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EXPLANATORY NOTES AND LEGEND

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Geological map of the Tertiary Adamello batholith (Northern Italy) Explanatory notes and legend

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In memory of Angelo BIANCHI and Giambattista DAL PIAZ

ABSTRACT - The geological map of the Adamello Batholith, on the 1:50 000 scale, is introduced and commented and a slightly revised English version is given of the Italian legend as printed on the map. The evolution of geological knowledge of the Adamello area and its representation on geological maps are briefly summarised. The outlined topics include aspects of igneous petrology, contact metamorphism, stratigraphy and tectonic structures. Reference is made to papers published before 2001 and the bibliography also lists existing maps and numerous unpublished reports on the Adamello geology.

K e y w o r d s : *Geological map of the Adamello batholith, Tertiary magmatism in the Alps, Periadriatic igneous Province, petrology of tonalitic rocks, stratigraphy of the Adamello surroundings, dyke rocks, age determinations, contact metamorphism.*

RIASSUNTO - Viene presentata la Carta Geologica del Batolite dell'Adamello alla scala 1:50 000 e viene fornita una versione in lingua inglese, con leggere modifiche della leggenda, stampata nella carta in italiano. Viene illustrata, per sommi capi, l'evoluzione delle conoscenze geologiche sull'area dell'Adamello ed il modo di riportare sulla Carta i dati geologico-petrografici frutto di nuove revisioni e di nuovi rilevamenti. Vengono discussi in particolare gli aspetti riguardanti la petrologia ignea, il metamorfismo di contatto, la stratigrafia e le strutture tettoniche. La bibliografia si riferisce alle pubblicazioni anteriori al 2001, ed è integrata con un elenco delle carte geologiche esistenti e con una lista di numerosi lavori inediti riguardanti la geologia e la petrografia dell'Adamello.

P a r o l e c h i a v e : *carta geologica del batolite dell'Adamello, magmatismo terziario nelle Alpi, Provincia ignea periadriatica, petrologia delle rocce tonalitiche, stratigrafia del margine dell'Adamello, rocce filoniane, determinazioni dell'età, metamorfismo di contatto.*

INTRODUCTION

The current geological map of the Adamello batholith by Callegari, Dal Piaz and Gatto, was printed in 1998. The aim of the present note is to make this document available to a wider public and to provide additional information on its evolution and significance. For this purpose, a slightly updated English version is given of the original Italian legend as printed on the map. The focus of the current geological map is centred on the igneous units of the Adamello batholith and on surrounding rocks, particularly the Paleozoic to Mesozoic cover of the Southalpine basement. The new Adamello map is the first coherent, uniform modern representation of the Adamello geology, after the 1:75 000 geological map compiled by Salomon and published almost a century ago (1908-10). On the official geological maps issued in the meantime by the Italian Geological Survey, the Adamello batholith covers areas on four different sheets. These maps, on the 1:100 000 scale, were produced over a span of more than 20 years (1948-1970), thus reflecting significant changes in geological knowledge. The larger scale of the current map (1:50 000) allowed more detailed representation of geological features, particularly of the igneous units and sedimentary border rocks. Only with respect to crystalline basement lithologies does detailed knowledge still largely correspond to the information provided by the maps and notes of the Italian Geological Survey.

Other objectives of the present note are to summarise briefly the long history of the current map, as well as of important steps in the evolution of geological knowledge on the Adamello area. Attention also focuses on results of recent research on the Adamello geology. For this purpose, summaries are given of the main steps in the evolution of geological maps of the Adamello sector, ideas on the origin of the Adamello magmas, the stratigraphy and tectonic structures of the border rocks, and aspects of contact metamorphism. Further information may be found in the references, including results which became available after the main phase of data compilation for the present map. Lastly, a list is provided of numerous unpublished reports on geological aspects of the Adamello area. The reports are kept in the libraries of the Mineralogical-Petrological and Geological Departments of the University of Padova and at the Department of Earth Sciences at ETH Zürich.

NOTES ON THE HISTORY OF THE PRESENT MAP

In 1937, Angelo Bianchi and Giambattista Dal Piaz - directors of the Mineralogical and Geological Institutes at the University of Padova - published a remarkable geological map on the scale of 1:12500 of the Bazena-Mt. Frerone area in the southernmost Adamello massif. This study opened a new era in the geological and petrographical exploration of this well-known Tertiary batholith. The map illustrated for the first time the complex internal architecture of the batholith and the intricate structural relationships between individual igneous bodies, and was accompanied by explanatory notes and an atlas.

In the following years, Bianchi and Dal Piaz extended their field work to other sectors of the massif, although their activity came to a prolonged halt during the Second World War. Upon resuming their scientific activity, Bianchi and Dal Piaz initiated a new study on the Adamello-Presanella igneous massif and country rocks by means of extensive field surveys and laboratory work. The project benefited from the financial support of the Italian National Research Council (C.N.R.). Until the end of the 1960s, many senior and young researchers and numerous students were involved in the project. Among these were the following: B. Accordi, C. Adami, A. Alberti, S. Borsi, M. Cadrobbi, E. Callegari, A. Cavinato, G. Cevales, D. Colbertaldo, N. Cortellazzo, L. De Marco, R. De Pieri, I. Dieni, E. Locardi, G. Fenoglio, G. Ferrara, F. Ferrasin, O. Hieke Merlin, P.G. Jobstraibizer, E. Justin Visentin, S. Lorenzoni, R. Malaroda, A. Masperoni, L. Masperoni, S. Morgante, G. Ogniben, A. Riedel, F.P. Sassi, G. Schiavinato, E. Semenza, C. Viterbo, B. Zanettin and G. Zirpoli.

The wealth of new geological and petrological data collected until the second half of the 1950s convinced Bianchi and Dal Piaz that the time was ripe for compiling a new geological map of the Adamello massif and its surroundings, on a scale of 1:50 000. The task of compiling and drawing of the map was assigned to Dario Locatelli, assisted by Dal Piaz and Dieni. Locatelli carefully assembled the original field maps produced over several years by researchers and students. This work was in an advanced stage when, in the mid-1960s, Locatelli left the university. The compilation of the geological map thus came to a first significant halt. Meanwhile, Bianchi and co-workers had improved knowledge of the internal structure of the igneous complex, and its inferences had to be dealt with in the Adamello map. However, in 1970, Angelo Bianchi suddenly died. This was a major blow to the project and caused a second long halt.

Ten years later, the scientific council of the C.N.R. "Centro di Studio per i Problemi dell'Orogeno delle Alpi Orientali" at the University of Padova was approached by its chairman Dal Piaz, with a new proposal for the completion of the 1:50 000 Adamello map. The scientific value of the still incomplete manuscript map was reaffirmed by the C.N.R. council and E. Callegari (University of Torino) was entrusted with completing the project. A request for financial support was approved in May 1981.

In the meantime, the body of researchers from different institutions and potentially interested in the publication of the Adamello map was considerably enlarged and many of them met in Padova (February, 1982): F. Bakos (Agip); A. Castellarin (University of Bologna); A. Boriani, M. Gaetani, G. Schiavinato (University of Milano); Gb. Castiglioni, Gb. Dal Piaz, G.O. Gatto, B. Zanettin (University of Padova and C.N.R.); A. Boni, G. Cassinis, G.F. Peloso, P.L. Vercesi (University of Pavia and C.N.R.); R. Malaroda, E. Callegari (University of Torino); S. Morgante (University of Trieste). These colleagues were asked for their original cartographic contributions on selected sectors of the Adamello area. During the same meeting, it became clear that the legend of the Adamello map had to be updated by improving the chronostratigraphic approach with modern formational criteria. However, this implied further field work and modification of existing drafts, so that the printing of the map was inevitably delayed. Todesco of the technical staff at the Geological Institute of University of Padova, was appointed to implement the new data and the drawing of the final map. For the igneous units, Todesco was assisted by Callegari, and for the basement and cover rocks by Gatto. Although the revision started immediately, it turned out to be time-consuming, especially because previous formational subdivisions were available only for parts of the rocks of the Adamello border zone. Once again, the compilation of the map was slowed.

However, good can come from evil: in the meantime a great amount of new geologic and petrographic data had been collected in the southern Adamello area, thanks to a co-operative research program lead by E. Callegari and V. Trommsdorff and developed between the Petrographic Institute of the University of Torino and the Institute of Mineralogy and Petrography of ETH Zürich. Between 1979 and 1991, a group of ETH students, engaged with their diplomas and Ph.D. theses, re-mapped vast crucial areas of the southern, western and north-western Adamello border, producing important results on both the geology and the petrology of the Adamello massif. In addition, new information on the age of emplacement and the isotopic compositions of the main igneous Adamello bodies were provided by another cooperative research program including the Petrographic Institute of the University of Torino and the C.N.R. Radiometric Laboratory in Pisa, headed by G. Ferrara and S. Borsi. The internal structure of the Adamello batholith as previously recognised by Bianchi, Dal Piaz and co-workers was largely confirmed and reinforced by these new data.

In 1985, the *Società Elaborazioni Cartografiche* (SELCA) at Florence was entrusted with the printing of the map. It was agreed that, within one year of submission of the final drafts, the map would be issued as a single large sheet. At that time, it seemed as if we were within a stone's throw of the long-awaited end of the enterprise. However, an unexpected chain of unlucky events again delayed completion of the map, originally scheduled for the end of 1990. Efforts by Callegari and Gatto to finalise the map, in order to present at least the proofs in time for the ninetieth birthday of Dal Piaz in September 1994, were again unsuccessful and in the following year Dal Piaz died. He had devoted so much of his life to the Adamello map, but was in the end unable to see the final product! This was another major blow to the history of the map, but the nadir was still not reached. One year later, Gatto died unexpectedly. He had been liaising with SELCA and was co-ordinating the final contributions to the map. Fortunately, Giorgio V. Dal Piaz soon took over these duties and, in 1998, the Adamello map was finally ready for printing.

The work initiated many decades ago by Bianchi and Dal Piaz is now concluded. This was possible only thanks to the help of numerous colleagues, first of all those who contributed with their original maps. Their names are indicated in the map inset giving details of the geological survey ("*Quadro rilevatori*"). Special thanks go to the Adamello group of ETH Zürich, headed by Volkmar Trommsdorff. The modern data produced by this team substantially contributed to the revision of the Adamello map. Peter Ulmers' surveys were essential for the cartographic interpretation of the mafic rocks in the southern Adamello area. Thanks also go to the director of the C.N.R. laboratory in Pisa, Giorgio Ferrara, and to all members of his scientific staff. The following deserve special acknowledgements: G.B. Castiglioni for revisions of the Quaternary deposits; F. Bakos and G. Cassinis, for helpful suggestions on Permian stratigraphy; A. Boni, A. Castellarin, G.F. Peloso and P.L.Vercesi, for their maps of the sedimentary formations east of the Adamello batholith; S. Morgante, for his map of the igneous rocks north-west of Lago della Vacca; and S. Martin for her help on the Austroalpine and Southalpine basements and some small igneous intrusions along the Giudicarie Line. Warm thanks also go to the draftsmen of the map, D. Locatelli and F. Todesco. A special acknowledgement goes to W. Hansmann (Zürich) for his contribution on dating the Adamello rocks, who unexpectedly died during the final stages of preparation of these notes. Lastly, we would like to thank Giorgio Vittorio Dal Piaz for his continued encouragement and support.

IGNEOUS PATTERNS IN THE ADAMELLO BATHOLITH AND THEIR REPRESENTATION ON GEOLOGICAL MAPS

The Adamello igneous massif is the largest body among the numerous Tertiary intrusions in the Alps which are scattered along the Insubric (Periadriatic) Line. Salomon (1897) considered these and other igneous bodies as a cogenetic suite of plutons and parts of a "Periadriatic igneous province". In Salomon's (1903) view, the Adamello intrusion is a particular type of funnel-shaped igneous stock, for which he coined the term "ethmolith" (see Brack, 1985, for details and a short discussion). Bianchi and Dal Piaz used expressions such as "Adamello igneous massif" or "Adamello pluton". Callegari (1985) preferred the term "Adamello batholith", to account for its large aerial extension of approximately 670 km^2 and the complex internal structure of the igneous massif.

A petrographic description of plutonic rocks from the Adamello area was published by Vom Rath (1864). Based on field observations as well as petrographic and chemical results, Vom Rath coined the new rock name "tonalite", named after the Tonale Pass area north of the Adamello massif (but erroneously referred to Mt. Tonale outside the Adamello intrusives) and clearly described the widely varying proportions of hornblende and biotite in the Adamello tonalites. *The first coherent geological map* (1:75 000 scale) of the entire Adamello massif and its surroundings was published by Salomon in his monumental memoir *"Die Adamellogruppe"* (1908-1910). From him and other sources (e.g., Hammer and Trener, 1908), we know of the existence, at the *Geologische Reichsanstalt* in Vienna, of an unpublished hand-coloured map, on the 1:75 000 scale by Stache and co-workers. During the very last period of his field survey, Salomon was allowed to consult the Stache map, but only a few, rather irrelevant details could be adopted for his own map. Instead, the geological surveyors Hammer and Trener had access to the Stache map for their own 1:75 000 geological survey of the northernmost part of the Adamello batholith (Fig. 1). Salomon's map shows a fairly accurate picture of the stratigraphy, especially of the Permian-Triassic cover rocks lying unconformably on the phyllitic basement. The map also elucidates the cross-cutting relationships between the intrusive mass and the border rocks, as well as the bedding attitudes of strata at some distance from and along the igneous contacts. On the basis of mineralogical or textural criteria, Salomon described different types of magmatic rocks such as normal tonalite, border facies tonalite, fine-grained acicular tonalite and very coarse-grained tonalite ('*Riesentonalit*'). However, none of these petrographic distinctions were indicated on his map.

Trener (1912) was *the first who clearly recognised the composite nature* of the Adamello mass. In Trener's view, the Adamello pluton is a succession of six main intrusions, for which a chronological order could be established (Fig. 2). The 'granitic to granodioritic' masses of Corno Alto and Sostino on the eastern border of the batholith were considered as the oldest intrusions, followed by mafic ('hornblende rocks') and tonalite magma pulses. Granitic intrusives and aplite-pegmatite dykes or apophyses were thought to be the last members in this magmatic sequence. Based on textural differences, Trener recognised and mapped two separate large tonalitic masses, *i.e.*, the fine-grained "Mt. Re di Castello tonalite" to the south and the coarse-grained "Adamello tonalite" to the north. The contacts between the two tonalites are sharp, and Trener's observations on cross-cutting relationships clearly pointed

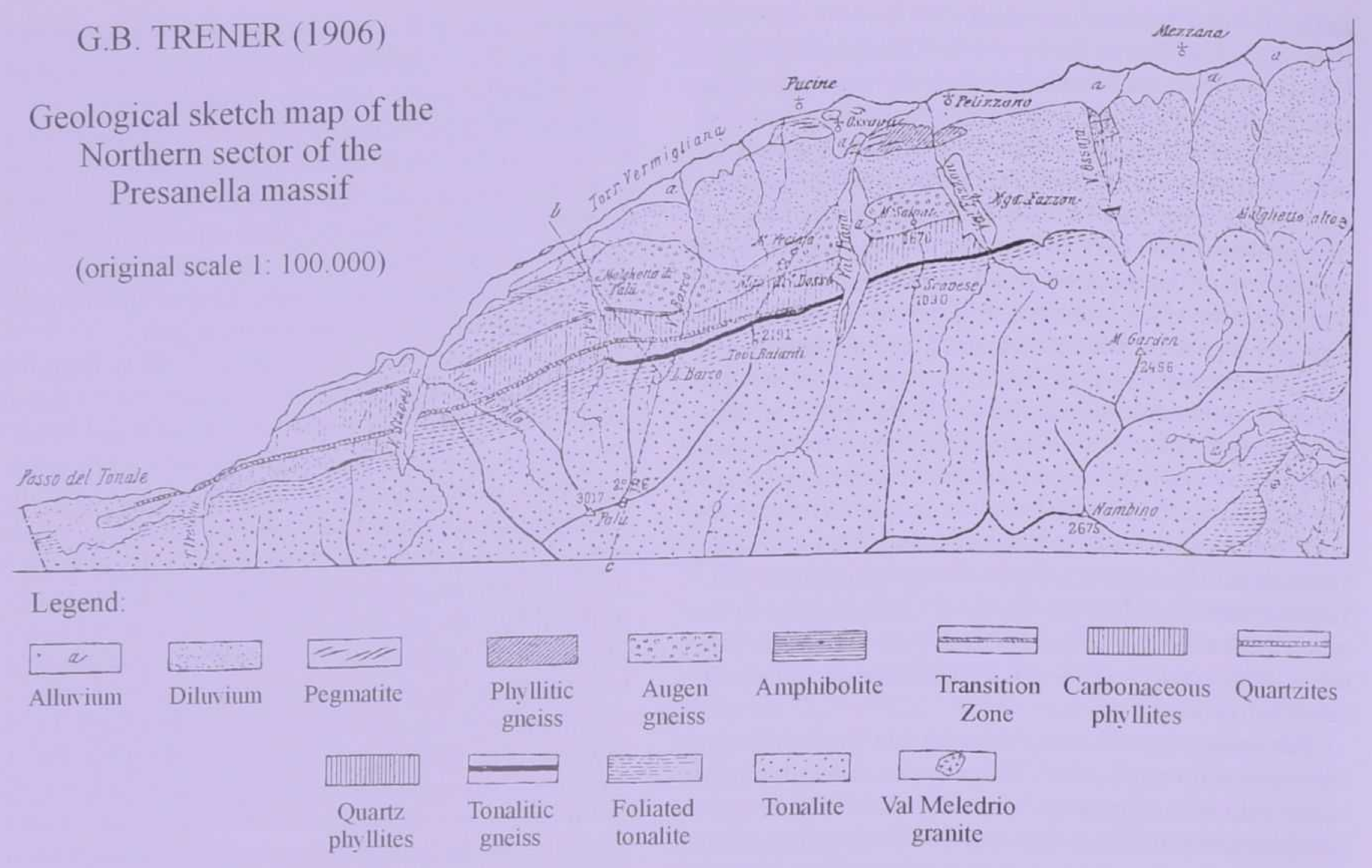


Fig. 1 - Textural varieties of tonalite (massive, foliated, gneissic) as distinguished by Trener (1906) in northern Adamello batholith. Note that Trener did not indicate Tonale Line, as recognised by Salomon since 1891 (1891c, see also 1901).

