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REPORT ON A STRUCTURAL AND SEDIMENTOLOGICAL ANALYSIS IN THE URANIUM PROVINCE OF THE OROBIC ALPS, ITALY

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ABSTRACT

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Detailed structural and sedimentological studies have been conducted in two areas near the Val Vedello uranium mine in northern Italy These studies indicate that both the Variscan basement (locally called the Orobic basement) and the Permian cover rocks were thrust southward during the Alpine orogeny. Variscan mylonitic zones were rejuvenated during the Alpine orogeny and became fault boundaries for the Permo-Triassic basins. Alpine faults also are related to contemporaneous east—west folds and these faults have displaced Permo-Triassic uranium deposits. Uranium mineralisation is attributed to a Late Permian to Triassic geothermal event which leached uranium from Permian ignimbrites and transported it along Permo-Triassic faults. Detailed mapping indicates that the host sediments formed in an arid, closed basin characterised by alluvial fans and perennial saline lakes.

1 INTRODUCTION

Structural investigations were undertaken during 1982 and 1983 in the Southern Alps, northern Italy on the Orobic basement and its Upper Paleozoic volcanic and terrigenous cover with the aim of better placing the Val Vedello uranium deposits in the regional tectonic setting of the Orobic Alps (Fig. 1).

This interest appears to be justified by a number of observations that show the uranium mineralisations to be related to fault lines and to specific stratigraphic levels in the Val Vedello uranium mine and its surroundings. In

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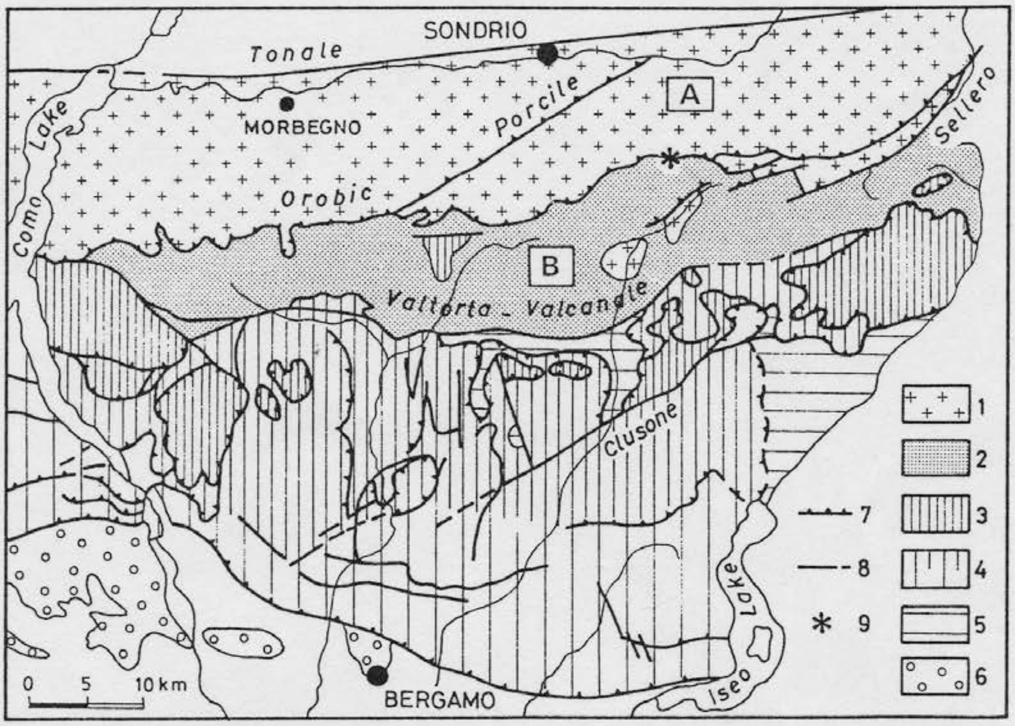

Fig. 1. Tectonic sketch map of the Orobic—Bergamask portion of the Southern Alps between lakes Como and Iseo, simplified from Gaetani and Jadoul (1979); Jadoul and Rossi (1982), and Castellarin and Sartori (1983). *Legend: 1* = Variscan Orobic basement units; *2* = "Orobic anticline" thrust system, mainly Permian sequences; *3* = upper cover units *4* = lower cover units (a) and faulted-fold units (b); *5* = lowermost parautochthonous units; *6* = southern fold—thrust belt (mainly of Tortonian age); *7* = thrusts and faulted folds; *8* = faults; *9* = Val Vedello uranium mine; mapped areas of Figs. 2 (*A*) and 6 (*B*) are located in *squares*.

the sedimentary cover a very low metamorphic grade is associated with a relatively simple folding pattern and with a more complex grid of tectonic lines marked by faults, overthrusts and mylonitic zones of Alpine age. The underlying basement, characterised by amphibolitic assemblages with a later greenschist imprint, both of Variscan age, shows synmetamorphic folding and later, apparently postmetamorphic, superposed folds. The possibility therefore exists of separating (within the basement) the tectonic imprint connected with the Variscan metamorphic history from the structures related to the Alpine event of thrusting and folding in the cover.

The cover tectonics, of Alpine age, was believed by De Sitter and De Sitter-Koomans (1949) and De Jong (1967, and references therein) to be a gravitational effect. These authors made the first modern geological description of the Orobic—Bergamask Alps. However, a later interpretation of the tectonics was of a compressive imbricated thrust system of Meso-Alpine age (Gaetani and Jadoul, 1979) or of Paleogene age (and even earlier) (Castellarin and Sartori, 1983).

In our study the degree of penetrative Alpine fold deformation of the basement, and thrusting of the cover, are evaluated in the light of detailed structural mapping performed in two areas: the first is located in a portion of the basement between the Porcile fault line and the Orobic fault zone near Pizzo di Rodes and the second in the cover sequences of the Monte Cabianca—Pizzo Salina area (Fig. 1). This latter map attempts to define a depositional model of the upper clastic member of the Lower Permian Collio Formation and to provide a more precise frame of reference for describing the detailed tectonics of Alpine age in the test area.

2. GEOLOGIC SETTING

The Orobic—Bergamask Alps extend between the Tonale (Insubric) line and the recent deposits of the Po Plain. They include the Variscan (locally Orobic) basement units and the allochthonous and parautochthonous cover units of the Bergamask Prealps, respectively lying north and south of the Orobic tectonic line.

2.1 Basement rocks

The basement of the Orobic Alps has been affected by Variscan (or even pre-Variscan?) orogenic events before the deposition of the Upper Carboniferous—Permian cover, and has later been fragmented by the Permian and Alpine tectonic phases. It is composed of two units, probably referable to a single Lower Paleozoic sedimentary sequence. The first is mainly composed of metapelites and quartzites which include the Edolo Mica Schists and the closely similar Ambria Phyllites of the *Geological Map of Italy*, scale 1.100,000 [sheets *18* (Sondrio) and *19* (Tirano), respec. Bonsignore et al., 1971, and Beltrami et al., 1971, and references therein] The second corresponds to a metapsammitic sequence, also known as the Morbegno Gneisses. In addition, a number of flat bodies of orthogneisses derived from Late Caledonian intrusives and subvolcanics), minor metabasites, metagabbros, carbonate-rich paraschists, marbles and some Late Variscan deformed granitoids also occur.

