ART N° 473
Contribution COB N° 655

Phil. Trans. R. Soc. Lond. A **294**, 51–61 (1980) [51]
Printed in Great Britain

Deep drilling results of Leg 47b (Galicia Bank area) in the framework of the early evolution of the North Atlantic Ocean†

BY J. C. SIBUET,[1] W. B. F. RYAN,[2] M. ARTHUR,[3] R. BARNES,[4] G. BLECHSMIDT,[5] O. DE CHARPAL,[6] P. C. DE GRACIANSKY,[7] D. HABIB,[8] S. IACCARINO,[9] D. JOHNSON,[10] B. G. LOPATIN,[11] A. MALDONADO,[12] L. MONTADERT,[6] D. G. MOORE,[13] G. E. MORGAN[14] G. MOUNTAIN,[2] J. P. REHAULT,[15] J. SIGAL[16] AND C. A. WILLIAMS[2]

[1] *Centre Océanologique de Bretagne, B.P.* 337, 29273 *Brest, France*; [2] *Lamont-Doherty Geological Observatory, Palisades, New York* 10964 *U.S.A.*; [3] *Department of Geological Sciences, Princeton University, Guyot Hall, Princeton, New Jersey, U.S.A.*; [4] *Walla Walla College, Marine Station,* 174 *Rosario Beach, Anacortes, Washington* 98221, *U.S.A.*; [5] *Department of Oceanography, University of Washington, Seattle, Washington* 98105 *U.S.A.*; [6] *Institut Français du Pétrole,* 1–4 *Avenue de Bois-Préau,* 92506 *Rueil Cedex, France*; [7] *Ecole Nationale Supérieure des Mines de Paris,* 60, *Boulevard Saint-Michel,* 75272 *Paris Cedex* 06, *France*; [8] *Queens College of the City, University of New York, Flushing, New York* 11367, *U.S.A.*; [9] *Institute of Geology, University of Parma, Via Kennedy* 1, *Parma, Italy*; [10] *Exxon Production Research Co., P.O. Box* 2189, *Houston, Texas* 77001, *U.S.A.*; [11] *Research Institute of the Geology of the Arctic, Scientific Technical Complex Sevmorgeo, Ministry of Geology, Moyka Embankment,* 120, *Leningrad* 190121, *U.S.S.R.*; [12] *Instituto 'Jaime Almera' de Investigaciones Geologicas Seccion de Estratigrafia y Sedimentolo Auda, Jose Antonio,* 585, *Universida de Barcelona, Barcelona* 7, *Spain*; [13] *Scripps Institution of Oceanography, Deep Sea Drilling Project A*–031, *La Jolla, California* 92093, *U.S.A.*; *University of Leeds, Leeds LS*2 9*JT, U.K.*; [15] *Station de Géodynamique sous marine,* 06230 *Villefranche-sur-Mer, France*; [16] 33, *rue de Montreuil,* 94300 *Vincennes, France*

Lithologic and stratigraphic evidence from D.S.D.P. Site 398 (3910 m water depth, 1740 m total penetration) and regional seismic reflexion data are placed in the context of the early tectonic evolution of the North Atlantic ocean. The morphology of the western Iberian continental margin is the result of two main tensional episodes dated Permo-Lias and Upper Jurassic – Lower Cretaceous, during which the initial basins between Grand Banks and Iberia were created by subsidence and tilting of continental blocks. A limited oceanic opening had probably occurred in Jurassic time between these two tensional episodes. There was no relative motion during Lower Cretaceous between North America and Iberia.

One of the main results is that the 398 drillhole penetrated into the basement structure of a tilted block of the continental margin. Borehole data indicate an Uppermost Aptian age for the end of the Upper Jurassic – Lower Cretaceous tensional episode at the level of the site. The subsequent beginning of sea floor spreading in the Uppermost Aptian is associated with a change of sedimentary facies from graded sequences interbedded with slump beds or debris flows to dark, detritic shales. The continental margin had subsided on a regional scale since this time.

† Contribution no. 655 of the Centre Océanologique de Bretagne.

