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NEW THERMOBARIC CONSTRAINTS ON THE EXHUMATION HISTORY OF THE LIGURIDE ACCRETIONARY WEDGE, SOUTHERN ITALY

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ABSTRACT

New constraints on the thermobaric evolution of the Liguride complex of the Southern Apennines are provided by inorganic and organic thermal indicators. In detail, quantitative data on the thermobaric signature of the medium-to low-metamorphic Frido Unit and non-metamorphic North-Calabrian Unit have been derived using different methodologies such as clay mineralogy, fluid inclusion microthermometry, fission tracks analyses, and organic matter maturity. A good convergence among data from different, indipendent methods was obtained. The Frido Unit underwent temperatures in the range of anchizone (250-300°C) according to data derived from both clay mineralogy and fluid inclusion microthermometry. Pressure estimates by white mica b_0 parameter are typical of accretionary wedges and in the range of 6-8 kbar.

In the non metamorphosed North Calabrian Unit, clay mineralogy, organic matter maturity and fluid inclusion microthermometry record thermal conditions from diagenesis (~ 130°C) to the late diagenesis - anchizone boundary (~ 200°C) for the Crete Nere Fm., and diagenetic conditions (temperatures around 100-110°C) for the Saraceno Fm. In a regional framework, these data help to better constraint the thermal evolution of the units belonging to the Liguride complex with respect to the timing of final exhumation at 5-6 My, as suggested by apatite fission tracks data.

INTRODUCTION

The Southern Apennines are thought to be a crucial area to understand the geodynamics of the western-central Mediterranean resulting from the Africa-Europe convergence since Cretaceous times (Dewey et al., 1989; Schettino and Scotese, 2005). In the area, remnants of continental paleomargins, ocean basin floor and sedimentary cover crop out within a NE-verging accretionary wedge with a complex geometry. Blocks of the ophiolite-bearing Liguride Units occur on the top of the thrust pile, whereas the lowermost tectonic units consist of Mesozoic and Cenozoic rocks derived from the sedimentary cover of the foreland plate. These include both carbonate platform (Apennine Platform) and pelagic basin (Lagonegro Basin) successions (e.g., Scandone, 1967), locally passing to foredeep and/or thrust-top basin sediments (e.g., Sgrosso, 1998).

Literature already provides a number of contributions on the time-space evolution of the Southern Apennines (Scandone, 1967; Vezzani, 1969; Amodio-Morelli et al., 1976; Lanzafame et. al., 1979; Bonardi et al., 1988a; Casero et al., 1991; Monaco and Tortorici, 1995; Cello et al., 1996; Schiattarella, 1998; Pescatore et al., 1999). Nevertheless only some of them point out the importance of studying the exhumation processes for understanding modes and times of deformation (Wallis et al., 1993; Knott, 1994; Mazzoli, 1998; Thomson, 1998; Rossetti et al., 2001 and 2004).

In this paper we propose an integrated investigation on inorganic and organic thermal parameters (clay mineralogy, fluid inclusion microthermometry, vitrinite reflectance and fission track analyses). Our study is focussed on sedimentary and low-medium grade metamorphic units in which the thermal and thermochronological dataset is poor. It provided the thermobaric evolution and age constraints on exhumation of the Liguride complex in the north-eastern sector of the Pollino ridge area.

GEOLOGICAL SETTING

In the study area, located in the Southern Apennines, two main tectonic elements are regionally superposed: the ocean-derived Liguride complex (*sensu* Ogniben, 1969) in the hanging wall, and the carbonate succession belonging to the Apennines (i.e. Campania-Lucania) platform (Pollino-Ciagola Unit after Iannace et al., 2005) in the footwall.

The Liguride complex crops out in the Southern Apennines from the Cilento promontory to the Calabria-Lucania border and in the Northern Calabria area (Fig. 1). It is a complex assemblage of ophiolite-bearing units, mainly composed of Jurassic to Oligocene sedimentary covers and Miocene siliciclastic units, locally affected by medium to very low grade metamorphism (Knott, 1987; Bonardi et al., 1988a; Monaco et al., 1995; Mauro and Schiattarella, 1998; Di Leo et al., 2005). In some areas blocks of continental basement rocks also crop out. All these units formed an accretionary wedge due to subduction of the Ligurian oceanic lithosphere and, probably, fragments of continental crust, later thrust onto the carbonate platform units of the African passive margin (Campania-Lucanian or Apenninic platform

Auctorum) during Miocene times. The Liguride complex is the geometrically highest element of the southern Apennines fold-and-thrust belt (Fig. 1b). Pliocene-Quaternary brittle tectonics highly dissected the units along the Calabria-Lucania border (Schiattarella, 1998 and references therein; Cello and Mazzoli, 1999), and the structural relationships among them are nowadays rather complicate to understand.

The Liguride complex in southern Lucania crops out along a wide belt north of the Pollino Mts. carbonate morphostructure. Within such a belt, cover units prevail (the metamorphic Frido Unit and the non metamorphosed Nord-Calabrian Unit, Bonardi et al., 1988a), although serpentinite bodies, gabbros and metabasites also crop out (Bonardi et al., 1988b).

More in detail, the Frido Unit is made of mafic and ultramafic rocks, metabasites, quartzites, slates, and calc-silicates (Vezzani, 1969). The Episcopia tectonic mélange, according to Bonardi et al. (1988a), is made of serpentinite-rich blocks and fragments of continental crust within a serpentine-phyllosilicate matrix, overlying the Frido Unit. Actually, a new survey revealed that serpetinite blocks are included into the Frido Unit, whereas the gneissic and granit bodies have to be considered apart (Geological Map of Italy, 2006).

Finally, terrains from the North-Calabrian Unit (Late Jurassic-Late Oligocene, Bonardi et al., 1988a) tectonically overlie, on a regional scale, the Frido Unit. This latter include: i) the Crete Nere Fm., a succession made of quartz-arenites and dark, organic matter-rich, grey shales, that can be considered as a "broken formation" (Monaco and Tortorici, 1995); ii) the Saraceno Fm., composed of calcareous turbidites with the siliciclastic fraction increasing upwards (Fig. 3).

According to previous works (Monaco et al., 1995; Di Leo et al., 2005), the Frido Unit can be divided into two sub-units: i) a mainly shaly sub-unit and, ii) a mainly meta-calcareous sub-unit, roughly corresponding to the shale member and meta-limestone member of the Frido Fm. of Vezzani (1969). Monaco et al. (1995) suggest the presence of a tectonic contact between the Frido meta-calcareous sub-unit, and the underlying shaly sub-unit, marked by the interposition of serpentinite and metabasite slivers (Di Leo et al., 2005; Geological Map of Italy, 2006). Within the North-Calabrian Unit, the stratigraphic continuity between the Saraceno Fm and the underlying Crete Nere Fm has been observed (Di Leo et al., 2005).

