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# THERMAL HISTORY OF THE CARNIC ALPS (NE ITALY-S. AUSTRIA) USING CAI ANALYSIS

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*Key words.* Carnic Alps, Conodont Color Alteration Index, Metamorphic zonation.

*Riassunto.* Al fine di vincolare alcuni aspetti dell'evoluzione metamorfica delle Alpi Carniche, un'area che ha subito una storia deformativa complessa attraverso più fasi, è stato condotto uno studio delle temperature massime raggiunte, attraverso l'Indice di Alterazione del Colore dei Conodonti (CAI).

Attraverso il metodo CAI è stato possibile riconoscere e distinguere gli eventi tettonotermici ercinico ed alpino. A seguito dell'evento ercinico si sono sviluppate temperature compatibili con condizioni fino al basso grado metamorfico. La tettonogenesi alpina, invece, non ha prodotto temperature oltre alla zona diagenetica. L'applicazione del metodo CAI ha inoltre permesso di riconoscere una sovraimpressione legata a fluidi idrotermali di età permo-triassica od oligocenica al di sopra della pre-esistente zonazione regionale.

*Abstract.* Thermal patterns of an area which underwent a polyphase deformation history such as the Carnic Alps were analyzed using the Color Alteration Index (CAI) of conodonts in order to constrain some aspects of the metamorphic history of this part of the Southern Alps.

Hercynian and alpine tectonothermal events were distinguished using CAI analysis. The Hercynian event developed temperatures up to low metamorphic conditions. Alpine tectonogenesis did not produce thermal levels in excess of the diagenetic zone. Moreover, CAI patterns allow recognition and evaluation of a hydrothermal metamorphic overprint of Permo-Triassic or Oligocene age that was superimposed on the pre-existing regional metamorphic zonation.

## Introduction

Conodonts are one of the most useful tools for Palaeozoic and Triassic stratigraphy, because of their wide environmental tolerance and their rapid evolution providing a high-resolution biostratigraphic framework. Because conodonts are composed of apatite, they can be easily extracted from carbonate rocks and remain identifiable in rocks that have undergone low and even medium grade metamorphism. Moreover, their use as an index to organic metamorphism is widely accepted (Epstein et al. 1977; Rejebian et al. 1987).

Organic matter is trapped within the laminated structure of conodont elements. This organic matter undergoes progressive alteration in response to increasing temperature producing changes in color from light yellow to dark yellow, golden brown, dark brown and finally black, due to carbonization. With increased heating, carbon is lost and recrystallization of phosphate occurs. Consequently, conodonts change from black to gray, white, and then translucent. These colour changes have been studied and recorded as Conodont Color Alteration Indices (CAI) by Epstein et al. (1977) and Rejebian et al. (1987). The experimental reproduction of conodont colour changes proves that CAI is temperature and time dependent (Epstein et al., 1977).

Several regional investigations (Epstein et al. 1977; Harris et al. 1978; Harris et al. 1980; Wardlaw & Harris 1984; Rejebian et al. 1987; Nowlan & Barnes 1986; Kovács & Árkai 1986; Königshof 1992; Belka 1993; Helsen & Königshof 1994; Bender & Königshof 1994; Helsen 1995; Árkai et al. 1995; Garcia-Lopez et al. 1997; Bastida et al. 1999) demonstrated the application of CAI as a reliable organic maturity index, helpful stable with correlation of different tools. It may also be used to constrain the geothermal and burial history of sedimentary basins.

In this paper, CAI data supplemented by geological mapping, are used to describe the metamorphic overprint in the Carnic Alps, an area that underwent a polyphase deformation history. Moreover, the consistency of the CAI data set was tested against previously published organic and inorganic metamorphic indices (Läufer 1996; Läufer et al. 1997; Rantitsch 1997).

## Geological setting

It must be stated first that the terms inner and outer here refer to the orogenic polarity, so that the

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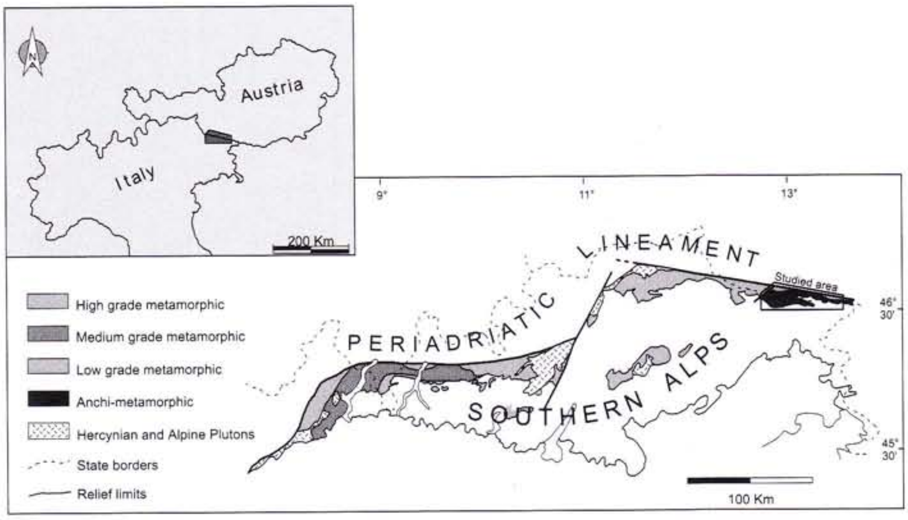


Fig. 1 - Metamorphic zonation of basement rocks in the Southern Alps (modified from Castellarin & Vai, 1981).

progradation of the deformation goes from the inner to the outer part of the belt.

The Hercynian cover units and the Hercynian basement of the Carnic Alps (CA; NE. Italy - S. Austria) represent the outermost part of the Hercynian belt within the Southern Alpine domain. They are located in the northernmost part of the Southern Alpine domain, where they are thrusted over the Alpine cover, and are separated from the Austroalpine units by the Gailtal line, a segment of the Periadriatic lineament (Figs. 1, 2).

The Palaeozoic stratigraphic sequence in the CA Hercynian cover is almost continuous and fossiliferous and ranges from Late Ordovician through middle Carboniferous (Selli, 1963; Vai, 1976; Spalletta et al., 1982; Schönlaub, 1985). From Caradocian through Lochkovian the basin morphology is ramp type, siliciclastics during the Caradoc and then mainly carbonatic. From the Pragian a carbonate buildup develops, assuming rimmed shelf characters with reefs and related environments during Pragian and between Eifelian and Frasnian. After the reefs drowning at the Frasnian-Famennian boundary, the basin morphology can be assimilated again to a ramp until the Visean. During the middle Carboniferous the so called Hercynian Flysch deposition depict the beginning of Hercynian tectogenesis.

The late Hercynian Permo-Carboniferous succession (late Palaeozoic cover units) was deposited in fault-controlled basins (Venturini, 1990). The Alpine cycle developed during the Mesozoic and Cenozoic.