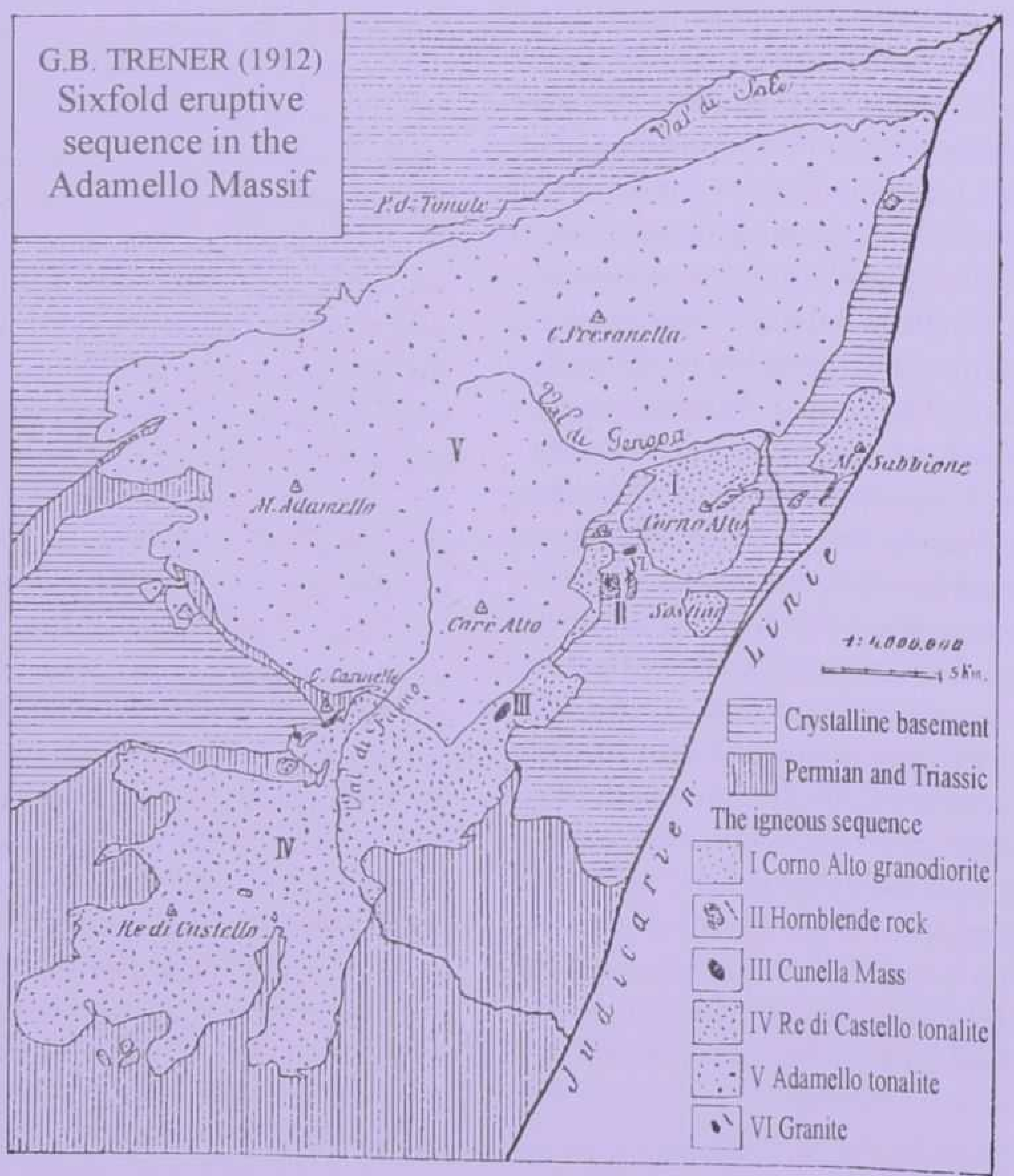


Fig. 2 - Distribution and sequence of emplacement of main igneous masses in Adamello batholith according to Trener (1912, fig. 4): note sharp boundary between Mt. Re di Castello and Adamello tonalite.

to the younger relative age of the "Adamello tonalite" (Fig. 3).

Bianchi and Dal Piaz (1937a) also *demonstrated a composite structure inside the Mt. Re di Castello mass.* Their 1:12 500 geological map of the region between Val Stabio and Val Caffaro in southern Adamello (Fig. 4) showed that, even within a relatively small area, Trener's Mt. Re di Castello tonalite is in reality a mosaic of several igneous bodies crossed by numerous dykes. Complex field relationships were clearly documented in a comprehensive atlas which appeared in the same year (1937b). Bianchi and Dal Piaz interpreted the magmatic rock sequence as the products of igneous differentiation. Over ten years later, Bianchi and Dal Piaz (1948a) published an outstanding paper with a new sketch-map of the entire Adamello massif, on the 1:250 000 scale. The paper summarises the main results of research by Bianchi and Dal Piaz and co-workers for the survey of sheet no. 20 ("*Mt. Adamello*") of the 1:100 000 Geological Map of Italy. A few years later, the "*Magistrato alle Acque di Venezia*" issued this sheet, which had been produced under the supervision of Giorgio Dal Piaz (1953), the father of Gb. Dal Piaz. The sketch-map by Bianchi and Dal Piaz (Fig. 5) is a clearcut evolution of Trener's map. The "Adamello tonalite" of the latter author had been split into two parts, separated by a belt of 'granodioritic to granitic' rocks extending from Val d'Avio to the lower Val di Genova. The two main tonalite parts were still considered as a single mass, renamed "Adamello-Presanella Tonalite". Granodioritic rocks were also recognised in the Mt. Bruffione area (southern Adamello). Contrary to Trener (1910b, 1912), Bianchi and Dal Piaz (1950) considered the Corno Alto mass to be younger than the tonalitic rocks. Bianchi and Dal Piaz's map is also remarkable for (a) the representation of many gabbroic bodies scattered along the borders of the batholith, especially in the Mt. Re di Castello area, and (b) the overall distribution of igneous rocks with parallel or foliated textures.

Towards the end of the 1960s and following the new proposals for the nomenclature of igneous rocks by Streckeisen (1967), Callegari was appointed by Bianchi with a revision of the nomenclature of the Adamello igneous rocks. A detailed petrographic analysis was carried out on the rich collection of thin sections of Adamello rocks at the Mineralogical and Petrographical Institute in Padova. From this study, systematic differences emerged in both the mineralogy and the texture of the tonalitic rocks, depending on their location within the batholith. Observations made between 1965-1969 by Bianchi and Callegari on trips across the massif confirmed that, in most cases, such differences could also be recognised on the scale of a hand specimen. As a result, Bianchi *et al.* (1970) were able to draw a new geological sketch-map of the entire batholith (Fig. 6), showing the existence in it of four large, mainly tonalitic superunits (Mt. Re di Castello, Adamello, Presanella, Corno Alto), each consisting of a discrete number of relatively large intrusions, as follows:

1. *Mt. Re di Castello superunit*: (a) biotite-hornblende tonalite (*Mt. Re di Castello* type); (b) biotite-hornblende granodiorite to leucotonalite (*Lago Boazzo* type); (c) biotite granodiorite (*Mt. Bruffione* type); (d) biotite leucoquartzdiorite (*Val Fredda* type); (e) trondhjemite to granite (*Malga Ervina* type).

2. *Adamello superunit*: (a) biotite-hornblende tonalite (*Western Adamello* type); (b) biotite quartzdiorite of Central Adamello, including three different varieties, *i.e. Val d'Avio* type, *Central Peaks* type, and the middle to lower *Val Genova* type.

3. *Presanella superunit*: (a) biotite-hornblende tonalite (*Central Presanella* type); (b) biotite-hornblende tonalite (*north-eastern Presanella* type); (c) hornblende-bearing biotite-quartzdiorite (*Val Nambrone* type).

4. *Corno Alto superunit*: (a) muscovite-bearing biotite leucoquartzdiorite (*Corno Alto* type); (b) hornblende-bearing biotite granodiorite (*Sostino* type).

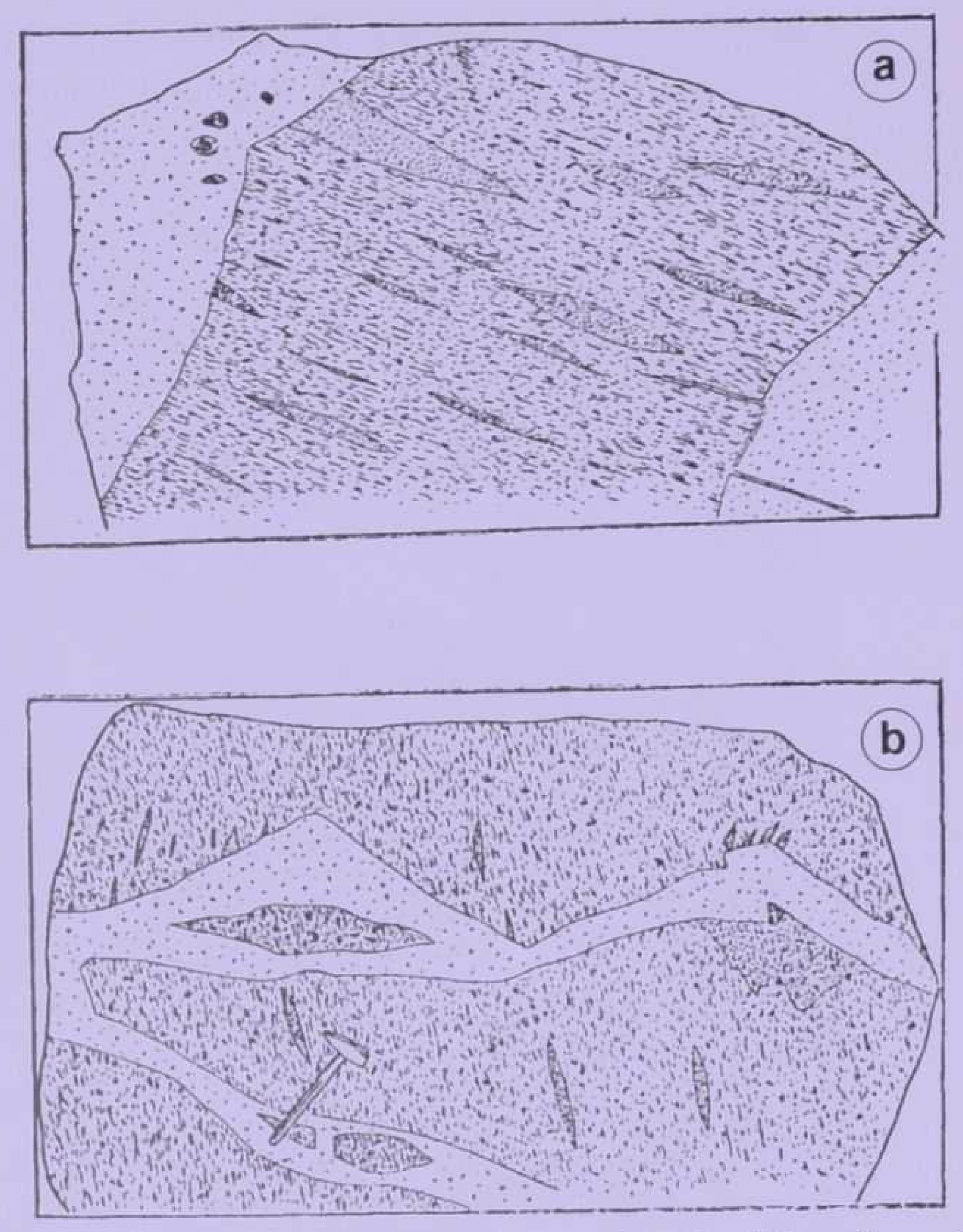


Fig. 3 - Examples of contacts between Mt. Re di Castello and Adamello tonalite (from Trener, 1912, figs 1, 2): a) Cross-cutting relationships between younger massive Adamello tonalite (light dots) and older foliated Mt. Re di Castello tonalite. Foliation is emphasised by parallel orientation of disk-shaped dark inclusions. b) Veins of massive Adamello tonalite cross-cut foliated Mt. Re di Castello tonalite.

The principal mineralogical and textural features of the various igneous units were exhaustively discussed in the memoir by Bianchi *et al.* (1970). Callegari and Dal Piaz (1973) illustrated the field relationships between the various masses of the batholith, and concluded that the Adamello superunit was preceded by the Mt. Re di Castello superunit, but that it was older than the Presanella superunit. Because of the tectonic nature of the contacts between the Corno Alto superunit and the lower Val Genova quartzdiorite, the chronological position of the Corno Alto superunit still remained an open question. Nevertheless, following Bianchi and Dal Piaz (1950),

A. BIANCHI and Gb. DAL PIAZ (1937)
Geological map of Southern Adamello Massif (detail)
(original scale 1:12 500)

A. Mafic dikes
B. Scythian
C. Anisian
D. Upper Anisian
E. Dolomites and dolomitic limestones of the "Esino Formation" (contact metamorphosed Ladinian)
F. Norian

1. Tonalites
2. Foliated tonalites
3. Porphyritic granites and granodiorites
4. Diorites
5. Gabbros and olivine-hornblendites

Fig. 4 - Map showing intricate relationships between differing types of intrusive rocks in Mt. Frerone - Lago della Vacca area in southern Mt. Re di Castello superunit (from Termier and Termier, 1956, Plate 36, interpreted after Bianchi and Dal Piaz, 1937a). Note presence of rocks with igneous foliation. Various generations of dykes are also indicated.

whose opinion was in apparent agreement with available radiometric ages on biotites (Ferrara, 1962, Borsi *et al.*, 1966), a younger age (with respect to the tonalites) was assumed for the Corno Alto mass.

A systematic geochronological study by Del Moro *et al.* (1985a) confirmed the chronological sequence of these superunits as indicated above, with the notable exception of the Corno Alto mass (Fig. 7). Isotopic age data suggest that: (a) the formation of the batholith occurred within a time-span of around 10-12 Ma, and (b) that ages decrease progressively from the Mt. Re di Castello superunit (41-38 Ma) to the Presanella superunit (32-29 Ma). The iso-

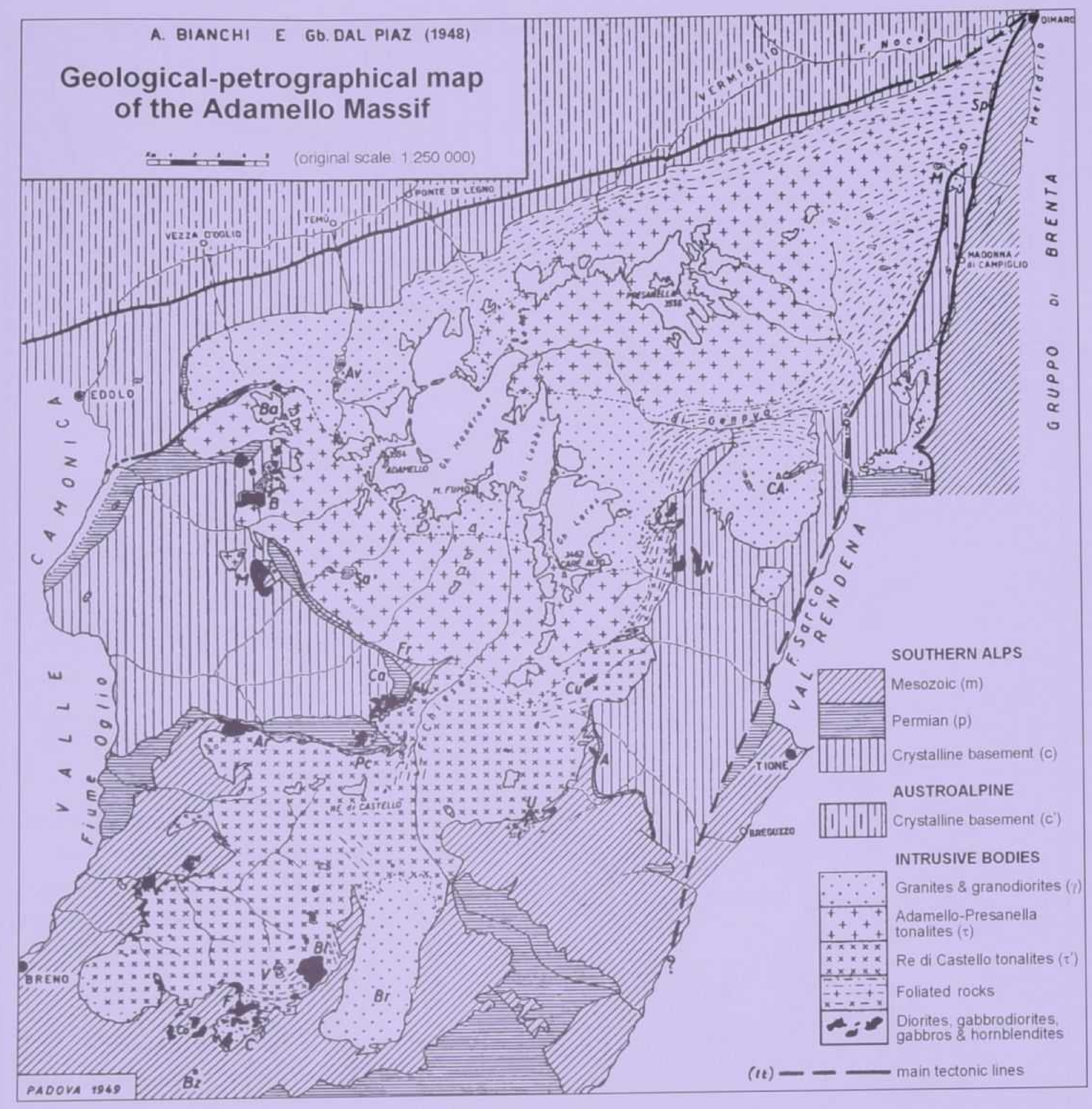


Fig. 5 - Distribution of main tonalite-granodiorite and gabbro units in Adamello batholith, after Bianchi and Dal Piaz (1948a). Foliated lithologies include rocks characterised by either igneous and/or tectonic foliation, the latter being developed in zones close to Tonale and Giudicarie Lines in northern and eastern sectors of batholith.

topic age data obtained on Corno Alto rocks gave different values for coexisting biotite and muscovite (33-34 Ma and 41-42 Ma respectively). The age of emplacement of the Corno Alto mass was considered as being close to the muscovite ages. The younger biotite ages may be the result of very slow cooling or resetting of the isotopic system during subsequent low-temperature tectonic processes along the Giudicarie fault. The period of emplacement of the Corno Alto mass largely corresponds to the age of the oldest rocks of the Mt. Re di Castello superunit, thus supporting Trener's (1910b) interpretation of the 'old' age of the Corno Alto mass.

In a thorough geochemical study of the Rb-Sr systematics of the Adamello rocks, Del Moro *et al.* (1985b) clearly established that each of the igneous superunits recognised by Bianchi *et al.* (1970) shows characteristic ranges of Sr initial ratios, with only minor overlap (Fig. 8). Again, the only exception is the Corno Alto mass, the Sr initial ratios of which match the range of values typical for the Mt. Re di Castello superunit. This is further evidence that the Corno Alto mass must be considered as an igneous member of the Mt. Re di Castello superunit and it is shown as such on the geological map. Del Moro *et al.* (1985a,b) also showed that the rocks of the Avio mass are clearly distinguished from those of the other units of the Adamello mass, both for their younger age and their characteristically high values of the strontium initial ratio. The Avio mass was, therefore, now considered as an independent superunit. Its aerial extent was modified to include also the biotite tonalite of the middle Val di Genova and partly those of the lower valley, the age, mineralogy, texture and isotope composition of which are identical with those of the Avio biotite tonalites. In the current geological map, the names of the plutonic rocks are given according to the rules of the IUGS Subcommission on the systematics of igneous rocks (Le Maitre, 1989). Following earlier proposal by Streckeisen (1967), Bianchi *et al.* (1970) called the Avio rocks "biotite quartzdiorite", here renamed "biotite tonalite".

The recognition in the Adamello batholith of four large

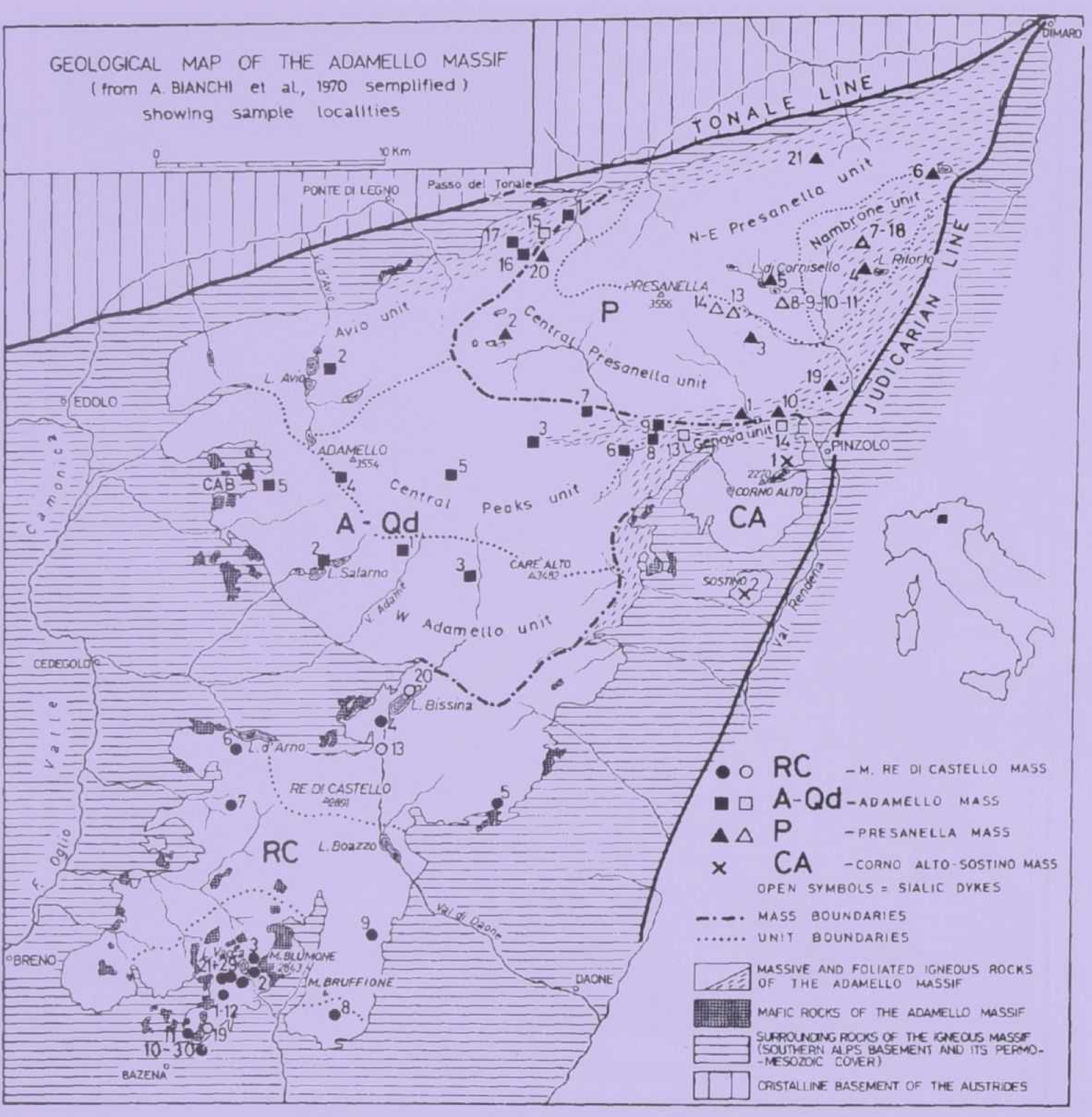


Fig. 6 - Main superunits and related units (indicated here as "masses") in Adamello batholith, as distinguished on basis of textural properties by Bianchi *et al.* (1970). Figure is taken from Jobstraibitzer *et al.* (1985), and symbols indicate sample localities referred to in this article.

igneous superunits (Mt. Re di Castello, Adamello, Avio, Presanella) was further strengthened by data on rock geochemistry (Macera *et al.*, 1985) and mineral chemistry (Jobstraibizer *et al.*, 1985). Each superunit shows a composite internal structure, consistent with a pattern of igneous differentiation with gabbroic rocks usually among the oldest and granitic dykes as the youngest products. With the exception of the Mt. Re di Castello area, knowledge of the internal structure of the other igneous superunits is still fragmentary.

