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Isotopic U—Pb Ages of Monazites and Zircons from the Crust-Mantle Transition and Adjacent Units of the Ivrea and Ceneri Zones (Southern Alps, Italy)

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Abstract. The *Ivrea zone* forms a part of the Southern Alps and is composed of basic rocks interfingered with granulite facies acidic rocks. According to geophysical evidence, this zone represents the transition between crust and uplifted and overthrusted mantle. Towards the *Ceneri zone* the metamorphic grade changes to amphibolite facies. Paragneisses, migmatites and anatectic gneisses dominate, within which postmetamorphic granites occur.

Concordant *monazite* U—Pb ages of 275 + 2 m.y. were obtained from paragneisses of the Ivrea zone. The apparent zircon ages are discordant indicating a minimum age of 1900 m.y. for the oldest population and an apparent lead loss of 99 to 85% about 285–300 m.y. ago. The zircons show features such as rounded habitus, low trace element contents and well ordered crystal lattices characteristic for detrital, recrystallised populations.

Monazite from the neighbouring Ceneri zone migmatite yielded concordant U—Pb ages at 295 ± 5 m.y. The discordant zircon age pattern indicates a time of formation of 450 m.y., similar to other newly formed zircons in anatectic rocks of the Ceneri zone, and an episodic or continuous lead loss at, or until 300 m.y. ago. The majority of the zircons are euhedral and have elevated trace element contents, features typical for zircons formed in the present-day host rocks.

Concordant, 295 ± 5 m.y. old *monazite* dates the formation of the postmetamorphic Mont' Orfano granite. Again zircon fractions yielded discordant ages, pointing in contrast to the above discordancies to a recent or continuous lead loss.

The concordant ages of the *monazites* demonstrate the usefulness of this mineral for dating purposes in metamorphic and granitic rocks and contrast with the discordant age patterns of all zircon suites.

From the general agreement between the monazite ages and the time of lead loss inferred from the zircon age patterns as well as from the geological relationships of the rocks and their metamorphic grade it is concluded that 295 ± 5 m.y. is the minimum age for the regional granulite to upper amphibolite facies metamorphism of the Ivrea zone and that the uplift and overthrust of the upper mantle started prior to 295 m.y. ago, and that the basic rocks of the Ivrea zone are synmetamorphic intrusions.

The decrease from 310–320 m.y. to 170–200 m.y. of the K—Ar and Rb—Sr mineral ages from the Ceneri towards the Ivrea zone is accompanied by decreases from 450 m.y. to 295 m.y. and on to 275 m.y. in the U—Pb ages of monazites. The zircon age pattern also shows a decrease from 450 m.y. to approximately 300 m.y. The main lowering of the ages occurs approximately at the petrographic boundary between the two zones and is related to the Hercynian uplift and overthrust of the mantle which may have started as early as 450 m.y. ago.

The Insubric line which terminates the Ivrea zone towards the North must therefore be of pre-Alpine age, or a precursor of the Insubric line must have existed at the time of the mantle uplift.

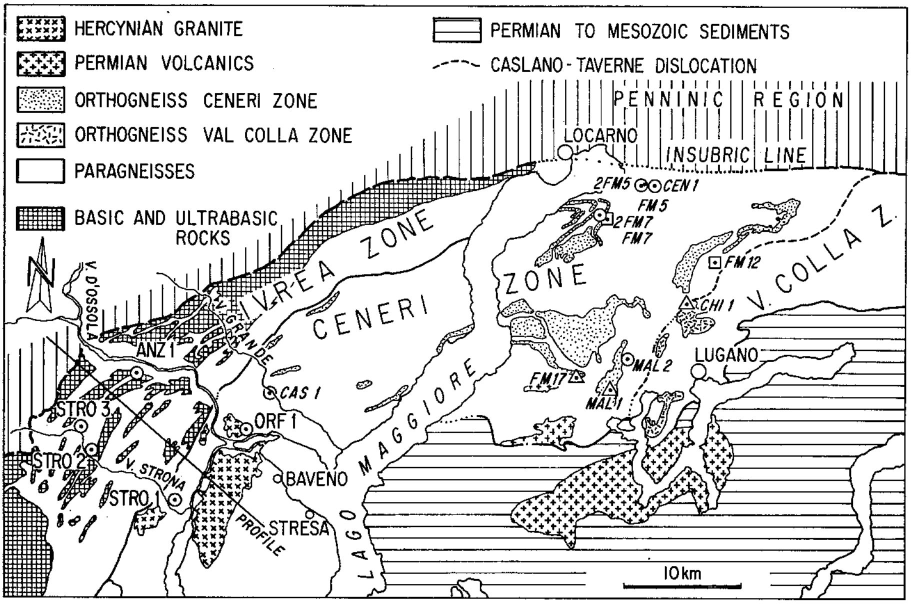

Fig. 1. Geological sketch map of the Southern Alps showing the sample locations. Sample designations in italics refer to samples discussed in Pidgeon *et al.* (1970) and Köppel and Grünenfelder (1971). Trace of profile in Fig. 7

1. Introduction

By investigating the U—Th—Pb systems of zircons and monazites from rocks of the Ivrea and neighbouring Ceneri zone of the Southern Alps, we attempted to establish the chronology of geological events in an area that has attracted in recent years broad petrological and geophysical interest. Furthermore, we hoped to gain information concerning the behaviour of the U—Pb systems of zircons of genetically different rock types.

1.1. The Geological and Geophysical Setting

The Ivrea zone is a 10–20 km broad belt extending from Locarno in a southwesterly direction towards Turin over a distance of 120 km and consists of basic to ultrabasic rocks interfingered with more acidic rocks both of granulite to upper amphibolite facies (Fig. 1).

The belt is characterized by pronounced magnetic anomalies (Pavoni, 1968) and a positive gravity anomaly (Vecchia, 1968; Goguel, 1968). Seismic investigations show that upper mantle type rocks almost and in places actually reach the surface. The northwestern flank of the Ivrea body overlies sialic crust, whereas the southeastern flank dips continuously to a depth of about 30 km. A cross section vertical to the Ivrea zone shows the bird's head structure of an overthrusted and uplifted upper mantle (Fig. 2) (German Research Group for Explosion Seismology, 1968; Ansorge, 1968; Kaminski und Menzel, 1968; Giese, 1968).