1. Introduction

D.S.D.P. Site 398 is located on a passive continental margin, south of Galicia Bank, 20 km to the south of Vigo Seamount (figure 1). Although Galicia Bank is continental, the nature of the crust of the interior basin between Galicia Bank and the Iberian continental margin is not firmly established. The initial creation of the interior basin filled with at least pre-Neocomian sediments may be related to the Permo–Triassic–Liassic and/or late Jurassic – early Cretaceous distensive episodes which occurred on land on each side of the North Atlantic (Pautot *et al.* 1970; Amoco 1973; Montadert *et al.* 1974; Arthaud & Matte 1975; Ziegler 1975; Jansa & Wade 1975; Schlee *et al.* 1976; Van Houten 1977; Groupe Galice 1979) and/or with

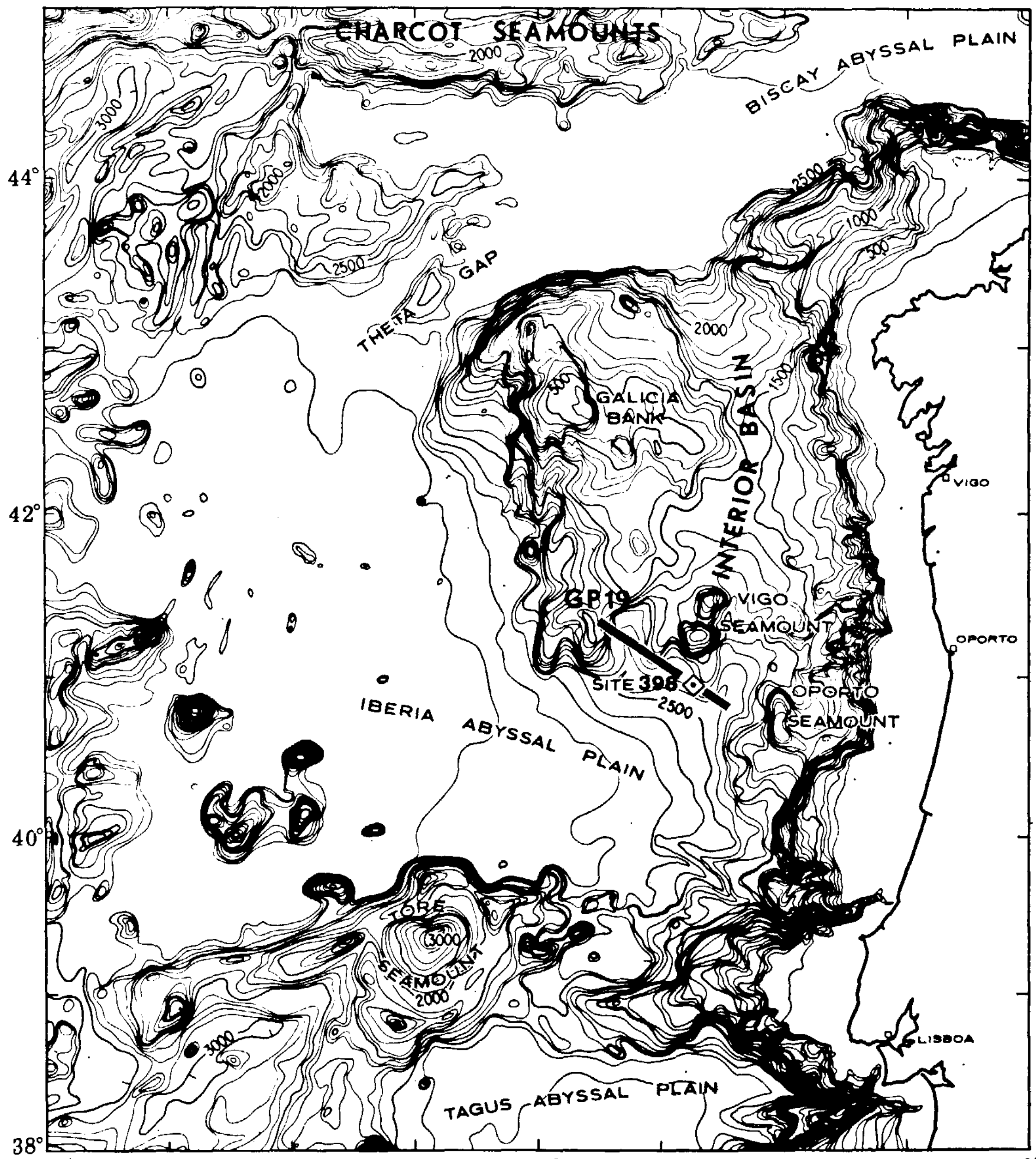

Figure 1. Bathymetric map of the Galicia Bank area (Laughton *et al.* 1975) in corrected fathoms and position of Site 398.

