Tertiary metamorphic conditions in the eastern Lepontine Alps

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by *Martin Engi[1], Clifford S. Todd[1,2]* and *Dirk R. Schmatz[1]*

Abstract

We present a comprehensive analysis of data on metamorphic assemblages equilibrated during the main (syn- to post-D_2) thermal peak in the eastern part of the Lepontine zone of the Central Alps. A set of selection criteria applied to data available from the literature yielded a database of only 39 well documented samples appropriate for this investigation. In the present study, these data were complemented by the analysis of 31 newly acquired samples. For the thermobarometric analysis of the parageneses a multi-equilibria method (BERMAN, 1991), based on consistent, optimized thermodynamic models, was used.

This study yields a set of coherent *P-T* values, with important implications for the evolution of this orogenic area. Isotherm and isobar contour maps constructed from our results serve as a basis for systematic comparison with previous thermobarometric data for the Central Alps. Agreement with earlier temperature estimates is fairly good, but pressure values are, in some cases, quite different compared to previous studies. The isotherms roughly reflect the previously known concentric pattern of mineral zones assumed to be produced by the Tertiary metamorphic event. The temperatures recorded increase from the north to the south, with a maximum (~ 670 °C) reached at the Insubric Line. In contrast, recorded pressures show a maximum (~ 7 kbar) about 20 km north of the Insubric Line, whereas they are considerably lower near the Insubric Line.

Tectonic interpretations of the pressure and temperature distribution are tentative at this time. Based on an assessment of those mineral age data considered thermally most robust (represent age of peak metamorphism), a two-stage model is proposed: The northern portion reached its T_{max} at 35–38 Ma following nappe formation during subduction. In the southern and central parts of the belt, the thermal structure was subsequently modified by emplacement of hot tectonic units (Adula/Cima Lunga nappe, magmatic bodies); here T_{max} was reached between 28 Ma (south) and 20 Ma (central part).

Keywords: petrology, thermobarometry, multi-equilibria method, Lepontine, Central Alps, Tertiary metamorphism, regional metamorphism, metamorphic gradient, tectonics.

1. Introduction

The Barrow-type facies series of Tertiary metamorphism in the Central Alps (Ticino and adjacent areas) forms an asymmetric dome of isograd surfaces exposed by uplift and erosion of the deepest parts of the Alpine nappe pile. Metamorphic grade increases from north to south reaching sillimanite grade near the Insubric Line, which truncates the dome. The nappes consist of pre-Alpine continental basement with intercalated (at least in part Mesozoic) sediments and ophio-lites. In general, nappe boundaries are discordantly cut by more steeply inclined isograds (FOX, 1975; THOMPSON, 1976). This has been taken to indicate that the amphibolite facies metamorphism reached its peak after nappe formation and emplacement – or at least outlasted it; however, this interpretation is not undisputed (MILNES, 1975; STECK and HUNZIKER, 1994). Since the publication of the first mineral distribution maps by NIGGLI (1960, 1970) much work has been devoted to mapping regional mineral zones and to determining isotopic ages. Results have

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been reviewed repeatedly (NIGGLI, 1970; FREY et al., 1974; FREY et al., 1980; TRÜMPY, 1980; HUN-ZIKER et al., 1993).

With the introduction of electron micro-probes some 30 years ago, workers started to obtain quantitative estimates of the pressures and temperatures of metamorphism. Commonly, thermobarometric techniques used individually calibrated mineral equilibria. Over the years, additional methods have been applied, including fluid inclusion studies (WALTHER, 1983), oxygen isotope thermometry (HOERNES and FRIEDRICH-SEN, 1980) and piezobarometry using birefringent halos of quartz inclusions in garnet (ADAMS et al., 1975). Initially, many results were fairly crude, owing to limitations in the calibrations and thermodynamic data used. Progress in thermobarometric methods has been steady over the years (e.g., POWELL and HOLLAND, 1988; BERMAN, 1991; GORDON, 1992), but no effort has been made to assess the two-dimensional geographic distribution of metamorphic pressure and temperature in the Central Alps. One reason for this may lie in the difficulties one faces when trying to assess P-T-data from diverse sources in the literature. Usually these data are not regionally comparable and interpretable, owing to mutual inconsistencies in the thermobarometric calibrations used. In addition, the required analytical data published in different studies commonly are not documented adequately. This impairs the use of this data in general and the reinterpretation of phase equilibrium data in particular. Ideally, all values of P and T should be based on the same set of calibrations, in order to compare pressures and temperatures on a regional scale. In the best case, i.e. for samples that are suitably documented, this necessitates recalculating P and T from assemblage and mineral chemistry data, using uniform thermobarometric methods.

We report here on a comprehensive search of the literature, aimed at extracting complete mineral assemblage and chemistry data suitable for current methods of thermobarometry. We used a multi-equilibria method (BERMAN, 1991), based on consistent, optimized thermodynamic models – including solution models – to derive estimates of the pressures and temperatures of equilibration for 39 samples described in the literature. We applied the same thermobarometric technique to 31 new samples acquired in the present study in order to complement the geographic distribution of data from the literature. We then used the P-T results to construct isotherm and isobar maps for the Eastern part of the Lepontine area. This paper first describes the criteria used to select paragenesis data, then presents these data and

the tools used to document, calculate and compare temperature and pressure values. Finally, we address some aspects of petrologic interpretation and some of the implications this work has on the tectonic history of the Central Alps and on the Tertiary metamorphic evolution in this area.

2. Database and documentation

We searched some 350 studies (mostly Ph. D. theses, diploma theses and regular journal papers; some unpublished data) dealing with Tertiary metamorphism in the Central Alps for rock sample descriptions and, most importantly, adequate paragenesis and mineral chemistry information. In addition to data extracted from the literature, a suite of samples was collected and documented in this study. The scale of this work required a set of tools for the collection, analysis, and representation of the data and results. The database we specifically designed for this purpose (ParaDIS) was described in detail by SCHMATZ et al. (1995).

2.1. EVALUATION CRITERIA

The three minimum requirements for a rock sample to be included in our analysis were its exact geographic location, a description of the fabric, and its mineral chemistry. If one of these items was incomplete or missing, a sample from the literature either revealed only part of its information (e.g. only one of a number of possible mineral equilibria could be calculated due to lack of mineral chemistry information for some phases) or had to be completely rejected (e.g. no location). Additionally desirable is information concerning the extent or lack of compositional zoning, the tectonic unit from which the sample originated, and the modal abundance of minerals. This information was used for control purposes and for resolving ambiguities concerning crystallization/deformation relations.

Although many authors have followed NIGG-LI's (1960) recommendation by attempting to characterize the Alpine metamorphism using only metasediments of post-Hercynian protolith age (i.e. Permian and younger), ambiguities about the precise timing of metamorphism remain. Metamorphism in the Central Alps being polyphase, several parageneses may be identified in a single rock sample, even in a thin section. In order to obtain P and T estimates for a specific phase of metamorphism, a clear description of the parageneses found in a rock sample is absolutely essential. Petrographic criteria, when used

Tab. 1 Common problems with sample documentation in the literature (the list is ordered according to frequency of occurrence).

Problems	Explanation of insufficiencies and errors encountered
association of data	Crucial relationships cannot be reconstructed (e.g. analysis to mineral, mineral to paragenesis, paragenesis to handspecimen); generally due to wrong or missing identification labels or codes. Microprobe data of minerals 'forming a paragenesis' in fact derive from different handspecimens.
missing information	No description of the outcrop or handspecimen, parageneses or minerals, or no modal estimates.
location	Information missing, information wrong (e.g. impossible coordinates).
microprobe data	No analyses, only 'representative' data (averages, extracts) available; probe data could not be obtained from authors. Analyses are of insufficient quality.

in conjunction with careful structural analysis and detailed microprobe studies, have commonly allowed convincing assignment of crystallization/deformation relations.

Because two distinct phases ("meso-" and "neo-Alpine") of Tertiary metamorphism have been established in the Central Alps, we concentrated on fresh, pervasively recrystallized samples, showing structural characteristics of the latest regional phase of deformation recognized locally. Minerals which are in contact with each other and which show no reaction textures were assumed to be part of the same paragenesis. Care was taken to avoid relic fabrics (e.g. isolated minerals included in neoblasts), reaction textures (e.g. corroded minerals) or late alterations and products of reequilibration (e.g. "cooling rims" of garnets). For each suitable sample, we required complete phase compositions, fabric and petrographic characteristics. Chemical analyses had to be of coexisting minerals, devoid of evident retrogression, and had to be of good quality. For anhydrous minerals, the sum of the oxide components from microprobe analysis must equal $100 \pm 2\%$. Mineral formulae calculated from normalized analyses had to yield stoichiometries that satisfy known crystal-chemical criteria, such as exchange operations and site occupancy.

2.2. EVALUATION OF LITERATURE DATA

In assessing paragenetic data from the literature, we used the authors' descriptions of the samples and field relations to determine if the sample was appropriate for our study. If this information was incomplete or absent, we relied on the authors' conclusions regarding equilibration between mineral phases and the age of metamorphism (meso- or neo-Alpine vs older events).

Unfortunately, in many studies crucial information is not available, or some data cannot be assessed with certainty. Where ambiguous, assemblage data could not be used. In some cases, arbitrary choices were unavoidable, e.g. multiple compositions for a mineral were averaged. Many studies do not list the compositions of minerals in metamorphic rocks, and many of the metamorphic rocks studied are not appropriate for inclusion in the present study because they (may) represent earlier metamorphic events. But for those potentially usable works, the most common reasons for rejection of data and even entire studies was neither missing compositional information nor data of poor quality. We found that *most of the data in a majority of potentially appropriate studies* (see Appendix) could not be used owing to logistic ambiguities and errors. Due to these, crucial *relationships* could not be reconstructed, usually for simple reasons such as incorrect identification labels or missing sample codes. For example, it is frequently not clear to which mineral assemblage a given analysis pertains, or to which rock specimen an analyzed mineral may belong. Table 1 lists the most common insufficiencies encountered, in order of decreasing frequency of their occurrence. Further detail is contained in SCHMATZ (1993).

Applying the above set of criteria to data available in the literature yielded a database of

only 39 samples! Data for these samples originate from the following studies: TEUTSCH (1982), KLAPER (1982), KOCH (1982), IROSCHEK (1983), FISCHER (1986), WABER (1986), STAPS-OHNMACHT (1991), and THOENEN (1990). To improve the geographic coverage, these data from the literature were complemented by new paragenetic data from 31 samples.

