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Illite crystallinity patterns in the Anti-Atlas of Morocco

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Key words: Anti-Atlas, low-grade metamorphism, Illite crystallinity, paleo-geothermal gradient, Carboniferous

ABSTRACT

The low-grade metamorphism of the sedimentary cover of the Moroccan Anti-Atlas is investigated using Illite crystallinity (IC) method. More than 200 samples from three key areas (southwestern, central and eastern Anti-Atlas) have been taken from a maximum of different stratigraphic levels and have been analysed. The metamorphism is of low to very low degree throughout the southern flank of the Anti-Atlas. It increases from northeast to southwest. Whereas in the eastern Anti-Atlas diagenetic and anchizonal IC-values are predominant, in the western and central Anti-Atlas also epizonal IC-values are found. In every respective area the IC improves with stratigraphic age. At the scale of the entire Palaeozoic Anti-Atlas basin the IC correlates best with estimated paleo-overburden. However, burial metamorphism cannot be the cause even though considering missing sedimentary pile of Late Carboniferous age. The 'abnormal' paleo-geothermal gradient of 43–35 °C/km we evidenced for the Carboniferous is a true one, and has to be related to a basement sequence enriched in heat producing elements such as series of the West African Craton.

1. Introduction

For more than fifty years the area of the Anti-Atlas (AA) in southern Morocco has attracted the interest of many geologists and palaeontologists because of the presence of a very complete, nearly un-metamorphosed Palaeozoic sedimentary sequence. The Precambrian-Cambrian boundary is well exposed over a very large area in the AA (e.g., Boudda et al. 1979; Bertrand-Sarfat 1981; Buggisch & Flügel 1988). A structural overview of the region can be found in Burkhard et al. (2006 and references therein) as well as in Robert-Charrue & Burkhard (this volume) for the eastern AA.

Previous studies of the AA metamorphism have either concentrated on one distinct stratigraphic horizon or on specific locations. Buggisch (1988) studied the low and very low-grade metamorphism of the Cambrian 'Grès terminaux' in the Anti-Atlas on the basis of 'Illite Crystallinity' measurements and quartz deformation. Results show that the Illite crystallinity improves from E to W, which was interpreted as the result of mobility of the basement during the Hercynian orogeny implying that the metamorphism is of Variscan age. Belka (1991) investigated the thermal and burial history of the eastern Anti-Atlas in Late Palaeozoic time using conodont color alteration data whereas Bonhomne & Hassenforder (1985) produced K/Ar and Rb/Sr data to constrain the Hercynian metamorphism in the late-to post-Panafrican units of the western Anti-Atlas (see discussion).

The objectives of this paper are thus to: 1) document and compare the post-Panafrican metamorphism (as expressed through Illite 'Crystallinity') along the ENE-WSW oriented Anti-Atlas belt, 2) investigate the relationship between stratigraphy and Illite 'Crystallinity' and 3) constrain the origin of the metamorphism observed along the southwestern flank of the Anti-Atlas.

2. Geological setting

The Anti-Atlas (AA) foreland fold belt of south-western Morocco is a part of the Variscan Appalachian-Ouachita-Mauritanides orogenic belt. It is located at the north-western border of the West-African Craton (WAC) and to the south of the High-Atlas (Fig. 1). Large scale basement cored domes with irregular shape and uneven distribution form a large southwest-northeast trending anticlinorium. These so-called "bou-

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tonnières" (Choubert & Marçais 1952; Choubert 1963), which is classically understood as vertical block movements with very few horizontal shortening only, are hold responsible for most of the deformation, except in the south-westernmost areas (Soulaimani et al. 1997; Belfoul et al. 2002).

Above, a thick series of post-Panafrican passive margin sediments is involved in disharmonic but mostly gentle folding at different scales. The shortening in the western part of the AA lies between 15% and 25% (Helg et al. 2004; Burkhard et al. 2006). No large-scale thrusting or duplexing is known. The Variscan metamorphism is generally of low to very low degree (Faure-Muret 1971; Michard 1976; Piqué & Michard 1989; Piqué et al. 1991; Piqué 2001; Soulaimani et al. 1997 & 1998; Choubert 1963; Bonhomme & Hassenforder 1985).

The pre-Variscan sedimentary cycle of the AA started in the uppermost Precambrian (Ediacaran) with the deposition of complex series of coarse grained detrital deposits, most probably in a intracontinental rift related context. It lasted until the Early Carboniferous (Visean) in the folded domain (eastern AA) and is almost complete. In the western AA up to 10 km of varied clastic and calcareous sediments were deposited in a dominantly shallow epicontinental sea (Michard 1976) where deep subsiding basins differentiated during the Devonian (Ouanaini & Lzreq 2008; Baidder et al. 2008). Eastward, toward the central Anti-Atlas this thickness is decreasing to about 8 km. The basin fill is characterized by a high amount of fine grained detrital, clay rich sediments: siltsones, mudstones and shales. Quartzites, sandstones, limestones and conglomerates form thin but continuous beds at different stratigraphic levels. These horizons form spectacular, continuous crests, easily visible on satellite and aerial images.