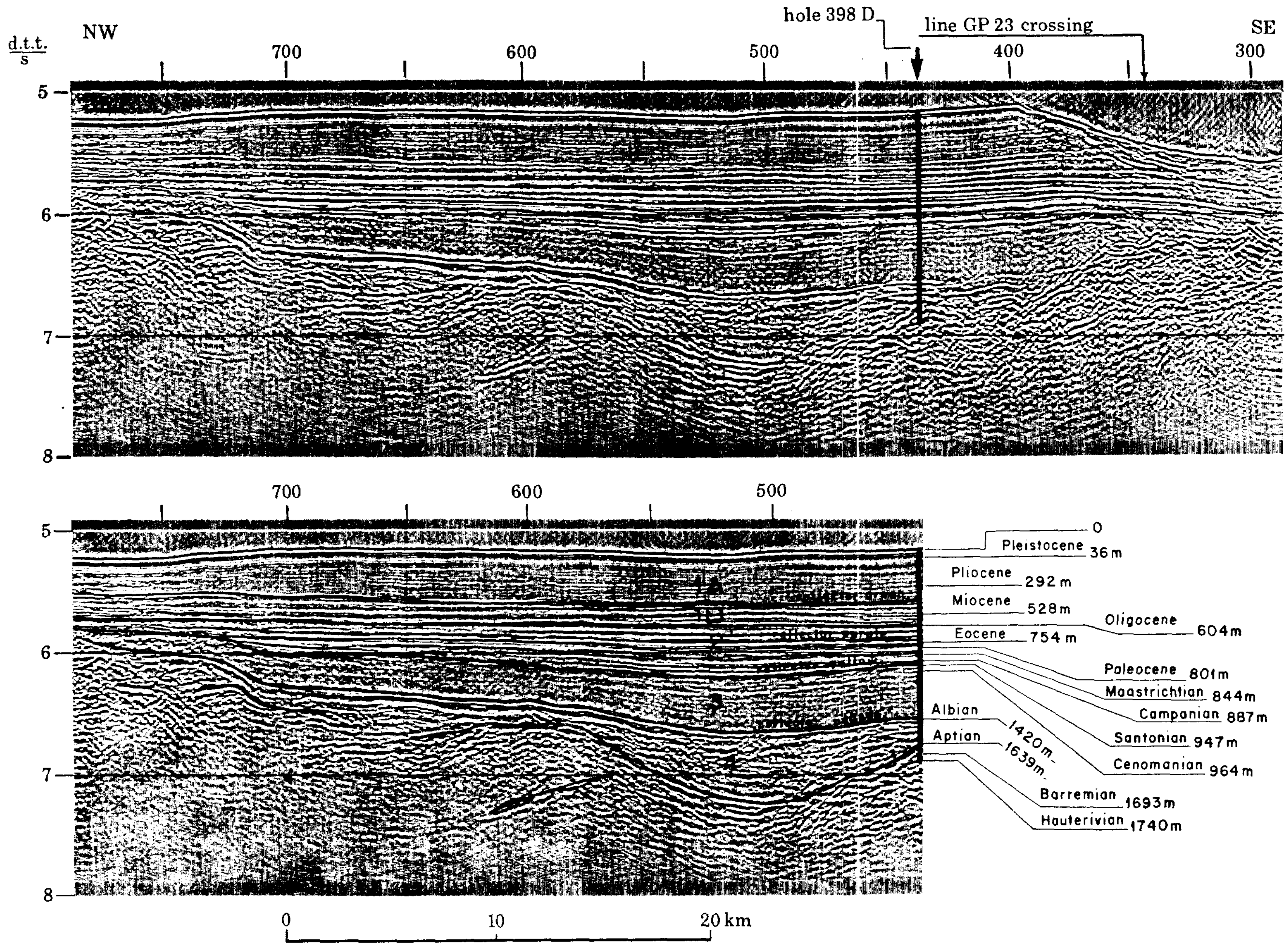

FIGURE 2. Migrated section of the Flexichoc seismic profile GP19 (I.F.P.–C.N.E.X.O.–C.E.P.M.) located on figure 1. Shot numbers at the top of the profile. Shot spacing = 50 m. Horizontal scale in the lower part, vertical scale in seconds of double travel time. The main seismic reflectors and acoustic units are shown on the interpreted profile. Limits and depths of geological stages after site 398 results on the right side.

synchronous or posterior N330 strikeslip motions along the northeastern border of the interior basin (Le Pichon *et al.* 1977; Groupe Galice 1979). Site 398 is consequently located in the southern part of the interior basin in an area greatly affected by rifting (Groupe Galice 1979).

