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Conodont colour alteration indices (CAI) of Upper Ordovician limestones from the Iberian Peninsula

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Abstract

Conodont colour alteration index (CAI) data in Upper Ordovician rocks from several areas of the Variscan domain in the Iberian Peninsula indicate conditions ranging from diagenesis to low-grade metamorphism. In most of the areas, where studies using other indicators, such as illite crystallinity (IC) or vitrinite reflectance are lacking, the CAI method has permitted a preliminary estimation of the metamorphic grade. In the Almadén syncline (Central-Iberian Zone), where IC studies are available, the thermal conditions inferred from CAI data agree with those obtained by the IC method. In the Puertollano–Almuradiel syncline, the thermal interval obtained primarily from fluid inclusions (270–370°C) overlaps considerably with that obtained from CAI data (180–340°C). In general, cleavage in rocks is present in anchizonal or epizonal conditions, whereas in diagenetic conditions with CAI ≥ 2.5, cleavage is scarce. The conodont texture changes with increasing metamorphism, and apatite recrystallisation appears in general with CAI ≥ 5. Variation of CAI values within a single sample and/or within short stratigraphic distances observed at several localities is due to hydrothermal activity.

Introduction

The organic matter present in conodont elements shows colour changes with increasing temperature. These changes were used by Epstein et al. (1977) to establish a conodont colour alteration index (CAI), providing a geothermometer for temperatures ranging between 50 and 600°C. Hence, conodonts are useful for the study of the transition from diagenesis to metamorphism and for determining low- to medium-grade metamorphism. Several authors have described the origin, calibration and geological application of the CAI (e.g. Epstein et al. 1977, Rejebian et al. 1987, Burnett 1988, Nöth 1991, Königshof 1992). They have shown that the CAI is time- and temperature-dependent and results chiefly from burial, or regional or contact metamorphism. This simple and inexpensive method provides a determination of the degree of heating experienced by sedimentary and low- to medium-grade metamorphic rocks.

Two physical characteristics accompanying colour changes in conodonts are correlated with increasing metamorphism: 1) deformation and fracturing, especially common in delicate forms, 2) surface texture changes from smooth to sugary and granular (Burnett 1988, Königshof 1992, García-López et al. 1997).

At present, the application of the CAI method and its calibration, with results obtained by other thermal indicators, are of great value in checking the suitability of the method for investigating the tectonothermal history of rocks, especially in the transition from diagenesis to metamorphism. The purpose of this paper is to present CAI values of Asghill conodonts from different tectonic domains in the Iberian Peninsula, and to analyse the geological significance of these values. Ordovician sequences in the Iberian Peninsula are dominated by clastic deposits. Locally, generally thin limestone levels occur in the Upper Ordovician. Ashgill carbonate units have been studied from several localities in the Iberian Variscan belt, the

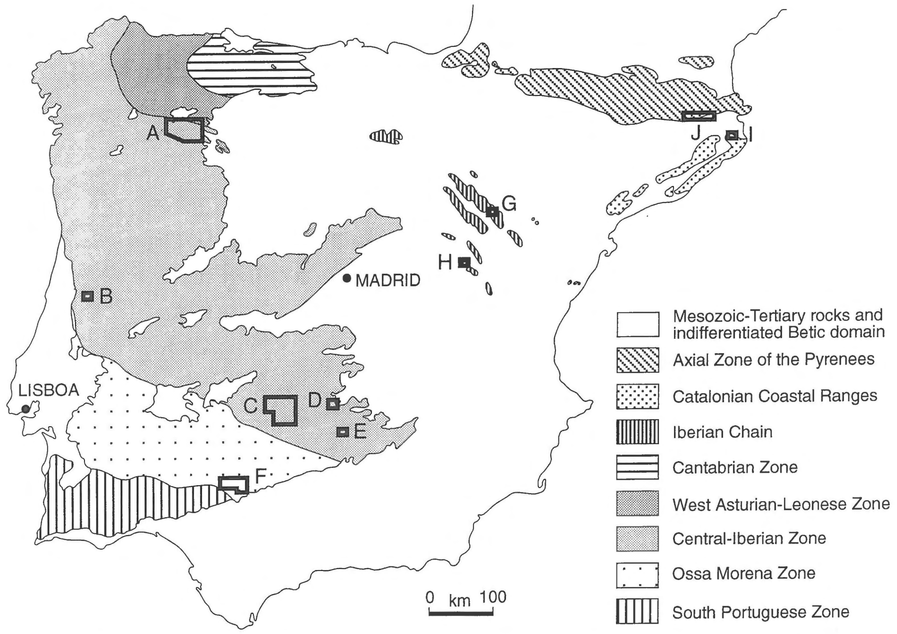

Figure 1. Location of the areas with CAI data from Upper Ordovician rocks of the Variscan domain in the Iberian Peninsula. A) Truchas syncline and Teleno anticline (Figure 2); B) Buçaco syncline; C) Almadén and Guadalmez synclines (Figure 3); D) Corral de Calatrava syncline (Figure 4); E) Puertollano-Almuradiel syncline; F) Valle and Cerrón del Hornillo synclines (Figure 5); G) Fombuena area; H) Nevera Massif; I) Les Gavarres Massif; J) Bruguera unit and Segre Valley. Variscan zones according to Julivert et al. (1972).

Axial Zone of the Pyrenees and the Catalonian Coastal Ranges (Figure 1); all of these zones were affected by Variscan deformation. Several zones were also affected by Alpine deformation, which was particularly intense in the Axial Zone of the Pyrenees.

Previous geological information on the zones is variable. Metamorphism studies based on the mineral assemblages or on illite crystallinity (IC) have been undertaken in some areas where it is possible to compare the metamorphic parameters with those derived from CAI data. In areas lacking metamorphic studies, CAI values give the first information on the metamorphism. A comparison between the results obtained in the studied zones and those obtained from a reference transect, located in the Cantabrian Zone (the external part of the Iberian Variscan belt in NW Spain), is useful. In this transect, a correlation between CAI values and IC has been established for the transition from diagenesis to metamorphism ($5.5 \geq$ CAI > 4 for the anchizone; García-López et al. 1997).

The samples, 177 in total, were dissolved in an 8% acetic acid solution, avoiding any etching of the conodont element surfaces and leaching of the apatite, which may lead to an artificial alteration of the original colour. CAI values were determined by comparison with a set of standards of conodonts prepared at the U.S. Geological Survey under the supervision of A. Harris. In general, determination of the CAI was possible to a precision of 0.5. From each of the 31 investigated localities several samples have been analysed, with a minimum of five conodont individuals counted per sample. Two people cross-checked each CAI result to avoid possible observer errors.

Textures were studied within a range of magnifications between 500 and 10 000. In agreement with Burnett (1988) and Königshof (1992) a clear correlation between increasing metamorphism and textural changes has been found. Scanning electron microscope (SEM) microphotographs of diagenetically altered and metamorphosed conodont elements are shown in Plates 1 and 2.