Except for the Caradocian and Carboniferous successions, the Hercynian sequence is mainly conodont-bearing carbonate rocks.

Both Hercynian and Alpine orogenies affected this sequence, thus producing a rather complex struc-

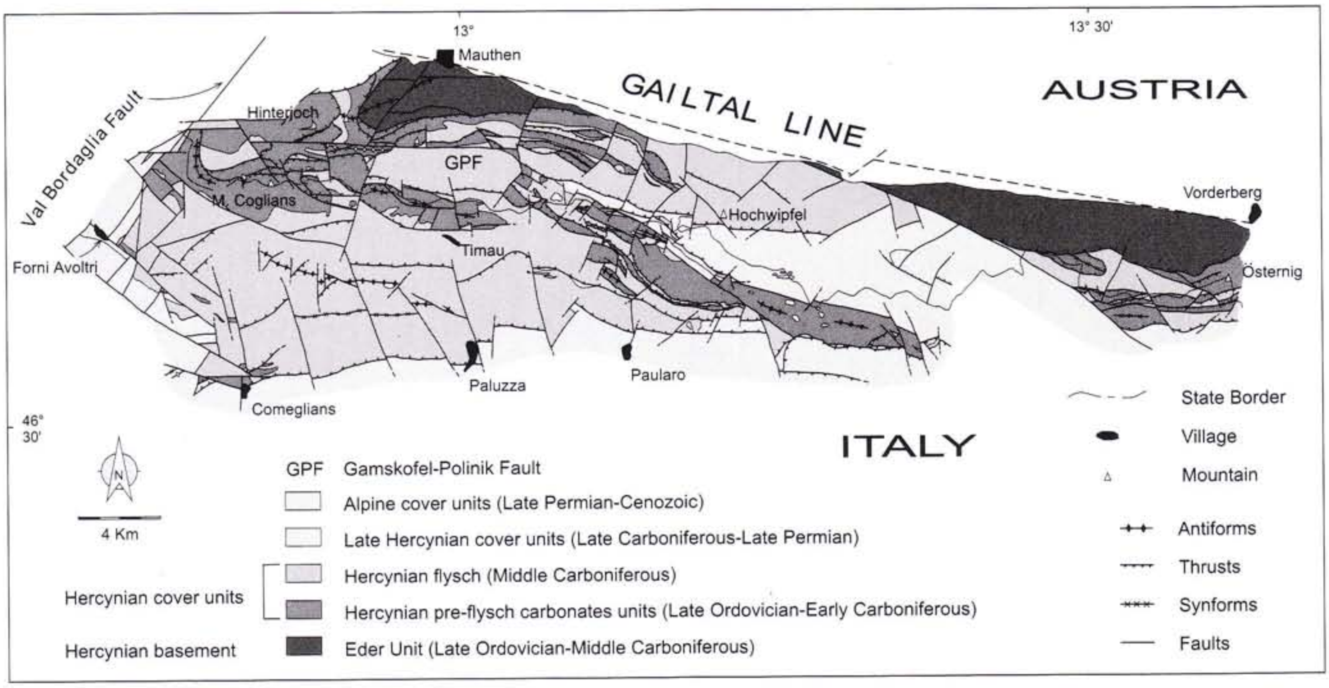


Fig. 2 - Schematic geological map of the studied area.