Two tectonometamorphic events affected these sequences; the first developed under polyphased intermediate- to low-pressure amphibolite-facies assemblages (mainly garnet, biotite and plagioclase ± staurolite ± kyanite ± sillimanite; Bocchio et al., 1980; Crespi et al., 1980), possibly grading into coeval greenschist associations, and produced a group of foliations now recognisable as S_1 The second tectonometamorphic event developed a pervasive S_2 mineral layering, zones of grain-size reduction in quartz and white micas, mylonitic zones and an irregularly distributed retrogradation under greenschist conditions.

The F_3 fold deformation in the basement is not associated with pervasive regional foliations; its age is Alpine because it also deforms the sedimentary cover all over the Orobic—Bergamask Alps. This phase of deformation is coherent with a model of south-verging thrust stacks and faulted folds as depicted by Dozy (1935), Dozy and Timmermans (1935 and De Sitter and De Sitter-Koomans (1949) for the entire Orobic—Bergamask belt and, further to the east, by Brack 1981, 1983 1984) in the Camonica valley where it predates the Adamello intrusives.

The F_3 fold generation is cut by andesite dykes probably related to the Tertiary calc-alkaline magmatic activity developed along the Peri-adriatic lineament. Siderite veins, with minor sulphides, quartz and baryte of Alpine age also occur along faults of the Orobic system.

2.2. Sedimentary and volcanic cover

The Upper Paleozoic succession, which unconformably covers the Variscan basement, consists of the "Basal Conglomerate" (Upper Carboniferous?—Lower Permian), followed by volcanogenic and terrigenous sequences of the "Collio Formation" (Lower Permian), and by the overlying "Verrucano Lombardo" (Middle?—Upper Permian) (Assereto and Casati, 1965 Cassinis, 1966; Casati and Gnaccolini, 1967· Beltrami et al. 1971 Bonsignore et al., 1971).

The *Basal Conglomerate* is discontinuous and is organised into two superimposed upward-fining cycles, each 50 m thick, formed by moderately sorted cobble conglomerates and showing high compositional maturity (80% quartz, 20% basement rocks, with rare intermediate volcanics). Both are capped by reddish-mauve highly bioturbated sandstones and siltstones. They represent a sedimentary product of a braided plain depositional environment. The paleocurrent pattern in the Fregabolgia—Grabiasca area shows a main trend of sediment transport toward the south-southeast.

The overlying *Collio formation* comprises a lower member ($\sim$ 500 m thick), mainly formed of rhyolite ignimbrites, tuffs and minor lavas, interfingering with lacustrine and alluvial deposits. This volcanic activity is thought to have been caused by partial melting of the South Alpine continental crust under a highly anomalous geothermal gradient.

The upper terrigenous member of the "Scisti di Carona" 1000 m thick, consists of interfingering of sandy-shaley and ruditic deposits. The rudites characterize the marginal deposition and to the west are represented by the alluvial-fan Ponteranica conglomerates. To date, scanty information exists for the eastern margin, which is less well exposed.

The Verrucano Lombardo rests unconformably over the Carona Schists and contains red conglomerates and sandstones, deposited in braided plains and alluvial plains crossed by meandering rivers. It is capped by the Scythian marine fossiliferous Servino Formation.

3. BASEMENT HISTORY IN THE LAGHETTI DI S. STEFANO—PIZZO BIORCO AREA

The description of the structure of a portion of the Orobic basement situated 5 km NE of the Val Vedello uranium mine (Fig. 1) forms the basis for understanding the Variscan tectonometamorphic history An area around Laghetti di S. Stefano has been mapped (Fig. 2) and cross-sections (Fig. 3) constructed. It is located close to an area mapped in detail by AGIP Nucleare (1983), in which the Permian cover is also represented. A structural cross-section between the two maps was studied to ensure consistency of the connection between them *C—C* in Fig. 3).

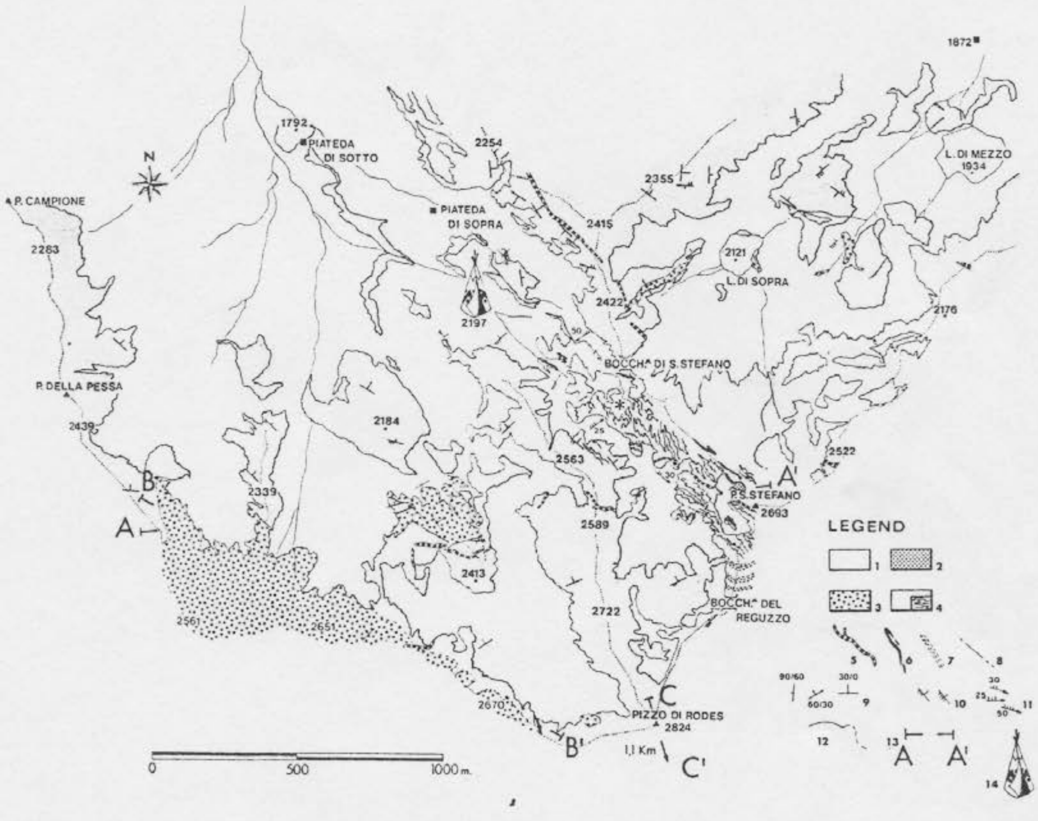

Fig. 2. Geological map of the Laghetti di S. Stefano—Pizzo di Rodes area, Orobic basement, located in Fig. 1. It is reduced from an unpublished 1 5000 map; the quartzitic stripes are originally mapped at 1 .200 to 1:1000 scales. *Legend.* *1* = Quaternary cover and pre-Permian basement; *2* = hornblende—garnet-biotite Variscan metagabbro; *3* = two mica—garnet Variscan orthogneisses (Pizzo Meriggio Gneisses); *4* = garnet-biotite Variscan mica schists (Edolo Mica Schists and Ambria Phyllites), locally with interlayered micaceous quartzites; *5* = Tertiary unmetamorphosed andesite dykes; *6* = Variscan mylonitic zones; *7* = Alpine mylonitic zones. *Symbols:* *8* = faults; *9* = attitude of lithological layering with dip; *10* = attitude of successive foliations S_2, S_3, S_4 (ages indicated by *barbs*); *11* = axes of successive fold generations (ages indicated by *barbs*); *12* = geological boundaries; *13* = location of cross-sections of Fig. 3 *14* = good camp site. The *asterisk* on the map locates the superimposed folds of Fig. 4.