Conodont fauna

Conodont assemblages from Ashgill limestones of the Iberian Peninsula are rather uniform, and are characteristic for the *Amorphognathus ordovicicus* Biozone. The following taxa have recently been recognised by Sarmiento (1993), Sarmiento et al. (1995) and Sanz-López & Sarmiento (1995), as well as during this study: *Amorphognathus ordovicicus* Branson & Mehl, *Sagittodontina robusta* Knüpfer, *Scabbardella altipes*

(Henningsmoen), *'Eocarniodus' gracilis* (Rhodes), *Panderodus gracilis* (Branson & Mehl), *P. panderi* (Stauffer), *P. sulcatus* (Fahraeus) s.f., *Icriodella superba* Rhodes, *Hamarodus europaeus* (Serpagli), *Pseudooneotodus mitratus* (Moskalenko) and *'Oistodus'* sp. The species *Plectodina tenuis* (Branson & Mehl), *Walliserodus amplissimus* (Serpagli), *Rhodesognathus elegans* (Rhodes) and *Aphelognathus rhodesi* (Lindström) may also be present, but the small number of elements prevent accurate identifications.

From a palaeobiogeographic point of view, the abundance of genera such as *Scabbardella, Sagittodontina* and *Amorphognathus* favours the ascription of the Iberian assemblage to the Mediterranean Province of the North Atlantic conodont realm (Sweet & Bergström 1984). The Iberian faunas represent a shallow-water community developed along inshore environments of the perigondwanan area, and show differences with the Anglo-Baltic, Sardic and Alpine biofacies recognised in the same province (Sweet & Bergström 1984, Ferretti & Serpagli 1991).

Iberian Variscan belt

Ordovician conodonts have been found in the Central-Iberian Zone (CIZ), Ossa Morena Zone (OMZ) and Iberian Chain (IBC; Figure 1); however, no conodonts have been found in the rare Ordovician limestones from the Cantabrian Zone (CZ) and West Asturian-Leonese Zone (WALZ). Carbonate rocks of this age are not exposed in the South Portuguese Zone (SPZ).

Central–Iberian Zone

The Central–Iberian Zone is a large zone that includes most of the central and northwestern parts of the Iberian Peninsula (Figure 1). Rocks vary in age from Precambrian to Carboniferous. Ordovician rocks exhibit a remarkable uniformity of facies. The Lower and Middle Ordovician are dominantly formed by siliciciclastic rocks; the Upper Ordovician includes a limestone formation in several sectors of the zone (Gutiérrez-Marco et al. 1990), where the conodont samples have been collected. Two different tectonic domains have been distinguished in the zone (Díez Balda et al. 1990): a northern domain with recumbent folds, and a southern domain with upright folds. The metamorphism shows a distribution of isograds in elongated areas closely related to granite outcrops, where middle-grade conditions are reached (Martínez & Gil Ibarguchi 1983, Martínez et al. 1990). Epizonal, anchimetamorphic or diagenetic conditions appear outside the more metamorphic elongated areas.

CAI values have been determined in five areas of the zone (Figure 1). One of these areas is located in the domain of recumbent folds, and is formed by rocks of the Truchas syncline and Teleno anticline. The other four areas are located in the domain of upright folds. These areas are: Buçaco syncline, Almadén and Guadalmez synclines, Corral de Calatrava syncline and Puertollano-Almuradiel syncline.

Truchas syncline and Teleno anticline. This area is located near the northern boundary of the domain with recumbent folds (Figure 2). Conodont samples have been collected in the Aquiana limestone, in the lower member of the Agüeira Formation, and from calcareous pebbles in the middle member of the Agüeira Formation. All of these rocks have been affected by regional metamorphism to greenschist facies (chlorite zone; Pérez-Estaún 1978, Barrera et al. 1989). CAI values for conodonts from this area range from 5 to 7 (mostly 5.5–6; Table 1). The conodont elements are opaque, often recrystallised and deformed, and show cleavage (Plate 1: 8, 10, 16, 17; Plate 2: 9–11). Only small differences in CAI are observed in the area. CAI values in the core of the Truchas syncline are slightly greater than those in the rest of the localities, and show a greater variance at individual localities, suggesting hydrothermal activity, which is corroborated by the presence of sulphides in limestone pebbles included in the mainly siliciclastic, middle member of the Agüeira Formation (Sarmiento et al. 1994). According to the CAI of 5.5 obtained for the anchizone-epizone boundary in the Cape Peñas-Cape Torres reference transect, the CAI values for the Teleno-Truchas area agree with the metamorphic conditions indicated by the mineral assemblage quartz-muscovite-chlorite (Pérez-Estaún 1978). Both indicators show that Ordovician rocks in this area underwent a regional metamorphism in the upper part of the chlorite zone.

Buçaco syncline. This fold is a NW–SE major structure developed mainly in Ordovician rocks. Conodonts have been collected in this area from one locality in the basal part of the upper dolomite member of the Ferradosa Formation (Ashgill). This locality is along the San Miguel de Poiares-Venda Nova road, 400 m south of the latter village (ca. 10 km east of Coimbra). Conodonts have CAI values of 6 and 6.5, are strongly recrystallised and partially dissolved (Plate 1:

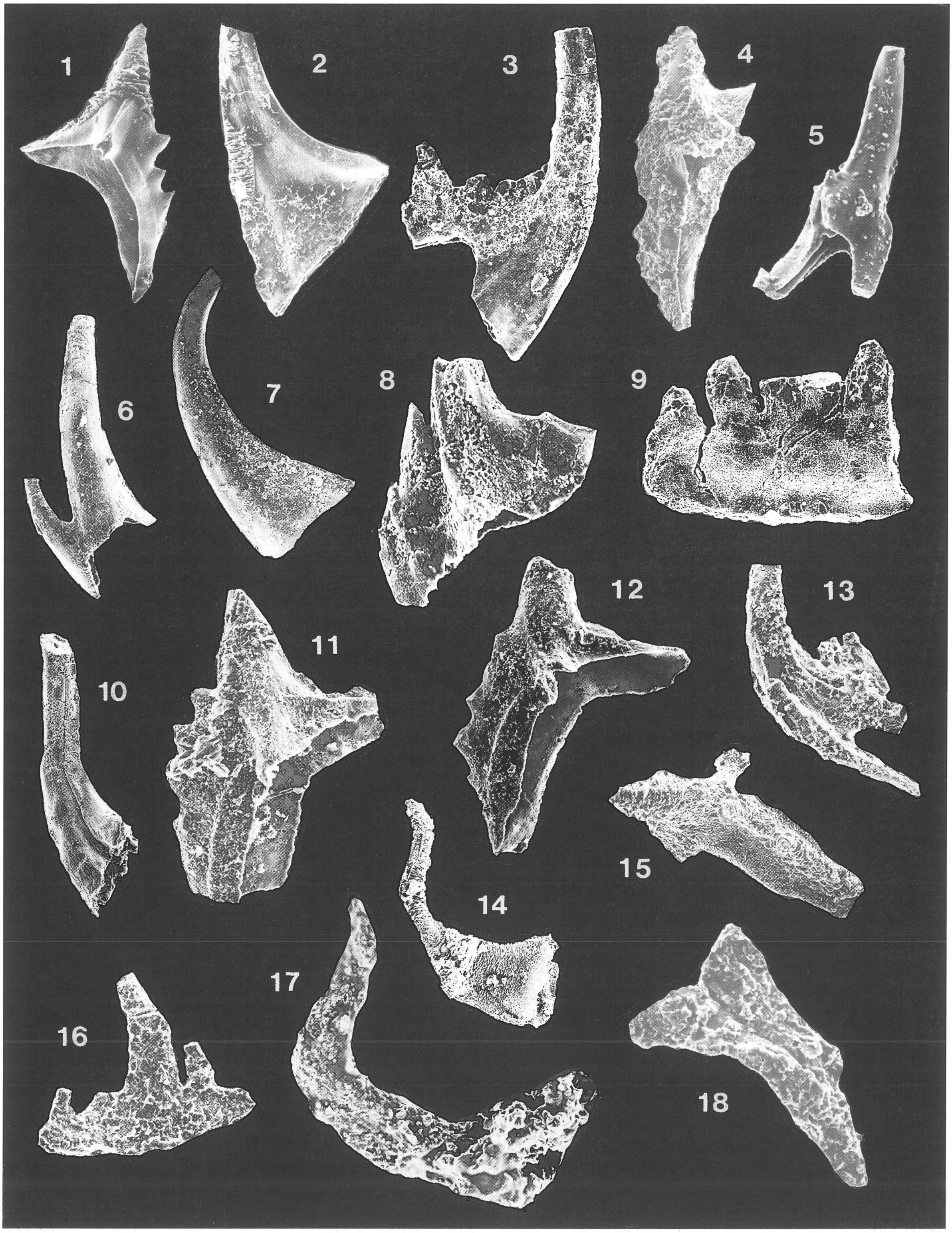

Plate 1.