Tab. 1

| Sample | Location | Litostratigraphic unit | Age | CAI |
|---|---|---|---|---|
| CON 7 | Ovaro | Alpine cover units | Ladinian-Carnian | 3 |
| OVARO | Ovaro | Alpine cover units | Ladinian-Carnian | 2.5 - 3 |
| A (Nicora & Rizzi, 1998) | Aupa Valley | Alpine cover units | Ladinian-Carnian | 3 - 3.5 |
| ZON 00 | Monte Zoncolan | Alpine cover units | Scythian | 3.5 |
| ZON 000 | Monte Zoncolan | Alpine cover units | Scythian | 3.5 |
| VAL 1 | Monte Zoncolan | Alpine cover units | Scythian | 4 |
| CON 3 | Monte Zoncolan | Alpine cover units | Scythian | 3-3.5 |
| CON 4 | Monte Zoncolan | Alpine cover units | Scythian | 3.5 |
| MS | Rio Maestrin | Alpine cover units | Scythian | 4 |
| ARV | Monte Zoncolan | Alpine cover units | Scythian | 3.5 |
| MM 2 | Sutrio | Alpine cover units | Scythian | gray patina |
| SR 5 | Sutrio | Alpine cover units | Anisian | 3 |
| CRS B | Creta Rio Secco | Late Hercynian Sequence | Upper Carboniferous | 4 |
| CRS A | Creta Rio Secco | Late Hercynian Sequence | Upper Carboniferous | 3 |
| CRS | Creta Rio Secco | Late Hercynian Sequence | Upper Carboniferous | 3.5 - 4 |
| MCV A | Monte Cavallo | Pramosio limestones | Visean | 4 |
| MCV B | Monte Cavallo | Pramosio limestones | Visean | 3 |
| CRS C | Creta Rio Secco | Pramosio limestones | Visean | 4 |
| PRT | Monte Pricot | Pramosio limestones | Visean | 4 |
| MCV A II | Monte Cavallo | Pramosio limestones | Visean | 4 - 4.5 |
| Stop 46 | Rifugio Marinelli | Pramosio limestones | Visean | 4.5 |
| RCA | Rio Chianaletta | Pramosio limestones | Visean | 4.5 |
| RC | Rio Chianaletta | Pramosio limestones | Visean | 4.5 |
| CS A | Passo M. Croce | Pramosio limestones | Tournaisian-Visean | 4 - 4.5 |
| DL | Rifugio Marinelli | Pramosio limestones | Tournaisian-Visean | 4 - 4.5 |
| DL Est | Rifugio Marinelli | Pramosio limestones | Tournaisian-Visean | 4 - 4.5 |
| DL Ovest | Rifugio Marinelli | Pramosio limestones | Tournaisian-Visean | 4 - 4.5 |
| SCP | Cima Plotta | Pramosio limestones | Tournaisian-Visean | 4 - 4.5 |
| PS | Monte Coglians | Pramosio limestones | Tournaisian-Visean | 4 |
| FM | Forcella Monumenz | Pramosio limestones | Tournaisian-Visean | 4 |
| SSFM | Forcella Monumenz | Pramosio limestones | Tournaisian-Visean | 4 |
| SA | Sella di Aip | Pramosio limestones | Tournaisian-Visean | 4 |
| CC 201 | Cresta Verde | Pramosio limestones | Tournaisian | 4 |
| CC 155 | Forcella Monumentz | Pramosio limestones | Tournaisian | 4 - 4.5 |
| CT | Rio Uqua | Pramosio limestones | Tournaisian | 4.5 |
| PPLE | Cima Plotta | Pramosio limestones | Tournaisian | 4 - 4.5 |
| PL | Cima Plotta | Pramosio limestones | Tournaisian | 4 |
| PLP | Cima Plotta | Pramosio limestones | Tournaisian | 4.5 |
| SP | Monte Coglians | Pramosio limestones | Tournaisian | 4 |
| TOR | Cima Plotta | Pramosio limestones | Tournaisian | 4 |
| SP B | Monte Coglians | Pramosio limestones | Tournaisian | 4 |
| Passo Beta | Cima Plotta | Pramosio limestones | Tournaisian | 4 - 4.5 |
| PZ C | Monte Zermula | Pramosio limestones | Tournaisian | 4.5 |
| KR 9 | Romanstraße | Bänderkalk | Tournaisian | 5 - 5.5 |
| CCS | Cresta Verde | Pramosio limestones | Famennian-Tournaisian | 4 |
| TR | Pal Grande | Pramosio limestones | Famennian-Tournaisian | 4 - 4.5 |
| TR A | Pal Grande | Pramosio limestones | Famennian-Tournaisian | 4 - 4.5 |
| CC 72 | Cava di marmo | Pramosio limestones | Famennian | 4 - 4.5 |
| CC 45 | Casera Pal Grande di Sotto | Pramosio limestones | Famennian | 4 - 4.5 |
| CC 41 | Casera Pal Grande di Sotto | Pramosio limestones | Famennian | 4 - 4.5 |
| CC 70 | Casera Pal Piccolo | Pramosio limestones | Famennian | 4 - 4.5 |
| CC 204 | La Scaletta | Pramosio limestones | Famennian | 4 - 4.5 |
| CC 203 | La Scaletta | Pramosio limestones | Famennian | 4 - 4.5 |
| CC 221 | Casera Pal Piccolo | Pramosio limestones | Famennian | 4 |
| CC 96 | Casera Pal Piccolo | Pramosio limestones | Famennian | 4 - 4.5 |
| CC 200 | Casera Collinetta di Sopra | Pramosio limestones | Famennian | 4 - 4.5 |
| CC 202 | Cresta Verde | Pramosio limestones | Famennian | 4 |
| CC 150 | Pal Piccolo | Pramosio limestones | Famennian | 4 |
| CC 80 | Passo M. Croce Carnian | Pramosio limestones | Famennian | 4 - 4.5 |
| CC 69 | Casera Pal Piccolo | Pramosio limestones | Famennian | 4.5 |
| CC 222 | Casera Pal Piccolo | Pramosio limestones | Famennian | 4 - 4.5 |
| CC 29 | Pal Piccolo | Pramosio limestones | Famennian | 4 |
| KR 14 | Pal Piccolo N | Pramosio limestones | Famennian | 4 - 4.5 |
| KR 10 | Hydrosolar | Pramosio limestones | Famennian | 4.5 |
| KR 42/1 | Obere Bischof Alm | Pramosio limestones | Famennian | 4.5 |
| KR 18 | Obere Bischof Alm | Pramosio limestones | Famennian | 4.5 |
| KR 43 | Plöckenhäus | Pramosio limestones | Famennian | 4.5 |
| KR 162 | Cuestalta | Pramosio limestones | Famennian | 4.5 |
| PZ 2 | Plan di Zermula | Pramosio limestones | Famennian | 4.5 |
| CVG | Cava Val Grande | Pramosio limestones | Famennian | 4 |
| CCLE | Pizzo Collina | Pramosio limestones | Famennian | 4 - 4.5 |
| WG | Volaia | Pramosio limestones | Famennian | 4.5 |
| LD | Monte Lodin | Pramosio limestones | Famennian | 4 - 4.5 |
| RB | Pramosio | Pramosio limestones | Famennian | 4.5 |