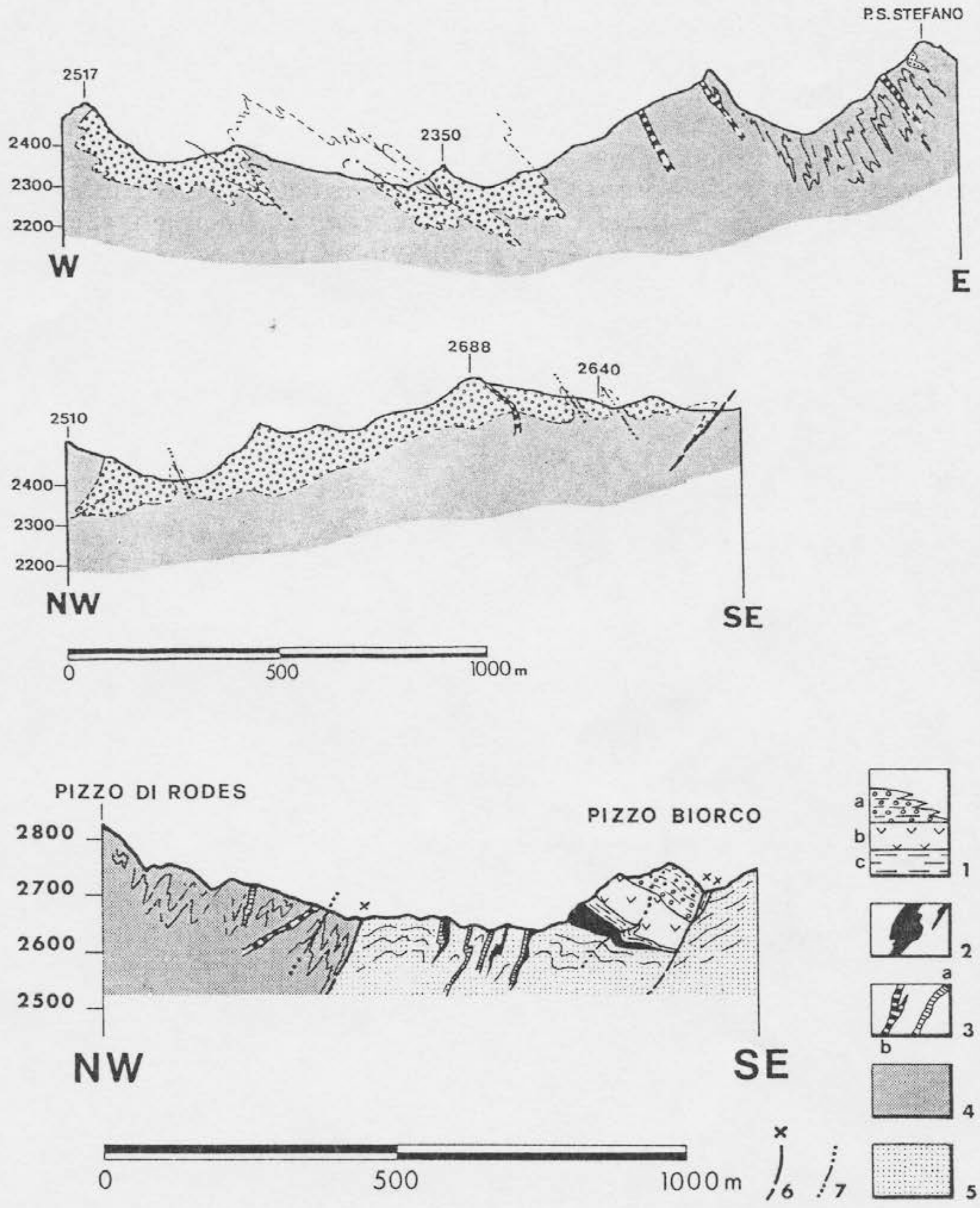

Fig. 3. Cross-sections showing megasuperimposed folds of pre-Alpine age (*A—A* and *B—B'*) and the basement—cover relationships (*C—C'*) in the Laghetti di S. Stefano—Pizzo Biorco area. The legend of sections *A—A* and *B—B'* corresponds to that of Fig. 2. Traces of axial surfaces of folds are *dashed-stippled lines* with *number of stipples* corresponding to fold generation. The legend of cross-section *C—C'* is as follows: *1* = Collio Formation, mainly arenaceous (*1*a: debris flow; *1*b: ignimbrites; *1*c: siltites); *2* = mylonitic zones; *3* = dykes (*3*a. Tertiary unmetamorphosed andesites; *3*b: foliated pre-Alpine andesites); *4* = garnet-biotite Variscan mica schists, *5* = biotite-garnet ± staurolite Variscan gneisses; *6* = faults; *7* = trace of axial surfaces of F_3 folds.

Two main lithological complexes are exposed in the Laghetti di S. Stefano area. a sequence of mica schists, rich in quartz, with albite, chlorite and green-brown biotite, preserving relics of garnet and red biotite (Edolo Mica Schists and Ambria Phyllites) and quartz, albite, chlorite and epidote orthogneisses, with magmatic relics of albitised K-feldspar and metamorphic relics of garnet and red biotite (Pizzo Meriggio Gneisses). The orthogneisses occur in bodies of several kilometres size and in thin bands or pods.

A small lens of amphibolitised metagabbro is embodied within a mylonitic band in the mica schists.

Swarms of quartzites are intercalated in the mica schists; together with the orthogneiss bands they provide a basic geometrical reference for compiling structural maps. Different scales of mapping had therefore to be used to collect the complete geometrical information on the synmetamorphic tectonics recorded in variably thick multilayers.