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Plate 1. General and superficial features of Upper Ordovician conodont elements from diverse thermal regimes, Iberian Peninsula. All specimens are from the *Amorphognathus ordovicicus* Zone. They are deposited at the Departamento de Paleontología, Universidad Complutense (Madrid). Capital letters and roman numbers before the arabic specimen numbers correspond to a locality or section shown in Figures 1 to 5. 1 – *Amorphognathus ordovicicus* Branson & Mehl, Pb element, CO-A-8670, × 190, Corral de Calatrava syncline (1 in Figure 4). CAI = 2.5, most of the surface is smooth with mineral overgrowths on the upper part of the cusp (detailed on Plate 2: 14). Diagenetic zone. 2 – *Scabbardella altipes* (Henningsmoen), a element, CO-B-8486, × 130, Corral de Calatrava syncline (2 in Figure 4). CAI = 3, smooth conodont surface with mineral overgrowths (partially dissolved) covering a part of the specimen (detailed on Plate 2: 12). Diagenetic zone. 3 – *Hamarodus europaeus* (Serpagli), Sc element, HZ-IA–6567, × 190, Puertollano-Almuradiel syncline (4 in Figure 4). CAI = 4, faint corrosion and clay minerals, tiny parallel fractures. Diagenesis close to anchizone boundary. 4 – *Amorphognathus ordovicicus* Branson & Mehl, Pb element, AO-XXII-8669, × 170, Guadalmez syncline (9 in Figure 3). CAI = 3.5, smooth conodont surface (see the clean part of the cusp) with mineral crust (from a dolomitised limestone level). Diagenetic zone. 5 – *Sagittodontina robusta* Knupfer, Sa element, CT-I-8675, × 220, Cerrón del Hornillo syncline (3 in Figure 5). CAI = 4, smooth surface (detailed on Plate 2: 2). Diagenesis close to anchizone boundary. 6 – *Sagittodontina robusta* Knüpfer, Sc element, CO-B-8478, × 210, Corral de Calatrava syncline (2 in Figure 4). CAI = 4.5, corrosion, sugary texture and tiny parallel fractures (detailed on Plate 2: 3). Diagenesis-anchizone. 7 – *Scabbardella altipes* (Henningsmoen), a element, AO-XXI-8679, × 85, Guadalmez syncline (8 in Figure 3). CAI = 3–3.5, sugary texture, incipient dissolution, few clay-mineral adherences. Diagenetic zone. 8 – *Sagittodontina robusta* Knüpfer, Pb element, CCB-I-8480, × 285, Truchas syncline (4 in Figure 4). CAI = 5.5, strong dissolution, border of the basal cavity corroded, fractures. Anchizone. 9 – Indeterminate fragment, HZ-IB-9509, × 160, Puertollano-Almuradiel syncline (2 in Figure 4). CAI = 5, sugary texture, corrosion, fractures. Anchizone. 10 – *Panderodus sulcatus* (Fahraeus), falciform element, CCB-II-6793, × 95, Truchas syncline (6 in Figure 2). CAI = 6, sugary texture, faint superficial etching, slightly deformed. Anchizone-epizone. 11 – *Amorphognathus ordovicicus* Branson & Mehl, Pb element, HZ-A-8427, × 285, Puertollano-Almuradiel syncline (4 in Figure 4). CAI = 5.5, sugary texture, incipient recrystallisation, clay-mineral adherences (detailed on Plate 2: 8). Anchizone. 12 – *Amorphognathus ordovicicus* Branson & Mehl, Pb element, FB-X-8427, × 230, Fombuena locality (F in Figure 1). CAI = 5.5, sugary texture, incipient recrystallisation. Anchizone. 13 – *Amorphognathus ordovicicus* Branson & Mehl, Sd element, CXI-XX-8425, × 260, Almadén syncline (3 in Figure 3). CAI = 6?, bleached, dolomitised, not indicative of temperature range. 14 – *Scabbardella altipes* Henningsmoen, indeterminate element, AO-XXI-6559, × 70, Guadalmez syncline (8 in Figure 3). CAI = indeterminate: mineral overgrowths on the entire surface, deformed. 15 – *Amorphognathus ordovicicus* Branson & Mehl, Pa element, AC-XX-8667, × 170, Almadén syncline (5 in Figure 3). CAI = 2.5 (determined on several specimens of the same sample), mineral overgrowths on the entire surface (detailed on Plate 2: 13). 16 – *Eocarniodus? gracilis* (Rhodes), CD-I-8431, × 330, Truchas syncline (2 in Figure 2). CAI = 7, recrystallised (detailed on Plate 2: 10), deformed. Epizone. 17 – *Scabbardella* sp., e? element, CCB-III-7677, × 120, Truchas syncline (5 in Figure 2). CAI = 6.5, recrystallised, deformed. Epizone. 18 – Indeterminate specimen, BU-P-8429, × 285, Buçaco syncline (B in Figure 1). CAI = 6.5, recrystallised, deformed. Epizone.

18; Plate 2: 6). These values indicate low-grade metamorphic conditions (chlorite zone), agreeing with the regional metamorphic data (Dias & Ribeiro 1994).

Almadén and Guadalmez synclines. These structures have WNW–ESE subvertical axial surfaces; they exhibit Devonian and Carboniferous rocks in their cores (Figure 3). They are separated by the Valle de Alcudia anticline, which has Precambrian rocks in its core. Ordovician rocks are present in the limbs of both synclines.

A rough cleavage appears in the Almadén syncline. It is developed mainly in its southern limb, and is occasionally present in the northern limb. This cleavage exhibits an oblique orientation in relation to the fold, and cuts it; hence, the cleavage is post-syncline (Aller et al. 1986). A weak cleavage was also described in the mudrocks of the Guadalmez syncline (Martínez-Rius 1983).

The transition from diagenesis to regional metamorphism in the Almadén syncline was studied by Saupé et al. (1977), Blachère (1978) and Saupé (1990) using illite crystallinity and the reflectivity of organic matter. According to Blachère (1978), IC data indicate an increasing metamorphism towards the south in the Palaeozoic rocks of the Almadén syncline from mainly diagenetic in the northern limb and the core to anchizonal and epizonal in the southern limb.

CAI values have been obtained from conodonts from five localities in the northern limb of the Almadén syncline, three localities in the northern limb of the Guadalmez syncline (Figure 3), and two localities in the southern limb of the latter syncline. The rocks sampled belong to the Urbana limestone (Ashgill). CAI data from Ordovician rocks have been complemented by CAI data obtained from several Devonian and Lower Carboniferous limestone samples collected in the cores of the Almadén (three localities; A-C in Figure 3) and Guadalmez (four localities) synclines (García López et al., in press).