The lithological members recognised in the *Presanella superunit* correspond to those originally described by Bianchi *et al.* (1970), as outlined above.

The *Avio superunit* is still the least well-known. A few gabbroic intrusions in the surrounding basement rocks (e.g., at Corno d'Aola, see Adami, 1963; Baita Pozzuolo; Passo Tonale) are the only other rock-types which may be associated with the rather monotonous Avio biotite tonalite. Garnet-bearing Avio tonalite is found in some peripheral zones (e.g., Passo Gallinera).

The *Adamello superunit* comprises two large tonalitic masses, the Western Adamello Tonalite and the Central Peaks Leucotonalite. The contact or transition zone between these units is still poorly known. Gabbroic intrusions are located near the border of the Western Adamello Tonalite, e.g., at M. Marsèr (Zanettin, 1956), Lago Baitone (Cereghetti, 1988) and Malga Macesso (Dal Piaz, 1953).

The *Mt. Re di Castello superunit* has recently been restudied and re-mapped in more detail by students from ETH Zürich and by British researchers (see references). In 1983, based on a field study in close co-operation with Ulmer, Brack (1985) presented *a first sketch-map of the Mt. Re di Castello mass,* showing its very complex internal structure (Fig. 9). A more detailed geological map of this superunit was compiled by Brack and Ulmer on the

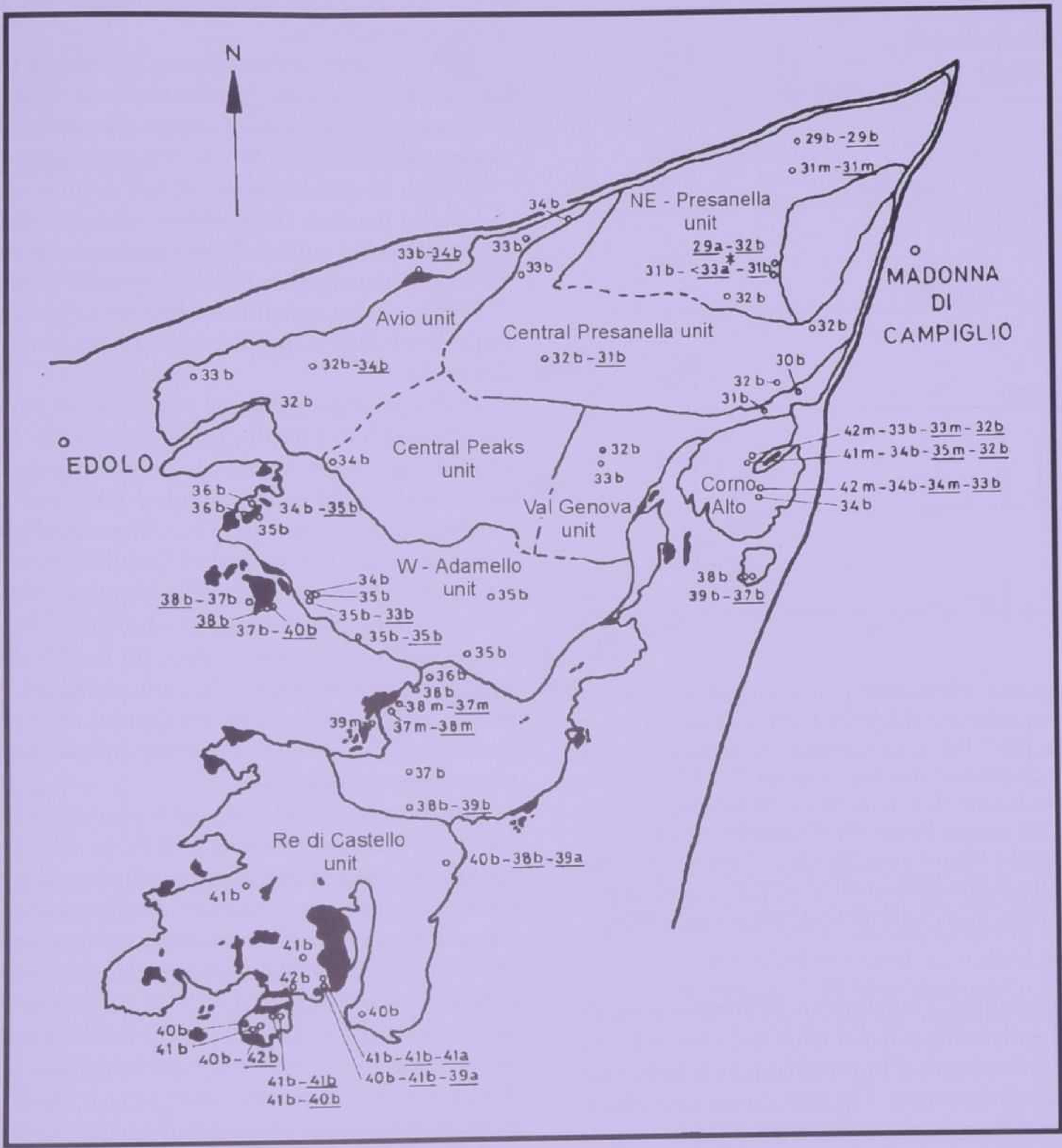


Fig. 7 - Distribution of isotopic age data of main igneous units in Adamello batholith (from Del Moro *et al.*, 1985a, fig. 6). Abbreviations: b, m = Rb/Sr age and b̲, m̲ = K/Ar age on biotite and muscovite respectively; a, a̲* = K/Ar and $^{40}Ar/^{39}Ar$ ages on hornblende.

scale of 1:25 000 (Brack, 1984). Much of this information was also incorporated in the current 1:50 000 geological map of the Adamello batholith. More than ten tonalitic to granodioritic igneous units are now recognised within the Mt. Re di Castello mass. Some of the small plutons show complex compositional and structural features (e.g., Val Fredda unit, Listino ring structure), resulting from interactions of physical and chemical phenomena that occurred in the solidifying magma during its emplacement. These include processes such as crystal fractionation, magma mingling, expansion and volume contraction, and overhead stoping (Brack, 1985; John and Blundy, 1993). Intrusions of mafic magma are concentrated along the border zones of the Mt. Re di Castello superunit. Some of these bodies were studied before 1970 by the Padova researchers (Bianchi and Dal Piaz, 1937c; Colbertaldo, 1940, 1950; Hieke, 1945; Malaroda, 1954; Callegari, 1963) and have been re-examined more recently (Morgante, 1972, 1981; Sonderegger, 1980; Schellhorn, 1980; Brack, 1980; Ulmer, 1982; Wersin, 1985; Mäder, 1983). In the southern part of the Mt. Re di Castello superunit, Ulmer *et al.* (1985) recognised two distinct stratified gabbroic complexes, *i.e.* the Val Fredda and Blumone gabbros, each characterised by different sequences of mineral crystallisation. Both masses were dismembered by subcontemporaneous to subsequent injections of magma, resulting in rock-types ranging from fine-grained gabbro to granodiorite or trondhjemite. In the present geological map, the two stratified mafic bodies are indicated as distinct units. Moreover, the stratified Blumone gabbro is separated from a sequence of heterogeneous rocks of predominantly gabbroic to dioritic composition, referred to as the "Blumone complex" by Ulmer *et al.* (1985).

Fine-grained acicular hornblende gabbro is predominant among the mafic rocks in the Mt. Re di Castello superunit, and similar types are also found in the border zone of the Adamello and Avio superunits. Textural uniformity alone does not necessarily imply a coeval age for

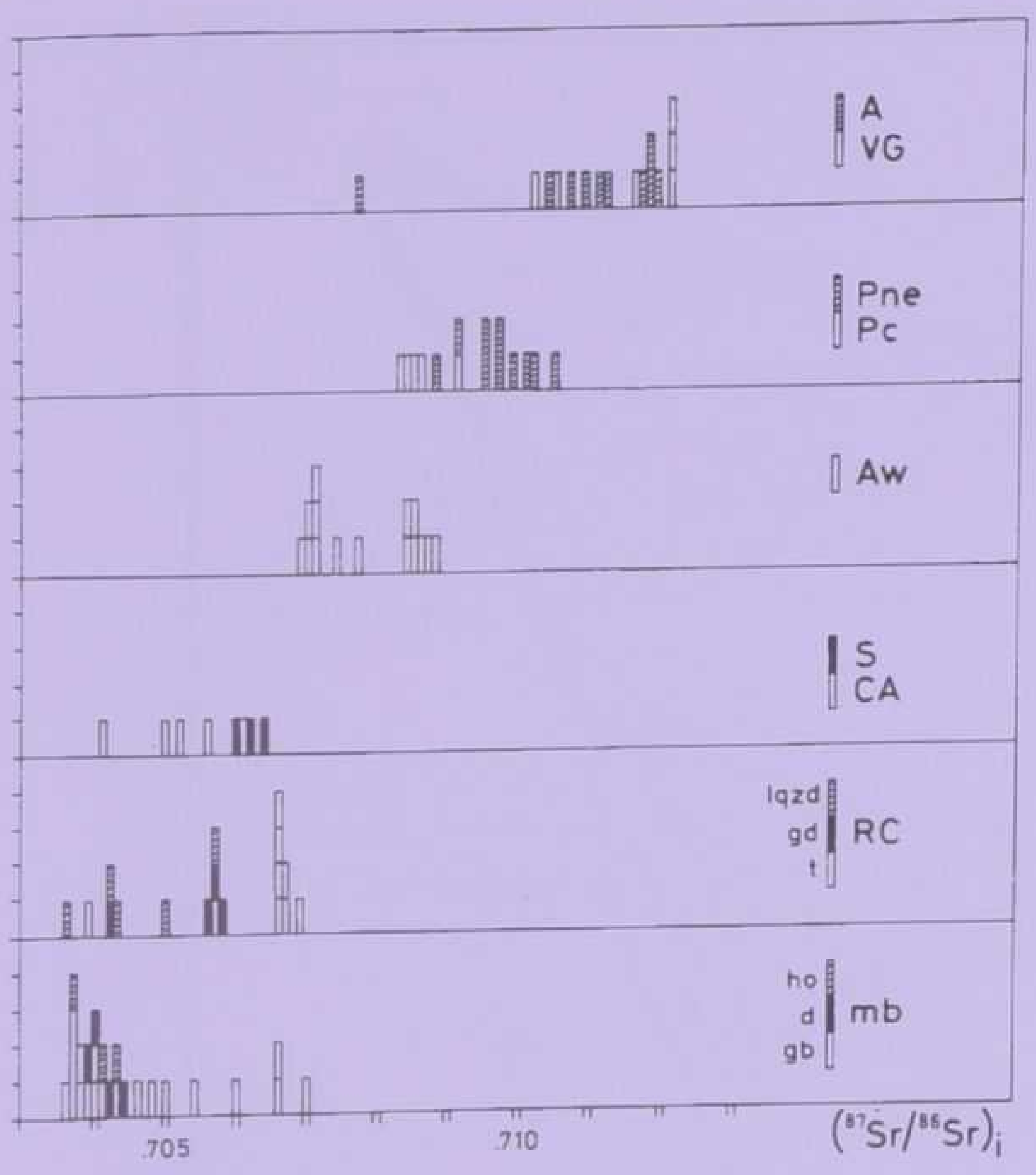


Fig. 8 - Histograms showing distribution of initial Sr isotope ratios in main superunits of Adamello batholith (vertical axis = number of samples). Values of radiogenic Sr increase for each unit from south-west to north-east (from Del Moro *et al.*, 1985b). Abbreviations: A = Avio; VG = Middle Val Genova; Pne, Pc = North-eastern Presanella, Central Presanella; Aw = Western Adamello; CA = Corno Alto; So = Sostino; RC = Mt. Re di Castello (t, tonalite; gd, granodiorite; lqzd = trondhjemite); mb = mafic masses (ho, hornblendite; d, diorites; gb, gabbros).

these gabbroic bodies. Therefore, in the present map, all fine-grained and mostly acicular gabbro is shown in the same colour, irrespective of its possible genetic links with different igneous superunits. The radiometric ages of several acicular gabbros are reported in the legend.

Numerous dykes crosscut the plutonic masses of the Adamello batholith and their surrounding rocks. Their composition ranges from picrobasaltic to granitic. Calc-alkaline lamprophyres are especially abundant in the Mt. Re di Castello area. Riva (1896, 1897), Salomon's first student, provided a petrographical and chemical characterisation of dykes in the Adamello massif. Subsequently, many authors added information on dyke rocks in the Adamello area. A list of 229 dykes was given by Salomon (1908-1910). Beside the evidently post-tonalitic dykes, Salomon postulated the presence of a suite of pre-tonalitic dykes. He also noted that the lamprophyres are younger than the aplites, a view shared by Bianchi and Dal Piaz (1937a,b,c). Petrographic data on dyke rocks may be found in numerous papers of the Padova school (e.g., Colbertaldo, 1942, 1950; Dieni and Viterbo, 1960, 1961; Callegari, 1963a,b) as well as in the reports of the ETH group (Brack, 1980, 1984; Ulmer, 1982, 1986; Rösli, 1982; Ulmer *et al.*, 1985). The existence of pre-tonalitic dykes was confirmed by Dieni and Viterbo (1960, 1961) and Callegari (1963). In the southern part of the Mt. Re di Castello mass (area of Mt. Frerone), a complex succession of dyke injections (Figs 10a,b) was mapped by Brack (1980, 1984). There are several generations, referring to three main episodes:

1. Pre-tonalitic dykes of possibly middle to late Triassic age; they cross the border rocks up to and including sediments of presumably Carnian age, and were deformed during pre-Adamello Alpine tectonic compression.
2. Pre- to syn-tonalitic dykes as precursors of the Adamello magma; these dykes crosscut the Alpine regional folds but suffered syn-magmatic deformation and contact metamorphism induced by subsequent intrusions.
3. Syn- to post-tonalitic undeformed dykes crosscutting both the intrusives and the contact metamorphosed border rocks.

In the present geological map, the pre-tonalitic dykes are grouped into a single class ("Porphyrite") irrespective of their age or petrographic composition. The syn- to post-tonalitic dykes are divided into four groups, according to their petrographic characteristics. The first group includes the so-called "undifferentiated dykes", *i.e.*, rocks which are texturally identical to the main igneous masses (tonalite, granodiorite). The second includes aplitic to pegmatitic dyke rocks. Picrobasaltic lamprophyre (without plagioclase phenocrysts) form a third group, which is older than another set of dykes with predominantly basaltic to andesitic composition but with phenocrystic plagioclase.

The distribution of foliated intrusive rocks is indicated in the map inset labelled *"Schema dei rapporti strutturali"*. On the geological map, foliations are shown only for the "Listino ring structure" in the southern Mt. Re di Castello superunit. This conspicuous feature was first reported by Brack (1985) and is perhaps related to a phase of 'ballooning' induced by the emplacement of the Listino leucotonalite in its core area. More recently, emplacement-related deformation structures of intrusive rocks in the Lago della Vacca area (southern Mt. Re di Castello superunit) were mapped in detail and interpreted by John and Blundy (1993).

EVOLUTION OF PETROLOGY AND ISOTOPE-BASED IDEAS ON THE ORIGIN OF THE ADAMELLO MAGMA

The magmatic origin of the Adamello batholith has never been questioned seriously. The wide thermal aureole and sharp discordant contacts with the surrounding basement and cover rocks provide convincing evidence for its magmatic emplacement in a shallow crustal environment. During the first half of the last century, most geologists considered the composite nature of the batholith to be a result of igneous differentiation processes (e.g., Bianchi and Dal Piaz, 1937c, 1948a). The role of magma contamination by *in situ* assimilation was considered to be irrelevant or of local importance, whereas study of the mafic rocks in the border areas became more and more important for unravelling the problem of the parent magma. Bianchi and Dal Piaz (1937c) considered the mafic rocks in the southernmost Mt. Re di Castello mass to be the product of gabbroic magma intrusions. Instead, Colbertaldo (1940) assumed that the Blumone gabbro may have originated from tonalitic magma by assimilation of

