Eoalpine /Tertiary; or as ages from regions without a pronounced break in the P-T-conditions between the Eoalpine and Tertiary evolution.

2) The 45-30 Ma period marks the Mesoalpine metamorphic phase, found dominantly outside the area. therefore The term Lepontine phase (as used by the Bern group) for this age range implies a more local distribution and is thus inapropriate.

3) Ages between 30 and 0 Ma mark the Neoalpine event, subdivided (arbitrarily at 15 Ma - a more or less quiet period) into early and

4) late Neoalpine.

The Alpine movements of major tectonic lines, such as the Insubric line, the Simplon line and the Aosta-Ranzola line, have been dated both during their ductile as well as their brittle movements, by means of mineral ages. Thus periods of polyphase Alpine movements, ranging from as early as Jurassic and lasting throughout the whole Tertiary have been identified. Also Jurassic, Cretaceous, and Miocene movements along major thrust planes of nappes have been dated with success, principally by the K-Ar and Ar-Ar methods on dynamically recrystallized K-white micas. Cooling curves for a great variety of different regions in the Central Alps have been established.

Résumé

Le présent travail représente une revue des trente-deux dernières années d'activité géochronologique dans les Alpes centrales et occidentales. Les âges sont montrés sur sept cartes. Trois d'entre elles, à l'échelle de 1:800'000, couvrent un territoire s'étendant de la limite Alpes-Apennin près de Gênes jusqu'à la Silvretta occidentale. La carte I contient les âges obtenus sur minéraux par la méthode Rb-Sr. La carte II rassemble les âges obtenus sur minéraux par les méthodes K-Ar et Ar-Ar. La carte III montre les résultats des mesures U-Pb et roche totale, elle contient donc nos connaissances géochronologiques de l'histoire anté-alpine. Quatre cartes montrent la partie centrale des Alpes à une échelle de 1:635 000. Les cartes IV et V donnent les âges obtenus par la méthode des traces de fission, respectivement du zircon et de l'apatite. Sur les cartes VI et VII les âges obtenus par les méthodes K-Ar, Ar-Ar et Rb-Sr pour des micas des Alpes Centrales sont donnés de nouveau à la même échelle pour faciliter les comparaisons.

Les âges sur minéraux sont interprétés à la lumière du concept de température de refroidissement et de fermeture, concept qui est discuté en détail. Tous les âges sont donnés sur la base des nouvelles constantes.

La présente compilation révèle des inhomogénéités dans la distribution spatiale et temporelle. La majorité des âges concernent les métamorphismes alpins et le refroidissement après les orogenèses alpines. Peu d'âges Rb-Sr et U-Pb ont été mesurés dans les Alpes occidentales.

La période anté-varisque est encore mal connue géochronologiquement. Jusqu'à présent aucun âge anté-varisque n'a été obtenu sur les micas. Dans le socle polymétamorphique anté-varisque les âges maximum de sédimentation vont de 1000 à 500 Ma.

Les granitoïdes varisques, qui sont fréquents dans certaines zones, datent de 360 à 280 Ma. Un plutonisme et un volcanisme calco-alcalins tardi-varisques ont débuté vers 300 Ma pour durer jusqu'au Permien moyen. Ces phases magmatiques tardi-varisques se sont accompagnées d'un flux thermique élevé et d'hydrothermalisme, phénomènes qui ont modifié les systèmes chimiques des roches adjacentes et ont ainsi rajeuni leurs âges radiométriques.

Des âges de micas situés entre 240 et 140 Ma marquent le refroidissement du Sud-Alpin, lentement soulevé depuis la croûte profonde jusqu'au niveau de la croûte supérieure.

L'orogenèse éo-alpine a été subdivisée en un stade éclogitique précoce (140-85 Ma) et un stade tardif en faciès métamorphique de schistes à glaucophane (85-60 Ma).

Le magmatisme daté d'environ 30 Ma sépare les événements tertiaires en phases méso-alpine et néo-alpine. L'ensemble du Cénozoïque est subdivisé en quatre parties. La période allant de 60 à 45 Ma est caractérisée par un calme relatif (la phase de restauration de TRÜMPY). Les âges apparents tombant dans cette période peuvent s'interpréter comme âges mixtes entre l'anté-Alpin et le Tertiaire ou entre l'Eo-alpin et le Tertiaire. L'intervalle allant de 45 à 30 Ma correspond à la phase métamorphique méso-alpin, que l'on trouve surtout en dehors et autour de la région lépontine. Les âges entre 30 et 0 Ma caractérisent la phase néo-alpine, elle même subdivisée en Néo-alpin précoce et tardif (de manière arbitraire à 15 Ma, un moment relativement calme).

L'histoire du refroidissement telle que la révèlent les traces de fission des zircons et des apatites montre un soulèvement différentiel: certaines unités sud-alpines et austro-alpines sont passées par la température limite de 225°C dès le Trias, alors que la zone Sesia l'a traversée au Méso-Alpin et la région simplo-lépontine seulement au Néo-Alpin tardif. Les mouvements alpins, ductiles ou cassants, qui ont eu lieu le long de lignes tectoniques comme la ligne insubrienne, la ligne du Simplon ou la faille Aosta-Ranzola, ont été datés.

Zusammenfassung

Die vorliegende Arbeit ist eine Zusammenfassung der letzten 32 Jahre geochronologischer Forschung in den Zentral- und Westalpen. Einige dieser Daten in über 240 Arbeiten verstreut, sind schlecht zugänglich und fingen an aus dem Blickwinkel der Alpengeologen zu verschwinden. Die Daten wurden auf 7 Karten dargestellt, von welchen 3 im Massstab 1:800'000, das Gebiet von der Alpen/Apenningrenze in der Nähe von Genua, bis zur westlichen Silvretta bedecken. Karte I enthält Rb-Sr Glimmerdaten. Karte II fasst die K-Ar und Ar-Ar Mineraldaten zusammen. Karte III zeigt U-Pb und Gesamtgesteinsaltersbestimmungen, stellt also unser Wissen der voralpinen Geschichte dar. Die Alter auf Karte I und II werden durch einen Farbkode dargestellt, die Symbolform steht für das spezifische Mineral. Eine Zahl in der Nähe des Symbols ermöglicht das Auffinden der Referenz im Literaturverzeichnis, welches sowohl den Zahlen nach geordnet, als auch alphabetisch geordnet wurde. 4 Karten der Zentralalpen im Massstab 1:635'000 ergeben einen Ausschnitt. Karte IV + V zeigen Apatit- und Zirkonspaltspuralterswerte; auf Karte VI + VII werden nochmals die K-Ar, Ar-Ar, respektive die Rb-Sr Glimmeralterswerte im selben Massstab zum Vergleich gegeben. Die Interpretation der Mineralalterswerte folgt dem Abkühlungs und Schliesstemperaturkonzept, welches im Detail besprochen wird. Alle Alterswerte wurden auf Grund der neuen Konstanten berechnet.

Die derzeitige Zusammenfassung der gesamten geochronologischen Untersuchungen in Zentral- und Westalpen zeigt erstaunliche Inhomogenitäten, sowohl in regionaler als auch in zeitlicher Hinsicht. Aus den Westalpen fehlen Rb-Sr und U-Pb Messungen grösstenteils. Die überwiegende Mehrheit der Daten belegen die alpine Metamorphose und die Abkühlung nach der alpinen Gebirgsbildung. Über vorvariszische Ereignisse kann nur wenig sicheres ausgesagt werden; bisher wurden keine prevariszischen Glimmeralter gefunden. Weitverbreitet sind variszische granitoide (360-280 Ma), welche mit abnehmendem Alter immer saurer werden. Diese Granitoide intrudieren einen vorvariszischen polymetamorphen Sockel mit Affinitäten zur unteren Kruste. Dieser Sockel zeigt maximale Sedimentations Modellalter zwischen 1000 und 500 Ma. Vor ca. 300 Ma begann ein sowohl intrusiver als auch extrusiver kalkalkaliner

Magmatismus, der bis ins mittlere Perm reichte und von der Verrucano Sedimentation abgelöst wurde. Diese spätvariszische magmatische Phase fällt zusammen mit dem Anfang der kontinentalen Ausdünnung und dem Rifting, gekennzeichnet durch hohe Wärmeflüsse und einhergehend mit hydrothermalen Erscheinungen entlang bevorzugter lystrischer Brüche. Diese Phänomene haben die benachbarten Gesteine geochemisch total verändert und haben auch die radiometrischen Alterswerte heruntergesetzt. In den Austroalpin/Südalpin-Einheiten belegen Glimmeralterswerte zwischen 240-140 Ma den langsamen Aufstieg von der unteren in die obere Kruste und damit gekoppelt, die Abkühlung dieser Region.

Die Eoalpine Orogenese wurde in zwei Abschnitte geteilt; einen frühen, eklogitischen, der von 140-85 Ma reicht, und einen späteren Abschnitt in blauschiefer Fazies, mit nachträglicher Abkühlung (85-60 Ma). Die Konkordanz von zwei (oder mehr) verschiedenen Chronometern erleichtert hier die Interpretation der Eoalpinen Daten.

Das Tertiäre Geschehen wurde in vier Abschnitte unterteilt, wobei der ± 30 Ma alte kalkalkaline Magmatismus das Tertiär in Mesoalpin und Neoalpin gliedert.

1) Die Zeitspanne zwischen 60 und 45 Ma (Trümpy's 1961er Restorationsphase), ist durch relative Ruhe charakterisiert. Diese Alterswerte können unterschiedlich interpretiert werden: beispielsweise als Prealpin/Tertiäre Mischalterswerte, als Eoalpin/Tertiäre Mischalter, oder auch als Alter aus Regionen ohne Bruch in den P-T-Bedingungen zwischen der Eoalpinen und der Tertiären Orogenese.

2) Alter zwischen 45 und 30 Ma charakterisieren die Mesoalpine Phase, hauptsächlich ausserhalb des Lepontins altersmässig erfassbar, desshalb wurde die Bezeichnung "Lepontine Phase", (wie sie von der Berner Gruppe benutzt wurde) fallengelassen. Alterswerte zwischen 30 und 0 Ma stehen für das Neoalpine Ereignis, welches bei 15 Ma, einer mehr oder weniger ruhigen Periode, nochmals unterteilt wurde, in eine

3) Frühneoalpine Phase und eine

4) Spätneoalpine Phase.

Die Alpinen Bewegungen entlang der tektonischen Hauptlinien, wie der Insubrischen Linie, der Simplonlinie und der Aosta-Ranzola Linie, wurden sowohl während ihrer duktilen, als auch während ihrer spröddeformations Phase mit Mineralaltern erfasst. Einzelne Perioden der polyphasigen Alpinen Bewegungen wurden erfasst, die von frühjurassischer Zeit bis und mit dem Spättertiär reichen. Ebenso wurden Deckenbewegungen jurassischen, kretazischen und miozänen Alters erfolgreich, vor allem mit der K-Ar und der Ar-Ar Methode datiert. Abkühlkurven aus einer grossen Anzahl verschiedener Regionen der Alpen wurden erarbeitet.

Riassunto

Questo lavoro vuole riassumere ed analizzare gli studi geocronologici compiuti negli ultimi 32 anni nelle Alpi Centrali ed Occidentali. Alcuni di questi dati, distribuiti in oltre 240 lavori, sono difficilmente accessibili a tal punto che i Geologi alpini cominciano a prenderli sempre meno in considerazione.

I dati sono stati rappresentati in 7 Carte differenti, 3 delle quali, alla scala 1: 800.000, coprono l'area alpina compresa tra il contatto Alpi-Appennini presso Genova e la regione occidentale della Suretta. La Carta I contiene i dati Rb/Sr, la Carta II riassume i dati ottenuti con il metodi K/Ar ed Ar/Ar sui concentrati minerali. La Carta III mostra i dati relativi ai metodi U/Pb e roccia totale, e come tale riassume quanto si conosce della storia pre-Alpina delle Alpi Centro-occidentali. Le età delle Carte I e II sono rappresentate tramite differenti colori, mentre i differenti simboli rappresentano i concentrati minerali. Un numero, stampato in prossimità dei simboli, indica il riferimento bibliografico, che può essere cercato sia sotto ordine numerico che sotto quello alfabetico. Vengono inoltre proposte 4 Carte delle Alpi Centrali alla scala 1: 635.000. Nelle Carte IV e V sono stati inseriti i dati relativi alle tracce di fissione rispettivamente di apatite e zircone. Nelle Carte VI e VII sono stati riportati i dati ottenuti rispettivamente con i metodi K/Ar e Rb/Sr, proposti alla stessa scala in modo da poter essere più facilmente comparati. L'interpretazione dei dati ottenuti direttamente dai separati minerali è fondata sui principi di temperature di raffreddamento e chiusura del sistema, le cui tematiche vengono discusse in una sezione apposita. Tutte le età sono state calcolate usando le costanti più recenti.

La compilazione generale degli studi geocronologici nelle Alpi Centrali ed Occidentali rivela delle sorprendenti discontinuità nella distribuzione regionale dei dati nonchè in quella temporale. Nelle Alpi Occidentali, per esempio, le età ottenute con i metodi U/Pb e Rb/Sr sono pressochè assenti. La maggioranza dei dati si referisce al metamorfismo alpino o al raffreddamento che ha fatto seguito all'orogenesi alpina.

Per quanto riguarda le età pre-Varisiche, solo pochi dati sono sicuramente affidabili; basti pensare che nessuna mica ha donato fino ad ora età Varisiche. Al periodo varisico (360-280 Ma) vanno riferite le intrusioni di grosse masse di granitoidi ad evoluzione acida che intrudono un basamento polimetamorfico pre-Varisico costituito essenzialmente da crosta di origine profonda; i protoliti di tale basamento potrebbero essere ricercati in sequenze di copertura aventi un'età di sedimentazione massima compresa tra 1000 e 500 Ma. Intorno a 300 Ma inizia un ciclo magmatico calcoalkalino, sia intrusivo che effusivo, che termina attorno al Permiano medio seguito dalla sedimentazione in facies Verrucano. Queste fenomenologie magmatiche tardo-Varisiche segnano l'inizio della fasi di assottigliamento della crosta continentale e della sua apertura; questa fase distensiva permette la risalita di importanti correnti di calore e causa fenomeni idrotermali che, oltre a provocare la completa alterazione delle roccie che incontrano, causano un ringiovanimento delle loro età radiogeniche. Nelle unità Austroalpine ed Sudalpine, l'età delle miche comprese tra 240 e 140 Ma indicano la lenta risalita e raffreddamento di queste zone, da condizioni di crosta profonda a quelle di crosta superiore.

L'orogenesi Eoalpina è stata suddivisa in una fase eclogitica precoce (140-85 Ma) ed in una successiva fase scisti blu e di raffreddamento (85-60 Ma). La coincidenza di due o piu differenti cronometri facilita l'interpretazione dei dati sulle età eolalpine.

Il Terziario è stato suddiviso in quattro fasi; 2 fasi (60-45 e 45-30 Ma) vengono riferite al Mesoalpino; il magmatismo calcoalkalino situato intorno a 30 Ma suddivide il Cenozoico in Mesoalpino e Neoalpino.

1) Il periodo compreso tra 60 e 45 Ma é caratterizzato da una quiescienza relativa (fase di restaurazione secondo Trümpy, 1961). Queste età possono essere interpretate in differenti maniere: per esempio come melanges di età pre-Alpine e Terziarie o Eoalpine e Terziarie; oppure come età provenienti da settori alpini dove non si è verificato un salto pronunciato nelle condizioni P/T tra evoluzione Eolpina e Terziaria.

2) 45-30 Ma indicano la fase metamorfica Mesoalpina, che domina nella zona attorno all'area Lepontina cosicchè il termine di fase Lepontina, utilizzato dalla scuola bernese, è stato abbandonato.

   Le età comprese tra 30 Ma e il presente testimoniano l'evento Neoalpino suddiviso arbitrariamente a 15 Ma, in corrispondenza di un momento relativamente tranquillo in

3) Neoalpino precoce (30-15 Ma)

4) Neoalpino superiore (15-0 Ma)

I movimenti alpini delle maggiori linee tettoniche quali la linea Insubrica, la linea del Sempione e la linea Aosta-Colle della Ranzola, sono stati datati sia durante la loro fase duttile che durante quella fragile, tramite le analisi sui concentrati minerali. In questo modo sono state identificate diverse età nei movimenti polifasici Alpini, che vanno dal Giurassico inferiore fino all'intero Terziario.

Sono inoltre stati datati con successo alcuni movimenti giurassici, cretacici e miocenici lungo i più importanti piani di sovrascorrimento delle diverse Unità alpine, utilizzando soprattutto i metodi K/Ar e Ar/Ar su miche sincinematiche. Sono state infine ricostruite numerose curve di raffreddamento per diversi settori delle Alpi Centrali e Occidentali.