The Ordovician conodonts are transparent or opaque, and have a sugary texture (Plate 1: 4, 7, 13–15; Plate 2: 1, 13). Their CAIs are 2.5, 3, 4 and 6 for the localities in the Almadén syncline and 3 to 4 for the localities in the Guadalmez syncline. In most cases, diagenetic conditions are clearly present, and CAI values indicate the same conditions as those indicated by IC values in the Almadén syncline (Blachère 1978). Some CAI anomalies in this syncline suggest the effects of hydrothermal fluids.

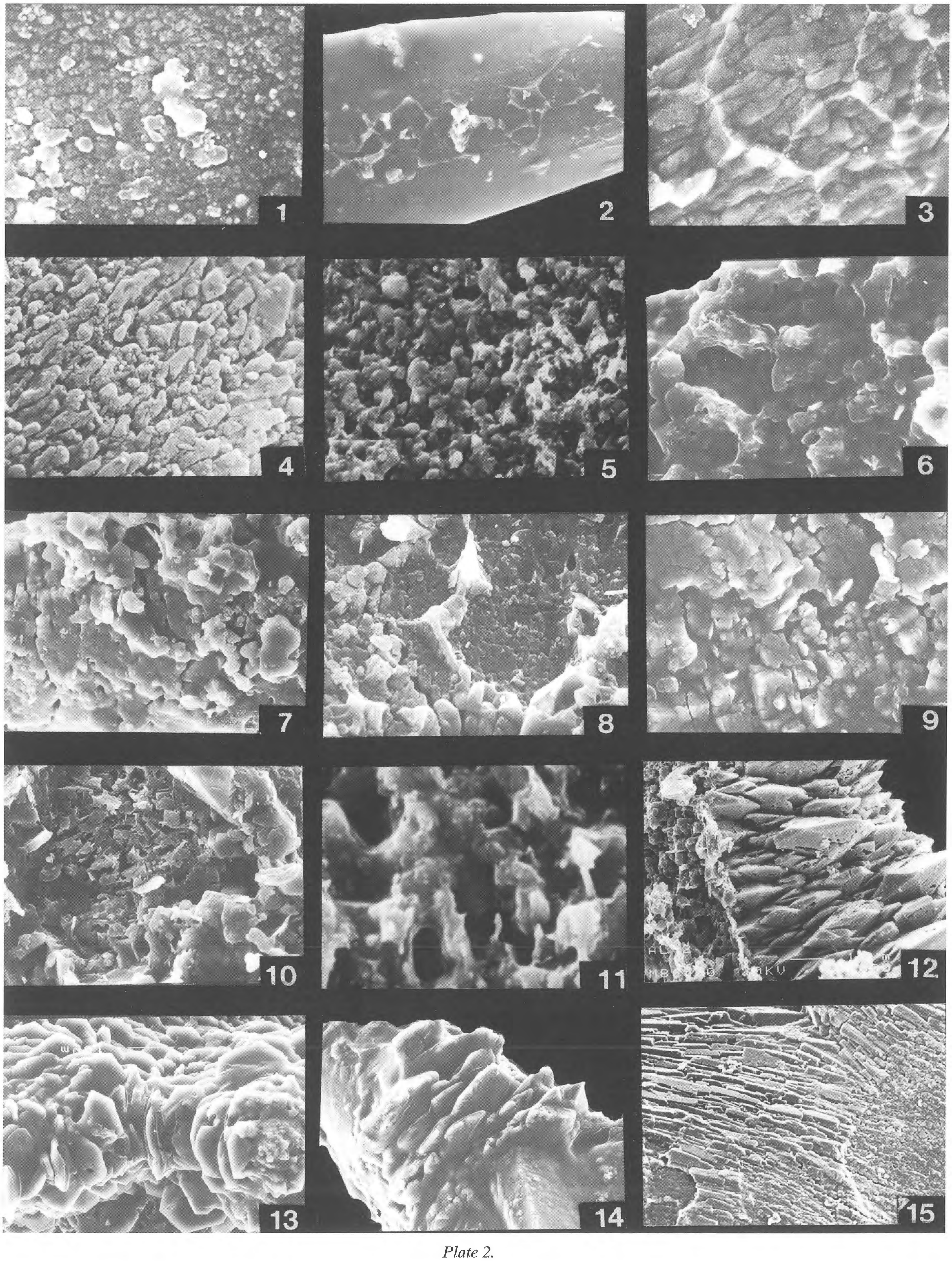

Plate 2.

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Plate 2. Textures of Iberian Upper Ordovician conodonts with different CAI values. 1 – *Amorphognathus ordovicicus* Branson & Mehl, Pb element, AC-XX-9508, × 9500; Almadén syncline (5 in Figure 3). CAI = 2.5, unaltered texture. Diagenetic zone. 2 – *Sagittodontina robusta* Knüpfer, Sa element, CT-I-8675, × 1400; Cerrón del Hornillo syncline (3 in Figure 5). CAI = 4, incipient polygonal pattern. Diagenesis close to anchizone boundary. 3 – *Sagittodontina robusta* Knüpfer, Sc element, CO-B-8478, × 2850; Corral de Calatrava syncline (2 in Figure 4). CAI = 4.5, faintly delineated polygonal depressions. Diagenetic zone-anchizone. 4 – *Amorphognathus ordovicicus* Branson & Mehl, Pb element, MCL-5001, × 9500; Les Gavarres Massif (H in Figure 1). CAI = 5, recrystallised aligned apatite crystals following the primary morphology. Anchizone-epizone. 5 – *Amorphognathus ordovicicus* Branson & Mehl, Pb element, HX-B-8951, × 3800; Puertollano-Almuradiel syncline (4 in Figure 4). CAI = 5, homogeneous grain size of recrystallised apatite, corroded and pitted surface. Anchizone. 6 – *Scabbardella altipes* Henningsmoen, a? element, BU-P-8430, × 2400; Buçaco syncline (B in Figure 1). CAI = 6.5, recrystallised and corroded surface. Epizone. 7 – *Amorphognathus ordovicicus* Branson & Mehl, Sb element, HZ-B-8426, × 1900; Puertollano-Almuradiel syncline (4 in Figure 4). CAI = 5.5, recrystallised blocky crystals. Anchizone. 8 – *Amorphognathus ordovicicus* Branson & Mehl, Pb element, HZ-A-8427, × 4750; Puertollano-Almuradiel syncline (4 in Figure 4). CAI = 5.5, polygonal depressions. Anchizone. 9 – *Amorphognathus* sp., Pb element, RN-X-8485, × 4750, Teleno anticline (1 in Figure 2). CAI value = 5.5, recrystallised blocky crystals. 10 – *Eocarniodus? gracilis* (Rhodes), CD-I-8431, × 4750; Truchas syncline (2 in Figure 2). CAI = 7, strongly recrystallised with clay-minerals within the newly formed porosity. Epizone. 11 – *Sagittodontina* sp., Sc element, CCB-III-9000, × 2850; Truchas syncline (5 in Figure 2). CAI = 6.5, recrystallised and corroded surface. Epizone. 12 – *Scabbardella altipes* Henningsmoen, a element, CO-B-8486, × 950; Corral de Calatrava syncline (2 in Figure 4). CAI = 3, crystallites growing perpendicular to the outermost conodont lamella. Diagenetic zone. 13 – *Amorphognathus ordovicicus* Branson & Mehl, Pa element, AC-XX-8667, × 950, Almadén syncline (5 in Figure 3). CAI = 2.5, crystal overgrowths parallel to the outermost conodont lamella. Diagenetic zone. 14 – *Amorphognathus ordovicicus* Branson & Mehl, Pb element, CO-A-8670, × 950; Corral de Calatrava syncline (1 in Figure 4). CAI = 2.5, crystal overgrowths. Diagenetic zone. 15 – *Sagittodontina robusta* Knüpfer, Sc element, HZ-A-2930, × 930; Puertollano-Almuradiel syncline (4 in Figure 4). CAI = 4.5, incipient recrystallisation with apatite microcrystallites oriented parallel to the cusp. The underlying lamella is formed by smaller crystals with the same arrangement. Diagenetic zone-anchizone.