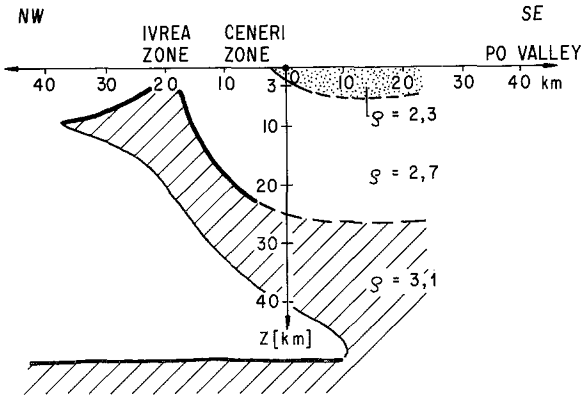

Fig. 2. Structural model of the uplifted and overthrusted mantle based on gravimetric and seismic data (German Research Group for Explosion Seismology, 1968)

Strontium and lead isotope measurements support the view of a mantle origin of the basic rocks (Graeser and Hunziker, 1968; Graeser, 1970).

Towards the northwest, the Ivrea zone terminates sharply against the Insubric line (Gansser, 1968) which separates the Alpine mountain range from the Southern Alps. Towards the southeast basic rocks become less abundant and the metamorphic grade changes from granulite to amphibolite facies. A zone rich in pegmatite and marbles serves as a lithologic boundary between the Ivrea and Ceneri zones. Detailed petrographic descriptions of the investigated area are found in Schilling (1957), Schmid (1966, 1967, 1968), and Bertolani (1968a, 1968b).

Within the Ceneri zone, which consists of rocks of upper amphibolite facies, postmetamorphic granites occur, the Baveno and Mont'Orfano granites being the two more important ones (Fig. 1).

1.2. Results of Previous Geochronological Investigations

In Table 1, the results of Rb—Sr and K—Ar measurements on minerals and whole rock samples are listed. The mineral ages from the Ivrea zone vary from 160 to 250 m.y. and cluster between 170 and 200 m.y. Graeser and Hunziker (1968) interpreted the ages as a result of either a reheating approximately 180 m.y. ago or else as marking the time of cooling to about 300° C of the regional high grade metamorphism.

McDowell and Schmid (1968) concluded from the scatter of the ages that an event later than 170 m.y. ago caused incomplete Ar loss.

Graeser and Hunziker (1968) obtained a whole rock Rb—Sr isochron of 310 m.y. by analysing a number of 1 cm thick slices of a banded granulite facies gneiss sampled next to a metagabbro. The age is interpreted as the time when the small scale Sr homogenisation ceased and as a minimum age for the intrusion of the metagabbro. Data points of larger whole rock samples yielded a maximum age of 1000 m.y. for the chemical formation of the rock.

Whole rock Sr isotope ratios of the gabbro indicate a mantle origin. The $^{87}Sr/^{86}Sr$ ratio of the gabbro of 0.7083 contrasts with the high initial ratio of the 310 m.y. isochron of the neighbouring gneiss of 0.7166.

Table 1. Rb—Sr and K—Ar age values from the Ivrea and Ceneri zones west of Lago Maggiore

Zone	Locality	Rock type	Mineral	Age m.y.		Reference
				Rb—Sr	K—Ar	
Ivrea	Finero	peridotite	phlogopite		246 ± 4	Krummenacher (1960)
Ivrea	Finero	peridotite	phlogopite	160 ± 100		Graeser und Hunziker (1968)
Ivrea	Finero	peridotite	whole rock	290 maximum age		Graeser und Hunziker (1968)
Ivrea	Bettola	garnet-biotitegneiss	biotite		171 ± 5	McDowell and Schmid (1968)
Ivrea	Albo	garnet-bearing-biotitegneiss	biotite		176 ± 5	McDowell and Schmid (1968)
Ivrea	Cuzzago	hornblende-granulite	hornblende		208 ± 6	McDowell and Schmid (1968)
Ivrea	Anzola	garnet-sillimanitegneiss	biotite (2)	184 ± 15		Graeser und Hunziker (1968)
Ivrea	Anzola	garnet-sillimanitegneiss	whole rock isochron	310		Graeser und Hunziker (1968)
Ivrea	Nibbio	amphibolite	biotite	172 ± 13		Jäger *et al.* (1967)
Ivrea	Nibbio	amphibolite	biotite	176 ± 5		Colloquium, Geochronology (1969)
Ivrea	Candoglia	pegmatite	muscovite	236 ± 10		Graeser und Hunziker (1968)
Ivrea	Brissago	pegmatite	muscovite	216 ± 9		Jäger *et al.* (1967)
Ivrea	Ronco	pegmatite	biotite	163 ± 8		Jäger *et al.* (1967)
Ivrea	Ronco	pegmatite	biotite	157 ± 8		Jäger *et al.* (1967)
Ceneri	Spasu	biotite-plagioclasegneiss	muscovite		201	McDowell (1970)
Ceneri	Spasu	biotite-plagioclasegneiss	biotite		192	McDowell (1970)
Ceneri	Giazzo	biotite-plagioclasegneiss	muscovite		236	McDowell (1970)
Ceneri	Giazzo	biotite-plagioclasegneiss	biotite		200	McDowell (1970)
Ceneri	Canobbio	biotite-plagioclasegneiss	muscovite fine		289	McDowell (1970)
Ceneri	Canobbio	biotite-plagioclasegneiss	muscovite coarse		301	McDowell (1970)
Ceneri	Canobbio	biotite-plagioclasegneiss	biotite fine		262	McDowell (1970)
Ceneri	Canobbio	biotite-plagioclasegneiss	biotite coarse		258	McDowell (1970)
Ceneri	Orfano	postmetamorphic granite	biotite	274 ± 11	268	Jäger and Faul (1959)
Ceneri	Orfano	postmetamorphic granite	K-feldspar	275		Jäger and Faul (1959)
Ceneri	Baveno	postmetamorphic granite	biotite		269	Jäger and Faul (1959)

Age determinations have been also carried out on the postmetamorphic granites. Deutsch *et al.* (1958) reported ages based on pleochroitic halos of about 20 m.y. (compare also Graeser and Hunziker, 1968). Jäger and Faul (1959) determined K—Ar and Rb—Sr ages of biotite and a Rb—Sr age of K-feldspar of 270 m.y. Pasteels (1964) analysed zircon concentrates from the Baveno and Mont'Orfano granites and concluded that 275 m.y. is the best age estimate for both granites. Radiation damage ages of zircons range from 73 to 96 m.y. (Chessex, 1964).