2. Acoustic stratigraphy

Site 398 has been drilled about 400 m laterally off the I.F.P.–C.N.E.X.O. Flexichoc seismic line GP19 near shot 440 (figure 2, see location on figure 1), in a water depth of 3910 m. A total penetration of 1740 m was obtained. Four main acoustic units overlie the acoustic basement (Groupe Galice 1979, figure 2).

The acoustic basement is of clear sedimentary origin on this profile. It is generally diffractive and shows strong reliefs either as broad undulations or as sharp crests corresponding to buried highs. Some of these highs may pierce the seabed and outcrop on other seismic profiles. Sharp crests and strongly dipping layers in the basement suggest the presence of tilted fault-blocks frequent in passive continental margins. On some profiles, several highs are flat topped and covered by a thin sedimentary blanket which suggest that they have been affected by subaerial erosion.

Formation 4 which is a moderately to strongly layered formation, is distinguished from the overlying formation 3 by a strong reflector. Formation 4 lies in troughs between horsts and tilted blocks. Layering is quite conformable with the structural top of the basement in the lowest part of the fills and may be nearly flat at the top of the formation. This indicates that sedimentation occurred during tilting motion of basement blocks.

Formation 3 is generally transparent or slightly layered and fills in depressions. For that, it could be compared with formation 4 but actually differs from it by less inclined or horizontal bedding. This formation may be absent on the tops of structural highs.

Formation 2 seems to have been deposited in many cases on an almost flat topography. It is a layered sequence with several good reflectors. Bedding is generally flat or conformable with the lower boundary.

Formation 1 is acoustically transparent or slightly and regularly layered.

3. Stratigraphy from piston cores, dredge samples and hole 398 D cores

The above acoustic formations can be related to the lithologic column of Site 398 and to the stratigraphy obtained from core and dredge samples (Dupeuble *et al.* 1976; Ryan *et al.* 1979; Groupe Galice 1979; de Graciansky & Chenet 1979; Sigal 1979; Maldonaldo 1979).

On a basis of correspondence between lithologic and acoustic units, stratigraphic and seismic hiatuses, physical properties, mineralogical composition of sediments and acoustic impedances, we believe that the deepest 75 metres were drilled beneath the acoustic basement (Site 398 chapter, Ryan *et al.* 1979; Bouquigny & Willm 1979). They consist of marlstone, siltstone and white indurated limestone of Late Hauterivian to Early Barremian age which are part of complex sequences in this lower unit. The white indurated limestones were deposited under pelagic conditions and the marlstone and siltstone layers could have been emplaced by low density turbidity currents in a very quiet environment. Limestones have been deposited shallower than the CCD but probably at depths reaching 2 km at the level of the site (Ryan *et al.* 1979).

Acoustic formation 4 of Late Barremian to Uppermost Aptian age is constituted of sand–silt–clay graded sequences interbedded with thick (1–10 m) slumped beds or debris flows. These sequences are due to the redeposition of previous deposits on submarine slopes and on a subsiding seafloor (De Graciansky *et al.* 1979). A stratigraphical break exists in the Uppermost Aptian and corresponds both to a sharp lithological change and to a major reflector between formations 4 and 3.

Acoustic formation 3 of Lower Albian to Middle Cenomanian age is constituted at its base of Lower to Middle Albian laminated dark shales mostly of continental provenance, followed by interbedded dark shales and marlstones from Middle to Late Albian overlaid by Late Albian to Middle Cenomanian redeposited marl and chalk of pelagic origin. The well known hiatus from Cenomanian to Early Senonian separates acoustic formations 3 and 2.