The sequence of pervasive ductile deformations of the mica schists and interlayered quartzites revealed by the overprinting relationships shows two earlier sets of isoclinal folds (F_1 and F_2). These two groups display interference patterns of type *3* and less frequently of type *2* (Ramsay 1967); the orientation of the b_1-axes is poorly defined. F_1 folds are rootless and may rarely be traced continuously over some tens of metres. Spectacular interference patterns of type *2* (Fig. 4) and less frequently of type *3* are formed by overprinting of F_3 on F_2 or F_1 folds. The F_3 structures are open folds, with steep axial surfaces closely E—W striking; axial-plane-related faults or mylonitic zones occur commonly within large folds in the Permian cover (*C—C* in Fig. 3). F_3 folds are regional structures which correspond to those mapped by Dozy 1935 and by Dozy and Timmermans (1935). These authors clearly stressed the connection between the F_3 folds of the basement and the large, commonly faulted folds in the overlying sedimentary sequences. Similarly a correspondence of this geometrically coherent folding both in the basement and in the cover, that coincides in our scheme to the F_3 deformation of the basement, may be gathered from the literature (Dozy 1935; Dozy and Timmermans, 1935).

Other structures are a group of steep kink bands (F_4) which gently bend the pre-existing patterns at the size of a few kilometres.

The orientation data of the mesoscopic fabric elements are plotted in Fig. 5.

The regional distribution of the main lithologic markers such as the quartzitic bands and the orthogneisses appears, therefore, to be controlled by the F_1 and F_2 fold groups. The disruption of these two lithologies into smaller bodies is mostly due to the F_1 fold system. Worthy of note is the existence of blastomylonitic bands older than the F_2 folding; these zones taper away over some tens of metres and are located either in the mica schists or at the main lithologic contacts.

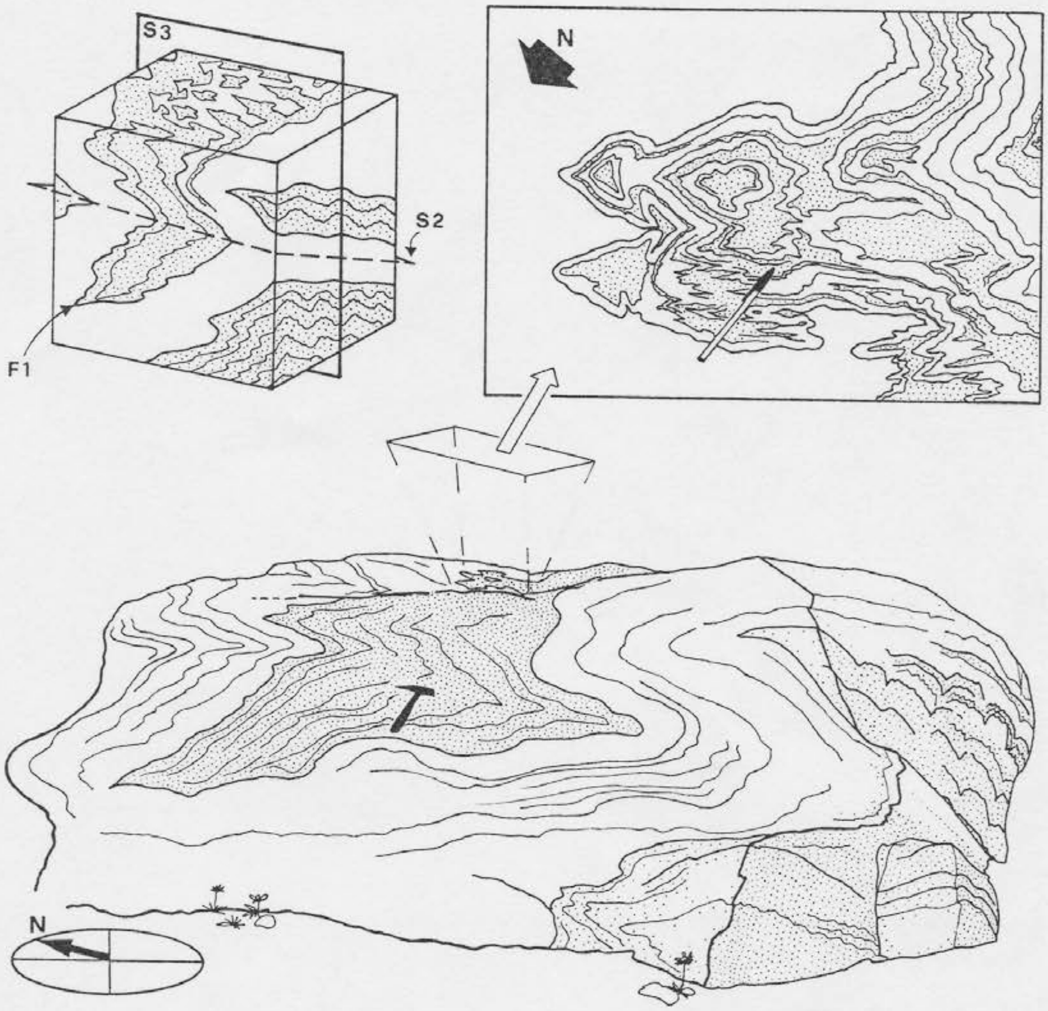

Fig. 4. Small-scale Alpine F_3 folds overprinting Variscan F_2 folds in quartzites and mica schists. Several interference patterns are reproduced, from type *1* to *2* of Ramsay (1967). Locality corresponding to the *asterisk* in Fig. 2.

3.1 Microstructures

The history of mineral growth can be deduced with the aid of mesoscopic analysis in both the orthogneisses and the mica schists. Garnet and red-brown biotite existed prior to the regional S_2 mineralogical layering; the rational boundaries of grains of both minerals in mutual contact suggest that they were in equilibrium under amphibolite-facies conditions before the S_2 regional foliation.

The S_2 foliation, generally associated with mineral differentiation, forms along with the replacement of red-brown biotite by chlorite and of garnet by chlorite, white mica and albite. Chlorite and new green-brown biotite also grew independently within the S_2 foliation, outside of the garnet or of

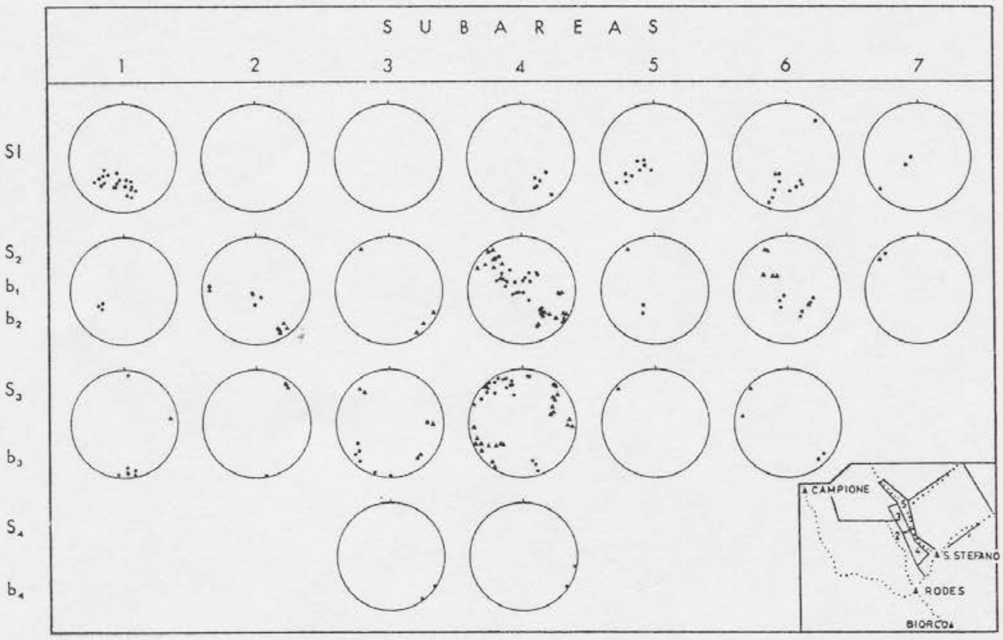

Fig. 5. Schmidt plots of the fabric elements (lower hemisphere) in the Laghetti di S. Stefano—Pizzo di Rodes basement area. The local coincidence of b_2- and b_3-axes is due to conjugated sets of the F_3 folds. *Inset* shows the location of subareas.

the red-brown biotite sites. Albite porphyroblasts replace the kinked white micas aligned in the S_2 microlithons. This replacement appears to be static and preferentially localised within mylonitic zones; it postdates the S_2 crenulation and in all cases it predates the F_3 deformation.

