Colour Alteration Index (CAI) of Visean conodonts from the Azrou-Khénifra Basin (Moroccan Meseta)

Indices d’altération de la couleur des conodontes (CAI) du Viséen du Bassin d’Azrou-Khénifra (Meseta marocaine)

Amal NEQQAZI*, Mohammed RAJI & El mostafa BENEFRIKA

Abstract. Colour Alteration Index (CAI) of conodonts from the Middle and Late Visean sediments in the central domain of the Azrou-Khénifra Basin showed values between 2.5 and 4.5 corresponding to paleotemperatures between 90 °C and 250 °C. The present day thermal maturity may be explained by sedimentary burial, emplacement of gravity-driven nappes and thrust westward during the Visean stage of the Variscan orogeny. A gradual increase in CAI values eastward is compatible with a gradual transition from diagenesis in the west to low-grade metamorphism in the east.

Key words: Conodont, CAI, Visean, Azrou-Khénifra Basin, Variscan orogeny.

INTRODUCTION

Conodont elements are small (mainly 0.2 to 2 mm), apatitic remains of primitive marine animals of unresolved taxonomic affinity (Turner et al. 2010) common in Cambrian to late Triassic rocks. These tooth-like microfossils become a widely used tool in integrated basin analysis and hydrocarbon exploration because of their coupled use as precise biostratigraphic markers and thermal maturity indicators (Voldman et al. 2010).

The conodont Colour Alteration Index (CAI) was established by Epstein et al. (1977). They determined five stages of progressive and irreversible colour changes ranging from yellow to black (1<CAI<5) due to carbon-fixing of organic matter in their skeleton. Then, Rejebian et al. (1987) extended the CAI scale to index 8 explaining colour changes from black to crystal clear (5<CAI<8) as a result of carbon loss release of water of crystallization and recrystallization of apatite. Epstein et al. (1977) and Rejebian et al. (1987) calibrated the different CAI values, ranging in temperature from 50 to ~600 °C, by means of laboratory experiments, and extrapolated their experimental data to geologic time scales through the Arrhenius plot (Fig. 1). The CAI method was widely used in the reconstruction of the thermal history of sedimentary basins and in determining thermal aureoles related to igneous intrusions (e.g., Belka 1991, Harris et al. 1994, García-López et al. 1997, Königshof & Boncheva 2005, Voldman et al. 2010, Zielinski 2012).

The purpose of this study is to recognize the thermal maturation trends in the Middle and Late Visean rocks of the Azrou-Khénifra Basin in the central domain by method of condont Colour Alteration Index (CAI), and also to interpret their causes and geological significance.

GEOLOGICAL SETTING

The central Moroccan Meseta (Fig. 2A) belongs to the external Moroccan Variscides (e.g., Piqué et al. 1993, Hoepffner et al. 2005). Within that tectonically complex structural domain, the Sidi Bettache Basin and the Azrou-Khénifra Basin are placed (Fig. 2B). The latter comprises Carboniferous siliciclastic and carbonate rocks resting unconformably on, and in thrust contact with, Ordovician to Devonian rocks, all affected by the later Variscan Orogeny (e.g., Allary et al. 1976, Hollard 1978, Piqué 1983, Beauchamp & Izart 1987, Hoepffner 1987, Bouabdelli & Piqué 1996, Hoepffner et al. 2005).

The Tournaisian rock is composed mainly of conglomerates and greywackes, with the laminated sandstones (Fig. 3). Unconformable limestones were deposited then during Middle Visean time (Berkhli et al. 2000), followed by Late Visean turbiditic series whose upper parts contain olistostromes (Beauchamp & Izart 1987). In the central domain of the Azrou-Khénifra Basin, the thickness of the Carboniferous deposits changes from about 2300 m in the northern part to about 1600 m in the southern part (Bouabdelli 1989).

During the Early Carboniferous, the Azrou-Khénifra Basin was affected by an important tectonic activity, especially at its eastern margin. Here, the olistostromes (ordovician to carboniferous materials) that were deposited have been related (i) to the emplacement of gravity-driven nappes gliding towards central part of the Azrou-Khénifra
Basin from its eastern uplifted margin (e.g., Allary et al. 1976, Huvelin 1977, Jenny & Le Marrec 1980, Bouabdelli 1989, Jenny et al. 1989), (ii) to some extension faults (e.g., Beauchamp & Izart 1987, Verset 1988, Berkli et al. 2000, Izart et al. 2001b), or (iii) to the dislocation of shelves by extension faults at the nose of a duplex complex moving from east to west during the Visean-Namurian (Benabbou 2001, Benabbou et al. 2001).