| | | | | |
|---|---|---|---|---|
| PT A | Pizzo di Timau | Pramosio limestones | Famennian | 4.5 |
| LAGO C | Pramosio alta | Pramosio limestones | Famennian | 4.5 |
| LAGO B | Pramosio alta | Pramosio limestones | Famennian | 4.5 |
| LAGO A | Pramosio alta | Pramosio limestones | Famennian | 4.5 |
| PT B | Pizzo di Timau | Pramosio limestones | Famennian | 4 - 4.5 |
| PR 224 | Pramosio | Pramosio limestones | Famennian | 4 - 4.5 |
| M B | Pramosio | Pramosio limestones | Famennian | 4 - 4.5 |
| M A | Pramosio | Pramosio limestones | Famennian | 4 - 4.5 |
| P B | Pramosio | Pramosio limestones | Famennian | 4 - 4.5 |
| PR B | Pramosio | Pramosio limestones | Famennian | 4 |
| M C | Pramosio | Pramosio limestones | Famennian | 4 - 4.5 |
| EL | Pramosio alta | Pramosio limestones | Famennian | 4 - 4.5 |
| PG | Pal Grande | Pramosio limestones | Famennian | 4 - 4.5 |
| OLE | Fontanone | Pramosio limestones | Famennian | 4.5 |
| CAV B | Passo Cavallo | Pramosio limestones | Famennian | 4 - 4.5 |
| RG A | Pal Grande | Pramosio limestones | Famennian | 4 - 4.5 |
| Pizzul | Pizzul | Pramosio limestones | Famennian | 4.5 |
| CLC 1 | Arnoldstein | Pramosio limestones | Famennian | 5.5 - 6 |
| LD B | Monte Lodin | Pramosio limestones | Famennian | 4.5 |
| CVP 1 | Cima Val di Puartis | Pramosio limestones | Famennian | 4.5 |
| KR 105 | Valentin Törl | Pramosio limestones | Famennian | 4.5 |
| PZ A | Plan di Zermula | Pramosio limestones | Famennian | 4.5 |
| Blocchi C.C. | Cava Cantoniera | Pramosio limestones | Famennian | 4 |
| LC | Las Callas | Pramosio limestones | Famennian | 4 - 4.5 |
| ML | Pramosio | Pramosio limestones | Famennian | 4 - 4.5 |
| Cava Cant. | Cava Cantoniera | Pramosio limestones | Famennian | 4 |
| CS B | Passo M. Croce | Pramosio limestones | Famennian | 4 - 4.5 |
| PMC | Passo M. Croce | Pramosio limestones | Famennian | 4 - 4.5 |
| CM | Cava Monumenz | Pramosio limestones | Famennian | 4.5 |
| SCM | Cava Monumenz | Pramosio limestones | Famennian | 4.5 |
| CSC | Passo M. Croce | Pramosio limestones | Famennian | 4 - 4.5 |
| SS D | Cresta Verde | Pramosio limestones | Famennian | 4 - 4.5 |
| SCV | Cresta Verde | Pramosio limestones | Famennian | 4 - 4.5 |
| SS A | Cresta Verde | Pramosio limestones | Famennian | 4 - 4.5 |
| SS B | Cresta Verde | Pramosio limestones | Famennian | 4 |
| SS C | Cresta Verde | Pramosio limestones | Famennian | 4 |
| VG | Val Grande | Pramosio limestones | Famennian | 3.5 - 4 |
| S 146 A | Passo M. Croce | Pramosio limestones | Famennian | 4 |
| S 146 B | Passo M. Croce | Pramosio limestones | Famennian | 4 |
| S 148 | Passo M. Croce | Pramosio limestones | Famennian | 4 - 4.5 |
| CHR | Chiarsò | Pramosio limestones | Famennian | 4 - 4.5 |
| CRC | Cercevesa | Pramosio limestones | Famennian | 4 - 4.5 |
| KR 120 | Hinterjock | Pramosio limestones | Famennian | 6, 6.5 |
| PZ B | Monte Zermula | Pramosio limestones | Famennian | 4.5 |
| KR 148 | Weidegger Hohe | Pramosio limestones | Famennian | 4.5 |
| KR 115 | Hinterjock | Pramosio limestones | Famennian | 6, 6.5 |
| PCZ | Porto di Cozzi | Pramosio limestones | Frasnian - Famennian | 4 - 4.5 |
| ÖS | Monte Östernig | Pramosio limestones | Frasnian - Famennian | 5.5 |
| PCL | Pizzo Collina | Pramosio limestones | Frasnian - Famennian | 4 - 4.5 |
| FL | Monte Zermula | Pramosio limestones | Givetian - Famennian | 4 - 4.5 |
| CC 35 | Pal Piccolo | Pramosio limestones | Frasnian | 4 - 4.5 |
| CC 212 | La Scaletta | Pramosio limestones | Frasnian | 4.5 |
| CC 151 | Pal Piccolo | Pramosio limestones | Frasnian | 4 - 4.5 |
| CC 152 | Pal Piccolo | Pramosio limestones | Frasnian | 4 - 4.5 |
| CC 36 | Pal Piccolo | Pramosio limestones | Frasnian | 4 |
| PT C | Pizzo di Timau | Pramosio limestones | Frasnian | 4 - 4.5 |
| PR A | Pramosio | Pramosio limestones | Frasnian | 4.5 |
| PR C | Pramosio | Pramosio limestones | Frasnian | 4 - 4.5 |
| CVC | Cava Val Collina | Pramosio limestones | Frasnian | 4 - 4.5 |
| FN B | Fontanone | Pal Grande calcarenites | Frasnian | 4.5 |
| CK 44 | Poludnig | Pramosio limestones | Frasnian | 6, 6.5 |
| CK 23 | Obere Frondell Alm | Pramosio limestones | Frasnian | 4.5 |
| Pramosio 327 | Pramosio | Freikofel rudstones | Givetian-Frasnian | 4.5 |
| KR 15/4 | Plöckenhäus | Pal Grande calcarenites | Givetian-Frasnian | 4.5 |
| KR 117 | Hinterjock | Pramosio limestones | Givetian | 7, 7.5 |
| PT D | Pizzo di Timau | Pramosio limestones | Givetian | 4.5 |
| KR 42/4 | Obere Bischof Alm | Pal Grande calcarenites | Givetian | 4.5 |
| CC 32 | Pal Piccolo | Pal Grande calcarenites | Givetian | 4 - 4.5 |
| P | Pramosio | Pal Grande calcarenites | Givetian | 4.5 |
| FN C | Fontanone | Pal Grande calcarenites | Givetian | 4.5 - 5 |
| FN D | Fontanone | Pal Grande calcarenites | Givetian | 4.5 |
| FN A | Fontanone | Pal Grande calcarenites | Givetian | 4.5 |
| CU A | Monte Culet | Pal Grande calcarenites | Givetian | 4.5 |
| KR 95 | Nölblinger Höhe | Pal Grande calcarenites | Givetian | 4.5 |
| CC 66 | Val Collina | Coglians massive limestones | Givetian | 4.5 |
| KR 72 | Lamprecht | Bänderkalk | Givetian | 5.5, 6.5 |