3. Methodology

For very low-grade sedimentary series such as the AA ones, the combined mapping of 'Illite crystallinity' values and the occurrence of index minerals is a well-suited tool because rapid and inexpensive, to estimate the evolution from diagenesis to low-grade metamorpshism (Frey & Robinson 1999; Kisch 1980, 1987). However, they should primarily be understood as statistical means, i.e. if the construction of isocrysts is the aim, sufficient area coverage is crucial and large numbers of samples have to be analyzed (Burkhard & Goy-Eggenberger 2001). Even if not detected in sufficient samples for the mapping of true isogrades, index minerals can be an important piece of information to 'calibrate' iso-crystallinity patterns. Vitrinite reflectance (VR) is a classical tool used for the study of low-grade metamorphic rocks. Vitrinite sensu stricto is considered to be non-existent in pre-Silurian rocks, and we therefore decided not to use this method. Although methods exist to cope with pre-Silurian rocks (essentially by studying vitrinite-like macerals) a break at Ordovician-Silurian boundary remains and hampers the direct comparison of pre-Silurian with younger rocks. The IC-Method is thus well-suited for the AA because it can be applied to the entire sedimentary succession, and allows a straightforward comparison of different sections.

3.1. Illite crystallinity

The Illite 'crystallinity' index (IC) has been determined by measuring the width at half height of the 001 Illite reflection ($\Delta°2\theta CuK\alpha$) on air dried and glycolated slides. With progressively higher metamorphic grade the 001 Illite reflection becomes narrower whereas the width of the peak at half height (the so-called Scherrer Width, 'SW') decreases, the Illite crystallinity is said to 'increase' (or to 'improve'; Frey & Robinson 1999; Burkhard & Goy-Eggenberger 2001). All samples have been analyzed at the XRD-laboratory of the Geological Institute at the University of Neuchâtel using a SCINTAG equipment, and standard conditions. The diagenesis-anchizone boundary is defined at 0.33 ($°2\theta CuK\alpha$) whereas the anchizone-epizone limit is defined at 0.22 ($°2\theta CuK\alpha$).

3.2. Sampling

The sedimentary cover of the Anti-Atlas is generally of low structural complexity except in the south-westernmost areas (Ifni) which are not considered here. Large scale thrusts or nappes are absent and the sedimentary succession is undisturbed. Therefore we consider a specific sample a priori representative for a much larger area. IC-values can be compared and averaged over wider distances than in complexly deformed terrains. As a consequence, rather than aiming to achieve a regular distribution of sample sites, we focused on sampling a maximum of different stratigraphic levels. Most of the samples come from the south-eastern flank of the Anti-Atlas anticlinorium since here almost the entire Palaeozoic is exposed (Fig. 1). We concentrated on three key areas where a more or less complete stratigraphy can be sampled, these are from SW to NE (Fig. 2) the 1) Goulimine-Assa (Assa-Zag road, SW Anti-Atlas), 2) Tata Area (Central Anti-Atlas) and finally 3) Tafilalt area (eastern Anti-Atlas).

3.3. Sample preparation and XRD measurements

Oriented clay mounts were prepared according to the standard method of Kübler (1967). The following conditions were used for the measurement of XRD profiles: X-ray powder diffractometer (Scintag's XDS 2000); the spectral counter (KEVEX PSI1, PELTIER cooled silicon detector); wavelength of 1.5406 A Cu-Kα1; generator settings of 45 kV and 40 mA; slits – emitter: 2 mm, 4 mm; receiver: 0.5 mm, 0.3 mm; goniometer speed of 1°/min; chopper increment of 0.03; continuous scan from 2° to 70° 2T; and circular glass plates (D = 2.5 cm), spinning about a vertical axis. The files generated with SCINTAG are of raw data, which are routinely reduced to 'net intensity' by the application of a fast Fourier noise filter, background subtraction and Kα2 stripping. All measurements were made on the 'net intensity' files using the SCINTAG DMS program. The IC measure-