2.3. NEWLY ACQUIRED SAMPLES

Since the geographic spread of appropriate samples from the literature is sparse in much of the area (Fig. 1), we acquired additional samples from the field. In order to examine the latest phases of the Alpine orogeny, great care was taken during the sample selection. Wherever possible, the samples collected were of Mesozoic protolith age, usually metasediments. This effectively excluded rocks that underwent metamorphism during the Variscan or older orogenies. In some areas, notably in the southeastern part of the field area, the protolith age of metasediments is controversial. In these areas we collected metasediments that were deformed during the (structurally defined) latest Alpine event in order to increase the chances that any possible older metamorphism was completely overprinted. Samples used here were either pelites (the vast majority) or marls in composition. In collecting these, we relied heavily on earlier work, which we used to identify geographic areas or even specific outcrops, likely to contain appropriate material. In addition to our own samples, several colleagues generously provided material. Notably, P. Graeter shared a suite of his Maggia samples, and P.H. Thompson donated Mesolcina samples he collected for his classical study (THOMPSON, 1976). Further material came from the collections of E. Wenk, M. Frey, and R. Gieré.

All of the newly acquired samples were first examined petrographically. Samples were then chosen for analysis by electron microprobe only if the following three criteria were met: 1) No mineral textures indicating disequilibrium (symplectites, corona textures) were found; 2) retrograde textures (chloritized or oxidized biotite, sericitized plagioclase, etc.) were absent or at least not affecting the entire thin section; 3) the equilibrium mineral assemblage had the potential of yielding several linearly independent thermodynamic equilibria.

Microprobe analysis of minerals was done on the Cameca SX-50 at the University of Bern. Accelerating voltage: 15 kV, sample current: 20 nA. A slightly defocussed beam was used to analyze feldspars, a focussed beam was used in all other cases.

Biotite, garnet, ilmenite, plagioclase, and white mica were analyzed for use in thermodynamic calculations. In assessing our own microprobe data, we applied the same quality control criteria as stated above for literature data. Of the minerals used in thermobarometry, only garnet and plagioclase show substantial compositional zoning or variation within a thin section in some samples. For zoned garnets, the composition just inside of the cooling rim (if present) was used for thermobarometric calculations. Plagioclase is homogeneous in most samples. However, in some cases, large crystals are zoned (visible in thin section or backscatter electron images). If it seemed clear which part of the plagioclase had a chance to equilibrate with the rest of the assemblage, plagioclase was used in thermodynamic calculations. If it was unclear, plagioclase was included only if the *P-T* results were but weakly dependent on the plagioclase composition, within limits observed in that sample. Where veining in plagioclase was noticeable (in backscatter images), these veins were avoided during electron microprobe analysis.

Sample sources

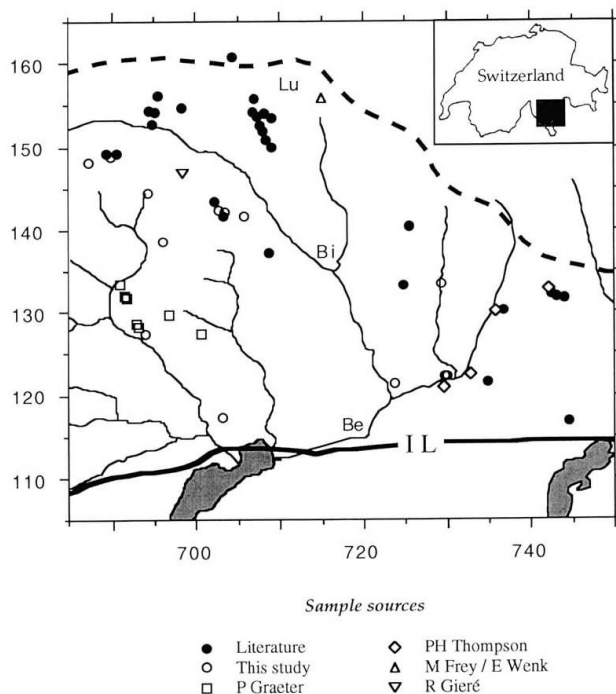|			
●	Literature	◇	PH Thompson
○	This study	△	M Frey / E Wenk
□	P Graeter	▽	R Gieré

Fig. 1 Location of Tertiary metamorphic belt north of Insubric Line (IL). Dashed line represents outer margin of amphibolite facies metamorphism (SPICHER, 1980). Symbols indicate sample source. Be = Bellinzona, Bi = Biasca, Lu = Lucomagno. Grid along edge of diagram in km (Swiss national grid).

A complete list of microprobe analyses is too lengthy to include in this publication. Abbreviated sample and composition information, both for new samples and those extracted from the literature, is listed in tables 2 and 3. A complete list of all of the microprobe data used can be obtained from the authors.

3. Thermobarometry

Mineral stoichiometries were calculated from microprobe data either by the program *MINSORT* (PETRAKAKIS and DIETRICH, 1985) or by individually programmed Excel spreadsheets. Normalization schemes, and treatment of iron are as follows: Bt and Mu: 11 anions, all Fe^{2+}; Grt: Fe + Mn + Mg + Ca = 3, all Fe^{2+}; Pl: Ca + Na + K = 1, all Fe^{3+}; Ilm: cations = 2, anions = 3. Thermodynamic calculations were performed using GEØ-CALC software (BERMAN et al., 1987; BROWN et al., 1988), using the database of BERMAN (1988) with 1992 updates. All calculations were done in the system Na_2O–K_2O–CaO–MgO–FeO–Al_2O_3–SiO_2–TiO_2–H_2O. The only mineral species used for thermobarometric calculations were: almandine, grossular, pyrope, annite, phlogopite, albite, anorthite, muscovite, paragonite, quartz, kyanite, sillimanite, rutile, and ilmenite. Activities of end member mineral components were calculated using the models listed in table 4. The thermodynamic models (endmember properties and/or activity models) for epidote, chlorite, staurolite, and chloritoid are considered less reliable at present. Therefore, equilibria involving these species were not calculated. Present solution models for garnet do not predict the activity of grossular well at low mole fractions. In particular, if $X_{grs} < 0.10$ then grossular was excluded from calculations.

We used the method described by BERMAN (1991) to calculate pressure and temperature estimates. Briefly, all possible equilibria, stable and metastable, are calculated. (An example is documented in Section 3.2.) The pressure and temperature location of the intersection of each pair of equilibria is tabulated, and the weighted average of the whole lot is taken (BERMAN, 1991). Two consecutive weighting schemes are applied to the intersection points. First, the datum is weighted by the angle of intersection; equilibria that intersect at a high angle are given more weight than those that intersect at a small angle. Second, the datum is weighted by a variable related to the $\Delta_r S$, $\Delta_r V$ at the point of intersection and the equilibria stoichiometric coefficients. This factor gives more weight to equilibria which are less influenced by errors in the thermodynamic properties

of the endmembers and solid solutions of the constituents of the equilibria. For each sample, thermodynamic calculations were done using all minerals in the assemblage for which data exist in the thermodynamic database.

For some samples, typically from the literature, only one equilibrium could be calculated, usually the garnet-biotite exchange thermometer. In others, only two independent equilibria could be calculated, and the *P-T* estimate is the invariant point of that system. In many samples, systems with three or more linearly independent equilibria could be calculated. It is in this situation that the benefits of multi-equilibria techniques come to bear, for the dispersion of equilibria in *P-T* space serves as a test of assumptions inherent in thermobarometry: (a) chemical equilibrium was reached at some time, (b) all phase compositions have remained unchanged since that time, (c) the thermodynamic models available calculate the true *P-T* locations of all equilibria. It is important to realize that failure of *any* one of these assumptions may introduce error into thermobarometric results, regardless what technique is being used. Using multi-equilibria techniques (POWELL and HOLLAND, 1988; BERMAN, 1991; GORDON, 1992), these assumptions are at least testable, provided more than two independent equilibria can be calculated. In such a situation, if the intersection cluster was dispersed, as assessed visually or statistically, an attempt was made to determine which mineral(s) or mineral endmember(s) appear to be out of equilibrium with the rest of the assemblage. The removal of one endmember (in 12 cases) or two endmembers (in 2 cases) left *P-T* patterns with an acceptably tight cluster of intersections. If, after applying this method to a sample, the equilibria in the *P-T* diagram still showed a large spread (> ± 100 °C and/or ± 2 kbar), we assumed that chemical equilibrium had not been attained or had been subsequently disturbed or was not properly located in *P-T* space owing to inadequate thermodynamic models used. Such samples were rejected in this study, the primary goal of which was to determine the *P-T* values corresponding to peak metamorphic conditions. In all, 70 samples were accepted, four samples were disregarded at this stage; further work is required to understand better why the latter did not yield reliable *P-T* results.

3.1. ACCURACY AND PRECISION

The accuracy of geothermometers is often stated to be ~ 50 °C, and that of geobarometers ~ 0.5 to 1 kbar, compatible with the results from this

Tab. 2 a) Location of literature samples.