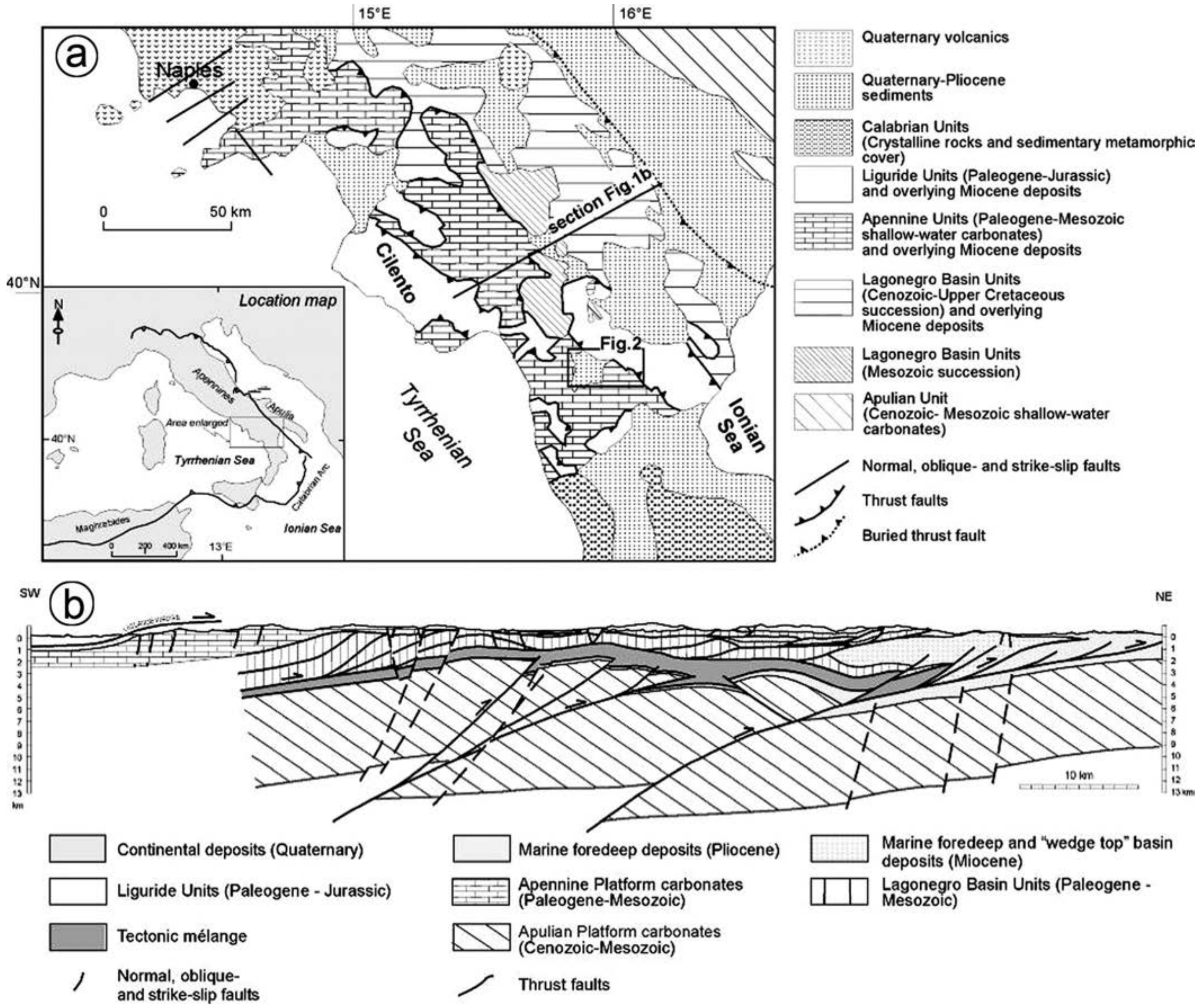


Fig. 1 - Geological sketch map of the Southern Apennines (a), and schematic cross section (b), through the chain (after Mazzoli et al., 2006). Location of the studied area of Fig. 2 in the square.

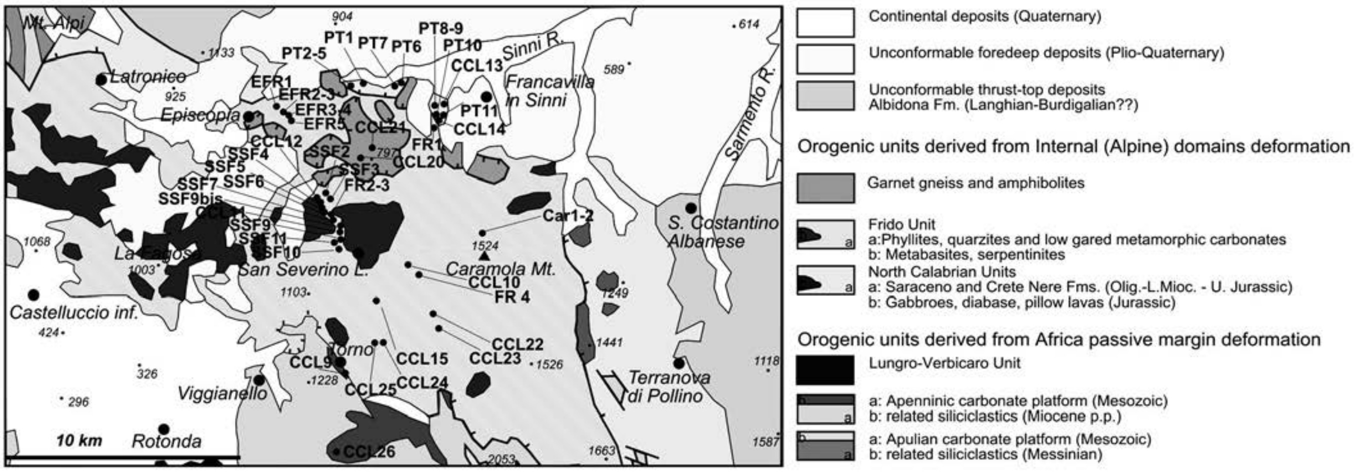


Fig. 2 - Schematic geological map of the study area. Sample sites are indicated.

Finally, within the Apennines platform units (i.e. Alburno-Cervati-Pollino Unit, cf. Pollino-Ciagola Unit, after Iannace et al., 2005), we examined only the Bifurto Fm. siliciclastic sediments, which were deposited during the Burdigalian-Langhian on top of the Mesozoic-Paleogene carbonate platform (Selli, 1962; Patacca et al., 1992).

Previous petrological and geochemical studies provided fundamental information on the origin and evolution of ophiolite-bearing units at the Calabria-Lucania border (Bonardi et al., 2001 and references therein). The Frido Unit contains T-MORB-type basalts which underwent HP-LT conditions (P > 6 Kbar up to 8-10 Kbar; T < 400-450°). Rapid exhumation was inferred by aragonite relicts within calc-schists (Spadea, 1994). Among the North-Calabrian Units, the Crete Nere Fm. shows very low grade metamorphic conditions (cf. sub-greenshist facies of the Calabro-Lucano Flysch, after Monaco et al., 1995).