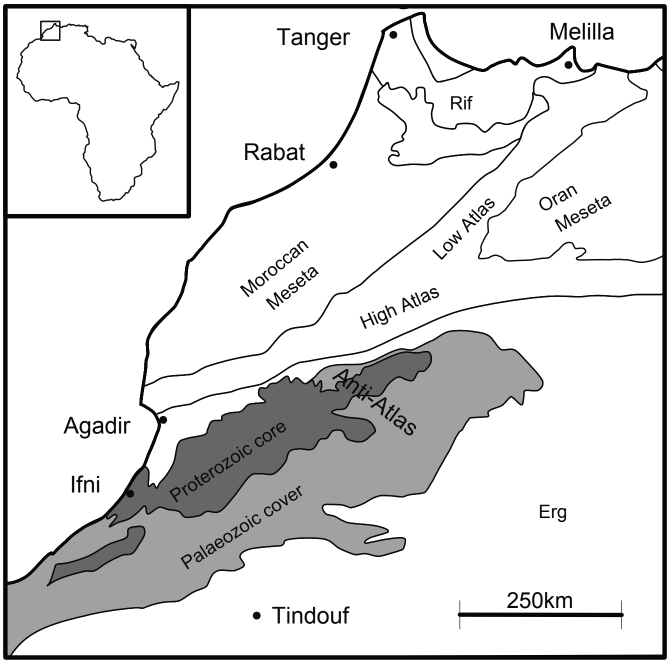

Fig. 1. Location map of the Variscan Anti-Atlas belt in the southern part of Morocco. A virtually complete stratigraphy of the folded Palaeozoic Anti-Atlas series is exposed along the southern flank of the anticlinorium.

ments were made on the first (10 Å) mica reflection of oriented clay XRD pattern. The IC were measured on air-dried samples in the <2 μm and partially 2–16 μm grain size-fraction.

4. Results

A total of 202 Palaeozoic samples have been analyzed. 114 samples consisted of fine-grained rocks such as shales, slates, mudstones, siltstones. 49 samples were marls, sandy limestones, and 'pure' micritic limestones. 39 samples were 'impure' silty, clay-rich sandstones.

Despite the varying lithologies, Illite and chlorite were by far the most common clay minerals in the <2 μ fraction. Mixed-layer clay minerals are detected only occasionally and always in small quantities. From all the typical index minerals only kaolinite, smectite, rectorite, paragonite and pyrophyllite could be found in quantities sufficient to be reliably identified. However, for kaolinite and smectite a post-metamorphic neo-formation cannot be completely excluded. These minerals have been detected throughout all metamorphic zones, albeit in low quantities. We therefore believe that they are mainly the result of weathering.

Figure 2 shows the results for the three study areas. Depicted are the Illite cristallinities of the air dried samples using the classical zone limits. The anchizone has not been further subdivided. Illite cristallinities from all three metamorphic zones could be found. Results confirm that the Variscan metamorphism of the Anti-Atlas is of low to very low- grade. Considering all three key areas a distinct increase of metamorphic grade from NE to SW is observable: Epizonal Illites are predominant in the SW Anti-Atlas whereas in the northeastern part they are absent (Fig. 2). Our results are in good agreement with the observations made by Buggisch (1988) in the Cambrian '*grès terminaux*'.

Southwestern Anti-Atlas

In the southwestern Anti-Atlas outside of the Ifni region (Fig. 2), all Palaeozoic series were sampled and analyzed. Despite the irregular distribution of the sample sites, a distinct correlation of metamorphic grade and stratigraphic age can be recognized. Adoudounian and Cambrian rocks are characterized mainly by epizonal IC-values whereas the Ordovician are characterized by typical anchizonal Illites or by coexisting epi- and anchizonal Illites (Assa area) (Fig. 2). Silurian and Devonian rocks show mixed anchizonal and diagenetic IC values, whereas Carboniferous series only yields diagenetic IC values (Fig. 3). The apparent South-North trend of increasing IC is a consequence of progressively older sediments towards the North while many exceptions from a simple S-N trend can be found (Fig. 2).

The increase of IC with stratigraphic age is also reflected by the decreasing arithmetic mean of the Scherrer Width (Fig. 3) from diagenetic values (0.53 °2θCuKα) for the Carboniferous samples to epizonal values (0.18 °2θCuKα) for the Adoudounian samples. The increase of metamorphic degree towards stratigraphically older units is also reflected by the decrease of variability of observed IC-values. On the western flank of the Kerdous inlier (Fig. 2A), Bonhomne & Hassenforder (1985) found mainly epizonal IC values for the lower part of the stratigraphic column (i.e. Adoudounian to Cambro-Ordovician series, Fig. 3). Such results are in agreement with ours, indicating that up-sequence until Late Cambrian series, epizonal Illites are predominant.

Central Anti-Atlas

Sampling in the central Anti-Atlas was restricted to Adoudounian up to the middle Devonian series (Fig. 2B). The IC generally increases from the SE to NW, which roughly reflects an increase in stratigraphic age. The increase of IC with stratigraphic age and the decrease of the variability of IC values are very distinct (Fig. 3). The mean IC value decreases from diagenesis/anchizone (33 °2θCuKα) for the Devonian samples to epizone (19 °2θCuKα) for the Adoudounian samples.