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|---|---|---|---|---|
| KR 36/A | Mauthner Klamm | Bänderkalk | Givetian | 5.5 - 6 |
| FLW | Monte Zermula | Pramosio limestones | Eifelian | 4 - 4.5 |
| CC 50 | Casera Pal Grande di Sotto | Pal Grande calcarenites | Eifelian | 4 - 4.5 |
| CC 60 | Freikofel | Pal Grande calcarenites | Eifelian | 4 - 4.5 |
| PGS | Pal Grande di Sotto | Pal Grande calcarenites | Eifelian | 4 - 4.5 |
| PGS A | Pal Grande di Sotto | Pal Grande calcarenites | Eifelian | 4 - 4.5 |
| CAV A | Passo Cavallo | Pal Grande calcarenites | Eifelian | 4 - 4.5 |
| FRK A | Freikofel | Pal Grande calcarenites | Eifelian | 4 - 4.5 |
| RN | Creta di Collinetta | Pal Grande calcarenites | Eifelian | 4.5 - 5 |
| LMB | Lambertenghi | Cuestalta limestones | Eifelian | 4.5 - 5 |
| KR 55 | Würmlach | Bänderkalk | Eifelian | 5 - 5.5 |
| CK 65 | Sella di Lom | Cuestalta limestones | Eifelian | 5.5 |
| CK 42 | Poludnig | Cuestalta limestones | Eifelian | 5.5 |
| CC 34 | Pal Piccolo | Pal Grande calcarenites | Middle Devonian | 4 - 4.5 |
| CC 105 | Monte Coglians | Coglians massive limestones | Middle Devonian | 4.5 |
| CC 55 | Freikofel S | Rauchkofel limestones | Lower-Middle Devonian | 4.5 |
| CU B | Monte Culet | Pal Grande calcarenites | Emsian | 4.5 |
| CPR | Cava Pramosio | Pal Grande calcarenites | Emsian | 4.5 |
| KR 172 | Lago Volaia | Cuestalta limestones | Emsian | 6, 6.5 |
| KR 147 bis | Weidegger Hohe | Cuestalta limestones | Emsian | 4.5 |
| KR 15/3 | Plöckenhäus | Cuestalta limestones | Emsian | 4.5 + 5.5, 6 |
| KR 89 | Würmacher Alpe | Cuestalta limestones | Emsian | 5.5 |
| KR 228 | Pöludnig | Cuestalta limestones | Emsian | 5 |
| STR | Stua Ramaz | Cuestalta limestones | Emsian | 5 |
| CK 32 | Poludnig | Pal Grande calcarenites | Emsian | 5 -5.5 |
| KR 114 | Hinterjock | Cuestalta limestones | Emsian? | 6, 6.5 |
| KR 52 | Romanstraße | Bänderkalk | Emsian? | 5 -5.5 |
| FRK | Freikofel | Pal Grande calcarenites | Pragian | 4.5 |
| KR 87 | Zollner Höhe | Cuestalta limestones | Lochkovian | 5.5 |
| KR 92 | Nölbling | Rauchkofel limestones | Lochkovian | 4.5 |
| KR 25 | Garnitzer Klamm | Nölbling Fm. | Lochkovian | 5 - 5.5 |
| KR 199 | Egger Alm | Rauchkofel limestones | Lochkovian | 5.5 |
| KR 149 | Mauthner Klamm | Bänderkalk | Lochkovian | 5.5 |
| CK 132 | Volaia | Cuestalta limestones | Lochkovian | 5 -5.5 |
| CK 72 | Poludnig | Pal Grande calcarenites | Lochkovian | 5.5 |
| RS | Rio Sglirs | Cuestalta limestones | Lochkovian | 4.5 |
| 142 b | Cresta Verde | Cuestalta limestones | Lochkovian | 4.5 |
| KR 112 | Nölblinger Hohe | Cuestalta limestones | Lochkovian | 6, 6.5 |
| KR 147 | Weidegger Hohe | Cuestalta limestones | Lochkovian | 4.5 - 5 |
| CONF | Freikofel | Rauchkofel limestones | Lochkovian | 4.5 |
| CK 115 | Volaia | Rauchkofel limestones | Lochkovian | 4.5 |
| KR 155 | Obere Valentin Alm | Coglians massive limestones | Lochkovian | 5.5 |
| RM | Rio Malinfier | Cuestalta limestones | Lower Devonian | 5 |
| KR 86 | Dellacher Alm | Cuestalta limestones | Lower Devonian | 5.5 - 6 |
| CC 61 | Freikofel W | Rauchkofel limestones | Devonian | 4.5 |
| KR 62 | Plöckenstrasse | Cuestalta limestones | U. Silurian-L. Devonian | 6.5 |
| KR 173 | Comeglians | Cuestalta limestones | U. Silurian-L. Devonian | 4.5 |
| KR 108 | Maderkopf | Coglians massive limestones | U. Silurian-L. Devonian | 6 |
| KR 91 | Nölbling | Rauchkofel limestones | U. Silurian-L. Devonian | 5 |
| KR 63 A | Tillacher | Rauchkofel limestones | U. Silurian-L. Devonian | 5 |
| CC 46 | Rio Grande | Rauchkofel limestones | U. Silurian-L. Devonian | 4.5 |
| KR 63/B | Tillacher | Rauchkofel limestones | U. Silurian-L. Devonian | 5 |
| KR 26 | Garnitzer Klamm | Bänderkalk | U. Silurian-L. Devonian | 5.5 |
| KR 84 | Gratzhof | Coglians massive limestones | U. Silurian-L. Devonian | 5.5 |
| KR 22 | Tillacher | Cuestalta limestones | U. Silurian-L. Devonian | 5.5 |
| KR 90 | Polinik | Orthoceras limestones | U. Silurian-L. Devonian | 5.5 |
| KR 109 | Maderkopf | Coglians massive limestones | Pridolian-Lower Devonian | 5 |
| CC 220 | Freikofel W | Rauchkofel limestones | Pridolian-Lochkovian | 4.5 -5 |
| MC II (Corradini, in prep.) | Mount Cocco | Orthoceras limestones | Llandovery - Lochkovian | 4 |
| KR 101 | Rauchofel | Orthoceras limestones | Upper Silurian | 5, 6.5 |
| KR 111 | Gunderscheimer Alm | Nölbling Fm. | Ludlovian-Pridolian | 5.5 |
| KR 96 | Nölblinger Höhe | Uqua Fm. | Ashgillian | 4.5 |
| FV | Rio Uqua | Uqua Fm. | Ashgillian | 4.5 - 5 |

Tab. 1 - Geographic, stratigraphic, age, and CAI data for samples studied.

