Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Terre, 2014, n° 36, 13–18. ***e-ISSN : 2458-7184***

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 BENFRIKA

*University Hassan II of Casablanca, Faculty of Sciences Ben M'sik, Department of Geology, Boulevard Cdt Driss Harti, B.P. 7955, Ben M'Sik, Casablanca, Morocco *(neqqazi.amal@gmail.com).*

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.

Résumé. Les indices d'altération de la couleur des Conodontes (CAI) du Viséen moyen à supérieur dans le domaine central du bassin d'Azrou-Khénifra, ont montré des valeurs de CAI allant de 2,5 à 4,5 correspondants à des températures de 90 °C à 250 °C. Ces valeurs peuvent être expliquées par l'enfouissement sédimentaire, la mise en place de nappes gravitaires et par le chevauchement du domaine oriental sur le domaine central pendant la phase intraviséenne de l'orogenèse varisque. Une augmentation progressive de CAI, observée vers l'Est, est compatible avec un passage d'une zone diagénétique à l'Ouest vers une zone métamorphique à l'Est.

Mots clés : Conodontes, 'CAI', Viséen, bassin d'Azrou-Khénifra, orogenèse varisque.

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 its 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, Garcia-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, Berkhli *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).

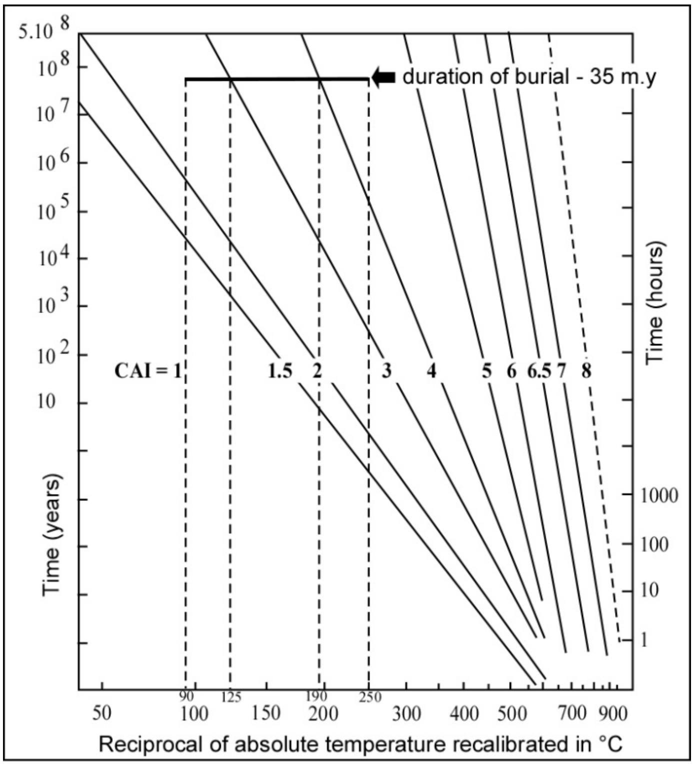

Figure 1. Epstein *et al.* (1977) and Rejebian *et al.* (1987) Arrhenius plot of conodont temperature data showing the range of minimum burial temperatures for Visean conodonts (CAI values from 2.5 to 3) from the central domain of the Azrou-Khénifra Basin. Duration of burial has been taken as 35 m.y,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