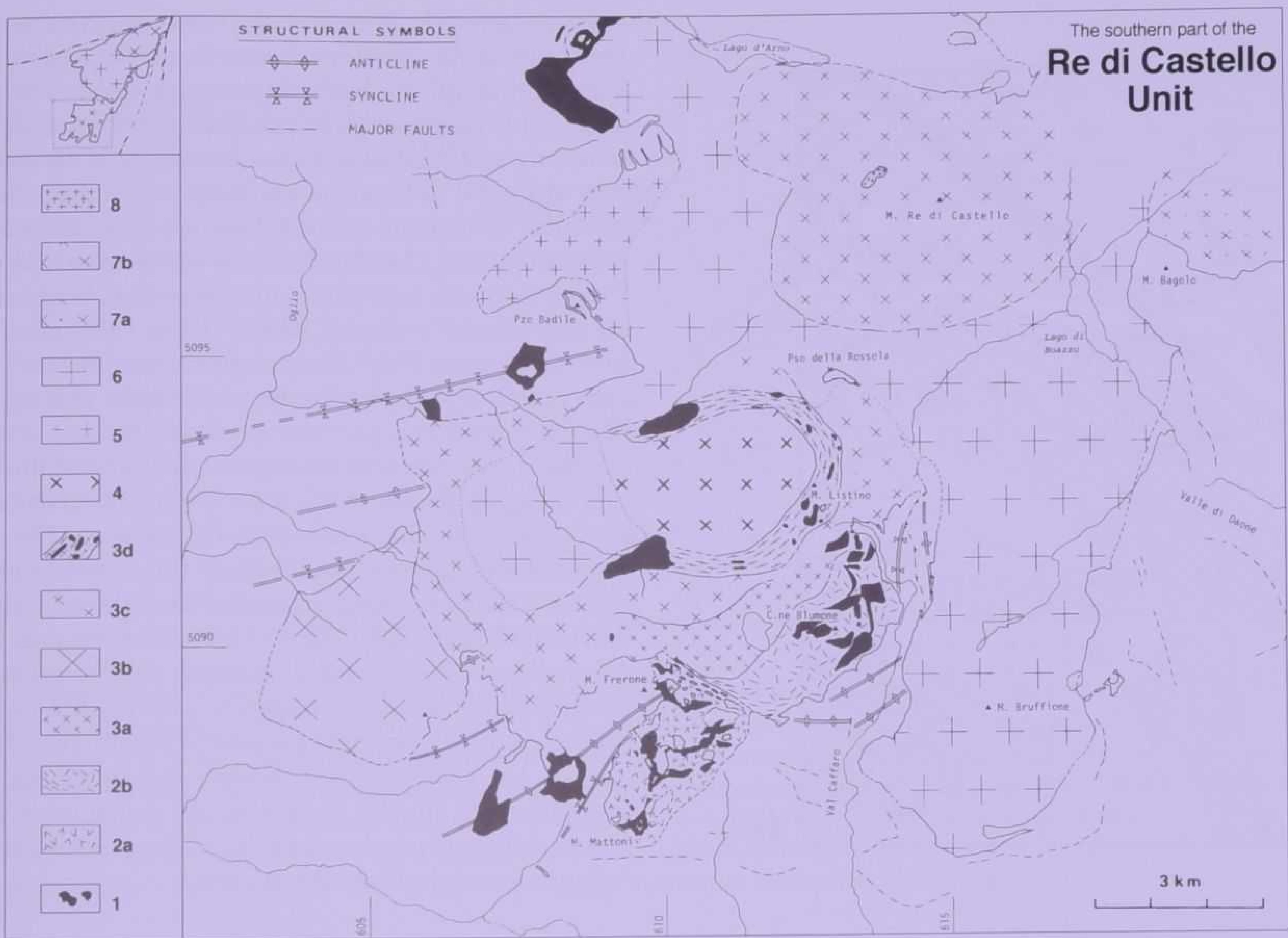
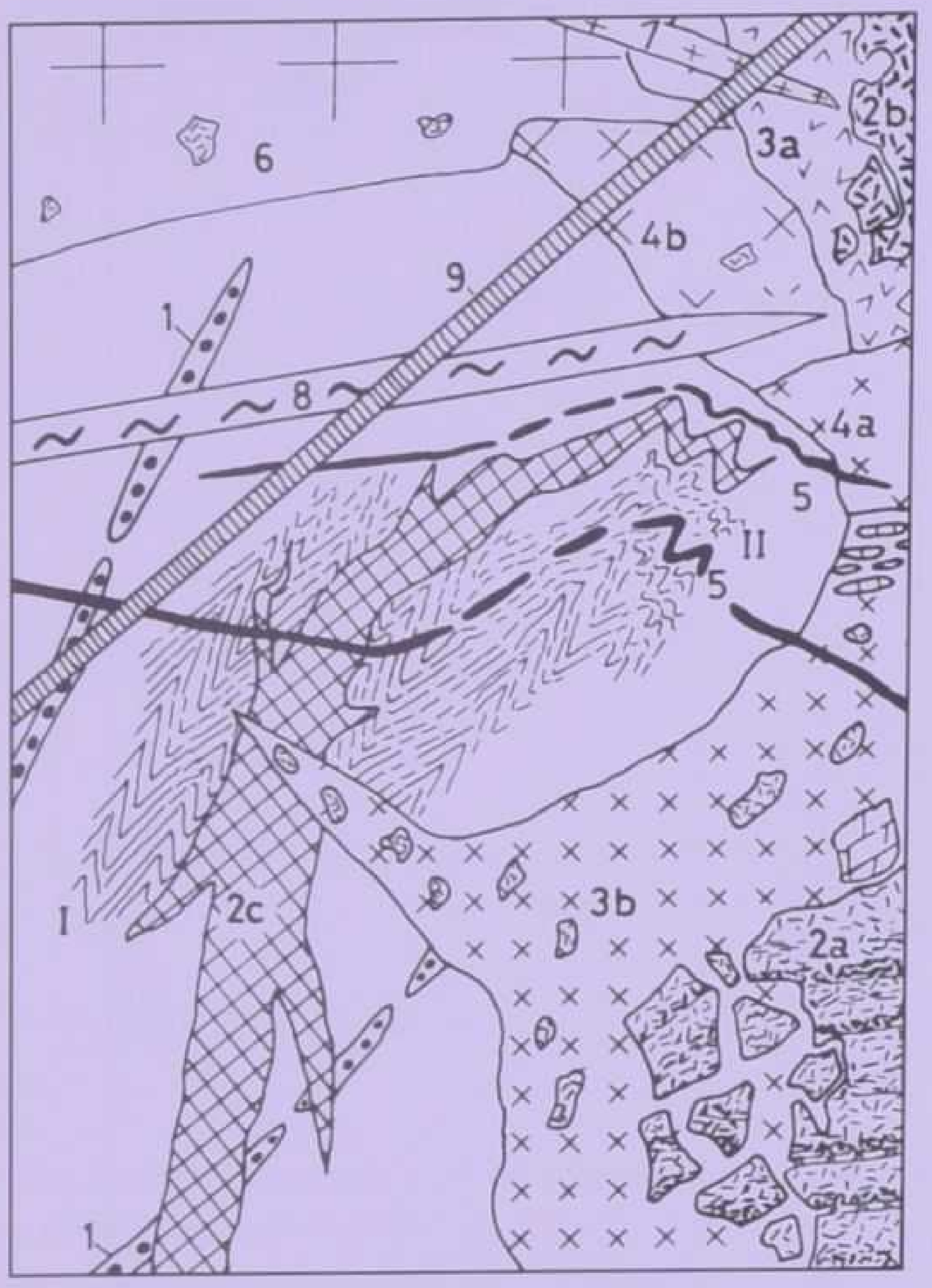


Fig. 9 - Sketch-map of internal structure of Mt. Re di Castello superunit (from Brack, 1985 and Ulmer *et al.*, 1985). Traces of pre-intrusive large-scale folds and of main and presumably syn-intrusive normal faults in border rocks are also indicated. Mapped plutonic units are listed in roughly chronological order, starting with oldest intrusives (1 and 2a,b are largely age-equivalent): 1. Gabbros; 2a. Val Fredda leucotonalite to trondhjemite; 2b. Blumone complex; 3a. Lago della Vacca tonalite; 3b. Alta Guardia tonalite; 3c. Several types of fine-grained tonalites; 3d. Listino ring structure; 4. Listino tonalite; 5. Badile granodiorite; 6. Bruffione-Lago Boazzo-Lago d'Arno granodiorite and leucotonalite; 7a. Val Bona tonalite; 7b. Mt. Re di Castello tonalite; 8. trondhjemite and granite.

Mesozoic carbonate rocks. Zanettin (1956; M. Marsèr) and Adami (1963; Val Seria) proposed a similar origin for the mafic bodies along the western and northern borders of the Adamello batholith. By contrast, on the basis of petrographic and petrochemical evidence, Callegari (1963b) showed that assimilation of carbonate rocks in tonalitic magma cannot explain the origin of the acicular gabbro at Cima Uzza (south-eastern Adamello).

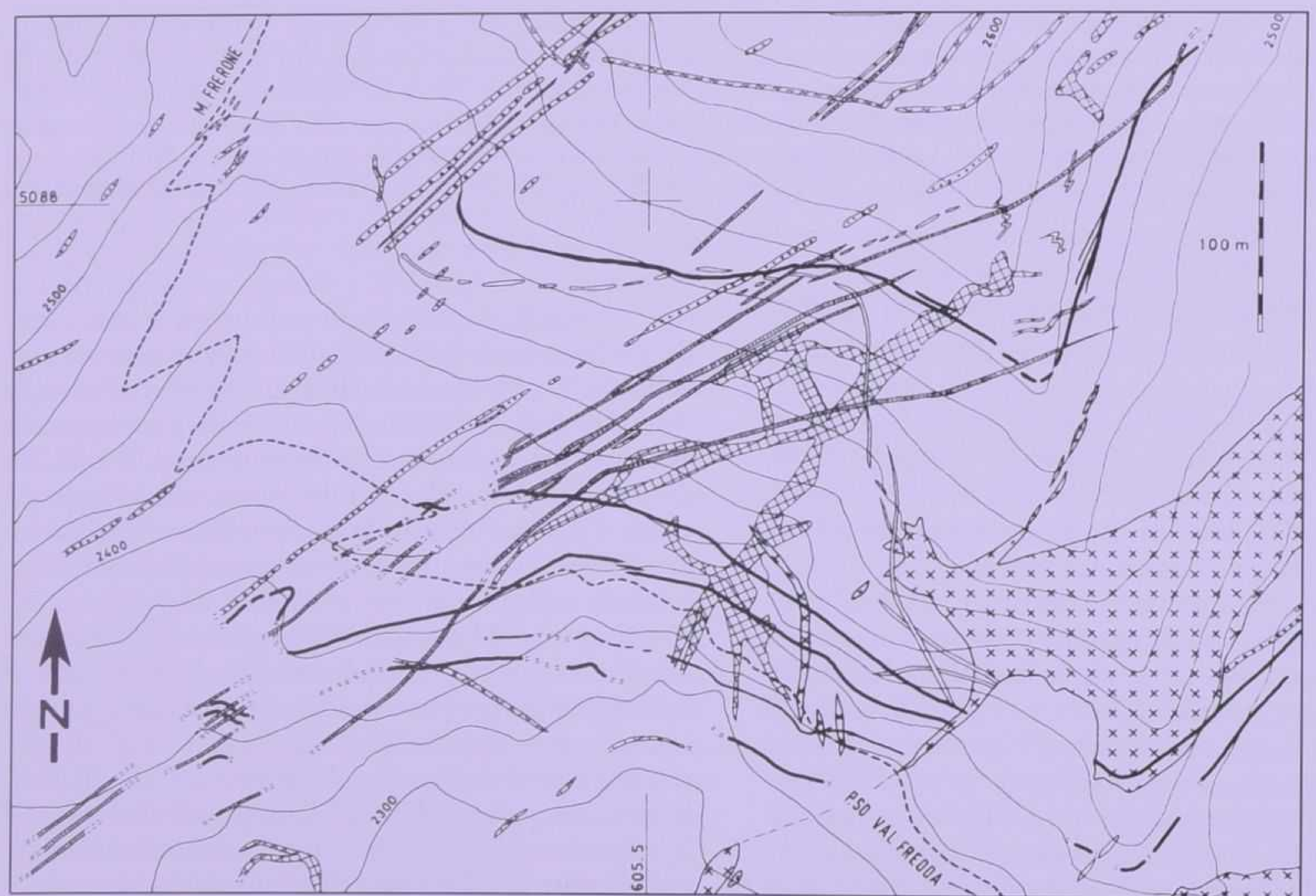
In the 1980s, the question of the origin of the Adamello gabbroic rocks was re-examined through systematic geochemical studies on the whole batholith. The results clarified the origin of both mafic and tonalitic-granodioritic rocks. Based on a positive correlation between strontium and oxygen isotopes, Cortecci *et al.* (1979) proposed two alternative models for the origin of the Adamello igneous rocks. The first is based on differentiation of a parent basaltic magma, with increasing incorporation of crustal material. The alternative envisages the melting of a chemically stratified crust. Reinterpreting the data of Cortecci *et al.*, Taylor (1980) concluded that the Adamello massif is a good example of magma evolution by crystal fractionation of a mafic magma, coupled with increasing assimilation of crustal material (AFC). Del Moro *et al.* (1985a) documented a stepwise increase in initial Sr isotope compositions from south-west to north-east, crossing the boundaries between various igneous superunits of the batholith. Moreover, bulk Sr contents decrease in the same direction. Del Moro *et al.* noted that gabbroic rocks behave in the same manner as tonalitic ones. The Mt. Re di Castello gabbros displays the lowest initial Sr isotope ratios, the values of which are within the range typical for mantle-derived magmas. By integration of Sr isotope systematics with radiometric rock ages, Del Moro *et al.* (1985b) proposed a model involving multiple intrusions of mafic magma modified by increasing degrees of crustal assimilation to generate tonalitic magma (Fig. 11). The amounts of assimilated material increase with the decreasing ages of the tonalite. A mantle source for the mafic rocks in southern Mt. Re di Castello was also assumed by Ulmer *et al.* (1985). Their conclusions relied on mineral chemistry and petrographic constraints.

The true nature of the parent magma was a related topic which received considerable attention after 1980. Using their own REE, Nb and Zr data, together with still unpublished radiometric results of Del Moro *et al.*, Dupuy *et al.* (1982) arrived at the conclusion that the Adamello parent magma was a melt similar to the high-alumina basalts of continental margins. On petrographical and minero-



(b)

chemical grounds, Ulmer *et al.* (1985) put constraints on the nature of the southern Adamello parent magma. They showed that: (a) the high-alumina acicular gabbro types were not primary melts in equilibrium with mantle compositions, and (b) that picrobasaltic dykes in the southern part of the Re di Castello superunit may satisfy the geochemical constraints required for a parent magma. The mineralogy and chemistry of this picrobasalt may be in equilibrium with a potential mantle source. Starting from such picrobasalt material, Ulmer (1986, 1988) carried out high-pressure and high-temperature experiments. The results did show that picrobasalt may coexist with a garnet-bearing mantle at a pressure of about 30 kbar, and that polybaric crystallisation accompanied by crystal fractionation may explain the rock associations observed in the southernmost Re di Castello area. Bigazzi *et al.* (1986) used a quantitative approach to interpret the evolution of trace elements and Sr isotopes, extended to all the lithologies of the Adamello batholith. Their conclusions were that: (a) the Adamello granitoids have a common parent magma, the composition of which corresponds to a Mg-rich tholeiite; (b) each intrusive unit was generated by different degrees of ACF, *i.e.*, combined assimilation and crystal fractionation processes; (c) the trace element distribution in the magma is more dependent on mineral fractionation than on composition of the assimilated crust.



(a)

Fig. 10a,b - Differing generations of dykes in southern Mt. Re di Castello superunit (from Brack, 1980, and Brack *et al.*, 1985): a) Detailed map of dykes in south-western slope of Mt. Frerone. b) Sketch of relationships between intrusive rocks and structures of border rocks (I: pre-intrusive chevron folds in Angolo Lst.; II. syn-intrusive disharmonic folds and boudins). Note that syn-intrusive deformation affects intrusives up to and including unit no. 5. Legend: 1. Pre-tectonic (pre-tonalitic) porphyrite dykes; 2a. Mattoni-Cadino-Frerone gabbro; 2b. Cornone di Blumone gabbro; 2c. small aplitic masses; 3a. gabbro to tonalite of "Blumone complex"; 3b. Val Fredda leucotonalite to trondhjemite; 4a. Lago della Vacca tonalite; 4b. Cima Terre Fredde tonalite; 5. sub-horizontal lamprophyre dykes; 6. Mt. Bruffione granodiorite; 7. Aplite/Pegmatite dykes; 8. hornblende gabbroic porphyrite; 9. sub-vertical lamprophyre dykes.

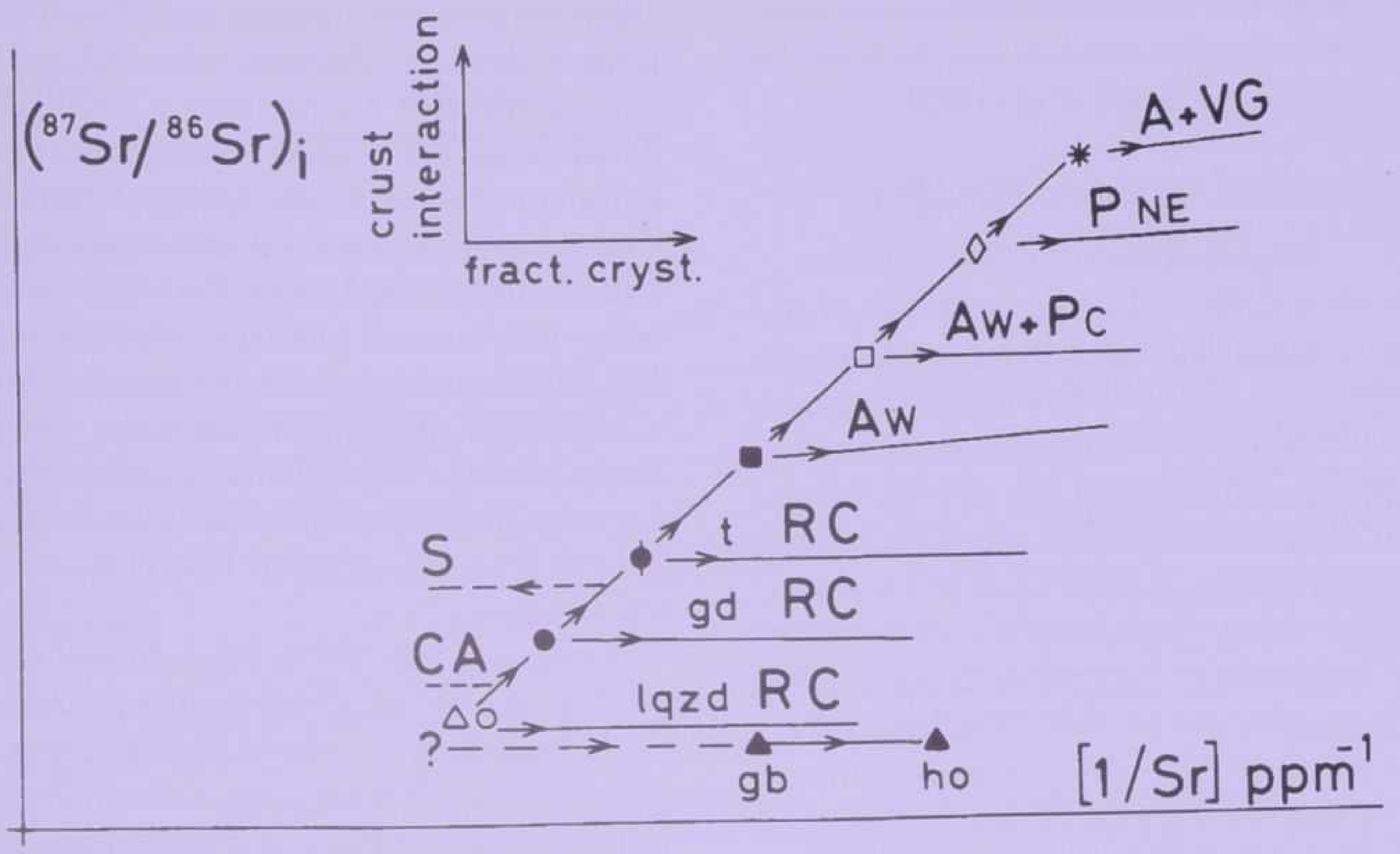


Fig. 11 - Initial (^{87}Sr/^{86}Sr)$_0$ versus 1/Sr plot for main intrusions of Adamello batholith (from Del Moro *et al.*, 1985b; for a plot of original data, see fig. 6 therein). Horizontal lines refer to different igneous units, each line representing rocks of constant Sr isotope ratio and variable 1/Sr values. Rocks plotting on same line were generated mainly by crystal fractionation processes. Figure shows that Adamello batholith is composed of several igneous sequences, the contents of which of radiogenic strontium are inversely correlated with rock ages, as shown by inclined line passing through points representative of more "primitive" tonalitic members of each igneous sequence. Figure suggests that ACF processes (crystal fractionation plus assimilation) were essential for evolution of Adamello magmas and that crustal contribution increases in younger magmatics. Abbreviations: see Fig. 8.

A close link between gabbro and tonalite was inferred by Blundy and Shimizu (1991) from the distributions of trace elements in plagioclase from the southern Mt. Re di Castello area. Their data show that the calcic cores of tonalitic plagioclase derived from gabbroic rocks. Using new Sr and Nd isotope data, Kagami *et al.* (1991) also addressed the question of the origin of the gabbro to tonalite associations in southern Mt. Re di Castello. The results confirmed a close genetic link between the various members of the rock associations. At the same time, Kagami *et al.* showed that, in each intrusive unit, the transition from gabbro to tonalite is characterised by increasing amounts of assimilated crustal material up to 40-70% by weight. The contribution of crustal material to the evolution of the Mt. Re di Castello intrusives was also discussed by Hansmann (1986) and Hansmann and Oberli (1991) in the light of U-Pb zircon isotope composition. Zircon in all studied rocks was found to contain variable amounts of radiogenic lead from various crustal sources. The inferred ages of inherited zircon components range between 450 to 1100 Ma. The survival of relicts of 'old' zircons in the tonalitic and more basic magma was explained in terms of dissolution kinetics.