Sample	X-Coord.	Y-Coord.	Elev. (m)	Location	Reference
MF1746	704,350	160,700	583	drill core 1317.2 m, Lukmanier Pass	Fischer (1986)
MF1755	704,350	160,700	480	drill core 1420.2 m, Lukmanier Pass	
AI349	702,900	142,700	2500	Cave dei Ingegneri, Alpe Sponda, TI	Irouschek
AI378	702,200	143,300	2600	Alpe Sponda, TI	(1983)
AI405	703,300	141,500	1986	Alpe Vedle, TI	
AI518	708,800	137,200	1580	Val Cramosino, TI	
Fus46a	689,490	149,205	1780	Campo la Torba, Val Sambucco, TI	Klaper (1982)
Fus70	689,490	149,200	1780	Campo la Torba, Val Sambucco, TI	
Fus80b	690,700	149,200	1900	Pizzo del Corno, Val Sambuco, TI	
RT140	742,800	132,125	2200	Passo della Forcola, GR	Teutsch (1982)
RT150	743,120	131,860	2260	Passo della Forcola, Italy	
RT159	743,950	131,560	1920	Passo della Forcola, Italy	
NW033	698,330	154,730	2360	Val Piora, TI	Waber (1986)
NW076	698,335	154,735	2360	Val Piora, West of Pro do Roduc, TI	
NW077	698,335	154,735	2360	Val Piora, TI	
NW079	698,335	154,735	2360	Val Piora, West of Pro do Roduc, TI	
NW080	698,330	154,730	2360	Val Piora, TI	
NW142	698,330	154,730	2360	Val Piora, TI	
NW158	698,330	154,730	2360	Val Piora, W of Lei Piccolo, TI	
TT337	707,050	155,750	2110	W of Caderluem, Valle Santa Maria, TI	Thoenen (1990)
TT379	709,050	153,500	1460	W of Campra di qua, V. Sta. Maria, TI	
TT416	706,850	154,150	1760	Frodalera, Valle Santa Maria, TI	
TT479	708,250	153,950	1650	Valle Santa Maria, TI	
TT480	708,250	153,950	1650	Valle Santa Maria, TI	
TT513	707,450	154,050	1750	Broenich, Valle Santa Maria, TI	
B367	734,900	121,600	1140	Val Grono, GR	Koch (1982)
EK45	744,500	116,800	650	Valle di Lioo, Italy	
KL185	725,500	140,300	2140	Alpe di Caldöz, TI	
KL437	724,800	133,300	2100	Alpe d'Oerz, TI	
Th46	736,800	130,300	1100	Lostallo, GR	
Staps010	708,500	150,800	2200	Alpe di Stuolo, Valle Leventina, TI	Staps-Ohnmacht
Staps012	708,100	151,900	2340	E of Pizzo di Campello, TI	(1991)
Staps014	707,700	152,500	2100	E of Pizzo di Campello, TI	
Staps025	707,400	153,700	1730	Valle Santa Maria, TI	
Staps038	695,000	154,200	1810	Piora, TI	
Staps059	709,100	150,000	2200	Fiesso, Valle Leventina, TI	
Staps077	694,900	152,800	1180	N of Piotta, Valle Leventina, TI	
Staps121a	695,500	156,100	2060	Alpe Tom, Val Piora, TI	
Staps133	694,700	154,300	1930	Piora, TI	

study. Of the 70 samples considered here, 19 of them use three or more linearly independent equilibria to determine pressure and temperature, and subsequently have an error associated with P and T. The average error in temperature is 44 °C, and that for pressure is 0.77 kbar.

Unless tectonically disturbed, samples in the vicinity of one another should give similar P-T results – if indeed they formed during the same metamorphic event. Usually the local variation in our data set is not excessive. But closely located samples (e.g. from the Lukmanier region) some-times show rather differing results. Especially the pressure estimates vary, even where the samples originate from the same geological units. Assuming that the rocks in a small geographic area did reach equilibrium under similar environmental conditions, there are several possible reasons for variations in P and T estimates: 1) errors in the electron microprobe data propagate into P-T estimation (Lieberman and Petrakakis, 1991); 2) endmember thermodynamic mineral data are incorrect; 3) solid solution models are incorrect; 4) chemical equilibrium was (partially) reset in

Tab. 2 b) Location of new samples.

Sample	X-Coord	Y-Coord	Elev. (m)	Location	Samples from
DS04	729,700	122,230	300	Roveredo, Valle Mesolcina, GR	this study
DS05	729,850	122,250	300	Roveredo, Valle Mesolcina, GR	
DS06	729,350	133,350	1040	Cauco, Val Calanca, GR	
DS07	702,775	142,200	2230	Alpe Sponda, TI	
DS08	703,525	142,038	2180	Moncucco, Alpe Sponda, TI	
DS09	705,830	141,510	1290	Cala, Chironico, TI	
DS10a	723,700	121,300	260	Castione, TI	
Ma9353	694,030	127,340	500	Someo, Valle Maggia, TI	
Ma9355	696,090	138,640	980	Mnt San Carlo, Valle di Prato, TI	
Ma9356	696,090	138,640	980	Mnt San Carlo, Valle di Prato, TI	
Ma9364	703,150	117,180	1215	Monteggia, Valle dei Croadi, TI	
Ma9477	689,960	149,090	1755	Val Sambuco, TI	
Ma9479	689,960	149,090	1755	Val Sambuco, TI	
Ma9484	687,310	148,120	2290	Lago del Naret, TI	
Ma9494	694,290	144,370	1350	Fusio, TI	
Mag063	693,180	128,260	940	Carpagnone, Valle Maggia, TI	Paul Graeter
Mag096	696,750	129,620	2000	Cortone, TI	
Mag193	690,970	133,400	600	Besso, TI	
Mag310	691,710	131,980	995	Mad. del Monte, V. Cignolascio, TI	
Mag352	701,390	122,870	1600	Aiarlo, Valle Maggia, TI	
Mag431	692,880	128,600	1030	Ruscadella, Valle Maggia, TI	
Mag452	700,720	127,420	2145	Pizzo Pianascia, Valle d'Osola, TI	
Mag540	691,550	132,060	1055	Mad. del Monte, V. Cignolascio, TI	
T022	742,280	132,680	1970	Alpe de Quarnei, TI	Peter H. Thompson
T032bI	739,580	125,600	2400	Pizzo di Cressim o Roggione, TI	
T046	736,750	130,300	1065	Cobi, TI	
T069I	729,800	120,880	435	above Roveredo, TI	
T082a	732,970	122,460	700	Val Grono, TI	
T110b	735,970	130,000	600	Lostallo, GR	
Blen03	715,100	155,700	1100	Olivone, Lucomagno, TI	Martin Frey
RG8c	698,500	146,650	2290	Campolungo, TI	Reto Gieré

some of the samples. As stated above, geothermometers and geobarometers are not presently 100% accurate, and all data – notably including thermodynamic data – have associated uncertainties. Hence there is no reason to expect that the exact same values of pressure or temperature are recorded even in a small cluster of samples. Petrologic reasons for a spread, especially in pressure determinations, due to a failure to equilibrate under the exact same conditions are explored in the interpretation section, below.

Even though the application of a multi-equilibria technique enhances the coherence of P-T results, we found occasionally that spurious results occur. Outliers were identified by examining the regional P-T distributions, provided the sample density was sufficient. In the interest of a robust data set, we discarded samples if they yielded P-T results that are out of local context (as calculated by interpolation) by more than two estimated standard errors. Applying this criterion

lead us to remove three P-T data from our final set because the indicated pressure is $\geq$ 1.5 kbar (or temperature $\geq$ 100°) above or below regional context.

3.2. RESULTS

A pelitic schist (sample TT479, THOENEN 1990) from Sta. Maria, Lucomagno, serves as an example of the procedures used. The sample contains garnet, biotite, muscovite, chlorite, plagioclase, kyanite, staurolite, quartz, epidote, rutile, ilmenite, and tourmaline. Chemical analyses of the first five minerals of these are reported by THOENEN and are listed in table 3.

Because garnet contains 12% grossular, equilibria involving that component were included in the calculations, whereas chlorite was excluded because the quality of thermodynamic models available. No analysis of ilmenite was reported,

Tab. 3 a) Composition of parageneses from literature samples.

Sample	Rock type	Paragenesis	Mineral compositions
MF1746	csil	Ms Qtz Bt Cal Czo Grt Mrg Chl Ilm Po Tur Gr Opk	**Bt:** .402 .426 .025 .146 .960 – **Grt:** .178 .089 .714 .001 – **Ms:** .714 .107 .884 –
MF1755	csil	Qtz Bt Mrg Ms Czo Cal Dol Grt Chl Ilm Po Tur Gr	**Bt:** .420 .412 .033 .135 .948 – **Grt:** .145 .097 .704 .026 – **Ms:** .570 .129 .903 –
AI349	mpel	Bt Crd Ky Ms Pl Qtz St Grt Chl	**Bt:** .462 .361 .033 .141 .914 – **Chl:** .594 .406 – **Grt:** .098 .122 .645 .109 – **Ms:** .130 .851 .978 – **Pl:** .254 .746 .000 – **St:** .755 .225
AI378	mpel	Bt Grt Ky Pl Qtz St Ms Chl Ilm Rt Ap Tur Gr	**Bt:** .405 .402 .035 .158 .931 – **Chl:** .524 .476 – **Grt:** .043 .137 .782 .038 – **Ms:** .740 .260 .914 – **Pl:** .154 .842 .005 – **St:** .783 .200
AI405	mpel	Bt Ms Pl Qtz St Grt Ky Ap Chl Ep	**Bt:** .375 .426 .029 .169 .949 – **Chl:** .511 .489 – **Grt:** .061 .113 .785 .025 – **Ms:** .809 .191 .912 – **Pl:** .187 .808 .005 – **St:** .800 .194
AI518	mpel	Bt Grt Ky Pl Sil St Qtz Ms	**Bt:** .406 .404 .035 .154 .942 – **Grt:** .087 .141 .747 .021 – **Pl:** .290 .708 .002 – **St:** .800 .191
Fus46a	mpel	Bt Czo Grt Ky Ms Pl Qtz Chl	**Bt:** .500 .298 .051 .147 .979 – **Grt:** .177 .115 .682 .012 – **Pl:** .295 .699 .006
Fus70	csil	Bt Cal Dol Ep Grt Ky Mrg Ms Pl Qtz	**Bt:** .445 .390 .035 .128 .982 – **Grt:** .086 .148 .714 .032 – **Ms:** .906 .094 .873 – **Pl:** .314 .682 .004
Fus80b	mpel	Bt Grt Ky Ms Pg Pl Qtz St Chl	**Bt:** .457 .351 .034 .156 .950 – **Grt:** .137 .127 .709 .004 – **Pl:** .402 .592 .006
RT140	mpel	Bt Grt Ilm Ky Ms Pl Qtz St Chl	**Bt:** .391 .401 .025 .183 .969 – **Chl:** .380 .620 – **Grt:** .088 .133 .738 .031 – **Ms:** .863 .128 .850 – **St:** .7951 .1946
RT150	csil	Bt Cal Chl Czo Grt Ms Pl Qtz	**Bt:** .368 .445 .040 .139 .982 – **Grt:** .205 .048 .650 .082 – **Ms:** .969 .031 .863
RT159	mpel	Bt Grt Ilm Ky Ms Pl Qtz St Chl Tur	**Bt:** .479 .342 .031 .144 .950 – **Chl:** .591 .409 – **Grt:** .046 .156 .700 .084 – **Ms:** .794 .202 .893 – **Pl:** .196 .788 .015 – **St:** .806 .177
NW142	mpel	Qtz Pl Bt Grt Ms Kfs Chl Ep Czo Cld Opk	**Bt:** .374 .454 .045 .127 .975 – **Grt:** .198 .077 .725 .000
NW158	mpel	Qtz Bt Pl Ms Hbl Grt Chl	**Bt:** .430 .473 .033 .064 .975 – **Grt:** .240 .087 .674 .000
NW033	mpel	Pl Qtz Ms Bt Grt Ky St Chl Gr Ilm Tur Hem	**Bt:** .382 .437 .032 .148 .980 – **Grt:** .065 .112 .786 .024
NW076	mpel	Ky Ms Qtz Bt Pl Grt St Chl Zrn Tur Ap Rt Mag Hem And Gr	**Bt:** .432 .370 .025 .173 .940 – **Chl:** .578 .422 – **Grt:** .074 .127 .799 .000 – **Ms:** .763 .237 .916 – **Pl:** .300 .700 .000 – **St:** .798 .202
NW077	mpel	Qtz Pl Ms Bt Grt Ky St Chl Zrn Tur Toz Rt Gr Hem Ilm And Ap	**Bt:** .392 .427 .030 .151 .950 – **Grt:** .096 .114 .790 .000 – **Ms:** .768 .232 .947 – **Pl:** .167 .833 .000
NW079	mpel	Qtz Pl Bt Ms Grt Ky St Chl And Zrn Gr Ilm Tur Hem Mnz	**Bt:** .423 .405 .028 .143 .985 – **Chl:** .471 .529 – **Grt:** .053 .125 .779 .018 – **Ms:** .867 .133 .915 – **St:** .800 .191
NW080	mpel	Pl Qtz Ms Bt Grt Ky St Chl And Tur Zrn Ap Gr Hem Ilm	**Bt:** .406 .443 .000 .151 .976 – **Grt:** .027 .112 .783 .023 – **Pl:** .148 .845 .007