The Devonian and Lower Carboniferous conodonts mainly exhibit a sugary texture and have CAI values of 4 and 4.5 in the Almadén syncline, and 2, 2.5 and 3 in the Guadalmez syncline. These values indicate transitional diagenesis–anchizone conditions in the former syncline and diagenetic conditions in the latter (García López et al., in press). Recrystallisation occurs at a CAI of 4.5.

The transitional diagenesis–anchizone conditions deduced for the core of the Almadén syncline from CAI values contrast with the single IC value obtained by Blachère (1978) in Devonian rocks of the same area. Nevertheless, when the IC values map of Blachère (1978, Figure 42 bis) is examined in detail, the three Silurian localities on the northern limb, close to Devonian CAI localities, indicate the diagenesis–anchizone boundary. Hence, an increase of metamorphic grade is suggested from the northern limb to the core of the Almadén syncline in a direction from WNW to ESE. This increase extends southward so that epizonal conditions are detected by IC values in the southern limb of the syncline (Blachère 1978). The distribution of the cleavage in the Almadén syncline agrees with the distribution of the metamorphism (Aller et al. 1986) and it suggests that cleavage and metamorphism were simultaneous. This interpretation agrees with the fact that both the metamorphism isogrades and the cleavage cut the Almadén syncline.

Corral de Calatrava syncline (Figure 4). The Palaeozoic succession of this structure includes a notable volcanic component in the Ordovician and Silurian rocks. On the other hand, the Tertiary and Quaternary volcanism of the Campos de Calatrava could have had some effect on the CAI values. Metamorphism has not been detected in the Palaeozoic rocks (Portero et al. 1988).

CAI values have been determined from conodonts of the Urbana limestone in two sections located in the northern limb of this syncline (Figure 4). In section 1, CAI values are 3, 3.5, 4 and 4.5 (3.5 is the most common value), and in section 2, they are 2, 2.5, 3, 4 and 6 (4 is the most common value). In both sections the conodonts are transparent or opaque and have a grey patina and sugary texture (Plate 1: 1, 2, 6; Plate 2: 3, 14). These values suggest mainly diagenetic conditions, and the high variation in CAI values may be due to hydrothermal activity. This interpretation is supported by the textural features. It is difficult to determine the age of the hydrothermal activity, since it could be a result of the Early Palaeozoic and/or recent volcanism. Section 2 is located near to the recent volcanic rocks and exhibits a greater variation of CAI values and more highly developed textural features related to fluids than section 1. These facts suggest an influence on CAI values of hydrothermal activity associated with the recent volcanism.

Puertollano–Almuradiel syncline. This syncline exhibits Silurian and Devonian rocks in its core. Mudrocks of this zone present a primary cleavage which is less developed in the sandstone (Palero &

Table 1. CAI values and characteristics of Upper Ordovician conodonts, Iberian Peninsula. N_l/N_s, number of localities/samples with CAI determinations. * Deduced exclusively from CAI values. ** Hydrothermal activity inferred from variation in CAI in all cases. *** IC measured as width of the 10 Å peak at half of its height. IC for anchizone-diagenesis boundary = 4.5 (after Blachère 1978).

Zone, area	N_l/N_s	CAI, Metamorphic grade*	General features and texture of conodonts	Remarks**
Central–Iberian Zone				
Truchas syncline and Teleno anticline	6/43	5–7 (mainly 5.5–6) Mainly epizone	Often recrystallised, deformed and with cleavage, opaque, 'ghost conodonts'	Chlorite zone mapped, cleavage in rocks, hydrothermal activity
Buçaco syncline	1/6	6–6.5 Epizone	Strongly recrystallised, opaque, partially dissolved	Cleavage in rocks
Almadén syncline	5/15	2.5, 3, 4, and 6 Diagenesis	Transparent or opaque, sugary texture	Cleavage in rocks is scarce, hydrothermal activity. IC*** $\geq$ 4.5 (diagenesis)
Guadalmez syncline	5/14	3–4 Diagenesis	Transparent or opaque, sugary texture, bleached	Weak cleavage in rocks
Corral de Calatrava syncline	2/31	2–4.5 and 6 Mainly diagenesis	Transparent or opaque, grey patina, sugary texture	Hydrothermal activity
Puertollano-Almuradiel syncline	2/23	4–5.5 and 6 Anchizone	Commony cleaved, transparent opaque, some sugary and recrystallised textures, grey patina	Cleavage in rocks. T = 270–370°C (deduced from fluid inclusions), hydrothermal activity
Ossa Morena Zone				
Valle and Cerrón del Hornillo synclines	5/18	4 Diagenesis (close to anchizone boundary)	Transparent, smooth texture	
Iberian Chain				
Fombuena area	1/17	4–6 Mainly anchizone	Smooth and sugary textures, bleached, grey patina	Hydrothermal activity, cleavage in rocks
Nevera Massif	1/3	5.5–6 Mainly epizone	Smooth and sugary textures, grey patina	Cleavage in rocks
Catalonian Coastal Ranges				
Les Gavarres Massif	1/3	5–6 Transition anchizone-epizone	Opaque, sometimes cleaved, strongly recrystallised, some deformed	Some hydrothermal activity, cleavage in rocks
Axial Zone of Pyrenees				
Bruguera unit (Cavallera Massif)	1/2	5–6 (mainly 6) Transition anchizone-epizone	Cleaved, recrystallised	Cleavage in rocks
Segre Valley	1/2	6 Epizone	Cleaved, recrystallised	Cleavage in rocks

Martín-Izard 1988). Sphalerite and galena mineralisation is found in the area. Palaeotemperatures of 270 and 370°C have been obtained from sulphur isotopes in sphalerite and galena, and from fluid inclusions in quartz (Palero 1991; pers. comm. 1996) at two localities in this syncline.

CAI values have been obtained from samples from two sections across the Urbana limestone near the core of the syncline, located ca. 15 km south of Calzada de Calatrava. CAI values ranging mainly from 4 to 5.5, and a common cleavage in the conodonts suggest anchizonal conditions. Conodonts are transparent or opaque and show a grey patina and some sugary and recrystallised textures (Plate 1: 3, 9, 11; Plate 2: 5, 7, 8, 15).

Ossa Morena Zone

In the Ossa Morena Zone, a pre-orogenic to post-orogenic Palaeozoic succession, which extends into the Lower Permian, overlies the Precambrian rocks. Ordovician fossiliferous rocks are restricted to a few areas (Gutiérrez-Marco et al. 1984, Robardet & Gutiérrez-Marco 1990). They comprise mainly siliciclastic units with a few limestone beds in the Upper Ordovician.

