AAPG International Conference
Barcelona, Spain
September 21-24, 2003

M. Sahabi[1], J. L. Olivet[2], D. Aslanian[2], M. Patriat[2], L. Geli[2], L. Matias[3], J. P. Rehault[4], J. Malod[4], M. El Mostaine[5], M. Bouabdelli[6] (1) Faculte des Sciences El Jadida, El Jadida, Morocco (2) DRO/GM, Plouzane, France (3) ICTE, Lisboa, Portugal (4) IUEM, UBO, Plouzane, France (5) Onarep, Rabat, Morocco (6) Faculte des Sciences, Semlalia, Morocco

A Revised Reconstruction of The Central Atlantic at Liassic Times

Abstract

Based on a careful analysis of all available seismic data, the mapping of the salt diapir provinces on the American East Coast and North West African conjugated margins is revisited, and the magnetic data off NW Africa are reinterpreted. We propose that the magnetic anomaly S1 in the NW Morocco basin and the West African Coast Magnetic Anomaly (WACMA) offshore Mauritania are located at the western boundary of the salt diapir province, delineating the ocean / continent boundary on the NW African margin. A new reconstruction of the Central Atlantic during Liassic times (ca 200 Ma ago) is presented, based on the hypothesis that the S1/WACMA system is the equivalent of the East Coast Magnetic Anomaly (ECMA), that is generally interpreted as delineating the ocean/continent boundary on the North East American margin. This reconstruction reconciles plate kinematics and available geophysical data, seismics and magnetics.

Introduction

Previous initial reconstructions of the Central Atlantic (Le Fort & Van der Voo, 1981 ; Wissmann & Roeser, 1982 ; Le Pichon et al., 1977 ; Olivet et al., 1984 ; Klitgord et Schouten, 1986) do not take into account the real geometry, at late Triassic times, of the North West Morocco (on the African plate) and Nova Scotia (on the American plate) conjugate salt basins. Since then, new seismic data have been collected on the NW Morocco Canadian margin that provide new constraints for mapping the boundaries of these evaporitic basins. In addition, relatively recent compilations of magnetic data (Verhoef et al., 1996 and this study) help revisit the identification of magnetic anomalies on the North West African margin. The initial reconstruction that we propose is based on these new elements.

Salt diapir provinces of the Central Atlantic conjugate margins

On the NW African margin, the presence of evaporites below the Seine Abyssal Plain was first evidenced by Le Pichon et al. (Nestlante Cruise, 1970), based on seismic data. Halite sampled by DSDP drillhole 546 was then shown to be Rhetian - Hettangian, contemporaneous of the early opening stage of the Central Atlantic (Hinz, Winterer et al., 1984), suggesting that the first basins that were created by the North-America / Africa continental breakup evolved in confinement conditions that favoured salt deposition.

- On the NW Morocco margin (Fig. 1 & 2), the salt diapir domain extends over 800 km, between about latitudes 34.6°N and 28.5°N. South of 33°N, the position of the western boundary of the domain is generally accepted by all authors. North of 33°N, however, using seismic data collected during cruises Meteor M67, Rifano and Sismar (Fig. 3a & Fig. 3b), we show that autochtonous salt diapirs are present as far as 100 km west of the boundary proposed by previous workers (e.g. Hinz et al., 1982).

- Offshore Mauritania, between latitudes 16°N and 19°N, seismic data show the existence of deep basins, oriented N-S and filled with evaporites (Wissmann, 1982), supposedly Liassic in age (Lehner & Ruiter, 1977), thus contemporaneous with the initial stages of intra-continental rifting

Copyright © 2003 by AAPG

On the north-east American margin (Fig. 4), an important salt diapir province extends from Newfoundland down to 40°N. This province is more or less symmetrical and contemporaneous (of age Rhetian-Hettangian, after Jansa & Wade, 1975 ; Manspeizer, 1988 ; Holser et al., 1988) to the NW Morocco diapiric basin. This province appears to be divided into 2 sub-domains :

- South of 42.5°N, the sub-domain is delineated by the East Coast magnetic Anomaly (ECMA), which corresponds to the ocean / continent transition (Keen & Potter, 1995a). East of ECMA, Jurassic sediment layers are not affected by diapirism and deposited on oceanic crust (Salisbury & Keen, 1993).

- North of 42.5°N, the diapiric province spreads out, about 100 km east of ECMA. The careful analysis of seismic data (line 89-1, Keen & Potter, 1995b, for instance) however, suggests that the diapirs present east of ECMA are allochtonous : the salt has probably glided from its original position west of the ECMA, during a tectonic phase which affected the evolution of the Central Atlantic in Mid/Upper Jurassic times.

