PERGAMON

Journal of Structural Geology 22 (2000) 323–334

JOURNAL OF STRUCTURAL GEOLOGY

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Paleomagnetism as a structural polarity criterion: application to Tunisian diapirs

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Received 22 March 1999; accepted 27 September 1999

Abstract

In the Upper Aptian–Albian units, close to Triassic displaced bodies of northwestern Tunisia, the primary magnetization acquired during the Cretaceous period of normal magnetic polarity yields an unquestionable structural polarity criterion. The use of this criterion confirms the diapiric origin of these Triassic bodies and aids understanding of the evolution of the diapirs. It also appears to be a useful tool for the analysis of the geometry of overturning. An Eocene halokinesis on the platform south of the Tunisian Channel is also indicated by analysis of magnetic overprint in the Jebel Slata. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The determination of the structural polarity (i.e. right way-up vs. overturned) of stratigraphic units is a key element in structural analyses. Usually, it is determined from sedimentological features and/or stratification–cleavage intersections if they exist. However, except in flysches and detrital continental series, such structural polarity criteria are rare and insufficiently frequent to solve the question in every instance. Another method that can be used is paleomagnetism (Rouvier et al., 1998). This obviously requires the knowledge of the magnetic polarity at the time of sediment deposition and lock-in of the magnetization. This is precisely known for the Upper Aptian–Albian sedimentary units cropping out near evaporitic bodies in northwestern Tunisia, when there was a long period of normal magnetic polarity. A controversy exists (Vila et al., 1996a; Perthuisot et al., 1998) concerning the mode of emplacement of these bodies (diapirs or salt glacier), which can be solved by determining the structural polarity of the beds in key areas.

2. Geological setting and sampling

This study was devoted to two Triassic salt bodies in Tunisia (Fig. 1). These structures are representative of two well-characterized paleogeographic areas, the Tunisian Channel ('Sillon Tunisien') and its southern border, the Tunisian platform. The Ben Gasseur–El Kef 'diapir' (Fig. 2) is a good example of the large Triassic bodies which lay along the axis of the Tunisian Channel, a subsiding NE–SW sedimentary basin where the Cretaceous formations are mainly represented by thick argillaceous series. The Bou Jaber–Slata diapir (Fig. 3) belongs to the family of overhanging diapirs on the southern margin of the Channel. This border corresponds to a wide platform that is characterized by the deposition of neritic limestones

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PII: S0191-8141(99)00155-8

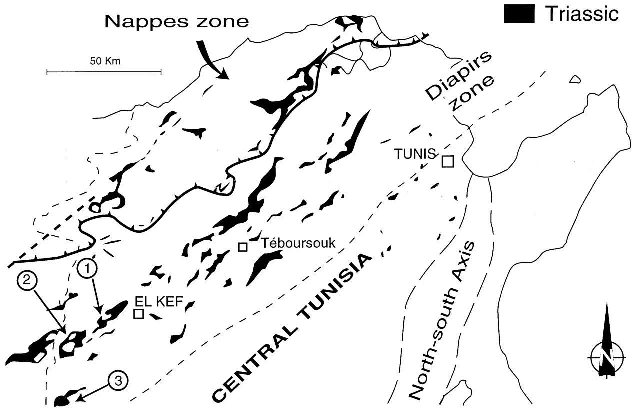

Fig. 1. Geographical and structural setting of the study sites in central and northern Tunisia. (1: Jebel Debadib; 2: Jebel Ben Gasseur; 3: Jebel Slata.)

during the Upper Aptian, with the development of reefs on top of the diapiric structures. The Cenozoic Alpine compressions strongly deformed the Tunisian Channel and its southern border, giving a remodeling of the diapiric structures and locally halokinesis reactivation. The final geometry, resulting from all these movements, is very complicated. This justifies the use of paleomagnetism to constrain arguments about the structural polarity of the beds close to these Triassic bodies. From a lithological point of view, the only formations sampled for paleomagnetism were carbonaceous, black silty limestone, rich in organic matter, in the Upper Albian, and a beige limestone with *Orbitolinidae* in the Upper Aptian.

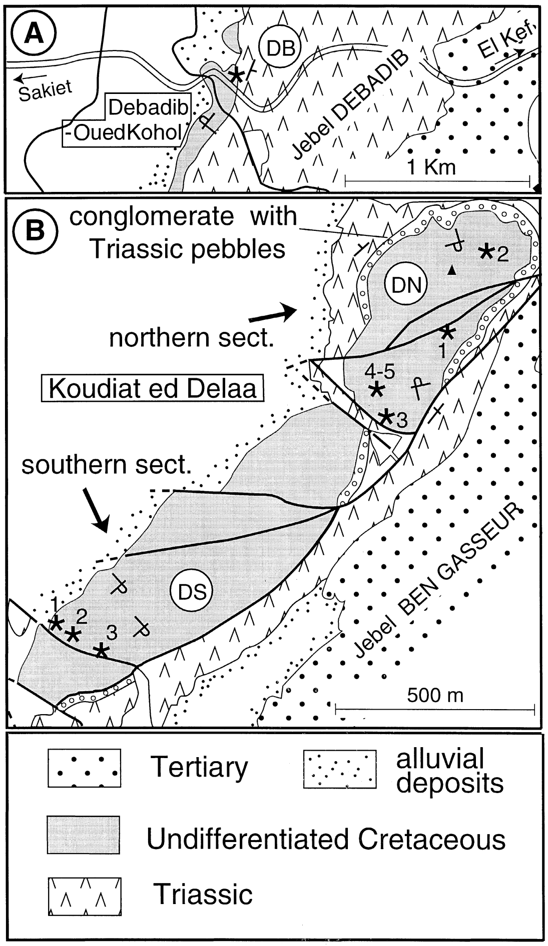

Fig. 2. Location of sampling sites close to the Debadib–Ben Gasseur diapiric structure. (a) Jebel Debadib:Debadib–Oued Kohol district (DB); (b) Jebel Ben Gasseur:Koudiat ed Delaa district (northern Delaa: DN; southern Delaa: DS).