The K—Ar ages of 3 muscovite-biotite pairs from the Ceneri zone, analysed by McDowell (1970) are also listed in Table 1. The decrease of the ages, as one approaches the Ivrea zone, from 301 and 285 to 201 and 192 m.y. respectively, should reflect a reheating in upper Triassic to lower Jurassic time. East of Lago Maggiore the mica ages are higher and cluster around 310–320 m.y. The author estimated therefore the time of amphibolite facies metamorphism at 325 m.y.

In contrast to McDowell (1970), Pidgeon *et al.* (1970) and Köppel and Grünenfelder (1971) concluded from concordant monazite ages of 450 m.y. and from nearly concordant zircon ages of 450 m.y. that the regional amphibolite facies metamorphism of the Ceneri zone is of Caledonian age.

1.3. The Aim of the Present Investigations

The available data on the chronology of events in the Ivrea and western Ceneri zones left questions open, some of which might be answered by analysing the U—Pb systems of zircons and monazites. For an understanding of the geological history of the region, answers were sought to questions concerning the time relationship between

— the intrusion of the basic rocks and the regional metamorphism of the Ivrea zone,

— the formation of the Ivrea zone rocks and the postmetamorphic granites of the Ceneri zone, and

— the regional metamorphism of the Ivrea and Ceneri zones.

In addition to obtaining information concerning the behaviour of zircons under granulite facies conditions, a comparison of the zircon U—Pb age patterns with ages of other uranium bearing minerals should show whether zircons yield information concerning the time of high grade metamorphism.

2. Results

2.1. Zircon Description

Postmetamorphic Granite of Mont'Orfano, Sample ORF 1. The zircons are euhedral and longprismatic. The fractions of lower magnetic susceptibility contain mainly transparent zircons whereas the fraction of higher magnetic susceptibility is enriched in zircons with translucent to opaque domains and entirely opaque crystals. Such grains often contain saw tooth like protruding intergrowths of xenotime.

Migmatite, Sample STRO 1. The majority of the zircons are euhedral with dominating prisms. Many are optically zoned, and often contain translucent to opaque domains. They closely resemble the zircons of sample MAL 1 (Fig. 5 in Köppel and Grünenfelder, 1971). Some of the transparent grains are more isometric and are at least partially rounded, thus resembling the paragneiss zircons. The coarser grain size fractions contain about 20% zircons of this

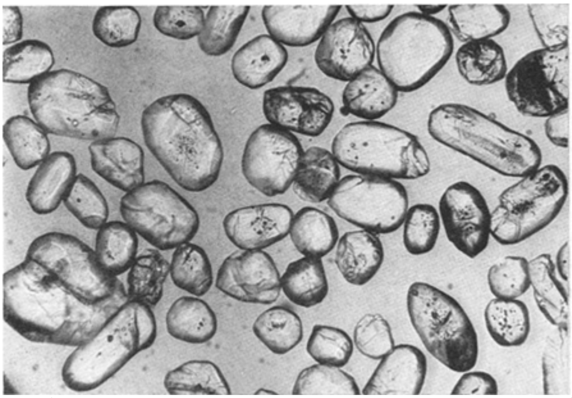

Fig. 3

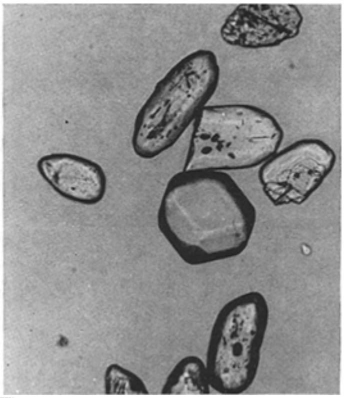

Fig. 4

Fig. 3. Zircons (100×) of the pyriclasite, sample STRO 3, +75, n.m. The crystals are short prismatic with a rounded habitus. Most of the grains have developped new crystal faces. The crystals are transparent, and some contain numerous inclusions. The zircons of samples STRO 2 and ANZ 1 are indistinguishable under the microscope from the ones shown in this figure

Fig. 4. Zircons (150×) of the kinzingite (paragneiss) sample STRO 2. The crystal in the center shows exceptionally well developped crystal faces. The isometric habitus reflects the originally rounded habitus of the detrital grain

type, the smaller grain size fractions approximately 10%. The zircon population of sample STRO 1 is therefore most likely of a mixed origin.

Paragneisses, Samples STRO 2, STRO 3, ANZ 1. The zircons are oval to round, transparent and contain numerous inclusions (Fig. 3). Growth of new crystal faces is widerspread but they usually do not obscure the rounded habit. Fig. 4 shows an exceptionally well recrystallised individual with dominating pyramids and therefore an isometric habitus reflecting the originally rounded form.

2.2 Results of Isotope Analyses

The analytical results are listed in Table 2. The data points are plotted on a U—Pb diagram (Figs. 5, 6).

The most outstanding finding is that all U—Pb ages of monazite samples, separated from four different rock types, are concordant and hence contrast with the discordant ages of all zircon suites.

Two monazite size fractions of the Ceneri zone migmatite, located between the post-metamorphic granite of Baveno and the Ivrea zone, yielded concordant U—Pb ages of 295 ± 5 m.y. The same age was obtained from a monazite sample of the post-metamorphic granite of Mont'Orfano. Monazites from Ivrea zone rocks yielded concordant ages of 275 ± 2 m.y.

The Th—Pb ages agree within the analytical uncertainties with the U—Pb ages in two samples. The monazites of the samples ORF 1 and ANZ 1 have suffered a preferential ^{208}Pb loss or a Th gain.