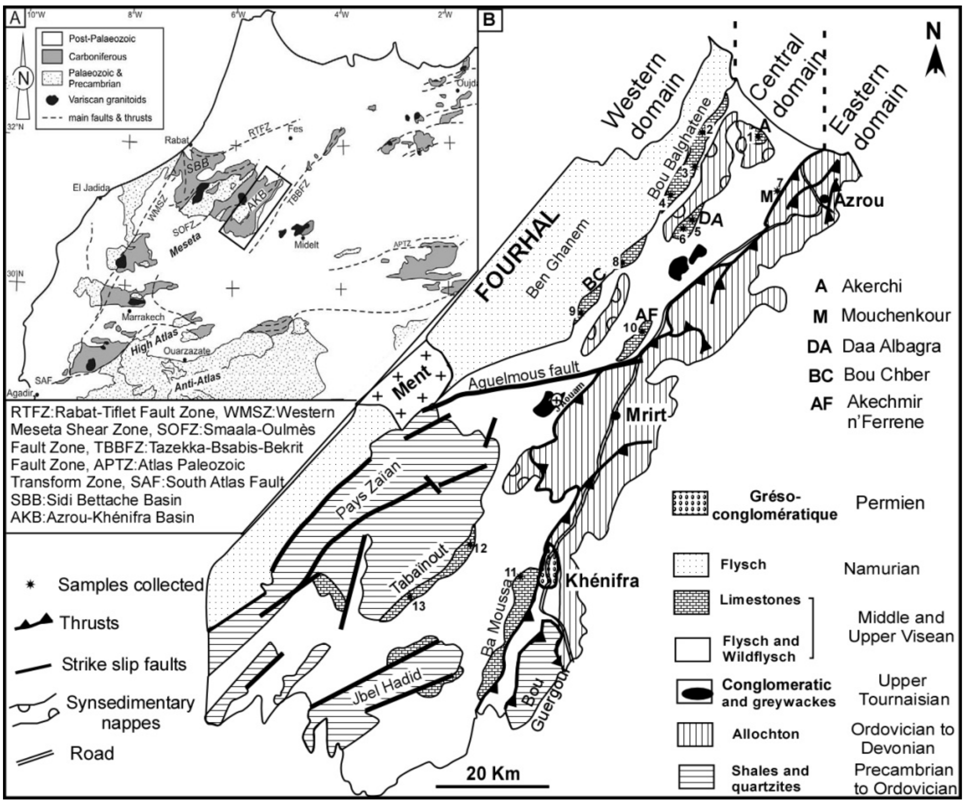

Figure 2. Main structural subdivision of northern Morocco (map modified from Hoepffner *et al.* 2005) (A), and location of the studied area in the Azrou-Khénifra Basin (Bouabdelli & Pique 1996) (B).

The regional evolution of the Azrou-Khénifra Basin suggests the development of a foreland basin (Bouabdelli & Piqué 1996, Benabbou 2001, Benabbou *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 northwestward 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 neoformed 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).

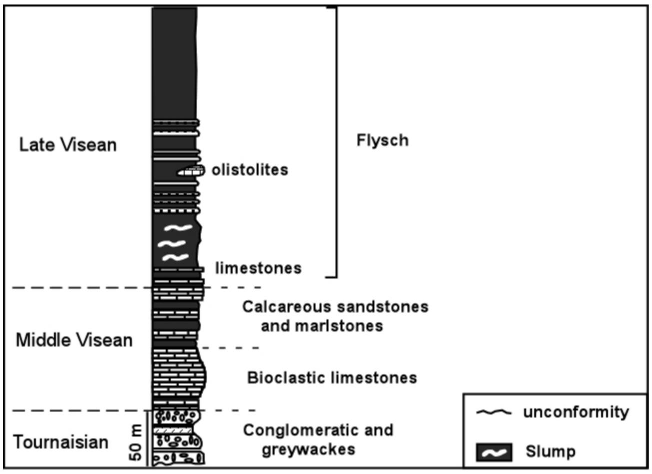

Figure.3. Synthetic stratigraphic log of Lower Carboniferous in the central domain of the Azrou-Khénifra basin (according description of Bouabdelli 1989).

MATERIAL AND METHODS

The present paper is based on Early Carboniferous (Visean) conodont samples collected in the central domain of the Azrou-Khénifra Basin. The majority of samples were obtained from limestones and calcareous sandstones. Among more than 80 surface samples collected, only 20 from 12 localities (Fig. 2B) were productive. The numbers examined are as follows: Middle Visean (2) and Late Visean (18). The localities, their geographic location, age of samples, and CAI values are given in Table 1. The CAI values analyses were performed on the conodont genera *Lochriea* (*L. commutata, L. mononodosa, L. homopunctatus*), *Gnathodus* (*G. girtyi, G. bilineatus*) and *Mestognathus* (*M. bipluti*).

All the samples were treated with standard techniques for extracting conodonts, using acetic acid (Jeppsson *et al.* 1985). CAI values were determined by comparison with a standard conodont CAI scale provided by Anita Harris of 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).

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 enregistred in this zone (Bouabdelli 1989). The passage to relatively high values (4–4.5), 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, Benabbou *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

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^{e}.