The first diapir studied was that of El Kef–Ben Gasseur (Fig. 2). On the northwestern side of the El Kef diapir, on the flank of the Jebel ed Debadib, the Albian silty limestones form a monocline which plunges under the Triassic evaporites. Locally, a conglomerate with pitted pebbles from the Triassic unit is interbedded between the Triassic and Cretaceous formations. This shows that the Triassic units pierced up to the surface at this period and that the formation of the conglomerate cannot predate the emplacement of the Triassic evaporites. The series are therefore overturned. Although the presence of this conglomerate has been described, these Albian units have been considered (Vila et al., 1996a) as being the 'floor', in an upright position, of a 'salt glacier' interbedded in the Albian formations. The limestones of the monocline have been sampled at one site (Fig. 2) to confirm that they are overturned. On the northwestern side of the Ben Gasseur diapir (Koudiat ed Della, southwestward prolongation of the El Kef diapir), a half-window of overturned Albian limestones crops out under Triassic rocks, again with an interbedded conglomerate. These units are folded in an antiform and surrounded by Triassic evaporites. These limestones were sampled at eight sites (Fig. 2) in order to define, as at the Jebel ed Debadib, their structural polarity, because they were here also considered to be in an upright position (Vila et al., 1994).

The Bou Jaber–Slata diapir (Smati, 1986; Perthuisot et al., 1988) is the first structure on the southern platform south of El Kef city (Fig. 3). Three different structural phases are known in this area, explaining the present pattern:

- A first diapiric doming, with piercing by Triassic evaporites, occurred before the Upper Aptian. The shape and the orientation of this first doming are not well known, although it is likely to have been lengthened along a NE–SW direction, but also possibly along direction N140°. This emplacement of the Triassic body controlled the sedimentation of the Upper Aptian neritic limestones, and particularly the location of the reefs that were covered by Lower to Middle Albian marly deposits.

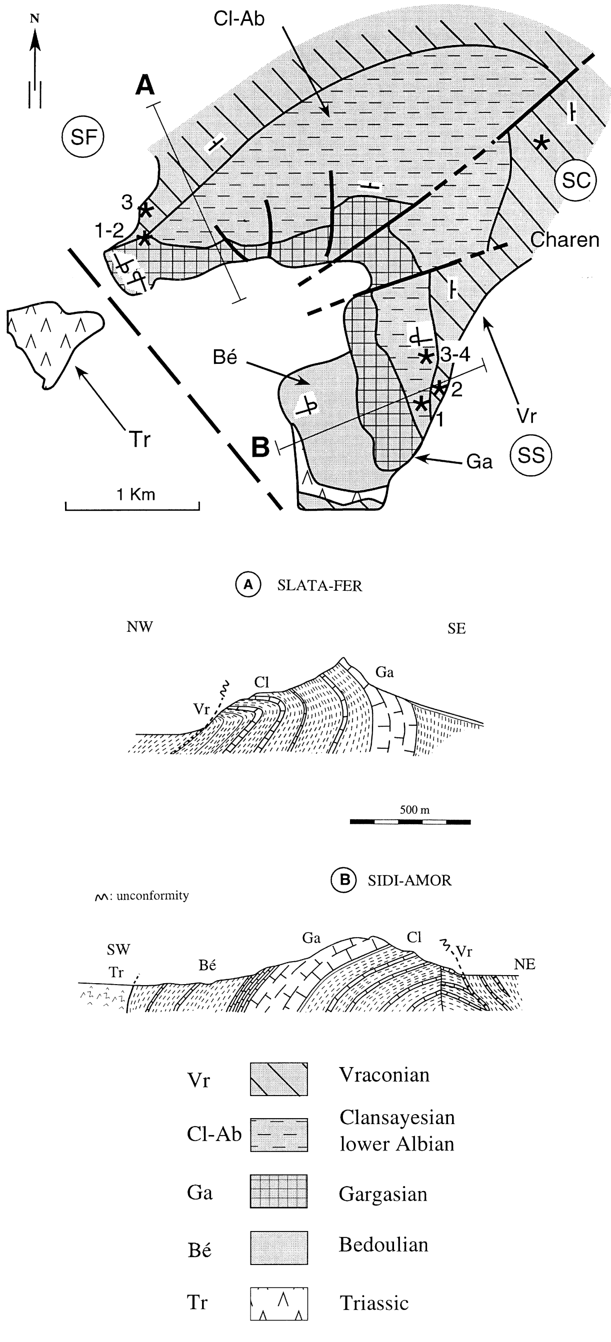

Fig. 3. Sampling sites of Jebel Slata structure in their geological environment, illustrated by the map and two cross-sections (A, B): SC: Slata–Charen district; SF: Slata-Fer district; SS: Sidi Amor ben Salem district.

- A second piercing occurred before the Upper Albian, followed by deposition of conglomerates, and then of marls and limestones from Upper Albian to Eocene times.
- Neogene compressions then deformed of the previous structures, resulting in the present NE–SW orientation of the main fold.

Another event in the history of this diapir is mineralization in the form of galena, plus sphalerite, at Sidi Amor ben Salem on its southern limb and barite plus siderite–ankerite at Slata-fer on its northern limb. Even if dating arguments are missing for the iron carbonate mineralization, Smati (1986) showed that all or a part of the sulphides were formed after emplacement of the diapir. In fact, sulphides have filled up a karstic cavity developed within the overturned Aptian limestones on the southern limb of the diapir.

The paleomagnetic study was carried out in three places on the northeastern pericline, which culminates at the Jebel Slata:

- On the fold axis of the Jebel Slata (Charen area), the Upper Albian silty limestones are in stratigraphic continuity with the Upper Aptian neritic limestones and the Lower Albian silty limestones. They were sampled at one site (Fig. 3).
- On its limbs, a conglomerate with pebbles of Aptian limestones, Triassic dolomites and sandstones are interbedded between these two series. Under this conglomerate, the Aptian and Lower Albian beds have a very steep dip or are even overturned. The transition of the Aptian limestones from the fold axis (Charen area), where they are in upright position, to the limb where they are overturned, is progressive and clearly observable on the northwestern border. Southwestwards they reach a vertical position, and then are strongly overturned with a sharp hinge, clearly visible in the field. On the southeastern border, for the Aptian beds, the transition between upright and overturned position corresponds to a fault. The two limbs were sampled (Fig. 3) in the transgressive Albian cover, including the conglomerate, and in the underlying overturned Upper Aptian series (four sites at Sidi Amor ben Salem, on the southeastern limb, and three sites at Slata-fer on the northwestern limb).