1. Aim of the work and methods

An attempt has been made to provide a summary of all the radiometric data available from the Western and Central Alps. This seemed especially useful in view of the more than 240 references distributed partly in poorly accessible journals, or in unpublished PhD or Diploma theses. Such highly valuable information is often not readily available to Alpine geologists and risks being completely lost. A further goal of the present paper was to show the validity and usefullnes of the cooling and closure temperature concept in the Alpine metamorphic domain. The close correlation of the homogeneous age fields with the detailed regional geology best illustrates this point. The data for the Eastern Alps have been compiled and presented on maps by Frank et al. (1987) and we refer to this paper for the eastern continuation of the present work. A unification of both data sets in one paper unfortunately turned out to be impossible; hopefully a further attempt in the future may reach this goal. The present synthesis of radiometric data was compiled also in view of the incompleteness of a prior attempt by our Italian collegues (Radiometric geochronology of Central Alps, by Boriani et al.1985, and Review of radiometric dating in the Western Italian Alps, by Dal Piaz et al. 1985). There the data have been represented on tables rather than on maps, a condition "sine qua non" for geochronologic data, according to the present authors. Furthermore the authors of the Italian compilation, mostly not being geochronologists, were sometimes not aware of all the existing data, especially data hidden in unpublished PhD theses. Some of this information has also most likely escaped our attention in the present work.

The frame of our maps has been chosen such that they include the whole Penninic domains from the Ligurian Alps to eastern Switzerland. Part of the Austro-Alpine Silvretta nappe appears on our maps and the South Alpine domain as far as the western boundary of the Adamello massif, so that a certain overlap with Frank's paper is reached.

All data are given calculated or recalculated with IUGS recommended constants (Steiger & Jäger, 1977). The results are represented on seven maps. Three maps at 1/800'000 scale concern the entire Western and Central Alps. The structural basemap for these has been drawn after the new Structural Model of Italy (sheet 1, by Bigi et al. 1990).

Map I contains the Rb-Sr mineral data.

Map II contains the K-Ar and ^{40}Ar-^{39}Ar mineral data (including potassic white mica, biotite, amphiboles and glauconite). K-Ar Feldspar data (Ferrara & Malaroda, 1969; Purdy & Stalder, 1973 ; Leutwein et al., 1970 ; Arnold, 1972) and others have been omitted because most of the rather scarce measurements have been performed on late cleft adularia, and would need representation on a separate map with only few data .

Map III shows the whole rock K-Ar and Rb-Sr, the Sm-Nd and both zircon and monazite U-Pb data.

On maps I and II, the ages are represented by a colour code and the minerals by a symbol form (see legend on the maps). With the mica data we have distinguished between normal grained micas bigger than 60 micrometers and smaller sized mica grains because of differences in purity of the mineral separates resulting from grain size. These differences stem from the different separation technique for the illitic micas through settling, yielding at best a high enrichment but never a 99.9 % purity.

In areas with high sample density several coinciding data may be represented by a single point. The references to the original papers are given by numbers adjacent to the points and can be found in the reference lists at the end of this paper, one numerical list and one in alphabetical order. Abstracts are referenced, as many of the measured data never reached the stage of proper publication. When the same results have been reported in different papers or abstracts, each reference has been given a separate number and all numbers are given on the maps. On map III the symbol form represents both the method and the type of the analyzed material. Because of the ambiguity of U-Pb zircon and Sm-Nd data, no colour code was used here for age groups. The corresponding ages will have to be looked up in the original papers.

In addition, four maps of the Central Alps are presented on a scale of 1/635'000. Maps VI and VII again show, respectively, the K-Ar and Rb-Sr mineral data for the Central Alps. Maps IV and V show respectively fission track apatite and zircon age results. The fission track data are presented only on the Central Alps basemap owing to the scarcity of data in the western and southwestern part of the belt. However, these few data will be included in the discussion. In two cases, the Gran Paradiso massif and the Sesia-Lanzo zone, alternative data sets are available (Hurford & Hunziker, 1989 and Hurford et al., 1991 on one hand, Carpena, 1984 on the other hand). Hurford's data have been used because of inconsistencies in Carpena's data with all the other available data and the lack of published international standardization, a condition "sine qua non" of fission track work. (Hurford 1990) This is the only filter ever used in the present work. Thus, before drawing personal conclusions from the presented data, the reader is encouraged to consult the original references as to the reliability and error limits of the measurements.

The colour code for the mineral ages has been chosen according to the following criteria. First of all, the main orogenic cycles have been grouped together, e.g. ages greater than 600 Ma are called "Proterozoic". Lower Palaeozoic data of 600 to 400 Ma, as well as Proterozoic ages do not exist on the mineral age maps. On purpose the term Caledonian is not used in this context, the region of the Alps not belonging to the Caledonian orogenic domain. Ages refering to that part of the basement evolution that is now often called Pan-African or late Pan-African fall partly in the "Proterozoic" and partly in the lower Palaeozoic group. A 600 Ma younger limit of the "Proterozoic" instead of the Precambrian/Cambrian transition, and a 400 Ma older limit of the Variscan, have been chosen for the sake of rounded numbers and not on the ground of geological reasoning. For the Alpine metamorphic domains these remote periods are still imprecisely known, so that a more elaborate determination of the boundaries currently seems inappropriate.

The Variscan orogeny has been subdivided into a Variscan (black points, 400-280 Ma) and a late Variscan s.l. (grey points, 280-240 Ma) period. After the Variscan orogenesis, precursory Alpine events have been put into a single age group from 240 to 140 Ma. (white points). These Triassic-Jurassic periods are currently regarded as times of high heat flow and hydrothermal activity related to early rifting, as well as subduction and magmatic phases. In the Western and Central Alps evidence of early to late Kimmerian orogenic events so far is unclear. Some of these Triassic-Jurassic ages, however, may also be simply interpreted as mixed ages between pre-Alpine and Alpine.

We have chosen to subdivide the Alpine orogenies into Eo-Alpine, Meso-Alpine and Neo-Alpine as discussed in Hunziker et al. (1989) (Eo-Alpine=140-60 Ma, Meso-Alpine=45-30 Ma, Neo-Alpine=30-0 Ma)

The Eo-Alpine orogeny has been subdivided into an early, eclogitic, phase between 140 and 85 Ma (deep blue points) and a late, glaucophane-bearing, phase between 85 and 60 Ma, including cooling ages of the early Eo-Alpine event (light blue points). Between 60 and 45 Ma violet points characterize a relatively quiescent period

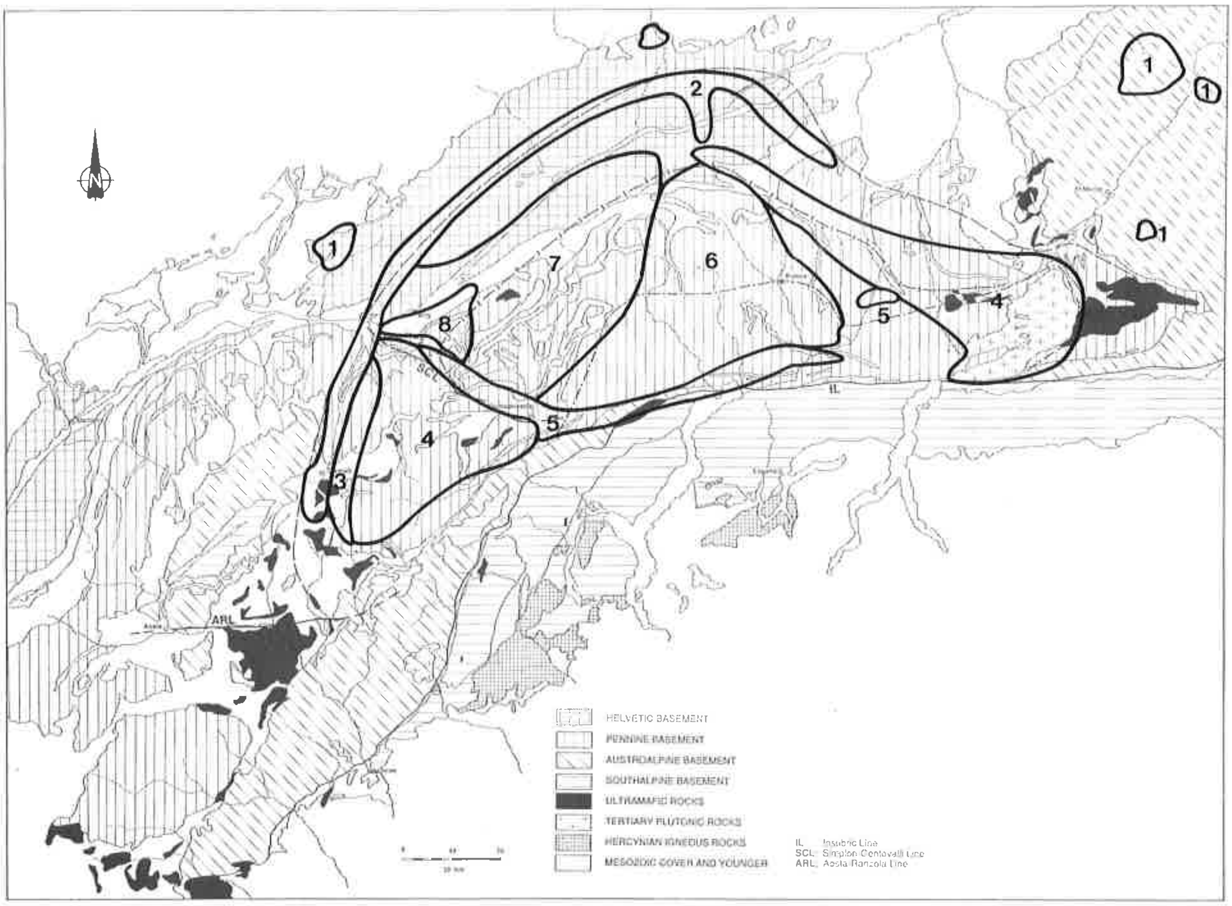

Fig. 1): Regional distribution of Rb-Sr ages on biotites, as represented by Graeser et al. 1969. The area of the partly rejuvenated Variscan biotites from the Alpine foreland regions coincide with the stilpnomelane- out boundary, which at that time was taken to be around 300 °C. 1) 200 Ma, 2) 40-200 Ma., 3) 30-40 Ma., 4) 20-30 Ma., 5) 18-20 Ma., 6) 15-18 Ma., 7) 12-15 Ma., 8) 12 Ma.

(the restoration phase of Trümpy (1961).

Most ages falling into this interval can be interpreted as mixed pre-Alpine/Alpine or Eo-Alpine/Tertiary ages.

Alternative interpretations found in the literature are that the Eo-Alpine phase lasted longer in certain places, or that high P and T conditions of the metamorphism do not show any pronounced break between the Eo-Alpine and Meso-Alpine; or else to a cooling of the eclogitic slab by underthrusting of a cool oceanic lithosphere suppressing the real recovery during uplift (Rubie, 1984). The ± 30 Ma calc-alkaline and alkaline magmatism subdivides the Cenozoic era into Meso-Alpine (45-30 Ma, red points) and Neo-Alpine (30-0 Ma).

A 15 Ma boundary between an early (orange points) and a late (yellow points) Neo-Alpine period has been chosen because of the relative quiescence around 15 Ma appearing in the data set.

With respect to the entire pre-Tertiary evolution of the Alpine belt, (in particular the Variscan and earlier evolution), correlation of age groups with established tectonic phases are provisional. This is especially true for Proterozoic and lower Paleozoic groups which are likely to be subdivided differently in the future when further data become available. In this synthesis, the age groups will also not be translated into established series of the stratigraphic timescale.

The wide spread of total lead results obtained mainly in the sixties, has been omitted because of obvious problems of reliability in polymetamorphic and polyphasic regions (Chessex et al. 1964, Bertrand et al. 1965, Chessex et al. 1966). The U-Pb system of zircons normally contains Pb at the time of the crystallization, not accounted for in the total Pb method. Moreover, most zircons show discordant patterns reflecting post-crystallization lead losses which occurred during one or more events and which cannot be accounted for. Both facts contradict the closed system behaviour required of the total lead method.

The radiation damage ages are also not included in our compilation, again because in polymetamorphic and polyphasic rocks annealing phenomena exert an important influence which, so far, has not been quantified. This method also suffers from poor standardization.

Almost certainly some data have escaped our attention and have been omitted from this compilation. To those analysts who find their data absent we offer our apologies and would appreciate being informed of our omission.

2. Interpretation of the data

2.1. The cooling and closure temperature concept

In the early to mid-1960s, Jäger and co-workers proposed that Rb-Sr mica ages in the Central Alps do not date the peak conditions of amphibolite facies metamorphism, but rather provide the time of a post-peak cooling below a certain temperature (Jäger, 1962; Jäger et al. 1967). From the coincidence of the external limit of the Alpine field of rejuvenated biotites with the stilpnomelane-biotite isograd in the Central Alps, a closure temperature of 300 ± 50 °C was deduced by these authors (Fig. 1). Similarly, the overlap of Alpine rejuvenated and/or newly grown potassic white mica with the staurolite-chloritoid boundary in the Central Alps, (the Alpine mica field slightly overlapping towards lower temperatures (in external zones)), was interpreted as closure temperature of 500 ± 50°C for the Rb-Sr system of potassic white mica.

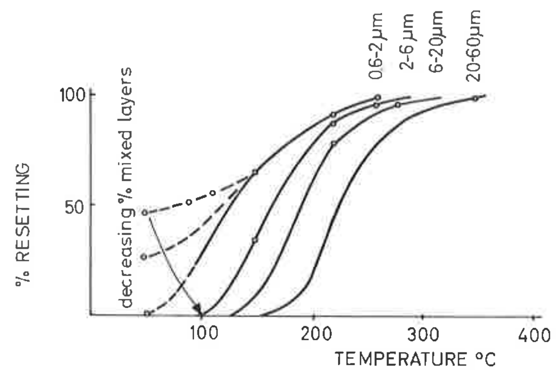

Fig. 2) The resetting of radiometric ages on fine grained illitic micas is grain size dependent. Finer grains reach zero age at lower temperatures than coarser grains. Figure modified from Hunziker 1986.

Since these early days, a considerable amount of new data, both radiometric and thermometric encourage a closer look at the basis of these assumptions. From the beginning of the closure temperature concept a great amount of criticism and controversy has been attracted from involved scientists (e.g. in the Alps: Dodson, 1973; Chopin & Maluski, 1980; Desmons et al., 1982; Del Moro et al. 1982). Deformation, grain size, fluid percolation, duration of the metamorphic event, cooling speed, chemical composition of the minerals involved defects, dislocations, exsolutions and other criteria have been proposed as mainly governing the mechanism of rejuvenation. Nevertheless, in a cold environment none of these factors, even in combination, has any effect. It has been accepted by most workers that heat is the main driving force, only the exact amount of heat remains a matter of debate. The combination with the other parameters, however, may considerably influence the closing behaviour. Let us consider some of these parameters in a more empiric way.

1) Deformation: this mechanism induces the initiation of many lattice defects, and may end in complete recrystallisation of the strained grain. Kinking may be considered as a transitional stage, and it is evident that growing amounts of kinking represent larger amounts of lattice defects, which finally will lead to complete rejuvenation, with or without recrystallisation. During the transitional stage lowering of the radiometric ages will result, yielding mixed ages between the starting point and the endpoint. Accordingly only in extreme cases will meaningfull radiometric ages result. In addition, deformation generally allows the enforced introduction of fluids into the system, thus enhancing the possibility of exchanges. In other words kinked micas might not follow strictly the closure temperature concept .

2) Grain size: size plays an important role in considerations of solid state diffusion e.g.Dodson, (1973). Nevertheless, normal medium- to high-grade metamorphic rocks show little grain size differences. Following Dodson, a mean grain size of 0.7 mm can be taken into account. The picture becomes more complex if we take very low grade rocks and, on the other extreme, pegmatites into consideration. Here we are dealing with at least six orders of difference in grain size, a fact that has to affect closing temperature considerations. Hunziker et al. (1986), and Hunziker (1986) have shown, that for very fine grained K-white micas (finer than 2 micrometers), closure temperatures can be up to 100°C lower, see fig 2. That the cores of coarse pegmatite micas still can show older ages above the closure temperature of medium grained muscovite is a widespread phenomenon in the Central Alps, see map I.