Also, we note that south of 40°N, on the Carolina margin, a narrow salt province is present between 30°N and 35°N, with diapiric structures oriented NNE-SSW and dated Lower Jurassic (Dillon et al, 1983).

Magnetic anomalies of the Central Atlantic conjugate margins

On the NW African margin (Fig. 1), the main magnetic anomalies that have been identified are : anomaly S1, off Morocco (Roeser, 1982 ; Verhoef et al., 1996 ; Roeser et al, 2002) ; the West Africa Magnetic Anomaly (WACMA), off South Morocco and Mauritania (Wissmann et Roeser, 1982) ; and the Senegal Basin magnetic anomaly (Roussel & Liger, 1983). Other magnetic anomalies, of low amplitude, are also identified, such as : anomalies S2, S3 et S4 on the NW Morocco continental shelf ; and a few magnetic lineaments, visible onshore, in the Senegal basin.

- Anomaly S1 is clearly identified between latitudes 26.2°N and 33.2°N. Over seven degrees of latitude, the anomaly borders to the west the salt province of the NW Morocco margin. North of 33.2°N, its amplitude decreases and the anomaly becomes difficult to identify (Fig. 1). According to Roeser et al. (2002), the anomaly is parallel to the coast line. However, considering that S1 represents the first anomaly after the onset of seafloor spreading, this hypothesis is not supported by the presence of autochtonous salt diapirs observed east of 10°W on Sismar Lines 4 and 10 (Fig. 3a ; 3b). In this study, we propose that - consistent with the south of 33.2°N - the positive magnetic anomaly that bounds the salt province to the west actually delineates Anomaly S1 north of 33.2°N.

- The West African Coast Magnetic Anomaly (WACMA) exists between 26.2°N and 21°N. Between 26.2°N and 25.5°N, this anomaly is located onshore (Querol, 1966 in Wissmann and Roeser, 1982). Between 25.5° and 21°N, its location is well known, due to a good data coverage (Hayes & Rabinowitz, 1975). South of 20°N, previous workers (Klitgord & Schouten, 1986 and Olivet et al., 1984) have proposed that the southern continuation of WACMA is represented by the Senegal Basin magnetic anomaly, visible onshore, between latitudes 18°N and 15°N, along longitude 16°W. However, this hypothesis is not consistent with the presence in the area of a salt diapir basin, dated Lower Jurassic or older. In this study, we propose that the WACMA is actually located offshore Mauritania, again bordering the salt diapir basin to the west (Fig. 1).

On the north American margin, the major magnetic anomalies are (Fig. 4) : the East Coast Magnetic Anomaly (ECMA), a prominent, high amplitude (300 to 500 nT) anomaly that borders the America East Coast margin along 2500 km, between 44°N and 30.5°N (Vogt et al., 1973) ; the Brunswick Magnetic Anomaly (BMA), located west of ECMA, between 30°N and Cape Hatteras ; the Blake Spur Magnetic Anomaly (BSMA), located about 200 to 220 km east of ECMA and estimated to be of Callovian age (ca 165 Ma), based on DSDP Hole data (Sheridan, Gradstein et al., 1972).

The ocean - continent boundary

On the US East Coast margin, south of 40°N, the ocean-continent boundary is delineated by the East Coast Magnetic Anomaly (ECMA), which is associated with seaward dipping reflectors resulting from thick volcanic sequences emplaced during the early rifting phase (Klitgord et al., 1988 ; Talwani et al., 1995). North of 40°N, the progressive northwards decrease in amplitude of the ECMA suggests that the volcanic activity along the margin decreased north of

this latitude (Keen & Potter, 1995b). In addition, north of 40°N, the salt diapirs found east of ECMA have been shown to be allochtonous, reinforcing the hypothesis that there is a ubiquitous correspondence between ECMA and ocean/continent boundary.

On the NW African margin, the salt diapir province appears to be bounded to the east by Anomaly S1 in the NW Morocco margin, and by WACMA off southern Morocco and Mauritania. The salt diapirs being autochtonous, we propose that anomalies S1 and WACMA delineate the ocean - continent boundary on the NW African margin. This assumption is supported by refraction seismics results (Contrucci et al., 2003), showing a non-oceanic crust east of the diapir boundary. It implies that the S1/WACMA and ECMA are conjugate magnetic anomalies that mark the first stage of seafloor spreading, 195 Ma ago (Le Roy & Piqué, 2001).