N° sample locality	Sheet 1/50000	Numbre of samples	Lithology of host rock	Age	CAI
1 Akerchi	El Hajeb	3	calcareous sandstones	Late Visean	4.5
2 BouBalghatene	Aïn Leuh	2	calcareous sandstones	Late Visean	2.5
3 BouBalghatene	Aïn Leuh	1	limestones	Late Visean	3
4 BouBalghatene	Aïn Leuh	2	limestones	Late Visean	2.5
5 Daa Albagra	Aïn Leuh	1	calcareous sandstones	Middle Visean	3
6 Akechmir n'Bou Annou	Aïn Leuh	1	Limestones	Middle Visean	3
7 Tizi Mouchenkour	Aïn Leuh	1	Limestones (olistolites)	Late Visean	4
8 Afroug	Bou Chber	1	Limestones	Late Visean	2.5
9 Tichout Oulabas	Bou Chber	2	calcareous sandstones	Late Visean	2.5
10 Akechmir n'Ferrane	Bou Chber	2	Limestones (olistolites)	Late Visean	3
11 BaMoussa	Khénifra	1	Limestones (olistolites)	Late Visean	3
12 Tabaïnout	Kef en Nsour	1	Limestones	Late Visean	3
13 Tabaïnout	Kef en Nsour	2	Limestones	Late Visean	4

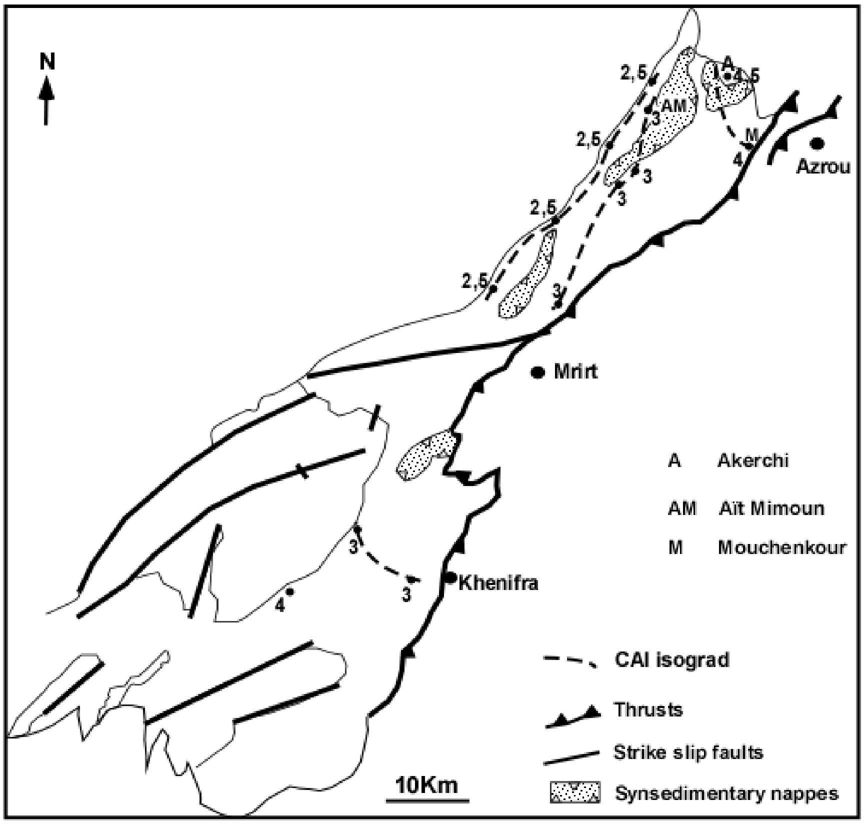

Figure 4. CAI map for the Middle and Late Visean in the central domain of the Azrou-Khénifra Basin.

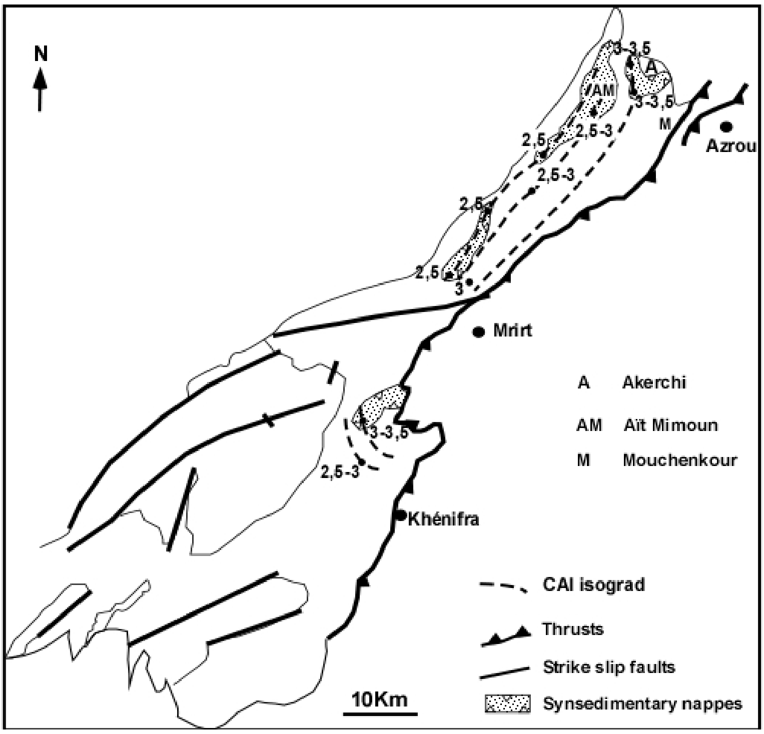

Figure 5. CAI map for the Devonian in the central domain of the Azrou-Khénifra Basin (Raji & Benfrika 2009).