Figure 1. Epstein et al. (1977) and Rejebian et al. (1987) Arrhenius plot of conodont temperature data showing the range of minimum burial temperatures for Visean conodonts (CAI values from 2.5 to 3) from the central domain of the Azrou-Khénifra Basin. Duration of burial has been taken as 35 m.y, assuming beginning of unloading in Late Carboniferous time.

Figure 2. Main structural subdivision of northern Morocco (map modified from Hoepffner et al. 2005) (A), and location of the studied area in the Azrou-Khénifra Basin (Bouabdelli & Pique 1996) (B).
The regional evolution of the Azrou-Khénifra Basin suggests the development of a foreland basin (Bouabdelli & Piqué 1996, Benaboub 2001, Benaboub et al. 2001) parallel to the Variscan deformation front. There, folding occurred during Late Visean time (Huon 1985). It developed northwest facing recumbent folds, from Tazekka massif to Khénifra. Locally, these structures were thrust northwest during the latest stages of the deformation. After these thrust episodes, the depocenter of the foreland basin moved westward (Bouabdelli 1989). Marine sedimentation persisted up to early Westphalian time in some western parts of the basin (Bouabdelli & Piqué 1996). Finally, the Carboniferous series were folded during the Late Carboniferous phase (Piqué 1989). The Late Carboniferous deformations affected the whole Central Meseta. Considered as the major phase by Michard (1976), these deformations post-dated the Westphalian and predated the Stephanian-Permian. Small neofomed micas developed during this deformation yielded K/Ar isotopic ages between 300 and 290 Ma (Huon et al. 1987). This deformation is complex and polyphased. The general direction of the folds is NNE-SSW to NE-SW (Bouabdelli & Piqué 1996, Hoepffner et al. 2005).

**RESULTS**

In this study, the CAI isograd map has been compiled for one stratigraphic interval Middle and Late Visean (Fig. 4). A general pattern with CAI values increasing from NW to SE can be observed in the northern part of the central domain. The highest values (CAI 4.5) are concentrated in Jebel Akerchi. Away from this area, in northwesterly direction, the CAI decreases with a minimum value of 2.5 recorded near western margin of the central domain. In the southern part of the central domain, conodont samples have been obtained only from two localities of Late Visean age, in the vicinity of BaMoussa and Jebel Tabainout. Their CAI values range from 3 to 4. All conodont elements of this zone show a bright lustre and smooth surfaces.

**INTERPRETATION AND DISCUSSION**

It seems that the observed CAI pattern in the central domain of the Azrou-Khénifra Basin (Fig. 4) is a product of sedimentary burial and deformation. The moderate CAI values (2.5±3) in the northwest, corresponding to temperatures of 90±125 °C (Fig. 1), are compatible with a Visean-Namurian sedimentary overload of 2300 m and geothermal gradient of 40 °C/km enregistered in this zone (Bouabdelli 1989). The passage to relatively high values (4.5±4.5), corresponding to temperatures of 190±250 °C (Fig. 1), toward the east may be explained by observed increases of deformation shown by westward-directed folding and thrusting, during the Late Visean-Namurian (Allary et al. 1976, Bouabdelli & Piqué 1996, Benaboub et al. 2001). These deformation are related to the emplacement of the oriental domain.

The gradually increase of CAI can be also correlated with a progressive passage from diagenetic zone (IC = 8) in the west to metamorphic zone (anchizon to epizone ; IC = 2.7) in the east of the central domain (Bouabdelli 1989 and 1994).

Because the recognized maturation patterns reflect the Variscan depositional and burial patterns, it becomes evident that the Carboniferous rocks in the Azrou-Khénifra Basin achieved their present-day maturation level during the Carboniferous subsidence prior to the Variscan orogeny. It can not be established for certain, however, when the maximum burial and heating occurred. Based on data from the Azrou-Khénifra Basin, it is suggested that folding and uplift of the central Meseta took place during the Late Carboniferous (Piqué 1989), most probably after the Westphalian. The Westphalian age of folding has been suggested by K/Ar isotopic, between 300 and 290 Ma (Huon et al. 1987) for the regional deformation. If unloading began just after the Westphalian, the maximum time for burial and heating of the Visean rocks is not more than 35 m.y. Using the correlation of time with the CAI rank of Epstein et al. (1977), it is possible to estimate the maximum burial paleotemperatures. Taking into account the United States Geological Survey (USGS) using the standard method described by Epstein et al (1977).

Once a sample is indexed, a temperature range can be determined using an Arrhenius plot of the experimental data of Epstein et al (1977) (Fig. 1).

**MATERIAL AND METHODS**

The present paper is based on Early Carboniferous (Visean) conodont samples collected in the central domain of the Azrou-Khénifra basin (according description of Bouabdelli 1989).