The existence of garnet and red-brown biotite in equilibrium conditions before S_2 and the growth of green-brown biotite, albite and epidote during or after S_2 indicate that a greenschist re-equilibration began with the F_2 regional deformation.

The metagabbroic body of Punta S. Stefano confirms the equilibration of the basement complexes under amphibolitic conditions, since garnet and green amphibole are the first metamorphic minerals formed in these rocks; chlorite, zoisite—clinozoisite and albite grew later

Minor effects of grain boundary re-adjustment are contemporaneous or postdate F_3 folding. White micas and chlorites show kinking in zones of F_3 intense deformation with intragranular suturing of kink boundaries. The F_3 regional deformation is not associated with a continuation or a re-activation of the metamorphism in the basement rocks.

4. SEDIMENTOLOGY AND STRUCTURE OF THE PERMIAN COVER IN THE MONTE CABIANCA—PIZZO SALINA AREA

The succession studied represents the infill of the central to intermediate portion of the Carona basin, which is one of a series of ensialic Permian basins in the Southern Alps. The selected area, mapped at 1 5000 scale (Fig. 6), belongs structurally to the Orobic anticline between the Orobic and Valtorta—Val Canale tectonic lines (Fig. 1). Three main facies associations terrigenous, evaporitic and volcanogenic have been distinguished in these deposits (Fig. 7).

4.1 Terrigenous deposits

Several different terrigenous facies types have been recognised and are described from the margin to the center of the Carona basin.

4.1 1 Conglomerate and sandstone facies. The deposits of this facies consist chiefly of litharenites, polymictic conglomerates and minor shales. The mineralogical composition indicates a provenance from the Variscan basement and Permian ignimbrites. Cannibalistic processes over subaerial carbonate precipitates (mainly dolomite or ferroan dolomite produced a third sort of clasts, which become more common basinward (synsedimentary clastic dolomite, sensu Smoot, 1978). Four main subfacies characterise this group. The first, rarely observed, is represented by massive, poorly to moderately sorted, framework-supported sandy cobble (minor pebble) conglomerates Gm facies of Miall, 1982). They build up lenticular bodies with several metres deep basal scours and a slight fining-upward trend consisting of superimposed, amalgamated units.

Based on their geometry and coarse clast size, they represent a transition between the incised channels of the fan apex e.g., Hardie et al., 1978) and the braided channels of the middle fan.

The second subfacies is composed of moderately sorted, grain-supported, sandy pebble-conglomerate units with crude horizontal stratification (Gm facies) and characterised by broad shallow-erosional bases. These 1—2 m thick, graded conglomeratic units, capped by pebbly sandstone, represent a channel-bar system of the middle fan subenvironment (Bull, 1972).

Thirdly, a massive unsorted, matrix-supported cobble conglomerate represents a sedimentary product of debris-flows (Gms facies); only two examples of this subfacies were observed, 0.8 and 2 m thick respectively, and crudely interbedded in the sandy deposits of the fan toe. This position may be indicative of a catastrophic climatic and/or seismotectonic event.

Finally moderately to poorly sorted sandstones form laterally continuous units up to a few metres thick, which are superimposed, creating sequences several tens of metres thick. They display erosinal bases, often lined by pockets and lenses of extrabasinal conglomerates. The most common features are: grading, horizontal discontinuous and low-angle stratification (Picard and High, 1973); antidunes (Harms and Fahnestock, 1965), erosional scours with intraclasts (Se facies of Miall, 1982); θ and π cross-stratification (Allen, 1963) steep-edge erosion (Picard and High, 1973) and intraclasts scattered through the bed. In addition the coarser sandstone units are some-