Our interpretation differs from Klitgord and Schouten (1986), who considered that the African equivalent of the southern ECMA was the Senegal basin anomaly. In this study, we suggest that the Senegal basin anomaly and the Brunswick magnetic anomaly could be related to old basement sutures or to intra-continental structures emplaced during the early rifting phase, comparable to Anomaly S3, on the NW Morocco margin. However, the Blake Spur and E magnetic anomalies are both oceanic.

Closure reconstruction of the Central Atlantic

The closure reconstruction presented in this study is based on the assumption that S1/WACMA and ECMA are conjugate magnetic anomalies that were juxtaposed at Lower Lias times (195 Ma ago). This interpretation implies that :

- the Morocco Meseta block and the Africa block evolved independently during Mesozoïc times. The boundary between these two blocks is supposedly located within the present day Atlas domain, which experienced rifting during Liassic times and compression after Upper Jurassic times (Mattauer et al., 1977 ; Laville, 1985). Our reconstruction suggests the existence of a post-jurassic continental shortening of about 20 km to the west and 80 km to the east of the Meseta (Fig. 5b).

- the 40°N / Kelvin Seamounts structural lineament on the American plate and the South Atlas fault / Canary seamounts on the African plate are not homolog structures (Fig. 5a), as previously proposed by Le Pichon et al. (1977) and Arthaud & Matte (1977).

- Conjugate salt basins of the NW African and NE American margins were juxtaposed, suggesting that the crust was of normal, continental thickness during Triassic times. Models that attempt to explain the formation of the continental margin should take into account this geological constraint.

Acknowlegments : We thank the Captain and crew of R/V Nadir and R/V Almeida Carvalho for their efforts in collecting the data during the Sismar cruise. R. Bartolome, H. Nouzé, I. Contrucci and J. Perrot processed the seismic data (reflexion and refraction) after the cruise. We also greatfully acknowledge H. A. Roeser for providing data from Meteor cruises.

Figure captions

Figure 1 : Map of the Northwest Africa margin. Symbols are explained in inset, Figure 4. Black lines indicate structural features recognized on the free air gravity anomaly map of Sandwell and Smith (1997). Red lines and dots are for magnetic anomaly contours and maxima. The salt diapir province is shaded in green. Blue dots indicate salt diapir locations. The S1 magnetic anomaly (Fig.1b) and the West African Coast Magnetic anomaly (Fig. 1c) have been redefined in the present study, based on the interpretation detailed in insets. S1 anomaly on the NW Morocco margin, north of 33.2°N, is based on the re-interpretation of R/V Meteor M67 data (Roeser at al., 2002). The WACMA, offshore Mauritania, is based on magnetic profiles collected by different vessels over the years and compiled in the Geodas database. The intra-continental Senegal basin and S3 magnetic anomalies are indicated.

Figure 2 : Revised structural map of the North-West Morocco evaporitic basin superposed on magnetic anomaly contours of Verhoef et al. (1996). The structural information is based on Hinz et al. (1982), and on seismic data from

Meteor M67 (courtesy H. A. Roeser), Rifano and Sismar cruises. The redefined western boundary of the basin is delineated by Magnetic Anomaly S1. The location of Sismar and Meteor seismic profiles is shown.

Figure 3 : Interpreted SISMAR seismic lines 4 (Fig. 3a) and 10 (Fig. 3b). Red line indicates the basement ; purple, blue and green line are not dated, but help appreciate basement depth. Salt structures are underlined by purple symbols " ^ ". Note the termination of the purple reflector intersecting a basement high (black arrow) that coincides with the location of magnetic anomaly S1. Red arrows and numbers indicate Ocean Bottom Seismometers positions. Refraction seismic results suggest that the crust is not oceanic east of OBS 13.

Figure 4 : Map of the North-East America margin. Symbols are explained in inset (see also caption, Fig. 1). Note : 1) the presence of salt diapirs off Nova Scotia and in the Carolina basin ; 2) the position of magnetic anomalies ECMA, BSMA, BMA and E. The ECMA delineates the eastern boundary of the salt province, except north of 42.5°N, where the salt province spreads out to the east of ECMA. Insets indicate seismic lines 89-1 and 88-1A (Keen and Plotter, 1995) re-inrepreted in the present study. The basement is in red. Beige, green and blue lines are for Oligocene (A^u), Barremian (B) and Callovian/Lower Oxfordian (J_2) discordances (Wade and Mac Lean, 1990). Line 89-1 indicates that the salt diapirs (purple symbols ^) located to the east of ECMA come from a sediment layer lying over the J_2 discordance and deposited on oceanic crust. This suggests that the salt diapirs located east of ECMA are allochtonous.