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CAI values from 2.5 to 3, observed in the central domain of the Azrou-Khénifra Basin and a duration of burial of about 35 m.y, estimated burial temperatures range between 90 °C and 125 °C (Fig. 1).

A previous CAI study in the Devonian of the area (Raji & Benfrika 2009) shows that the CAI values are ranged from 2.5 to 3.5 (Fig. 5), indicating a temperature interval from 90 °C to 170 °C. These values are observed in autochthonous unit and in allochthonous unit. A comparison between CAI values of the Devonian and the Early Carboniferous conodonts of the central domain shows similar variation.

Table. 1: Details and conodont CAI data for samples from Visean rocks in the central domain of the Azrou-Khénifra Basin. Each numbered entry corresponds to a numbered location on Fig. 1. Locality frames and coordinates are taken from the map of Morocco 1/50 000°.

<table>
<thead>
<tr>
<th>Nº sample locality</th>
<th>Sheet 1/50000</th>
<th>Number of samples</th>
<th>Lithology of host rock</th>
<th>Age</th>
<th>CAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Akerchi</td>
<td>El Hajeb</td>
<td>3</td>
<td>calcareous sandstones</td>
<td>Late Visean</td>
<td>4.5</td>
</tr>
<tr>
<td>2 BouBalghatene</td>
<td>Ain Leuh</td>
<td>2</td>
<td>calcareous sandstones</td>
<td>Late Visean</td>
<td>2.5</td>
</tr>
<tr>
<td>3 BouBalghatene</td>
<td>Ain Leuh</td>
<td>1</td>
<td>limestones</td>
<td>Late Visean</td>
<td>3</td>
</tr>
<tr>
<td>4 BouBalghatene</td>
<td>Ain Leuh</td>
<td>2</td>
<td>limestones</td>
<td>Late Visean</td>
<td>2.5</td>
</tr>
<tr>
<td>5 Daa Alhagra</td>
<td>Ain Leuh</td>
<td>1</td>
<td>calcareous sandstones</td>
<td>Middle Visean</td>
<td>3</td>
</tr>
<tr>
<td>6 Akechmir nô Bou Annou</td>
<td>Ain Leuh</td>
<td>1</td>
<td>Limestones</td>
<td>Middle Visean</td>
<td>3</td>
</tr>
<tr>
<td>7 Tizi Mouchenkour</td>
<td>Ain Leuh</td>
<td>1</td>
<td>Limestones (olistolites)</td>
<td>Late Visean</td>
<td>4</td>
</tr>
<tr>
<td>8 Afroug</td>
<td>Bou Chber</td>
<td>1</td>
<td>Limestones</td>
<td>Late Visean</td>
<td>2.5</td>
</tr>
<tr>
<td>9 Tichout Oulabas</td>
<td>Bou Chber</td>
<td>2</td>
<td>calcareous sandstones</td>
<td>Late Visean</td>
<td>2.5</td>
</tr>
<tr>
<td>10 Akechmir nô Ferrane</td>
<td>Bou Chber</td>
<td>2</td>
<td>Limestones (olistolites)</td>
<td>Late Visean</td>
<td>3</td>
</tr>
<tr>
<td>11 BaMoussa</td>
<td>Khénifra</td>
<td>1</td>
<td>Limestones (olistolites)</td>
<td>Late Visean</td>
<td>3</td>
</tr>
<tr>
<td>12 Tabâînout</td>
<td>Kef en Nsour</td>
<td>1</td>
<td>Limestones</td>
<td>Late Visean</td>
<td>3</td>
</tr>
<tr>
<td>13 Tabâînout</td>
<td>Kef en Nsour</td>
<td>2</td>
<td>Limestones</td>
<td>Late Visean</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 4. CAI map for the Middle and Late Visean in the central domain of the Azrou-Khénifra Basin.
CONCLUSION

The conodont CAI values from the Middle and Late Visean of the central domain of the Azrou-Khénifra basin range from 2.5 to 4.5. The moderate values (CAI = 2.5 to 3) can be explained by the sedimentary overburden. These suggest burial paleotemperatures of 90 °C and 125 °C, respectively. The conodont CAI pattern shows that the Visean rocks of the central domain of the Azrou-Khénifra attained their present-day maturation level during the Late Carboniferous prior to Variscan uplift.

The high CAI values (≫4.5; 195–250 °C) were found in the central domain. They probably result of the sedimentary overburden influence and emplacement of nappes during the Variscan deformation. The CAI pattern of the Early Carboniferous conodonts shows a similar variation to that of the Devonian (Raji & Benfrika 2009).

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