Sample	Type	Assemblage	Data
TT337	mpel	Bt Chl Czo Grt Ms Pl Qtz St Cld Tur Ap Ep Ilm	**Bt:** .463 .377 .027 .132 .952 — **Chl:** .555 .445 — **Cld:** .769 .231 — **Grt:** .120 .111 .740 .001 — **Ms:** .822 .154 .885 — **Pl:** .363 .634 .002 — **St:** .833 .167
TT379	mpel	Bt Grt Ky Pl Qtz St Ms Chl Ilm Tur	**Bt:** .506 .326 .027 .139 .957 — **Chl:** .6283 .3717 — **Grt:** .101 .165 .710 .001 — **Ms:** .132 .809 .932 — **Pl:** .191 .802 .007 — **St:** .7312 .2688
TT416	csil	Bt Chl Grt Ky Ms Pl Qtz Hbl Czo Cal Dol Tur Rt Ilm	**Bt:** .494 .360 .031 .114 .967 — **Chl:** .541 .459 — **Grt:** .161 .117 .672 .014 — **Ms:** .895 .080 .861 — **Pl:** .655 .343 .002
TT479	mpel	Bt Chl Grt Ky Ms Pl Qtz St Czo Tur Rt Ilm	**Bt:** .558 .299 .029 .112 .937 — **Chl:** .677 .323 — **Grt:** .125 .161 .651 .006 — **Ms:** .775 .214 .936 — **Pl:** .324 .654 .022
TT480	mpel	Bt Chl Grt Ky Ms Pl Qtz Czo Ilm Rt Tur	**Bt:** .514 .330 .022 .132 .954 — **Chl:** .625 .375 — **Grt:** .153 .134 .675 .004 — **Ms:** .936 .062 .815 — **Pl:** .396 .600 .004
TT513	mpel	Bt Grt Ky Ms Pl Qtz St Hbl Chl Tur Ap Ep Ilm	**Bt:** .492 .355 .026 .126 .958 — **Chl:** .636 .364 — **Grt:** .111 .147 .678 .034 — **Ms:** .873 .115 .856 — **Pl:** .418 .577 .005 — **St:** .750 .246
B367	mpel	Ms Qtz Bt Pl Sil Grt St Ky Chl Ap Rt Opk	**Bt:** .401 .421 .048 .129 .924 — **Grt:** .043 .167 .715 .075 — **Ms:** .924 .070 .889 — **Pl:** .250 .743 .007 — **St:** .7847 .1463
EK45	mpel	Bt Qtz Pl Sil Grt Ms Chl Opk	**Bt:** .319 .461 .067 .150 .945 — **Grt:** .032 .102 .749 .116 — **Ms:** .924 .070 .889 — **Pl:** .216 .766 .018
KL185	mpel	Sil Ms Bt Pg Qtz Pl St Grt Chl Cld Ep Rt Opk	**Bt:** .406 .399 .030 .164 .952 — **Chl:** .544 .456 — **Grt:** .058 .129 .800 .009 — **Ms:** .749 .244 .916 — **Pl:** .236 .764 .000 — **St:** .802 .194
KL437	mpel	Qtz Ms Pl Sil Bt Grt St Ky Chl Ap Rt Opk	**Bt:** .394 .426 .035 .144 .947 — **Grt:** .071 .154 .741 .034 — **Ms:** .795 .204 .904 — **Pl:** .214 .786 .000 — **St:** .789 .197
Th46	mpel	Qtz Pl Bt Ms St Grt Sil Ky Ep Ap Rt Opk	**Bt:** .387 .409 .043 .160 .951 — **Grt:** .045 .132 .759 .061 — **Ms:** .826 .174 .910 — **Pl:** .133 .862 .005 — **St:** .792 .195
Staps010	mpel	Bt Grt Ky Ms Pl Qtz St Chl Gr Ilm	**Bt:** .455 .363 .028 .154 .917 — **Chl:** .599 .401 — **Grt:** .187 .085 .690 .013 — **Ms:** .151 .849 .976 — **Pl:** .220 .773 .007 — **St:** .792 .208
Staps012	mpel	Bt Grt Ky Ms Pl Qtz St Chl Opk Gr	**Bt:** .468 .363 .031 .138 .962 — **Chl:** .600 .400 — **Grt:** .137 .110 .727 .015 — **Ms:** .759 .241 .935
Staps014	mpel	Bt Grt Ky Ms Pl Qtz St Chl Gr	**Bt:** .457 .366 .028 .147 .948 — **Chl:** .602 .398 — **Grt:** .141 .132 .644 .041 — **Ms:** .784 .216 .938 — **St:** .775 .211
Staps025	mpel	Bt Grt Ky Ms Pl Qtz St Chl Opk Gr	**Bt:** .481 .347 .031 .141 .965 — **Chl:** .598 .402 — **Grt:** .088 .138 .731 .025 — **Ms:** .798 .202 .907 — **Pl:** .205 .788 .007 — **St:** .782 .209
Staps038	mpel	Bt Chl Grt Ky Ms Pl Qtz St Gr	**Bt:** .462 .360 .029 .149 .958 — **Chl:** .522 .478 — **Grt:** .067 .142 .748 .025 — **Ms:** .789 .211 .915 — **Pl:** .109 .888 .003 — **St:** .800 .195
Staps059	mpel	Bt Ms Grt Ky Pl Qtz St Chl Gr	**Bt:** .449 .374 .031 .145 .946 — **Chl:** .588 .412 — **Grt:** .106 .114 .745 .024 — **Pl:** .194 .801 .004
Staps077	mpel	Bt Grt Ky Pg Pl Qtz St Chl Gr Ilm	**Bt:** .466 .360 .029 .144 .951 — **Chl:** .608 .392 — **Grt:** .061 .149 .735 .044 — **Ms:** .095 .878 .971 — **Pl:** .156 .840 .004 — **St:** .788 .203
Staps121a	mpel	Bt Grt Ky Ms Pl Qtz St Chl Gr Mrg	**Bt:** .420 .400 .034 .146 .984 — **Chl:** .572 .428 — **Grt:** .162 .087 .714 .014 — **Ms:** .938 .062 .907 — **St:** .814 .182
Staps133	mpel	Bt Grt Ky Ms Pl Qtz St Chl Gr	**Bt:** .444 .380 .028 .149 .953 — **Chl:** .592 .408 — **Grt:** .027 .141 .801 .007 — **Ms:** .747 .253 .926 — **Pl:** .012 .983 .006 — **St:** .790 .210