The geodynamic context for the origin of the Adamello parent magmas is still unclear. Von Blanckenburg *et. al.* (1988, and references therein) have briefly discussed some current ideas on melt generation linked to subduction, lithospheric extension or thermal boundary layer detachment. Processes related to slab breakoff in a subduction scenario and advocated by these authors (see also Davies and von Blanckenburg 1995; von Blanckenburg and Davies, 1995) could possibly explain petrologic and isotopic data of magmatic rocks from the Adamello batholith. However, alternative models including subduction-related melt generation in a tectonic setting restored for Middle Eocene - early Oligocene times of magmatic activity remain to be thoroughly evaluated.

The origin of the foliation in tonalite along the northern and eastern border zones of the Adamello batholith has long been debated. These rocks show a moderate to pervasive mylonitic and cataclastic fabric. Salomon (1908-1910) and Malaroda (1948) related the deformation of already solidified rocks to movements along fault systems bordering the igneous massif. Other authors (e.g., Trener, 1906, Mendum, 1976) considered these textures to be mainly the result of magmatic processes, due to radial expansion of border zones during magma solidification. The question as to whether the foliations are post-emplacement tectonic deformation structures or syn-magmatic features is still open. Recent studies on foliated tonalites in the northern Adamello batholith suggest that the foliation may have formed as a primary magmatic feature but with some tectonic overprint (e.g., Mendum, 1976; Werling, 1992; Montresor and Rigatti, 1995; Matile, 1996). Disequilibrium of hydrogen isotope distributions between co-existing biotite-hornblende is indeed typical for foliated rocks of the Adamello plutonics (Kuroda *et al.*, 1985).

For more details on debated emplacement mechanisms and P-T conditions of Adamello magmas, readers are referred to McRae (1983), Oxburgh and McRae (1984), Brack (1985) and Matile (1996). The paper by Blundy and Sparks (1992) focuses on the genesis of mafic inclusions in tonalitic rocks. Evidence for magmatic fracturing and melt segregation is given in John and Stünitz (1997). For other topics, see the literature list. Results and additional references on studies of igneous and metamorphic minerals may be found in Jobstraibizer *et al.* (1985) and Brack *et al.* (1985).

ESSENTIAL ADVANCES IN STRATIGRAPHY OF THE ADAMELLO BORDER ROCKS

The presence around the Adamello batholith of old metamorphic schists overlain by a heterogeneous sequence of volcanic rocks, clastic sediments and predominantly Triassic carbonate successions, was recognised in the mid-19th century. The first widely acknowledged (bio)stratigraphic discoveries from the area were provided by geologists from Vienna. In 1869, E. Suess reported remnants of Permian (Dyas) landplants in dark schists of the "Collio Fm." south of the Adamello intrusions. This was the first undisputed evidence of the existence of Permian rocks in the Southern Alps. A few years later, it was the name *Daonella*, derived from Val Daone, that entered the literature on the Triassic. E. von Mojsisovics (1874) assigned this name to a biostratigraphically important group of thin-shelled pelagic bivalves which were well-known to occur in sediments near Prezzo in the lowermost part of Val Daone. In 1878, the German geologist Lepsius published a remarkable monograph on the geology of the western South Tyrol. In this report, Lepsius gave a comprehensive overview of the stratigraphic successions of the eastern (then Austrian) Adamello sector. Nevertheless, many details of the facies patterns in Middle Triassic sediments still remained unclear. In the following years, new data were provided by members of the Imperial Austrian Geological Survey (the famous *"k.k. geologische Reichsanstalt")*. A. Bittner (1881) gave a concise account of the stratigraphy of the Giudicarie sector. Together with the (bio)stratigraphic results of Mojsisovics (1880, 1882), Bittner's compilation remained the stratigraphic standard for a long time. In particular, the results gained on Middle Triassic rocks, including levels rich in age-diagnostic macrofossils (ammonoids, *Daonella*), were of prime importance for the Triassic time-scale.

A major advance in knowledge of the Adamello border rocks came from the systematic mapping of the entire Adamello massif by Salomon. Stratigraphic data collected on numerous trips between Giudicarie and Val Camonica are summarised in the first part of Salomon's Adamello monograph, issued in 1908. Salomon largely relied on Bittner's subdivisions, added further details, and was able to identify most stratigraphic units, even in areas with a strong contact-metamorphic overprint. Fossils collected by Salomon were studied by his students, but the data of only a few were published (e.g., Völker, 1931). In his discussion of the Adamello stratigraphy, Salomon systematically referred to the Triassic stages. Unfortunately, in some cases, he applied litho- and chronostratigraphic terms as largely equivalent expressions. Salomon also recognised differences in the basement lithologies east and west of the Adamello intrusion.

Immediately after the publication of Salomon's first Adamello monograph, the arguably most complete stratigraphic successions in the Adamello border (*i.e.*, along the ridge between Mt. Ignaga and Forcel Rosso, west of the present-day Lago Bissina) was analysed in more detail by Trener (1910a). Trener was a *'Sektionsgeologe'* for the Trentino area of Vienna Geological Survey and had been a student of Suess. In the Ignaga-Forcel Rosso succession, Trener recognised several new stratigraphic intervals (e.g., equivalents of the Lower Permian Collio Schists, a thin carbonate interval perhaps referred to the Bellerophon Fm.) and considered the youngest sediments of the succession to be of Upper Triassic age. Later (1912), he concluded that the Forcel Rosso stratigraphy includes lithologies as young as the Rhaetian. However, at present we believe that no sediments at Forcel Rosso are younger than the Carnian.

Starting in the 1930s, Bianchi and Dal Piaz and many of their students and co-workers studied the geology of the Adamello area. The main focus was on petrographical aspects of intrusive and contact metamorphosed rocks, but the Padova group also mapped a good share of the border rocks. With few exceptions, Salomon's and Trener's stratigraphic conclusions were largely adapted and confirmed.

In the 1960s, the names and definitions of many Permian and Triassic stratigraphic units in the wider surroundings of the Adamello batholith were thoroughly revised. Earth scientists from Pavia (Boni, Cassinis and co-workers) provided new information on the well-exposed Permian and Lower Triassic successions south of Adamello (see Cassinis, 1985 for a summary of stratigraphic results on Permian rocks in the area), whereas stratigraphers from Milan mainly worked on the Triassic units (e.g., Assereto and Casati, 1965; see Gaetani, 1985, for a review of studies on Triassic rocks around Adamello). Other geologists provided alternative interpretations for the peculiar relationships found in the Middle/Upper Triassic stratigraphy west of Val Camonica (e.g., Rossetti, 1966) or focused on sedimentological aspects of Triassic sequences, mainly in Giudicarie (e.g., Unland, 1975; Epting *et al.*, 1976). Later, many of these predominantly lithostratigraphic results were successfully extrapolated to the sedimentary sequences thermally metamorphosed along the contacts with the Adamello intrusions. In particular, the remapping, by students from ETH Zürich, of the classical area around Mt. Frerone and in the upper Val Caffaro thoroughly modified the interpretation of the stratigraphy of this sector. The revision was triggered by the discovery of hitherto unknown sedimentary successions at Mt. Colombine in Val Caffaro, as well as by lithological and geochemical comparisons of contact-metamorphic rocks with corresponding non-metamorphosed sediments to the west of Val Camonica. The relevant stratigraphic results are summarised in Brack *et al.* (1985). When possible, the new information was also included (although in a simplified form) in the present Adamello map.

With the exception of the north-western Adamello border (e.g., Mottana and Schiavinato, 1973), relatively little attention has been paid in the recent decades to the Southalpine basement rocks around the Adamello batholith. Nevertheless, a few studies elaborate on special

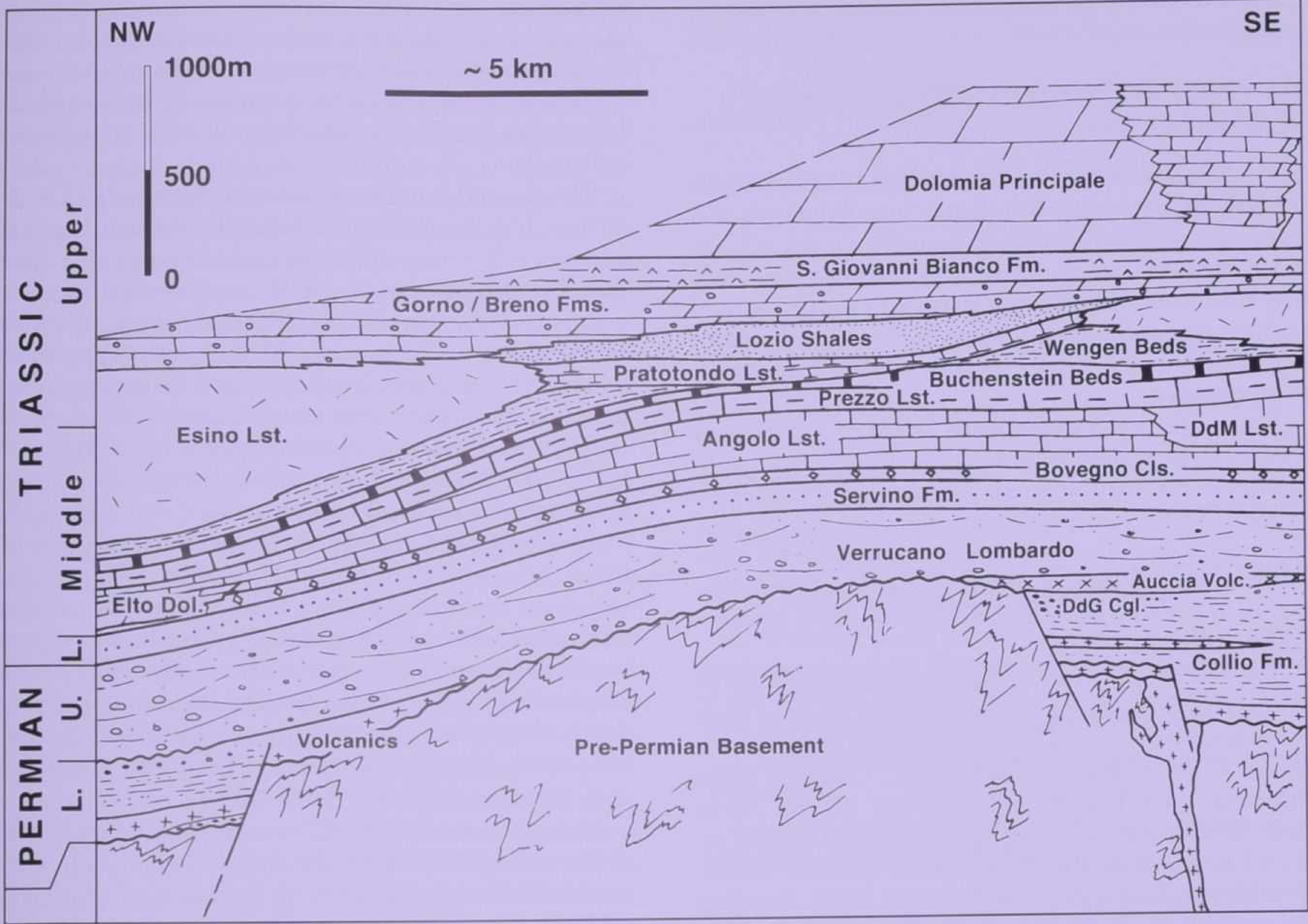


Fig. 12 – Diagram of stratigraphic relationships observed in rocks of southern and western borders of Adamello batholith (modified and complemented after Brack, 1984). For additional information on Permian and Triassic units, see also Brack *et al.* (1985), Cassinis (1985) and Gaetani (1985).

topics such as contact metamorphism and deformation (e.g., Werling, 1992). Attempts at reinterpreting Permian lithologies in the immediate (western) Adamello border have also been made (e.g., Massari and Cadel, 1979; Imbach, 1989). New results on the Permian successions south of the Adamello intrusives are summarised in Cassinis *et al.* (1999).

Substantial improvements were recently made on the bio- and chronostratigraphy of sediment intervals, particularly of the Middle Triassic. Eighty years after the pioneering works of Bittner and Mojsisovics, the biostratigraphic analysis of Upper Anisian to Upper Ladinian pelagic successions was revived. Numerous "classical" fossil localities south and west of the Adamello batholith were restudied in detail and additional fossils were discovered. Biostratigraphers from the University of Milano (Assereto, Gaetani and later Balini) focused their attention on macrofossils in the Upper Anisian Prezzo Limestone in Val Camonica and the Giudicarie area, including the classical successions around Mt. Corona-Stabol Fresco. The most important results of (bio)stratigraphic relevance are summarised in Gaetani (1993). Numerous specimens of hitherto only poorly known ammonoids were also found in the Buchenstein Beds at Bagolino, as well as in successions at a shorter distance from the Adamello intrusives (Brack and Rieber, 1986, 1993). In combination with isotopic age data from the same intervals (Mundil *et al.*, 1996), recent biostratigraphic results from the Upper Anisian to Upper Ladinian successions in the Adamello area provide an outstanding biostratigraphic reference for the Anisian/Ladinian boundary.

The reconstructed stratigraphy of the Adamello border in the south-western sector (area of Lago d'Arno, Pizzo Badile-Concarena, Mt. Frerone-upper Val Caffaro-Mt. Colombine-Cima Bondolo-Val Daone) is shown in Fig. 12. The lateral relationships of stratigraphic units of the Middle/Upper Triassic interval were mainly inferred from contact metamorphosed sediments (Brack, 1984). Identical geometrical relationships have recently been reported from corresponding sediments in the eastern Bergamask Alps (Balini *et al.*, 2000). More importantly, the latter study provides the first information on the age of hitherto poorly constrained stratigraphic units, such as the Pratotondo Limestone.

Nevertheless, the stratigraphic assignments of some rock units in the Adamello border is still speculative. Due to their heterogeneous distribution and/or poorly distinctive lithological features, metamorphosed intervals of Permian clastic and volcanic rocks and metasediments of presumably Carnian age are in many cases difficult to unambiguously correlate with stratigraphic successions exposed further away.

TECTONIC STRUCTURES IN THE ADAMELLO BORDER ROCKS

Small-scale tectonic structures in basement rocks, particularly in metapelitic lithologies, are ubiquitous and show signs of polyphase deformation. On a regional scale, these structures are presumably of Variscan age, since they are unconformably overlain by Permian volcanic and sedimentary rocks. Still unclear is the significance of Alpine deformation in the basement rocks of the Adamello border zone.

Syn-sedimentary extensional faults of Permian or Mesozoic age, similar to those inferred from stratigraphic successions in the wider surroundings of the Adamello batholith, are suspected to occur in the Adamello border rocks as well. These structures may account for some rather abrupt changes in the stratigraphic successions, but their identification and distinction from younger faults is difficult.

The existence of small- and medium-scale folds cut by dykes and small intrusions have long been reported from the sedimentary successions of the western and southern border of the Adamello batholith (e.g., Cozzaglio 1894; Salomon, 1908; Bianchi and Dal Piaz, 1937b). These structures were initially considered as due to magma-induced deformation or as syn-magmatic (possibly tectonic) folds (e.g., Cozzaglio, 1894; Salomon, 1903). Based on the available literature, Spitz (1915) deduced *a close relationship between the (pre-intrusive) Gallinera fault and similar thrusts known in the Orobic Alps.* Cornelius (1928) supported Spitz's conclusion, and demonstrated the post-kinematic age of contact metamorphism in deformed sediments in the footwall of the Gallinera Line. Nevertheless, structures such as the Gallinera Line were often considered as post-intrusive features (e.g., De Sitter and De Sitter-Koomans, 1949; Castellarin and Gatto, 1981). Reaffirming the pre-tonalitic age of the Gallinera Line, Brack (1984) proposed close kinematic relationships between the Gallinera thrusts involving the Southalpine basement and the large-scale folds and thrusts in detached sediments of the eastern Bergamask Alps. Some of these folds and corresponding structures continue in the border rocks of the southern Adamello area, where large- and small-scale folds are cut and deformed by the 42-38 Ma Re di Castello intrusives (Brack, 1981, 1985). The maximum age of this pre-Adamello (Orobic) tectonic phase is still poorly constrained. Doglioni and Bosellini (1987) suggested an Eo-Alpine age (Late Cretaceous - Paleogene *p.p.*). K/Ar and Ar/Ar dating of dykes cutting similar structures in the Bergamask Alps (Fantoni *et al.*, 1999) seem to support this assumption. Nevertheless, the published age data are far from being definitive, and dykes petrographically similar to those analysed by Fantoni *et al.* are found crossing the Eocene Mt. Re di Castello intrusives.

In the immediate surroundings of the south-western Mt. Re di Castello superunit (e.g., Val Paghera, Mt. Frerone, upper Val Caffaro) and due to forceful magma emplacement, the pre-intrusive large- and small-scale folds in the meta-sediments show synintrusive deformation of variable intensity and orientation (Fig. 9). For a sketch and additional information of the structural patterns in the southern and western border of the Adamello batholith, readers are referred to Brack (1985; figs 4 and 6 therein).

The age and significance of movements related to the tectonic lines bordering the Adamello Massif to the north and east still remain to be fully assessed and quantified. Based on lateral transitions of zones of cataclasite and mylonite in the Southalpine basement rocks along the northern Adamello border, Werling (1992) concluded that movements related to the Tonale Line occurred when temperatures in the contact aureole were still high. In the north-eastern edge of the Adamello batholith, brittle faults related to the Giudicarie Line truncate the foliation of the igneous rocks, the orientation of which is parallel to the Tonale Line. East of Mt. Spolverino the contact between non-metamorphosed Mesozoic sediments and cataclastic tonalite of the Presanella superunit was considered by Salomon (1901, 1908) as conclusive evidence for the post-intrusive age of the deformation related to the Giudicarie Line. Recent data and additional references on the Giudicarie fault system is given in Castellarin and Sartori (1982), Martin *et al.* (1991, 1996, 1998), Castellarin *et al.* (1993) and Prosser (1998, 2000).

In the tectonic sketch *("Schema dei rapporti strutturali")* of the geological map of the Adamello batholith, some prominent tectonic features are incorrectly displayed: (a) the Gallinera Line does not continue inside the Adamello plutonics; (b) the two "synclines" indicated to the west of the Adamello superunit do not exist.

CONTACT METAMORPHISM

For reasons of clarity, the contact aureole is drawn only schematically in the present map, and these indications are limited almost exclusively to the basement areas. In reality, the rocks surrounding the various intrusive units of the Adamello batholith display clear signs of contact-metamorphic overprinting along more than 90% of the Adamello border. Thermally non-metamorphosed lithologies in this border are found only along tectonic contacts with the Presanella intrusives, *i.e.*, along a branch of the post-intrusive Giudicarie Line between Carisolo and Dimaro (e.g., Mesozoic sediments east of Mt. Spolverino). On a plane view, the size of the contact aureole usually ranges between 1-2 km, but may locally be much wider (up to 4 km).

Salomon (1890, 1891a,b, 1892, 1894, 1895, 1896) was *the first to carry out systematic researches on contact-metamorphosed rocks* of the Adamello border zones. In 1897, he made one of the first proposals for a classification of contact metamorphosed rocks. Names such as "aviolite" (after Mt. Aviolo) and "edolite" (after Edolo, Val Camonica) were introduced in the petrographic nomenclature. The schist hornfelses from the northern and north-eastern areas of the Adamello massif were described in detail by Trener (1906) and Gottfried (1930). Field aspects of metamorphism in the Adamello aureole were reported by Salomon in his famous memoir (1908-1910). A first synoptic description of metamorphic processes in the Adamello contact aureole was given by Bianchi and Dal Piaz (1948b). Since then, numerous petrographic descriptions of contact-metamorphosed rocks in the Adamello batholith have been provided by students of the Padova and Zürich schools (see references and list of unpublished reports). However, a comprehensive up-to-date compilation of data on contact metamorphism in the Adamello region is still incomplete.