METHODS AND RESULTS

Thermal and pressure constraints

The clay mineralogy

Pelites and metapelites from Frido Unit (mainly shaly samples) and Nord-Calabrian Unit (Crete Nere and Saraceno Fms.), both belonging to the "Liguride Units" (*sensu* Bonardi et al., 1988a), sampled along the Frido River Valley and close to the village of San Severino Lucano (Fig. 2), constitute an excellent set of materials to study thermal maturity and to estimate maximum burial conditions of these successions using inorganic indicators such as the Kübler illite index (KI, Kübler, 1967), % of illite layers in illite/smectite mixed layers (% I in I/S), and relative abundance of white mica polytypes.

Mineralogical analyses have been carried out by X-ray powder diffraction (XRD). The relative abundances of mineral phases in the bulk samples and in the < 2 μm fraction were estimated by using a Rigaku diffractometer, mod. Miniflex (CuK_α radiation and sample spinner) and the software MacDiff ver. 4.2. The prograde sequence of minerals usually observed in regularly repeating sequences as function of grade [i.e. smectite → illite/smectite (I/S) mixed layers → illite → muscovite and smectite → chlorite/smectite (C/S) mixed layers → chlorite], has been monitored by XRD and computer modelling (software NEWMOD; Reynolds, 1985). The clay minerals reaction progress has been defined by measuring illite crystallinity, expressed as Kübler Index (Kübler, 1967, hereafter KI), and chlorite crystallinity expressed as Árkai Index (Árkai et al., 1995; hereafter AI), calibrated to the Crystallinity Index Standards scale proposed by Warr and Rice (1994). Well crystallized (WCI) and poorly-crystallized illite (PCI) were detected using the deconvolution procedure suggested by Gharrabi and Velde (1995). KI values were estimated for both WCI and PCI, although only those relative to WCI were used to estimate a maximum temperature for the Frido Unit and Crete Nere Fm. The pressure conditions of the studied samples were constrained using the K-white mica *b* cell dimension based geothermometer (Sassi and Scolari, 1974), commonly used as a comparative geobarometer in low and very low-grade metapelitic rocks (Robinson and Bevins, 1986). The K-white mica *b* cell dimension has been estimated also by XRD using dioctahedral mica (060) reflections and the deconvolution procedure (Huon et al., 1994), clearly avoiding samples with high paragonite content (Guidotti and Sassi, 1986).

Mineralogical data are reported in Table 1 and Figs. 4a, 4b, and 4c. For temperature estimation only KI values from "diagenetic" illite were used, avoiding any possible contamination from "non diagenetic" illite, which is abundant in the Bifurto and Saraceno Fms. (Fig. 2). The latter formation shows, toward the top, an increase in detrital input, i.e. of "non diagenetic" illite and chlorite, having been deposited in non steady-state conditions due to tectonic instability of the source area. This fact may be interpreted as a prodrome of the Oligo-Miocene contractional tectonic phase that led

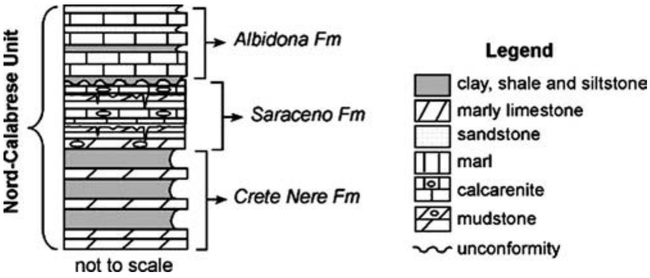


Fig. 3 - Simplified stratigraphic column of the North-Calabrian Unit (after Di Leo et al., 2005, modified).

Table 1 - Mineral distibution in the "Liguride units" and Bifurto Fm (wt. %).

Sample	*Unit-Formation*	*< 2 µm fraction mineralogy*							*bulk mineralogy*							
		Kaol	*Ch*	*I/S*	*Par*	*WCI*	*PCI*	*% I in I/S*	*CM*	*Qtz*	*Kfs*	*Pl*	*Cc*	*Do*	*Kaol*	*Ch*
CL10.1	Frido Unit	-	15	-	16	44	25		62	14	-	tr	10	-	-	12
CL10.2		-	12	-	16	54	18		69	14	tr	tr	-	-	-	15
CL10.3		-	11	-	22	39	28		80	6	-	6	-	-	-	8
CL10.4		-	17	-	17	44	22		64	17	tr	tr	-	-	-	16
CL10.5		-	16	-	21	34	29		77	8	tr	tr	-	-	-	11
CL10.6		-	18	-	19	39	23		49	11	tr	tr	-	-	-	36
CL12.1		-	8	-	18	54	20		63	7	-	tr	12	-	-	14
SSF1		-	5	-	7	79	9		71	12	-	4	-	-	-	13
SSF2		-	9	-	9	70	12		72	6	tr	tr	tr	-	-	16
SSF3		-	8	-	7	74	10		79	11	-	tr	tr	-	-	6
SSF4		-	8	-	10	71	12		84	tr	-	4	tr	-	-	8
SSF5		-	11	-	9	72	8		64	5	tr	tr	11	-	-	16
SSF6		-	17	-	26	48	9		76	tr	tr	7	-	-	-	14
SSF7		-	8	-	9	72	11		67	5	tr	5	6	-	-	16
SSF8		-	11	-	16	61	13		48	6	tr	6	7	-	-	32
SSF9		-	8	-	11	69	12		56	4	tr	6	13	-	-	20
SSF10		-	11	-	16	57	16		64	7	tr	tr	tr	-	-	23
SSF11		-	13	-	17	57	13		59	4	tr	5	tr	-	-	30
FR2*		-	8	1	10	65	16		80	4	tr	tr	tr	-	-	11
FR3*		-	10	tr	11	56	20		58	7	tr	tr	tr	1	-	25
FR4 *		-	10	4	41	23	21		76	tr	-	4	-	-	-	17
FR5 *		-	7	tr	21	48	23		32	15	-	7	11	-	-	32
EFR1*		-	26	-	20	40	14		78	7	-	tr	-	-	-	13
EFR2*		-	16	-	13	52	19		62	13	-	tr	6	-	-	16
EFR3*		-	26	-	8	51	15		64	13	-	tr	-	-	-	21
EFR4*		-	27	-	11	51	12		70	16	tr	tr	-	-	-	12
PT1	Saraceno Fm	tr	4	61	-	25	10	78	77	8	-	tr	13	-	-	-
PT2		tr	8	70	-	13	7	80	79	5	-	tr	13	-	tr	tr
PT3		tr	tr	85	-	7	5	80	84	9	-	-	7	-	-	-
PT4		tr	7	66	-	15	10	84	80	9	-	-	9	-	tr	tr
PT5		tr	10	50	-	23	16	89	52	10	-	tr	34	-	tr	tr
PT6		tr	10	45	-	24	20	87	59	11	-	tr	26	-	tr	tr
PT7		4	20	46	-	17	13	87	71	16	-	tr	9	-	tr	tr
PT8		tr	30	47	-	11	10	87	77	10	-	tr	6	-	tr	tr
PT9		4	33	18	-	23	21	89	58	9	-	tr	27	-	tr	tr
CCL13.1		-	11	62	-	-	28	66; 86	78	8	-	tr	12	-	-	tr
CCL13.2		-	tr	69	-	-	28	90	73	14	-	tr	11	-	-	-
CCL13.3		-	tr	75	-	-	32	62; 80	72	10	-	tr	15	-	-	-
ESa01*		-	tr	-	-	97	-		86	4	-	tr	-	-	-	7
ESa02*		-	5	tr	-	94	-		79	6	tr	tr	-	-	-	12
ESa1*		tr	tr	67	-	20	9	72; 86	65	14	-	-	21	-	-	-
ESa2*		tr	5	60	-	19	14	88	66	18	-	-	15	-	-	tr
Sa1*		-	10	28	-	48	14	85	70	6	-	tr	21	-	-	tr
Sa2 *		-	10	44	-	37	10	84	58	7	-	-	28	tr	-	5
Sa3 *		-	10	68	-	16	6	69; 85	73	7	-	tr	18	-	-	tr
Sa4*		-	7	58	-	26	9	73; 85	62	13	-	tr	23	-	-	tr
Sa5 *		-	5	66	-	19	11	67; 84	81	6	-	-	12	-	-	-
Sa6*		-	14	70	-	9	7	71; 87	80	12	-	-	6	-	-	tr
PT10	Crete nere Fm	tr	25	8	-	40	26	0	74	5	-	tr	9	-	4	7
PT11		tr	23	41	-	22	13	90	51	18	tr	-	28	-	tr	tr
CCL14.1		5	10	85		-	-	88; 90	75	14	-	tr	7	-	-	tr
CCL14.2		-	21	31	-	34	14	88	79	8	-	tr	-	-	-	12
CN1*		tr	6	tr	-	61	28	78	82	7	-	tr	4	-	-	6
CN2*		-	33	tr	-	37	28		47	21	-	tr	15	tr	-	12
CN3*		-	14	tr	-	-	85		73	10	-	tr	12	-	-	tr
CN4*		-	8	5	-	51	36		66	15	-	tr	4	tr	-	9
CN5*		-	13	tr	-	-	84		68	18	-	tr	-	-	-	11
CN6*		-	10	tr	-	-	86		72	tr	tr	tr	-	-	-	24
CN7*		-	5	7	-	66	23		53	15	-	tr	tr	1	-	26
CCL9.1	Bifurto Fm	-	45	12	-	26	25	84	57	6	-	tr	21	6	-	7
CCL9.2		-	37	29	-	24	14	78	54	7	-	tr	23	4	-	9
CCL9.3		-	16	44	-	37	23	70; 85	81	7	-	tr	-	-	-	10