Tab. 3 b) Composition of parageneses from new samples

Sample	Rock type	Paragenesis	Mineral compositions
DS04	mpel	Qtz Ms Bt Pl Grt Sil Ilm Rt Ap Tur Zrn Ky	**Bt:** .312 .484 .054 .149 .971 — **Grt:** .085 .118 .757 .032 — **Ilm:** .961 .019 .001 .018 — **Ms:** .921 .079 .899 — **Pl:** .396 .596 .008
DS05	mpel	Qtz Pl Bt Ms Grt Sil Ky Chl Opk Ap Tur Zrn	**Bt:** .303 .498 .058 .139 .963 — **Chl:** .437 .563 — **Grt:** .038 .110 .756 .049 — **Pl:** .267 .717 .016 — **Ms:** .920 .080 .896
DS06	mpel	Qtz Bt Pl Ky Ms Grt Opk Ap Py Zrn	**Bt:** .395 .408 .035 .158 .961 — **Grt:** .041 .136 .755 .067 — **Ms:** .780 .219 .930 — **Pl:** .151 .844 .006
DS07	mpel	Qtz Pl Bt Ms St Ky Grt Ilm Chl Opk Ap Zrn	**Bt:** .395 .419 .030 .153 .963 — **Chl:** .506 .494 — **Grt:** .035 .128 .765 .050 — **Ilm:** .955 .001 .049 — **Ms:** .721 .278 .935 — **Pl:** .156 .839 .005 — **St:** .818 .166
DS08	mpel	Qtz Pl Bt Ms Grt St Ky Ilm Chl Ap Zrn	**Bt:** .425 .392 .030 .149 .954 — **Chl:** .521 .479 — **Grt:** .038 .133 .741 .049 — **Ilm:** .946 .002 .048 — **Ms:** .822 .178 .902 — **Pl:** .202 .792 .005 — **St:** .801 .181
DS09	mpel	Qtz Pl Bt Ms Grt St Ky Ilm Rt	**Bt:** .411 .395 .040 .153 .963 — **Grt:** .106 .167 .711 .024 — **Ilm:** .934 .043 .003 .020 — **Ms:** .852 .148 .910 — **Pl:** .177 .817 .006
DS10a	mpel	Qtz Pl Bt Sil Grt Ms Ky Chl Opk Ap Rt Py Tur Zrn	**Bt:** .340 .369 .044 .243 .947 — **Grt:** .033 .141 .719 .057 — **Ms:** .897 .103 .901 — **Pl:** .245 .746 .009
Ma9353	mpel	Qtz Grt Ms Pl Ilm Rt Ky Bt	**Bt:** .390 .401 .039 .168 .954 — **Grt:** .030 .190 .735 .045 — **Ilm:** .961 .038 .001 .000 — **Ms:** .859 .141 .924 — **Pl:** .277 .718 .005
Ma9355	mpel	Qtz Bt Grt Ms Pl Ilm Ky St Rt	**Bt:** .399 .403 .037 .160 .974 — **Grt:** .080 .130 .760 .030 — **Ilm:** .964 .014 .004 .017 — **Ms:** .787 .213 .923 — **Pl:** .072 .924 .004 — **St:** .713 .154
Ma9356	mpel	Qtz Bt Grt Ms Pl Ilm Ky Rt St	**Bt:** .413 .392 .041 .153 .970 — **Grt:** .091 .151 .722 .037 — **Ilm:** .984 .016 .000 .000 — **Ms:** .843 .157 .911 — **Pl:** .169 .826 .005
Ma9364	mpel	Qtz Bt Grt Ms Pl Gr Ilm Ky Rt	**Bt:** .364 .438 .053 .145 .956 — **Grt:** .060 .125 .765 .050 — **Ilm:** .981 .018 .001 .000 — **Ms:** .897 .102 .889 — **Pl:** .310 .683 .007
Ma9477	mpel	Qtz Bt Grt Ms Pl Ilm Ky St Rt	**Bt:** .463 .343 .035 .159 .972 — **Grt:** .150 .146 .702 .002 — **Ms:** .807 .192 .925 — **Pl:** .230 .765 .005 — **St:** .776 .222 — **Ilm:** .975 .005 .001 .018
Ma9479	mpel	Qtz Bt Grt Ms Pl Ilm Ky St Rt	**Bt:** .468 .349 .034 .150 .945 — **Grt:** .121 .138 .734 .007 — **Ilm:** .980 .001 .005 .013 — **Ms:** .793 .206 .898 — **St:** .776 .219
Ma9484	mpel	Qtz Bt Grt Ms Pl Ilm Ky St Rt	**Bt:** .471 .329 .033 .166 .981 — **Grt:** .164 .139 .681 .016 — **Ilm:** .976 .012 .012 .000 — **Ms:** .950 .049 .913 — **Pl:** .428 .566 .006 — **St:** .783 .202
Ma9494	mpel	Qtz Bt Grt Ms Pl Ky	**Bt:** .426 .378 .050 .146 .965 — **Grt:** .227 .092 .680 .010 — **Ms:** .937 .062 .884 — **Pl:** .219 .770 .011
Mag063	mpel	Qtz Bt Grt Ms Pl Gr Ilm Ky Rt	**Bt:** .373 .435 .040 .152 .950 — **Grt:** .032 .174 .770 .032 — **Ilm:** .965 .009 .007 .019 — **Ms:** .864 .136 .911
Mag096	mpel	Qtz Bt Grt Ms Pl Ilm Ky St Rt	**Bt:** .391 .400 .036 .172 .952 — **Grt:** .045 .125 .760 .070 — **Ilm:** .997 .000 .002 .000 — **Ms:** .830 .170 .915 — **Pl:** .249 .745 .006 — **St:** .766 .196
Mag193	mpel	Qtz Bt Grt Pl Ilm Ky Rt	**Bt:** .500 .324 .030 .146 .948 — **Grt:** .051 .275 .661 .021 — **Ilm:** .989 .000 .009 .000 — **Pl:** .337 .660 .003 — **St:** .687 .225
Mag310	mpel	Qtz Bt Grt Ms Pl Gr Ilm Ky Rt	**Bt:** .422 .376 .041 .160 .963 — **Grt:** .071 .164 .718 .047 — **Ilm:** .944 .035 .005 .015 — **Ms:** .860 .139 .906 — **Pl:** .322 .673 .005
Mag352	mpel	Qtz Bt Grt Ms Pl Ilm Ky St Rt	**Bt:** .349 .469 .041 .139 .948 — **Grt:** .060 .130 .744 .067 — **Ilm:** .942 .011 .008 .040 — **Ms:** .851 .148 .866 — **Pl:** .316 .676 .008 — **St:** .839 .146

Mag431	mpel	*Qtz Bt Grt Ms Pl Gr Ilm Ky Rt*	**Bt:** .431 .378 .041 .148 .975 — **Grt:** .099 .181 .689 .032 — **Ilm:** .932 .051 .003 .013 — **Ms:** .912 .088 .899 — **Pl:** .351 .644 .005
Mag452	mpel	*Qtz Bt Grt Ms Pl Ilm Ky St Rt*	**Bt:** .380 .432 .041 .148 .945 — **Grt:** .027 .131 .813 .028 — **Ilm:** .987 .011 .002 .000 — **Ms:** .799 .200 .926 — **Pl:** .173 .822 .006 — **St:** .797 .177
Mag540	mpel	*Qtz Bt Grt Pl Ms Ilm Rt Ky St*	**Bt:** .393 .411 .036 .158 .965 — **Grt:** .073 .161 .748 .018 — **Ilm:** .972 .012 .003 .013 — **Ms:** .849 .151 .917 — **Pl:** .351 .645 .004 — **St:** .799 .148
T022	mpel	*Qtz Bt Grt Pl Ms Ilm Rt Ky St*	**Bt:** .428 .375 .033 .162 .970 — **Grt:** .080 .135 .738 .062 — **Ilm:** .932 .008 .000 .069 — **Ms:** .799 .201 .929 — **Pl:** .242 .754 .004 — **St:** .7897 .1728
T032bI	mpel	*Qtz Bt Grt Pl Ms Ilm Rt Ky Sil*	**Bt:** .319 .474 .053 .151 .957 — **Grt:** .039 .091 .743 .128 — **Ilm:** .881 .107 .001 .011 — **Ms:** .871 .129 .902 — **Pl:** .214 .778 .008
T046	mpel	*Qtz Bt Grt Pl Ms Ilm Rt Ky St*	**Bt:** .364 .441 .043 .150 .952 — **Grt:** .069 .156 .746 .040 — **Ilm:** .903 .057 .006 .032 — **Ms:** .848 .152 .912 — **Pl:** .211 .783 .003 — **St:** .7980 .1692
T069I	mpel	*Qtz Bt Grt Pl Ms Ky*	**Bt:** .412 .368 .063 .150 .980 — **Grt:** .140 .155 .574 .155 — **Ms:** .956 .044 .873 — **Pl:** .737 .258 .006
T082a	mpel	*Qtz Bt Grt Pl Ms Sil St Ky*	**Bt:** .291 .510 .060 .136 .955 — **Grt:** .032 .095 .778 .107 — **Ms:** .889 .130 .922 — **Pl:** .204 .792 .003 — **St:** .7645 .1578
T110b	mpel	*Qtz Bt Grt Pl Ms Ilm Rt Ky St*	**Bt:** .336 .443 .044 .176 .950 — **Grt:** .041 .116 .803 .048 — **Ilm:** .973 .014 .004 .009 — **Ms:** .852 .147 .920 — **Pl:** .174 .815 .010 — **St:** .799 .158
Blen03	csil	*Qtz Bt Grt Pl Ms Ilm*	**Bt:** .415 .406 .038 .139 .982 — **Grt:** .181 .072 .709 .040 — **Ilm:** .933 .060 .001 .006 — **Ms:** .956 .033 .885 — **Pl:** .8085 .1845 .007
RG8c	mpel	*Qtz Bt Grt Ms Ilm Rt Ky St Tur*	**Bt:** .418 .397 .029 .155 .922 — **Grt:** .018 .176 .802 .004 — **Ilm:** .982 .004 .013 .002 — **Ms:** .724 .274 .931 — **St:** .7823 .1973

Rock type: csil = calcsilicate; mpel = metapelite. Mineral abbreviations according to KRETZ (1983). Minerals printed in italics are assumed to have equilibrated near the peak of metamorphism. Mineral compositions: **Bt:** X_{Mg} X_{Fe} X_{Ti} X_{Al} X_K — **Chl:** X_{Mg} X_{Fe} — **Cld:** X_{Fe} X_{Mg} — **Grt:** X_{grs} X_{prp} X_{alm} X_{sps} — **Ilm:** X_{ilm} X_{Mg} X_{Mn} X_{Hem} — **Ms:** X_K X_{Na} X_{Al}^{VI} X_{Al}^{VI} — **Pl:** X_{an} X_{al} X_{or} — **St:** X_{Fe} X_{Mg}. For Chl, St and Cld, $X_{Mg} = Mg/(Mg + Fe)$.

Tab. 4   Activity models.

Mineral	Species	Activity model
Biotite	annite, phlogopite	McMULLIN et al. (1991)
Garnet	almandine pyrope grossular	BERMAN (1990)
Ilmenite	ilmenite	$a_{ilm} = X_{Fe^{2+}}$ ideal one-site model, where $$X_{Fe^{2+}} = \frac{Fe^{2+}}{Fe^{2+} + Mn + Mg + Zn + Fe^{3+}/2}$$
Plagioclase	albite, anorthite	FUHRMAN and LINDSLEY (1988)
White mica	muscovite, paragonite	CHATTERJEE and FROESE (1975)

Quartz, kyanite, sillimanite and rutile were assumed to be pure.

making impossible the use of several equilibria involving ilmenite and rutile, including the GRAIL geobarometer.

Thermobarometric analysis yields six fluid-conserved equilibria, three of which are linearly independent (Fig. 2). Visual inspection shows most intersections in T to be near 550 °C, those in P range between 5 and 8.5 kbar. The average calculated by TWQ, considering all weighted intersections of the equilibria shown, is 565 ± 9 °C and 7.11 ± 0.73 kbar. The standard errors turn out to

Fig. 2   Equilibria for sample TT479 (from THOENEN, 1990); all are H_2O-conserved. 1) grs + 2 Ky + αQtz = 3 an; 2) alm + ms = αQtz + 2 Ky + ann; 3) phl + alm = ann + prp; 4) ms + grs + alm = ann + 3 an; 5) prp + ms = 2 Ky + phl + αQtz; 6) prp + ms + grs = 3 an + phl.

be rather less than might be inferred from figure 2. When compared to P-T results obtained from nearby samples by this same method, the temperature value for TT479 agrees within one standard error with the contour value (570 °C); the pressure value lies 1.2 kbar (< 2 std.err.) higher than the contour value (5.95 kbar). Based on this analysis, this sample was included in the P-T data base.