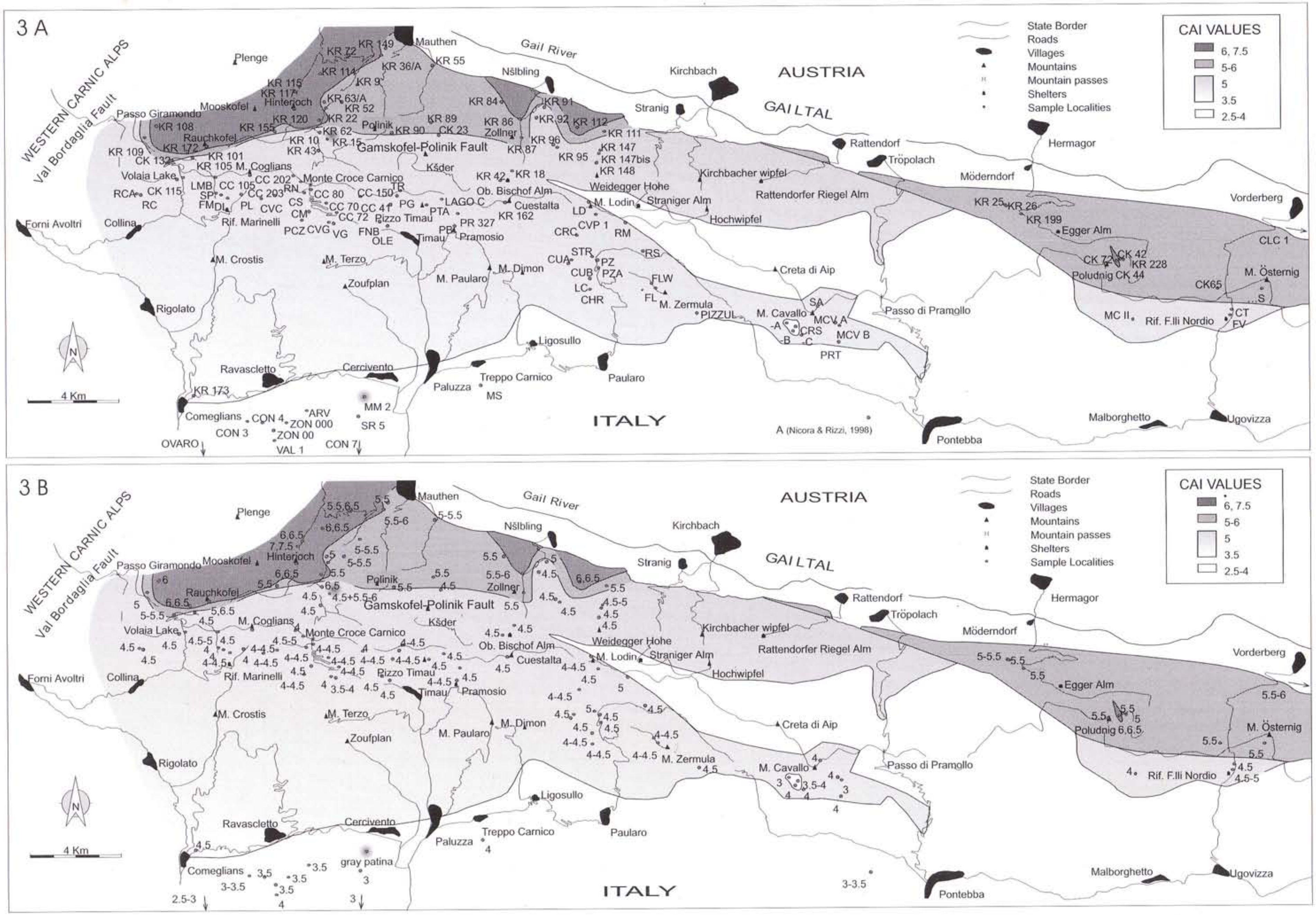



Fig. 3 - CAI isograds for the eastern Carnic Alps. 3A - Location of the samples. CC, KR and CK labels were collected by the author. The other sample localities were gently provided by the collections of M.C. Perri and C. Spalletta, exept for A (Nicora & Rizzi, 1998) and MC II (Corradini, in prep.). All the samples were used to compile the map, but a part of them is not shown in this map because they are geographically too close at this scale. 3B - CAI values for the samples shown in 3A. A determination of 4-4.5 indicates the CAI value is *between* 4 and 4.5; a determination of 6, 7 indicates *both* CAI 6 and 7 values are present, that is, the sample is not homogeneous. The very gradual transition from CAI values 3.5 to 5 is indicated by the gradational pattern. The halo of dots near samples MM2 and KR 15 corresponds to the area of conodont whitening.

tural framework, characterized by a thin-skinned fold-and-thrust belt with reactivation of some structures and disruption of others (Venturini, 1990; Bressan et al., 1998; Pondrelli, 1998; Fig. 2). Huge *Schlingen Tektonik* features occur in the northwestern portion of the studied area, due to the right and left strike-slip Gailtal and Val Bordaglia lineaments, respectively (Läufer, 1996; Läufer *et al.*, 1997; Pondrelli, 1998; Fig. 2).

The classic interpretation of the metamorphic zonation of the Southern Alps basement shows decreasing Hercynian metamorphism west to east (Boriani et al., 1976; Castellarin & Vai, 1981; Fig. 1). The CA represents the anchi-metamorphic succession of this domain. However, a low-grade metamorphic unit (Eder unit) occurs near the Periadriatic Lineament (Fig. 2).

The metamorphic evolution of the CA has been studied using both organic, (such as vitrinite reflectance: Rantitsch, 1997) and inorganic (such as fluid inclusions: Rantitsch, 1997; and illite crystallinity: Läufer, 1996; Läufer et al., 1997; Rantitsch, 1997) indices, but little CAI data was available. Illite crystallinity and vitrinite reflectance data allow a tectonothermal event to be distinguished.

Läufer (1996) and Läufer et al. (1997), using K-Ar and Ar-Ar analysis, interpreted the Eder unit as a fault-bounded block metamorphosed during Oligocene large-scale dextral shearing along the Gailtal Line. Rantitsch (1997) related the fluid inclusions to plutonic activity along the Periadriatic Lineament, probably during the Oligocene.

#### Materials and methods

More than 200 sample localities were studied, chiefly in the Hercynian sedimentary cover and basement but some localities were also sampled in the Alpine cover units for comparison (Tab. 1; Fig. 3). Because CAI values are affected by host-rock composition (Mayr *et al.*, 1978; Nowlan & Barnes, 1987; Benlloch & De Santisteban, 1993; Belka, 1993), only limestones were sampled in order to avoid complications.

The samples were processed using standard techniques for extracting conodonts; only dilute acetic acid was used. CAI determinations were made by comparison with a set of CAI standards assembled from the collections of the U.S. Geological Survey (Reston, Virginia) under the supervision of Dr. A.G. Harris. Several CAI determinations were made for each sample. All CAI values were used to produce an isograd map (Tab. 1; Fig. 3).

#### CAI patterns

Considering Hercynian cover units and basement, Late Palaeozoic and Mesozoic cover units, the youngest is the age of the determined rock, the lowest are the CAI values (Tab. 1; Fig. 3). On the contrary, inside the Hercynian cover units and basement, there is no notable difference between CAI values in samples of different age within the same section.

Only a few samples were collected from the Alpine and especially late Hercynian cover units, so that the isograds were drawn only tentatively following stratigraphic-structural boundaries (Tab. 1; Fig. 3).

Conodont samples from the Triassic, mainly Scythian, Alpine cover units which crop out close to the Hercynian basement, have CAI values from 2.5 to 4 (Tab. 1; Fig. 3). Higher values (MM2) are associated with a whitening effect. This feature, also called gray patina, was related to a rapid loss of near-surface organic matter during hydrothermal activity (Rejebian et al., 1987).

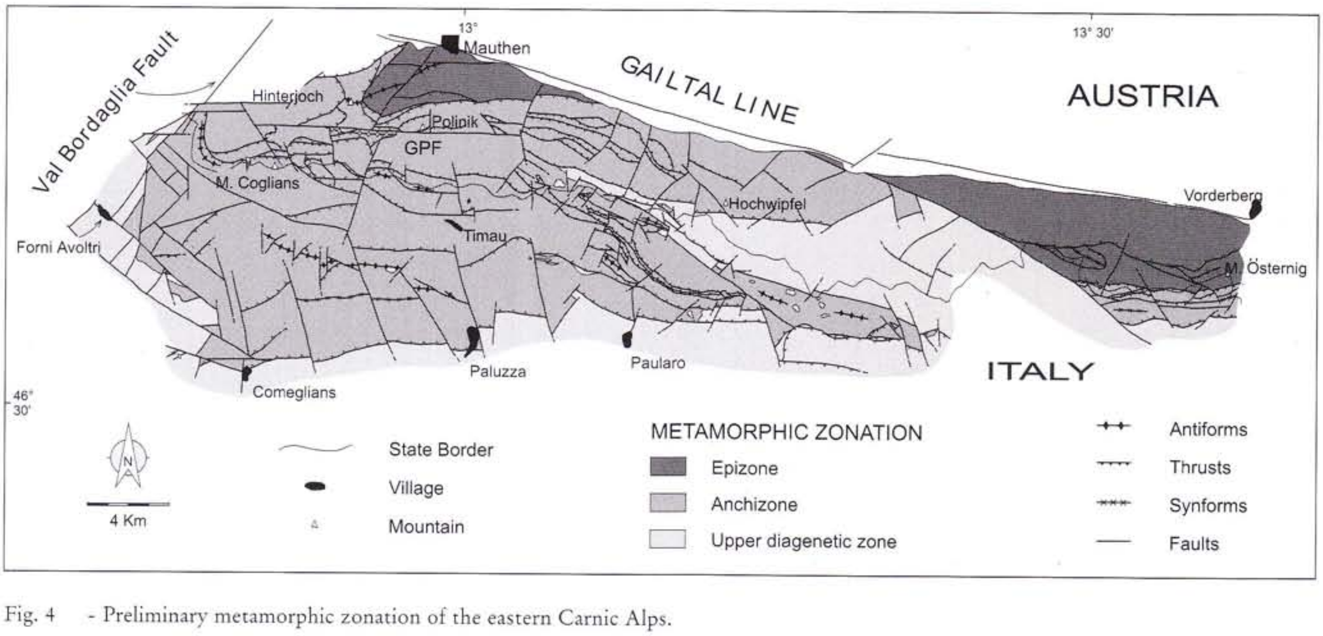



Fig. 4 - Preliminary metamorphic zonation of the eastern Carnic Alps.