Kaol- kaolinite; Ch- chlorite; I/S- illite /smectite mixed layers; Par- paragonite; PCI- poorly crystallized illite; WCI- well crystallized illite; % I in I/S- percentage of illite layers in illite /smectite mixed layers; CM- clay minerals; Qtz- quartz; Kfs- k-feldspar; Pl- plagioclase; Cc- calcite. * Data from Di Leo et al. (2005).

to deformation of the Ligurian basin (Di Leo et al., 2005). On the other hand, for pressure constraint only samples from the Frido Unit and Crete Nere Fm were used to measure the K-white mica *b* cell dimension.

According to the AI (Árkai Index) and KI (Kübler Index) values measured in pelites and metapelites (Fig. 4a), and to the relative abundance of the three mica polytypes, 1M, $1M_d$, and $2M_1$ (Fig. 4b), the Liguride complex cropping out along the Calabria-Lucania border shows low-grade metamorphism, ranging from late diagenesis (*sensu* Merriman and Frey, 1999) with AI and KI values respectively > 0.30 $\Delta 2\theta$ and in the range of 0.42-0.70 $\Delta 2\theta$, to lower anchizone conditions (*sensu* Merriman and Frey, 1999) with AI and KI values respectively < 0.30 $\Delta 2\theta$ and in the range of 0.31-0.42 $\Delta 2\theta$. K-white mica *b* cell dimension values range from 9.0461 ± 0.00027 Å to 9.0391 ± 0.00026 Å (Fig. 4c) corresponding to those reported for a *high pressure facies* from Guidotti and Sassi (1986). They are typical of accrectionary prisms (Frey and Robinson, 1999) and allow to confine pressure in the range of 6-8 kbar.

Fluid inclusions microthermometry

Quartz-calcite and calcite veins related to the deformation history have been sampled for fluid inclusion microthermometry from the Frido Unit (shale and meta-limestone) and North-Calabrian Units (Crete Nere and Saraceno Fms.). A detailed field meso-structural analysis was conducted on the selected outcrops. Previous works (Knott, 1994; Spadea, 1994; Mazzoli, 1998) related the main foliation to