In contrast to the similar and concordant U—Th—Pb ages of the monazite samples, the zircon age patterns are distinctively different for each of the three

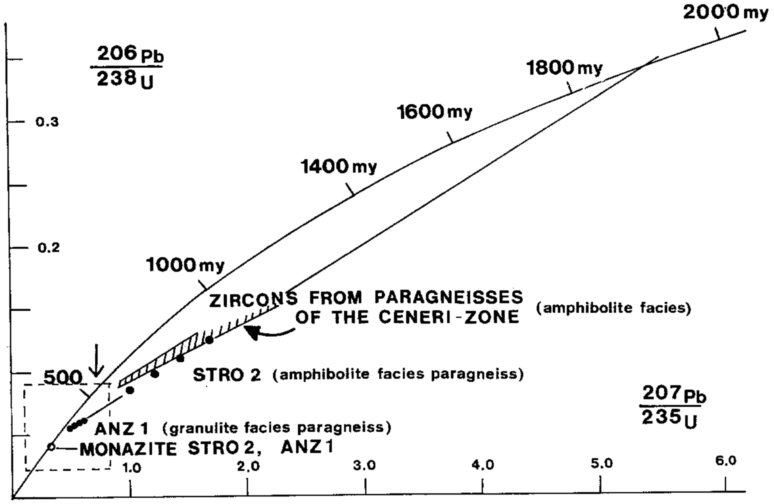

Fig. 5. U—Pb evolution diagram, showing the data points of zircons and monazites of two paragneiss samples from the Ivrea zone and the data field of the Ceneri zone paragneiss zircons (Pidgeon *et al.*, 1970; Köppel and Grünenfelder, 1971) (see Fig. 6 for enlargement of enclosed area)

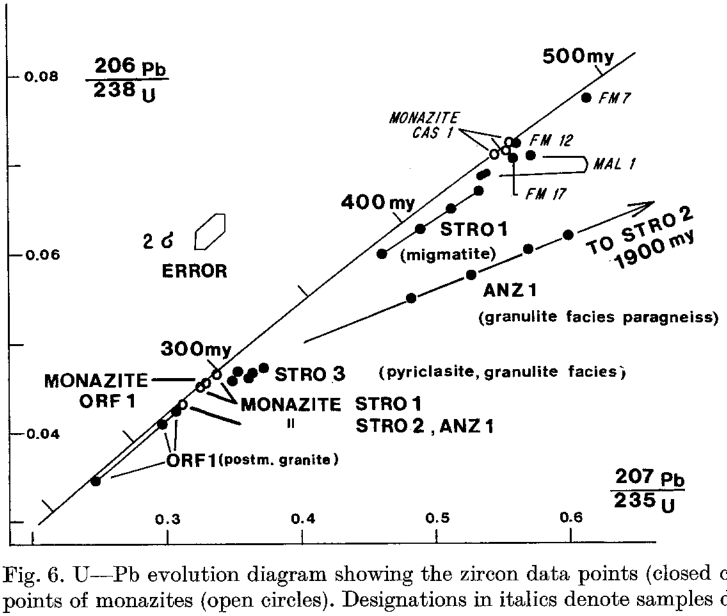

Fig. 6. U—Pb evolution diagram showing the zircon data points (closed circles) and the data points of monazites (open circles). Designations in italics denote samples discussed in Pidgeon *et al.* (1970) and in Köppel and Grünenfelder (1971)

rock types. According to Figs. 5 and 6, one may distinguish the following age groupings:

1) The zircon ages of the postmetamorphic granite are discordant. The linear array of data points suggests a primary age of 325 m.y. and a recent or continuous lead loss.

Table 2. Analytical data of zircons and monazites ($\lambda_{238} = 1.5369 \times 10^{-10}$ y^{-1}; $\lambda_{235} = 9.7216 \times 10^{-10}$ y^{-1}; $^{238}U/^{235}U = 137.7$)

Mineral	Grain-size (micron)	Magnetic suscept. at 1.6 A	U (ppm)	Th (ppm)	Radio-genic Pb (ppm)	Observed ratios			Apparent ages (m.y.)			
						$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{232}Th$
Postmetamorphic granite of Mont'Orfano, sample ORF 1												
Zircon	+75	n.m.	1118	252	44.4	2616	152.2	231.9	261	268	325	268
Zircon	−42	n.m.	1317	394	55.0	3007	171.1	316.0	270	273	301	261
Zircon	53−42	m.	6068	917	197.6	2656	152.6	183.3	219	226	298	246
Monazite			799	37040	492.0	292.5	29.69	4041	290	293	317	282
Migmatite, Ceneri Zone, sample STRO 1												
Zircon	+75	n.m.	1104		69.1	2878	181.4	135.2	418	440	545	
Zircon	75—53	n.m.	1346		81.6	3316	204.1	131.7	409	425	514	
Zircon	53—42	m.	1520		88.0	3317	199.8	101.1	395	405	461	
Zircon	−42	m.	2212		121.3	3570	213.1	94.16	376	387	452	
Monazite	+125		10200	62870	1263	3452	193.9	7156	289	290	295	301
Monazite	−125		13730	63130	1428	2972	171.0	4542	297	301	327	306
Paragneiss (Kinzingite), Ivrea Zone, sample STRO 2												
Zircon	+75	n.m.	352.3		46.4	969.7	109.2	161.9	763	1019	1625	
Zircon	75—53	n.m.	399.6		45.6	1809	186.3	252.6	674	916	1562	
Zircon	53—42	m.	447.7		46.1	4046	377.3	431.2	611	822	1446	
Zircon	−42	n.m.	495.6		43.0	4118	361.4	473.6	538	714	1324	
Monazite			4699	39390	658	992.8	65.9	2660	275	277	293	273
Monazite			2562	38480	643	7876	421.1	21220	277	277	279	280
Pyriclasite, Ivrea Zone, sample STRO 3												
Zircon	+125	n.m.	443.3		19.4	1160	79.04	111.2	289	308	455	
Zircon	+75	n.m.	447.4		19.9	1917	123.3	165.3	293	317	499	
Zircon	75—53	n.m.	457.8		20.7	1969	126.8	172.8	301	326	510	
Zircon	53—42	n.m.	512.3		22.9	1198	82.16	112.4	296	319	491	
Zircon	−42	m.	641.0		28.6	1347	87.82	109.8	299	311	406	
Paragneiss (Stronalite), Ivrea Zone, sample ANZ 1 (for Rb-Sr data see KAW 447-54, Graeser und Hunziker 1968)												
Zircon	+75		462.5		28.5	1102	91.65	133.3	390	483	960	
Zircon	75—53		501.5		30.1	1152	92.60	132.4	381	464	891	
Zircon	53—42		528.6		29.9	1504	114.1	150.2	364	436	837	
Zircon	−42		554.5		29.7	1225	91.89	116.0	349	405	740	
Monazite			2936	41540	598	4516	247.4	19840	275	275	277	264

Common lead correction: $^{206}Pb/^{204}Pb = 17.66$; $^{207}Pb/^{204}Pb = 15.26$; $^{208}Pb/^{204}Pb = 37.04$.