North-eastern Anti-Atlas

Rocks from the eastern Anti-Atlas (Fig. 2C) only yielded diagenetic and anchizonal IC-values. The increase of IC towards older stratigraphic units is less distinct.

Cambrian and Ordovician series show a lower metamorphic grade compared to similar units of the western and central Anti-Atlas: IC reaches epizonal mean values in the SW and

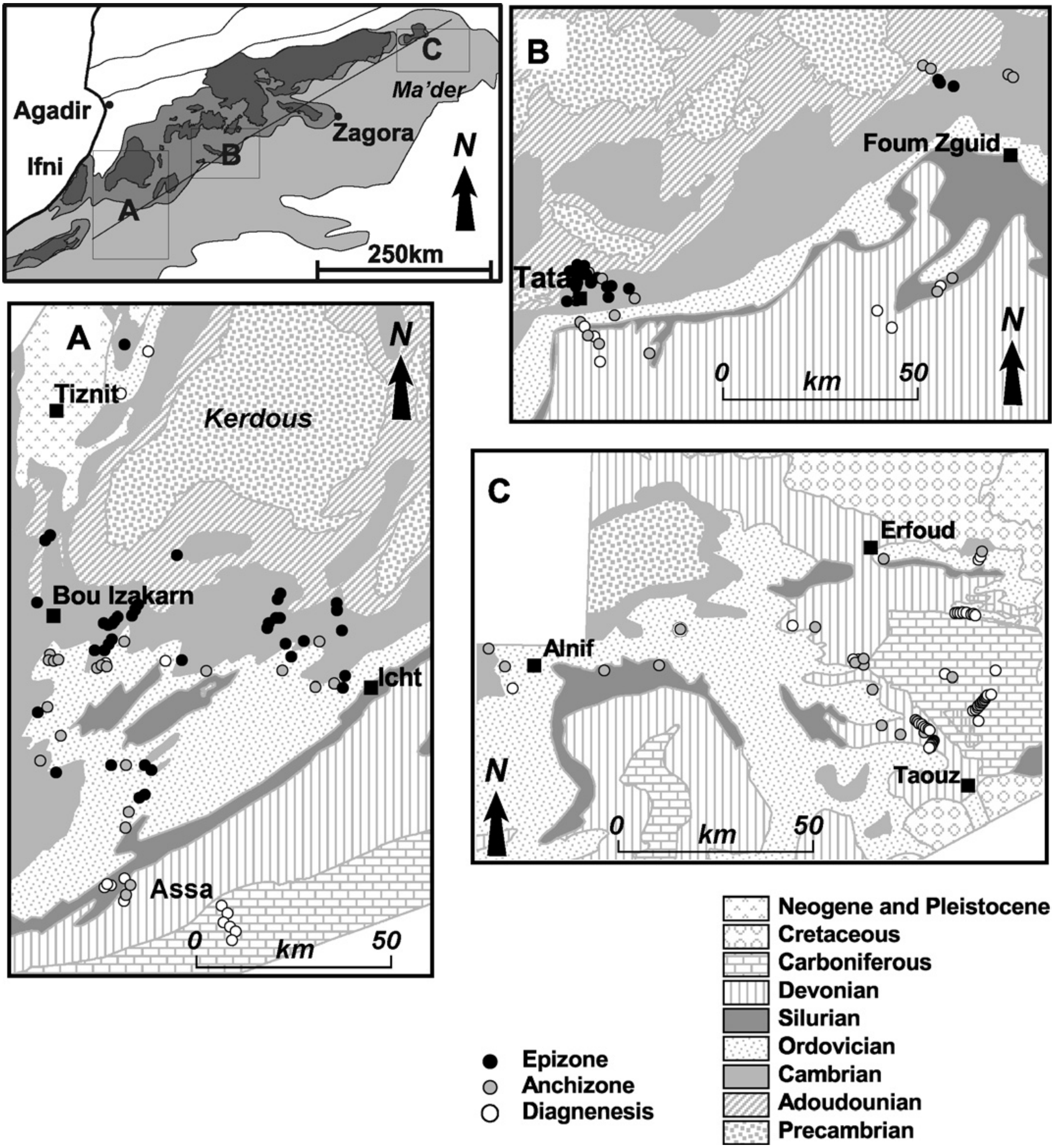

Fig. 2. Sampling map and results. Illite cristallinities from air dried samples (<2 μ) for the three key areas on the southern flank of the Anti-Atlas. The Illite cristallinities outline low-grade metamorphic zones. In the southwestern and central Anti-Atlas all three low-grade metamorphic zones can be found. In these areas the correlation between IC and stratigraphy is fairly distinct. In the eastern Anti-Atlas epizonal samples are absent and no clear trend is recognizable.