Variscan deformation is not well known in the zone, and changes from one domain to another. In general, it gave rise to large recumbent folds and southwest-directed thrusts that were later refolded. Variscan metamorphism is characterised by the presence of several thermal domes in which medium- to high-grade conditions are reached; the rocks located outside these thermal domes are mainly in the chlorite metamorphic zone. Igneous rocks are widely present (Corretgé 1983, Sánchez Carretero et al. 1990).

CAI values have been determined from samples of the Pelmatozoan limestone (Ashgill) in two areas of the zone, which are located in the Valle syncline (two sections sampled) and the Cerrón del Hornillo syncline (three sections sampled; Figure 5). These folds, which show ESE–WNW axial traces, have Ordovician and Silurian rocks in their cores, and are strongly affected by faults. In both areas, the conodonts have a CAI of 4, are transparent, and exhibit a smooth texture (Plate 1: 5; Plate 2: 2). Regional metamorphism of the pelitic rocks to greenschist facies has been described in this area (Angoloti et al. 1975). However, the CAI values and the conodont texture suggest diagenetic conditions, close to the diagenesis-anchizone boundary. This disagreement is probably due to the difficulty of distinguishing very low-grade metamorphism in pelitic rocks on the basis of mineralogical assemblages. Hence, the CAI values presented provide a new precision to the knowledge of the transition between diagenesis and metamorphism in this zone.

Iberian Chain

In the Iberian Chain, mostly formed by Mesozoic and Tertiary rocks, a Precambrian and Palaeozoic basement, affected by the Variscan deformation, is exposed in several antiformal areas that result from Alpine deformation. The Cambrian to Carboniferous succession has a thickness of ca. 7000 m. Lower Palaeozoic rocks are similar to those of the West Asturian–Leonese Zone, with a mainly siliciclastic Ordovician succession, that includes an Ashgill limestone level (Cystoid limestone) in the upper part. Devonian and Carboniferous rocks occur in few localities.

The Variscan structure of the chain is a result of two main deformation phases (Capote & González-Lodeiro 1983). The first gave rise to upright or north-easterly facing folds with an associated cleavage; the second gave rise to northeast-directed thrusts. In general, metamorphism is of low or very low grade.

Two areas have been sampled in the chain (Figure 1): the Fombuena area, which consists of a strongly fractured anticline, and the Nevera Massif, which is formed by a set of upright open folds developed in Ordovician and Silurian rocks.

CAI values from samples of the Cystoid limestone collected in a section 1 km WNW of Fombuena range from 4 to 6. This variation in CAI over such a short distance, which is also observed within a single sample, indicates hydrothermal activity. Although Hernández et al. (1983) noted a lack of metamorphism in this area, CAI values suggest mainly anchizonal conditions.

Conodonts of the Nevera Massif, collected from a limestone pebble in the Orea shales (Upper Ordovician), 1.5 km east of Checa (Checa-Orea road), have CAI values of 5.5 and 6. Conodont elements have smooth and sugary textures and a grey patina (Plate 1: 12). Detailed studies of the metamorphism in this area are not available, but epizonal conditions are suggested by the CAI values.

The presence of anchizonal or epizonal conditions in the Fombuena area and the Nevera Massif agrees with the general occurrence of an S_1 cleavage and with the common interpretation of both areas as an extension of the West Asturian–Leonese Zone.

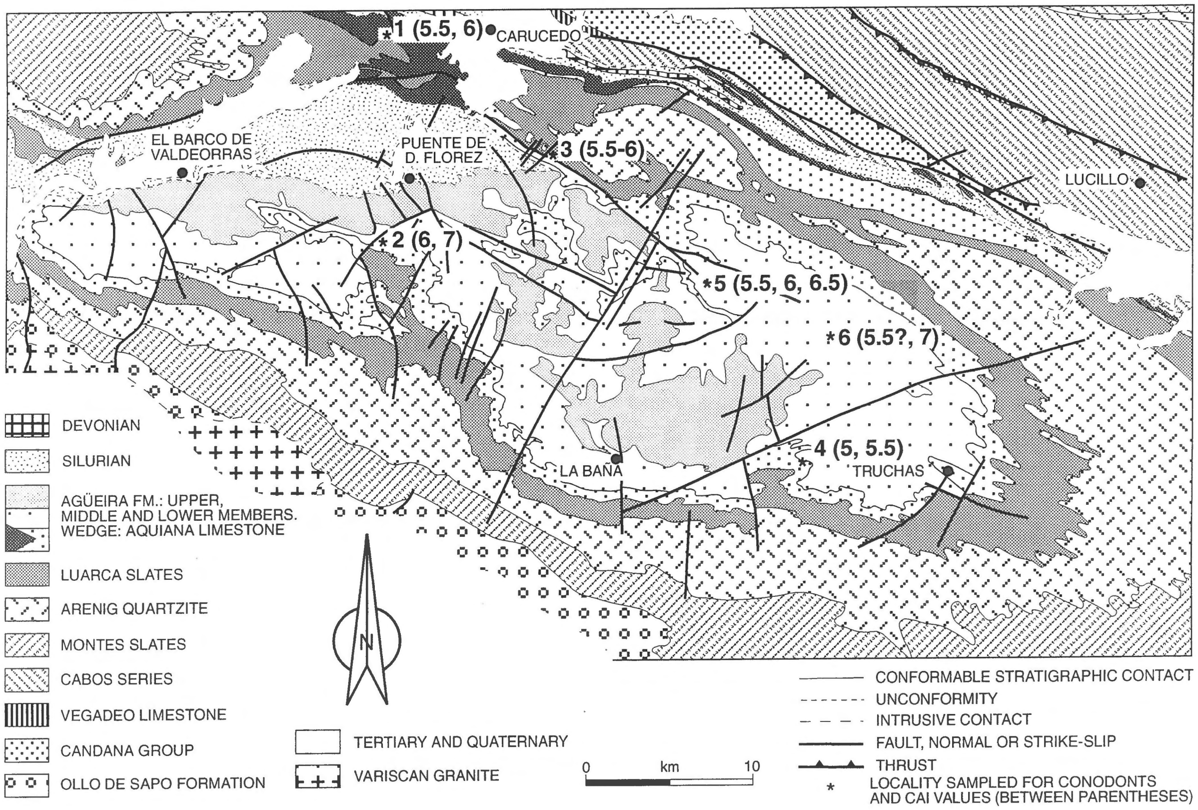

Figure 2. Localities with CAI data in the Truchas syncline and Teleno anticline (Central–Iberian Zone). 1) RN-X; 2) CD-I; 3) PDF-I; 4) TR-XX; 5) CCB-III; 6) CCB-II. The ages of the rocks from Cándana Group to Agüeira Formation range from Cambrian to Ordovician. Geological map after Martínez-Catalán et al. (1992).

Catalonian Coastal Ranges

The Catalonian Coastal Ranges (CCR) are two small mountain chains separated by a graben and roughly parallel to the Mediterranean coast (Figure 1). They are formed by a Cambrian to Carboniferous basement which is overlain by an unconformable Mesozoic-Tertiary cover. Nodular carbonate or limestone levels of Ashgill age occur in the upper part of the Ordovician succession in some places. Late Variscan granitoids intruded the Palaeozoic rocks over a large area.