Figure 5 : Reconstruction of the Central Atlantic at Liassic times (200 Ma ago ; Fig. 5a), showing the relative positions of the Africa - Meseta - North America blocks. Symbols are explained in inset (see also caption, Fig. 1). The present-day boundaries of the salt diapir provinces off Nova Scotia and off NW Morocco are indicated. Inset (Fig. 5b) illustrates the juxtaposition of the ECMA/S1 conjugate magnetic anomalies, 200 Ma ago.

Reconstruction poles ; age (200 Ma) :

African plate to North American plate :	65.84 N	12.72 W	-76.84
Meseta blok to North American plate :	64.58 N	14.87 W	-73.97

References

Arthaud, F., and P. Matte, 1977, Late palezoic strike slip faulting in southern europe and northern Africa : results of a right lateral shear zone between the Appalachians and the Urals: Geological Society of America Bulletin, v. 88, p. 1305-1320.

Contrucci, I., F. Klingelhöfer, J. Perrot, R. Bartolome, M. A. Gutscher, M. Sahabi, J. A. Malod, and J. P. Réhault, Submitted, The Crustal Structure of the NW Moroccan Continental Marginb from Wide-angle and Reflection Seismic Data: Geophys. J. Int.

Dillon, W. P., K. D. Klitgord, and C. K. Paull, 1983, Mezosoic development and structure of the continental margin off the south Carolina, *in* G.G.S., ed., Studies related to the Charleston, South Carolina, earthquake of 1886 ; Tectonics and seismicity, U.S. Geological Survey Professional Paper 1313-N, p. 16 p.

Hayes, D. E., and P. D. Rabinowitz, 1975, Mesozoic magnetic lineations and the magnetic Quiet Zone Off Northwest Africa: Earth Planet. Sci. Lett., v. 28, p. 105-115.

Hinz, K., H. Dotsmann and J. Fritsch, 1982, The continental margin of Morocco : Seismic Sequences, Structural Elements and Geological Development, *in* U. Von Rad, K. Hinz, M. Sarnthein, and E. Seibold, eds., Geology of the North West african continental margin: Berlin Heidelberg New York, Springer-Verlag, p. 34-60.

Hinz, K., Winterer, E. L. et al., 1979. Initial Repts. DSDP, 79:Washington (U.S. Govt. Printing Office).

Holser, W. T., G. P. Clement, L. F. Jansa, and J. A. Wade, 1988, Evaporite deposits of the North Atlantic Rift, *in* W. Manspeizer, ed., Triassic - Jurasic Rifting ; Continental Breakup and the origin of the Atlantic Ocean and Passive Margins, v. B: Amsterdam, Elsevier, p. 525-553.

Jansa, L. F., J. P. Bujak, and G. L. Williams, 1980, Upper Triassic salt deposits of the Western North Atlantic: Can. J. Earth Sci., v. 17, p. 547-558.

Jansa, L. F., and J. A. Wade, 1975, Geology of the continental margin off Nova Scotia and Newfoundland, *in* W. J. M. Vander Linden, and J. A. Wade, eds., Offshore Geology of Eastern Canada, 2. Regional Geology, v. 74 & 30, Canada Geological Survey, p. 51-106.

Keen, C. E., and D. P. Potter, 1995a, Formation and evolution of the Nova Scotian rifted margin : evidence from deep