3) Duration of metamorphism: absolute

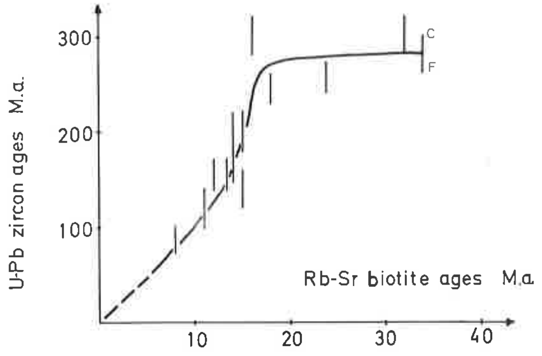

Fig 3) Lead loss of zircons of Variscan granitoids in the central Lepontine, depends on the duration of the Alpine event. U-Pb zircon ages from Variscan granitoids of the central Lepontine amphibolite facies terrain (Allègre et al. 1974) plotted against biotite Rb-Sr ages, see map I. The effect of the Tertiary Meso and Neoalpine metamorphism on the resetting of zircon U-Pb ages, is clearly evident. A duration at elevated temperatures of metamorphism of 550-600 °C up to 20 Ma (biotite ages 20 Ma and older) does not change the U-Pb ages of the zircons; while a longer time at the same temperatures for more than 20 Ma (biotite ages younger than 20 Ma. i.e. buried at elevated temperatures for a longer time) results in resetting the zircon ages drastically. The finer fractions F being rejuvenated to a greater extent than the coarser fractions C of the same sample. Energy and grain size dependence of lead loss are in agreement with a diffusional loss model. Fig. from Hunziker & Martinotti 1984

temperature is obviously not the sole critical factor but has to be considered together with the time during which the system remains at elevated temperatures. By heating up a mineral for a restricted amount of hours in a furnace, we do not expect to find its closure temperature. Extrapolation of the time factor to geological times remains very critical. Hunziker and Martinotti (1984) have shown that, for instance, zircons from Central Alpine Variscan granitoids show a lead loss depending more on the duration of the Alpine event, than on the absolute temperature suffered during this same event, see Fig.3.

4) Changes in cooling speed: Dodson (1973) showed, that cooling speed can

considerably affect closure temperatures, fast cooling resulting in higher, slow cooling in lower closure temperatures, see fig 4.

5) Changes in chemical composition of a given mineral: Hofmann and Giletti (1970) and Giletti (1974) have shown, that phlogopite has a higher closing temperature than annite by more than 100 °C. Most of the age work, however, is performed on the most common rock types, and therefore such great changes in chemical composition are rarely confronted.

In conclusion: by purposly choosing the most extreme conditions, one might arrive at completely wrong solutions to the closure temperature problem. Nevertheless, the great uniformity of the pattern on maps I and II, in view of the amount of published data from the Alps seems a strong confirmation of this old but valuable concept.

In the Central Alps the works of Niggli & Niggli (1965), Trommsdorff (1966), Bernotat & Bambauer (1982) and Frey (1970, 1974, 1987), Frey et al. (1974, 1980) have enriched the paragenetic picture considerably (Fig. 5). It is, however, noteworthy that these so-called isograds of "Tertiary metamorphism" actually are not all of the same age, in other words do not represent conditions of only one phase of Alpine metamorphism. For instance, the stilpnomelane-out boundary in the St. Moritz region of the Engadine is of late Eo-Alpine age, whereas stilpnomelane in the Aar massif is of Neo-Alpine age, as can be seen from the age of the associated white micas on map VI. The same argument holds for the staurolite-in isograd : in the Adula region staurolite is in equilibrium with potassic white micas of Meso-Alpine age, oriented along the main axial plane schistosity of the nappe, whereas in the region of the Gotthard massif and the Lukmanier pass, staurolite, as well as kyanite, have been transposed into a younger schistosity and are in equilibrium with the new textures yielding Neo-Alpine mica ages. Nevertheless, as a first order approach, this paragenetic information is the best we have - more detailed petrologic work on the analysed samples is definitely needed in the future.

In contrast, through stable isotope measurements, we have learned to distinguish between neoformation (formation of a new mineral), rejuvenation due to recrystallization (in part breaking old lattice structures) and rejuvenation of an old lattice under preservation of the SiO_2 tetrahedral structure, the latter rejuvenation mainly controlled by solid-state diffusion processes.

The region of the Gotthard and Aar massifs in the Central Alps is especially well studied in respect of both, mineral parageneses and radiometry. Dempster (1986) presented the detailed profile of mica ages across the Aar massif using the Rb-Sr and the K-Ar methods (Maps VI and VII, Fig. 5 and 6). The first guess of the 500 ± 50°C blocking temperature of the Rb-Sr system for potassic white micas is fully substantiated by the subsequent data. Within the the staurolite isograd, i.e. at Cenozoic temperatures greater than 550°C, not a single pre-Alpine mica age has been measured so far. The first pre-Alpine muscovite ages are found a few kilometers outside the staurolite field. According to Fig. 5 the stilpnomelane-out line rather falls into the 350 to 400°C metamorphic temperature range. Nevertheless, the biotite field in the Aar massif coincides with temperatures of around 300 °C or slightly higher.

The stilpnomelane-out line seems to delimit Alpine from pre-Alpine K-Ar potassic white mica ages, in agreement with postulated blocking temperatures of around 350 ± 50°C for these systems (Purdy & Jäger, 1976).

Fission track ages have always been considered as cooling ages and annealing temperatures have been determined both from laboratory experiments and from deep borehole studies.

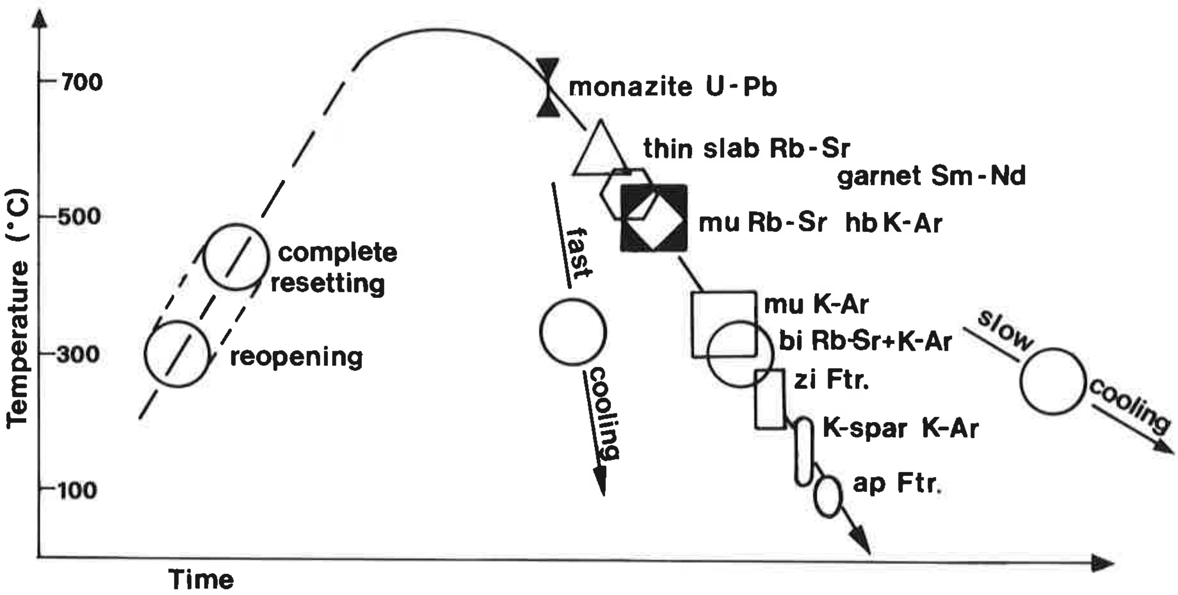

Fig 4) "Best estimates" of closure temperatures from regions, cooling at intermediate speeds of around 30°C/Ma, for different systems as used in this paper in degrees centigrade

Monazite U-Pb,	*(Metzger et al. 1992)*	*730-650 .*
Thin slab Rb-Sr isochron,	*(Thöni 1985)*	*650-550*
Garnet Sm-Nd,	*(Metzger et al. 1992)*	*600-500.*
K-white mica Rb-Sr,	*(Jäger et al. 1967)*	*550-450.*
Hornblende K-Ar,	*(this paper)*	*550-450.*
Muscovite K-Ar,	*(Purdy and Jäger 1976)*	*400-300.*
Biotite Rb-Sr and K-Ar,(	*Armstrong et al. 1966)*	*350-250.*
Zircon fission tracks,	*(Hurford 1986)*	*250-200.*
K-feldspar K-Ar,	*(Harrison et al.,1979)*	*300-200.*
Apatite fission tracks,	*(Hurford 1986)*	*120-60.*

Temperatures of reopening and closing are assumed to be identical, although complete resetting in a dry statically reheated basement may be considerably higher than for closing at decreasing temperatures. Cooling speeds deviating from 30 °C/Ma also change closing temperatures by about ±30 °C., already accounted for in the given uncertainties.

A combined approach to determine the critical temperatures for fission tracks of apatite and zircon has been used by Hurford (1986) and Hurford (1991). Here, the temperatures for annealing of the apatite fission tracks have been given between 60 and 120°C, whereas for zircons a critical temperature of 225 ± 25°C was proposed. A summary of our presently accepted best estimates is compiled in Fig. 4.

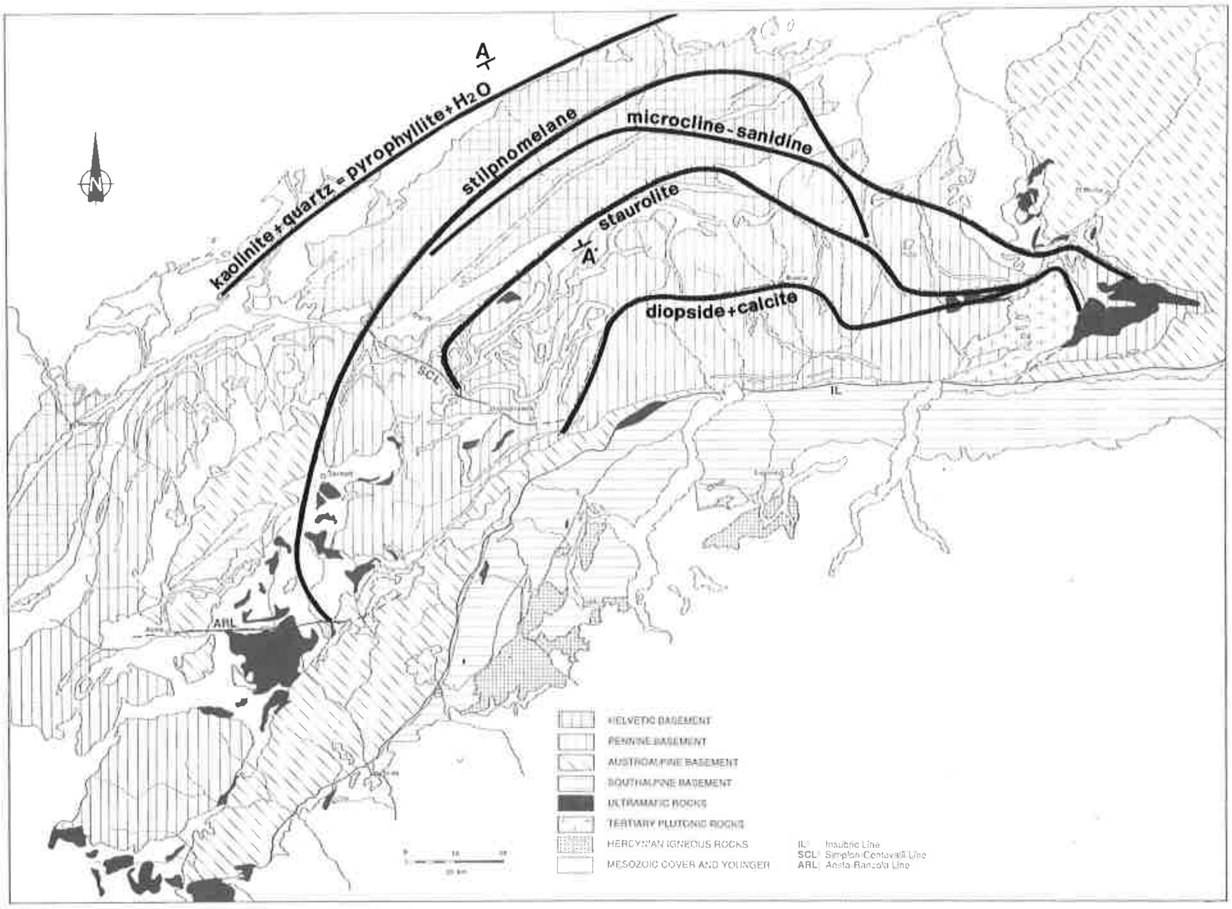

Fig. 5) Tectonic map of the Central Alps, as used as base for maps IV-VII, with Alpine "isograds".

2.2. Rb-Sr mica data: maps I and VII

At first glance there appears a very heterogeneous density of Rb-Sr mineral data, with more than 80 % of the analyses being in the Central Alps. Apart from the Helvetic-Dauphiné massifs, there are very few Rb-Sr mineral data in the Western Alps. For example, south of the Aosta valley, in the Dora-Maira and Gran Paradiso massifs together with the Briançonnais zone, the Piemonte zones and the Canavese zone, fewer than 10 Rb-Sr ages have been measured.

In the Penninic zones of the Western Alps, one late Variscan, probably mixed Variscan/Alpine age, Eo-Alpine biotite as well as phengite ages and both Meso- and Neo-Alpine mica ages have been found. Both Pre-Alpine and Alpine mica data can be expected from these regions where future efforts need to be concentrated.

Besides the differences in blocking temperatures between muscovite and biotite, a further pecularity seems to be that biotite shows a higher tendency than muscovite to record mixed pre-Alpine/Alpine ages.

In the Helvetic-Dauphiné massifs, Variscan and late Variscan ages have been obtained relating to the amphibolite to greenschist facies assemblages and their cooling. Intermediate ages can be interpreted as pre-Alpine/Alpine mixed ages because they are yielded only by biotite. The same has to be said for the Eo-Alpine biotite ages as long as the same age range has not been recorded in potassic white micas. In these external zones, the grade of the Variscan metamorphic phases has obviously been too high for pre-Variscan ages to be preserved in the rocks containing metamorphic mineral relics. However, both Tertiary phases have been found in the Mont Blanc massif where the Alpine greenschist metamorphic facies can be pervasive. In the Central Alps, the central-Penninic part of the Alps north of the Insubric Line predominantly shows Neo-Alpine ages. Meso-Alpine ages are present only west and east of this zone, in the higher Penninic nappes. This is why the term "Lepontine phase" has been dropped and replaced by the term Meso-Alpine (following Hunziker & Martinotti,1984, and Hunziker et al., 1989), "Lepontine" ages not occurring in the Lepontine region as defined by Wenk (1956, 1962). The Eo-Alpine orogeny is poorly documented by Rb-Sr mica data (only 14 analyses). Variscan muscovite ages are recorded outside the staurolite isograd, mainly in pegmatites. In the Prealps, mylonites of an early basal thrust of the nappes show concordant Rb-Sr, K-Ar and ^{40}Ar-^{39}Ar mica ages reflecting an event of Late Cretaceous-early Tertiary age.

The Austro-Alpine (Silvretta, Valpelline) and the South-Alpine domains are dominated by

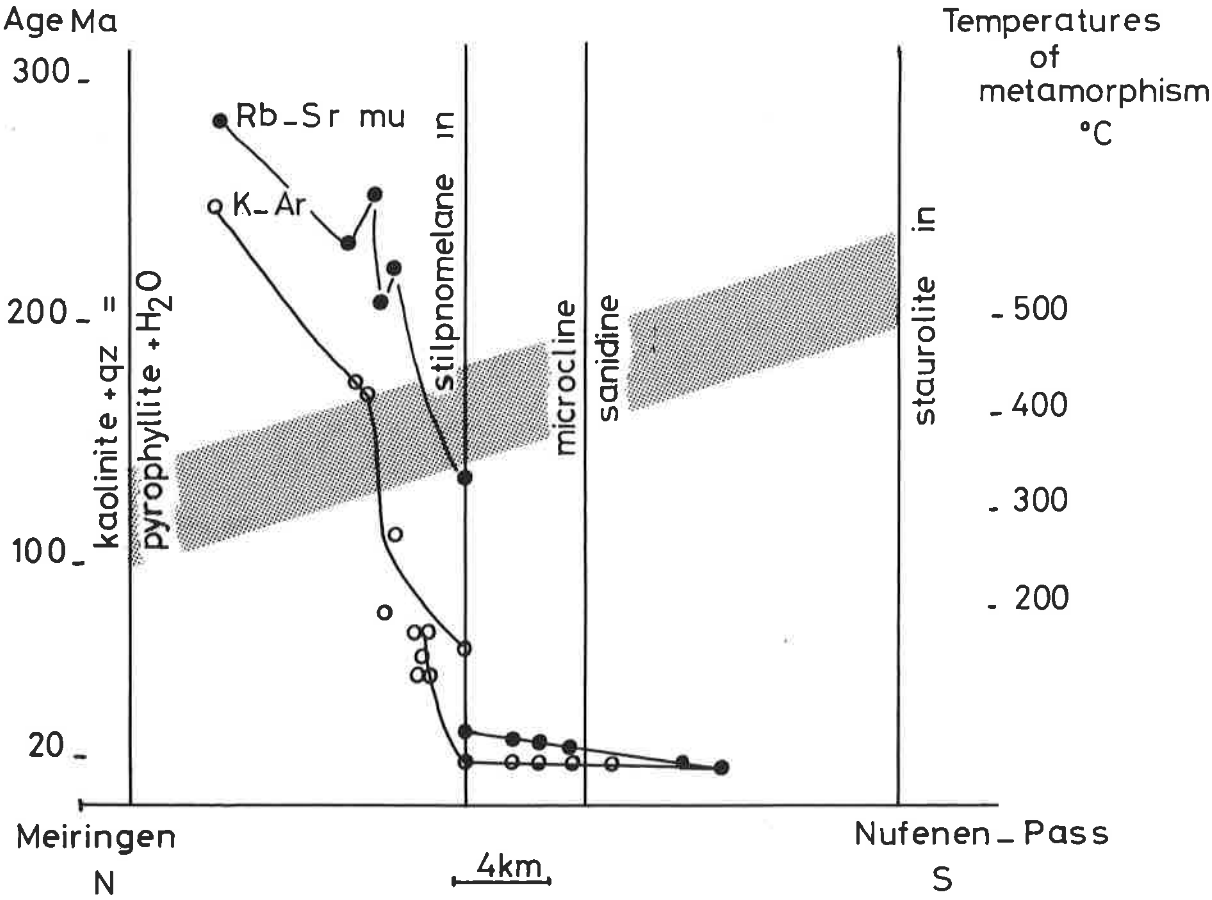

Fig 6) Rb-Sr, and K-Ar mineral data from a N-S cross section through the Aar massif (Dempster, 1986), plotted against temperatures of metamorphism resulting from mineral paragenesis. The resetting of Variscan micas starts for the K-Ar system at 300 °C and is completed at 400 °C, while for the Rb-Sr system K-white mica resetting starts at 350 °C and is completed at 500 °C, in good agreement with the data reported in Fig.4. and maps VI and VII.