3. Rock magnetism

In order to define the magnetic mineralogy, hysteresis loops and Curie curves were generated for several samples using, respectively, a translation inductometer within an electromagnet capable of reaching 1.6 T and a CS2-KLY2 (Agico, Brno). The analysis of the hysteresis loops shows that the coercive force and the remanent coercive force are moderate. Therefore the magnetic grains are pseudo-single-domain (Day et al., 1977). The Curie curves exhibit mineralogical alteration at temperature as low as 180°C. Up to at least 580°C, the alteration is mainly indicated by a decrease of the susceptibility during partial cooling loops. The mineralogical phase that formed is therefore not magnetite. A dramatic drop in the susceptibility at about 580°C shows that the magnetite is present as a pre-existing magnetic mineral in these dark carbonates. During heating to 700°C, new magnetite is formed, resulting in the strong increase of the susceptibility visible in the final cooling curve. The magnetic carrier is therefore PSD grains of magnetite, which are favorable for paleomagnetic studies. In dark carbonates, magnetite is a frequent syngenetic or diagenetic mineral. In the deformed areas, the remanent magnetization can be affected by internal strain. Therefore measurements of anisotropy of magnetic susceptibility were performed on several samples from different sites. The anisotropy appeared to be very weak, of the order of 1% on average. The principal axes are scattered, without relation to a weak fracture cleavage, only locally visible. These rocks are therefore not affected by significant internal strain.

4. Paleomagnetic analysis

The specimens were left in a zero-magnetic field shielded space for more than two weeks before measuring in order to reduce the Viscous Remanent Magnetization (VRM) acquired in situ and after sampling. The intensity and the direction of the Natural Remanent Magnetization (NRM) were measured on a JR-4 spinner magnetometer (Agico, Brno). Alternating magnetic field (AF) and thermal demagnetization techniques were performed at the Saint Maur Laboratory using an AF demagnetizer, which automatically limits the parasitic anhysteretic remanence (Le Goff, 1985), and a magnetically shielded furnace. Both instruments were constructed at the Saint Maur Laboratory. The intensity of the magnetization was relatively variable, from 4 to 10 000 in 10^{-8} Am^2/kg. Thermal demagnetization of pilot samples showed that the directions of remanent magnetization often became erratic at temperatures from 350 to 550°C. The thermal demagnetization was therefore performed on the basis of the corresponding pilot

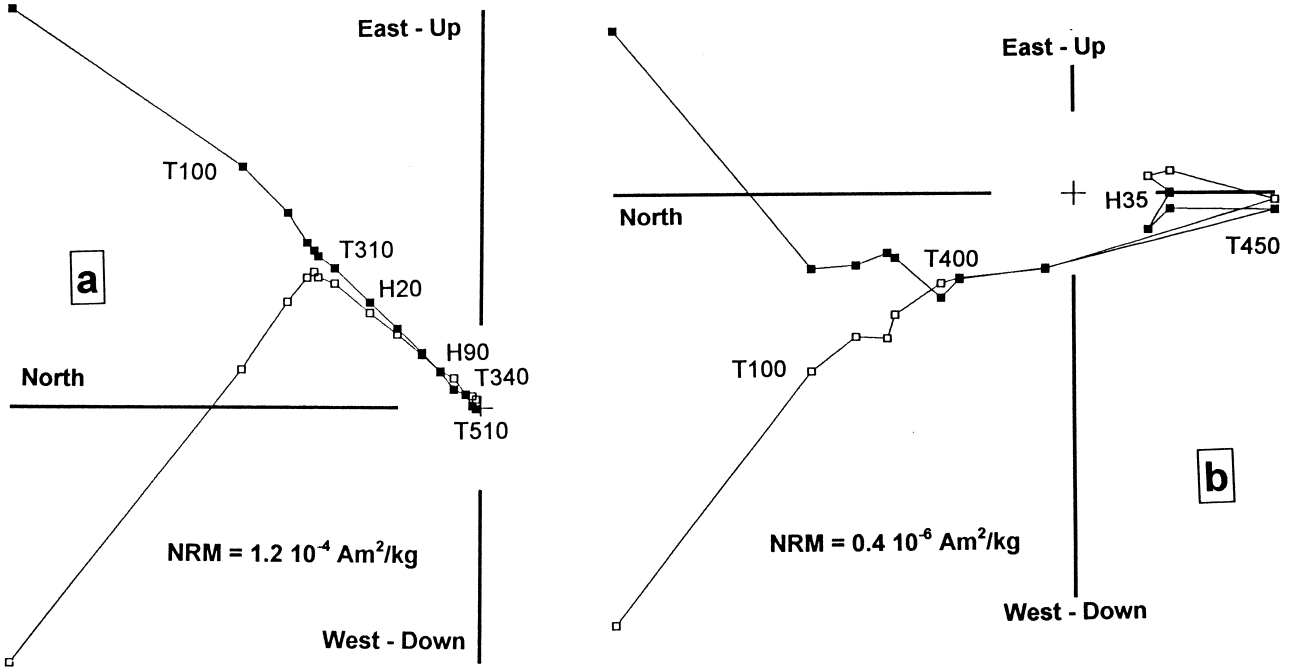

Fig. 4. Evolution of the magnetization vector during progressive demagnetization (an isolated magnetization component corresponds to linear segment on both projections). Projections on horizontal (open squares) and vertical (full squares) planes (orthogonal vector plot): specimens (a) DB041 (Jebel ed Debadid) and (b) SL303 (limb of Jebel Slata); *T* in °C and *H* in mT.