The calculated P-T results for all of the samples studied are shown in table 5. A comparison with previous P-T estimates is included where possible.

4. Regional P-T distribution

The Alps are an area of high physical relief. Samples less than 3 km apart in horizontal distance can be up to 2 km different in elevation. Elevation differences of this magnitude may have a noticeable influence on the recorded P and T of the rocks, and even the mineral assemblage (FOX, 1975; THOMPSON, 1976), now exposed at the surface. In order to compensate for this effect, a simple and conservative geothermal gradient adjustment (25 °C and 300 bar per vertical km) was applied in order to represent the P and T at an elevation of 1 km above sea level. Since metamorphism in the field area is diachronous, there is no strict justification in applying a static geothermal gradient to adjust the data. For example, if the geothermal gradient described above was valid at the time a sample (now 2000 m above sea level) last equilibrated its P-T, the actual rock that is 1 km below this sample may have last equilibrated its P-T either before or after this moment, at a different elevation within the metamorphic pile, and hence under different physical conditions than those implied by the geothermal gradient correction from the

Tab. 5 P-T results

Literature samples

Sample	TWQ values					Literature values	
	T (°C)	T ±	P (kbar)	P ±	indep. rctns	T (°C)	P (kbar)
MF1746	576				1	510 ± 40	
MF1755	566				1	513 ± 35	
AI349	556		4,41¥		2		
AI378	587		5,23		2	595 ± 27	6,8–9,9
AI405	576		4,43		2	470–640	
AI518	630				1	622–655	6,5–9
Fus46a ¥	400		5,10		3	560	6,8
Fus70	624		5,34		2	560	5,4
Fus80b	534	60	5,92	1,17	4	560	6,8
RT140	625		4,65		2	622	
RT150	477				1	513	
RT159	564	21	5,66	0,30	3	627	6,8 ± 1,0
NW033	591				1	577	
NW076	545	55	5,16	0,84	3		
NW077	585		4,32		2		
NW079	558		4,82		2	558	
NW080	564				1		
NW142	574				1	481	
NW158	618				1		
TT337	530		5,56		2		
TT379	577		6,41		2		
TT416	534	84	5,98	1,37	3		
TT479	565	9	7,11	0,73	3		
TT480	548		4,78		2		
TT513 †	578	128	6,08	2,23	3		
B367	706		6,45		2	645 ± 28	7,2
EK45	601		3,68		2	631 ± 44	6,5
KL185	570	13	5,62	0,19	3	595 ± 26	7,3
KL437	693		6,02		2	664 ± 33	9,5
Th46	600		5,04		2	643 ± 35	8,4
Staps010	495		5,74		2	478	
Staps012	523		5,08		2	457	
Staps014	608		4,82		2	570	
Staps025	543	33	7,05	0,52	3	561	
Staps038	558		6,38		2	450–540	10,1–13,8
Staps059	544				1	504–532	7,5–7,8
Staps077	567		5,54		2	535–577	6,7–7,5
Staps121a	517		3,27¥		2		
Staps133	548		6,92		2	540	

New samples

Sample	T (°C)	T ±	P (kbar)	P ±	indep. rctns
DS04	791		6,12		2
DS05	682		4,38		2
DS06	606		5,22		2
DS07	600		7,00		2
DS08	576		6,62		2
DS09	712	2	6,69	0,04	3
DS10a	622		4,99		2
Ma9353	716	32	7,07	0,59	3
Ma9355	610		6,58		2
Ma9356	642	50	5,58	0,73	3
Ma9364	638		6,57		2
Ma9477	602		6,14		2
Ma9479	561	24	5,38	1,24	3
Ma9484	589		7,54		2
Ma9494	569		9,48¥		2
Mag063	665		7,53		2
Mag096	617	77	6,42	1,71	3
Mag193	610	91	6,65	0,88	3
Mag310	651	3	6,29	0,07	3
Mag352 †	669	104	5,03	2,57	3
Mag431	687	53	6,12	1,04	3
Mag452	597		5,40		2
Mag540	695	36	6,63	0,87	3
T022	580		5,18		2
T032bI †	561	153	5,37	2,36	3
T046 †	713	94	6,35	2,44	3
T069I	723		4,99		2
T082a	640		3,88		2
T110b	610		4,86		2
Blen03	495		5,24		2
RG8c	643	11	7,52	0,42	3

† removed because of large P-T scatter
¥ removed because of local P-T context
(see text, Section 3.1)

sample above. However, since the vertical adjustments are less than 1 km in most cases, we feel that they are justified.

Our samples cover the map area of kilometers 685–750 and 110–165 (Swiss coordinate system). Within this area, the sample locations are broadly and non-uniformly scattered, with several sparse domains (Fig. 1). Also, data values for both P and

T may vary greatly within groups of closely spaced samples. Kriging was chosen as the method to interpolate pressure and temperature data over the map area of interest. Punctual kriging is a spatial interpolation scheme (DAVIS, 1986) that employs weight factors based on the inverse (geographic) distance between the interpolation point and each data point. Pressure and temperature

were contoured independently. First, pressure or temperature values along an evenly spaced 3 km grid were estimated using the kriging routine. Then, the output was smoothed; each grid value was replaced by the average of that grid point and the eight surrounding grid points, five consecutive times. Third, the contour lines were generated by simple interpolation between grid locations and cut off beyond the data points and/or tectonic boundaries (e.g. Insubric Line). In order that the temperature contours extrapolate to the north in a manner consistent with mapped mineral zones, a number of locations along the stilpnomelane-out isograd were assumed to have equilibrated at 450 °C (NITSCH, 1970).

Effects of faults within the study area were not explicitly considered. Yet late faults, active after the peak of metamorphism, would certainly have cut the contour pattern and produced discontinuities in the contour lines; large-scale post-metamorphic deformation can disturb the isotherm and isobar pattern (KAMBER, 1993). If approximately parallel to the isotherms (and/or isobars), such faults would cause an apparent compression of these contour lines. At the scale of the present study, and with the data spacing presently available, the effects of small faults are not resolvable.

The data in table 5 are represented as isotherm and isobar maps (Fig. 3). The isotherms in figure 3A roughly reflect the previously known concentric pattern of mineral zones (e.g. NIGGLI, 1970) and isograds (e.g. TROMMSDORFF and EVANS, 1974). The temperature increases towards the Insubric Line where the temperature maximum is located; the center of this pattern lies near Bellinzona. The temperature gradient, reflected by the spacing of isotherms, decreases from the external, cooler parts of the Central Alps towards the thermal maximum.

The isobars (Fig. 3B) form a roughly concentric pattern as well, but the geographic location of the maximum recorded pressure is located about 20 km north of the Insubric Line, and thus does not coincide with the location of the temperature maximum. Towards the Insubric Line, we note a *decrease* in the pressures recorded. As with T, the P gradient decreases from the external, northern regions (Nufenen and Lukmanier region) towards the central regions. The data density in the central part of the Lepontine is still very low, and the location of the isobars there is considerably more uncertain than elsewhere.

Isotherms and isobars on contour maps were produced using the kriging routine in the Macintosh program Spyglass™ Transform.

5. Interpretation

5.1. *P-T*-t EVOLUTION

ENGLAND and RICHARDSON (1977) argue that rocks record conditions at which their paragenesis reached maximum entropy, S_{max} which roughly corresponds to T_{max}. If so, one may assume that T_{max} and thus $P_{T_{max}}$ (the pressure at T_{max}) are recorded in regionally metamorphosed samples. This simple reasoning is by no means undisputed and is not defensible for relatively dry rocks. However, we note that the vast majority of samples used here were derived from relatively H_2O-rich sedimentary precursors. Fluids produced by devolatilization reactions likely catalyzed metamorphic reactions on the prograde path. Retrograde hydration reactions can occur, but these samples are avoided during sample collection and petrographic examination.

Based on a simple model of subduction-related metamorphism leading to a clockwise *P-T*-t path, these rocks may have experienced isothermal decompression near T_{max} during part of the tectonometamorphic history; diachronous parageneses can thus be expected, reflecting a range in P, all equilibrated within a few degrees of T_{max} (THOMPSON and ENGLAND, 1984).

Even on the retrograde part of the *P-T*-t path, fluid independent reactions *may* occur, e.g. continuous cation exchange reactions. Textural observations and electron microprobe analyses commonly allow the identification of such retrograde alterations, but it cannot be excluded that sometimes $T < T_{max}$ and $P_{T < T_{max}}$ values are recorded. This applies especially to assemblages of higher grade, as can be illustrated with the zonation of garnet. In many pelitic parageneses, garnet is the mineral with the lowest chemical diffusion rate. The closure temperature for ionic exchange with its neighbors depends on the geometry of the garnet and on the cooling rate (CYGAN and LASAGA, 1985). For garnets with a diameter of 0.1 mm to 1 mm and a reasonable cooling rate for the Lepontine area (5–10 °C/Ma[1]), the closure temperature lies between 600 and 680 °C.

Diffusional resetting in garnet from the highest grade in the Central Alps is thus expected. Temperatures in the external parts of the Lepontine area (e.g. Lukmanier area) were far below these closing temperatures, and the effect of diffusional reequilibration following Tertiary meta-

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[1] For the Oligocene, HURFORD (1986) documented cooling rates of 10–12°/Ma for the southern Lepotine.

morphism should be limited. On the other hand, growth zoning of garnets can survive in these cooler regions, as observed by KLAPER (1985) in the Nufenenpass area and by STAPS-OHNMACHT (1991) in the Lukmanier area. Unless rim compositions are used in deriving P-T values for such samples, conditions established prior to T_{max} and $P_{T_{max}}$ could be recorded. Further south, in the region of Alpe Sponda, IROUSCHEK (1983) described garnet showing not only clear growth zoning but also cooling rims. In the region of the highest grade metamorphism (Bellinzona area), where temperatures were higher than the closing temperature, the memory of former parageneses may be (partly) deleted due to diffusion. BÜHL (1981) described garnets that are homogeneous except for a cooling rim in this area. Our own observations on newly acquired samples essentially confirm these patterns.