Acoustic formation 2 of Senonian to Upper Eocene age consists of two main lithological units: a reddish to yellowish brown marly nanno chalk, calcareous mudstone, claystone and siliceous mudstone in the lower part which underlies siliceous marly nanno chalk and mudstone interbedded with turbiditic sand–silt–marl sequences.

Acoustic formation 1 of Oligocene age to present is essentially constituted by marly nanno ooze, nanno ooze, marly nanno chalk and nanno chalk with rhythmic beddings.

4. Magnetic data: the early evolution of the North Atlantic

Let us consider the sedimentary evolution of this continental margin in the general context of the kinematic and tectonic evolution of the North Atlantic. All published kinematic solutions of the evolution of the Atlantic north of the Azores–Gibraltar line and reconstructions of the positions of continents before their separation (Le Pichon 1968; Pitman & Talwani 1972; Laughton 1972; Le Pichon *et al.* 1977; Groupe Galice 1979) are based on magnetic lineations and/or fracture zone trends. As a general rule, the fit of corresponding magnetic anomaly lineations, on each side of ridge axis, from anomaly 32 (upper Cretaceous) to present gives quite a good idea of the kinematic evolution of the North Atlantic (Pitman & Talwani 1972; Laughton 1972). No magnetic data were available to give other kinematic constraints between the anomaly 32 fit and the pre-opening positions of continents. These were deduced from the shape of the continental margins, the correspondence of trends of the oldest oceanic portions of fracture zones and of pre-rift linear markers on land (Le Pichon *et al.* 1977).

Figure 3 shows a compilation of magnetic lineations in the northeast Atlantic based on published data north of the Charlie–Gibbs fracture zone (Pitman & Talwani 1972; Kristoffersen & Talwani 1977), west of anomaly 25 (Williams & McKenzie 1971; Pitman & Talwani 1972; Williams 1975; Laughton *et al.* 1975; Cande & Kristoffersen 1977), and on a new re-examination of magnetic profiles east of anomaly 25. Magnetic anomalies 33 and 34 have been identified from the proposed criterion of Cande & Kristoffersen (1977).

A triple point junction probably existed west of the Bay of Biscay at the time of anomalies 33 and 34 as proposed by Williams (1975). Although Upper Cretaceous to Upper Eocene compressive movements have affected the initial configuration of anomalies 33–34 in the Bay of Biscay, the shape and amplitude of these anomalies associated with the Charcot–Biscay–Cantabria seamounts topographic feature do not seem to have been strongly affected by this compressive episode.

Magnetic anomalies of around 150 nT amplitude exist in the Iberian Abyssal plain, west of the Iberian peninsula and east of anomaly 34. The size and spacing of these anomalies are close to those of the Cretaceous quiet zone west of North Africa (Hayes & Rabinowitz 1975). From south to north, the eastern limit of this domain corresponds to the Tore–Madeira rise along the J anomaly (Pitman & Talwani 1972; Olivet *et al.* 1976; Rabinowitz *et al.* 1979) then to a positive anomaly which prolongates the Tore–Madeira rise until the 41° N parallel and which could correspond to the M0 anomaly, and finally to a line which bounds the N.W. corner of Galicia Bank. The J anomaly has been identified with the M0–M1 anomaly by Rabinowitz *et al.* (1979) which is dated as Upper Aptian (leg 53, Francheteau, personal communication; Van Hinte 1976). Consequently, if those assumptions are correct, the wide area located between anomaly 34 and this feature corresponds to the quiet magnetic zone. East of this feature, the M sequence does not exist. Nevertheless, this does not necessarily mean that oceanic crust created by seafloor spreading is lacking east of the J anomaly.