2) The zircon ages from the migmatite are discordant. A best fit straight line through the array of data points intercepts the concordia curve at 345 and 950 m.y.

3) The zircon ages from the paragneisses of the Ivrea zone are also discordant. All data points exhibit the same linear array pointing to a drastic lead loss 285–300 m.y. ago and to an apparent primary age of 1900 m.y.

The same apparent primary age was observed in three paragneiss zircon suites from the Ceneri zone (Köppel and Grünenfelder, 1971).

3. Discussion

3.1. Postmetamorphic Granite of Mont'Orfano, Sample ORF 1

Within the analytical uncertainties the U—Pb ages of the xenotime are concordant and suggest an age of 295 ± 5 m.y. for the Mont'Orfano granite. The age is 20 m.y. higher than Pasteels' estimate based on the agreement between the U—Pb zircon ages and the Rb—Sr ages of feldspar and biotite (Jäger and Faul, 1959). However, one would obtain an equally good agreement with the concordant monazite ages if one uses the ^{87}Rb decay constant of 1.39×10^{-11}/year for calculating the Rb—Sr mineral ages.

The U—Pb zircon ages are discordant. A best fit straight line through the data points intercepts the concordia curve at 10 ± 150 m.y. and at $325 + 60 - 30$ m.y. Provided the zircons are cogenetic, the age of the granite would therefore be $325 + 60$, -30 m.y. which agrees with the age of 295 ± 5 m.y. derived from the concordant monazite age. However, the latter yields probably a better estimate of the age of the granite because the lead/lead zircon ages are likely to be on the high side due to the presence of small amounts of an older zircon generation. Pasteels (1964) reported variable ^{207}Pb/^{206}Pb ages for the Baveno and Mont'Orfano granites of 300 and 385 m.y. The abundance of xenoliths in the Mont'Orfano granite suggests, as Pasteels pointed out, that the high lead-lead age results from the presence of old inherited zircons. The present zircon sample was collected from a block free of xenoliths. The possibility nevertheless remains that a small fraction of inherited zircons is present in the granite itself. Therefore the 325 m.y. represent an upper age limit for the granite.

These zircons are the only ones in the region that yielded discordant ages pointing to a recent or continuous lead loss. The degree of lead loss is related to the trace element contents of the respective fractions. A full discussion of this

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Sample Locations

ORF 1: Quarry west of the railway station Pallanza—Fonda Toce, Mont'Orfano (coordinates: 679900/88550).

STRO 1: Road cut between Omegna and Germagno, Val Strona (coordinates: 674000/81900).

STRO 2: Road cut between Strona and Forno, Val Strona (coordinates: 666600/85550).

STRO 3: Road cut between Forno and Campello Monti, Val Strona (coordinates: 664950/87850).

ANZ 1: Quarry east of Anzola, Valle d'Ossola (coordinates: 670600/93100).
The coordinates refer to those of the Swiss Federal Topographic Survey.

aspect will be given in the following paper dealing with the electron microprobe analyses of the trace elements in the zircons (Köppel and Sommerauer, 1973).

The Th-Pb ages of all zircon fractions are lower than the monazite U—Th—Pb ages. The fractions of lower magnetic susceptibility yielded Th—Pb ages equal to or lower than the U—Pb ages, whereas the Th—Pb age of the fraction of higher magnetic susceptibility is higher than the U—Pb ages. The zircons are therefore not a homogeneous phase with respect to the U—Th—Pb system.

3.2. Migmatite, sample STRO 1

The sample location is situated within the Ceneri zone between the postmetamorphic Baveno granite and the Ivrea zone. The zircons, as well as the monazites, were separated from the leucocratic portion of a nebulitic migmatite (Bertolani, 1968b) consisting of a banded alkalifeldspar-plagioclase-gneiss with little biotite and some accessory garnet and sillimanite.

Two monazite size fractions yielded within the analytical uncertainties the same concordant U—Pb ages of 295±5 m.y. Interpreting these ages by themselves one may conclude that they signify the time of the migmatisation or that they reflect a later thermal event related to the intrusion of the neighbouring postmetamorphic granite of Baveno.

On the U—Pb diagram the data points of the zircon fractions are linearily related and the extrapolated best fit straight line intercepts the concordia curve at $345+25$, -55 m.y. and at 950 m.y. The line passes near the field of data points of zircons from the eastern part of the Ceneri zone (Fig. 6) with almost concordant ages at 450 m.y. (Pidgeon *et al.*, 1970; Köppel and Grünenfelder, 1971). These zircons are very similar with respect to the morphology, zonality, X-ray diffraction pattern and trace element concentrations to the majority of the zircons of sample STRO 1. One may therefore conclude that the zircons of sample STRO 1 were also formed during the regional amphibolite facies metamorphism of the Ceneri zone 450 m.y. ago. The migmatisation would therefore have occurred during a Caledonian metamorphism.

Whereas in the eastern part of the Ceneri zone the U—Pb systems of zircons have almost remained closed since 450 m.y. ago (Fig. 6), the age pattern of the sample STRO 1 indicates that the U—Pb system was open for, or reopened, some time after 450 m.y. ago. Because of different proportions of inherited zircons (see section 2.1.) in the different size fractions, the intercept at 345 m.y. of the extrapolated best fit straight line with the concordia curve has no geological meaning and therefore does not indicate the time when the U—Pb system was disturbed. The 10–20% inherited zircons can account for the age pattern pointing towards the 950 m.y. instead of the 450 m.y. mark on the concordia curve, if they apparently lost 90% of their radiogenic lead during the migmatisation process. From the concordant monazite ages, one may conclude that the lead loss occurred 295 m.y. ago; however, for geological reasons, which will be discussed later, we prefer to think of a continuous lead loss acting from 450 to 295 m.y. under high grade metamorphic conditions.

3.3. Paragneisses of the Ivrea Zone, Samples STRO 2, STRO 3, ANZ 1

The three samples are typical representatives of the paramaterial of the Ivrea zone showing different metamorphic facies and different degrees of acidity.