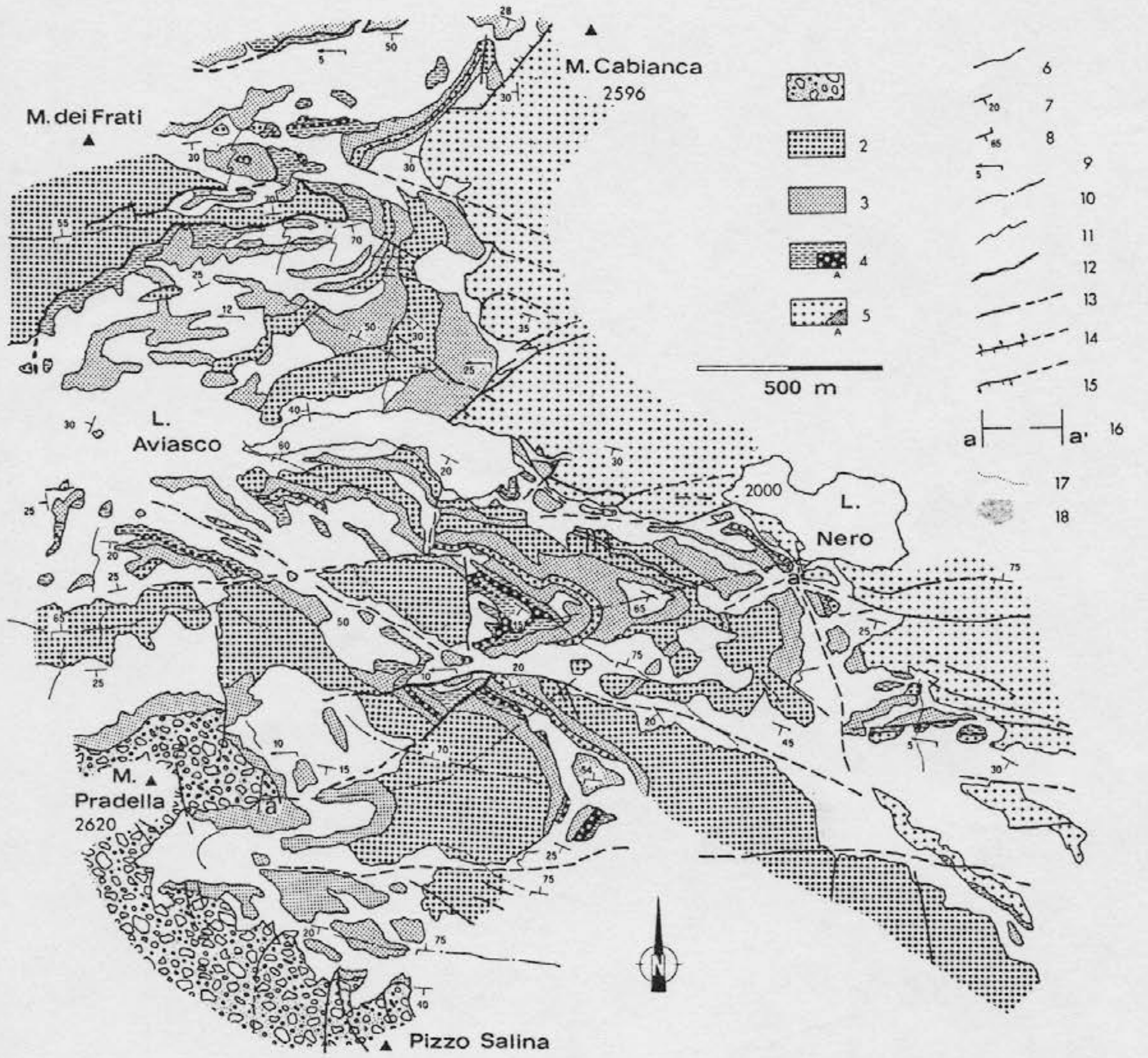

Fig. 6. Geological map of the Permian sedimentary and volcanic cover in the Monte Cabianca—Pizzo Salina area, located in Fig. 1. It is redrawn from a 1:5000 scale map. *Legend*. *1* = quartz and acid volcanic red pebble conglomerates and mauve sandstones (braided plain), Verrucano Lombardo (Upper Permian); *2* = green, gray sandstones, green pebble conglomerates with minor mudstones (alluvial fan), Carona basin, Collio Formation (Lower Permian); *3* = pink, gray sandstones with minor conglomerates and mudstones (sand flat), Carona basin, Collio Formation (Lower Permian); *4* = black mudstones with minor fine sandstones and silts, evaporitic dolostones and Ca-sulphates (mud-flat and perennial saline lake), *4*a: ash flow tuffs; Carona basin, Collio Formation (Lower Permian); *5* = mauve, green ignimbrites and tuffs; *5*a: mylonitic fabric· lower volcanic member, Collio Formation (Lower Permian); *6* = geological boundaries; *7* = bedding with dip value; *8* = foliation associated with the east—west folding generation and corresponding to the F_3 deformation of the basement; *9* = axes of east—west trending fold generation, with plunge; *10* = trajectory of the axial plane foliation *11* = minor fold asymmetry marked by lithological boundaries; *12* = thrust surfaces, marked by mylonites; *13* = faults and inferred faults; *14* = reverse faults with tick on downthrown side; *arrow* indicates dip of fault plane; *15* = normal faults, with tick on downthrown side; *arrow* indicates dip of fault plane; *16* = trace of sedimentological section shown in Fig. 7 *17* = unmetamorphosed Tertiary andesite dykes; *18* = cataclastic and mylonitic zones; *blank area* = Quaternary cover and lakes.

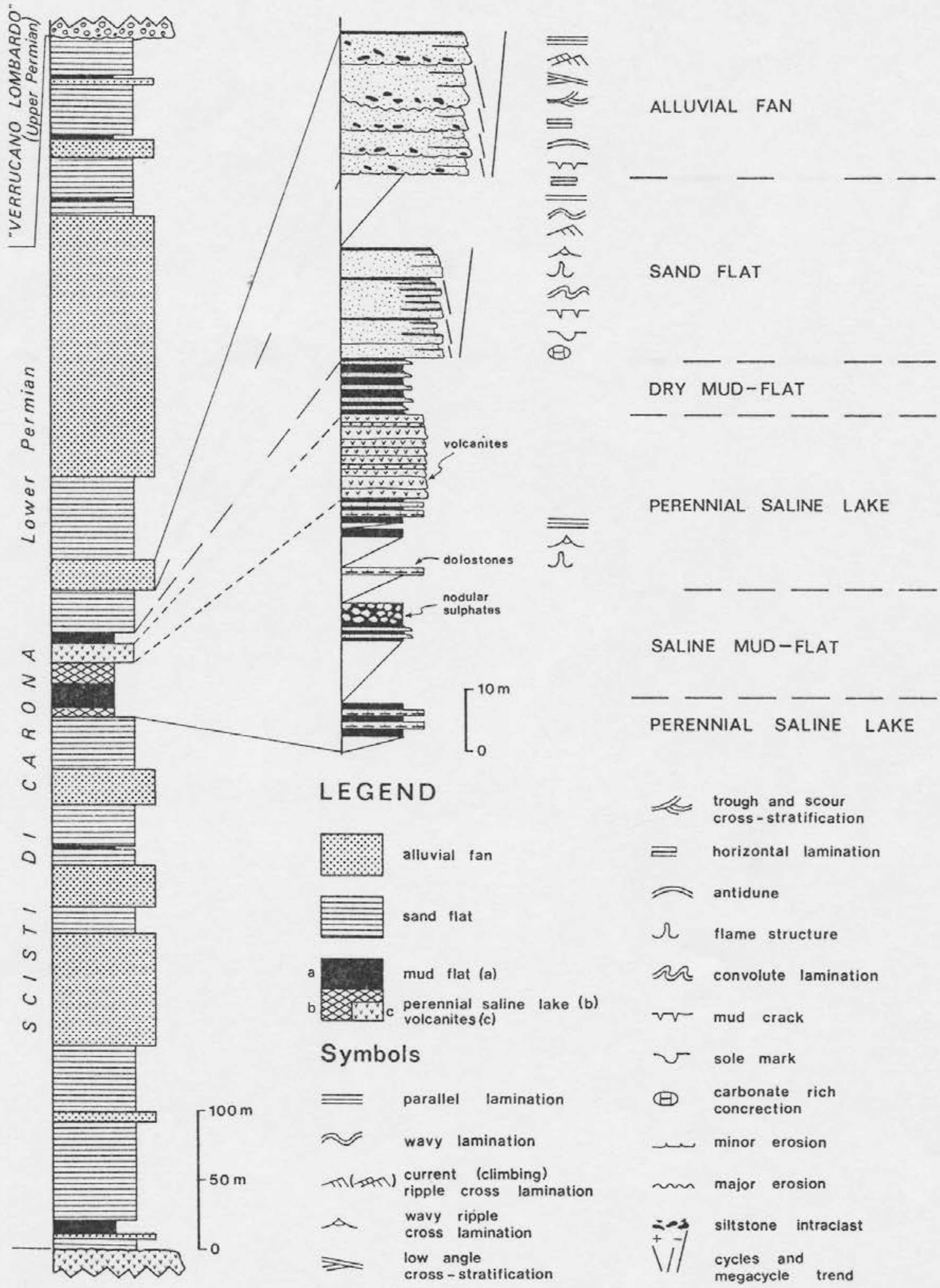

Fig. 7 Section through the Carona basin succession of the Collio Formation from the Lago Nero–Monte Pradella slope, located in Fig. 6.

times capped by finer sand layers containing climbing ripples in turn overlain by cracked curled) mud drapes. All these features are consistent with a fan toe environment (Hardie, 1973, see Hardie et al., 1978).