Table 1

ChRM in the different sites. Number of sites or samples (N), direction (D, I) and associated precision parameters (α_{95}, k); latitude (la), longitude (lo) and associated precision parameters (A_{95}, K) of the paleomagnetic pole. Dip correction without correction of the overturning, and assuming horizontal fold axis

		Before dip correction				After dip correction							
Site	N	D (°)	I (°)	k	α_{95} (°)	D (°)	I (°)	k	α_{95} (°)	lo.°E	la.°N	K	A_{95} (°)
DB↓	10	50.9	−10.7	260	2.7	41.1	−29.8	260	2.7	144.2	25.0		
DN1↓	8	194.9	−69.1	273	3.0	257.9	−58.8	273	3.0				
DN2↓	11	7.8	−87.3	338	2.3	253.4	−46.2	338	2.3				
DN3↓	15	207.3	−51.3	81	4.0	249.0	−55.2	81	4.0				
DN4↓	8	316.1	−47.5	125	4.4	244.5	−58.7	125	4.4				
DN5↓	7	303.8	−41.6	86	5.7	251.0	−48.9	86	5.7				
DN	49	253.8	−71.6	7	7.3	251.1	−53.5	83	2.2	79.9	33.1		
DN	5 sites	271.9	−70.4	6	24.9	251.2	−53.6	161	4.9	77.3	33.3	142	5.3
DS1↓	6	326.7	−33.2	162	4.5	17.6	−29.9	162	4.5				
DS2↓	11	336.5	−44.8	168	3.3	13.9	−30.2	168	3.3				
DS3↓	4	279.4	−64.5	29	13.0	29.2	−21.0	29	13.0				
DS	21	316.6	−46.0	24	6.2	18.1	−28.5	63	3.9	163.7	35.9		
DS	3 sites	313.1	−48.9	14	21.4	20.5	−27.2	83	8.8	163.9	35.9	95	8.3
SS	6	194.7	−33.5	15	14.8	210.2	−26.7	14	15.3	139.8	55.2		

sample up to 300 to 510°C. An alternating field demagnetization was then applied until occurrence of parasitic anhysteretic magnetization. If necessary, this was then followed by further thermal treatment.

4.1. Data analysis

The first component (A), probably a viscous overprint, was eliminated after treatment at 250°C. Two different behaviors were observed after this treatment. In the Jebel ed Debadib and in the Koudiat ed Delaa, a well-defined Characteristic Remanent Magnetization (ChRM) was obtained (Fig. 4). In the Jebel Slata sites, one or two components were present (Fig. 4). A component (B) was first isolated in many samples during alternating field treatment and heating until about 450°C. At higher temperatures, this magnetization became very unstable, but, a rough estimate of the ChRM (component C) was possible in six samples from two sites (SS1 and SS2). The polarity of the magnetization was clearly determined in 11 other samples from the three sites with overturned beds (SF1, SS1 and SS2).

The structural corrections and fold test were made assuming an upright position for all of the study area (Tables 1 and 2). Although the beds could be corrected to a horizontal position, it was not possible to return the overturned beds to their original upright position because the axis about which they were overturned was unknown. By applying this type of correction, the true magnetic declination is uncertain, but the 'apparent' magnetic polarity, based on the inclination relative to a horizontal bedding surface, could still be determined. After this correction was applied, the 'apparent' magnetic polarity of the ChRM was reversed in all the beds, C clearly identifying that they were in an overturned position. This demonstrated that, even in the absence of declination data, paleomagnetism could be used to determine the 'way-up' direction for a given sedimentary unit.

4.2. Conglomerate tests

In the Jebel Slata, at the Sidi Amor ben Salem (site SS3) and Slata-fer (site SF2) areas, conglomerate tests were carried out. Individual clasts of the conglomerate give the same paleomagnetic direction B as their matrix (Fig. 5). Thus the conglomerate unit was remagnetized during or after deposition.

4.3. Unconformity tests

At Slata-fer, the Upper Albian levels (SF2 site in the conglomerate—see above—and SF3 site in the carbonates) unconformably overlie the Aptian–Lower Albian (SF1 site). An unconformity test, best described as a combination of contact and fold tests, was performed using the B components obtained in these sites. These directions were well grouped before dip correction (Fig. 5 and Table 2). After dip correction, the scattering increased, but because the overturning axis was unknown, such a variation could be meaningless. In this case, the comparison must be made using the absolute values of the inclination. The standard deviation of the inclination values increases from 50 to 464 during dip correction, confirming that the best group-

Table 2
Component B in the different sites. Column headings as in Table 1

		Before dip correction				After dip correction				Before dip correction			
Site	*N*	*D* (°)	*I* (°)	*k*	α_{95} (°)	*D* (°)	*I* (°)	*k*	α_{95} (°)	lo.°E	la.°N	*K*	A_{95} (°)
SC	20	342.9	56.3	150	2.6	348.9	32.0	150	2.6	286.6	76.2		
SS1↓	7	358.8	24.1	15	13.5	8.0	24.7	15	13.5				
SS2↓	8	350.1	29.5	44	7.5	9.3	35.1	44	7.5				
SS3↑	11	0.5	27.2	198	3.0	25.9	8.6	198	3.0				
SS4↑	8	354.2	24.4	123	4.5	17.5	18.2	123	4.5				
SS	34	356.2	26.5	44	3.6	16.9	20.5	23	5.0	198.2	67.6		
SS	4 sites	356.6	26.4	228	4.6	15.6	21.8	36	11.7	197.3	67.6	22.9	4.6
SF1↓	17	347.9	66.6	57	4.5	246.1	63.2	57	4.5				
SF2↑	5	317.0	76.0	44	9.5	323.0	16.1	44	9.5				
SF3↑	12	34.3	75.3	79	4.6	331.8	26.1	65	5.0				
SF	34	357.1	72.7	36	4.0	304.4	50.3	5	10.3	4.3	67.9		
SF	3 sites	352.3	74.7	51	11.4	314.2	39.2	4	38.5	0.3	63.9	17	19.9