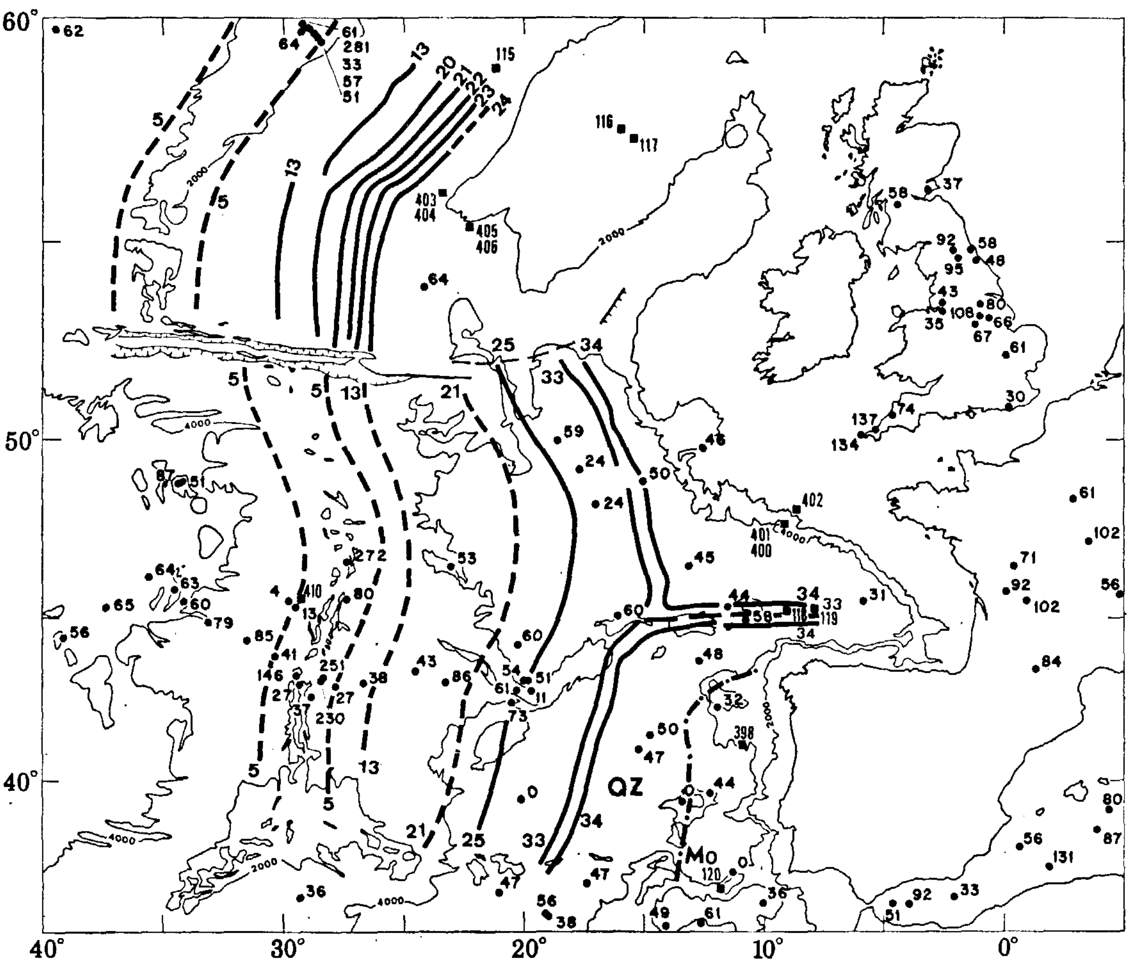

FIGURE 3. Magnetic lineations in the Northeast Atlantic. See text for data sources. Numbered full squares correspond to locations and numbers of D.S.D.P. sites.

5. Leg 47b results in the framework of the early evolution of the North Atlantic

(*a*) *Triassic–Liassic or older tensional episode*

The first epoch of rifting of continents in the North Atlantic is still debated, but is probably linked to several tensional phases occurring since Permian to Upper Lias in the continental