central Anti-Atlas 0.19 and 0.18 °2θCuKα, respectively (Fig. 3), whereas IC values from the eastern Anti-Atlas remain in the anchizonal zone (0.30 °2θCuKα). A similar trend is observed for the Ordovician series: anchizone values in the SW and central Anti-Atlas, and diagenetic ones for the eastern Anti-Atlas (Fig. 2). IC values do not change much for Early Carboniferous

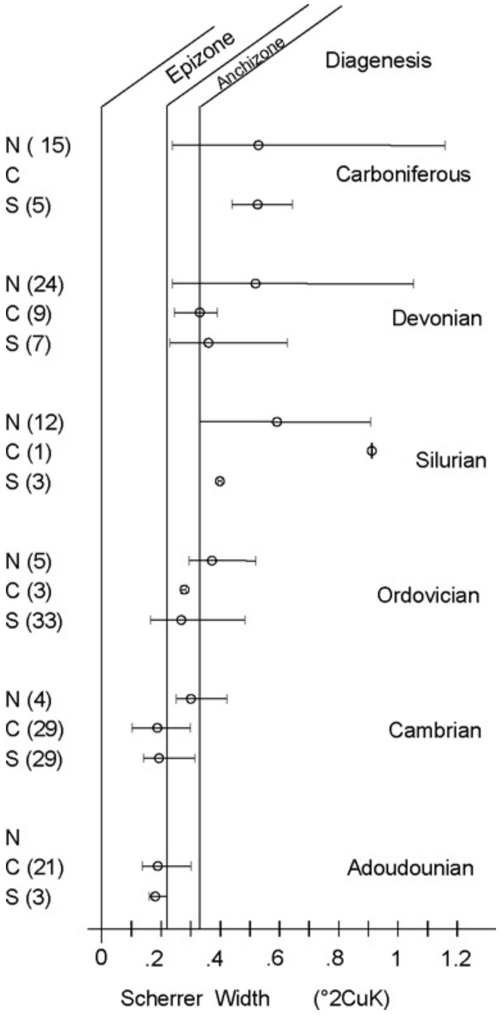

Fig. 3. Range and arithmetic mean (small circles) of the measured Scherrer Widths for the southwestern (S), central (C) and northeastern (N) Anti-Atlas respectively. In brackets: Number of samples. Note the decreasing spread of measured values toward the base of the stratigraphic column.

series between SW and E regions of the Anti-Atlas. However, anchizonal IC values coexist with diagenetic ones in the folded Tournaisian-Visean series of the Tafilalt (Fig. 2C) whereas these values are only diagenetic in the tabular Tournaisian-Namurian stata near Assa (Fig. 2A)

5. Discussion

IC versus stratigraphy

A cumulative stratigraphic thickness diagram has been constructed (Fig. 4). The sample sites have been projected into the diagram keeping their respective stratigraphic position. The diagram also contains samples from outside of the three key areas. The description of facies and thickness for the Early Palaeozoic comes from Destombes and others (1985) and for the Devonian mainly from Hollard (1981). The thickness variations described in the Early-Middle Devonian series of the central AA (Ouanaimi & Lazreq 2008) are not shown, as they can be neglected at the scale of this section. Geological maps of the central and eastern Anti-Atlas (scale 1:200.000) together with our own field data were used for the estimation of the thickness of the Carboniferous series. It must be emphasized that Carboniferous strata do not crop out in the folded domain of western AA, and are limited to the southern tabular domain (Tindouf basin), Folded Early Carboniferous (Tournaisian-Visean) deposits are preserved in the eastern AA. The projection distance for most of the stratigraphic units is small with respect to the length of the section. Somewhat speculative is the thickness and facies change of the Carboniferous and Upper Devonian in the central part.

The diagram (Fig. 4) shows increasing IC with progressively older stratigraphic units. Since the diagram represents the Anti-Atlas basin at around the time of maximum infill, the vertical position of the samples corresponds to their maximum burial position.

Burial metamorphism

Frey & Robinson (1999) defined different criterias to identify burial metamorphic pattern in metapelitic sequences that are: 1) a basin-wide correlation between grade and age of strata such that grade generally increases into older strata, 2) highest grades occur in anticlinal areas and lowest grades in synclinal area, 3) an approximate parallelism between isocryst surfaces and formational boundaries, with grade generally decreasing towards the youngest strata, and 4) where sufficient data are available, plots of ranges and mean values of IC show a down-section increase in metapelitic grade. Such criteria in IC patterns are met in the SW Anti-Atlas, suggesting that low-grade metamorphism corresponds to a burial metamorphic pattern. If burial is the main factor influencing the IC pattern, the lack of epizonal IC values in the eastern Anti-Atlas can be easily explained by an insufficient sedimentary cover to attain epizonal conditions.