Variscan, late Variscan and Triassic-Jurassic mica ages. The Ivrea zone shows the peculiarity of mica ages spreading over the 240-140 Ma period, reflecting a slow uplift during that period. These young, Triassic-Jurassic, ages are also found in some parts of the Silvretta and in the Valpelline nappe of the Dent Blanche system. No mica ages older than Variscan have been reported for the Rb-Sr method in these regions where repeated high heat flow and magmatism may be assumed.

In the Helvetic domain of the Central Alps, two cases have to be distinguished:

1) Pre-Triassic basement muscovites have the tendency to survive as mineral relics and then show Variscan ages. Recrystallized phengites, however, show Meso-Alpine ages. For biotites truly Variscan, mixed Variscan/Alpine, Eo-Alpine (most likely also mixed Variscan/Alpine), Meso-Alpine and Neo-Alpine ages are found.

2) In the Helvetic cover rocks, the mica ages in the Glarus Alps of around 90-60 Ma reflect partially rejuvenated systems as can be shown by the discrepancy between Rb-Sr and K-Ar ages measured on the same micas. The oldest concordant Rb-Sr and K-Ar mica ages in this region are 35 Ma, corresponding to the first metamorphic overprint of these Helvetic sedimentary rocks. From the Glarus thrust plane, ages of around 25-20 Ma are those of one movement phase which transported higher metamorphic (epizonal) rocks over lower metamorphic (anchizonal) rocks.

2.3. K-Ar and ^{40}Ar-^{39}Ar mineral data: maps II and VI

The density of the K-Ar and ^{40}Ar-^{39}Ar data points is more homogeneous than the Rb-Sr mineral data. A first glance, shows an inhomogeneous distribution of Alpine and pre-Alpine ages. In the deeper nappes of the Central Alps, within the Alpine staurolite isograd, all data points are coloured yellow and orange, the only exception being K-Ar amphibole data which yield a spectrum between 240 Ma and Neo-Alpine times, with no apparent regularity. Amphiboles, due to their normally low K-contents, are especially susceptible to problems of argon inheritance from former metamorphic phases. Here ^{40}Ar-^{39}Ar amphibole data will help to distinguish between geologically meaningful and meaningless results.

In contrast, in the South-Alpine as well as in the Ivrea zone and in the Dauphiné-Helvetic domain, pre-Alpine amphibole ages coincide with pre-Alpine mica ages in the same or adjacent rocks. This concordance strongly supports a geological event at that time. In the Briançonnais domain, pre-Alpine mica ages persisted side-by-side with Alpine ages. The late Variscan, i.e. Permian, potassic white mica ages of the Briançonnais zone are related to the high heat flow of this time rather than to a regional orogenic metamorphic phase which, if real, should have been recognized in the late Variscan cover rocks and/or the other Palaeozoic rocks.

A further noteworthy point is the wide distribution of Eo-Alpine ages, both for mica and amphibole, throughout the Western Alps. No regular trend of younging from internal to external domains of the Western Alps is seen in the Eo-Alpine ages, as proposed by Ernst (1973) and Goffé & Chopin. (1986), but rather an apparently erratic distribution between early Eo-Alpine, late Eo-Alpine and mixed Eo-Alpine/Tertiary ages. Indeed, Eo-Alpine ages are related to different metamorphic associations, and therefore, to different geotectonic environments. In the internal zones, the early Eo-Alpine ages are associated with the eclogitic assemblages and the late Eo-Alpine ages with glaucophane-bearing assemblages. Eclogitic assemblages dated as early Eo-Alpine are found in the Sesia zone, the Zermatt zone, the Monte Rosa, Gran Paradiso and Dora-Maira massifs. Glaucophane-bearing assemblages are com-

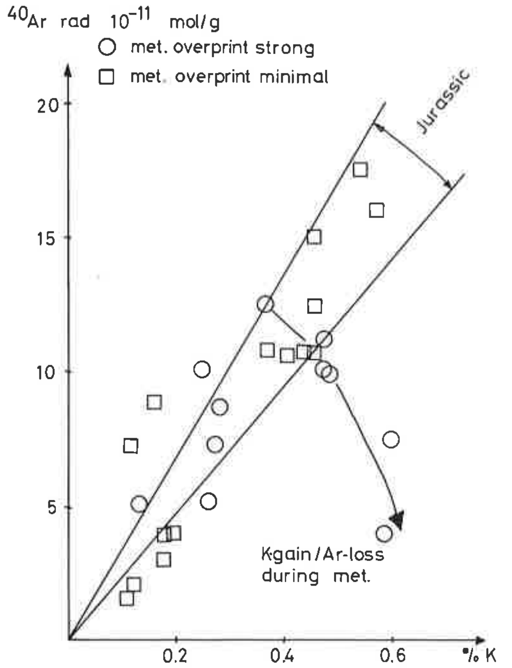

Fig.7) K-Ar amphibole and whole-rock ages, as given by Bertrand & Delaloye 1976, showing variable degree of Alpine overprinting, resulting in variable K-gain and/or Ar-loss during metamorphic overprint, as can be seen from the Mesozoic age brackets given for the most plausible emplacement ages.

mon to all internal zones of the Western Alps, and in the eastern part of the Central Alps. Eo-Alpine ages have also been obtained from amphiboles in a high-pressure meta-ophiolite from the Valais zone in France (Versoyen unit). Thus both parts of the Piemonte zone, the Zermatt and the Combin zones, which had been distinguished on the basis of this difference in high-pressure associations together with differences in their lithological contents, clearly evolved separately until late Eo-Alpine times. Commonly regarded as being derived one from the centre and the other from the marginal parts of the same basin (Dal Piaz et al., 1972; Boillot et al., 1984), the Zermatt and the Combin zones have now also been interpreted as derived from two different basins (Desmons, 1989; Desmons & Radelli, 1989b). In the external zones, Eo-Alpine mica ages could reflect much lower pressure and temperature conditions coinciding with the region of the pre-Senonian, E-W trending, folding phase.

The Gets ophiolites still constitute an open question. The oldest measured K-Ar amphibole ages had been interpreted as emplacement ages (Bertrand & Delaloye, 1976), but it is only one possible interpretation as a nearly linear correlation exists between the Alpine metamorphic overprint and the ages measured in the amphiboles (Fig. 7). These latter range from 220 to 97 Ma, 220 Ma appears rather a minimum age for the oceanic metamorphism that caused the growth of hornblende in these rocks. The apparent endpoint of the overprint in Eo-Alpine time coincides with part of the data of the Gummfluh Klippe in the eastern Prealps, interpreted as the first time of movement of this klippe, still within its depositional environment. This might well be coincidence, as a Meso-Alpine or even a Neo-Alpine overprint, or mixed ages can as well be envisaged as mechanisms for the rejuvenation of the Gets ophiolites. High precision ^{40}Ar-^{39}Ar measurements on these hornblendes should help to clarify these open questions, as well as U-Pb zircon data on plagiogranites and coarse grained gabbros.

No data have been reported so far from the Zone Houillère where the presence of abundant clastic mica grains has discouraged K-Ar measurements so far. However, such measurements would shed valuable light on the pre-Alpine history of the source areas.

From the Swiss molasse basin three data sets are available. Firstly, glauconite K-Ar measurements date stratigraphic deposition times. Secondly, illite ages from oil boreholes yielded partially reset pre-Alpine/Alpine ages as documented by ^{40}Ar-^{39}Ar measurements. Thirdly, the radiometric work performed for the radioactive waste management consortium (NAGRA) in boreholes is shown on the map. Here, two of the striking points are the Permo-Triassic resetting of radiometric systems suffered by some of the basement rocks and the late hydrothermal phase of possibly Cretaceous age. Chloritized biotites (greening effect) indicate a retrograde hydrothermal activity. The first age group are reminiscent of the Permian ages obtained in the Briançonnais and the South-Alpine basements as well as the Bernina nappe.

South of the Insubric line two domains can be distinguished.

1) Mineral ages from the Ivrea zone generally range from 240 to 130 Ma. Here the observed succession is: hornblende ages > muscovite ages > biotite ages, coinciding with generally accepted successions of blocking temperatures (Fig. 8). Some biotites in the neighbourhood of the Insubric line show a lowering of the K-values accompanied by interlayer chloritization effects, yielding apparent ages down to 130 Ma. This late transformation most likely originates in the hot hydrothermal fluids percolating along the Insubric line system, while this zone was slowly emerging from the conditions of the upper mantle-lower crust boundary to upper crustal conditions.

2) In the rest of the Southern Alpine basement, biotite ages range from Variscan to late Variscan. NE of the Ivrea zone, even mixed ages down to 140 Ma are found documenting the close relationship between the Ivrea geophysical body and the Ivrea zone : the geophysical disturbances of the Ivrea body can be traced eastward as far as Lake Como, 30 km east of the last outcrop of the Ivrea zone.

The Variscan mica ages range from 330 to 280 Ma, reflecting the end of the Variscan event in this area. The cooling curve of the Southern Alps (Fig.8) shows, however, that throughout the rest of the Palaeozoic until at least the late Mesozoic, the Southern Alps remained under a cover of 6-10 km, with the exception of the regions covered with upper Carboniferous sediments.

Micas grown in mylonites along the Insubric line date the fast uplift movements leading to mylonitization. These movements range in age from Eo-Alpine (76-61 Ma) in the region of Ivrea, through 43-30 Ma in the region of Biella and 32-29 Ma in the Val Strona, to 26-20 Ma from the Toce valley until the Valle della Mera (Zingg & Hunziker 1990, see fig 9). This implies that the Insubric line underwent several periods of movement, leading to uplift and cooling of the rocks in different areas along this line, according to the present level of erosion. The Neo-Alpine late uplift movements were also most likely active in the region of Ivrea, but here only under brittle regime and thus only recorded by fission tracks. In contrast, the early ductile movements of Eo-Alpine ages in the Toce-Mera domain of the line have been overprinted later, still under ductile conditions, and are only recorded by fission tracks in the southern block where temperatures at that time were already cold enough.

The Sesia zone has also been affected by the movements along the Insubric line. In the central part of the Sesia zone, eclogitic early Eo-Alpine and late Eo-Alpine ages dominate. East of the Toce valley, however, only Meso- and mainly Neo-Alpine mica ages are found. This trend in ages reflects a differential uplift and exhumation to the surface. In the area of Biella this exhumation led to molasse deposition at 30 Ma, whereas exhumation along the north-eastern part of the outcropping Sesia zone is younger than 10 Ma.

As already noted in the discussion of the Rb-Sr map, Neo-Alpine age values are found within the staurolite isograd of the central Lepontine region, reflecting late uplift and cooling of this area.

In the Simplon area, a field of late Neo-Alpine micas is associated with movements along the Simplon line under low greenschist conditions (Steck, 1984, 1987; Mancktelow, 1985). These movements are recorded by mica ages in the gneisses and

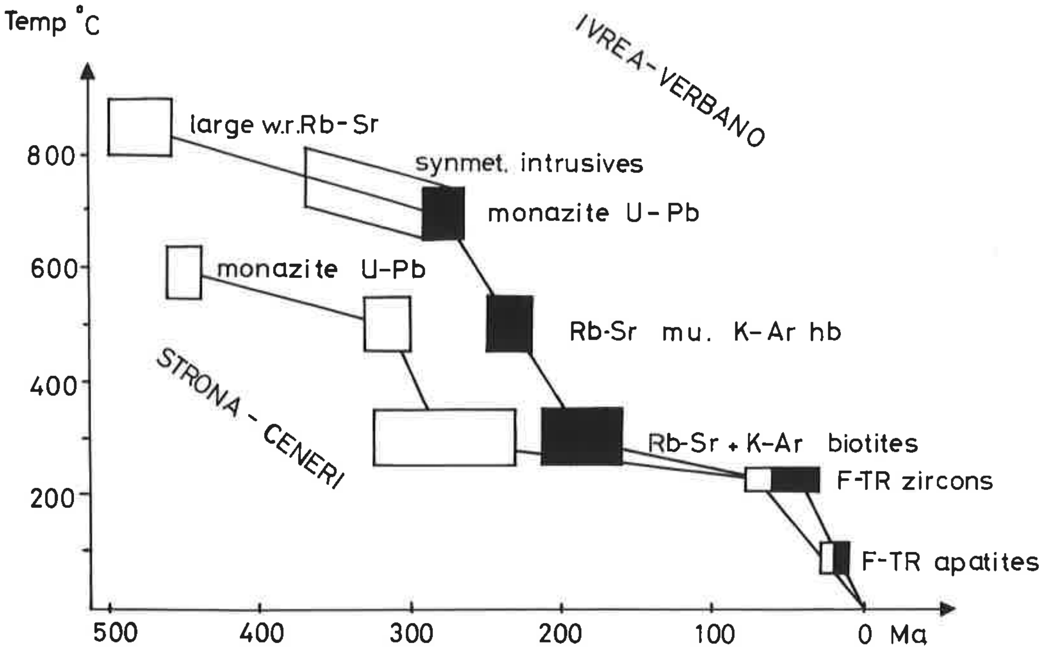

Fig. 8) Cooling curves over the last 500 Ma for the Strona-Ceneri zone (Southern Alps) and for the Ivrea-Verbano zone. Concordant monazites with ages around 450 Ma, from paragneisses of the Strona-Ceneri (Köppel & Grünenfelder 1971), mark the climax of pre-Variscan high grade metamorphism, in agreement with lower concordia intercepts of zircons from ortho-and paragneisses. In the Ivrea Verbano zone, ± 280 Ma old monazites (Teufel & Schärer, 1989) mark the onset of the transition, or uplift, from lower crustal to upper crustal conditions, with synmetamorphic magmatism, getting more and more acidic with time (Bürgi & Klötzli, 1990). Rb-Sr data collected from large whole rock samples are interpreted as marking the climax of this metamorphic phase in pre-Variscan times. Note the parallel trends in the cooling curves of both South Alpine blocks, that belong together in their evolution.

the Mesozoic calc-schists adjacent to the zone of maximum movement and further away from this zone, predominantly in the Mesozoic calc-schists. As already seen in the Rb-Sr map, west and east of the Lepontine region Meso-Alpine micas are again found outside of the staurolite field. Here, Variscan mica ages also occur, some of them corresponding to partial resetting of micas in pegmatites or to armoured relics in basic rocks.

East and west of the Lepontine region, Eo-Alpine ages are found recorded both by blue amphiboles and phengitic white micas.The concentric age zonation east and west of the Lepontine region is a good argument for the overprinting relations of Eo-Alpine overprinted by Meso-Alpine overprinted by Neo-Alpine assemblages.

These relationships yield a minimum age of 45 Ma for the high pressure event. For the data of the Glarus Alps, we refer to the above discussion (see Rb-Sr map).

2.4. Sm-Nd, Rb-Sr, K-Ar whole rock, zircon, monazite U-Pb analyses: map III.

Compared with more than 100 zircon fission track data generated in the last ten years, the lack of interest from geochronological laboratories for the pre-Alpine history of the Western Alps is surprising: apart from the analyses from the Dauphiné-Helvetic massifs, there are only 12 analytical points in the Western Alps.