In most of the ranges, Variscan deformation gave rise to slaty cleavage as the main foliation, and regional metamorphism occurred under greenschist-facies conditions (Julivert & Martínez 1980, 1983, Julivert & Durán 1990, Sebastián et al. 1990). Conodont samples have been collected from siltstone and limestone at Mas Cals (Ashgill) in Madremanya (Les Gavarres Massif), in an area where the mineral assemblages of pelitic rocks broadly suggest very low- or low-grade metamorphic conditions. CAI values range from 5 to 6. Conodonts always appear recrystallised, some showing cleavage. They are opaque and may be deformed (Plate 2: 4). The above CAI values and the microstructural features of the conodonts suggest metamorphic conditions in the anchizone-epizone transition. The variation of CAI values in some samples may have been produced by hydrothermal activity.

Axial Zone of the Pyrenees

In the Axial Zone (AZP), the Palaeozoic basement of the Pyrenean chain is well exposed. It was affected by Variscan and Alpine deformations. The pre-Variscan succession of this zone is formed by Ordovician to Lower Carboniferous strata. Cambrian (and Precambrian?) rocks are also present. The pre-Variscan rocks are unconformably overlain by late-Variscan,

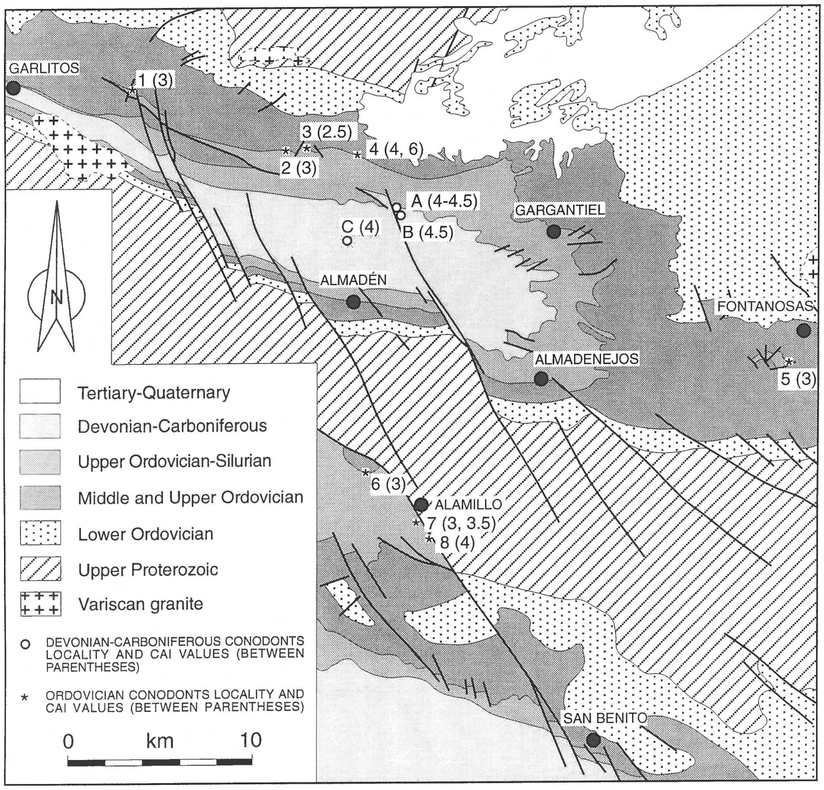

Figure 3. Localities with CAI data in the Almadén syncline and the northern limb of the Guadalmez syncline (Central–Iberian Zone). 1) GS-V; 2) CHI XIX; 3) CHI-XX; 4) CHI-XXI; 5) AC-XX; 6) CHI-XXII; 7) AO-XX; 8) AO-XXI. Geological map after Aguilar et al. (1987), Barranco et al. (1987), Molina et al. (1987), Mira et al. (1987) and García Sansegundo et al. (1987).

Stephanian or Permian rocks, and by a Mesozoic and Tertiary cover.

Lower Ordovician rocks are not well known in the zone. There is a Cambrian-Ordovician succession, pre-Caradoc in age, and an unconformable Upper Ordovician succession. The Variscan deformation was polyphasic (García Sansegundo 1992) and four successive foliations can be observed. Among these, the main foliation is S_2, although S_3 is the more visible cleavage in some areas. Variscan regional metamorphism is developed in the zone with conditions ranging from very low to high metamorphic grade (Zwart 1979, Soula et al. 1986; García Sansegundo 1992, Carreras & Capella 1994). Syn- to late-orogenic, mainly calc-alkaline Variscan granitoids were intruded in several areas. Alpine deformation gave rise to thrusts locally associated with a very low to low-grade metamorphism.

Samples for conodonts were collected in the eastern Pyrenees from the Ashgill Baell Formation in a section located along the Ribes de Freser-Bruguera road (Bruguera unit; Cavallera Massif), and from the Estana Formation in the high Segre Valley. The mineral assemblages indicate that the metamorphism is probably in the chlorite zone (J. Sanz-López pers. comm. 1997). CAI values range from 5 to 6 (6 is the most common value) in the Baell Formation and a value of 6 is obtained from the Estana Formation. In all cases the conodonts are recrystallised, and show cleavage. The CAI values suggest an epizonal metamorphism, close to the anchizone-epizone boundary.

Discussion and conclusions

CAI values from Upper Ordovician carbonate rocks of the Variscan domain in the Iberian Peninsula indicate diagenetic conditions or very low- to low-grade metamorphism (chlorite zone) in most of the studied areas (Table 1). Nevertheless, higher-grade metamorphism is also common in Lower Palaeozoic rocks of this domain, especially in Variscan shear zones or in thermal domes, usually associated with the presence of granites. Because Upper Ordovician limestones are absent in these areas, CAI values have not been determined.

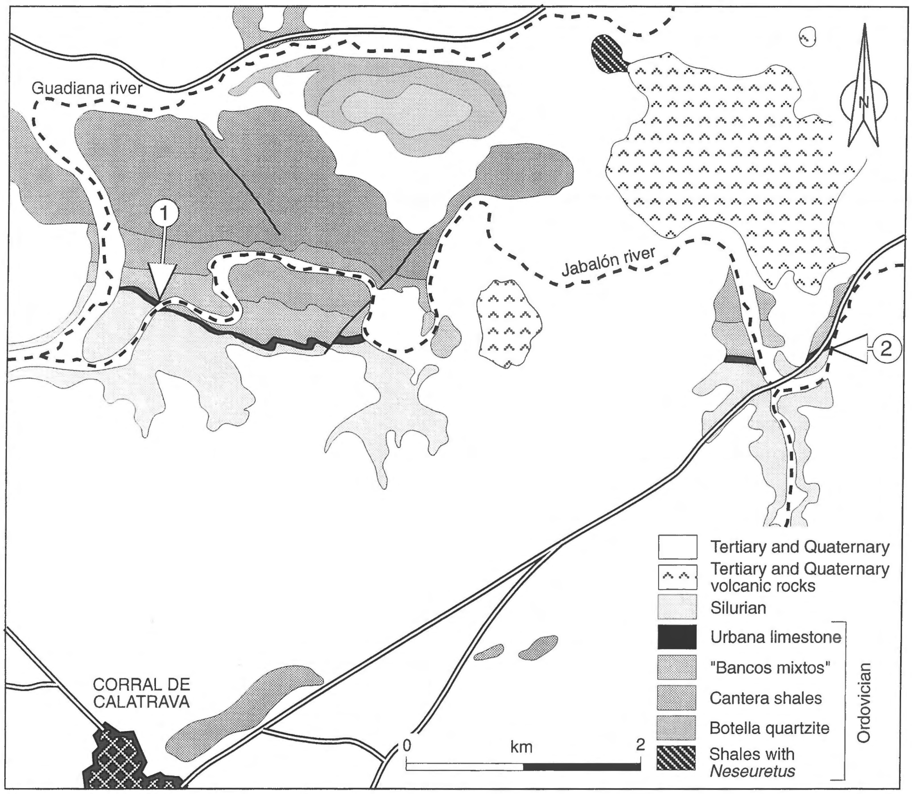

Figure 4. Localities with CAI data (arrows 1 and 2) in the Corral de Calatrava syncline (Central–Iberian Zone). Geological map after Portero et al. (1988).