Only three samples from the Late Hercynian cover units (late Carboniferous) produced conodonts; these have CAI values of 3 to 4.

The Hercynian cover and basement units (Eder unit) were closely sampled except for the zones between the villages of Ravascletto and Timau and around Rattendorfer Riegel Alm where only siliciclastic rocks of the so called Hercynian Flysch occur. In these areas, CAI trends are necessarily inferred.

In the outermost part of this belt, many productive sample localities allow refinement of CAI trends within the range of 3.5 to 5, with a gradual increase in values toward the innermost part of the chain (Tab. 1; Fig. 3).

Conodonts from sample KR15, north of Monte Croce Carnico Pass, have a gray overprint.

Northward, toward the innermost parts of the chain, CAI values increase up to 6. The increase is mainly gradual, such as between Mount Östernig and F.lli Nordio shelter, north of the village of Nölbling and around Volaia Lake (Tab. 1; Fig. 3). A slightly more abrupt change, observed north of Mount Köder, is related to the dextral strike-slip Gamskofel-Polinik fault (Tab. 1; Figs. 2, 3).

Higher CAI values, up to 7.5, were found in a narrow outcrop north of Mount Poludnig and in larger areas close to the village of Nölbling and between Volaia Lake and the village of Mauthen (Tab. 1; Fig. 3). The change to these high CAI values is mainly abrupt (for example, in the Mount Poludnig zone or between Volaia Lake and Mount Hinterjoch, Fig. 3). In several of these samples a broad range of CAI values occurs.

## Discussion

In agreement with the data on organic and mineral metamorphism presented by Läufer (1996), Läufer et al (1997) and Rantitsch (1997) for this area, the increase in organic metamorphism from the outer to the inner parts of the CA is well documented by CAI patterns. Thermal levels are consequently related to tectonic burial and not to pre-thrust burial metamorphism.

Based on the Arrhenius plot of Epstein et al. (1977) and Rejebian et al. (1987) and apart from the effects probably linked to hydrothermal activity (MM2 and possibly MS), late Hercynian and Mesozoic cover units display CAI values that indicate temperatures ranging roughly from at least 80°C to at least 250°C.

In the outermost Hercynian belt, CAI values range from 3.5 to 5 indicating temperatures reached at least 140°C to 300°C. The increase in CAI values from 3.5 to 5 toward the innermost part of the chain is extremely gradual. Such a gradual trend of increasing CAI values from upper Hercynian tectonic units toward lower units is linked to a regional metamorphic event. This is also supported by the uniformity of CAI values within relatively large areas. Increase in CAI values are correlated with an increase in corrosion and recrystallization of conodont surfaces (Königshof 1992; Garcia-Lopez et al. 1997; Pl. 1).

Whether the regional metamorphic event recorded in the Hercynian basement is of Hercynian or Alpine age can be assessed only tentatively by means of CAI analysis. Nevertheless, some points can be made.

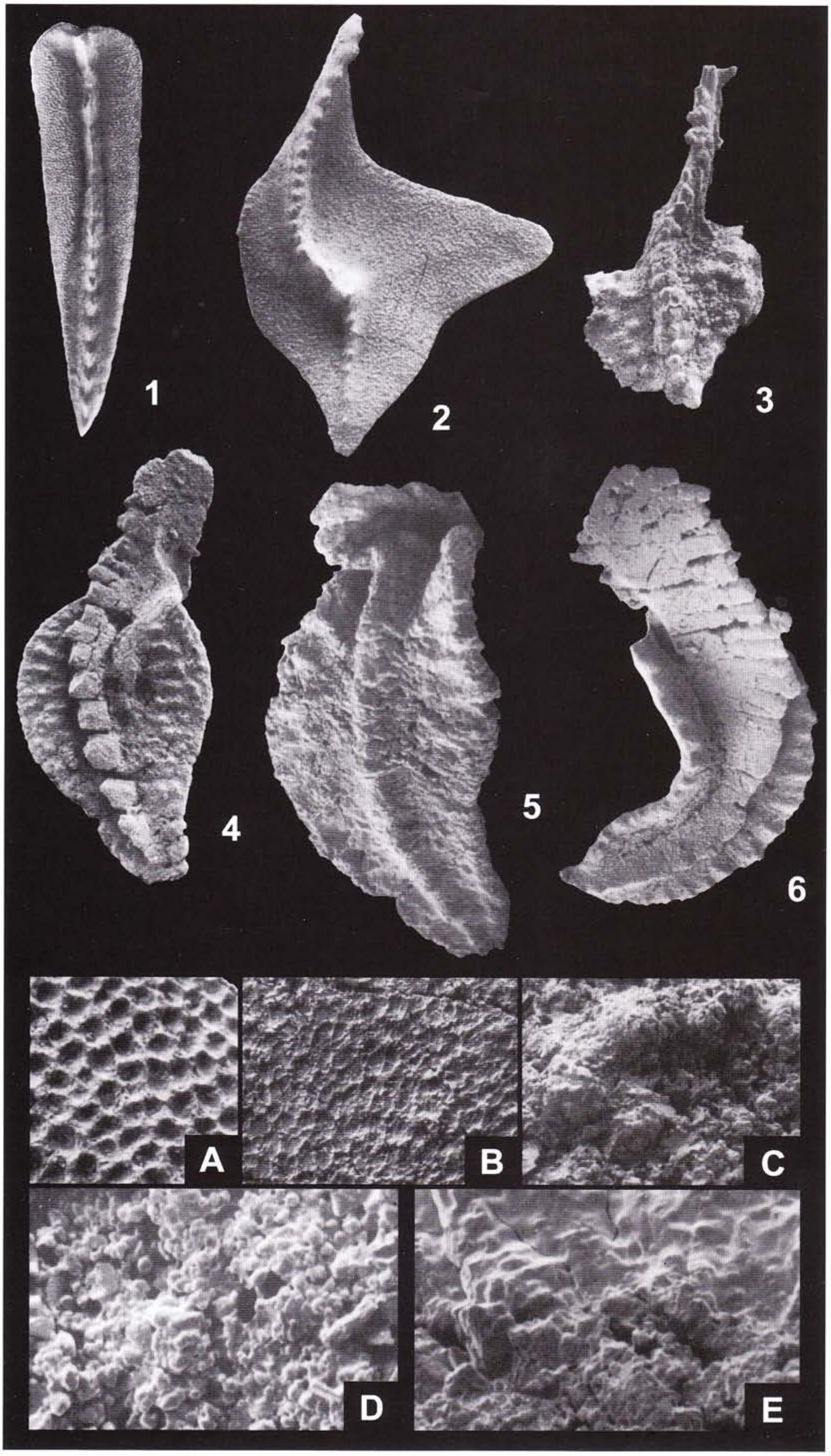
Surprisingly, there is no abrupt change in CAI values at the boundary between Hercynian basement units and Alpine cover units. Moreover, these data agree well with illite crystallinity (Läufer 1996; Läufer et al. 1997; Rantitsch 1997) and organic matter reflectance patterns (Rantitsch 1997), suggesting that Hercynian and Alpine events developed similar metamorphic temperatures. The Hercynian event seems to have developed slightly higher temperatures, but it should be taken into account that Hercynian units occupy the deepest tectonic position. Because CAI trends seem to follow Hercynian structural axes, a Hercynian age for this regional event seems likely.