seismic reflection data: Tectonics, v. 14, p. 918-932.
Keen, C. E., and D. P. Potter, 1995b, The transition from a volcanic to a nonvolcanic rifted margin off Eastern Canada: Tectonics, v. 14, p. 359-371.
Klitgord, K. D., D. R. Hutchinson, and H. Schouten, 1988, U.S. Atlantic Continental margin; Structural and tectonic framework, *in* R. E. Sheridan, and J. A. Grow, eds., The Atlantic Continental Margin, U.S.: Geological Society of America, The Geology of North America, v. 1-2.
Klitgord, K. D., and H. Schouten, 1986, Plate kinematics of the Central Atlantic, *in* P. R. Vogt, and B. E. Tucholke, eds., The Western North Atlantic Region. The Geology of North America, v. M, The Geological Society of America, p. 351-377.
Laville, E., 1985, Evolution sédimentaire, tectonique et magmatique du bassin jurassique du Haut Atlas (Maroc) : modèle en relais multiple de décrochements, 166 p.
Le Fort, J. P., and R. Van der Voo, 1981, A Kinematic model for the collision and complete suturing between Gondwanaland and Laurussia in the Carbiferous: The Jounal of Geology, v. 89, p. 537-550.
Le Pichon, X., J. C. Sibuet, and J. Francheteau, 1977, The fit of the continent around the North Atlantic ocean: Tectonophysics, v. 38, p. 169-209.
Le Roy, P., and A. Piqué, 2001, Triassic-Liassic Western Moroccan synrift basins in relation to the Central Atlantic opening: Marine Geology, v. 172, p. 359-381.
Lehner, P., and P. A. D. de Ruiter, 1977, Structural history of the atlantic margin of Africa: Amer. Assoc. Petrol. Geol. Bull., v. 61, p. 961-981.
Manspeizer, W., 1988, Triassic-Jurassic rifting and opening of the Atlantic : An Overview, *in* W. Manspeizer, ed., Triassic - Jurasic Rifting ; Continental Breakup and the origin of the Atlantic Ocean and Passive Margins, v. A: Amsterdam, Elsevier, p. 41-79.
Mattauer, M., P. Tapponnier, and F. Proust, 1977, Sur les mécanismes de formation des chaînes intracontinentales. L'exemple des chaînes atlasiques du Maroc: Bull. Soc. Géol. France, v. 7, 19, p. 521-526.
Olivet, J. L., J. Bonnin, P. Beuzart, and J. M. Auzende, 1984, Cinématique de l'Atlantique Nord et Central, Plouzané, CNEXO, p. 108.
Roeser, H. A., 1982, Magnetic anomalies in the Magnetic Quiet Zone off Morocco, *in* U. Von Rad, K. Hinz, M. Sarnthein, and E. Seibold, eds., Geology of the North West African Continental Margin: Berlin Heidelberg New York, Springer-Verlag, p. 61-68.
Roeser, H. A., C. Steiner, B. Schreckenberger, and M. Block, 2002, Structural development of the Jurassic Magnetic Quiet Zone off Morocco and identification of Middle Jurassic Magnetic Lineations: Journal of Geophysical Research, v. 107.
Roussel, J., and J. L. Liger, 1983, A review of deep structure and ocean-continent transition in the Senegal basin (West Africa): Tectonophysics, v. 91, p. 183 - 211.
Salisbury, M. H., and C. E. Keen, 1993, Listric faults imaged in oceanic crust: Geology, v. 21, p. 117-120.
Sandwell, D. T., and W.H.T. Smith, 1997, Marine gravity anomaly from Geosat and ERS1 satellite altimetry. J. Geophys. Res., v. 102, p. 10039 - 10054.
Sheridan R.E., F.M. Gradstein, et al., 1972, Early history of the Atlantic ocean and gaz hydrates on the Blake Outer Ridge : results of the Deep - Sea Drilling Project Leg 76, Geol. Soc. Amer. Bull., 03, 876 - 885.
Talwani, M., J. Ewing, R. E. Sheridan, W. S. Holbrook, and L. Glover, 1995, The edge expriment and the U.S. East Coast Magnetic Anomaly, *in* E. Banda, and al., eds., Rifted Ocean-Continent Boundaries: Netherlands, Kluwer Academic, p. 155-181.
Verhoef, J., W. R. Roest, R. Macnab, J. Arkani-Hamed, and M. o. t. P. Team, 1996, Magnetic anomalies of the Arctic and North Atlantic Oceans and Adjacent land areas, Geological Survey of Canada, p. 225.
Vogt, P.R., C.J. Anderson, and D.R. Bracey, 1973, Mesozoic magnetic anomalies, sea floor spreading, and geomagnetic reversals in the southwestern North Atlantic. J. Geophys. Res., 76, 20, 4796-4823.
Wade, J. A., and B. C. MacLean, 1990, The Geology of the Southeastern margin of Canada, *in* C. E. Keen, and C. A. Williams, eds., Geology of Canada. Geology of the Continental Margin of Eastern Canada, v. 2, Geological Survey of Canada, p. 167-238.
Wissmann, G., 1982, Stratigraphy and structural features of the continental margin basin of Senegal and Mauritania, *in* U. Von Rad, K. Hinz, M. Sarnthein, and E. Seibold, eds., Geology of the Northwest African Continental Margin: Berlin Heidelberg New York, Springer-Verlag, p. 160-181.
Wissmann, G., and H. A. Roeser, 1982, A magnetic and halocinetic structural pangea fit of Northwest Africa and North America: Geol. Jb., v. E 23, p. 43-61.