The paragneiss sample STRO 2 contains quartz, plagioclase, alkalifeldspar, sillimanite, garnet, biotite and some graphite, a mineral assemblage typical of the sillimanite-almandine-orthoclase subfacies of the amphibolite facies; such gneisses are also named "gneiss kinzigitici" (Schmid, 1967; Bertolani, 1968).

The sample STRO 3, a pyriclasite (Schmid, 1967), or a "granulite pirosseniche" (Bertolani, 1968) consists of plagioclase, garnet and pyroxene (diopside and enstatite) forming the primary mineral assemblage and of biotite and hornblende which form according to microscopic criteria a later mineral assemblage.

The sample ANZ 1 is according to Schmid (1967) a stronalite or according to Boriani (1968) a "granulite acide". It was collected 2 m away from the contact to the gabbro of Anzola and is identical to sample KAW 447 of Graeser und Hunziker (1968). The banded rock consists of quartz, alkalifeldspar, plagioclase, garnet, sillimanite, and little biotite.

The samples STRO 3 and ANZ 1 are rocks of granulite facies. Although sample STRO 3 is neither by its mineralogical nor its chemical composition a gneiss, it will be referred to, together with the samples STRO 2 and ANZ 1, as a paragneiss, unless reference is made to one specific sample.

The concordant monazite ages of 275 ± 2 m.y. of the samples STRO 2 and ANZ 1 are 20 m.y. lower than the concordant monazite ages of the sample STRO 1, the Ceneri zone migmatite, and of the sample ORF 1, the post-metamorphic granite of Mont'Orfano. Assuming identical behaviour of the U—Pb systems in all monazites this means that the temperature at which monazite becomes stable, or at which the U—Pb system is closed, was reached 20 m.y. later than in the neighbouring Ceneri zone located farther away from the crust-mantle transition.

The concordant monazite ages indicate that the Hercynian event is not of local character, due to the intrusions of the post-metamorphic granites, but rather of regional character in the Ivrea zone, as is also shown by the zircon age patterns.

The zircon populations of all three samples are homogeneous, and similar to each other in every respect. Their X-ray powder diffractions are well defined and contrast with the broader lines of the samples ORF 1 and STRO 1. All fractions have similar uranium concentrations ranging from 350 to 650 ppm and similar other trace element concentrations (Köppel and Sommerauer, this volume). As has been shown by Köppel and Grünenfelder (1971) for zircons from the eastern part of the Ceneri zone, these features are characteristic for detrital zircons which recrystallised during a high grade metamorphism.

On a U—Pb diagram the data points of the fractions of the three samples are alligned within the analytical uncertainties on one linear array. The extrapolated best fit straight line intercepts the concordia curve at 285 ± 10 m.y. and at 1900 m.y.

The degree of the apparent lead loss is roughly correlated to the metamorphic grade of the host rock. The zircons of the amphibolite facies sample STRO 2 lost apparently 85% of their lead, similar to other paragneiss zircons from the amphibolite facies rocks of the Ceneri zone, whereas the two zircon samples from granulite facies rocks lost 95%, respectively 99% of their lead.

As a first conclusion one may therefore state that the U—Pb system of detrital zircons partially survives under the *P*—*T* conditions of a granulite facies metamorphism.

The fact that we obtained one linear array, pointing to the event indicated by the monazite ages, from three different detrital paragneiss zircon suites argues for a systematic relationship between the behaviour of the U—Pb systems of zircons and their history; this in spite of the fact that the history of a detrital zircon population is a priori more complex than the one of a cogenetic suite that remained in its original host rock (Pidgeon *et al.*, 1970; Köppel and Grünenfelder, 1971).

Allègre *et al.* (1973) developped models which quantitatively explain the behaviour of the U—Th—Pb systems of zircons with complex histories. Considering all the zircon data from the Southern Alps it appears that the zircons from the Ivrea zone also suffered a lead loss 520–580 m.y. ago, which could either be related to the weathering and sedimentation cycle or else to a Cadomian metamorphism, but that the dominating event occurred in the Ivrea zone 300 m.y. ago.

If one disregards the limits set by the analytical uncertainties to any speculative interpretation of the age data one notes that the lower intercepts with the concordia curve of the best fit straight lines through the individual arrays of the zircon data points become progressively lower as one starts with the Ceneri zone sample STRO 1 at 345 m.y. and enters the Ivrea zone ending with sample STRO 3 at 280—290 m.y. going thus in the direction of increasing metamorphism. The shift of the lower intercepts may signify that the higher the metamorphic grade of a rock was, the later it cooled down to a temperature at which the U—Pb systems of zircons were closed. The monazite ages of samples STRO 1 and 2, and ANZ 1, concordant at 295 and 275 m.y., support such an interpretation.

4. Conclusions with Regard to the Chronology of Events in the Ivrea and Ceneri Zones

The age pattern of the three paragneiss zircon samples indicating an event 285 ± 10 m.y. ago irrespective of the type of their host rocks and their spatial relationships towards the basic rocks of mantle origin and the agreement between this inferred age and the concordant monazite ages supports the view that the basic rocks intruded synmetamorphously (Schmid, 1967).

The question arises how the ages of the monazites (275 ± 2 m.y., 295 ± 5 m.y.) and the age of the event inferred from the zircon age pattern (285 ± 10 m.y.) relate to the regional metamorphism and the mantle uplift. To answer this question one has to take into account the metamorphic facies of the Ivrea zone rocks and the observation that the postmetamorphic granites intruded into shallow depths of about 5 km, as can be seen from the presence of miarolithic vugs. One furthermore has to assume that the relative spatial relationship between the postmetamorphic granites and the Ivrea zone rocks, as we see it to-day, existed at the time of the consolidation of the granites.