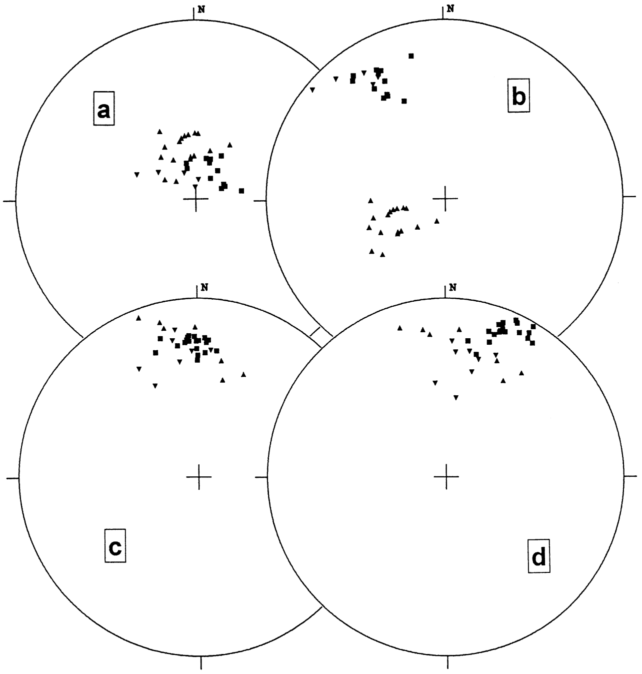

Fig. 5. Results of conglomerate test (a different orientation of the magnetization in pebbles and fine-grained rocks of a conglomerate points out a magnetization acquired before the deposition of the conglomerate) and unconformity test (a similar orientation of the magnetization in two units separated by an unconformity points out a magnetization acquired during or after the deposition of the upper unit) for component B. In overturned beds (triangles) with pebbles (tip downwards) and fine-grained rocks (tip upwards) and upright beds (squares) at Slata-fer (a, b) and Sidi Amor bou Salem (c, d), before (a, c) and after (b, d) dip correction. Stereographic projection, the full (empty) symbols corresponding to the lower (upper) hemisphere.

ing is before dip correction. The magnetization was therefore acquired during or after the Upper Albian times.

At Sidi Amor ben Salem, two sites were in the Upper Albian levels (SS3 site in the conglomerate—see above—and SS4 site in the carbonates) and two sites (SS1 and SS2) in the Aptian–Lower Albian. Again, the paleomagnetic directions B were well grouped before dip correction (Fig. 5 and Table 2) and the standard deviation of the inclination values increased from 60 to 142 during dip correction. The magnetization was acquired during or after the Upper Albian times.

4.4. Fold tests

4.4.1. Component B

A complete fold test could be made for the Upper Albian levels still in an upright position at the Jebel Slata. The sites were located in three different areas (SF2 and SF3 at Slata-fer, SC at Charen and SS3 and SS4 at Sidi Amor ben Salem) of a large fold. However, one limb of the fold seemed to be more complex because of the presence of faults within this limb. Moreover, the fold axis has a plunge of about 23° towards the NNE at Charen, but its inclination could be much steeper close to the center of the diapir. The dip correction was made in two steps, first by untilting the fold axis (using the value measured at Charen), and second by untilting the beds. The precision parameters ($N = 55$ samples) had a significant variation during progressive unfolding from 0 to 100%: for *k* (Fisher, 1953) from 12 to 34 (maximum 35 at 90%), and for $\sqrt{k_x \cdot k_y}$ (Henry and Le Goff, 1994) from 17 to

41 (maximum 44 at 85%). This indicates a synfolding magnetization, but the difference between values at 85 and 100% was not sufficient to reject the hypothesis of a prefolding magnetization using the simple but stringent McElhinny's (1964) criterion. The corresponding directions are $D = -5.1°$, $I = 23.4°$ (100% unfolding) and $D = -4.3$, $I = 24.0°$ (85% unfolding). The lengthening of the distribution of direction was moderate ($k_y/k_x = 3$).

A correction made without untilting of the fold axis (Table 2) clearly gives a lower clustering of the paleomagnetic directions. (For k, the maximum value is 19, for 44% unfolding, compared to 35 using untilting of the axis, and for $\sqrt{k_x \cdot k_y}$, the maximum value is 31, for 65% unfolding, compared to 44 using untilting of the axis.) The fold test is not really significant. The directional distribution became very lengthened ($k_y/k_x = 7$), showing that a structural correction applied in this manner did not correspond to the actual evolution of the structure and hence yielded a false result.

Using an inclination of the fold axis steeper than that measured at Charen, the maximum clustering occurred for a fold axis that plunges about 50° (k reaching 48 and $\sqrt{k_x \cdot k_y}$ 57.3; optimal unfolding at 108%; direction $D = -3.3°$; $I = 23.1°$). The structure is therefore likely to be more complex than a simple cylindrical fold but, in any case, the fold test is positive (Fig. 6). The other unknown element in this correction was the age of tilting of the fold axis relative to the acquisition of the magnetization. If this tilting predates the acquisition of the magnetization (i.e. it was a first phase of tilting before the main folding and magnetization acquisition), the beds have to be retilted in a third step of the dip correction.

4.4.2. ChRM

In the northern part of the Koudiat ed Delaa (DN1–DN5 sites), the potentially overturned series have an Alpine antiformal structure. The orientation of the Alpine fold axis cannot be really taken into account for the dip correction because of the visible curvature of this fold axis in this periclinal area. Therefore the correction was made by simple unfolding (Table 1). During progressive unfolding from 0 to 100%, the precision parameters ($N = 49$) showed a strong increase, for k from 7 to 83 (maximum 89 at 92%), and for $\sqrt{k_x \cdot k_y}$ from 9 to 92 (maximum 97 at 96%). The maximum values were not significantly different from the value for 100% unfolding. A correction made after untilting of a 'mean' fold axis dipping of 25° gave similar results, with the maximum value of the precision parameters being 74.1 at 104% for k and 83 at 110% for $\sqrt{k_x \cdot k_y}$. The fact that these last values are lower than for a dip correction without untilting of the fold axis, suggests that the periclinal structure is not related to a superimposition of deformations. Fig. 7 illustrates the variation of the confidence zone at 95% during progressive unfolding using site mean direction (Table 1). The fold test is clearly positive, indicating a prefolding magnetization. The main conclusion is obviously that the magnetization was acquired before the folding or during the first stages of the folding. In such a case, the method of Surmont et al. (1990) and Shipunov (1997) for determination of the best unfolding can be applied. The directions obtained are practically the same, and the mean optimal unfolding is of the order of 95% (fold axis non untilted) to 105% (fold axis untilted). The southern part of the Koudiat ed Delaa (DS1 to DS3 sites) is a moderately deformed monocline. Here again, though weak difference in dip, the fold test is moderately positive, and the magnetization therefore prefolding.