Paleo-geothermal gradient

Among the many factors that theoretically influence IC, such as protolith composition, integrated time-temperature history, strain intensity, fluid-rock interaction, porosity etc., the peak temperature reached during burial/metamorphism is generally regarded as the most important parameter (Burkhard & Goy-Eggenberger 2001). Several estimations exist on the temperature of the anchizone-epizone limit, which is currently fixed at ~300 °C (see Frey & Robinson 1999). A way to test if the hypothesis of a burial metamorphic pattern is valid is to verify if the paleo-geothermal gradient inferred from the correlation between the observed IC values and the stratigraphic thickness is reasonable.

We used the moving window technique (an arithmetic mean of a well defined subset of the samples) with different

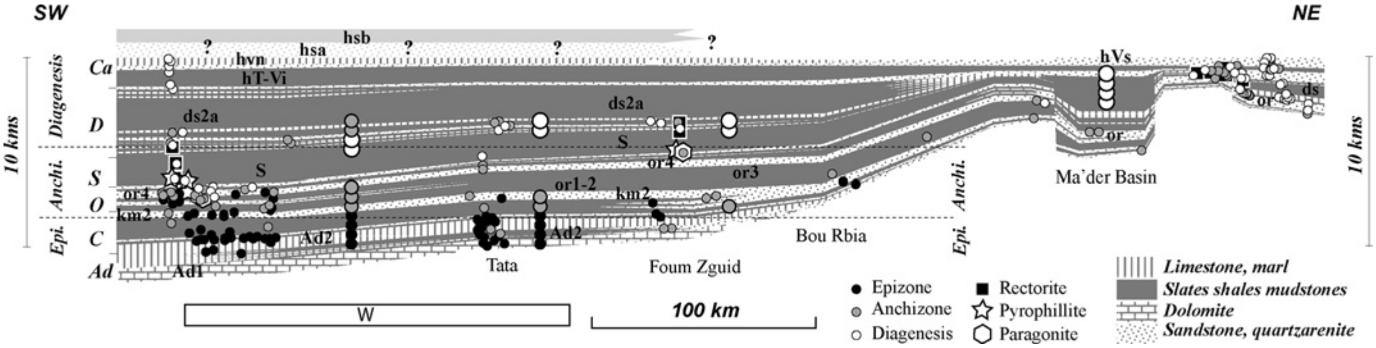

Fig. 4. Stratigraphy vs. IC – diagram at the end of the Palaeozoic sedimentary cycle. (The black line in the overview map of Figure 2 shows the position of the section). Thicknesses were compiled from 1) Boudda et al. (1979) for the Adoudounian and Cambrian series, 2) Destombes et al. (1985) for the Adoudounian, Cambrian, Ordovician and Silurian rocks, 3) Piqué (1994) and Mamet et al. (1966) for the Carboniferous series, and 4) Wendt & Aigner (1985) and Wendt (1985) for the Devonian of the eastern Anti-Atlas. Epi: Epizone, Anchi: Anchizone. Ad: Adoudounian, C: Cambrian, O: Ordovician, S: Silurian, D: Devonian, Ca: Carboniferous, Ad1: Lower limestones, Ad2: Lie-de-vin formation, Ad3: Upper limestones, km2: Tabanit Group, or1-2: Outer Feijas shale group, or4: 1st Bani sandstone group; S: Silurian, ds2: ArgIllites of the lower Drâa, ht-Vi: Tazout shales and sandstones, hVs-hVN: Limestones and marls of the Jbel Ouarkziz, hsa, hsb: Betana-series. The small circles depict the effectively measured values. The large circles show averaged values. Depicted are all averages which consist of 4 or more individual values. The rectangle ('w') shows the size of the moving window used for averaging.

widths and heights to localize the diagenesis-anchizone and the anchizone-epizone limit. In the western Anti-Atlas, the anchizone-epizone limit lies approximately at the Cambrian-Ordovician boundary whereas in the central Anti-Atlas it coincides with the Lower Cambrian – Middle Cambrian boundary (Fig. 4). The diagenesis-anchizone limit is less well defined whereas an apparent inversion of metamorphic zonation at the Silurian-Devonian boundary exists along the westernmost column of averaged IC-values. In our view this has two reasons: 1) Devonian series show an average IC very near to the anchizone in the SW Anti-Atlas (Fig. 3) with large error bars, hence the mean value can be in anchizone or still in diagenesis. 2) The Silurian black shales show throughout the Anti-Atlas relatively low IC-values, which do not correspond well to the index minerals found (Pyrophyllite, Rectorite). However, the retarding effect on Illite crystallinity of organic matter in black shales is well known. The filling up of a rock reservoir by oil probably prevented late diagenetic illitization (Chamley 1989). Thus, the diagenesis-anchizone limit would be best placed above the pyrophyllite found in the Silurian and below the (still diagenetic) Devonian strata (Fig. 3).