From the regional subvertical dip of the gneisses it follows that at the time of the granite intrusion the sillimanite bearing rocks would have been located at a depth of about 7–8 km. If the regional metamorphism leading to the formation of sillimanite bearing rocks in the Ivrea zone happened simultaneously with the intrusion of the granite then temperatures as high as 800° C would have occurred in the Ivrea zone rocks at a depth of 7–8 km (Richardson *et al.*, 1969). Because

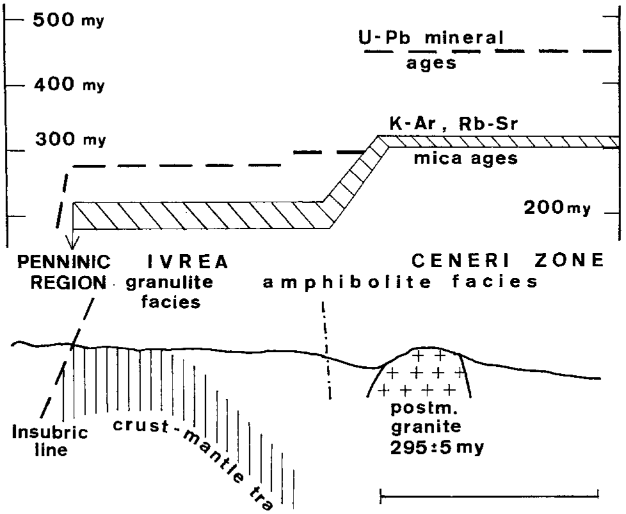

Fig. 7. Schematic profile across the Ivrea and Ceneri zones showing the Rb—Sr, K—Ar and U—Pb age relationships

of the high thermal gradient, a granite could hardly have intruded into a cooler surrounding producing contact metamorphism.

It appears more reasonable to assume that the regional metamorphism of upper amphibolite and granulite facies occurred at depths of the crust-mantle transition, i.e. at a depth of 30–35 km. Therefore the uplift and overthrust of the mantle must have had already started at the time the granites intruded. The 285–295 m.y. denote thus period after the paroxism of the metamorphism.

It must be noted again that this interpretation is based on the present-day spatial relationship between the Ivrea and Ceneri zones. Boriani (1970) pointed out the existence of a fault separating the two zones in the region of the Val Grande and also extending to the western side of the Valle d'Ossola (Boriani, oral communication). According to Schmid (oral communication) faulting may also be responsible for the step like increases of the metamorphic grade, as expressed by the model ratio $g = \text{garnet}/(\text{garnet} + \text{biotite})$, towards the northwest.

No faulting has so far been reported from the Val Strona region and we therefore favour the interpretation of the 275–295 m.y. ages as cooling ages postdating the granulite facies metamorphism.

Fig. 7. shows the age relationships along a simplified profile across the Ivrea and Ceneri zones. The conspicuous decrease of 150 m.y. of the monazite U—Th—Pb ages and the zircon U—Pb age patterns is accompanied by a lowering of the K—Ar and Rb—Sr mineral ages of about 120 m.y. The decrease is spatially related to the appearance of higher grade metamorphic rocks and the presence of the mantle-crust transition zone. The lowering of the ages takes place over a short distance of about 1 km and thus reflects the steep dip towards the southeast of the mantle as shown in Fig. 2.

Because there is no evidence that the Ivrea and the Ceneri zone sediments were deposited in different geosynclines one may reasonably assume that the metamorphism started in both zones simultaneously at least 450 m.y. ago. The lower ages of the Ivrea zone show that the rocks remained for a longer period under elevated P—T conditions. From the present data we can only conclude that the uplift and overthrusting of the mantle started prior to 295 m.y. ago and reached approximately 200 m.y. ago a cooling stage at which the micas formed closed Rb—Sr and K—Ar systems. The question as to what extent the structure of the Ivrea body was modified by the Alpine orogeny remains open.

A Hercynian uplift and overthrust of the mantle implies that the Insubric line is in the region of the Ivrea zone at least of the same age, or that a Hercynian precursor of the Insubric line existed in that region.

Wenk (1965) and Schmid (1967) suggested that the granulite facies rocks were deprived during the metamorphism of water, alkalies and silica and could therefore represent degranitised rocks.

In a petrographic study of the Val Strona, Bertolani (1968b) also thought of the possibility that the formation of the migmatites in the southeastern part of the valley may be related to the liberation of volatiles during the granulite facies metamorphism of the rocks now situated in the upper part of the valley. The present study was not aimed at testing this hypothesis, but it should be mentioned that the results do not contradict the view if one assumes that the high grade metamorphism was already active 450 m.y. ago and was of still considerable intensity 300 m.y. ago.

5. Summary

Zircons. All zircon ages are discordant. The age pattern of three paragneiss zircon suites points to an event 285 ± 10 m.y. ago in agreement with the concordant monazite ages of the same rocks. The degree of the discordancy is roughly related to the metamorphic grade of the host rocks. A net lead loss of approximately 85 % is indicated for detrital paragneiss zircons of amphibolite facies rocks, whereas in rocks of granulite facies the net lead loss reaches 95 to 99 %. Zircons appear therefore to be suitable for dating granulite facies metamorphism.

The age pattern of the zircons from the Ceneri zone migmatite between the Baveno granite and the Ivrea zone is interpreted as indicating a prolonged period of metamorphism starting 450 m.y. ago with migmatisation and new zircon growth the U—Pb systems of which remained open until about 300 m.y. ago as indicated by the concordant monazite ages. In spite of an admixture of detrital paragneiss zircons, the zircons from the migmatite still exhibit a linear array on the U—Pb evolution diagram, but the upper and lower extrapolated intercepts with the concordia curve have no significance.

The age pattern of the zircons from the post-metamorphic granite of Mont' Orfano is the only one pointing to a recent or continuous lead loss. In the following paper the results of an investigation of the distribution and concentration of some trace elements in the zircons are presented together with an attempt to explain this different and seemingly inconsistent behaviour of the U—Pb systems in zircons.

Monazite. The concordant U—Th—Pb ages of monazite demonstrate the usefulness of this mineral for dating purposes in metamorphic rocks as well as in granites.

The available data suggests that monazite is stable, or their U—Th—Pb system is closed, under amphibolite facies conditions close to anatectic melting.

Systematic studies are needed to evaluate the significance of the ages with respect to the history of a metamorphic cycle.

Chronology of Events. Because the discordant age pattern of three paragneiss zircon suites points, independently of the spatial relationship of the sample location towards the basic rocks of the Ivrea zone, to an event 285–300 m.y. ago, in agreement with the concordant monazite ages, it is concluded that the basic rocks intruded synmetamorphously.

From the spatial relationship between the Ivrea and Ceneri zone rocks, including the postmetamorphic granites, from the metamorphic facies and the agreement of the phosphate ages in all rock types, it is concluded that the overthrust and uplift of part of the upper mantle started prior to 295 m.y. ago and that this age is a minimum age for the granulite facies metamorphism of the Ivrea zone and for the Insubric line, or a precursor thereof, along the Ivrea zone.