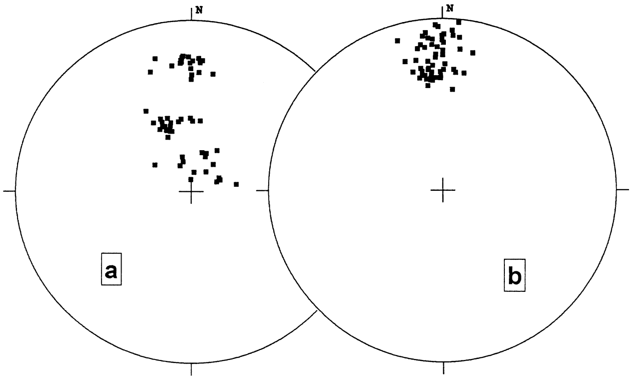

Fig. 6. Component B in upright beds of the Jebel Slata, before (a) and after (b) dip correction using fold axis 50° plunging towards NE. Stereographic projection, the full (empty) symbols corresponding to the lower (upper) hemisphere.

5. Age of the magnetization

The site data (Figs. 8–10 and Tables 1 and 2) are presented without correcting of the overturned units to their upright position.

5.1. Component B

Both the unconformity and conglomerate tests show that the component B is an overprint, and therefore was acquired during or after Upper Albian times. The fold test indicates a pre- or early Alpine folding remagnetization, i.e. acquisition before the Middle Miocene. To obtain better constraints on this age, the paleomagnetic pole was compared (Fig. 11) to the African Apparent Polar Wander Path (APWP) of Besse and Courtillot (1991). The best grouping of component B

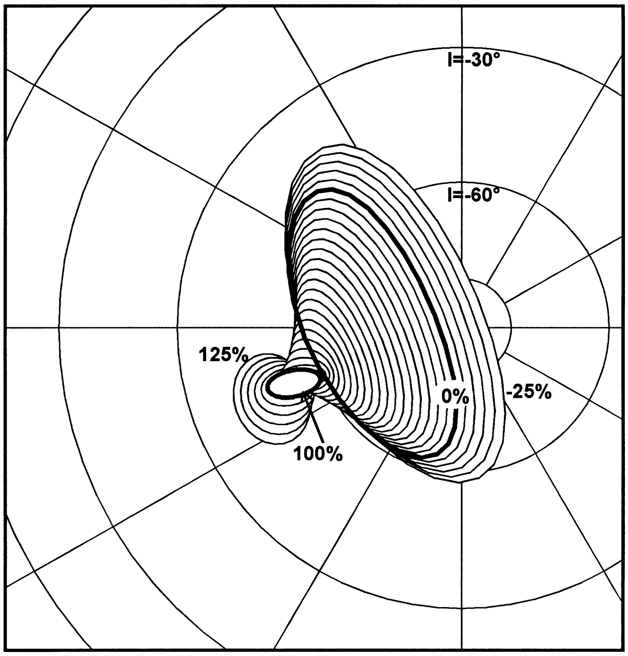

Fig. 7. Evolution of the confidence zone at 95% (Le Goff, 1990; Le Goff et al., 1992) of the ChRM during progressive unfolding (in percent) in the Northern Koudiat ed Delaa. Stereographic projection in the upper hemisphere.

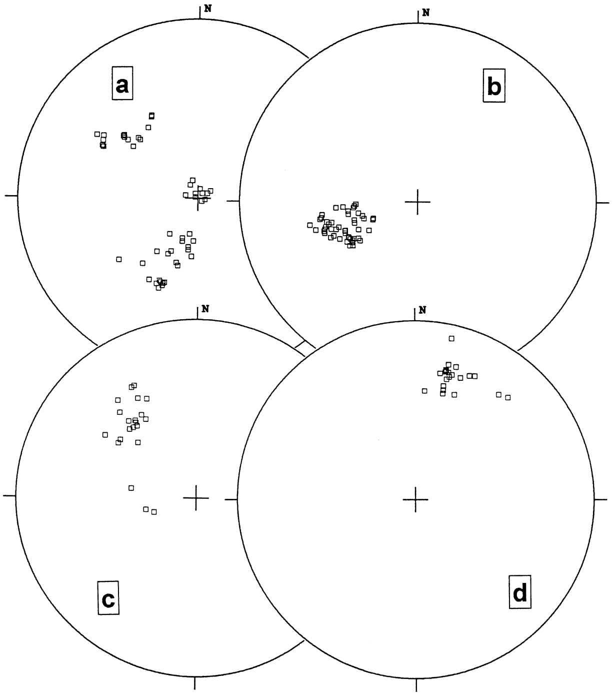

Fig. 9. ChRM in the northern (a, b) and southern (c, d) part of the Koudiat ed Delaa, before (a, c) and after (b, d) correction of the apparent dip. Stereographic projection, the full (empty) symbols corresponding to the lower (upper) hemisphere.

directions was found using a structural correction of about 100% unfolding and taking into account a dip of the fold axis. The location of the paleomagnetic pole for 100% unfolding does not appear greatly affected by the plunge of the fold axis: 200.6°E, 66.6°N for an horizontal axis (B on Fig. 9), 198.2°E, 66.1°N for a 23° plunging fold axis (C on Fig. 9—neighboring pole D corresponds to the optimal unfolding at 85%) and 196.3°E, 65.7°N for a plunge of 50°. Their location should correspond to an Eocene or Upper Cretaceous age, but none of these poles are very close to the APWP. Some uncertainties remain about the significance of a paleomagnetic pole in such an area. The initial comparison with African APWP assumes