Eurasian-American framework (e.g. Arthaud & Matte 1975; Groupe Galice 1979), and to the early history of the Mesogean realm (Aubouin 1977). As a general rule, the rifting episode is supported by the existence of thick evaporitic series linked to a fast subsidence of continental blocks. Reliable data around the Iberian peninsula and Grand Banks exist especially during the Trias–Lias episode. On Grand Banks, Jurassic and older formations are preserved in structural basins bounded by basement block faulted structures with presence of salt diapirism (Daily Oil Bulletin 1973). In Aquitaine, the Triassic–Liassic sedimentation is characteristic of a subsident basin filled up with thick detrital and evaporitic deposits (Winnock 1971; Dardel & Rosset 1971; Winnock *et al.* 1973). In initial reconstructions of continents, the Aquitaine basin could be prolongated towards the west by grabens and basins related to the Labrador–Biscay Fault (Laughton 1972; Le Pichon *et al.* 1971*a*). In the interior basin between Galicia Bank and Iberia, the deep sedimentary layers may be of Jurassic or older age (Groupe Galice 1979). Nevertheless, the very thick sedimentary series without evidence of salt diapirism detected in seismic profiles do not support clearly the fact that this area has been affected by a Triassic–Liassic episode of rifting. In the small basins of the continental slope, formations are affected by salt diapirism, as between the Porto seamount and the Portuguese shelf (Montadert *et al.* 1974; Wilson 1975; Groupe Galice 1979). Consequently, numerous studies support the hypothesis that the initial Eurasian–American continent has been affected, at least locally, by an intense fracturation and by an episode of rifting giving rise to subsiding basins filled with Triassic–Liassic evaporites and/or clastic sediments. The westernmost extension of these basins is located east of the eastern limit of the quiet magnetic zone (figure 3) but cannot be traced easily because of the sedimentary cover especially thick in the Iberian abyssal plain, south of Galicia Bank. In any case, it is difficult to precisely determine the amount of oceanic crust, if any, which has been created during this tensional episode.

(*b*) *Late Jurassic–Early Cretaceous tensional episode*

South of Grand Banks, on the western Scotian shelf there exists a Berriasian–Valanginian hiatus in a shallow marine deposit environment (Gradstein *et al.* 1975). On Grand Banks, the most striking structural feature is a major angular unconformity at the base of the Cretaceous section. Beneath this unconformity, Jurassic and older formations are preserved in structural basins bounded by basement block-faulted structures (Daily Oil Bulletin 1973). Coeval tensional episodes has been noticed in the Alpine–Mesogean domain (see, for example, Aubouin 1977).

In the Galacia Bank and Vigo areas, a major tectonic event has occurred in the Late Jurassic – Early Cretaceous and is at the origin of the main morphologic trends of the continental margin (Groupe Galice 1979). Faulted blocks are subsiding and rotating along faults of Panamean type. Indeed, rotating faults have functioned both on the Iberian and Armorican margins during this episode (Montadert *et al.* 1977). Nevertheless, as the last 75 m of the borehole drilled into a half graben structure seem to have been deposited above the CCD at a depth which can reach 2000 m (Site 398 chapter, Ryan *et al.* 1979), it is impossible to distinguish and quantify at the level of Site 398 what part of vertical motion is relevant to each of the two tensional episodes. Fan-shaped sedimentary figures, observed in the acoustic formation 4 (figure 2), show that sedimentation occurred during tilting motion of basement blocks (Ryan *et al.* 1979; Groupe Galice 1979). Borehole data date only the end of the Upper Jurassic – late Cretaceous episode as Uppermost Aptian.

The Cretaceous magnetic quiet zone is bounded towards the East by the J or M0 anomaly (figure 3). East of this limit, the M sequence is lacking but a flat magnetic domain exists and could be related either to a continental subsided area or to the Jurassic magnetic quiet zone. If these assumptions are correct, this would mean that either the Permian to Lias tensional episode has affected a large area between North America and the Iberian peninsula with oceanization of continental crust, or more probably, that an early limited opening has occurred during Jurassic time after the Permo–Lias tensional episode. In both hypotheses, as the M sequence is lacking, there is no creation of oceanic crust between North America and the Iberian peninsula in early Cretaceous before Upper Aptian.