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 (4–4.5; 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).

ACKNOWLEDGMENTS

This study is a part of the PhD thesis of the first author. We are indebted to Dr. Anita Harris of the United States Geological Survey for providing some of her conodont specimens to make CAI reference set. We thank Prof. Abdelfatah Tahiri, Department of Earth Sciences, Scientific Institute, University Mohammed V of Rabat (Morocco) for useful remarks and suggestions to the early version of this manuscript. The two anonymous reviewers are deeply indebted for providing thorough comments and corrections, which greatly improved the manuscript.

REFERENCES

Allary A., Lavenu A. & Ribeyrolles M. 1976. Etude tectonique et microtectonique d'un segment de chaîne hercynienne dans la partie sud-orientale du Maroc central. *Notes et Mémoires du Service Géologique du Maroc*, 261, 169 p.

Beauchamp J. & Izart A. 1987. Early Carboniferous basins of the Atlas-Meseta domain (Morocco): sedimentary model and geodynamic evolution. *Geology*, 15, 787–800.

Belka Z. 1991. Conodont colour alteration patterns in Devonian rocks of the eastern Anti-Atlas, Morocco. *Journal of African Earth Sciences*, 12, 417–428.

Benabbou M. 2001. *Dynamique des bassins d'avant-pays carbonifères: signatures tectoniques, sédimentaires et magmatiques de l'évolution de la chaîne hercynienne du Maroc Central septentrional*. Thèse de Doctorat ès-sciences, Université Cadi Ayyad, Marrakech, 312 p.

Benabbou M., Soula J.C., Brusset S. *et al*. 2001. Contrôle tectonique de la sédimentation dans le système de bassin d'avant pays de la Meseta marocaine. *Comptes Rendus de l'Académie des Sciences*, 332, 703–709.

Berkhli M., Vachard D., Paichler J.C. *et al*. 2000. Modèle sédimentaire et évolution géodynamique du Nord-Est de la Meseta occidentale marocaine au cours du Carbonifère inférieur. *Comptes Rendus de l'Académie des Sciences, Earth and Planetary Sciences*, 331, 251–256.

Bouabdelli M. 1989. *Tectonique et sédimentation dans un bassin orogénique: le sillon d'Azrou-Khénifra (Est du massif Hercynien central du Maroc)*. Thèse ès-Sciences, Université Louis Pasteur, Strasbourg, 262 p.

Bouabdelli M. 1994. Tectonique de l'Est du Massif hercynien central (zone d'Azrou-Khenifra). *In*: A. El Hassani, A. Piqué & A. Tahiri (Eds.) - Le Massif Central marocain et la Meseta orientale. *Bulletin de l'Institut Scientifique*, 18, 145–168.

Bouabdelli M. & Piqué A. 1996. Du bassin sur décrochement au bassin d'avant-pays: Dynamique du bassin d'Azrou-Khénifra (Maroc Hercynien Central). *Journal of African Earth Sciences,* 23, 213–223.

Epstein A.G., Epstein J.B. & Harris L.D. 1977. Conodont Colour Alteration- an index to organic metamorphism. *United States Geological Survey Professional*, Washington, 995, 1–27.

Garcia-López S., Brime C., Bastida F. *et al*. 1997. Simultaneous use of thermal indicators to analyse the transition from diagenesis to metamorphism: an example from the Variscan Belt of northwest Spain. *Geological Magazine*, 134, 323–334.

Harris A.G., Stamm N.R., Weary D.J. *et al*. 1994. Conodont color alteration index (CAI) map and conodont-based age determinations for the Winchester 30'x 60' quadrangle and adjacent area, Virginia, West Virginia, and Maryland. *Geological Survey Miscellaneous Investigations Series*, Washington, Map MF–2239.

Hoepffner C. 1987. *La tectonique hercynienne dans l'Est du Maroc*. Thèse ès-Sciences, Strasbourg, Université Louis Pasteur, 276 p.