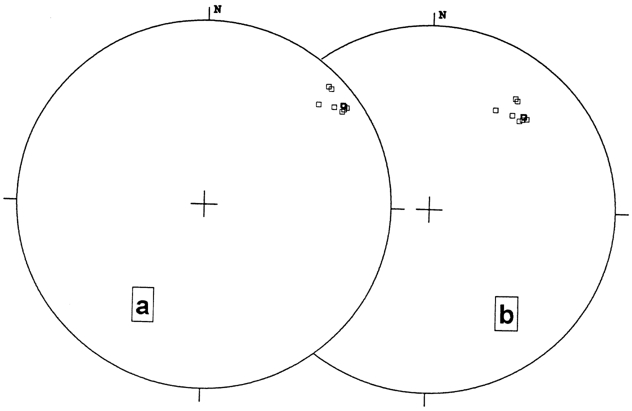

Fig. 8. ChRM in the Jebel ed Debadib, before (a) and after (b) correction of the apparent dip. Stereographic projection, the full (empty) symbols corresponding to the lower (upper) hemisphere.

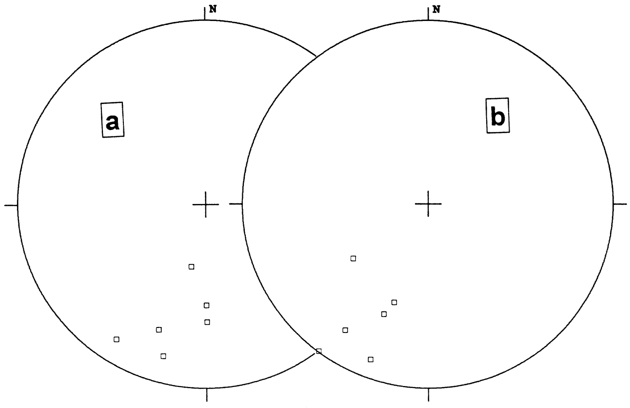

Fig. 10. ChRM in the Jebel Slata, before (a) and after (b) correction of the apparent dip. Stereographic projection, the full (empty) symbols corresponding to the lower (upper) hemisphere.

no movement of this region relative to stable Africa. This may not be the case (Ghorabi and Henry, 1992). Therefore, the pole was recalculated assuming a vertical axis of rotation relative to stable Africa in either a counterclockwise (D→F) or clockwise (D→G) direction (Fig. 11). None of the locations are significantly closer to the APWP than the original direction D. The age corresponding to the locations the closest to the APWP should be to Albian to Eocene; the maximum allowance for any rotation relative to stable Africa is restricted to a clockwise (maximum 20°) direction.

Another possible explanation for the discordant pole is related to the assumption that the plunge of the present fold axis was acquired after the acquisition of the magnetization. If the magnetization is younger than a simple tilt but older than the subsequent phase of folding, the paleomagnetic direction must be retilted after completion of the unfolding (untilting of the fold axis and unfolding) in order to obtain the true direction. Therefore the paleomagnetic pole was recalculated for progressive retilting (D→E on Fig. 11) of the fold axis. The poles for the different attitudes of the fold axis used for the original dip correction are similar so, for clarity, only one example is presented (Fig. 11) which shows that the paleomagnetic pole passes over the APWP for an initial dip of the fold axis of about 15°. The corresponding age is thus Lower Eocene.

Finally, assuming no tilting of the axis and synfolding magnetization (A on Fig. 11), an Eocene age could also be proposed. However, this appears to be an unlikely option, because of relatively large scattering of the paleomagnetic directions, and an important lengthening of the distribution. Moreover, this implies that more than the half of the Alpine folding was acquired during the Eocene, and therefore conflicts with the available geological evidence. For the B component, no age younger than Eocene is compatible with the obtained paleomagnetic pole, and the most probable age appears to be Eocene.

5.2. ChRM

This magnetization is prefolding. It could be either primary or represent another pre-Alpine overprint, assuming that the overturned beds are actually upright beds. This last hypothesis is impossible because all the directions, obtained in potentially overturned beds, are completely different from that of the Earth's magnetic field during and after the Cretaceous, even if allowance is made for a clockwise rotation relative to stable Africa between 0° and 20°. The directions obtained in the possibly overturned beds can only be explained by accepting that these beds are truly overturned and that the magnetization was acquired before they were over-

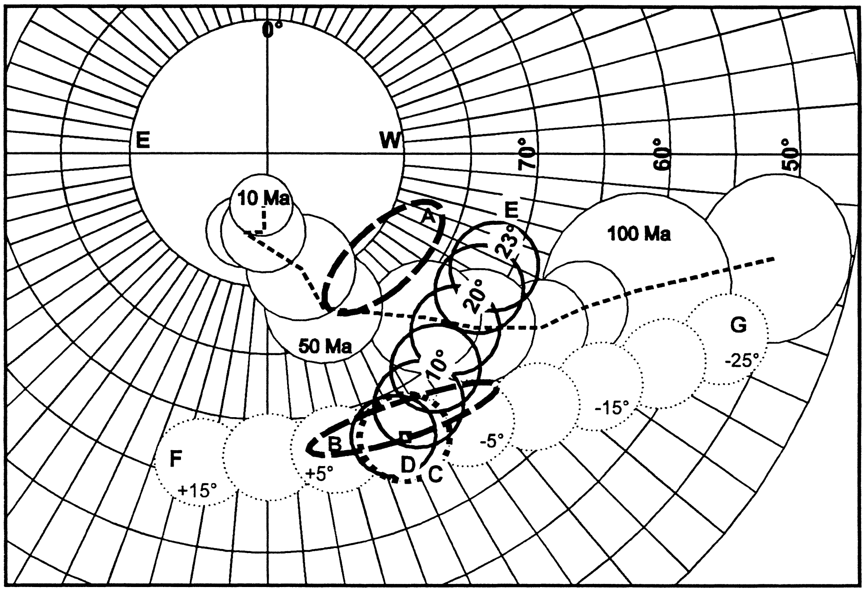

Fig. 11. African APWP (Besse and Courtillot, 1991) with corresponding age in Ma (Curve with confidence zone each 10 My and age in Ma), and confidence zone for the paleomagnetic pole associated with the B component using different structural corrections: fold axis non untilted (synfolding—A, or prefolding—B, magnetization) or untilted (synfolding—D, or prefolding—C, magnetization) and progressively retilted for synfolding (D→E—circles with thick continuous line; angle of axis retilting in degrees). Effect of a regional rotation on the pole location (D→F—counterclockwise, D→G—clockwise, dotted thin circles with rotation value counterclockwise in degrees). A and B are presented by ellipses, because their confidence zones are very lengthened, the other confidence zones are shown by circles because their lengthening is not significant.

turned. The scattering of the directions must then be due to the scattering of the axis of overturning for the different units.