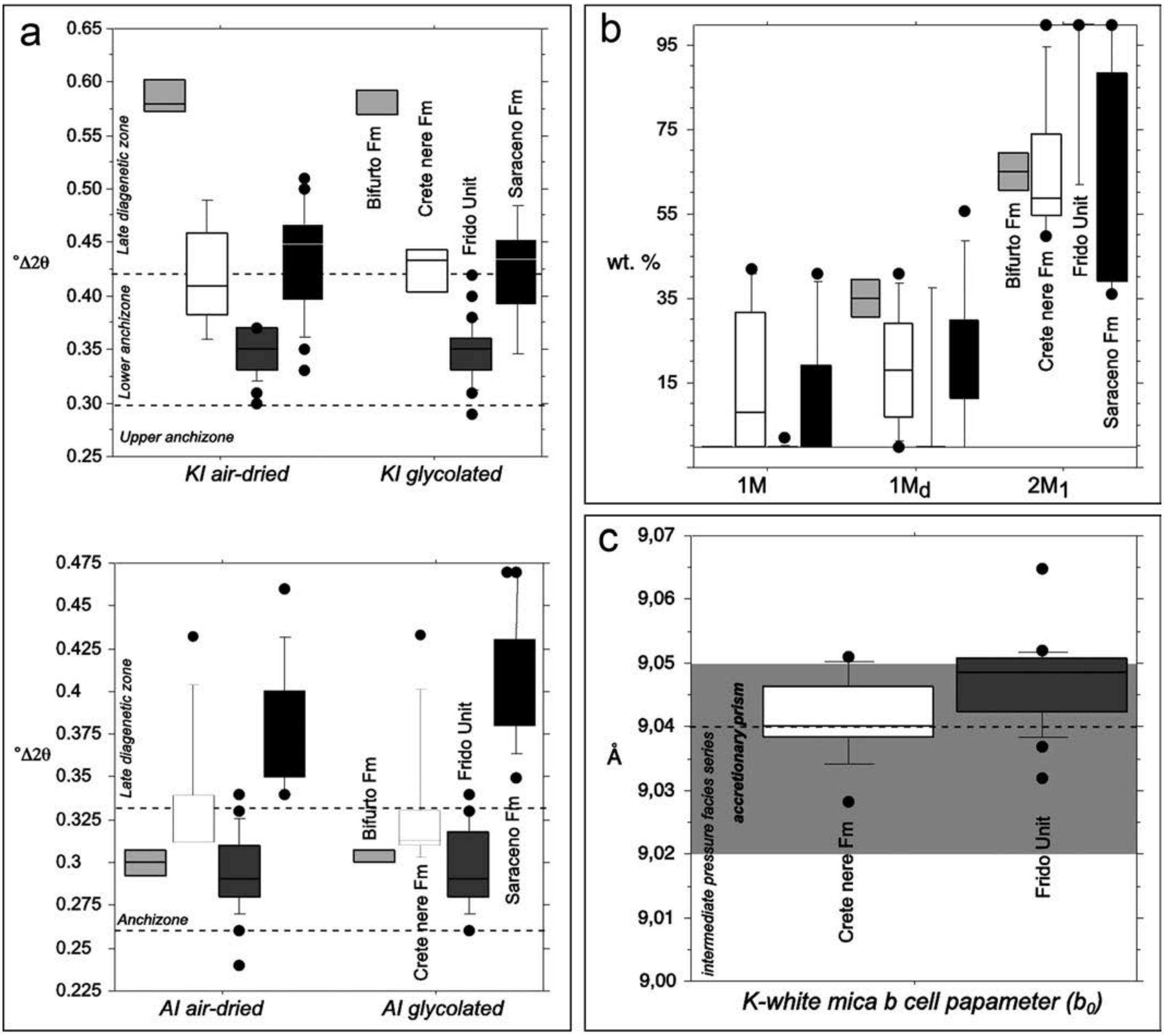


Fig. 4 - a) The clay minerals reaction progress has been defined by measuring illite crystallinity, expressed as Kübler Index (Kübler, 1967), and chlorite crystallinity, calibrated to the Crystallinity Index Standards scale proposed by Warr and Rice (1994). Kübler Index (KI) relative to the well crystallized illite and, Arkai Index (AI) calculated on both air-dried and glycolated oriented mounts. b) White mica polytype relative distribution. The percentage of polytypes was measured using a Nonius PDS X-ray diffractometer, following the quantification method proposed by Cressey and Scofield (1996) and Batchelder and Cressey (1998), and the LINKFIT program. Frido Unit and Crete Nere Fm. exhibit only the presence of the polytype stable at higher temperature. The $2M_1$ observed in the Bifurto and Saraceno Fms. has a "non diagenetic" origin (see text for explanation). c) K-white mica *b* cell parameter (b_0). The values were calculated by XRD, using the dioctahedral mica (060) reflections and the deconvolution procedure suggested by Huon et al. (1994).

the early stages of progressive non-coaxial deformation with strong transposition. Coeval extension veins at a high angle to the foliation were progressively rotated and folded within it. Based on our mesostructural analysis, veins stretched or folded within the main S_2 foliation have been sampled in each formation in order to check the presence of fluid inclusions related to the early stages of exhumation. Although within veins either parallelized to the main S_2 foliation or strongly folded, a number of re-equilibrated and/or decrepitated inclusions are present, careful petrographic analysis allowed to recognise some survived two phase primary inclusions, generally organized in well defined fluid inclusion assemblages.

Homogenization temperature (Th), related to fluid density, and ice melting temperature (Tm), related to fluid composition (Roedder, 1984) were obtained by micro-thermometric analyses, using an USGS Stage calibrated at 0°C, -56.6C° and 374°C with synthetic standards. When possible, two-phase (liquid + vapour) primary (P) and secondary (S) inclusions have been measured. They are related respectively to crystal growth, and to deformation after crystallization (healed micro-fractures). All the detected inclusions belong to the H_2O-NaCl system, and the freezing point depression suggest a very low salinity (1 to 5%wt NaCl equivalent). Th data from primary inclusions have been corrected to Tt (= trapping temperature, Roedder, 1984) using confining pressure conditions referred to previous petrographic analyses (Spadea, 1994) and b_0 results (Invernizzi et al., 2006, and present work). Tt was graphically extrapolated from a P/T diagram with iso-Th lines (= isochores, oblique lines in Fig. 5b, modified from Bodnar and Vityk, 1994).

Furthermore, secondary inclusions in early veins and primary inclusions in straight, high angle veins cutting through the main foliation have been measured. Straight veins are supposed to be related to late stages of exhumation. Therefore, no pressure correction was applied to Th because no data to confine pressure conditions are available. In these cases, Th was considered as indicative of minimum Tt (Barker and Goldstein, 1990; Goldstein and Reynolds, 1994).

Five samples from the Frido Unit (shale, meta-limestone) and gneiss blocks, two from the Crete Nere Fm and one from the Saraceno Fm. gave reliable results (Table 2). Sampled veins from the Frido Unit are related to early deformation stages: they are folded within the foliation (sample CCL10.2, CCL11.1 and CCL12.1) or belong to hydraulic fractured rocks, typical of fluid overpressure at considerable depth (sample CCL10.3). Microthermometric data from these veins are quite consistent (Fig. 5a): Th mainly ranges between 90° and 115°C for primary inclusions, with no relevant differences between meta-limestone and shale subunits. Furthermore, one sample from a gneiss block embedded within the Frido Unit (sample CCL20.1) records well constrained Th for primary inclusions in quartz veins around 90°C.

Taking into account that b_0 values attest an intermediate pressure and that petrographic data from previous works (Spadea, 1982; 1994; Beneduce, in press) suggest pressure values around 6-8 Kbar, a presumable trapping temperature (Tt) for primary inclusions is in the order of 270-300°C (Fig. 5b).

Veins from the Crete Nere Fm. were sampled from foliated, dark grey or dark green clayey levels. Samples CCL14.1 and CCL24.1 come from folded and/or stretched extension veins parallel to the foliation, and sample CCL22.1 belongs to a later vein related to roughly N-S-trending F_3 meso-folds (Knott, 1994). Unfortunately, very few data came from the first two samples, more clearly related to early deformation stages. An indicative Th can be suggested between 55° and 75°C. Data from sample CCL22.1 (late vein) show a mean Th = 91°C.

From petrographic (non metamorphic or very low metamorphic condition) and geologic (tectonic units thickness) considerations, a pressure correction of about 1.5 Kbars can be considered for the early veins and a Tt around 130-140°C can be inferred. For sample CCL22.1 (late veins), we suggest that Th = 91°C can be interpreted as a minimum Tt without pressure correction.

Finally, one sample from the Saraceno Fm. comes from veins related to F_2 folds and shows Th values around 130-150°C. Also in this case, little or no pressure correction is suggested.