Hoepffner C., Soulaimani A. & Piqué A. 2005. The Moroccan hercynides. *Journal of African Earth Sciences*, 43, 144–165.

Hollard H. 1978. L'évolution hercynienne au Maroc. *Zeitschrift der Deutschen Geologischen Gesellschaft*, 129, 495–512.

Huon S. 1985. *Clivage ardoisier et ré-homogénéisation isotopique K-Ar dans des schistes paléozoïques du Maroc. Etude structurale et isotopique. Conséquences régionales*. Thèse de Doctorat, Université Louis Pasteur, Strasbourg, 124 p.

Huon S., Piqué A. & Clauer N. 1987. Etude de l'orogenèse hercynienne au Maroc par la datation K-Ar de l'évolution métamorphique de schistes ardoisiers. *Sciences géologiques, Bulletin*, 40, 273–284.

Huvelin P. 1977. *Etude géologique et gitologique du massif hercynien des Jebilet (Maroc occidental)*. Notes et Mémoires Service Géologique Maroc, 232 bis, 308 p.

Izart A., Chèvrement P., Tahiri A. *et al*. 2001b. *Carte géologique du Maroc au 1/50 000, feuille de Bouqachmir. Mémoire explicatif*. Notes et Mémoires Service géologique du Maroc, 411 bis, 60 p.

Jenny J & Le Marrec A. 1980. Mise en évidence d'une nappe à la limite méridionale du domaine hercynien dans la boutonnière d'Aït Tamelil (Haut Atlas central), Maroc. *Eclogae Geologica Helvetica,* 73, 3, 681–696.

Jenny J., Izart A. & Lesage J.L. 1989. La boutonnière d'Aït Tamelil, évolution tectono-sédimentaire durant le Viséen et structuration du segment hercynien du Haut Atlas central (Maroc). *Notes et Mémoires Service Géologique Maroc*, 335, 239–250.

Jeppsson L., Fredholm D. & Mattiasson B. 1985. Acetec acid and phosphatic fossils - a warning. *Journal of Palaeontology*, 59, 4, 952–956.

Königshof P. & Boncheva I. 2005. Maturation patterns in Palaeozoic rocks of north-eastern Bulgaria based on conodont colour alteration index (CAI) data. *Bulletin of Geosciences*, 81, 223–237.

Michard A. 1976. *Eléments de géologie marocaine*. Notes et Mémoires Service Géologique Maroc, 252, 408 p.

Raji M & Benfrika E.M. 2009. *L'indice de l'altération de la couleur des conodontes : Indicateur d'activité hydrothermale. L'exemple du Dévonien de Mrirt (Maroc central oriental)*. Notes et Mémoires du Service Géologique du Maroc, 1, 530 p.

Rejebian V.A., Harris A.G. & Huebner J.S. 1987. Conodont color and textural alteration: an index to regional metamorphism, contact metamorphism, and hydrothermal alteration. *Geological Society of America Bulletin*, 99, 471–479.

Piqué A. 1983. Structural domains of the Hercynian Belt in Morocco. *In*: Schenk P.E (Eds.). Regional Trends in the Geology of the Appalachian Caledonian Hercynian Mauritanide orogen. *Reidel Publication Company*, Dordrecht, Holland, 339–345.

Piqué A. 1989. Variscan terranes in Morocco. *Geological Society of America, Special Paper*, 230, 115–129.

Piqué A., Bossière G., Bouillin J.P. *et al*. 1993. The southern margin of the Variscan belt. The northwestern Gondwana mobile zone (Eastern Morocco and Northern Algeria). *Geologische Rundschau*, 82, 432–439.

Turner S., Burrow C.J., Schultze H.P. *et al*. 2010. False teeth: conodont-vertebrate phylogenetic relationships revisited. *Geodiversitas*, 32, 545–594.

Verset Y. 1988. *Carte géologique du Maroc au 1/100 000, feuille Qasbat Tadla. Mémoire explicatif.* Notes et Mémoires Service Géologique Maroc, 340 bis, 131 p.

Voldman G.G., Albanesi G.L. & Ramos V.A. 2010. Conodont geothermometry of the lower Paleozoic from the Precordillera (Cuyania terrane), northwestern Argentina. *Journal of South American Earth Sciences,* 29, 278–288.

Zielinski M. 2012. Conodont thermal alteration patterns in Devonian and Carboniferous rocks of the Ahnet and Mouydir basins (southern Algeria). *Marine and Petroleum Geology*, 38, 166–176.

Manuscrit reçu le 15.07.2014
Version révisée acceptée le 04.03.2015
Version finale reçue le 14/06/2015
Mise en ligne le 23/06/2015