In one single case, structures comparable to the grain-flow cross-stratification of Hunter (1977) were observed in associated sandstones. They indicated an eolian origin for this horizon. In conclusion, this facies association may be easily lumped into an alluvial fan depositional environment, built up by ephemeral streams in an arid climate (Glennie, 1970; Picard and High, 1973, Hardie et al., 1978).

4.1.2. Heterolithic sand-dominated facies. The deposits belonging to this facies (medium to fine sands and minor shales) form sequences several tens of metres thick that originate by superimposition of laterally continuous, few metres thick, small-scale cycle coarsening or less frequently, fining upwards. Internally, minor cycles exhibit graded beds up to 20 cm thick that show erosional basal contacts with scours filled by muddy intraclasts, horizontal discontinuous stratifications, antidune wavy bedding (Hardie et al., 1978), medium-scale cross-stratification, current (often climbing) ripple cross-laminations, wave-ripple cross-lamination [form discordant, bundle-wise upbuilding type of Boersma 1970)] parallel lamination (Harms and Fahnestock, 1965), convolute laminations, sole marks, and carbonate-rich concretions. These sedimentary textures and structures resemble those of modern sand flats at the toes of the alluvial fans in Baja California, Mexico (Hardie et al., 1978).

4.1 3. Heterolithic mud-dominated facies. The deposits related to this facies occur as units (up to several metres thick) formed by very thin (often a few laminae thick) continuous or lenticular beds [lenticular and wavy bedding type of Reineck and Singh (1973)] of very fine sand or silt and by continuous drapes of mudstones. Features characteristic of this facies include: coarse tail grading, low-relief laminations, scattered sand-size mud intraclasts, pinch and swell, incipient lenses, horizontal lamination grading upward into cross-laminations [facies M_1, M_2, M_3 of Raaf et al. (1977)] parallel laminations, convolute laminations, flame structures, small growth faults, scours (flutes) and tool (groove and bounce) marks, and mud-cracks of different depth and size. All these features are consistent with a deposition in a dry mud-flat environment.

4.1 4. Mud facies. These deposits occur as units several metres thick and are formed by highly fissile clayey and clastic-dolomitic mudstones with minor intercalations of fine sand and silt. The mudstones are even-laminated and commonly graded, whereas the coarser sediments are lenticular or slightly more continuous, showing pinch and swell structures and incipient lenses; small growth faults are common. These deposits probably represent sedimentation in a perennial lake whose depth allowed occasional reworking by wind waves.

4.2. Evaporitic deposits

The chemical carbonate and Ca-sulphate deposits of this group have been subdivided into two types, the first subaerially precipitated, the second subaqueous. Sulphate precipitates belonging to the first type occur closely associated with the finer clastic facies as dispersed crystals or as continuous horizons showing enterolithic structures or chicken-wire fabrics. These features of the deposits clearly reveal formation by the evaporative pumping process (Hsü and Siegenthaler 1969); they are replaced in patches by carbonates. These deposits are characteristic of a saline mud-flat environment.

The second type is represented by carbonates and sulphates deposited as chemical precipitates from a supersaturated water body The carbonates form planar parallel, extremely continuous, thin to medium beds of massive dolomite that were deposited in a saline lake. Thin, roughly planar parallel, or slightly enterolithic layers of Ca-sulphates are intimately associated with these beds. The enterolithic layers were caused by a replacement of gypsum by anhydrite which is consistent both with subaerial and with subaqueous conditions; in the latter case the replacement took place a few centimetres beneath the water—sediment surface (Truc, 1978). The sulphates represent precipitation during phases of major contraction of a saline lake.

4.3. Volcanogenic deposits

During the deposition of the clastic and evaporitic facies, the area was affected by periodic volcanic activity (very likely extrabasinal) that produced several ash flow tuff units. The best developed of them forms a body 10 m thick (a very good marker) formed by moderately thick superimposed beds. Outside of the mapped area this unit was partially deposited in subaqueous conditions as indicated by an association with lacustrine mudstone and by the presence of dish and pillar structures. They are related to fluidization processes (Lowe and Lo Piccolo, 1974) due to a very high sedimentation rate of the volcanic ash.

A relationship appears to exist between the thickness of the subaqueous volcanic unit and the contemporaneous depth of the lake. Actually the volcanic deposition took place almost instantaneously, as suggested by the lack of relevant lacustrine partings, and therefore the role of the subsidence was inconsequential.

4.4. Paleocurrents

The sediment dispersion pattern is mainly based on measurement of sand-flat and mud-flat sole-marks and of the trough cross-stratification of the fan toe. The basal structures show a restricted spectrum, azimuths vary between 250° and 290° The cross-stratification is characterised by a wider range of orientations, extending between 0° and 270° The average of all the measurements indicate sediment transport direction of 290°

4.5. Cyclicity

The interfingering of the intermediate to distal alluvial fan and lacustrine deposits imprints a marked cyclicity on the sediment pile. Two very large-scale megasequences exist, which are characterised by nearly symmetrical trends: the lower, more important, upward-coarsening portions, respectively 220 and 360 m thick, and the upper portions slightly fining upwards, measuring respectively 150 and 130 m. At the top the sedimentary succession is truncated by the Verrucano Lombardo. The coarsening and fining upward portions of the megasequences represent respectively the main phases of progradation and of retreat of the marginal deposits and clearly reflect the changes in intensity and possibly also in the type of tectonic activity In addition, both first-order sequences are built up from smaller-scale cycles, several tens of metres thick. In the coarsening-upward portions of the megasequences the smaller cycles are also coarsening upward. In the fining-upward portions the minor cycles still show a coarsening upward trend and are characterised by progressively decreasing importance of the alluvial sediments toward the top.

The origin of the second-order cycles remains a moot point; it might be either allocyclic (tectonic or climatic) or autocyclic (lobe shifting). The area studied is too small to attempt an explanation for this vertical organisation in terms of type of tectonic regime that activated the basin. A certain affinity exists between the internal organisation of the Carona basin and that of the Devonian Norway basins which is also interpreted to be a trans-tensional regime (Gloppen and Steel, 1981).

Finally small-scale cycles, a few metres thick, are present in sand and/or mud-flat deposits. They are coarsening and thickening upward or, less frequently, fining and thinning, and may reflect, in accordance with the interpretation of Smoot (1983), fluctuations in lake level under the control of climate.

4.6. Remarks on the environmental evolution

The fill of the Carona basin originated by interaction of alluvial fan and lake depositional systems. In the study area only the intermediate and distal deposits of the fan system are present. Nevertheless, the latter fan system can be interpreted as an ephemeral stream, with stream flood and channel deposits passing distally into sheet flood deposits.

The lacustrine deposits are the sedimentary expression of a perennial saline lake subjected to long-term transgressions and regressions. During the stages of high-standing lake, attaining depths of several metres (as testified by the subaqueous acid volcanites), mainly clastic sedimentation took place. The lowering and contraction of the lacustrine water body (with consequent increase in salinity) enhanced the evaporitic character of the sedimentation, inducing the deposition of dolostones and finally of Ca-sulphates.