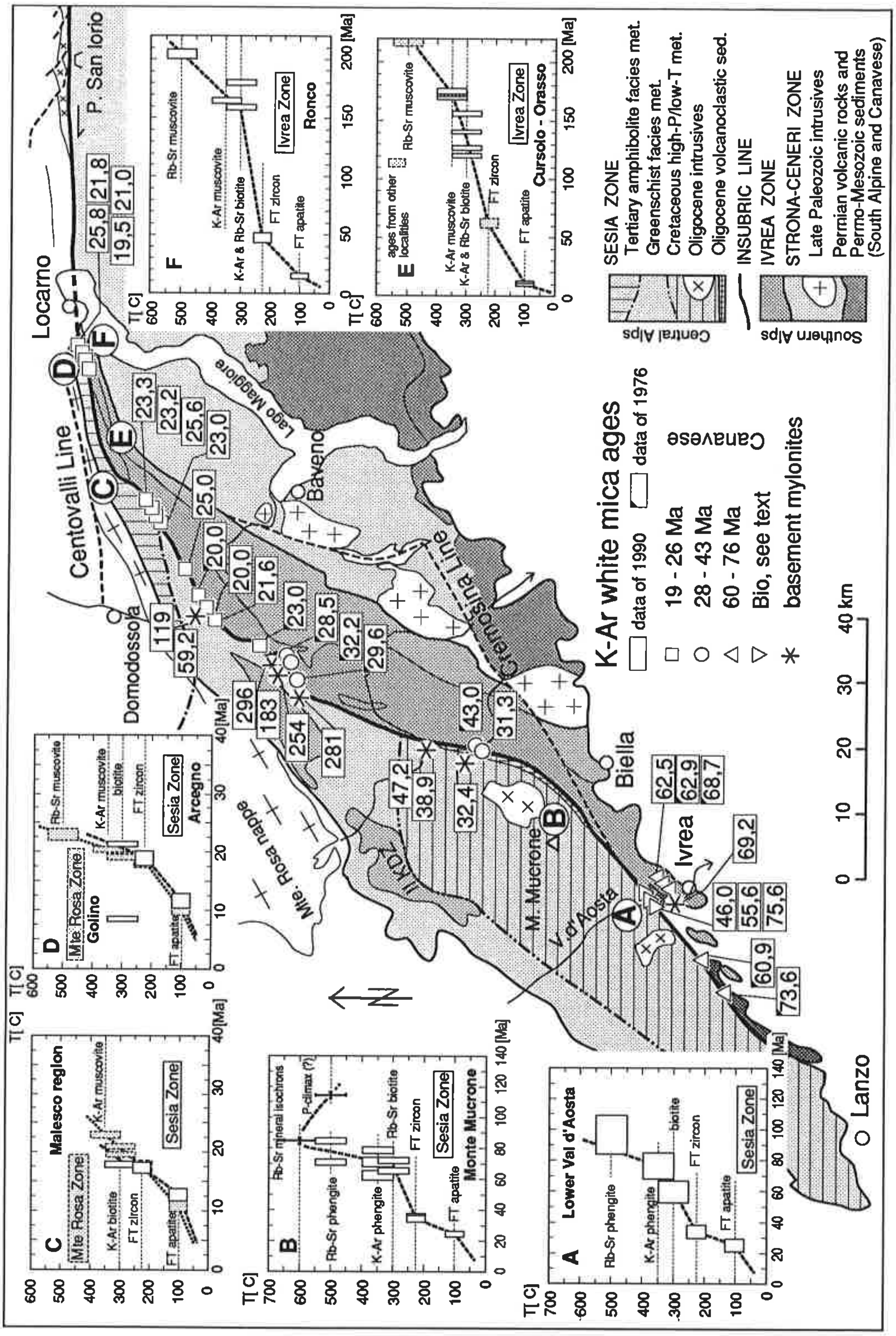

Fig. 9) Sketch map with the K-Ar white mica ages from the basement mylonites, and mylonitized Canavese sediments along the Insubric line. Insets : radiometrically derived thermal histories of the adjacent Ivrea, Sesia, and Monte Rosa zones. Figure modified from Zingg and Hunziker 1990.

In the Central Alps the main efforts have been concentrated on the Aar and Gotthard massifs as well as in the Southern Alps. The Penninic nappes between Monte Rosa and Suretta also show a highly heterogeneous density of the data points. So far only two workers have presented data from the western Silvretta.

This still inadequate data base, however, permits certain conclusions to be drawn. Hercynian granitoids are very widespread in all units of the Alps, and provide a clue for deciphering the ancient history of the pre-Triassic basement of the Alps. Rb-Sr whole rock and U-Pb zircon work on these granitoids has revealed ages between 360 and 240 Ma. (Ferrara & Malaroda, 1969; McDowell,1970; Allegre et al. 1974; Abrecht, 1975; Gulson & Rutishauser, 1976; Köppel et al., 1981; Demeulemeester, 1982; Biggiogero et al., 1982/83; Boriani et al., 1982/83; Dempster, 1986; Schaltegger, 1986a+b, 1989,1990; Schaltegger et al., 1991; Flisch, 1987; Bussy et al., 1989; Bürgi & Klötzli, 1990).

These Hercynian granitoids intruded a pre-Hercynian already metamorphosed, partly metapelitic-psammitic basement, the latter containing metamorphosed granitoids and mafic rocks (garnet amphibolites and eclogites). see fig 10. The older granitoids in turn show Rb-Sr whole rock and U-Pb zircon lower intercept ages of around 450-480 Ma, (Grünenfelder et al.,1964; Grauert & Arnold, 1968; Köppel & Grünenfelder, 1971; Köppel, 1974; Boriani et al., 1982). The zircon U-Pb upper intercept ages of this pre-Hercynian basement, yielded data points between 1900 and 2500 Ma (Grünenfelder et al., 1964; Grauert & Arnold, 1968; Köppel & Grünenfelder, 1971; Köppel, 1974), while Sm-Nd model ages point to a period between 1200 and 1800 Ma (Voshage et al., 1984). Rb-Sr maximum age extrapolations of paragneisses, point to 500-700 Ma. (Grauert, 1966/69; Grauert & Arnold, 1968; Hunziker & Zingg, 1980). Sm-Nd whole rock data on basic and ultramafic rocks gave 600 Ma maximum ages (Stille, 1979/80; Voshage et al., 1987/88/89). Pb-Pb ages in the entire Alps are never older than 700 Ma (Köppel, 1983).

The question of possible pre-Alpine metamorphic phases remains. In the Southern Alps, the Austroalpine and the Helvetic, as well as the Penninic Alps, a pre-upper Westphalian metamorphic phase has clearly been evidenced, by widespread Hercynian potassic white mica and biotite, as well as hornblende ages, (Grauert, 1968; Demeulemeester, 1982; McDowell, 1970; Hunziker, 1970; Desmons et al., 1974/82; Flisch, 1987). The intensity and duration of this Hercynian metamorphic phase still remains a matter of debate.

The proposal of a lower Palaeozoic high grade metamorphism in the Alps however is clearly a contentious issue, with one fraction completely rejecting such a possibility, (e.g. Boriani et al., 1982/83), whilst the other strongly favours such an event, at around 450-480 Ma. (Köppel & Grünenfelder, 1975; Hunziker & Zingg, 1980). The most intriguing feature in favour of a lower Paleozoic metamorphism in the Southern Alps, apart from the lower intercept U-Pb zircon data, are the concordant U-Pb monazite ages of Köppel & Grünenfelder, (1975) of 450 Ma on paragneiss-migmatites of the boundary Strona-Ceneri / Ivrea-Verbano zone, difficult to explain without a high grade metamorphism of this age, see fig 8.

In conclusion, the pre-Alpine history as revealed from radiometric data can be summarized as follows:

the oldest events recorded in rocks from the Alps are found in zircon cores of paragneisses of Helvetic, Penninic, Austro-Alpine, as well as South-Alpine rocks alike, where the upper concordia intercepts point to lower Proterozoic ages up to 2500 Ma.

In the Ivrea-Verbano-zone the granulite facies paragneisses show Sm-Nd whole rock ages of 1200-1800 Ma for the separation of their source material from the mantle.

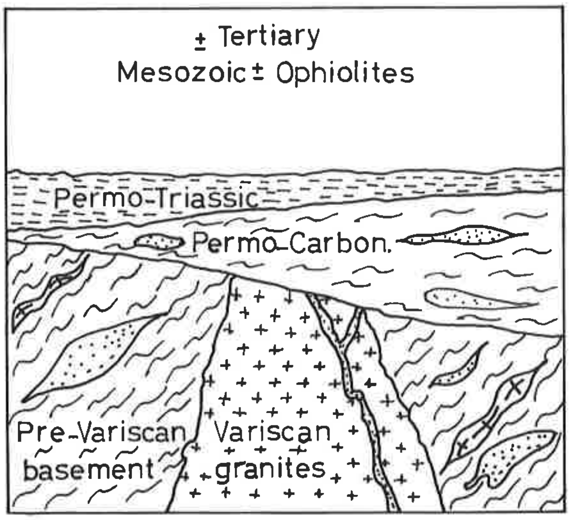

Fig.10) Evolution diagram of the Western Alps, with Variscan granitoids as fixpoints. These granitic rocks intruded into an amphibolite-granulite facies (sillimanite + K-feldspar) pregranitic metamorphic basement (metapelites-psammites), with widespread associated basic boudins (garnet amphibolites-eclogites) of pre-Variscan age (dotted boudins), and Pre-Variscan granitoid gneisses (boudins with elongated crosses). After the Variscan discordance we find a Permocarboniferous volcanosedimentary metamorphic sequence, a Permotriassic metapsammitic-pelitic series (Verrucano), and finally the Mesozoic to Tertiary metacarbonatic cover sequence, partly comprising ophiolites, and partly in flysch facies of variable Mesozoic and early Tertiary age.

Rb-Sr maximum age extrapolations in Helvetic Penninic and South Alpine rocks point to 500-700 Ma for the sedimentation of these units, in good agreement with Pb-Pb whole-rock data. Sm-Nd whole rock, as well as U-Pb zircon ages on mafic rocks from Penninic and South Alpine units yield ages around 600 Ma. The first metamorphic event clearly documented in the Alpine domain is of lower Palaeozoic age. A second metamorphic cycle of pre-upper Westphalian age and, in places, late cooling ages mark the Hercynian metamorphism.

The Permian is characterized by a widespread magmatic activity, with predominantly rhyolitic to granitic rocks. This magmatic activity can be interpreted as the beginning of crustal thinning. At the boundary of the Triassic, around 250 Ma ago, precursors of the Mesozoic ophiolites, the first Alpine gabbroic rocks, appear in the Mt.Collon-Matterhorn and Sondalo, interpreted as the starting point of the rifting and opening of the continental crust which gave birth to the Tethyan ocean. This thinning and opening phase is accompanied by a greening phase with intense chloritisation and sericitisation, due to pervasive hydrothermal activity along opening lystric faults. The growing amount of SHRIMP U-Pb zircon work, performed by Gebauer in the Alps, has not been discussed here as, so far few data have been published and their interpretation is still controversial.

2.5. Zircon fission track ages: map IV

More than 110 zircon fission track ages from the Central and Western Alps on map IV range from 8 to 220 Ma. All ages but one from within the stilpnomelane-in line, north of the Insubric line yield ages younger than 30 Ma, reflecting the cooling of this central Lepontine region to below ± 225 °C in Neoalpine times. The Sesia-Lanzo zone passed this temperature already in Mesoalpine times, thus in the Sesia zone only brittle deformation occurred in Neoalpine times. In the Gran Paradiso a cooling through the 225 °C isotherm around 30±1 Ma was recorded; no topographic effect could be detected. The late cooling of younger than 15 Ma recorded in the Maggia valleys and the Simplon area seems further on to follow the Rhone valley, and head into the Mont Blanc massif. In the South Alpine blocks, including the Ivrea-Verbano-Zone and the Silvretta nappe, slow cooling below 300°C started in Variscan times, and crossed the ± 225° C boundary recorded by zircon fission tracks as early as 220 Ma in some places.

In the Ivrea-Zone, the closer we approach the Insubric line from the south, the more zircon fission tracks converge to values recorded north of the line in the Alpine metamorphic block (see Figs. 11. and 12)

This fact can be interpreted as the effect of the hot northern block, uplifting rather fast during Neoalpine time, and reheating the already cooled (since Eoalpine times) southern block, or preventing the cooling southern block from further cooling before Neoalpine time. The Eoalpine zircon fission track ages recorded from the northern rim of the Aare massif, in view of the metamorphic temperatures of above 270° C reached in Alpine times (see fig 6), have to be interpreted as early cooling below 225° C in Cretaceous times. The Aosta-Ranzola Fault offsets fission track zircon ages of over 30 Ma in the south against ages lower than 30 Ma in the northern block. A feature better seen in the fission track apatite map, see also Fig. 13.

2.6. Apatite fission track ages: map V

On map V more than 210 apatite fission track ages range from 40 to 2 Ma. The striking phenomenon is that differences in thermal behaviour between north and south of the Insubric line seem to be absent, indicating a coeval passing through the ±100° C isotherm of both blocks, see Figs.11 and 12.

A further peculiarity is that fission track apatite ages are offset along the Aosta-Ranzola fault (Fig. 13), with an age pattern of around 20-25 Ma south of the fault and ages younger than 15 Ma north of the fault; this pattern continues across the Sesia zone, even where, so far, no fault is recorded, with the northern sector cooling 5-10 Ma later than the southern sector. In reality as has been verified in the field, the Aosta-Ranzola fault continues at least beyond the Sesia valley. The apatite fission track ages below 8 Ma along both the Toce and the Leventina culmination (late north-south striking updomings of the Lepontine region) are also noteworthy. Furthermore, the young ages of the Toce-Simplon region trend down along the northern slopes of the Valais, through the Aare massif, the Helvetic Wildhorn-nappe and southwestwards into the Mont-Blanc-Aiguilles-Rouges massifs. This region of young uplift, from Verampio, over the Simplon and down the Valais, coincides with an active geothermal anomaly, yielding many hot springs of up to 100° C source temperatures and rock temperatures of around 50° C, encountered during the construction of the Simplon tunnel. The cooling pattern of the block NE of the Simplon fault (Fig. 14) shows a rather fast cooling in Neoalpine times, down to 18 Ma. before present and then a period of slower cooling between 18 and 8 Ma, followed by a further rapid uplift and cooling during the last 5 Ma, with consequence of bringing hot rocks up to the surface.

3. Conclusions

The present compilation of 32 years of joint geochronological research in Central and Western Alps from over 15 laboratories, reveals astonishing inhomogeneities, both in regional distribution of the data as well as temporal distribution.

The Western Alps contain practically no Rb-Sr data and also the U-Pb measurements are very scarce, observations especially true for the Briançonnais region and the internal Penninic massifs.

A marked majority of the data deals with the Alpine metamorphic history and with cooling after the Alpine orogeny, as reflected by six of the seven maps presented in this compilation.