Nevertheless, recent detailed accounts based largely on studies of the Adamello rocks address specific processes related to contact metamorphism. They include: mechanisms of contact aureole formation (Bucher-Nurminen, 1982), thermal models in contact aureoles (Boriani and Origoni-Giobbi, 1982; Matile and Widmer, 1993), fluid flow, isotope exchange and vein formation in the innermost parts of contact aureoles (Drescher-Kaden, 1969; Baumgartner, 1986, Gieré, 1990a,b, 1992; Gieré and Williams, 1992, Abart, 1994, 1995, Gerdes *et al.*, 1995, 1999), the nature of fluid inclusions in high-grade carbonate to marly rocks (Trommsdorff *et al.*, 1985), metasomatism and phase relations in dolomite mable (Frisch and Helgeson, 1984), phase relations in high-grade argillaceous limestone and marl (Oterdoom, 1979, Ulmer, 1983) and the brittle/ductile transition of contact-metamorphosed dolomite (Vogler, 1986). Results from these studies suggest temperatures of 900-850°C for the innermost aureole of gabbroic rocks and 650-550°C in country rocks in contact with tonalite and granodiorite. Fluids in carbonates were essentially CO_2-rich during the stage of carbonate devolatilization and H_2O-rich during subsequent stages, probably dominated by fluids released from magma (Baumgartner *et al.*, 1989).

The great lithological variety of rocks surrounding the Adamello batholith has resulted in selective metamorphic and metasomatic processes and a wide spectrum of metamorphic rocks. Many of these lithologies have been illustrated in past decades, particularly by members of the Padova school (e.g., Bianchi and Dal Piaz, 1937c, 1948; De Lucchi, 1939; Hieke, 1945; Schiavinato, 1946; Minozzi-Boaretto, 1950; Lorenzoni, 1955; Zanettin, 1956; Callegari, 1963a; Adami, 1963; De Pieri and Justin-Visentin, 1968; Justin-Visentin and Zanettin, 1968; Rossi, 1970; Bianchi *et al.*, 1971; Beltrami *et al.*, 1971; Mottana and Schiavinato, 1973; Morgante, 1979). Surveys by students from ETH Zürich provide reconstructions of the metamorphic histories of various stratigraphic units surrounding the Adamello batholith. With the exception of the metamorphic evolution of the Permian formations (Riklin, 1983, 1985), most of these results are as yet unpublished.

In the legend of the present geological map the most common and typical contact-metamorphic rocks and minerals are indicated in the brief petrographic characterisations of lithostratigraphic units.

APPENDIX

LEGEND TO THE GEOLOGICAL MAP 1:50 000 OF THE ADAMELLO BATHOLITH

Scientific coordination: E. Callegari, Gb. Dal Piaz and G.O. Gatto, in cooperation with V. Trommsdorff

(Translation of the italian legend, partly re-arranged, integrated and in places implemented)

QUATERNARY DEPOSITS

(with personal contribution of G.B. Castiglioni; see also Castiglioni, 1961)

1. Marsh and peat (**Holocene**)

2. Recent and active alluvial deposits; alluvial fans (**Holocene**).

3. Moraines of the "Little Ice Age" (15th-19th century) and recent moraines; morainal belts and rock glaciers, active and inactive (**Holocene**)

4. Talus deposits (a); talus fans (b); alluvial cone (c) (**Holocene and Pleistocene p.p.?**)

5. Post-glacial alluvial deposits and aggradational terraces (in part lacustrine deposits) (**Upper Pleistocene**)

6. Würmian glacial deposits and post-würmian stadial moraines: pleniglacial Würmian glacial stage and early phases of pre-Gschnitz; Gschnitz, Daun and Egesen stades. Morainal belts and inactive rock-glaciers (**Upper Pleistocene**)

7. Interglacial alluvial deposits and cemented talus deposits (**Pleistocene**)

8. Ancient and cemented debris and landslide deposits of uncertain age (**? Lower - Middle Pleistocene**)

TERTIARY ADAMELLO BATHOLITH

(Radiometric ages: 42 - 29 Ma)

The Adamello batholith is the most important of the Tertiary igneous products of the "Periadriatic Igneous Province", an assemblage of plutonic, volcanic and volcanoclastic bodies which represent post-collisional magmatism in the Alps. It is located in a wedge-like crustal sector of the Southern Alps, bounded by the Tonale Line to the north and the southern Giudicarie Line to the east, and is hosted by the Southalpine crystalline basement and its Permo-Triassic cover rocks. The batholith consists of Eocene to Oligocene calc-alkaline igneous superunits, the age of which progressively decreases from south-west to north-east. Each superunit comprises several plutons of tonalitic to granodioritic composition and with macroscopically distinctive textures. The contacts between plutons are usually sharp. The mapped 'igneous units' represent major subdivisions within these superunits. The mafic rocks are considered as a separate group of igneous bodies, with its own subdivisions. All the plutonic rocks of the Adamello batholith are coarse-grained and their main constituents are visible to the naked eye. When describing rock textures, therefore the terms coarse- and fine-grained are used in a relative sense. The range of values for S_0 = initial $^{87}Sr/^{86}Sr$ ratios of the rocks is also included in the descriptions of each igneous superunit. Radiometric ages are reported from mineral separates of biotite, muscovite, hornblende, zircon and thorite. The following abbreviations are used to account for various analytical techniques and minerals: b = Rb/Sr on biotite, **b** = K/Ar on biotite; m = Rb/Sr on muscovite, **m** = K/Ar on muscovite; h = K/Ar on hornblende, **h** = $^{39}Ar/^{40}Ar$ on hornblende; z = U/Pb on zircon; t = U/Pb on thorite. The letter "i" indicates rock ages obtained on internal isochrone. Error values and original isotope data are reported in the following publications, Sr-isotope data: Del Moro *et al.* (1985b), Kagami *et al.* (1991); b, **b**, m, **m**, h, **h**: Del Moro *et al.* (1985a) and

Villa (1985); z, t: Hansmann (1986) and Hansmann and Oberli (1991).

PRESANELLA TONALITIC SUPERUNIT

(Radiometric ages: 33 - 29 Ma)

Coarse-grained hornblende-biotite tonalite characterised by pronounced elongation (up to 3-4 cm) of euhedral amphibole crystals. Amphiboles are less evident in the border zones, where the grain-size of the rocks is usually reduced; subordinate hornblende-bearing biotite tonalite (Val Nambrone). Massive rocks predominate in the central part of the superunit. In the border zone, close to the major tectonic lines, the tonalite shows more or less pronounced foliation. Under the microscope, this foliated tonalite displays a cataclastic to mylonitic fabric. Non-foliated tonalite usually displays some cm-sized green pseudomorphs on a prismatic mineral. These pseudomorphs consist of aggregates of colourless cummingtonite or green calcic amphibole, interpreted as alteration products of ortho- and clinopyroxene respectively. The tonalitic rocks contain numerous dark inclusions of fine-grained biotite-hornblende gabbro to quartz gabbro, usually showing a porphyritic texture due to the occurrence of a little elongated coarse hornblende and flakes of biotite, similar to those in the surrounding tonalite. In massive tonalite, the shape of most dark inclusions is subrounded; in the foliated varieties, the equivalent inclusions are more or less strongly flattened and elongated parallel to the rock foliation. As indicated on the map inset labelled *"Schema dei rapporti strutturali"*, the foliation of the igneous rocks along the northern border of the Presanella superunit is sub-parallel to the Tonale Line and crosses the contact zone with the Avio mass. Along the eastern border area of the Presanella mass, the foliation changes its trend from north-east (*i.e.*, parallel to the Tonale Line) in the northern sector to north-north-east (*i.e.*, sub-parallel to the Giudicarie Line) in the central sector, and east-north-east in the southern portion (Val di Genova). In the proximity of possible roof areas (e.g., Laghi di Cornisello) and in peripheral parts of the Presanella mass, contact metamorphosed relicts of the surrounding basement schists are often found as enclaves in the tonalite. Some roof-pendants are metre-sized. Slabs of fine-grained grey rocks with biotite-quartz-plagioclase, probably derived from gneissic host-rocks, are quite common in the Presanella mass. These rocks may be confused with dark gabbroic inclusions, from which they are distinguished thanks to their tabular shape and the absence of hornblende "phenocrysts". In thin section, these rocks show a granoblastic texture with unzoned or weakly zoned acid to intermediate plagioclase grains, whereas plagioclase crystals of gabbroic dark inclusions are usually strongly zoned and more calcic. The initial Sr isotope ratios Sr_0 of the tonalitic rocks range between 0.7083 and 0.7101.

9. Upper Nambrone Valley Tonalite – "Upper Nambrone Valley biotite quartz diorite" *Auct.* – Medium-grained, mostly foliated, hornblende-bearing biotite tonalite, generally containing few dark inclusions. Hornblende grains usually form small slender prisms. The rock foliation becomes more pronounced in the border zone of the massif (upper Val Nambrone, Pra da Lago, Lago Nambino, Lago Ritorto, Carisolo).

10. North-eastern Presanella Tonalite – Medium to coarse-grained hornblende-biotite tonalite with a slightly porphyritic texture, due to the occurrence of some large elongated hornblende crystals (up to 2.5 cm long and 0.5 cm wide); medium-grained varieties are found along the eastern and northern borders of this unit (Val Fazzon, Malga Artuic, Val Barco, Dimaro, Lago Ritorto). Typical microtextural features are reddish biotite and weakly pleochroic hornblende with homogeneous brownish cores and irregular pale green rims. Radiometric ages of tonalite: b = 31.9 - 29.4 Ma; **b** = 33.2 - 29.9 Ma; h = 29.8 - 44.2 Ma (excess argon !); **h** = 33 Ma. Radiometric ages of a pegmatitic dyke: m = 31.4 Ma; **m** = 32.5 Ma.

11. Central Presanella Tonalite –At hand-specimen size, this tonalite is very similar to the North-eastern Presanella Tonalite. Coarse to medium-grained rocks with a characteristic porphyritic texture, due to the occurrence of large elongated hornblende (up to 3.5 x 0.5 cm), predominate in the centre area of the massif (Cima Presanella, uppermost Val Nardis, Val di Genova, Val Presena). Medium-grained tonalite varieties with weak to strong foliation and amphibole of smaller dimensions than in the massive rocks prevail in the border zones, especially along the southern boundary of the Central Presanella Tonalite (lowermost Val Nardis, Val di Genova, Val Nambrone) but also along the northern border (e.g., Val Presena). Local concentrations of hornblende grains give rise to bodies of coarse-grained lamprotonalite which are up to a few hundred metres long (e.g., eastern flank of Lago Scuro, north of Rifugio Mandrone). Typical microstructural features of the Central Presanella mass are dark brown biotite and strongly pleocroic zoned hornblende with dark brownish-green cores (oscillatory zoned) and dark green rims. Radiometric ages of tonalites: b = 32.9 - 31.6 Ma; **b** = 33.5 - 31.9 Ma.

AVIO VALLEY TONALITIC SUPERUNIT

(Radiometric ages: 34 - 32 Ma)

Quite uniform medium-grained biotite tonalite, usually containing dark inclusions of hornblende-biotite gabbro to quartz gabbro, and hornblende-bearing to hornblende-free biotite quartz gabbro to quartz diorite. The rocks are massive in the more internal parts (Val d'Avio, Piano d'Aviolo, Val Seria) and become more and more foliated in the border zones, towards the Tonale Line (area between Val Narcane and lower Val Presena). The dark inclusions in these foliated rocks are flattened and elongated parallel to the foliation plane. The foliation runs parallel to the nearby Tonale Line (see inset labelled *"Schema dei rapporti strutturali"*). The post-intrusive origin of the foliation is inferred from: (a) the cataclastic to mylonitic texture, (b) the low-temperature mineral assemblage related to deformation, and (c) continuity of foliation across the boundary between the Avio and Presanella superunits. A few gabbroic bodies (e.g., lower Val Presena, Corno d'Aola, Baita Pozzuolo) seem to be closely related to the Avio mass. In the Avio Valley Tonalite, the initial Sr isotope ratios Sr_0 range between 0.7109 and 0.7119 and in the associated gabbros between 0.7077 and 0.7104.

12. Avio Valley Tonalite / "Avio Valley biotite quartz diorite" *Auct.* – Massive, medium-grained biotite tonalite, with grain-size reduction in the marginal zones, where enrichment in both dark inclusions and cornubianitic xenoliths is observed. Foliated textures are typically developed along the northern margin. In some border zones, the Avio Valley Tonalite contains garnet (e.g., Passo Gallinera area) or hornblende (e.g., upper Val d'Aviolo; contact zone with Central Presanella Tonalite, south of Passo Paradiso). A typical microscopic feature of this tonalite is the red colour of its biotite. Radiometric ages: 34-32 Ma (b), 31.9 Ma (i).

13. Middle to Lower Genova Valley Tonalite / "Middle to Lower Genova Valley quartz diorite" *Auct.* – Foliated medium-grained biotite tonalite in the middle Val di Genova and hornblende-bearing biotite tonalite in the lower part of the same valley. The foliation is of cataclastic to mylonitic origin. Mafic inclusions are relatively abundant. Locally xenoliths of pre-intrusion schistose rocks also occur (modified to different extents by metamorphic and metasomatic processes). The tonalite varieties with only biotite are very similar to the Avio Valley Tonalite. Radiometric ages: 32-33 Ma (b) for rocks of the middle Val di Genova; 31-30 Ma (**b**) for rocks of the lower Val di Genova. Sr isotope ratio Sr_0 = 0.7121 for tonalite of the middle Val di Genova.

ADAMELLO TONALITIC SUPERUNIT

(Radiometric ages: 36 –34 Ma)

This superunit mainly consists of massive coarse-grained hornblende-biotite tonalite to leucotonalite. In hand specimens, these rocks are characterised by equidimensional euhedral grains (about 1 cm wide and 1.5-2.0 cm long) of short prismatic hornblende and columnar biotite. The tonalite often contains variable amounts of relatively fine-grained dark inclusions of predominant gabbroic composition showing a porphyritic texture, due to the presence of a few coarse hornblende crystals similar to those in the surrounding rocks. The dark inclusions are rounded to subrounded. In peripherial zones, the tonalite sometimes contains numerous subangular or platey fragments of cornubianitic rocks derived either from the basement or from the Permian-Triassic cover rocks. Several bodies of fine to coarse-grained hornblende or pyroxene-hornblende gabbro (M. Marsèr, Lago Baitone) and some smaller bodies of fine-grained biotite quartz diorite (Malghe Macesso) are exposed in the border areas of the superunit. The initial Sr isotope ratios Sr_0 range between 0.7077 and 0.7086 in the gabbro and between 0.7069 and 0.7088 in the tonalite.

14. Western Adamello Tonalite – Coarse-grained hornblende biotite tonalite; a grain-size reduction is commonly observed in the border zones, close to the host rocks. Near major contacts with other igneous masses, the Adamello tonalite may show flow-bands or patches of concentrations of mafic constituents, especially hornblende (Val Borzago, Val Seniciaga, Lago Baitone, Lago Bissina). In thin section, the biotite shows a dark brown colour, along the direction of maximum absorption. Green hornblende crystals display a uniform composition. Radiometric ages: 35 - 34 Ma (b); 35.7 – 33.4 Ma (**b**); 34 Ma (i); 42.4 - 41.9 Ma (h).

15. Central Adamello Leucotonalite – Coarse-grained massive rocks similar to the previous ones, but more leucocratic and with around 10 vol% fewer mafic constituents (contents in hornblende are particularly reduced). Radiometric age: 33.8 Ma (b).

MT. RE DI CASTELLO TONALITIC TO GRANODIORITIC SUPERUNIT

(Radiometric ages: 42 - 38 Ma)

With the only exception of the Corno Alto mass, the tonalitic-granodioritic rocks of this superunit have a uniform fine-grained texture, characterised by the acicular to slender prismatic shapes of their hornblende crystals. The rock structure is generally massive, but in some areas the Mt. Re di Castello intrusives show a parallel texture marked by progressive flattening of mafic inclusions (Val Cadino, Lago della Vacca, Mt. Listino, Val Borzago). In contrast with the foliated tonalites of the marginal Avio and Presanella masses, the Mt. Re di Castello foliated rocks do not usually show significant post-crystallisation deformation. Unequant grains and, in particular, hornblende and plagioclase show a preferred orientation (fluidal structures). On all scales, the tonalitic-granodioritic and mafic magmas are intimately linked with the formation of intrusive breccias, as well as with rocks generated by large-scale magma mingling (Val Fredda, Val Cadino, Mt. Blumone). Numerous gabbroic bodies occur all around the Mt. Re di Castello superunit. Especially in the southernmost part, the tonalitic-granodioritic rocks are crossed by a large number of mafic dykes ranging from tholeitic picrobasalt to calc-alkaline andesite. Small to large igneous bodies of trondhjemitic composition are also found in this superunit, both south (e.g., Val Fredda) and north (Corno Alto). Close to the contacts with surrounding metasediments, numerous large and small fragments of contact metamorphosed rocks are dispersed in the tonalite (e.g., Cima Uzza, upper Val Cadino, Cima Sablunera). Typical ranges for Sr_0 isotope ratios are 0.7042 - 0.7070 (granodiorites), 0.7039 - 0.7069 (tonalites), 0.7088 (Dernal leucogranite).

A. NORTHERN MT. RE DI CASTELLO UNIT

16. Small confined leucocratic masses – Garnet-bearing biotite leucogranite (Passo Dernal); biotite leucogranite (Lago d'Avolo); two-mica trondhjemite (Malga Ervina). Radiometric ages of Passo Dernal leucogranite: 39.8 Ma (z); 38.8 Ma (t).

17. Mt. Re di Castello Tonalite – Relatively fine-grained biotite-hornblende tonalite, with a colour index close to the boundary between leucocratic and mesocratic rocks. The tonalite usually contains abundant dark inclusions, sometimes arranged as inclusion swarms. Some of these arrays seem to derive from large dismembered blocks of fine-grained hornblende gabbro (up to tens of metres long) fully immersed in the tonalite (e.g., Malga Nudole in the upper Val Daone). Several textural varieties of the Mt. Re di Castello Tonalite form small sharply bound igneous bodies (e.g., in the abandoned quarry and present car-park at the south-western tip of the Malga Bissina dam in upper Val Daone). The rock structure is usually massive. A parallel texture of fluidal origin is observed in the north-eastern part of the Mt. Re di Castello superunit (upper Val Borzago, upper Val San Valentino). Radiometric ages: 38 - 37 Ma (b) on tonalites; 39 - 37 Ma (m), 39 - 38 Ma (**m**) on pegmatite dykes crossing tonalite.

18. Corno Alto Trondhjemite – Coarse-grained leucocratic muscovite-bearing biotite trondhjemite with a slightly porphyritic character (plagioporphyric). In the western border zone (between Laghi di San Giuliano and Malga Germenega), the grain-size is reduced. Transitions to leucocratic muscovite-bearing biotite granodiorite (sometimes containing small amounts of hornblende) are locally observed. The rock structure is massive in the more internal parts and becomes increasingly foliated (cataclastic to mylonitic foliation) towards the eastern border of the intrusion close to the tectonic Giudicarie Line. Dark inclusions of gabbroic rocks, often with a plagioporphyritic texture, occur frequently, especially in the border zones. Fragments of hornfels are also found in the intrusives close to the contacts with the surrounding basement schists. Small mafic bodies of acicular gabbro occur in places, along the margins of the Corno Alto mass (Vallone dei Fontanazzi). Radiometric ages of trondhjemites: 35 - 33 Ma (b, **b**, **m**); 42 - 41 Ma (m).

19. Sostino Granodiorite – Medium-grained massive hornblende-bearing biotite granodiorite, locally showing a plagioporphyritic texture. Radiometric ages: 38 - 30 Ma (b).

B. SOUTHERN MT. RE DI CASTELLO UNIT

20. Mt. Bruffione Granodiorite – Relatively fine-grained and massive, hornblende-poor to hornblende-free biotite granodiorite. Radiometric ages: 38.6 Ma (b), 39.5 Ma (**b**), 39.5 Ma (h), 39.9 – 38.6 Ma (z), 39.9 Ma (t).

21. Lago Boazzo / Lago d'Arno Granodiorite – Relatively fine-grained, quite leucocratic and massive, hornblende-biotite granodiorite, locally passing to leucotonalite (Pizzo Badile). The rock is characterised by the euhedral habit of biotite. Dark inclusions are sometimes clustered and form elongated swarms (e.g., northern end of Lago Boazzo in upper Val Daone). Fragments of metasedimentary rocks are found close to the contacts. Radiometric ages: 41 - 39.5 Ma (b).

22. Mt. Listino Leucotonalite – Medium- to fine-grained massive hornblende-biotite leucotonalite (with subordinate granodiorite), characteristic for its euhedral biotite grains. No radiometric data are available for this rock type.