In the Jebel Slata, structural observations show that the overturning is ante-Albian. The magnetization of the overturned beds was therefore acquired between time of deposition and Upper Albian, i.e. it is very likely to be syngenetic or diagenetic. The inclination obtained is slightly different from that expected (28–34° for Aptian–Albian times, with an uncertainty of the order of 7°) in the northern part of the Koudiat ed Delaa. However, a clear fold test in this structure indicates a prefolding magnetization. This implies that a significant uniform dip existed but no folding had occurred prior to the acquisition of the magnetization, and that the magnetization is probably late diagenetic.

6. Structural polarity criterion

In all the beds, for which a debate existed about the structural polarity, the magnetic polarity is reversed after simple unfolding of the Alpine fold. The magnetization was acquired during the long Cretaceous period of exclusively normal magnetic polarity. These beds therefore cannot be in upright structural position. The polarity of the magnetization is therefore here an unquestionable criterion for the determination of the structural position of the beds, and the overturned position of the controversial beds is clearly established here.

7. Structural implications

7.1. Diapir or salt glacier?

A first obvious implication is that the model of diapirs, with emplacement related to halokinesis, is confirmed. A fundamental point in the salt glacier hypothesis, as presented by Vila et al. (1994, 1996a, b), was the presence in different localities of evaporites overlying Albian levels which should all still be in their upright positions. The diapir model predicts that some of these beds are overturned in several locations, as in Jebel Debadib and Koudiat ed Delaa. The overturned position of these Albian beds in these two localities was confirmed by this study.

The unconformity tests also testify against a simple interbedding of the Triassic rocks within the Albian series. The relative position (angular discordance) of the beds at the Jebel Slata was acquired before Oligocene times (component B of older age) and cannot be explained by Alpine tectonic events.

7.2. Eocene event in the Jebel Slata

The B component, likely of Eocene age, at the Jebel Slata shows that a significant event in the history of this diapir occurred at this period. The Pb, Ba, Fe mineralizations (Smati, 1986) are still undated, but such mineralizations are related to fluid migration and are often accompanied by a magnetic overprint (Symons and Sangster, 1994; Rouvier et al., 1995). The presence of ore deposits only in the diapir area shows that the mineralization is related to fluid migration using the diapiric pipe as a conduit. Owing to the more or less impermeable nature of the Triassic rocks, this fluid migration probably occurred during an halokinesis phase. Eocene halokinesis is known in diapirs from the Tunisian Channel. However, around the Jebel Slata, Eocene outcrops are too far away to give independent geological information about an Eocene event at the diapir. The Eocene paleomagnetic age therefore yields an argument in favor of such an Eocene halokinesis also on the platform south of the Tunisian Channel.

7.3. Overturning

An interesting point is the analysis of the geometry of the overturning of these sites. The paleomagnetic reference direction P is given by the data for stable Africa, with an uncertainty related to a possible clockwise rotation of 20°. A horizontal axis is assumed for the overturning. Knowing the paleomagnetic direction (O) before Alpine deformation (beds replaced in horizontal position, but overturned) and the paleomagnetic reference direction (P) before overturning, the small circle with horizontal axis including O and P traces out the trajectory of the paleomagnetic direction during the overturning. The axis of overturning is the axis of this small circle. In the Jebel Slata, this axis has been found to be roughly E–W for the Sidi Amor ben Salem area. It is here related to the first diapiric event, before the Upper Albian. For the other sites, the sampled levels correspond to the Albian cover of the Triassic bodies. The overturning of this cover cannot be related to the emplacement of these Triassic rocks. In the Jebel Debadib, the axis is N–S to NNE–SSW. This axis is not significantly different than that of the Alpine fold and the overturning here can only be due to Alpine tectonics. In the Koudiat ed Delaa, the axis is also N–S to NNE–SSW in the southern part. Here again, the overturning could be explained by Alpine tectonics. This is not the case for the northern part of the Koudiat ed Delaa, where the overturning axis is WNW–ESE. The overturning is not Alpine, nor related to ante-Upper Albian piercing. It is therefore related to another phase of piercing. In this location, the paleomagnetic inclination is higher than that expected, implying that the beds were not horizontal during the magnetization acquisition. The second piercing probably occurred during the Upper Albian or very shortly thereafter. The dip during magnetization acquisition was towards the SW to SE (for the ChRM, a higher inclination than expected). The sense of rotation is then known, because this dip is related to the start of the overturning. The piercing area was probably rather northwards of the Koudiat ed Delaa. The northern and southern part of the Koudiat ed Delaa were therefore initially formed as two different structures. This is confirmed by the presence of some outcrops of Triassic rocks in the valley between these two parts. The common structure in this area is of Alpine age.

8. Conclusions

The structural polarity criterion demonstrated by the magnetic polarity yields unambiguous data. However, its use requires a detailed paleomagnetic study to control the age of the magnetization. In the case of the Triassic bodies in Tunisia, it enables a clear choice between two opposite theories about the mode of emplacement. Moreover, paleomagnetism appears to be a very useful tool for the analysis of the geometry and the evolution of the diapirs (Weinberger et al., 1997). It suggests that the halokinesis event in Eocene times was not just limited to the Tunisian Channel area, and allows the determination of the overturning axes, pointing out in one of the studied structure a new halokinesis event during or slightly after the Upper Albian.

Acknowledgements

Fieldwork for this study was supported by the Péri-Téthys program. We are very grateful to the Office des Mines de Tunisie for logistical support, to D. Tarling and A. McCaig for very helpful reviews and to M. Lewchuk for help with the manuscript.

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