The petrographic boundary between the Ivrea and Ceneri zone corresponds roughly to an age boundary which reflects different periods of cooling attributed to the uplift of the upper mantle.

From the age data of both zones and especially from the zircon and monazite data from the migmatite located between the two zones one is lead to the conclusion that the metamorphism of the Ivrea zone and adjacent Ceneri zone rocks lasted at least 250 m.y., a time span that comprises what are thought to be two distinct orogenic cycles, the Caledonian and Hercynian.

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References

Allègre, C. J., Albarède, F., Grünenfelder, M., Köppel, V.: $^{238}U/^{206}Pb$—$^{235}U/^{207}Pb$—$^{232}Th/^{208}Pb$ zircon geochronology in Alpine and non-Alpine environment. Contr. Mineral. and Petrol. (in press)

Ansorge, J.: Die Struktur der Erdkruste an der Westflanke der Zone von Ivrea. SMPM **48** (1), 247–254 (1968)

Bertolani, M.: Squardo generale alla petrografia della Valle Strona (Novara). Guida all excursione. SMPM **48** (1), 314–328 (1968)

Bertolani, M.: La petrografia della Valle Strona (Alpi Occidentali Italiane). SMPM **48** (1), 695–732 (1968)

Boriani, A.: The "Pogallo Line" and its connection with the metamorphic and the anatectic phases of "Massicio dei Laghi" between the Ossola Valley and Lake Maggiore (Northern Italy). Boll. Soc. Geol. It. **89**, 415–433 (1970)

Chessex, R.: Déterminations d'âges sur les zircons des Alpes et des Apennins par la méthode des «radiation damage». SMPM **44**, 27–42 (1964)

Colloquium on the Geochronology of Phanerozoic and Orogenic Belts, Field Trip, Switzerland 1969

Deutsch, S., Picciotto, E., Niggli, E.: Age des halos pléochroitiques des granites de Baveno et Monte Orfano. Experientia **14** (14) (1958)

Gansser, A.: The insubric line, a major geotectonic problem. SMPM **48** (1), 123–144 (1968)

German Research Group for Explosion Seismology: Topographie des "Ivrea-Körpers" abgeleitet aus seismischen und gravimetrischen Daten. SMPM **48** (1), 235–246 (1968)

Giese, P.: Die Struktur des Erdkörpers im Bereich der Ivrea-Zone. Ein Vergleich verschiedener seismischer Interpretationen und der Versuch einer petrographisch-geologischen Deutung. SMPM **48** (1), 261–284 (1968)

Goguel, J.: La zone d'Ivrée au sens géophysique et ses rapports avec l'arc des Alpes occidentales. SMPM **48** (1), 227–234 (1968)

Graeser, S., Hunziker, J. C.: Rb—Sr and Pb Isotopen Bestimmungen an Gesteinen und Mineralien der Ivrea Zone. SMPM **48** (1), 189–204 (1968)

Graeser, S.: Pb isotopes in basic and ultrabasic rocks from the Alps. Eclogae Geol. Helv. **63** (1), 105–109 (1970)

Jäger, E., Faul, H.: Age measurements on some granites from the Alps. Bull. Geol. Soc. Am. **70**, 1553–1558 (1959)

Jäger, E., Niggli, E., Wenk, E.: Rb—Sr Altersbestimmungen an Glimmern der Zentralalpen. Beitr. Geol. Karte Schweiz, NF 134 (1967)

Kaminski, W., Menzel, H.: Zur Deutung der Schwereanomalie des Ivrea-Körpers. SMPM **48** (1), 255–260 (1968)

Köppel, V., Grünenfelder, M.: A study of inherited and newly formed zircons from paragneisses and granitised sediments of the Strona-Ceneri-zone (Souther Alps). SMPM **51** (2–3), 385–410 (1971)

Köppel, V., Sommerauer, J.: Trace elements and the behaviour of the U—Pb system in inherited and newly formed zircons. Contr. Mineral. and Petrol. **43**, 71–82 (1974)

Krummenacher, D., Evernden, J. F., Vuagnat, M.: Sur l'âge absolu de la péridotite micacée de Finero (zone d'Ivrée). Arch. Sci. Genève **13**, 369–373 (1960)

McDowell, F. W.: Potassium-argon ages from the Ceneri zone, Southern Swiss Alps. Contr. Mineral. and Petrol. **28**, 165–182 (1970)

McDowell, F. W., Schmid, R.: Potassium-argon ages from the Valle d'Ossola section of the Ivrea-Verbano zone (Northern Italy). SMPM **48** (1), 189–204 (1968)

Pasteels, P.: Mesures d'âges sur les zircons de quelques roches des Alpes. SMPM **44** (2), 519–542 (1964)

Pavoni, N.: Gesteinsmagnetische Untersuchungen in der Zone von Ivrea NW von Brissago. SMPM 48 (1), 295–297 (1968)

Pidgeon, R. T., Köppel, V., Grünenfelder, M.: U–Pb isotopic relationships in zircon suites from a para- and orthogneiss from the Ceneri zone, Southern Switzerland. Contr. Mineral. and Petrol. **26**, 1–11 (1970)

Richardson, S. W., Gilbert, M. C., Bell, P. M.: Experimental determination of kyanite-andalusite and andalusite-sillimanite equilibria, the aluminium silicate triple point. Am. J. Sci. **267** (3), 259–272 (1969)

Schilling, J.: Petrographisch-geologische Untersuchungen in der unteren Val d'Ossola. Ein Beitrag zur Kenntnis der Ivrea-Zone. SMPM **37**, 435–544 (1957)

Schmid, R.: Struktureller Aufbau der Zone Ivrea-Verbano zwischen Valle d'Ossola und Val Grande (Norditalien). SMPM **46**, 687–691 (1966)

Schmid, R.: Zur Petrographie und Struktur der Zone Ivrea-Verbano zwischen Valle d'Ossola und Val Grande (Prov. Novara, Italien). SMPM **47**, 935–1117 (1967)

Schmid, R.: Excursion guide for the Valle d'Ossola section of the Ivrea-Verbano zone. SMPM **48** (1), 305–314 (1968)

Vecchia, O.: La zone Cuneo-Ivrea-Locarno, élément fondamental des Alpes, géophysique et géologie. SMPM **48** (1), 215–226 (1968)

Wenk, E.: Khondalite and Stronalite. Indian Mineralogist **6** (1–2), 21–26 (1965)

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