From pre-Variscan times mostly due to the paucity of data, but also pervasive overprinting and thus masking of relations of the Alpine events, very little can be said with great certainty. Widespread Variscan granitoids intruded a pre-Variscan polymetamorphic basement of generally lower crustal origin. The age of this polymetamorphic basement is still a matter of debate. Sm-Nd measurements point to a magmatic contribution of basic and ultramafic rocks around 700 to 600 Ma before present with further addition in the lower Palaeozoic of both basic and acidic

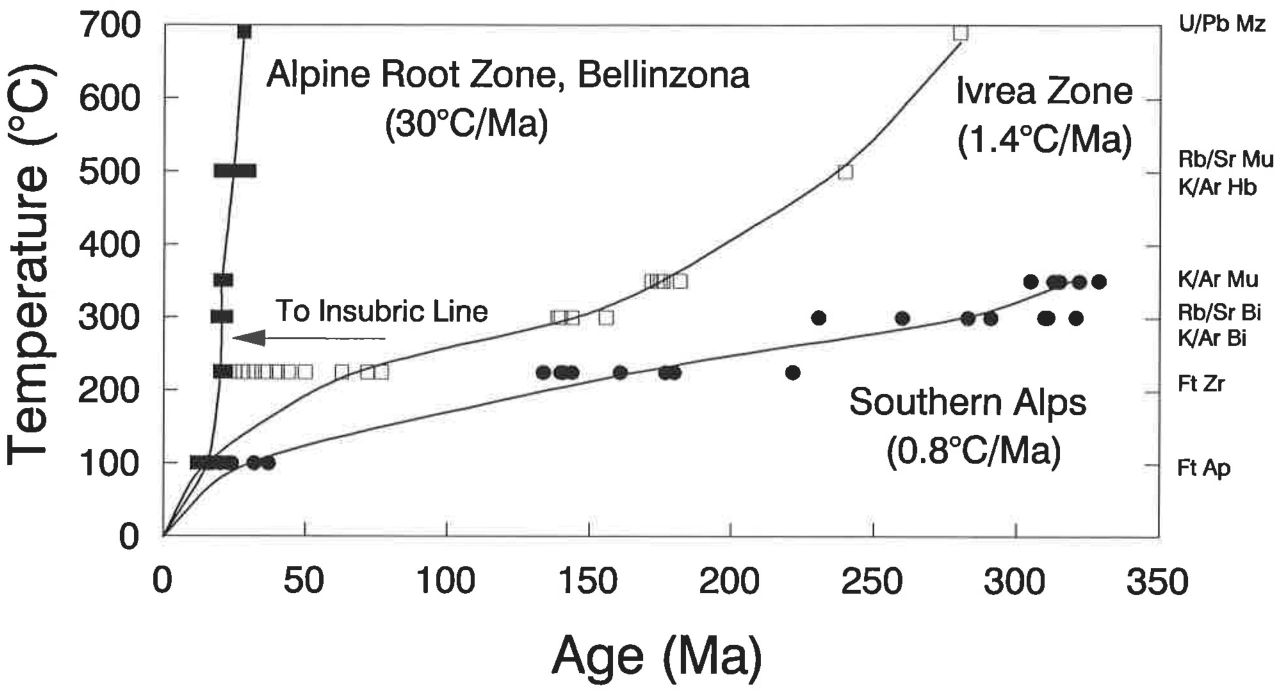

Fig. 11) *Cooling history of the Central Alpine root zone. The Alpine block underwent a rapid cooling, starting at the Meso-Neoalpine boundary, whereas slower cooling occurred in the southern block, already starting in Variscan times. In the Ivrea Zone, the closer we approach the Insubric line from the South, the more zircon fission tracks converge to values recorded North of the line in the Alpine metamorphic block. This observation can be interpreted as a consequence of the northern block, uplifting rather fast during Neoalpine time, and reheating the already cooled Southern block.*

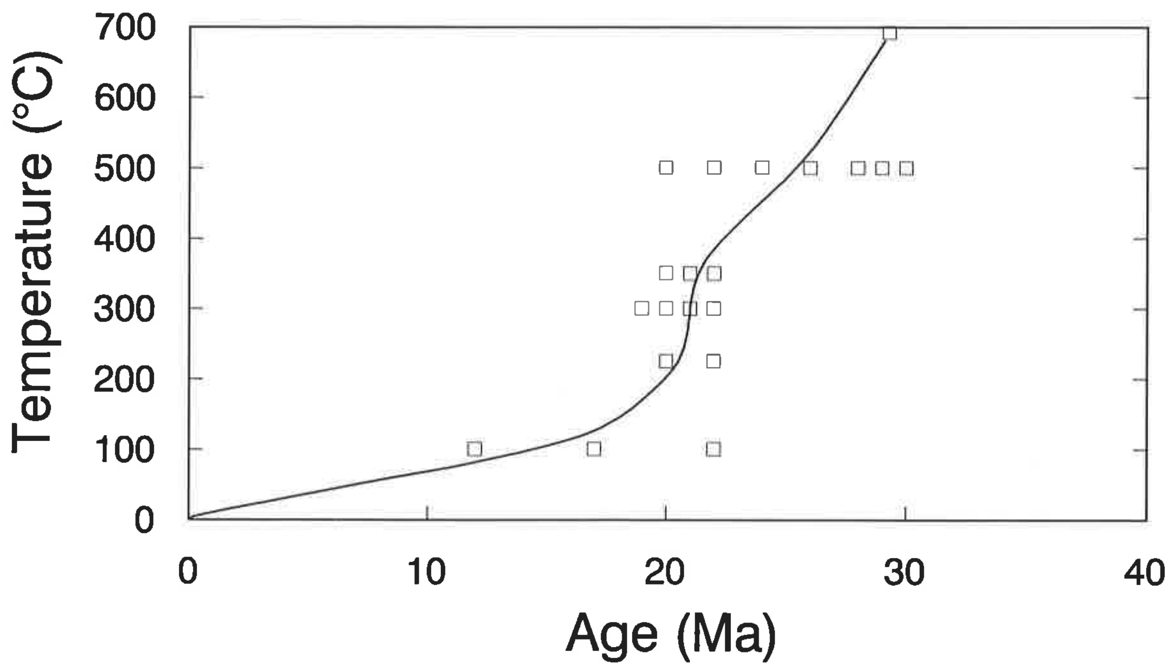

Fig. 12) Enlarged detail from fig. 11, of the Neo-Alpine cooling of the region of Bellinzona.

rocks. Rb-Sr whole rock extrapolations of several paragneiss suites from the central and western Alps point to maximum sedimentation ages between 1000 and 600 Ma.

The Variscan orogeny and metamorphism recorded in the pre-Triassic basement rocks of the Central and Western Alps was sufficiently pervasive to rejuvenate almost totally all the pre-existing mineral phases: no pre-Variscan mica ages have been found so far, and the few older amphiboles can safely be interpreted as due to Ar-inheritance. The only pre-Variscan minerals dated so far are zircons and monazites. A further potential of pre-Variscan ages recorded in minerals would be cores of large zoned garnets (e.g. from the Ivrea zone), where the Sm-Nd system could have survived the rather elevated temperatures.

In Variscan times, a series of granitoids intruded the pre-Variscan basement. These granitoids had a tendency to become more and more acidic with time. Around 300 Ma, calc-alkaline magmatism, both intrusive and effusive started, which lasted until mid-Permian, the onset of Verrucano sedimentation. These late Variscan magmatic phases mark the onset of a thinning and rifting phase, with high heat flow and consecutive hydrothermalism along preferred lystric planes, geochemically altering the adjacent rocks completely and thus lowering the radiometric ages.In the period between 240 and 140 Ma, during the Triassic-Jurassic period, this hydrothermal activity in the Variscan and late Variscan magmatic rocks led to a partial to total resetting of geochronometric systems. Biotite was partly chloritized (greening of the rocks), K-feldspar was partly transformed to muscovite, and in An-rich plagioclase cores both sericite and epidote minerals grew at temperatures around 300-350° C.This greening phase is recorded in the Helvetic pre-Triassic basement, both of the Helvetic massifs and the basement below the Swiss molasse basin, as well as in the Bernina (Jäger,1976).

In the Ivrea-zone, the Valpelline nappe of the Dent-Blanche system, as well as the intermediate Seconda Zona Diorito Kinzigitica (II DK), as well as parts of the Silvretta, mica ages between 240 and 140 Ma mark the slow uplift and cooling of these zones from lower to upper crustal conditions. Some micas, but only very few, showing these ages outside these two "Austroalpine" environments, can be interpreted as mixed Variscan-Alpine ages.

The age of emplacement of the Mesozoic ophiolites remains undated, despite the investment of much analytical effort. Although plagio-granites and coarse grained gabbros would yield enough zircons, so far no convincing magmatic U-Pb ages have been presented on Mesozoic ophiolites. Sm-Nd emplacement ages for these rocks are also lacking up to present. The only measurements that have been performed, are conventional K-Ar and a few Ar-Ar ages, both on whole rocks and on amphibole separates. Due to the fine grain of the matrix and/or the glass, exchanges during devitrification and subsequent oceanic and/or low grade regional metamorphism, whole-rock data are expected *a priori* to be unreliable.

Amphiboles in these rocks most likely derive from the oceanic metamorphism and subsequently, during low grade orogenic deformation and metamorphism (blueschist in the western Alps), show a tendency to exchange during recrystallisation (see Fig.7) An attempt to date ophiolite emplacement by fission tracks on zircons in the Alps (Carpena & Caby, 1984) and in the Apennines (Bigazzi et al., 1972) is difficult to assess. In the Apennines, fission tracks were measured on external surfaces of the grains, rendering the quantification of the geometry factor a difficult task. Zircon FT for an ophiolite sequence from the Piemontese zone of the Western Alps gave ages of 200 Ma, surprisingly appear to have survived the Eoalpine high pressure metamorphism of the Alps! In conclusion, we can state that the emplacement of ophio-

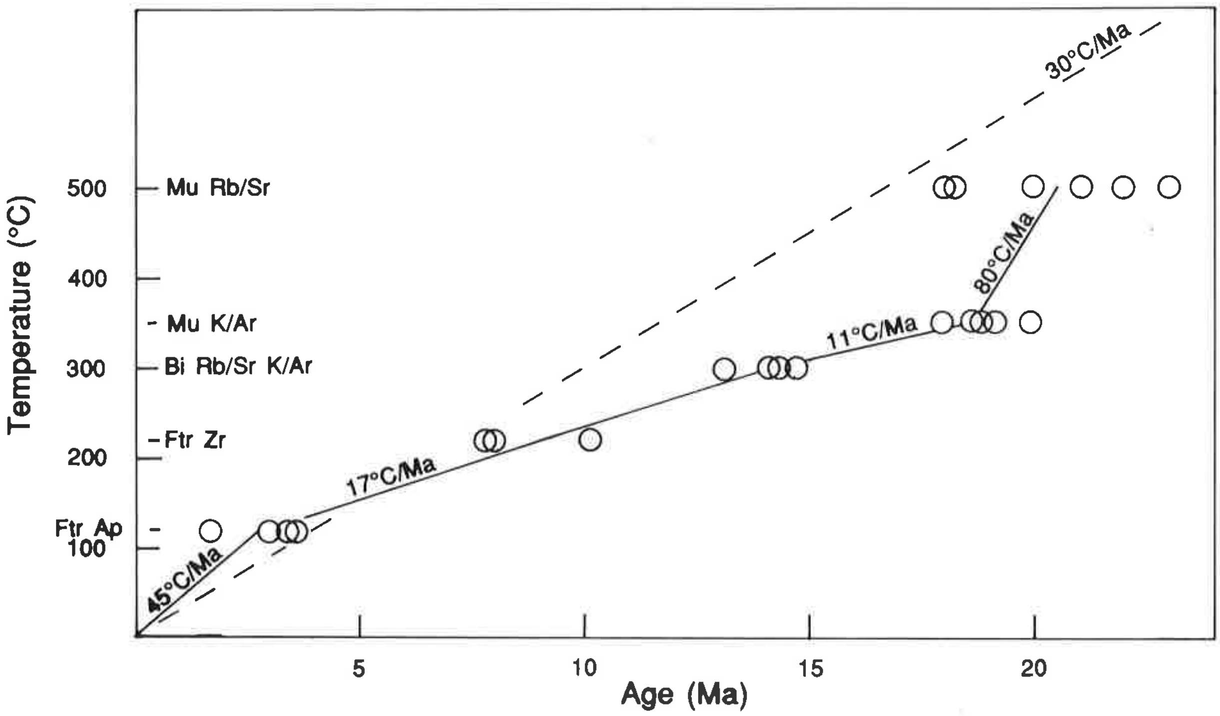

Fig. 13) Neo-Alpine cooling pattern NE of the Simplon fault-zone. After an initial period of fast cooling until around 18 Ma., cooling slowed down until 3-5 Ma, to speed up to around 45°C/Ma up to present. This late fast uplift brought hot rocks out of their thermal equilibrium to the surface and is responsible for the geothermal potential of this region.

lites in the Alps and Apennines is not yet satisfactorily dated radiometrically.

As the age of the associated sediments is not clear due to later tectonic transport into their present position and environment , also geologically speaking we only have good guesses.

The discussion of the Alpine mineral data from the Central and Western Alps needs special attention with regards to the Eoalpine event. In general, ages between Variscan and Alpine can be interpreted in two ways: either they are mixed Variscan-Alpine ages, or they represent a geologically meaningful event.

The coincidence of two or more different geochronological methods yielding the same age, normally can be taken as good proof of having dated a geological event.

A Rb-Sr whole-rock isochron of eclogitized meta-granitoid rocks from Monte Mucrone (Sesia-zone) yielded 129 Ma (Oberhänsli et al., 1985). A Rb-Sr mineral isochron of high pressure phases of the same eclogites gave an age of 110 Ma. In addition, Rb-Sr phengite measurements gave 85 Ma ages, nearly concordant with K-Ar ages of the same micas, and Hy (1984) reported Ar-Ar plateau ages of 90-110 Ma.from the same locality. In addition Chopin et al (1984) measured Ar-Ar plateau ages between 110 and 100 Ma from phengites of whiteschists of Monte-Rosa, Gran-Paradiso and Dora-Maira.

All these ages so far point to a Cretaceous age of the Eoalpine high pressure event in the Western Alps.

The younger limit of 30±2 Ma for this event being the discordantly cutting trachyandesitic magmatism (Scheuring et al,

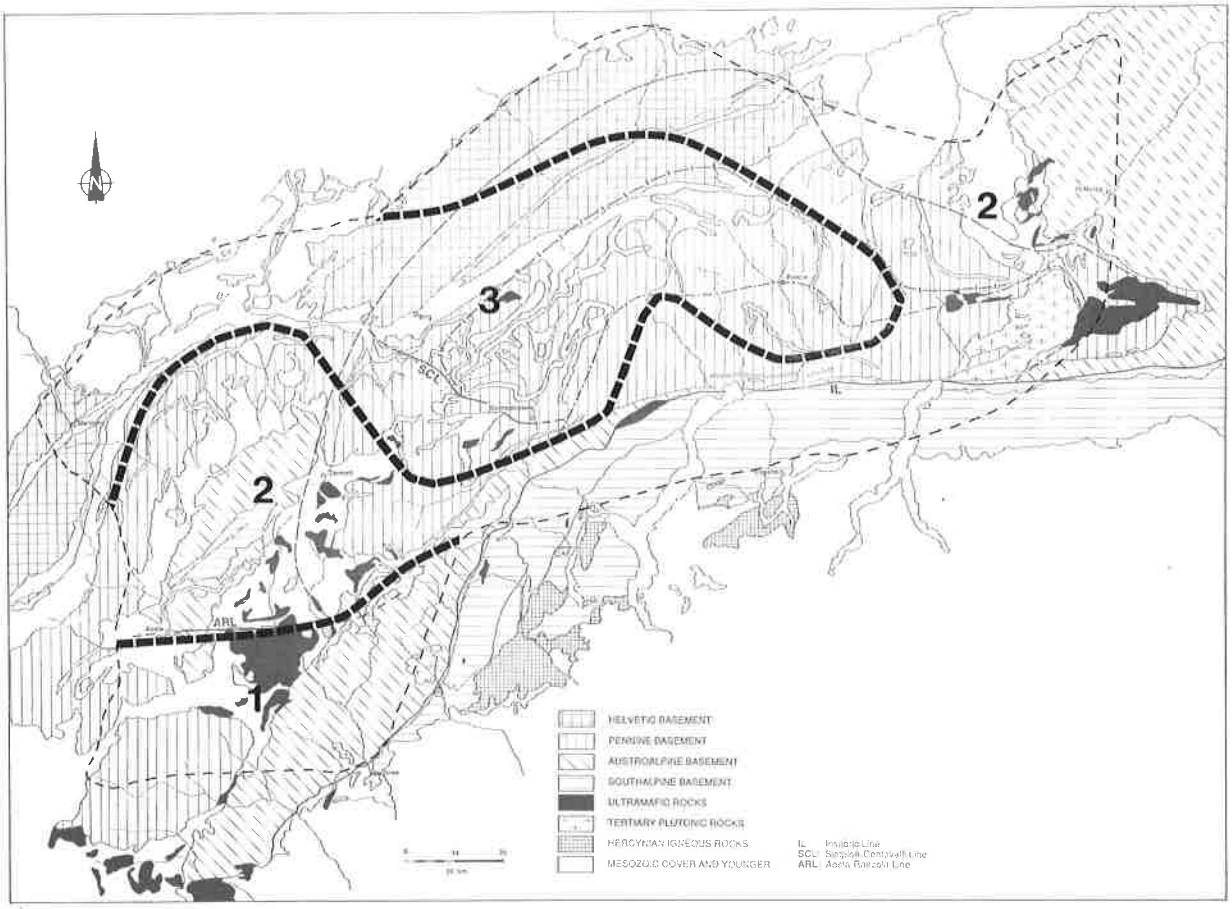

Fig. 14) The Aosta-Ranzola fault, offsetting zircon and apatite fission tracks. 1) Fission track apatite ages 25-20 Ma. 2) Fission track apatite ages 15-8 Ma. 3) Fission track apatite ages younger than 8 Ma. ARL) Aosta-Ranzola fault, offsetting the field of 25-20 Ma fission track apatite ages in the south, from a field of ages younger than 15 Ma in the north.