Organic matter

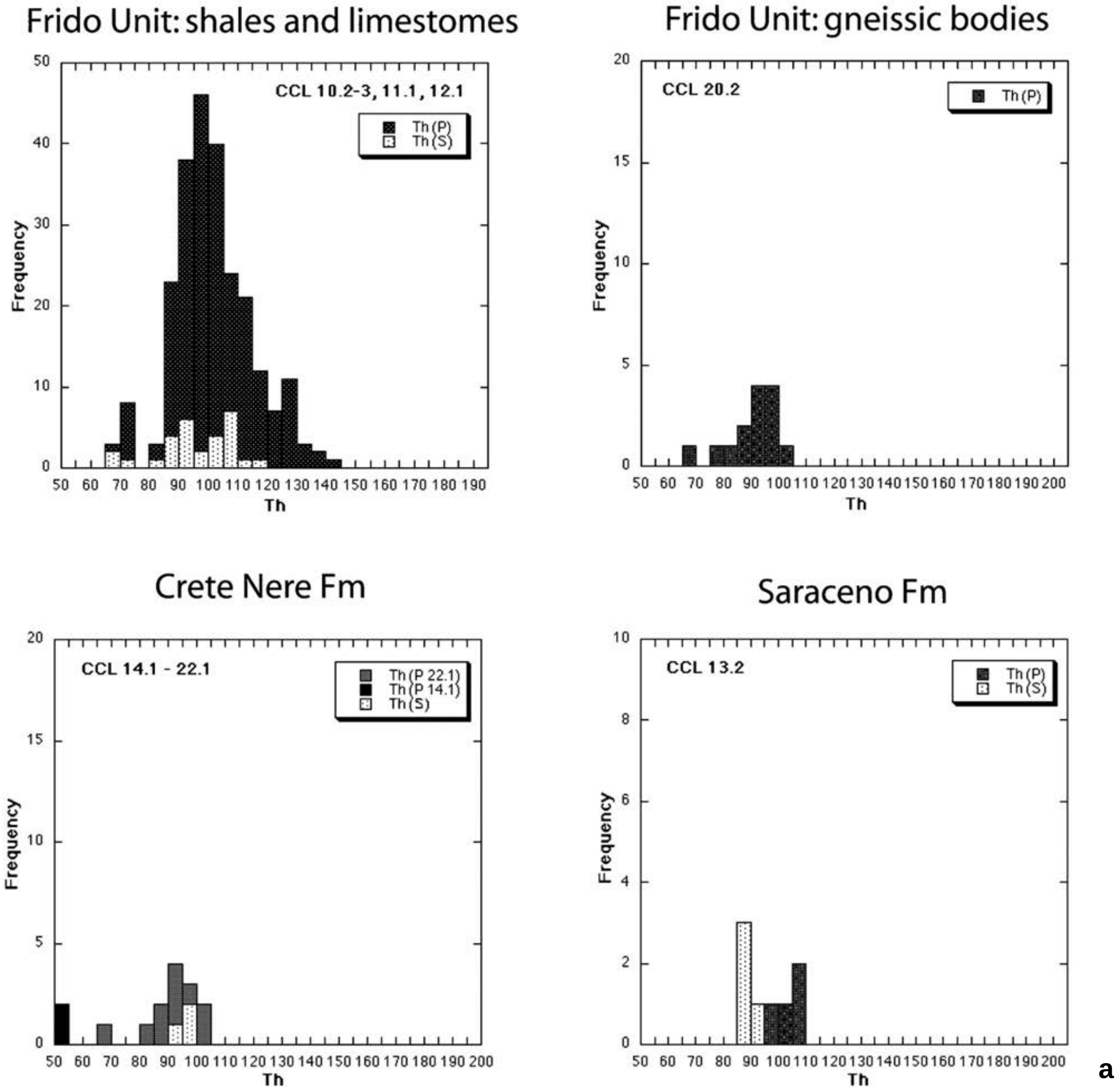
Results of optical analyses in reflected light on organic matter dispersed in sediments are listed in Table 2. Each sampled unit shows common optical features. In the Liguride complex, the non metamorphic North-Calabrian Unit shows different abundances of organic matter and macerals associations in the Crete Nere and Saraceno Fms.

Samples from the Crete Nere Fm. (CCL 9, CCL14, CCL24, PT 11) are generally barren or very scarce in dispersed organic matter, made up of macerals of the inertinite group (mainly fusinite), and very subordinately of the huminite-vitrinite group; oxidised pyrite may be present. Only sample CCL 9 contains scattered fragments with a mean R_0 of 1.05% and a not defined mode. Thus, no reliable parameters to constrain maximum temperatures are available.

Two samples from the Saraceno Fm. derive from site CCL13. Analysed kerogene is generally not very abundant and contains macerals of the inertinite group (mainly fusinite) and subordinately of the huminite-vitrinite group. In sample CCL13.1 Ro% data may be grouped into two main clusters: the first, mid-mature, well represented and probably indigenous (28 measurements) with a well defined mode (Ro = 1.02%), made up of medium sized fragments, generally squared and containing scarce not oxidized pyrite; the second, less abundant indicating the late stage of hydrocarbon generation and probably representing a reworked population. In sample CCL 13.2 Ro measurements are scattered in classes comprised between 1.3 and 2.2% with low frequency, indicating reworked input of vitrinite fragments. Thus this sample is not representative (not indicated in Table 2).

Data from the metamorphic Frido Unit (CCL 10) are mainly clustered in Ro classes between 3.7 and 4.3% (about 20 measurements on squared fragments) with a mean value of about 4.0%, indicating the overmature stage for hydrocarbon generation. Nevertheless, the poor state of conservation, the small fragment size and the high degree of thermal maturity cannot guarantee an indigenous population of vitrinite. Lower rank and higher rank fragments are also present but much more scattered.

Kerogene from the Miocene deposits lying on the top of the Apennines Platform units (CCL26 from Bifurto Fm.) is abundant and contains macerals of the inertinite group and subordinately of the huminite-vitrinite group. In the same way as in Saraceno Fm., vitrinite data are grouped into two main clusters: the first one, mid-mature, is probably indigenous and better represented (18 measurements) with a well



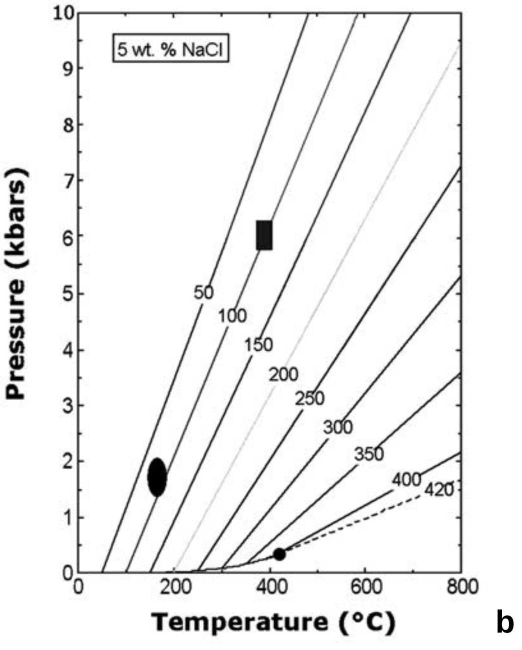


Fig. 5 - a) Histograms for Fluid Inclusion homogenization temperatures (Th). Microthermometry was performed by U.S.G.S. heating-freezing stage. b) P/T diagram with isochores (oblique lines, modified from Bodnar and Vityk, 1994). Th data are projected on isochores using pressure correction (see Table 4). Squared area: data from Frido Unit; circled area: data from Crete Nere Fm.

Table 2 - Data from organic matter maturity and Fluid Inclusion microthermometry.