23. Listino Ring Structure with parallel texture – Relatively fine-grained hornblende-biotite tonalite, with a color index at the boundary between leucocratic and mesocratic rocks. It shows a remarkable parallel texture, outlined by flattening of abundant dark inclusions. This concentrically foliated tonalite forms a ring-like structure having, at the core, the apparently younger unfoliated Mt. Listino Leucotonalite. No radiometric data are available for this unit.

24. Alta Guardia Tonalite – Medium- to coarse-grained massive hornblende-poor biotite tonalite with a slight porphyritic texture (biotite-phyric). No radiometric age data are available.

25. Lago della Vacca Tonalite – Relatively fine-grained and usually quite massive hornblende-biotite tonalite. It contains abundant subrounded to angular dark inclusions of differing gabbro types. Locally it shows a parallel texture and slightly flattened dark inclusions. Radiometric ages: 42 - 40 Ma (b, **b**), 42.9 Ma (t).

26. Val Fredda Leucotonalite / "Leucoquarzodiorite della Val Fredda" *Auct.* – Medium-grained massive biotite leucotonalite to trondhjemite, locally grading to biotite granodiorite (Laghi di Moje). It usually contains a large number of mostly subrounded to lobate dark gabbroic inclusions of variable size (up to a few metres large), which in places are so abundant as to overcome the tonalite itself (Mt. Cadino). The dark inclusions consist mostly of acicular hornblende gabbro, sometimes with chilled margins along the contacts with the leucotonalite. A slightly porphyritic (plagiophyric) biotite-hornblende variety of the Val Fredda leucotonalite outcrops on the southern slope of Mt. Frerone in the uppermost Val Cadino. This rock variety displays a fluidal texture (no cataclastic phenomena), also emphasised by the orientation of igneous and sedimentary inclusions. Foliation gradients are accompanied by increasing degrees of flattening of elongated inclusions. Radiometric ages: 42 - 40 Ma (b), 42 Ma (**b**), 42 - 39 Ma (z), 42 Ma (t).

MAFIC IGNEOUS MASSES

Each tonalitic superunit, especially the Mt. Re di Castello mass, is associated with small gabbroic to dioritic complexes, which appear to be concentrated in the marginal areas of the intrusions. The mafic rocks show remarkable variation in textures and composition. Hornblende gabbro and biotite-bearing hornblende gabbro predominate. Coarse-grained pyroxene- or hornblende-pyroxene gabbro is also well represented, especially in the layered gabbro complexes of the Mt. Re di Castello superunit (Mt. Mattoni, Cornone di Blumone). It may contain interlayered lenses of olivine-pyroxene hornblendite (Mt. Mattoni), wehrlite and anorthitic plagioclasite (Cornone di Blumone). The predominant types of hornblende gabbro are fine-grained rocks characterised by the acicular habit of hornblende. Rock textures are mostly massive, but parallel textures of fluidal origin are common in the region around Lago della Vacca. Initial Sr isotope ratios are highly variable, with Sr_0 ranging from 0.7036 to 0.7104, the lowest values being typical for the gabbros associated with the Mt. Re di Castello superunit: 0.7036 – 0.7050 (Mt. Mattoni), 0.7040 - 0.7060 (Cornone di Blumone), 0.7038 - 0.7042 (Mt. Cadino, Mt. Frerone), 0.7038 - 0.7070 (other Mt. Re di Castello gabbro). Ranges of Sr_0-values typical for the gabbroic rocks of the other superunits are: 0. 7070 - 0.7087 and 0.7077 – 0.7104, for the Adamello and Avio superunits respectively.

27. Hornblende gabbro to diorite. Fine-grained acicular hornblende gabbro is the most common mafic rock. It usually contains some biotite in amounts increasing from gabbro to diorite. Small pockets or veins of pegmatitic hornblende leucogabbros are characterised by the long-prismatic habit of hollow hornblende grains. This type of gabbro is very common in the Mt. Re di Castello superunit (Mt. Cadino, Val Bona, Mt. Costone, Cima Uzza, Cima Agosta, Mt. Campellio, Malga Nudole and Malga Nagrè, among others), but also occurs in the Adamello (e.g., Mt. Marsèr) and Avio superunits (Passo Tonale, Baita Pozzuolo). Radiometric ages show a wide range of values: 42 - 40 Ma (b) at Mt. Cadino; 36.8 - 36.7 Ma (b) and 40.8 - 38.6 Ma (**b**) at Mt. Marsèr; 34.4 – 33.0 Ma (b) at Passo Tonale and Baita Pozzuolo. Less common types of hornblende gabbro include: coarse-grained pyroxene-bearing hornblende gabbro, the stumpy hornblende grains of which look very similar to those in the surrounding Adamello tonalite (e.g., southern end of Lago Baitone; radiometric age on biotite: 36.3 Ma); coarse-grained biotite-hornblende gabbro, the slender amphibole grains of which look very similar to those in the associated Presanella tonalite (Lago Scuro gabbro); fine-grained hornblende-bearing to hornblende-free biotite quartzdiorite to tonalite (Malghe Macesso in Val Salarno; radiometric ages on biotite: 35 - 34 Ma).

28. Cornone di Blumone gabbroic to tonalitic complex – Massive or fluidally arranged medium- to fine-grained pyroxene-bearing hornblende gabbro, characterised by slender to acicular hornblende grains; radiometric ages show a narrow distribution between 41.7 and 40.8 Ma (b,**b**,h,**h**). Fine-grained hypersthene-hornblende diorite; medium-grained pyroxene- and/or biotite-bearing hornblende gabbro, diorite and tonalite characterised by stumpy hornblende grains with a subophitic (pecilitic) texture; radiometric ages: 41.6 - 40 Ma (b, **b**, h); 40.9 - 40 Ma (z); 41.6 Ma (t). These rocks intrude the layered gabbro.

29. Layered gabbro – Irregularly but steeply dipping layered rocks with alternating beds of coarse-grained hornblende-pyroxene gabbro and coarse-grained olivine-pyroxene gabbro to leucogabbro and anorthosite, with rare wehrlitic intercalations (Cornone di Blumone). Radiometric age: 41.7 Ma (h). Similar types of gabbro are also exposed in other places (lower Val di Dois, Forcellino di Mare, Malga Foppe). Roughly layered (flat) gabbro with alternating leucocratic and melanocratic beds of coarsely granular porphyritic pyroxene-hornblende gabbro (hornblende-phyric), sometimes containing lenses of olivine-enstatite-augite-bearing hornblendite (cortlandite) and intercalations of fine-grained acicular hornblende gabbro (Mt. Mattoni). Radiometric ages: 41.6 – 40.7 Ma (z); 41.5 Ma (h). Cortlanditic rocks have also been observed in other places (e.g., Val Braone).

DYKES

Several generations of dykes crosscut the Adamello batholith and the surrounding rocks. The age of the pre- to post-tonalitic dykes ranges from Permian to Oligocene. A Tertiary age is assigned with certainty only to dykes crosscutting the igneous masses. The age of all other dykes is mainly based on compositional, stratigraphical or structural criteria. Permian to Triassic dykes were folded, together with their host rocks, by a phase of post-Variscan pre-Adamello regional deformation affecting the Southalpine basement and cover successions. Inside the thermal aureole, these dykes show a contact-metamorphic overprint. Dykes younger than the Alpine phase of regional deformation may be recognised, due to their crosscutting relations with the folded

Permian-Mesozoic strata. In areas affected by syn-intrusive deformation, two different generations of these younger dykes are distinguished. After their intrusion into plutonic rocks and/or the surrounding sediments, the acidic and basic early-tonalitic dykes (in the southern Mt. Re di Castello area) were deformed, due to motions of the host magma or by the forceful effects of subsequent younger intrusions. A generation of undeformed post-tonalitic dykes ranges in composition from basalt to granitic aplite and pegmatite. In most cases, the aplite is older than the lamprophyric dykes. Aplite and pegmatite are concentrated around the borders of major intrusions. Doleritic dykes with transitional serial affinity but of uncertain age commonly occur in the crystalline basement near Edolo (Val Camonica).

A. DYKES OF THE TONALITIC CYCLE

30. Aplite and pegmatite – Granitic to tonalitic biotite aplite, sometimes with garnet and/or tourmaline and/or allanite and/or molybdenite; biotite or two-mica granitic pegmatite, sometimes with tourmaline and/or garnet.

31. Mafic to intermediate dykes – Dark grey to green porphyritic (plagiophyric) rocks, mostly composed of plagioclase and hornblende, with subordinate biotite and/or clinopyroxene. These dykes are common in the Mt. Re di Castello mass and rare in the central Adamello massif. Chilled margins are common features.

32. Lamprophyre – Green to dark green porphyritic (no plagioclase phenocrysts) rocks of picrobasaltic composition. Olivine, clinopyroxene and Cr-spinel are the main phenocryst phases; most of the groundmass consists of hornblende. These dykes seem to be restricted to the Mt. Re di Castello mass (Mt. Frerone, Lago della Vacca, Passo della Rossola, Cima Sablunera). Chilled margins are typical features. In thin section, these rocks show various degrees of late stage alterations, up to total replacement of the original phenocrysts.

33. Undifferentiated apophyses and dykes – Granular to slightly porphyritic rocks of tonalitic to granodioritic composition (e.g., Pizzo Badile), texturally similar to their massive igneous equivalents; plagiophyric porphyrite (Cima Laione) older than the mafic to intermediate dyke rocks.

B. PRE-TONALITIC and early tonalitic DYKES

34. Porphyrite – Grey, reddish-grey, green or violet hornblende and/or biotite porphyrite (Mt. Frerone, Cima Bondolo - Mt. Rema, Pizzo Badile, Mt. Ignaga, Mt. Colmo, Lago Baitone, Laghi Gelati) and some rare picrobasaltic dykes (Cima Uzza, Val Moja, Lago Baitone). They intrude the crystalline basement and pre-Norian cover rocks, and in most cases show signs of Alpine regional deformation. In the thermal aureole, the porphyrite is partially to totally recrystallised; its age is presumably Triassic. Hornblende porphyrite (upper Val Caffaro) and aplite (e.g., southern slope of Mt. Frerone, Cima di Blumone) crosses folds in Triassic sediments but were deformed during the emplacement of subsequent intrusions. Dykes of uncertain ages in the north-western and south-eastern sectors of the batholith: subalkaline porphyrites of mafic to intermediate composition and rare alkaline basalts (Mt. Sabion); dolerite ("diabase" *Auct.)* in the basement rocks (Edolo); rare small bodies of porphyrite (eastern Val Rendena) and rare diatreme breccias (Roncone), of possible Triassic age.

C. OTHER DYKES

35. Dykes and small masses of quartzite in the north-eastern sector of the Adamello batholith between the Corno Alto - Sostino mass and the Late Variscan pluton of Mt. Sabion. Some of these bodies are younger than the Tertiary intrusions (e.g., Mt. Sostino).

SOUTHERN ALPS

The Adamello batholith is roofed and/or surrounded by Permian-Mesozoic cover sequences (sedimentary and volcanic rocks) and a crystalline basement which includes pre-Permian paraschists, with a Variscan metamorphic imprint and some Upper Paleozoic intrusives.

SEDIMENTARY AND VOLCANIC COVER ROCKS

In the following (English) version of the legend for the sedimentary units only the most important lithological features are reported. Some descriptions of Triassic units are modified with respect to the original (Italian) legend of the map. For biostratigraphic information, readers are referred to the legend on the map. Updated and revised names of fossils may be found in the literature (for Middle Triassic ammonoid faunas, see e.g., Brack and Rieber, 1993; Balini, 1998, and references therein; for updates on Permian flora and ichnofauna, see Cassinis *et al.*, 1999).

CRETACEOUS - Basinal sediments of Cretaceous age are locally preserved tǒ the east of the Adamello batholith and Giudicarie Line. The Lower Cretaceous successions consists of chert-rich pelagic micrite ("Maiolica") and are almost free of terrigenous material. Middle Cretaceous strata, deposited during widespread anoxic conditions, also bear moderate clay contents. In the Late Cretaceous, the slow accumulation of hemipelagic sediments of the "Scaglia Rossa" was interrupted by the sudden influx of siliciclastic-rich turbidite. Conglomerates with quartz and carbonate pebbles (Mt. Sabion) point to the existence of a northern (Austroalpine) mountain chain. In the Maastrichtian, hemipelagic sedimentation of the "Scaglia" resumed. The uppermost Cretaceous Scaglia successions also comprise proximal turbidite with carbonate debris, possibly derived from a northerly adjacent (? Austroalpine) carbonate platform.

JURASSIC - Lowermost Jurassic platform carbonates ("Dolomia Superiore") accumulated in peritidal environments similar to those of the Late Triassic. During the Sinemurian, the carbonate platforms were cut by north-south and east-west striking faults which may, at least in part, have been established on older (e.g., Late Variscan) tectonic lines. After drowning of the platform tops, the entire area became part of the pelagic Lombardian basin. Whereas ammonite-bearing pelagic muds slowly accumulated on submarine topographic remnants located further to the south (Mt. dei Pini, Cima Palone), the basin portions received substantial amounts of bioclastic sand shed from the Venetian platform (Mt. Tofino, Val Concei). In the Late Jurassic, the submarine topography gradually vanished and pelagic sediments of the "Selcifero Lombardo" were deposited over the entire area.

TRIASSIC - In the Adamello area, the Lower Mesozoic sediments may be grouped into three dominant successions. A first transgressive succession follows on top of the continental Upper Permian "Verrucano Lombardo", and mainly consists of the mixed clastic-carbonate Servino Fm. of Early Triassic age. This interval includes the clearly marine gasteropod-oolite-horizon. Upwards, the open-shelf deposits of the "Servino" grade into the evaporite-bearing shallow-water deposits of the Bovegno Cargneules. This unit defines the base of a second super-succession which spans the entire Middle Triassic and a large portion of the early Late Triassic (Carnian). In the Adamello area, the Lower/Middle Anisian consists of neritic limestone with layers of thin marl (Angolo Limestone / "Calcare di Angolo"). A "lower" member of the Angolo Lst., up to 350 metres thick, is well developed in the Giudicarie area. The "upper" member of the Angolo Lst. thickens from Giudicarie towards the west, reaching a maximum of 500 metres in Val Camonica. Along the south-eastern Adamello border, the two members are partly age-equivalent but, in this case, they are separated in space by the platform carbonates of the Dosso dei Morti Limestone ("Calcare del Dosso dei Morti"). The overlying basinal limestone-marl/shale alternations of the Prezzo Limestone ("Calcare di Prezzo") and the starved siliceous carbonates of the Buchenstein Beds ("Formazione di Livinallongo") are rich in pelagic organisms and formed in open-marine conditions. The pelagic successions also contain cm-to-m thick acidic volcaniclastic layers ("Pietra verde") of Late Anisian to Ladinian age. A trend of shallowing basins is evident from the sedimentation pattern recognised in the subsequent basinal clastics of the Wengen Beds ("Formazione di La Valle"). In the vicinity of coeval carbonate platforms, the basinal successions also contain megabreccias and turbidites with platform-derived carbonate debris. The carbonates (Esino Limestone / "Calcare di Esino") of the rapidly expanding platforms eventually occupied a large part of the former basin area. A probably extended period of sea-level lowstand is recorded by sandstone and evaporite-bearing deposits of Carnian age (e.g., S. Giovanni Bianco Fm.) at the base of the third main Triassic succession. Long-lasting peritidal conditions in the Late Triassic gave origin to the growth of thick carbonate successions of the Dolomia Principale. Organic-rich dark limestone and dolomite accumulated in depressions of the large Dolomia Principale platform, as well as in intra-platform troughs.

PERMIAN - Permian rocks are exposed along the western and southern borders of the Adamello batholith. Thicker successions and more coherent outcrops of Permian rocks are found to the south of this area. These sequences are divided in two groups. The "Lower Group" consists of dominant rhyolite and terrigenous sediments, showing rapid lateral variations in thickness and facies. Between Val Trompia and Giudicarie, the so-called "Collio Facies" locally reaches more than 1000 metres in thickness. The "Upper Group" is 250 - 500 metres thick and consists of alluvial clastics, *i.e.* silty, sandy and conglomeratic red-beds.

36. Lombardian-type Flysch *(Turonian p.p. and Maastrichtian)* – Foliated argillaceous marl with intercalations of siliciclastic sandstone, calcsiltite and rare polygenic rudite with carbonate clasts. Thickness up to 200 metres (Val Croina).

37. Shale and sandstone similar to the above unit, but thicker (up to 800 metres, Mt. Sabion area). Large carbonate turbidite bodies within the "Scaglia Rossa" *(Upper Cretaceous)*. Shaly marl and nummulitic breccias *(Eocene)*.

38. Scaglia Rossa *(Cenomanian and Turonian p.p.)* – Micritic limestone with light grey to white ("Scaglia Bianca" *Auct.)* and dark red colours in the upper part. Average thickness around 40 metres.

39. Val Croina Formation *(Barremian p.p. and Albian)* – Interbeddings of grey-green and/or dark grey intensively foliated marl and light grey micritic limestone. The limestone shows thin bedding and contains dark micritic burrows (*Chondrites*); the succession grades upwards to marly limestone of the "Scaglia Variegata" type. Thickness around 90 metres.

40. Maiolica / "Biancone" *Auct. (Tithonian p.p. and Barremian)* – White to yellowish, slightly marly limestone grading upwards into densely stratified calcareous marl with, in the topmost portion, intercalations of black marl; bands and nodules of chert are common in the lower part and less frequent higher up. Submarine slump breccias occur in the basal portion of the unit ("Brecce di Ballino" *Auct.*). Average thickness around 120 metres.

41. Selcifero Lombardo *(Upper Bajocian and Tithonian p.p.)* – Radiolarite and chert layers of various colours; interbedded upwards with siliceous marl and marly limestone with rare *aptychus*; reddish limestone with ammonites ("Rosso ad Aptici" *Auct.*). Average thickness around 60 metres.

42. Tofino Formation / "Calcare di Medolo" *Auct. (Lower Liassic p.p. and Lower Bajocian)* – Evenly bedded siliceous limestone with radiolaria and sponge spicules, alternating with turbiditic and frequently channelized carbonate bodies. Megabreccia layers and bioclastic carbonate turbidite, sometimes with oolites, occur in the lower and middle portions. The upper part of the formation consists of brown-grey or rusty, partly siliceous limestone ("Formazione di Concesio" *Auct.*). Thickness between 300 - 800 metres.

43. Calcari Grigi and **Misone Limestone** *(Lower and Middle Liassic p.p.)* – Grey limestone with stromatolite; oolithic and bioclastic limestone.

44. Dolomia Superiore / "Corna", "Dolomia a Conchodon", "Dolomia Selcifera", "Dolomia del Pichea", *Auct. (Upper Rhaetian and Lower Liassic p.p.)* – Eastern sector: thick-bedded, light grey dolomite, calcareous dolomite and limestone with oolitic intervals, sometimes exhibiting sucrosic textures. South-eastern sector: compact limestone with transitions to dolomitic limestone and dolomite ("Dolomia del Pichea").

45. Zu Limestone ("Calcari and Calcari dolomitici", "Strati a *Triasina*") *(Rhaetian)* – Eastern sector: dark grey limestone and marly limestone, grading to dolomite and alternating with shaly dark marl; thin-bedded black shale with intercalations of neritic limestone.

46. Dolomia Principale *(Upper Carnian and Norian)* – Eastern sector and Mt. Colombine: thick-bedded dolomite and dolomitic limestone, micritic and partly recrystallised, in 1-5 metre-thick layers, sometimes with stromatholitic structures and, in the basal portion, intraformational breccias.

Contact-metamorphosed sediments: Saccharoidal white dolomite marble with forsterite, spinel and phlogopite among other minerals; diopside-garnet calc-silicate rocks and impure marble, with intercalations of thin hornfels layers (Mt. Colombine, Cima Uzza, Val Caffaro). Brucite marble ("Predazzite") may occur in the vicinity of intrusions.

47. San Giovanni Bianco Formation *(Upper Carnian p.p.)* – Alternances of dolomitic marl to marly dolomite and greenish shale layers in dm-thick beds; lenticular intervals of cavernous limestone, cargneules and dolomitic breccias; yellowish vuggy dolomite and dolomitic oosparite.

Contact-metamorphosed sediments: Calcite/dolomite marble, hornfels layers and cavernous marble (Mt. Frerone, Cima Uzza), difficult to differentiate from the metamorphic lithologies of the Breno Formation.