The minimum temperature for the onset of the anchizone is 200 °C (Kisch 1987; Frey & Robinson 1999) whereas the transition anchizone-epizone occurs at approximately 300 °C (Bucher & Frey 1994). Using depth estimates for the zone limits (the distance to the top of the hV-N unit) and temperature differences, the mean paleo-geothermal gradient from the surface would be in the range of 50–43 °C/km for the diagenesis-anchizone limit, and 45–35 °C/km for the anchizone-epizone limit. Both values are within the range of known geothermal gradients on the earth, but they are probably too high for a more than 10 km thick sedimentary basin as typical values for basins with thick infill are ~25 °C/km or less (Allen & Allen 1990).

A constant paleo-geothermal gradient throughout a basin is not a prerequisite for the recognition of a burial metamorphic pattern, nor does such a pattern imply invariable geothermal gradients. Some of the anchizonal IC-values of the eastern Anti-Atlas around the zones of rapid facies and thickness change (see also Fig. 4) could be due to a higher than normal heat flow as suggested by Belka (1991). The latter author estimated the geothermal gradient of the eastern Anti-Atlas to be about 50 °C/km and related this high value to crustal thinning since the Devonian in the eastern Anti-Atlas; such high geothermal gradient could also explain the occurrence of index minerals typical for the anchizone.

IC vs. deformation

Strain has been mentioned as one of the important factors influencing Illite crystallinity. Therefore the question arises if the observed increase of IC towards the basement could not simply be the result of higher penetrative strain as (micro-scale) deformation increases towards the basement inliers in the Anti-Atlas. The correlation of IC with strain has been observed by many investigators (see Kisch 1987 and references therein). However, this close correlation should not be used to infer that IC values depend on strain intensity. Rather, both strain intensity and IC are strongly dependent on temperature (Flehmig 1973; Flehmig & Langheirich 1974; Burkhard & Goy-Eggenberger 2001). In the lower stratigraphic units of the Anti-Atlas macroscopic expressions of penetrative strain (such as intersection pencils, spaced cleavage, fracture cleavage, slaty cleavage) are more common. However, we could observe that such features are not ubiquitous and very much dependent on structural position, lithology and structural behaviour of the individual units. For a given stratigraphic level, we could not find any difference in IC between those lithologies which underwent, or are susceptible to penetrative strain (mudstones, shales etc...) and the more competent lithologies (sandstones, quartz-arenites). It would thus be an oversimplification to state that in the Anti-Atlas the strain intensity increases systematically towards older sediments.

Stratigraphic thicknesses

The sedimentary thicknesses are known in the Anti-Atlas at least up to the middle Devonian. For these series, the projection distances are relatively small and drastic thickness changes between the locations of exposure and the section seem rather improbable whereas it is most probable for the youngest sediments of the Anti-Atlas basin. The epizone-anchizone (300 °C) and the anchizone-diagenesis-limit (200 °C) are separated by a 2.5–3 km thick sedimentary pile generating 33–27 °C/km paleogeothermal gradient. Such a value is much more in agreement with typical geothermal gradients in sedimentary basin than those we constrained with respect to the surface temperature (43 °C/km or 35 °C/km respectively). Thus, it appears that the thickness of the anchizone is correct but that its absolute depth is too low compared to its depths in underformed epicontinental basin with a mean geothermal gradient of ~30°/km

A special role may have been played by the Upper Carboniferous Betana series, i.e. the thick succession of syn-orogenic continental sediments deposited after the general regression of the sea from the Anti-Atlas. At the northern border of the Tindouf-Basin (Fig. 1), the Betana series are about 1500m thick but not met further north in the Anti-Atlas domain. Palaeogeothermal gradient reduce considerably if an additional 1.5 thick pile is added in the calculation (hsa and hsb; Fig. 4): from 43 to 33 °C/km for the depth of the diagenesis-anchizone limit, and from 33 to 30 °C/km for the depth of the anchizone-epizone limit. However, when considering the Betana-Series as the distal part of a large molasse wedge, a 1.5 km value is probably a too conservative estimate: a total thickness of 2.5 km would be necessary in order to obtain a paleo-geothermal gradient of 27 °C/km, or 3.5 km for a gradient of 25 °C/km. Moreover, Cavaroc et al. (1976) have shown that the Betana formation was sourced from the NW suggesting that the western AA was emergent and eroded during the Bashkirian-Westphalian-Stepahanian. When the IC pattern is explained by burial alone and using a geothermal gradient typical for sedimentary basins the estimated maximum thickness is about 15 kms.