Sample	*Unit-Formation*	*Organic matter*			*Fluid Inclusion*		
		R_o%	*Std*	*Nr.*	*Th°C(P)*	*Tf°C*	$P_{corr.}$ *Kbar*
CCL 20	Gneiss				90.0	270	6
CCL 10.1	Frido Unit shales	4.01	0.17	20			
CCL 10.2					99.50	280	6
CCL 10.3					104.13	300	6
CCL 11					100.50	290	6
CCL 13.1	Saraceno Fm.	1.02	0.13	28	103.65	140	1.5
PT 11	Crete nere Fm.	barren					
CCL 9		1.05	0.15	3			
CCL 14		barren			54.50	100	1.5
CCL 22					90.87		
CCL 24		barren			75.00	120	1.5
CCL 26	Bifurto Fm.	1.11	0.09	18			

P- primary inclusions; P_{corr}- pressure corrections for obtaining *Tt.*

defined mode of Ro = 1.1%; fragments are generally squared and poorly preserved, containing oxidized pyrite. The second one, less abundant indicating the late stage of hydrocarbon generation, is probably representative of a reworked population.

Constraints on the exhumation age

Fission tracks

Fission-track (FT) data are listed in Table 3. The oldest age comes from a gneiss sample from the Frido Unit in which 26 zircons have been dated. Statistical tests indicate a single age population, with age of 64.9±4.9 Ma, therefore pointing to a total reset of fission tracks. The annealing temperatures in zircon are highly sensitive to cooling rate and to the degree of radiation damage which, on its turn, is a function of the uranium and thorium contents of zircons and of the time elapsed since onset of cooling. In cases of high radiation damage, zircons may be reset at temperatures as low as 180-200°C, whereas in cases of low radiation damage zircons appear to be fully reset at temperatures in excess of 280-300 °C (Rahn et al., 2004; Garver et al., 2005; Fellin et al., 2006).

Apatite FT ages are much younger than zircon FT ages. Clearly, since ages result younger than the time of sediments deposition, maximum temperatures exceeded the total annealing temperature of fission tracks in apatite (about 130°C). Therefore, these data are related to the post-collisional exhumation history. The oldest age has been obtained on a sample from the Saraceno Fm. (CCL11.4 Ma) but all the others can be grouped in a short age range (5-6 Ma), although samples come from different units (Bifurto Fm., Frido Unit) and different localities.

DISCUSSION

From our analyses, new constraints about the thermobaric history of the several tectonic units cropping out in the studied area have been obtained. In particular, we show new data concerning the Bifurto Fm. of the Apennines Platform units. These data have been obtained from clay mineralogy, with extrapolated temperatures around 130°C (late diagenesis), vitrinite reflectance data, which suggest temperatures in the range of 140-165°C and totally annealed apatite fission tracks (AFT) data with exhumation age of 6 ±1.1 Ma (Fig. 6).

Only to the north, along the chain axis, the continuation of the same tectonic unit (still represented by carbonate platform successions and related siliciclastic non metamorphosed units) gave estimated paleo-temperatures lower than 100°C and non reset AFT. These data fit with a weak tectonic burial related to the chain building (Corrado et al., 2005). Finally, in the inner Aieta and Maratea tectonic windows, still along the Calabria-Lucania border, the carbonate platform units record slightly higher paleo-temperatures (Invernizzi et al., 2006) and a different deformation history. In fact, the Paleogene *Calcaire Plaquettes* shows evidence of ductile deformation, probably related to confined fluid circulation (Iannace and Vitale, 2004). An innermost sector of the same palaeogeographic unit of the passive margin (the Lungro-Verbicaro Unit, *sensu* Iannace et al., 2005), was affected by subduction processes (Iannace et al., 2005).

Regarding the Liguride complex, here divided in Frido Unit and North Calabrian Unit, our clay mineralogy data on the Frido Unit allow to infer a temperature in the range of 200-300°C and peak pressure conditions not lower than 6-8 Kbar (estimated from b_0 cell dimension). Dalla Torre et al. (1996) suggested that IC from shales and shale matrix mélange which underwent high-pressure/low-temperature metamorphism must be interpreted with caution. This is so because the KI values, estimated by deconvoluting the 10 Å reflection using only one peak (Kubler, 1977), are the results of a physical mixture of numerous small phengitic coherent scattering domains and smaller numbers of slightly larger muscovitic coherent scattering domains (Dalla Torre et al., 1996a; 1996b). However, using two peaks to deconvolute the 10 Å peak (respectively the WCI and PCI peaks, Meunier and Velde, 2004), and considering only the KI relative to the WCI, the maximum temperature inferred by clay mineralogy (see Fig. 4a) is in good agreement with those estimated by both vitrinite reflectance and fluid inclusion microthermometry data, in the range of 250-300°C, both for the calc-schists and the meta-pelites sub-units.

Furthermore, we obtained data on the gneiss blocks of continental crust embedded in the Frido mélange (Episcopia mélange). Thermo-chronologic data from zircon fission tracks (ZFT) and paleo-temperatures from fluid inclusion microthermometry are available, and show that these remnants of continental crust were already being exhumed at about 65 Ma ago and passed the 280-300°C isotherm. Afterwards, the total annealing temperature was never reached again. Fluid inclusions in quartz veins record the deformation history since the gneiss blocks and Frido Unit started

Table 3 - Central ages calculated using dosimeter glass CN5 and ζ-CN5 =3 66.5±3.5 for samples PT7, CCL) and CCL10 and a ζ-CN5 = 365.6±10.5 for sample CCL21.

Sample number	Mineral	No. of crystals	Spontaneous		Induced		$P(\chi)^2$	Dosimeter		Age (Ma) ± 1σ
			ρ_s	N_s	ρ_i	N_i		ρ_d	N_d	
PT7	apatite	20	1,09	97	1,97	1755	90,5	1,13	4322	11.4±1.2
CCL9	apatite	12	2,24	88	4,64	1827	10,9	0,86	4086	6.0±1.1
CCL10	apatite	10	0,64	13	2,11	429	81,9	0,91	4308	5.0±1.4
CCL21	zircon	26	87,30	610	4,48	313	97,1	0,18	7070	64.9±4.9

ρ_s: spontaneous track densities (x 10^5 cm^{-2}) measured in internal mineral surfaces; ρi and ρ_d: induced and dosimeter track densities (x 10^6 cm^{-2}) on external mica detectors (g = 0.5); N_i and N_d: total numbers of tracks; $P(\chi^2)$: probability of obtaining χ^2-value for ν degrees of freedom (where ν=number of crystals-1); a probability >5% is indicative of an homogenous population.

their common history. In fact, the coherence between paleotemperatures from veins belonging to these two lithologies represents a constraint for the development of the veins parallel to the gneiss foliation which testify the beginning of the deformation history recorded by fluid inclusion.

The younger thermal history for this Unit is confined by AFT at about 6 Ma.

Our data are in good agreement with previous works that used mineralogical and petrological data from metabasites. In particular, Monaco et al. (1991), Monaco and Tortorici (1995) and Spadea (1994) analysing metabasites and their meta-sedimentary cover suggested peak metamorphic conditions in the range of 6-8 Kbar and 250/350°C. This was recently confirmed by new data on the mineralogical assemblage of metabasites cropping out in the area of the San Severino village (Beneduce et al., in press). Furthermore, Spadea (1982) interpreted the blueschists facies overprinting of lower continental crust blocks as related to the Frido deformation history.