In the case of garnet, the potential hazards to thermobarometry are visible and usually avoidable. Analogous problems may affect coexisting minerals such as biotite and plagioclase. The combined effects on thermobarometric results are difficult to estimate and are likely to account for much of the observed variation in P and T among closely spaced samples. This is a justification to reject four extremely discrepant P-T values, as identified by comparison to nearby samples (see Section 3.1).

5.2. SPATIAL DISTRIBUTION OF P AND T

It must be stressed that the graphical display of isotherms and isobars in figure 3 does *not* imply a P-T distribution realized at any one time during the orogenic evolution of this area. Even if the local P-T values reflect maximum metamorphic conditions, these were established at different times in different areas, i.e. the contour patterns represent a diachronous field. The contour maps show the integrated effect of all the tectonometamorphic processes of the Central Alps, i.e. the sum total of burial, heating, tectonic and erosional unroofing and cooling.

The mineral facies of rocks at the surface lie on a locus of P-T conditions called the "metamorphic geotherm", "metamorphic field gradient" or "P-T array" (ENGLAND and RICHARDSON, 1977; ENGLAND and THOMPSON, 1984; THOMPSON and ENGLAND, 1984). Because P-T values are derived from metamorphic assemblages that formed at different times, a P-T array does not reflect any one geotherm through the rock pile. Within an area affected by a single metamorphic cycle, samples at lower grade com-
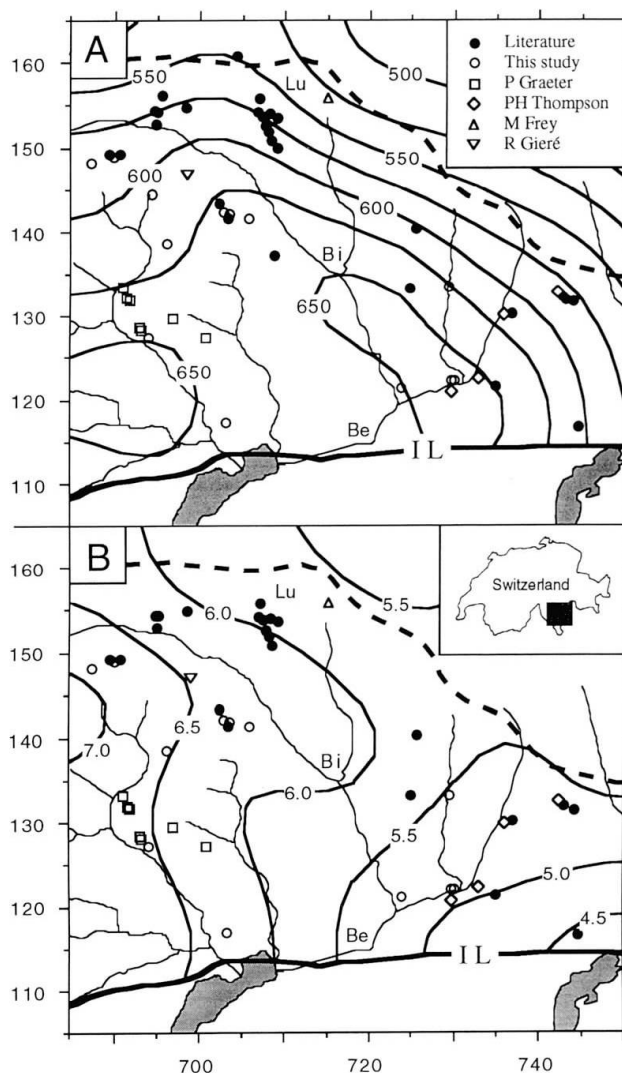

Fig. 3 Map of isotherms (A) and isobars (B) of Tertiary metamorphism; contours are labelled in °C and kbar, respectively. Abbreviations and symbols as in figure 1.

monly reflect conditions established earlier in the tectonic event than those at higher grade (ENGLAND and RICHARDSON, 1977). Assuming these theoretical conditions apply, the parageneses – and P-T estimates derived from these – found in the external regions of the Central Alps should be older than those found in the internal parts. This conclusion is borne out only in part by the presently available geochronological evidence, as discussed below.

5.3. TECTONIC IMPLICATIONS

In this paper, we present a preliminary assessment of the impact our P-T data has on current tectonic models. A more comprehensive tectonic model of our own, based on P-T data for the en-
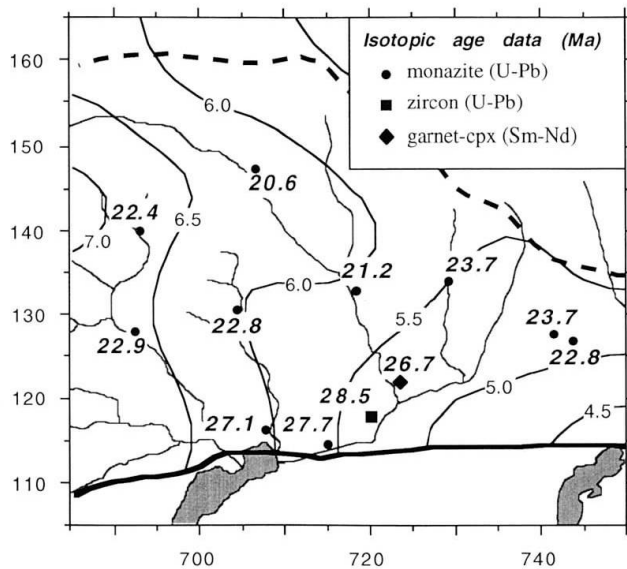
Fig. 4 Map of selected mineral age data and isobars (as in Fig. 3B). Data from KÖPPEL et al. (1975, 1978, 1981) and VANCE and O'NIONS (1992) depicted by symbols. Not shown individually are Rb–Sr dates on mica; ages of 35–38 Ma are common along the northern limit of amphibolite grade metamorphism (HUNZIKER et al., 1992). All of these ages are interpreted as reflecting the timing of maximum metamorphic conditions (T_{max}, $P_{T_{max}}$). Beyond that limit (dashed line), pre-Alpine ages occur (HUNZIKER and STECK, 1994).

tire Lepontine area, will come in a later publication.

As pointed out earlier, our samples were chosen so as to represent the main Alpine thermal "event", rather than a pre-Alpine or eo-Alpine metamorphic phase; the regional coherence of our data set indicates that this ambition has been successful. Tectonic models should use our thermobarometric data as documenting conditions near T_{max} and $P_{T_{max}}$ at a location presently 1000 m above sea level. Despite much effort (reviewed recently by HUNZIKER et al., 1992), geochronological evidence giving a reliable measure of the timing of the metamorphic peak in the amphibolite facies portion of the Central Alps is still scarce, and the significance of many isotopic age determinations remains controversial. Nevertheless, some mineral ages believed to represent the peak of metamorphism of rocks from this area do exist, and a regional pattern may be derived from these. In selecting chronological data for the Lepontine, the criteria applied were analogous to those used in our thermobarometric study, so that pre-Alpine dates are excluded. Only ages from samples of high metamorphic grade and evidence of associated high regional strain or those with a post-Hercynian protolith age were accepted, and only highly retentive systems were considered:

Nd–Sm for garnet (MEZGER et al., 1992), U–Pb for monazite (PARRISH, 1990) and for garnet (MEZGER et al., 1989). Only in the external (northern) parts of the area are the Rb–Sr data for white micas believed to date T_{max} (STECK and HUNZIKER, 1994). Near the northern margin of the Lepontine, the age of the strongest thermal overprint is documented as 35–38 Ma; in a more central E–W zone it is about 21–23 Ma, whereas in the Southern Steep Belt, T_{max} was reached some 28 Ma ago (Fig. 4).

The recent realization that very high-pressure relic assemblages present in the Adula / Cima Lunga nappe are of Eocene age (~ 40 Ma at Alpe Arami and Cima di Gagnone [GEBAUER et al., 1992; BECKER, 1993]) lead the latter author to propose a model of emplacement of the upper Penninic nappe stack as the primary cause of the Tertiary Barrovian metamorphism in the Central Alps. This model is compatible with the "lithospheric mélange" origin proposed previously by TROMMSDORFF (1990) for the evolution of the Adula and Cima Lunga. Included in figure 4 are selected *P-T* data and mineral age data for these units, taken from HEINRICH (1983, 1986), GEBAUER et al. (1992) and BECKER (1993). High pressure relics from the southern Cima Lunga nappe equilibrated at 850–900 °C and 35–40 kbar; reported ages, based on Sm–Nd in garnet and clinopyroxene, are consistently 40 ± 1 Ma (BECKER, 1993). Further north in the same unit, the *P-T* conditions document a somewhat shallower position (750–800 °C, 30–35 kbar), with ages between 42 and 39 Ma (GEBAUER et al., 1992). Recent data by BECKER and MEZGER (1995 and pers. comm.) indicate that relic eclogites from the central Adula yield U–Pb dates of 34 and 84 Ma for different rutile fractions, Sm–Nd dates of ca 34 Ma for garnet (rims), and ca 100 to 55 Ma for the (pre-eclogite) generation of garnet. For this same part of the Adula, HEINRICH (1983) documented a decompression history from early eclogite stage (700 °C, 12–20 kbar) to later amphibolite facies conditions.