48. Breno Formation *(Carnian)* – Lower part: light grey bedded limestone, sometimes oolithic; stromatholitic and *fenestrae*–bearing intervals with dessication structures (tepee and breccias), pisoids and sporadic large gasteropods. Upper part: well-bedded sometimes vuggy to saccharoidal dolomite and dolomitic limestone.

Contact-metamorphosed sediments: see description of San Giovanni Bianco Formation. Skarn in lithologies probably referable to the Breno Fm. (south-west of Malga Breguzzo) contains the rare mineral ludwigite.

49. Lozio Shales / "Argilliti di Lozio" *(Lower Carnian)* –

Dark laminated shale, sometimes with pyrite nodules, alternating with black to grey-brown marl in the upper part.

Contact-metamorphosed sediments: Homogenous brown-violet hornfels with quartz, plagioclase, biotite, cordierite and muscovite (e.g., Mt. Frerone, upper Val Caffaro, Forcel Rosso).

50. Esino Limestone *(Upper Ladinian and Lower Carnian)* – Light grey to pinkish limestone and dolomitic limestone and local dolomite (eastern sector), usually poorly bedded; locally they contain corals, algal and crinoid remnants. Thickness: 50 - 200 metres.

Contac-metamorphosed sediments: White marble with one or more of the following minerals: forsterite, spinel, thulite, phlogopite, diopside, tremolite, graphite, perovskite; coarsely-bedded grey marble with irregular intercalations of cavernous calcite marble (Cima Uzza). Along the contacts with the intrusive rocks the original carbonates are often transformed into green skarn bearing diposide, pargasite, spinel and clintonite among other minerals (e.g., Cima Uzza area).

51. Pratotondo Limestone *(Upper Ladinan and Lower Carnian)* – Micritic black and evenly bedded limestone, mainly of turbiditic origin, containing thin marly intercalations in the lower part. Thickness 25 - 150 metres.

Contact-metamorphosed sediments: Evenly bedded calcareous marble with thin dark hornfels layers containing spinel, phlogopite and rare scapolite (Forcel Rosso).

52. Wengen Beds / "Formazione di La Valle" or "Wengen" *Auct. (Upper Ladinian and lowermost Carnian?)* – Dark marl and siliciclastic to calcareous or tuffaceous sandstone, locally with abundant plant remains; well-bedded marly limestone and shale of variable colours. Thickness ranges between a few metres and 150 metres.

Contact-metamorphosed sediments: Shale is transformed into biotite-rich dark hornfels with rusty surfaces (alteration of pyrrhotite); marly rocks are converted to biotite-rich amphibole and/or diopside calc-silicate; fine-grained grey marble bears scapolite (Cima Uzza, Forcel Rosso); meta-sandstone bears newly formed biotite. In elevated metamorphic conditions, the marble-rich lithologies contain Ca-silicates; scapolite, diopside, vesuvianite, garnet and K-feldspar are found in the hornfels layers (Cima Uzza).

53. Buchenstein Beds / "Formazione di Livinallongo" or "Buchenstein" *Auct. (uppermost Anisian and Ladinian p.p.)* – Distinctly bedded nodular grey limestones with chert nodules and bands and intercalations of thin shale and volcaniclastic siltstone and sandstone ("Pietra Verde" *Auct.*). Thickness: 20 - 40 metres.

Contact-metamorphosed sediments: light grey nodular calcitic marble interbedded with violet (biotite) or greenish (diopside) hornfels layers (e.g., Cima Uzza, Mt. Frerone, upper Val Caffaro, Forcel Rosso); rims of wollastonite frequently occur along the boundaries between original limestone and cherty nodules. Conspicuously speckled thin hornfels layers with cordierite or corundum (e.g., Mt. Frerone, Cima Uzza) also occur.

54. Prezzo Limestone *(Upper Anisian)* – Irregularly nodular dark marly limestone interbedded with marly shale (lower part); evenly bedded alternations of dark limestone and marl (upper part). Thickness 80-100 metres in south-eastern Adamello, around 50 metres in central Adamello, more than 100 metres in Val Camonica.

Contact-metamorphosed sediments: Dark grey marble with tiny crystals of scapolite and tremolite, alternating with hornfels layers rich in biotite, K-feldspar, scapolite and vesuvianite among other minerals (Bazena-Val Fredda, Cima Uzza, Forcel Rosso); alternating calc-silicate-rich carbonate rocks and diopside-garnet-vesuvianite hornfels layers (e.g., Mt. Frerone).

55. Angolo Limestone *(Lower and Middle Anisian)* – Lower member: irregularly but generally thick-bedded, often bioclastic limestone with thin marly intercalations and strongly bioturbated nodular intervals. Upper member: thinly and evenly bedded alternations of neritic limestone and marl; nodular intervals also occur. This unit is well-developed to the west of Val Daone, with thicknesses increasing towards Val Camonica. Where the upper member of the Angolo limestone is lacking (e.g., in the Giudicarie area), the transition to the overlying Prezzo Limestone is marked by a thin nodular limestone interval, usually rich in brachiopods ("Banco a Brachiopodi" *Auct.*). Thickness 50 – 700 metres.

Contact-metamorphosed sediments: Regular alternations of thin beds of light calcite marble, calc-silicate rich carbonate rocks and hornfels-layers containing garnet, fassaite (diopside), epidote, phlogopite, and occasionally vesuvianite and wollastonite (e.g., Bazena, Cima Uzza).

56. Dosso dei Morti Limestone *(Middle Anisian)* – Light lagoonal limestone with oncoids, subtidal limestone and dolomitic limestone (carbonate platform with traces of sporadic emergence). Lateral equivalent of the Angolo Limestone (Giudicarie sector only). Thickness: 100-400 metres.

Contact-metamorphosed sediments: White calcite marble of coarse grain size, containing tremolite and Mg-chlorite. Occasional thin intercalations of reddish-brown hornfels occur in the Cima Uzza area.

57. Elto Dolomite *(uppermost Lower Triassic? and Lower Anisian?)* – Massive or thin-bedded grey to yellowish dolomite and dolomitic limestone (near Ceto). Thickness: less than 100 metres.

58. Bovegno Cargneules / "Carniola di Bovegno" *(uppermost Lower Triassic? and Lower Anisian?)* – Mostly vuggy, light grey and yellowish limestone and dolomitic limestone, locally grading to autoclastic breccias containing evaporite minerals; local lenses of gypsum and anhydrite also occur. Due to strong tectonic overprint, no reasonable estimates can be given for the primary undisturbed thickness of this unit.

Contact-metamorphosed sediments: Dolomitic and calcareous marble with forsterite and spinel; cavernous marble with phlogopite, diopside, amphibole, forsterite, spinel, clinohumite and talc (e.g., Forcel Rosso).

59. Servino Formation / "Servino" or "Werfen Fm." *(Lower Triassic)* – Arenaceous and micaceous marl and limestone with intervals of *"Oolite a Gasteropodi" Auct.*; laminated reddish to violet sandstone and siltstone; variously coloured marl; greenish-grey sandy calcareous marl. Micritic dolomite, limestone and silt prevail in the lower part of the formation. Thickness: 100 - 150 metres.

Contact-metamorphosed sediments: Alternating violet (cordierite, muscovite, biotite, andalusite, fibrolite, tourmaline) and green (diopside, pargasite, plagioclase, scapolite) hornfels and marble layers containing tremolite, forsterite and spinel. Zeolite minerals (chabasite, gismondine, offretite, mesolite, scolecite) are found in cavities (Forcel Rosso). Yellowish calcitic marble bearing phlogopite, diopside and tremolite are present in the basal part of the formation.

60. Verrucano Lombardo / "Formazione di Mt. Mignolo" *(Upper Permian)* – Lower part: red sandstone interbedded with conglomerates containing clasts of quartz and volcanic rocks. In the geological map, a deeper interval (a), *i.e.*, the so-called *"Conglomerato e Arenaria della Val Daone"*, is included in this unit. It comprises sandstone and conglomerates with clasts of quartz, sediments, volcanic and basement rocks. Plant debris is locally found in siltstone and shale. The age of the 100-metre-thick Val

azione cartografica : F. TODESCO[2]

Daone Conglomerate is uncertain. Upper part: reddish sandstone alternating with red siltstone.

Contact-metamorphosed sediments: Grey-greenish blastopsammite with recrystallised matrix bearing biotite, muscovite and tourmaline (Val Daone); grey to pink quartz-rich biotite-cordierite-andalusite hornfels, locally fibrolite-bearing (e.g., Lago Baitone, Forcel Rosso); tourmaline-bearing pegmatitic veins (Lago d'Avolo). In many places (e.g., Lago d'Arno, Lago Baitone) the hornfels layers show conspicuous spotted textures *("Leopardensandsteine" Auct.)*. Pink to reddish-brown hornfels layers with metamorphosed calcrete nodules (transformed to patches containing actinolite, diopside, and other minerals) have also been observed at several localities (e.g., Val Daone, Lago Baitone).

61. Dosso dei Galli Conglomerate *(Lower Permian)* – Area between Val Camonica and lower Giudicarie: Coarse conglomerate with clasts of quartz, volcanic and basement rocks grading to sandstone and finer-grained deposits often rich in mica; volcanoclastic intercalations also occur. Thickness varies between 0 and 450 metres. Red colours dominate the upper part of the unit; deeper strata also show greenish and grey colours. The lower transition is characterised by interbeddings with lithologies of the Collio Formation. Conspicuously bioturbated red sand- and siltstone known as *"Pietra Simona"* are interbedded in the lower part of the unit between Val Trompia and Val Caffaro; towards Val Camonica these lithologies also occur at higher levels and, in some cases, are found even above the Dosso dei Galli Conglomerate (Boario). The maximum thickness of Dosso dei Galli type conglomerates in the Adamello border successions is 50 metres (Laghi Gelati, Lago Baitone). The formation is partly age-equivalent with the "Collio Formation" and the early Permian "Porphyries". In Val Trompia and Val Caffaro, the unit is capped by a distinct interval of rhyolite *("Vulcaniti di Auccia")*, equivalents of which may also be recognised in the Adamello border rocks.

Contact- metamorphosed sediments: Metaconglomerate hornfels with newly generated biotite, muscovite, actinolite, chlorite and tourmaline (Lago Baitone, Forcel Rosso).

62. Collio Formation *(Lower Permian)* – Lithologically heterogeneous unit consisting of alternations of shale, silt and sandstone of various colours, but usually greenish to dark grey, sometimes with ripple marks, imprints of rain drops, mud cracks, and traces of arthropods and tetrapods, among other features. Locally, carbonate lenses also occur. In the type-area, south of the Adamello batholith, the clastic successions of the Collio Fm. and associated rhyolitic volcanic to pyroclastic rocks (ignimbrite, *"Porfidi quarziferi" Auct.*) reach a thickness of more than 1000 metres.

63. Lower Permian volcanics / *"Porfidi quarziferi" Auct.* – Pale-violet mainly rhyolitic lava, ignimbrite and tuff underlying the Collio Formation. Rare subvolcanic bodies are hosted in the Collio Fm. (Bagolino and Val Giulis). In the Val Trompia - Val Caffaro area, a distinct interval of phenocryst-rich violet ignimbrite *("Vulcaniti di Auccia" Auct.)* cover the underlying thick succession of continental clastics. In the immediate Adamello border successions, the thickness of the meta-volcanic rocks ranges between a few metres (Laghi Gelati) and 150 metres.

Contact-metamorphosed lithologies: Grey, usually compact, locally also slightly foliated rhyolite and tuff hornfels with phenocrystic quartz relics. Contact minerals include muscovite, biotite, and scarce amphibole. Andalusite and/or sillimanite and/or fibrolite may be minor constituents (Lago Baitone, Forcel Rosso, Lago d'Avolo).

CRYSTALLINE BASEMENT

The Southalpine basement mainly consists of polydeformed paraschists characterised by pre-Permian (probably Variscan) regional metamorphism, in conditions of greenschist (quartz-phyllite, albitic schist) to amphibolite facies (garnet-staurolite micaschist, e.g., Val Breguzzo). It includes minor concordant bodies of augengneiss and albite-rich amphibolite, both derived from pre-Variscan protoliths, and scarce interbeddings of marble and carbonate schists (Val Seria). The basement is also reported with classic regional terms as "Edolo Schists" (west of the Adamello batholith), "Rendena Schists" (east), or "Maniva Schists" (south). In Val Camonica, the supposedly deepest exposed parts of basement rocks in the Cedegolo Anticline consist of an association of augengneiss, amphibolite and quartzite ("Forno d'Allione Schists" *Auct.*). The Southalpine basement is intruded and thermally metamorphosed (biotite, andalusite, cordierite) by a few Late Paleozoic granitic bodies (Mt. Sabion, Caderzone; for isotope age data see Martin *et al.*, 1996, and references therein). Much more pervasive and extensive is the metamorphic aureole produced by the Tertiary Adamello intrusions. The first evidence of the thermal overprint, far from the contact, is given by new biotite and recrystallised quartz; approaching the contact, the Variscan schistosity progressively vanishes and is finally replaced by massive andalusite-cordierite ± sillimanite ± corundum ± hercynite hornfels rocks.

64. Upper-Paleozoic intrusive bodies – a) Coarse-grained hornblende-bearing biotite granodiorite and monzogranite (Mt. Sabion and Caderzone plutons, Zeledria small bodies). Radiometric ages: Mt. Sabion 272 Ma (b), Caderzone 267 Ma (b); Sr_0: 0.7098. **b**) Two-mica monzogranitic aplite, in places bearing andalusite and/or cordierite; marginal facies and dykes of Mt. Sabion pluton. Na-metasomatism (albitite) in the southern Mt. Sabion edge (Giustino). Radiometric ages: 271 Ma (m, b); Sr_0: 0.7123.

65. Metapelite – a) Sericite-chlorite quartz phyllite, locally carbonate-bearing, grading to albitic paragneisses *("Quarzlagenphyllit" Auct.)*; biotite- and/or garnet-bearing muscovite-chlorite schists and paragneisses (e.g., Mt. Sabion, Val Breguzzo, Val Caffaro, Val Saviore, Cedegolo); garnet-staurolite micaschists (Val Breguzzo) and rare intercalations of chlorite schists.

Contact-metamorphosed rocks: Spotted, nodular biotite-andalusite-cordierite schists occur in the outer aureole; inner aureola: cordierite-andalusite and/or sillimanite, K-feldspar ± corundum, spinel and plagioclase hornfels; schists with porphyroblastic andalusite; contact migmatite (Laghi Gelati south of Corno Baitone), including cordierite-bearing leucosomes and biotite-sillimanite-cordierite-plagioclase restite. **b**) Carbonaceous phyllite, locally mylonitic (Val di Sole, upper Val Camonica).

66. Marble – Metamorphic limestone (e.g., Castello dell'Acqua, Val Brandet) and impure marble.

Contact-metamorphosed rock: calc-silicate hornfels (Val Seria).

67. Quartzite – Foliated quartzite and micaceous-chloritic quartz-rich schists, grading to paraschists and paragneisses (with increasing mica and/or chlorite and albite).

Contact-metamorphosed rocks: massive quartzitic hornfels, including biotite, andalusite and/or fibrolite; cordierite and K-feldspar near contacts.

68. Amphibolite – Metre-scale lenses and bands of grey-greenish amphibole-albite ± epidote and chlorite rocks, mainly occurring in metapelite-metapsammite transition zones, and locally associated with albite-chlorite-epidote or actinolitic schists.

Contact -metamorphosed rocks: biotite-bearing plagioclase-amphibole hornfels.

69. Leucocratic orthogneiss (*"Colmiti"* and *"Gneiss del Palone di Sopressà" Auct.*) – Whitish biotite-bearing muscovite-chlorite flaser to augengneiss (K-feldspar porphyroclasts partly altered to chessboard albite e.g., Mt. Colmo, Lago Baitone, Breguzzo and S. Valentino valleys).

Contact-metamorphosed rocks: quartz-K-feldspar-sillimanite banded hornfels, with minor biotite and plagioclase.

AUSTROALPINE

CRYSTALLINE BASEMENT

The Austroalpine basement is exposed in the northern sector of the map. It is subdivided into two main tectonic units: the structurally composite Tonale Schists (Tonale Zone) and the underlying Ortler nappe. The "Tonale Schists" include the Tonale and Ulten units, located respectively west and east of the Pejo valley. They consist of Variscan high-grade metasediments (kinzigite, migmatite and granulite *Auct.*), with multiple interleavings of quartzite, marble, granitic gneiss, amphibolite and partly serpentinised spinel-garnet peridotite. More information may be found in Godard *et al.* (1996), Martin *et al.* (1998), Del Moro *et al.* (1999). The Ortler Nappe is exposed in the northwestern corner of the map. It mainly consists of micaschists and quartzphyllite, with minor interbeddings of metabasite and aplitic-pegmatitic bodies. The Tonale Schists are overthrust on the Ortler Nappe, the tectonic contact being marked by a thick mylonitic horizon of Cretaceous age, locally masked by late subvertical faults (Pejo Line). To the south, the Austroalpine basement is bounded by the Tonale Line, which extends eastwards up to the Giudicarie Line, near Dimaro. The Tonale Line is a wide mylonitic-cataclastic zone, locally including tectonic slices of Permian-Triassic clastic and carbonate rocks. The Austroalpine basement is crossed by Tertiary andesitic dykes and small granitic-granodioritic and dioritic apophyses, locally foliated (Val Mortirolo, Mt. Pagano).

70. Weakly foliated intrusive bodies of unknown age - **a**) Granite and granodiorite; **b**) amphibole-bearing diorite (Val Mortirolo, Mt. Pagano).

71. Metapelite and metasandstone of Ortler nappe – Quartz phyllite and phyllitic schists, locally bearing albite, biotite and/or garnet; staurolite-bearing garnet micaschists and paragneisses; multiple interleavings of quartzite, marble and albite-epidote-biotite (or amphibole) gneisses and amphibolites (e.g. Val di Pejo, Passo Cercen).

72. Tonale Schists (*"Kinzigitic Gneiss"* and *"Granulite" Auct.*) – Biotite-sillimanite-garnet paragneisses (west of Val di Pejo) and their deformed and retrogressed equivalents (chlorite-sericite schists); kyanite-staurolite-garnet gneiss; garnet-staurolite bearing two micas or biotite paragneisses and micaschists; migmatite (east of Val di Pejo).

73. Orthogneiss – Leucocratic bodies transposed parallel to the Variscan schistosity; in the proximity of the Tonale Line, they display extensive ductile and brittle deformation features (*"Stavel Gneiss"*).

74. Quartzite – Massive rocks, grading either to quartzitic gneiss (locally amphibole-epidote-biotite-bearing: from igneous protoliths ?) or staurolite-bearing quartzitic schists (e.g., Mt. Comegiolo, Punta Ercavallo); minor amphibole-bearing garnet-clinopyroxene quartzite (Passo Tonale).

75. Marble – Tabular and lenticular interbeddings of micaceous saccharoidal marble; impure marble and fels rich in quartz, feldspar, white mica, clinopyroxene and amphibole (Mt. Redival, Passo Cercen), sometimes bearing garnet, monticellite and vesuvianite; marble with olivine nodules (e.g., Mt. Tonale, Mt. Serodine, P. di Albiolo).

76. Amphibolite – Mafic rocks with compositional layering due to alternations of hornblende-rich and plagioclase-rich layers, locally bearing garnet and/or epidote and/or zoisite and/or quartz; amphibole-rich gneisses and schists.

77. Ultramafic rocks – Mantle peridotite and associated alteration products (talc schists, serpentinite); plagioclase-amphibole-quartz-titanite pyroxenite (Passo Tonale, Punta di Albiolo); pyroxene-rich gneiss and fels with minor garnet ± zoisite and titanite.

78. Aplitic and pegmatitic dykes

79. Cataclasite, mylonite and diaphtorite - Shear zones along the Tonale Line (Passo dell'Albiolo) and locally inside the Southalpine basement.

Addendum

To the list of survey geologists *("Quadro dei Rilevatori")* for the period 1937-1965, the following should be added: A. Bianchi and Gb. Dal Piaz (for sectors k, r, s, u). The name of S. Morgante is missing from the list of the revisers (for sectors k, r, s).

Erratum

On the present map, an earlier draft version has been printed erroneously as the tectonic sketch-map *("Schema dei rapporti strutturali")*. As indicated in section on "Tectonic Structures" of the Explanatory Notes, for the area west of the Adamello superunit, the printed scheme is partly incorrect. The traces of additional large-scale folds in the south-western border of the Mt. Re di Castello superunit are indicated in fig. 9 of these notes.

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