The clear increase from younger to older recorded in the post-Hercynian events (Late Hercynian and Alpine cover units of Fig. 2) may suggest a simple thrust history instead depositional burial after the Hercynian orogenetic events.

CAI values increase northward from 5 to 6, indicating temperatures ranging roughly from at least 270°C through 400°C. In an area roughly corresponding to the Eder unit, the transition to this interval seems to follow the regional metamorphic trend. This is confirmed by the gradual transition into the Eder unit in addition to

PLATE 1

Comparison of conodont texture and CAI values. 1. *Paragondolella bifurcata* Budurov & Stefanov, sample SR5; x 75 (magnification in A: x 750). CAI = 3, original polygonal micromorphology with incipient corrosion and recrystallization: diagenetic zone. 2. *Palmatolepis subperlobata* Branson & Mehl, sample KR105 ; x 75 (magnification in B: x 350). CAI = 4.5, faintly tectonically deformed, polygonal pattern still delineated, increasing corrosion and recrystallization: anchizone. 3. *Protognathodus praedelicatus* Lane, Sandberg & Ziegler, sample KR9; x 75 (magnification in C: x 350). CAI = 5-5.5, corroded and pitted surface, partially effect of dissolution in acetic acid: epizone. 4. *Polygnathus* sp., sample KR36/A; x 100 (magnification in D: x 2000). CAI = 5.5-6, corroded and pitted surface, recrystallized: epizone. 5. *Polygnathus aequalis* Klapper & Lane, sample KR115; x 150 (magnification in E: x 750). CAI = 6.5, plastic deformation, recrystallization and corrosion, in the upper part the newly generated crystals are partially hidden by the glue utilized to prepare the picture: hydrothermally altered. 6. *Polygnathus xylus* Stauffer, sample KR117; x 100. CAI = 7, plastic deformation: hydrothermally altered.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the uniformity of CAI values within samples and relatively large areas.

On the other hand, close to Mount Poludnig, north of the village of Nölbling and between Volaia Lake and the village of Mauthen, CAI values increase up to 7.5, showing large variability within small areas and inhomogeneity even within single samples. According to Rejebian et al. (1987), these data likely indicate a hydrothermal metamorphic overprint. The whitening effect (gray patina) recorded in samples KR15 and MM2, located north of Monte Croce Carnico Pass and south of the village of Cercivento, respectively, agree with this interpretation as does the plastic deformation of the conodonts.

More data are needed to determine the age of the hydrothermal event. Regional geologic data indicate that hydrothermal fluids were active during Hercynian (Frasnian-Famennian), late Hercynian (Permian) and Alpine (Oligocene) movements. Only minor effect should be related to Hercynian hydrothermal activity, because no synsedimentary faults or dramatic facies changes were found in the northwestern sector of the studied area, where the maximum extent of hydrothermal activity has been found. On the contrary, this area is bounded by the Val Bordaglia and the Gailtal, which were active both during the Permian (Venturini, 1990; Cassinis et al., 1997) and Oligocene (Sassi & Zanferrari, 1973; Laubscher, 1983; Läufer, 1996; Läufer et al., 1997). Both Oligocene (Sassi & Zanferrari, 1973; Laubscher, 1983) and Permo-Triassic (Schuster et al., 1999; Läufer, pers. comm.) extension are well documented along the Periadriatic Lineament, so the hydrothermal activity could have affected the Carnic Alps during both phases.

The Eder unit seems to represent the innermost part of a regional, probably Hercynian, metamorphic episode in the CA. A younger hydrothermal metamorphic overprint, probably of Oligocene age, affected at least part of this unit. This overprint could explain the K-Ar and Ar-Ar ages found by Läufer (1996) and Läufer et al. (1997).

conditions. However, temperatures associated the Hercynian tectonothermal event seem to be slightly higher. The Alpine regional metamorphic event reached maximum temperatures of about 250°C, whereas the Hercynian event developed temperatures from at least 140°C to 300°C-350°C in the outer part of the chain and up to at least 400°C in an area roughly corresponding to the innermost (Eder unit). Following these determinations a preliminary map showing metamorphic zonation was constructed (Fig. 4).

In the northernmost part of the CA, close to the Val Bordaglia and Gailtal Lines, CAI values range from 6 to 7.5. According to Rejebian et al. (1987), variation in CAI values both within a sample and a small area may well be related to contact and (or) hydrothermal metamorphism. The local occurrence of conodonts with a gray or white overprint suggests circulation of hydrothermal fluids. The hydrothermal metamorphism could probably be related to Permo-Triassic or Oligocene intrusions along the Periadriatic Lineament (Laubscher 1983; Schuster et al. 1999). These effects are superimposed on pre-existing regional metamorphic patterns of probable Hercynian age. The hydrothermal metamorphism can probably explain the radiometric data (Läufer 1996) which assess an Alpine age for the metamorphism of the Eder Unit.

The CAI data presented here are consistent with published data from other organic and inorganic metamorphic indices, and the CAI analysis could give furthermore constrains in a multi-methods approach in the complex areas.

## Conclusion

This regional CAI study supplemented by geological mapping provides some constraints on the metamorphic history of the CA.

A gradual increase in CAI values from upper to lower tectonic units has been recognized and attributed to a regional tectonothermal event.

CAI data can not provide direct information about the age of this regional metamorphism, but some observations can, nevertheless, be made. There is no sharp boundary between CAI values in pre- and post-Hercynian units. Hercynian and Alpine regional events appear to have developed under similar temperature

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