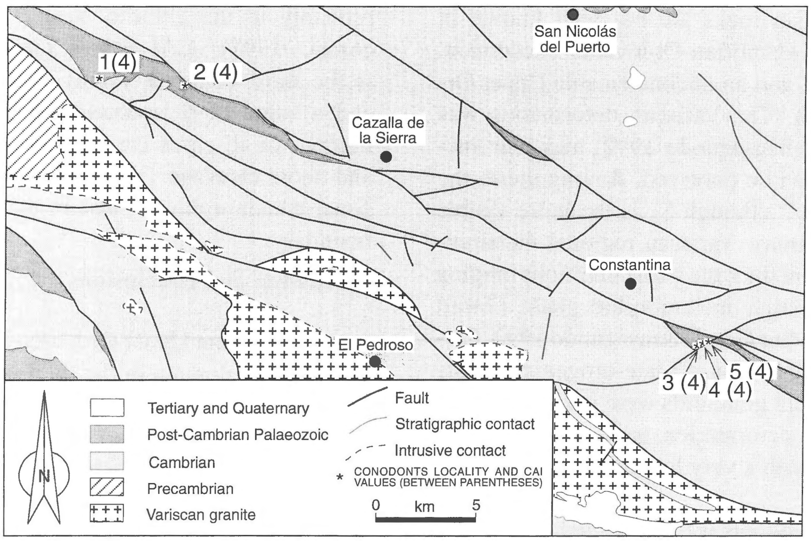

Figure 5. Localities with CAI data in the Valle and Cerrón del Hornillo synclines (Ossa Morena Zone). 1) CS-VIIA; 2) CS-VIIB; 3) CT–1; 4) CT-II; 5) CT-III. Geological map after Angoloti et al. (1975), García Monzón et al. (1974) and Sanz et al. (1975).

The anchizone boundaries applied in this paper are based on results obtained in a reference transect located in the Cantabrian Zone, where a correlation between CAI values and illite crystallinity (IC) has been established (5.5 $\geq$ CAI > 4 for the anchizone; García-López et al. 1997). This correlation agrees with that established by Gawlick et al. (1994) in the Northern Calcareous Alps and is slightly different from those established by Kóvacs & Árkai (1987) in the western Carpathians and by Keller et al. (1993) in the Argentinian Precordillera. New studies on the correlation between IC and CAI are necessary in order to obtain a greater refinement of the CAI values for the anchizone boundaries.

Frequent variations of CAI values within individual localities, and the occurrence of conodonts with a sugary texture in many of the studied areas imply some hydrothermal activity. These features have hampered the precise determination of the metamorphic grade in many localities.

According to the metamorphic grades established from CAI values in Upper Ordovician limestones, areas that underwent only diagenesis (CAI $\leq$ 4) are located in the Ossa Morena Zone (Valle and Cerrón del Hornillo synclines) and in the southern part of the Central–Iberian Zone (Almadén and Guadalmez synclines). Two anchizonal areas (5.5 $\leq$ CAI < 4) have been found: the Puertollano–Almuradiel syncline (southern part of CIZ) and the Fombuena Area (IBC). Many of the sampled areas show epizonal conditions (CAI > 5.5) or conditions in the anchizone-epizone transition: Truchas syncline, Teleno anticline and Buçaco syncline (CIZ), Nevera Massif (IBC), Les Gavarres Massif (CCR), and the Bruguera unit and Segre Valley (AZP). Within the Central-Iberian Zone, a decrease in CAI from epizonal values to diagenetic or anchizonal values towards the southeastern corner of the zone is evident.

In the Iberian Chain, an increase in CAI is observed from anchizonal values in the north (Fombuena area) to epizonal values in the south (Nevera Massif). This increase agrees with a similar increase towards the west in the West Asturian–Leonese Zone and with the interpretation of these areas of the chain as an extension of that zone. The presence of anchizonal conditions close to the boundary between the West Asturian-Leonese Zone and the Cantabrian Zone also accords with the extension interpreted for this boundary in the Iberian Chain, since the Fombuena area is close to the boundary.

Determination of IC or of clay-mineral assemblages in mudrocks, would be useful to provide further evidence for the metamorphic conditions. However, such studies have only been carried out in the Almadén syncline (CIZ; Saupé et al. 1977, Blachère 1978). In the northern limb of this structure, both CAI and IC values indicate mainly diagenetic conditions. In general, CAI values on this limb are $\leq$ 4, which is within the range of values obtained for diagenesis in the reference transect of Cape Peñas-Cape Torres (García-López et al. 1997). The presence of Devonian and Lower Carboniferous conodonts with anchizonal CAI values in the core of the Almadén syncline agrees with an increase of metamorphic grade southwards as found by Blachère (1978), who obtained epizonal IC values in the southern limb of this syncline. These data, together with the presence of a cleavage cutting the syncline (Aller et al. 1986) and probably associated with the metamorphism, indicate that the metamorphism is post-Almadén syncline.

In the areas with epizonal conditions, microscopic observation of the mineral assemblages allows determination of the metamorphic grade. In most cases, the results from previous studies in these areas agree with those obtained here from CAI values. Nevertheless, in areas with diagenetic or anchizonal conditions, CAI values have supplied new information regarding the metamorphic grade, since the information obtained from microscopic observation is limited. Cleavage is penetrative in the epizonal or anchizonal areas (CAI > 4), but it is weak or scarce in the diagenetic areas (4 $\geq$ CAI $\geq$ 2.5).

A thermal interval of 270 to 370°C in the Puertollano-Almuradiel syncline (CIZ) has been obtained by microthermometric methods (Palero 1991; pers. comm. 1996). The temperature range obtained from CAI values for this syncline is 180–340°C (CAI of 4–5.5); this range has been obtained from the Ahrrenius plot proposed by Epstein et al. (1977) and Rejebian et al. (1987), assuming a time of heating between 1 Ma (minimum time after Epstein et al. 1977) and 150 Ma (difference between the rock age and the beginning of the Stephanian, when most of the unloading by erosion in the Iberian Variscan belt had taken place). The determined thermal intervals do not coincide, but overlap considerably. The differences are probably due to local thermal variations, since different localities provided the samples used for the microthermometry and for the determination of CAI values.

Recrystallised conodonts generally occur in localities with CAI $\geq$ 5. Nevertheless, recrystallisation at CAI values of 4.5 is observed in some localities (Almadén and Puertollano–Almuradiel synclines). A minimum CAI of 5 for recrystallisation was also found by Rejebian et al. (1987), Kóvacs & Árkai (1987), Königshof (1992), and Keller et al. (1993), and is higher than that observed by García-López et al. (1997) in the Cape Peñas-Cape Torres transect (CAI = 4 for the onset of apatite recrystallisation).

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