1975) which in turn is younger than the Mesoalpine overprint of the Eoalpine Eclogites, as well as the coeval molasse sedimentation of the Sesia zone (Zingg et al., 1976). The older geological limit of the eclogites of the Western Alps is given by the Jurassic ophiolites that underwent this same high pressure metamorphism, and by the eclogitic metagranitoids of Mucrone, the chemistry of which speaks for a co-magmatic origin with the 275 Ma old Baveno granite suite (Hunziker & Zingg, 1980). In addition, these eclogitized metagranitoids yielded concordant Permian U-Pb zircon data (Bussy et al., in prep.; and Paquette et al., 1989). From a geologic point of view, the Eoalpine high pressure event or orogeny can thus be bracketed between 220 Ma the maximum emplacement age of the eclogitized ophiolites

Fig.15 shows a tentative effort to draw fields of equal Alpine K-Ar mineral ages

Considering the enormous amount of data, the resolution is still poor. The present compilation, we hope, will act as a useful resource for stimulating further researches in Alpine geology, particular in the area of geochronology.

4. Acknowledgments:

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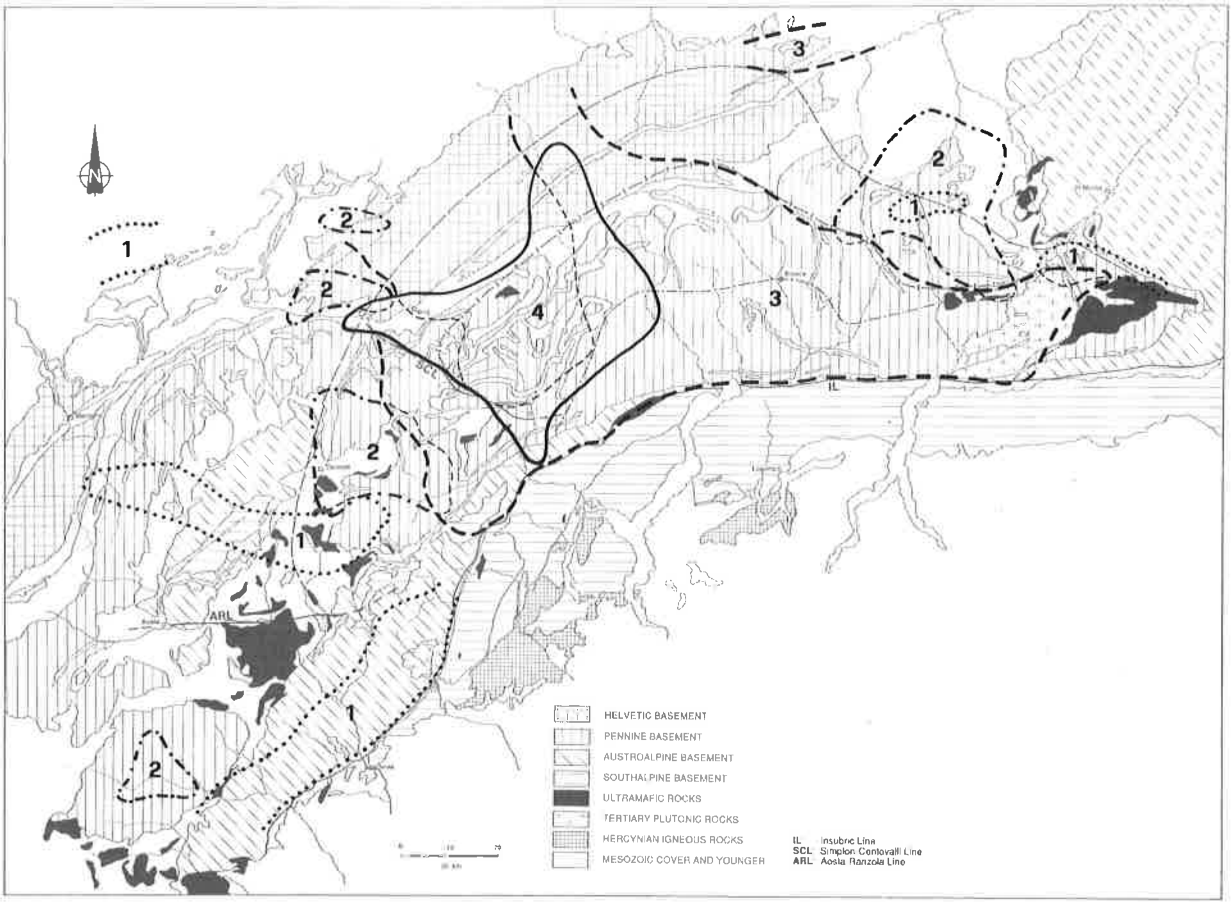

Fig. 15) *Distribution map of Alpine K-Ar mineral ages in the Central and Northwestern Alps. 1) 140-60 Ma. 2) 45-30 Ma. 3) 30-15 Ma. 4) 15-8 Ma.*

tical remarks on former drafts of this manuscript.

We owe our most sincere thanks to E. and G. Martinotti, without their continuous advice and painstaking help the work would never have reached the present quality. Last but not least we thank M. Tible, our printer for his enormous patience and skill during all stages of the printing.

Table 1: Additional previously unpublished K-Ar data.

(Analyst J.C.Hunziker)

Sa #	Locality	Coordinates	Mineral	40Ar (10^{-6} ccm/g)	rad %	rad%K	age Ma.
140	Chiggiogna		pheng	5.71	77.1	8.86	16.5 ± 1.0
155	Grevasalvas	143.975/774.475	stilp	0.58	31.0	0.231	63.4±1.0
			glauk	0.74	39.1	0.315	59.4±7.4
330	Chiareggio	779.88/131.81	bio	8.36	75.4	7.53	28.3±1.8
			pheng	13.15	86.0	8.54	39.2±2.2
367	Saas Fee	637.05/104.9	pheng	13.81	84.8	9.45	37.2±1.7
375	Furggtal	643.15/101.3	pheng	43.99	92.9	8.52	128±5
376	Furggtal	641.9/102.75	pheng	16.68	93.3	9.18	46.1±1.9
377	Saas Fee	638.3/106.9	pheng	16.12	87.8	9.33	43.9±1.9
404	Emd		pheng	9.09	64.8	9.45	24.6±1.5
644	Val Fedoz	778.8/136.8	bio	6.84	90.1	5.86	29.8±2.0
645	Val Fedoz	778.2 /138.8	pheng	24.21	94.8	9.07	67.4±2.8
651	Bernina	794.5/144.6	bio	58.20	73.6	5.90	237 ± 16
			bio+chlo	24.31	82.6	2.64	223 ± 13
Ber4	Bernina	792.9/147.75	bio+chlo	60.70	65.9	5.62	258 ± 20
			bio+chlo	46.98	95.4	4.44	254 ± 13
748	Ramosch	825.25/191.3	musc	101.4	98.3	7.73	309 ± 13
			chlo	4.82	72.5	1.47	82.5 ± 10
774	Val Fex	139.75/780.75	hornbl	1.24	62.2	0.302	103 ± 6
775	Val Fex	139.0/779.7	pheng	23.34	94.8	9.31	63.4±2.6
776	Val Fex	139.0/779.7	pheng	22.83	92.5	9.07	63.5±2.7
777	ValFex	138.4/780.6	pheng	22.35	90.6	9.22	61.2±2.6
778	Stretta	145.3/796.8	bio	72.06	94.5	6.71	257 ± 13
			musc	102.7	95.9	8.54	286 ± 13
779	Bernina		bio	73.36	98.1	7.49	236 ± 12
956	Ca Rotte	784.3/131.3	musc	26.34	91.4	8.85	75.0±3.2
			hornbl+bio	7.45	87.3	4.40	43.0±1.9
			chlor+bio	1.58	24.9	1.01	39.7±6.3
957	Ca Rotte	784.3/131.3	musc	26.85	87.1	8.84	76.5±3.9
958	Maloja Pass	773.44/141.98	pheng	38.0	91.9	9.01	105 ± 5
			musc	88.67	97.0	8.90	240 ± 10
959	Maloja Palace	773.6/141.95	musc	93.13	97.7	8.24	270 ±10
			musc+pheng	43.42	97.0	9.08	119 ±5
			pheng	28.48	94.8	9.21	77.8±3.2
999	Sella	795.56/133.19	musc	82.84	94.7	8.87	225 ± 9
1000	Margna	794.36/133.94	pheng	24.44	89.5	9.04	68.2 ±3.0
			hornbl	1.68	59.6	0.283	146 ± 10
1001	Passo d'Ur		hornbl	0.63	32.6	0.214	74.1±8.9
			musc	22.76	85.7	8.29	69.3 ±3.2

Table 2: Previously Unpublished Rb-Sr data. (Analyst J.C. Hunziker)

Rb-Sr whole rock isochron Anzola, Toce. Banded Ivrea granulite facies metapelitic gneisses

KAW Nr	^{87}Rb ppm	Sr ppm	^{87}Rb/^{86}Sr	87Sr/86Sr	isochron age Ma.
447	23.4	142.4	1.6773	0.72351	
448	20.1	138.0	1.4858	0.72213	
449	14.6	191.2	0.7815	0.71810	
450	9.14	207.8	0.4484	0.71521	
451	13.2	367.8	0.3677	0.71432	398 ± 93 Ma.
452	11.6	225.0	0.5277	0.71665	Sri .71303 ± 168
453	24.6	146.7	1.7127	0.72116	
454	22.3	113.3	2.0167	0.72422	
Rb-Sr whole rock isochron, Val Strona d'Omegna. Banded granulite facies metapelite gneisses KAW 508					
3a	10.4	103.6	1.0279	0.71618	
3b	8.11	93.0	0.8915	0.71603	
4a	21.8	121.6	1.8298	0.72024	
4b	19.9	131.9	1.5433	0.71933	
5a	15.5	125.3	1.2699	0.71813	
5b	12.2	90.28	1.3878	0.71814	344 ± 34 Ma.
6a	22.6	108.5	2.1337	0.72195	Sri .71154 ± 88
6b	24.6	122.5	2.0539	0.72169	
7	29.5	123.6	2.4378	0.72302	
9	35.1	205.0	1.7508	0.72029	
11	9.80	264.5	0.3787	0.71254	
13	45.8	179.3	2.6137	0.72469	

Fig 16 Rb-Sr whole rock isochrons of granulite-amphibolite facies banded Ivrea metapelites (see table 2)

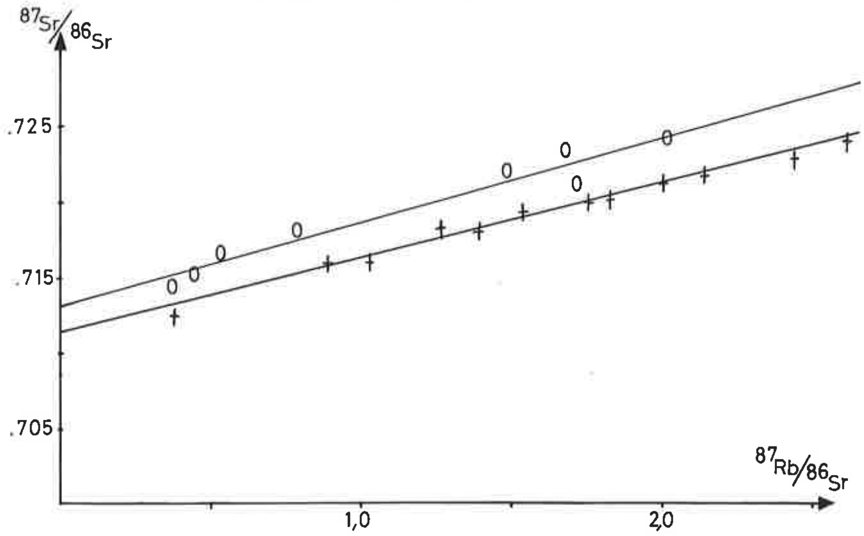

Table 3: Previously Unpublished Fission Track Data Measured for Suretta Nappe Samples by A.J. Hurford

Sample & Locality	Mineral & No. Crystals	Spontaneous ρ_s (N_s)	Induced ρ_i (N_i)	$P\chi^2$* or s' %	Dosimeter r_d (N_d)	Age (Ma) (±1σ)	Mean Track Length (μm) (No. measured)	MTL SD (μm)
KAW1237	apatite	5.380	85.26	1.8%	6.556	14.0±0.4	13.19±0.15	1.48
	190/200	(2019)	(5389)		(7788)		(n=100)	
	zircon	73.41	56.76	31%	1.014	22.1±1.4		
	20	(2231)	(1725)	*	(1224)			
KAW 1238	apatite-G	2.114	37.89	3.1%	6.556	12.4±0.6	13.38±0.13	1.27
	200/200	(835)	(2395)		(7788)		N=100	
	apatite-K	2.654	43.73	3.0%	6.556	13.5±0.6	13.47±0.14	1.36
	200/200	(671)	(2764)		(7788)		(n=100)	
	zircon	40.22	31.47	97%	1.006	21.8±1.5		
	15	(1094)	(856)	*	(1224)			
KAW 1240	apatite	1.416	20.62	2.5%	6.556	15.3±0.9	13.25±0.12	1.21
	200/200	(358)	(2932)		(7788)		(n=100)	
	zircon	29.04	23.99	92%	0.990	20.3±1.3		
	20	(1398)	(1155)	*	(1224)			
KAW 1243	apatite	0.041	0.711	6.4%	6.556	12.7±2.7	density	
	300/300	(24)	(421)		(7788)		too low	
	zircon	29.68	22.94	98%	0.974	21.3±1.5		
	20	(1084)	(838)	*	(1224)			
KAW 1246	apatite	1.947	43.51	3.1%	6.556	9.9±0.6	12.9±0.17	1.71
	200/200	(769)	(2750)		(7788)		(n=100)	
KAW 1247	apatite	0.162	2.688	13.4	6.556	13.4±2.1	density	
	200/200	(64)	(1062)	%	(7788)		too low	
	zircon	36.84	33.09	93%	0.958	18.1±1.2		
	20	(1604)	(1441)	*	(1224)			
KAW 1379	apatite	0.0371	0.564	6.4%	6.556	14±3	density	
	300/300	(22)	(334)		(7788)		too low	
KAW 1382	apatite	0.3367	5.450	4.8%	6.556	13.7±1.3	12.90±0.45	1.19
	200/200	(133)	(1378)		(7788)		(n=8)	
KAW 1383	apatite	0.1418	2.757	4.6%	6.556	11.4±1.6	density	
	200/200	(56)	(1089)		(7788)		too low	

Notes:

(i) Track densities (ρ) are as measured and are (x 10^5 tracks cm^{-2}). Numbers of tracks counted shown in brackets

(ii). Apatite analyses by population method; zircon analyses by external detector method.

(iii). Ages calculated using dosimeter glass SRM 612 and zeta-612 = 339 [Hurford and Green, 1983].

(iv). For EDM analyses $P(\chi^2)$* is probability of obtaining χ^2 value for v degrees of freedom (where v = No of crystals - 1)

(v). For apatite population method analyses, relative standard error of mean track count (s') is shown.