In the Lepontine, two main stages of thermal and structural overprint have long been recognized (commonly termed the meso- and neo-Alpine phases, respectively). Lithospheric modelers have loosely associated these tectono-metamorphic phases with the strain evolution at different stages of the transpressive convergence between the northern Adriatic and the southern European plates. We propose that the present shape of isotherms and isobars may be explained by two main phases in the metamorphic evolution. While the *P-T* pattern in the northern Lepontine was established during south-dipping (continental) sub-
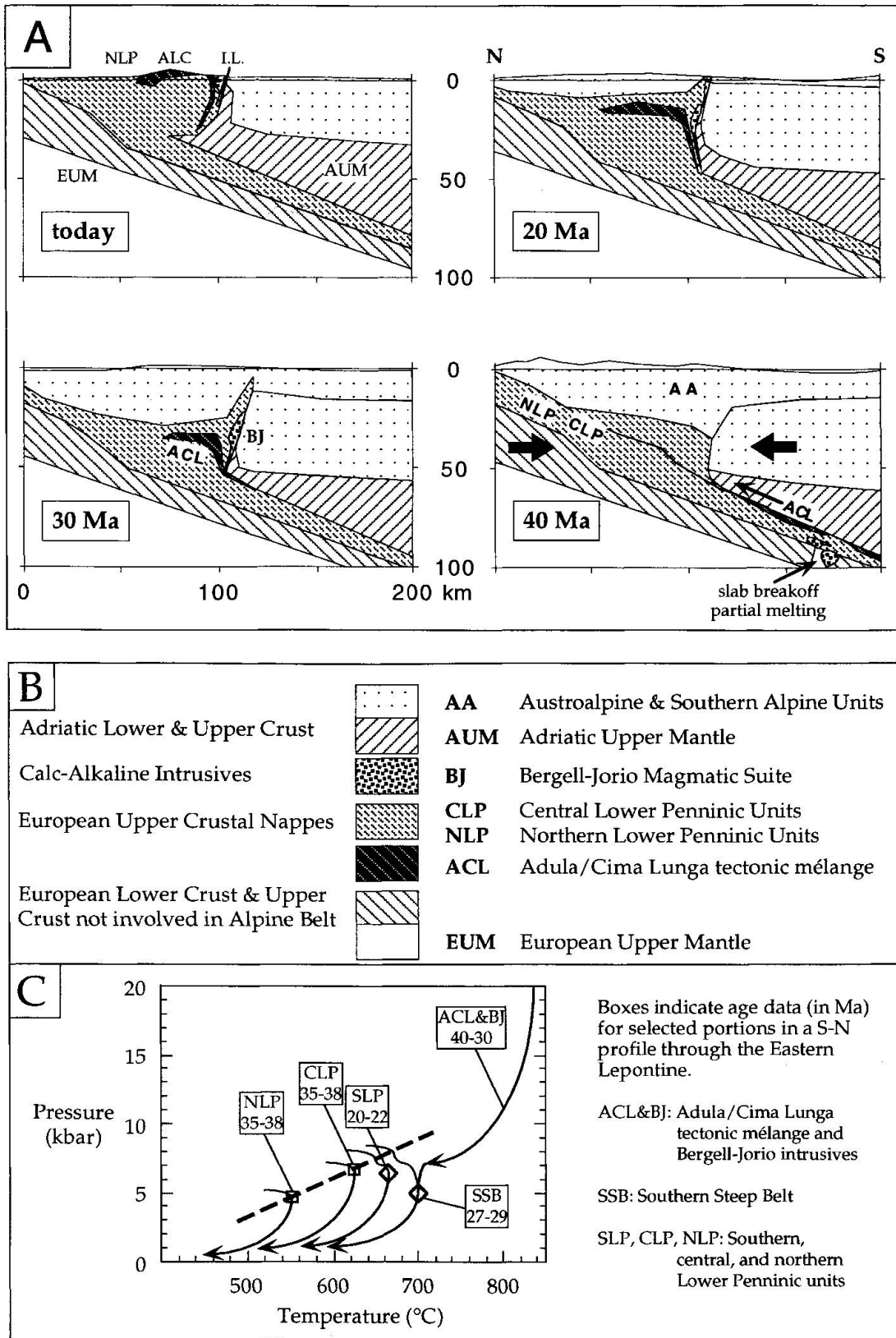
Fig. 5 Evolution of metamorphic conditions and tectonic framework. A) Cartoon of the tectonic evolution. Includes data and elements of the models by TROMMSDORFF (1990), PFIFFNER (1992), MARCHANT (1993), VON BLANCKENBURG and DAVIES (1994), DEUTSCH and STEIGER (1985), and others. B) Legend for 5A. C) Schematic P-T-t paths for various units of the Eastern Lepontine. The dashed line shows the Mesoalpine P-T gradient, extrapolated to the southern portions of the section. The effects of advected heat are visible in the southern parts of the section.

duction in which T_{max} was reached at 35–38 Ma (Fig. 5), mineral parageneses in the central and southern portions document later, transient heating conditions attending substantial decompression, with the hot Adula-Cima Lunga lid (and calc-alkaline magmatic bodies, at least in the Insubric area) being thrust onto the lower Penninic stack at around 30 Ma. According to this model, thermal relaxation of the (initially inverted) T-gradient provided heat to the footwall underneath the hot lid; in the central portions T_{max} was reached only at around 21 Ma, i.e. during the Insubric phase. A series of schematic sections outlining this model is depicted in figure 5A. We conclude that the regional metamorphism is a result of the superposition of two different mechanisms operating during the Tertiary.

The apparently sudden reversal in transport direction – from continental *subduction*, operating at least until 35 Ma ago, to *obduction* of a deep crustal slice, with exhumation starting prior to 32 Ma ago – may well be linked to a mechanism such as proposed by CHEMENDA et al. (1995). An important implication is that mineral assemblages now located in the southern parts of the (eastern) Lepontine, close to the advective heat sources, reached their T_{max} during ascent, earlier than those further north that were just reaching their thermal maximum during the neo-Alpine. In an E–W belt roughly between Biasca and Campolungo some samples may have been reset by this neo-Alpine heating, while others kept their (meso-Alpine) assemblages intact. At present, our data do not indicate a difference in the P-T conditions reached at the two stages in this area.

This tectonic model is compatible with the data and interpretations of HEINRICH (1982) and MEYRE and PUSCHNIG (1993) for crustal retrogression of Adula rocks. A near-perfect correspondence is noted with many features of the slab break-off model developed recently by VON BLANCKENBURG and DAVIES (1995) to explain the temporal and spatial link between magmatism and uplift during late Tertiary convergence in the Alps. Heat was advected into the southern (upper) parts of the Penninic nappe stack (a) by melt generation and migration along the deep subduction shear system and (b) by deep thrust slices that were expelled along that same shear zone from deep crustal (> 100 km) to middle crustal (~ 20 km) positions. In our opinion the high metamorphic temperatures in the Southern Steep Belt reflect the transient pulse of heat advected during emplacement of the hot Adula/ Cima Lunga units and of the magmatic bodies along the subduction/exhumation shear zone.

This would not only explain the sudden pulse of heat but also its rapid relaxation between 23 and 19 Ma (HURFORD, 1986). None of the thermal models proposed so far have included the effects and implications of heat thus advected into the lower Penninic units (i.e., WERNER, 1981; BRADBURY and NOELEN-HOEKSEMA, 1985).

The proposition made on structural grounds by MILNES (1975) and still held by many (e.g. STECK and HUNZIKER, 1994) of large-scale (back) folding of the metamorphic isograds along the northern and central parts of the Lepontine is not supported by our results.

Steep isograds had been previously proposed for the Northern Steep Belt (FOX 1975; KLAPER and BUCHER-NURMINEN, 1987). However, KAMBER (1993) recently showed in a detailed study that the steep thermal gradient in the Nufenenpass area is apparent only, due to a tectonic P-T discontinuity at the Penninic front. Given the resolution of our methods and the current sample density, the precise geometry of the isolines near the boundaries of the data are not well constrained, but our results in any case do not show closely spaced isotherms along the Northern Steep Belt. At present, the analysis of P-T conditions for the external parts of the Central Alps is limited by the quality of thermodynamic data for minerals of low-grade assemblages (chlorite, chloritoid, epidote, stilpnomelane, etc.). Once improved models are available for these minerals, discontinuities in metamorphic grade merit further investigation.

In our brief interpretation of the evolution of the Lepontine, we have not addressed effects due to the well established uplift patterns. Given the amount and complexity of recorded strain associated with the structural doming (MERLE et al., 1989), the geometric simplicity of the isotherm and isobar maps – as well as the map pattern of metamorphic isograds – is probably deceptive.

6. Conclusions

The application of multi-equilibria thermobarometric methods to a set of metamorphic assemblages selected to record the thermal maximum reached in the eastern Lepontine yields a coherent set of P-T data. Though diachronous, the metamorphic field gradients present may be portrayed by relatively simple isobar and isotherm maps. Their geometries differ substantially, with maximum P (up to 7 kbar) recorded in a central E-W belt, and lower values of P both to the N and S. By contrast, values obtained for T increase steadily from N (< 500 °C) to S (~ 700 °C), with a

domal isotherm pattern similar to the well established mineral isograds. The reliability of our P-T data owes much to the consistent methods used in sampling (or data selection from the literature), documenting, and applying thermobarometric computations. Even with these precautions, the uncertainty in each P-T datum is substantial, with sample to sample deviations showing local scatter of ~ 0.5–1 kbar and ~ 30 °C.

The implication of our P-T results on the tectonometamorphic evolution of the Central Alps has been preliminarily assessed. A two-stage model for the main thermal overprint of the eastern Lepontine appears to fit the data well. Only in the northern portion (N of Biasca) are meso-Alpine mineral equilibria commonly intact; these are interpreted as documenting a S-dipping subduction slab. In southern areas the thermal maximum was reached during ascent, due to emplacement of upper Penninic deep crustal slices and calc-alkaline magmatic bodies onto the lower Penninic nappe stack. The central areas of the eastern Lepontine area were affected to a lesser degree by that heat pulse and attained their T_{max} some 6 Ma later.

Acknowledgements

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Appendix:

Additional literature sources consulted

As described in Section 2.1 of the paper, our attempt was to extract – from the entire literature available on the Central Alps – as many adequately documented parageneses as possible for those lithological types considered most promising. For a variety of reasons (Tab. 1 and SCHMATZ, 1993) some works were not useable for our specific thermobarometric purposes. The list below assembles studies in which data were either inadequate for this study or simply not present. We stress that this in no way implies a quality judgment on the studies and publications listed.

As far as possible, the list is grouped by the geographic areas and/or tectonic units to which each publication pertains. This should serve anyone in search of primary petrological data on the Central Alps, regardless of the specific need or purpose. Note that most of the purely structural and isotopic studies are not included. Very abbreviated references (e.g. first author only) are given here; a more complete bibliographic list may be obtained from the authors.

Special journal abbreviations used in list:

BGKS   Beiträge zur Geologischen Karte der Schweiz
CMP   Contributions to Mineralogy and Petrology
EgH   Eclogae geologicae Helvetiae
EPSL   Earth and Planetary Science Letters
JGR   Journal of Geophysical Research
SMPM   Schweizerische Mineralogische und Petrographische Mitteilungen

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