The North-Calabrian Unit includes the Crete Nere and Saraceno Fms. For the Crete Nere Fm., clay mineralogy allowed to glean temperatures below 200°C, while vitrinite reflectance and fluid inclusion data are poor. A pressure correction of about 1.5 Kbar, suggested by mineralogic and geologic (tectonic unit thickness) considerations, implies Tt of 120-130°C for fluid inclusions.

The Saraceno Fm. gave T = 130-150°C from vitrinite reflectance, a result confirmed by clay mineralogy and fluid inclusion data.

Because mineralogical data from the Crete Nere and Saraceno Fms. (i.e. “non metamorphosed” ophiolite-bearing units) show a good fit in the temperature estimates, despite their different composition, we can argue that these successions followed similar trajectories in the accrectionary prism and reached the late diagenesis zone, therefore slightly exceeding a temperature of 130°C.

Considering the entire data set, obtained from analyses performed with diverse methods, and the geometric relationships between different units, we can envisage a continental crust exhuming at temperatures of 280-300°C at about 65 Ma. This was presumably an early exhumation of continental crust within a pre-existing accretionary complex generated during the Alpine subduction. Starting from this event, the continental crust continues its deformation history together with the Frido Unit at progressively lower temperatures, reaching the final exhumation at about 6 Ma (AFT closure temperature). This fact is also coherent with the history of the Alburno-Cervati-Pollino Unit (i.e. Apennines Platform), of

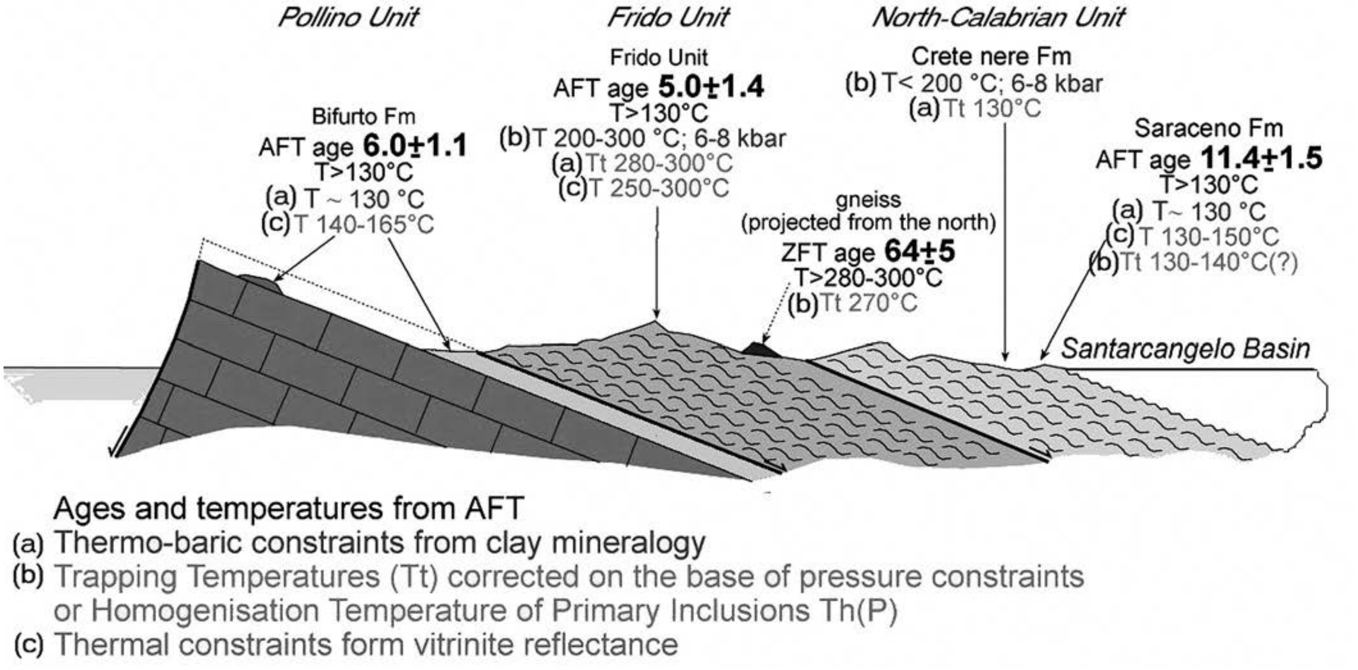


Fig. 6 - Schematic geological section showing the main results (see AA’ in Fig. 2).

which the examined Bifurto Fm. records the Miocene tectono-stratigraphic evolution, showing exhumation to the surface at the same time of the Frido Unit (about 6 Ma).

The final exhumation of the Apennines Platform Unit and the juxtaposed Frido Unit was most likely due to post-collisional extension which affected this portion of the chain. A similar mechanism was proposed also by Schiattarella et al. (2003; 2006), respectively for the Lucanian Apennine and the whole Southern Apennines, by Mazzoli et al. (2006) for the Mount Alpi area, and by Di Leo et al. (2005) for the Calabria-Lucania border area. Nevertheless, AFT data from the Saraceno Fm. indicate an exhumation event at about 11 Ma for this formation: this means that at least part of this complex was cooled below 110°C. There is no model able to explain exhumation related to that event. Thus, we suggest that such an event was probably related to fast and/or localised erosion, promoted by an embryonic mountain building phase. In addition, the severe eustatic fall that occurred on a regional scale at the end of the Serravallian - earliest Tortonian has to be taken into account. Afterwards, the Saraceno Fm. was overthrust by the same Liguride Units and then buried again without reaching anymore the total annealing of AFT.

CONCLUDING REMARKS

Our study allowed to better constrain the thermal history of the Liguride complex.

To summarise, two main groups of thermal data can be recognized from clay mineralogy, fluid inclusion microthermometry and organic matter maturity:

i) The late diagenetic zone, which includes samples from the Crete Nere and Saraceno Fms. and Alburno-Cervati-Pollino Unit;
ii) The anchizone, which which characterizes the Frido Unit.

From the thermo-chronological point of view, three fundamental events can be pointed out (Fig. 6):

i) At 64±5 Ma: syn-convergence exhumation of continental crust, now included as gneiss blocks within the tectonic mélange in the Frido Unit or, more frequently, occupying the apical position in the thrust stack of the Liguride complex. Zircon FT data also suggest that successive subduction/compression events never reached 250°-300°C;
ii) At about 11 Ma: a stage (deduced from apatite FT in the Saraceno Fm.) that can be interpreted as related to relevant erosive processes, bringing some units at very shallow levels before the final tectonic denudation due to extensional collapse;
iii) At about 5-6 Ma: the last and quick exhumation of the Liguride Units (detected from apatite FT data in the Frido Unit and Bifurto Fm.), mainly related to the extensional collapse of the Southern Apennines chain and to the consequent exhumation of the Apennine carbonate platform (i.e. Alburno-Cervati-Pollino Unit.)

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