Tectonic thickening and thermal events

One other possibility to explain the high paleo-geothermal gradient is the tectonic thickening of the sedimentary pile during the Variscan orogeny. The Variscan shortening in the western Anti-Atlas varies between 15 and 25% (Caritg et al. 2003; Helg et al. 2004; Burkhard et al. 2006; Robert-Charrue & Burkhard this volume). In a very simple model assuming constant cross section area, the tectonic thickening would be roughly of the same magnitude, i.e. 2 km at the site of the section. It is questionable whether such thickening really led to further burial, since it is unknown to which degree this was compensated by syn-orogenic denudation.

Buggisch & Flügel (1988) gave a review on the radiometric ages of the Precambrian-Cambrian boundary in the Anti-Atlas. The authors remarked that most of the whole rock Rb/Sr ages of the western and central Anti-Atlas were rejuvenated. Bonhomne & Hassenforder (1985) attempted to date the metamorphism on the western flank of the Kerdous inlier (Fig. 2). Using Rb/Sr and K/Ar isotopic data on the <2 μm fraction of whole rocks they found two ages: approximately 370 Ma, which they interpreted as a pre-Variscan thermal event and at approximately 290 Ma, which they attributed to an isotopic re-homogenization during the Variscan Orogeny. We believe that the first thermal event could be the result of burial metamorphism, especially since samples for which such thermal events have been reported stem from the lowermost part of the stratigraphic succession: e.g. from the 1) Precambrian Ouarzazate formation (Jurey & Lancelot 1974), 2) Adoudounian syenites in the Central Anti-Atlas (Ducrot & Lancelot 1977) or even from granites of the crystalline basement (Benziane 1974; Charlot 1976; Yazidi 1976). According to our model all these sites lie within the epizone and therefore were probably exposed to temperatures around 300–350 °C. The second phase of Bonhomne & Hassenforder (1985) is poorly constrained but new insights could come from Zircon Fission-Track data (Saddiqi et al. 2007). Fission-Track thermochronological analysis on zircon crystals (ZFT) have a temperature of closure comprised between 270 and 210 °C (Tagami et al. 1996), thus below the anchizone-epizone limit. ZFT ages were produced from basement inliers in the Kerdous region (Fig. 2) and range between 324 and 352 Ma with a mean age around 330–340 Ma (Saddiqi et al. 2007). The authors interpreted these Visean-Namurian cooling ages as the trace of the orogenic erosion of the western Anti-Atlas during the Variscan orogeny, after heating over 280 °C due to burial metamorphism and/or overpressurring fluids. It is important to note that these ZFT ages pre-date the deposition of the Late Carboniferous and syn-orogenic Betana-Series. An early phase of tectonic thickening may have occurred in the Devonian-Early Carboniferous within the Anti-Atlas but was rapidly associated to a later phase of denudation at ~340–330 Ma that is traceable by ZFT thermochronology. This later stage is traceable through the deposition of the syn-orogenic Betana series: the Betana pile could not have been in turn responsible for additional burial as its deposition post-dated a thermal event that is recorded by a thermochronometer with a closure temperature (270–210 °C) lower than the anchizone-epizone limit (300 °C). Hence, the abnormal paleo-geothermal gradient we calculated for the different limits as constrained by the analysis of the IC, cannot be minimized by an additional and missing sedimentary pile. The thermal causes of this very low-grade metamorphism remain unclear. However, we rather envisage high geothermal gradient for the Early Carboniferous in the Anti-Atlas. Geothermal gradients as high as 40–50 °C/km can be associated to thermal subsidence where basement sequences are enriched in heat producing elements (Sandiford et al. 1998). Such a scenario may thus be most likely for the northern termination of the Tinfouf Basin, i.e. the Anti-Atlas region of SW Morocco.

6. Conclusions

1) The post Pan-African metamorphism of the sedimentary cover on the southwestern flank of the Anti-Atlas is generally of low to very low-grade.
2) A distinct increase of IC with stratigraphic age has been documented for the western and central Anti-Atlas respectively.
3) At the scale of the entire SW flank of the Anti-Atlas, and disregarding local variations (particularly in the eastern AA), IC correlates best with estimated paleo-overburden. Thus, the observed IC pattern fulfils the conditions of burial metamorphism.
4) The observed metamorphic pattern is too high to be the result of burial in a 10–12 km thick epicontinental sedimentary basin. Adding 1.5–3 kilometres of sediments such as the 'missing' or eroded Carboniferous Betana-series would make it possible to obtain a reasonable paleo-geothermal gradient. However, new thermochronological ages from Pre-Cambrian inliers in the Anti-Atlas suggest that the phase of heating pre-dated the deposition of the Betana series, which in turn excludes the hypothesis of overburden.
5) The 'abnormal' paleo-geothermal gradient we evidenced for the Carboniferous is true, and may be due to the presence of a basement rich sequence enriched in heat producing elements such as rocks of the West African Craton.

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