Renewed expansion followed a period of extreme shrinkage, when salt-pan conditions were probably reached. These deposits represent sedimentation in an arid, very likely endorheic basin. Based on facies distribution and paleocurrent patterns, the succession constitutes, in the regional context, the eastern nearly marginal portion of the Carona basin, whose western counterpart might be represented by the Ponteranica conglomerates.

4.7 Deformation history

Within the mapped portion of the Scisti di Carona (Figs. 6 and 8) a consistent set of south-verging folds, associated with a pervasive foliation, is the dominant tectonic feature. Folding is most probably coeval with the formation of mylonitic or phyllonitic bands along significant lithologic discontinuities; the phyllonites are splayed across horizons of lacustrine and fluviatile beds and produce the illusion of an interval of sedimentary sequences of ~ 100 m over a length of 1 km at the level of the ignimbrites. The latter horizon of mylonites contains uranium showings. A connection with the regional tectonic lines, trending east—west, is highly probable and coincides with the east—west folding in the surrounding basement, dated geometrically as F_3

Brittle extensive east—west faulting postdates the fold system. These faults are followed in turn by new faults striking 120° and 90°

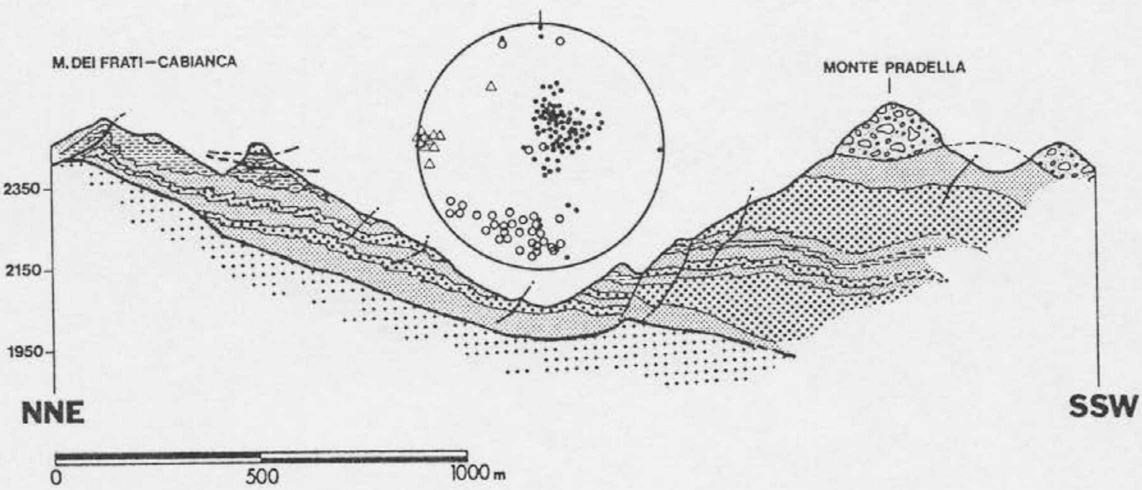

Fig. 8. Structural cross-section related to the map of Fig. 6. The pervasive foliation associated with the south-verging folds is represented by *dashed-stippled lines*; S and b_1 in the inset correspond to the F_3 deformation in the basement. *Symbols* as in Fig. 6. In the stereographic projection S_1 = *solid dots*, S = *open dots*, and b = *triangles*.

5. ENVISAGED RELATIONS BETWEEN THE GEOLOGIC HISTORY AND URANIUM MINERALISATIONS

The regional geology of the Central Orobic Alps and the detailed analysis of two test areas may pose some constraints on the general problems of uranium metallogeny which were already brought into focus by the work of AGIP Nucleare in the Val Vedello and Novazza mines.

The known types of mineralisation may be summarized as follows: 1) vein-type deposits related to major extensive faults and mylonitic zones between the basement and Permian cover; (2) disseminated mineralisation within the ignimbrites; (3) disseminated mineralisation in fluvial sandstones at the base of Verruccano Lombardo (Costa Magrera, Marifunt) (sandstone type deposits); (4) vein-type deposits associated with Alpine faults and mylonitic zones, mainly located in the Collio sequences (E—W trending at Belviso, Val Vedello, Passo della Scaletta, Pizzo Coca; NE—SW trending at Lago di Aviasco). Among them, only types *1* and *2* are of economic interest.

The source of the uranium anomaly of the Collio basin is regarded as being related to the anatectic magmatic activity developed during the Permian within the South Alpine continental crust. Removal and concentration of uranium are connected with the repeatedly activated circulation of hydrothermal fluids.

The opening and evolution of the Permian Collio basin, probably following pull-apart mechanisms related to a transtensional tectonics (Ziegler, 1980, and references therein), was geometrically controlled by the rejuvenation of Variscan mylonitic zones. The geochronological age of the uranium mineralisation (~ 250 Myr) shows a delay recurrent in the literature also from similar metallogenic events, with respect to the Lower Permian eruptions and suggests an interrelationship with a period of anomalous geothermal gradients and fluid circulation, nearly coeval with the emplacement of the Upper Permian—Lower Triassic layered gabbro of Sondalo and with Triassic calc-alkaline magmatic activity (Cassinis and Zezza, 1982, Jadoul and Rossi, 1982). Leaching solutions fed by the Permian ignimbrites and circulating along the main Permian and Triassic fault systems discharged uranium (and Pb-, Zn-, Cu-, Fe-sulphides) into structural-chemical traps located at shallow depths and at the intersections with convenient lithological units. These mineralisations also are characterised by carbonatisation in the country rocks. This hydrothermal mechanism seems to be responsible for the exposed economic mineralisation. Successively the mineralisations have been dismembered by Alpine phases of deformations and locally mobilised and redeposited into brittle E—W-trending faults.

The Alpine thrust tectonics described in the mine locality does not seem, therefore, to play an important metallogenic role at the exposed structural level. However in the uranium province of the Orobic Alps the grid of the regional Alpine thrusts and faults has until now been described in terms of geographical orientation and the only existing kinematic interpretation was conceived before the advent of thin-skinned tectonics (De Sitter and De Sitter-Koomans, 1949· De Jong, 1967).

Very recently Brack (1984) and Laubscher (1985) successfully applied thin-skinned tectonic concepts to the two regions, respectively east and west of the Orobic uranium province; they described extensive (tens of kilometres) south-verging imbricated thrust systems both in the Mesozoic cover and in the Variscan basement. The range of crustal shortening required to balance their cross-sections and the existence of lacustrine shales in the interposed Permian sequences, which may act as decollement horizons within the latter, make the existence of imbricate thrusts in the Permian cover of the Orobic Alps very apparent.

A new detailed description of the thrust systems of the Orobic—Bergamask Alps could redefine the kinematic interplay of the basement and Permian cover thrust sheets and could elucidate the uranium exploration potential of the Collio units that experienced Alpine translational processes at slightly deeper levels within the thrust stack.

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