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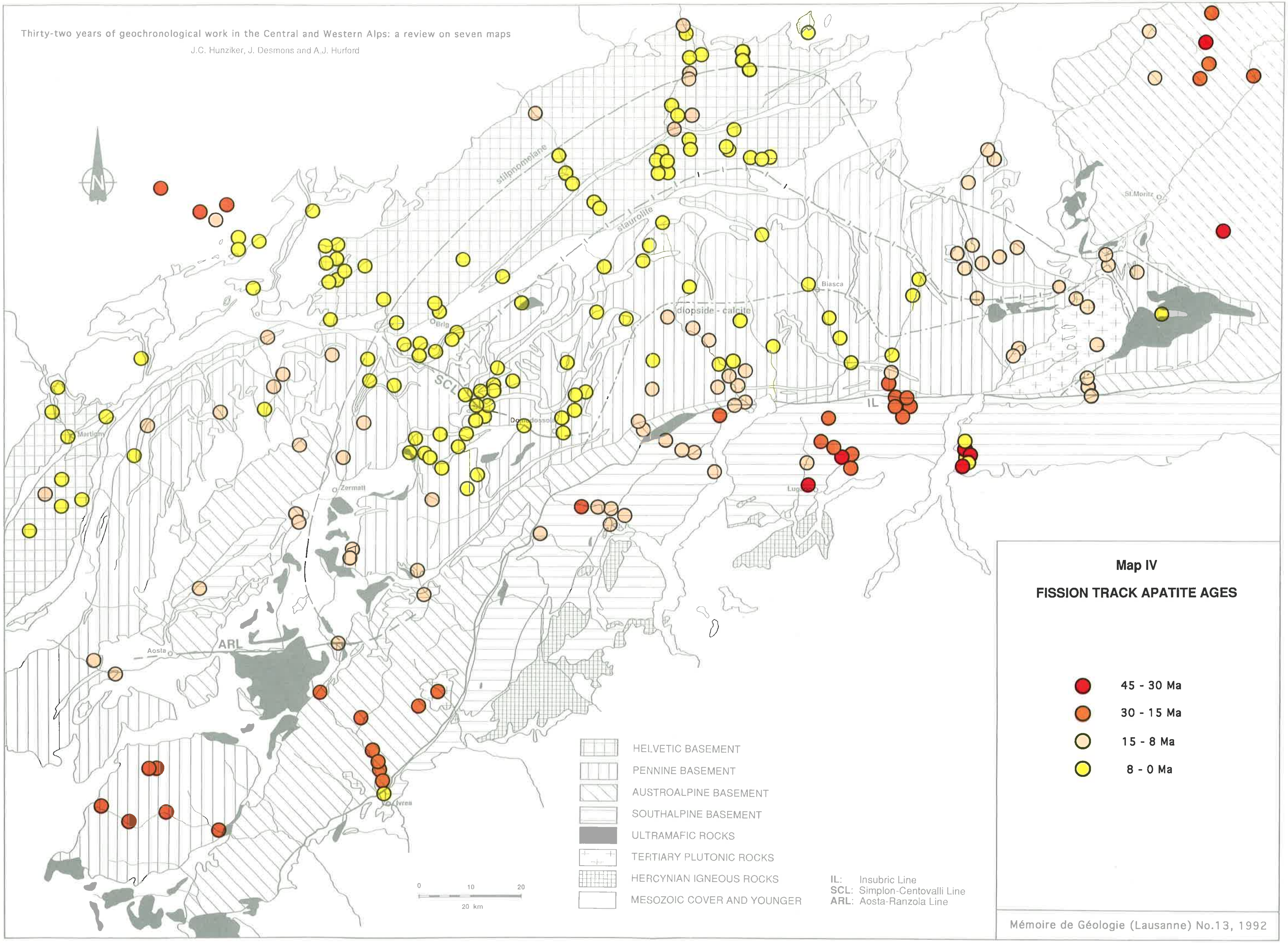

Thirty-two years of geochronological work in the Central and Western Alps: a review on seven maps
J.C. Hunziker, J. Desmons and A.J. Hurford
N
stilpnomelane
staurolite
diopside - calcite
Brig
SCL
Martigny
Zermatt
Aosta
ARL
Ivrea
Biasca
IL
St.Moritz
Map IV
FISSION TRACK APATITE AGES
45 - 30 Ma
30 - 15 Ma
15 - 8 Ma
8 - 0 Ma
HELVETIC BASEMENT
PENNINE BASEMENT
AUSTROALPINE BASEMENT
SOUTHALPINE BASEMENT
ULTRAMAFIC ROCKS
TERTIARY PLUTONIC ROCKS
HERCYNIAN IGNEOUS ROCKS
MESOZOIC COVER AND YOUNGER
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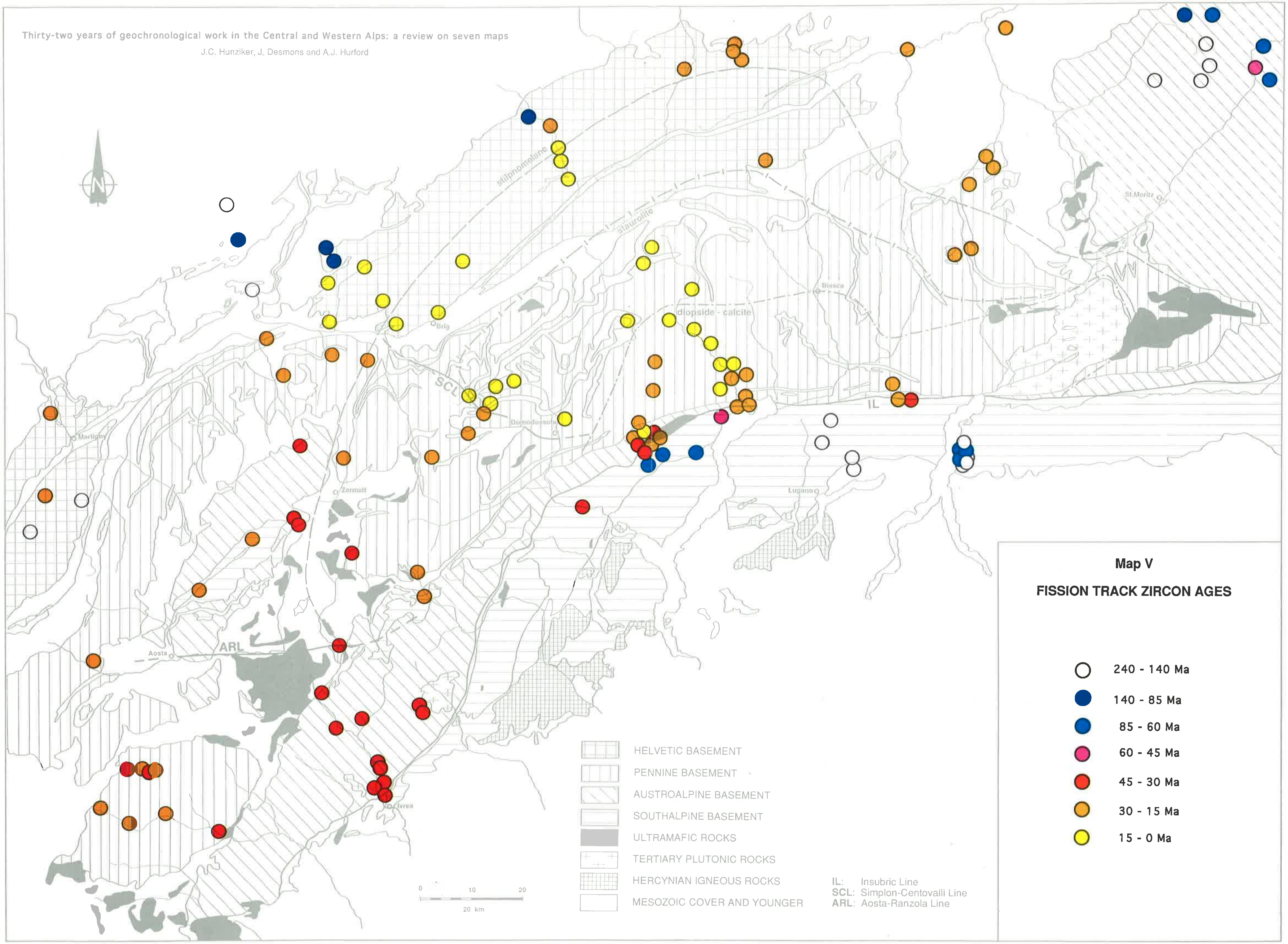
20 km
IL: Insubric Line
SCL: Simplon-Centovalli Line
ARL: Aosta-Ranzola Line
Mémoire de Géologie (Lausanne) No.13, 1992



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N
stilpnomelane
staurolite
diopside - calcite
SCL
IL
ARL
Brig
Domodossola
Martigny
Zermatt
Aosta
Ivrea
Biasca
Lugano
St.Moritz
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10
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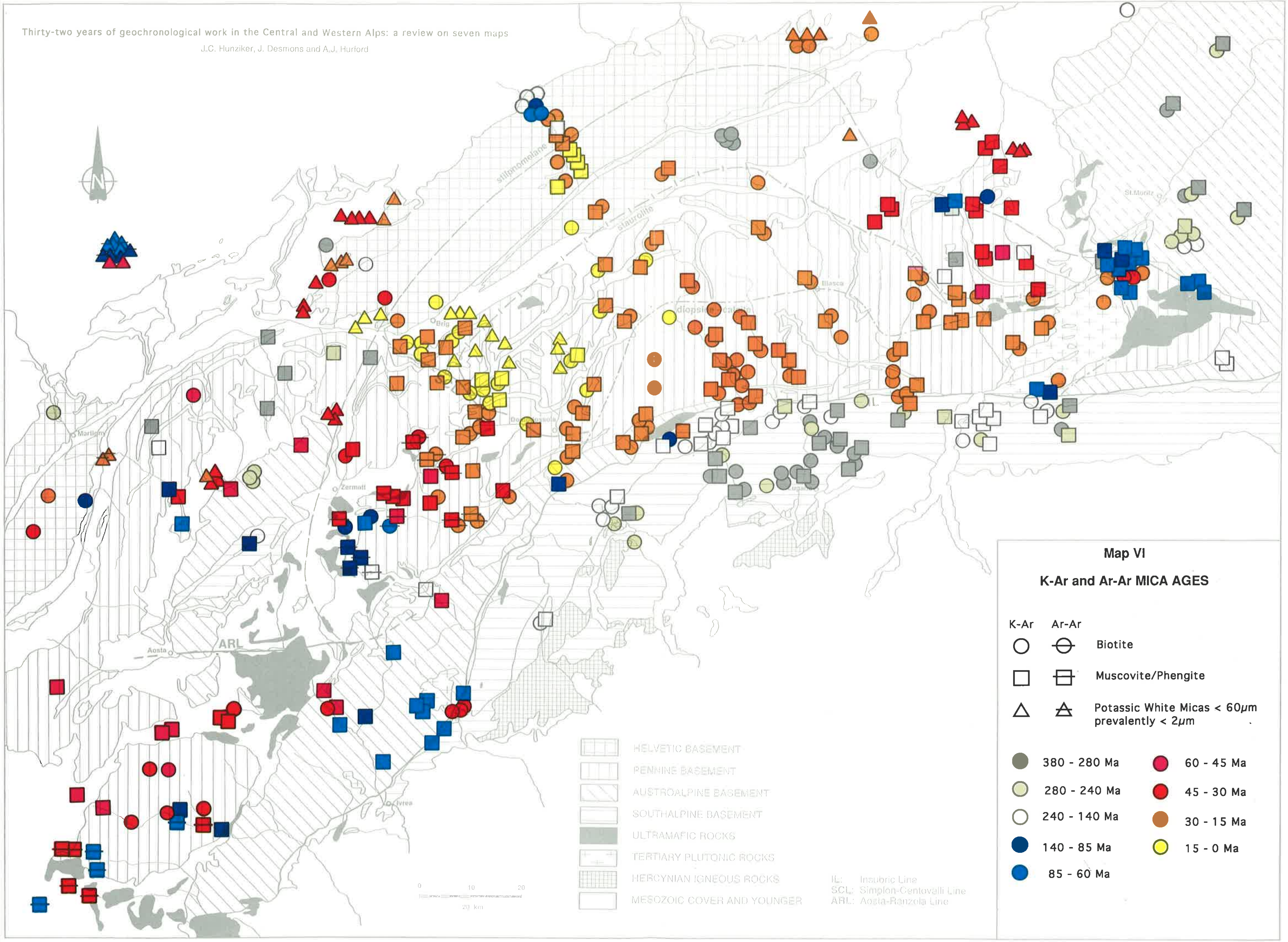
20 km
HELVETIC BASEMENT
PENNINE BASEMENT
AUSTROALPINE BASEMENT
SOUTHALPINE BASEMENT
ULTRAMAFIC ROCKS
TERTIARY PLUTONIC ROCKS
HERCYNIAN IGNEOUS ROCKS
MESOZOIC COVER AND YOUNGER
IL: Insubric Line
SCL: Simplon-Centovalli Line
ARL: Aosta-Ranzola Line
Map V
FISSION TRACK ZIRCON AGES
240 - 140 Ma
140 - 85 Ma
85 - 60 Ma
60 - 45 Ma
45 - 30 Ma
30 - 15 Ma
15 - 0 Ma


Thirty-two years of geochronological work in the Central and Western Alps: a review on seven maps
J.C. Hunziker, J. Desmons and A.J. Hurford
Map VI
K-Ar and Ar-Ar MICA AGES
K-Ar
Ar-Ar
Biotite
Muscovite/Phengite
Potassic White Micas < 60μm prevalently < 2μm
380 - 280 Ma
280 - 240 Ma
240 - 140 Ma
140 - 85 Ma
85 - 60 Ma
60 - 45 Ma
45 - 30 Ma
30 - 15 Ma
15 - 0 Ma
HELVETIC BASEMENT
PENNINE BASEMENT
AUSTROALPINE BASEMENT
SOUTHALPINE BASEMENT
ULTRAMAFIC ROCKS
TERTIARY PLUTONIC ROCKS
HERCYNIAN IGNEOUS ROCKS
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IL: Insubric Line
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N
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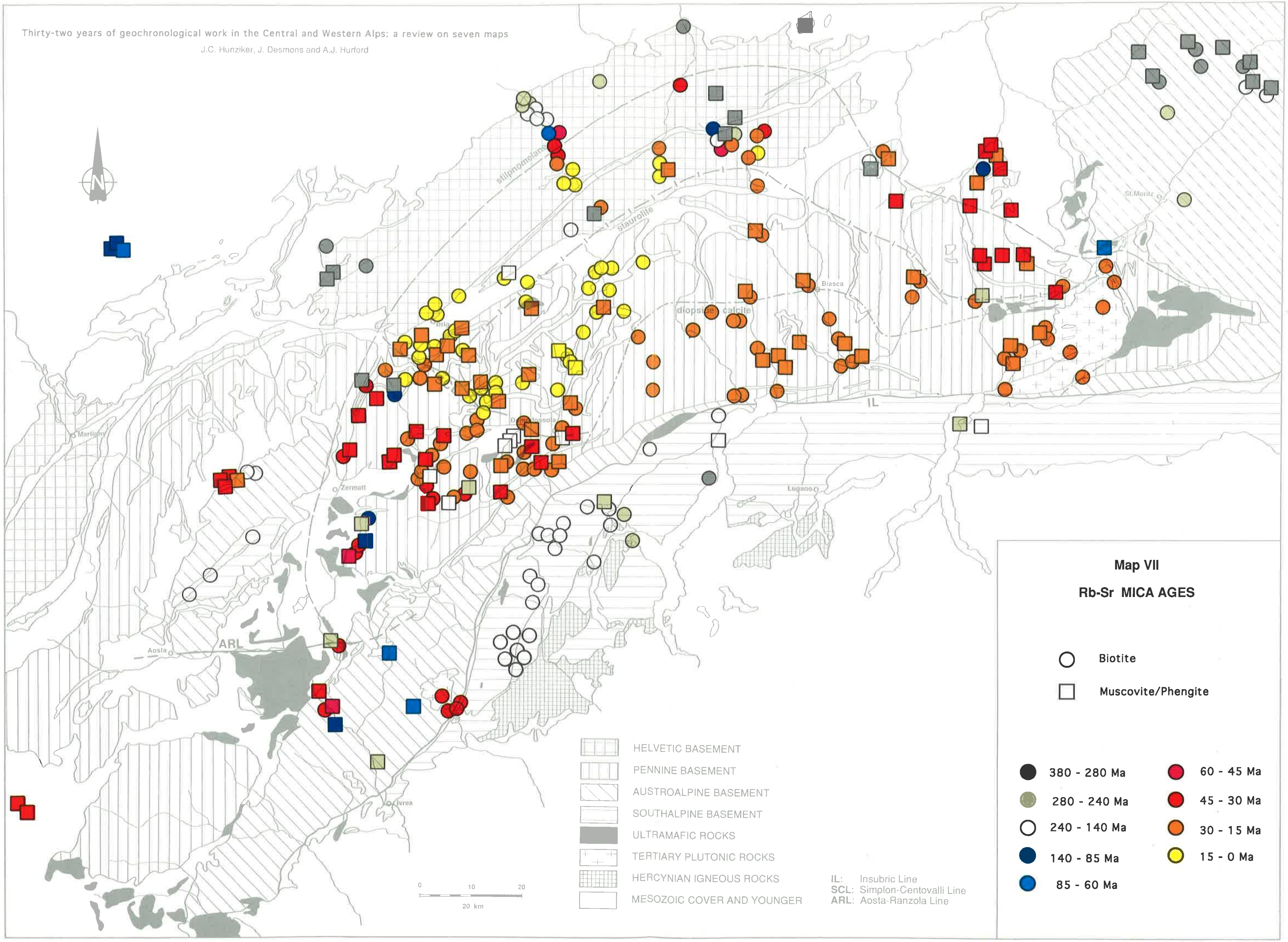
Ivrea
Brig
St.Moritz
stilpnomelane
staurolite
diopside-calcite
20 km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Map VII
Rb-Sr MICA AGES
Biotite
Muscovite/Phengite
380 - 280 Ma
280 - 240 Ma
240 - 140 Ma
140 - 85 Ma
85 - 60 Ma
60 - 45 Ma
45 - 30 Ma
30 - 15 Ma
15 - 0 Ma
HELVETIC BASEMENT
PENNINE BASEMENT
AUSTROALPINE BASEMENT
SOUTHALPINE BASEMENT
ULTRAMAFIC ROCKS
TERTIARY PLUTONIC ROCKS
HERCYNIAN IGNEOUS ROCKS
MESOZOIC COVER AND YOUNGER
IL: Insubric Line
SCL: Simplon-Centovalli Line
ARL: Aosta-Ranzola Line
0
10
20
20 km
N
stilpnomelane
staurolite
diopside
calcite
Biasca
St.Moritz
IL
Lugano
Zermatt
Martigny
Aosta
ARL
Ivrea