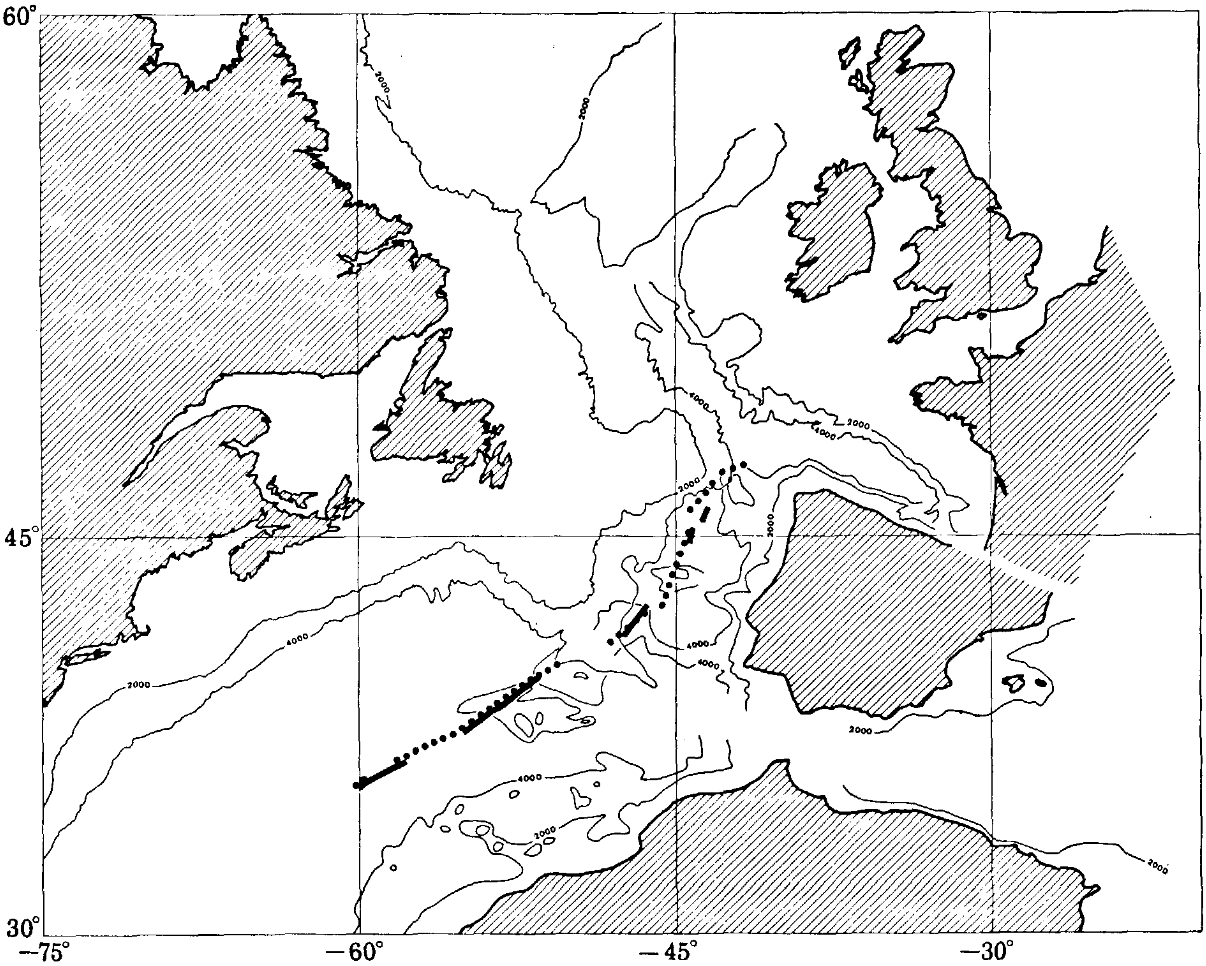

FIGURE 4. Tentative reconstruction of the positions of the continents at the time of anomaly J (Uppermost Aptian). Bathymetric contours in metres. America is kept fixed. J anomaly in dotted line on the eastern side and in continuous line on the western side of the North Atlantic.

(c) *J anomaly: the beginning of true sea floor spreading in the northern Atlantic*

The history of the Tethyan ocean becomes independent of the Atlantic evolution. While compressive phases induced the first Alpine deformations, the Atlantic opening is going on. A first approximate configuration of the land masses is given in figure 4. The relative positions of Africa and North America is very well documented and comes from a personal communication of H. Schouten in the paper of Rabinowitz *et al.* (1979). The relative position of the Iberian peninsula with respect to North America is based on a well documented definition of the eastern limit of the Cretaceous quiet magnetic zone seawards of the Iberian peninsula and on some limited reconnaissance of the J anomaly with available magnetic profiles located east of Grand Banks (Pitman & Talwani 1972). In a first attempt, positions of Europe and Rockall are those of the initial fit of Le Pichon *et al.* (1977), as no available data exist to give better relative positions of continents at the time of anomaly J. This fit must be understood as a first try which will be improved by a better definition of the shape of M0 anomalies on each side of the Northern Atlantic and by including fracture zone constraints, which is not the case in figure 4. Nevertheless, this new preliminary step in the kinematic evolution of the North Atlantic gives further constraints on the early opening and on the initial fit of continents.

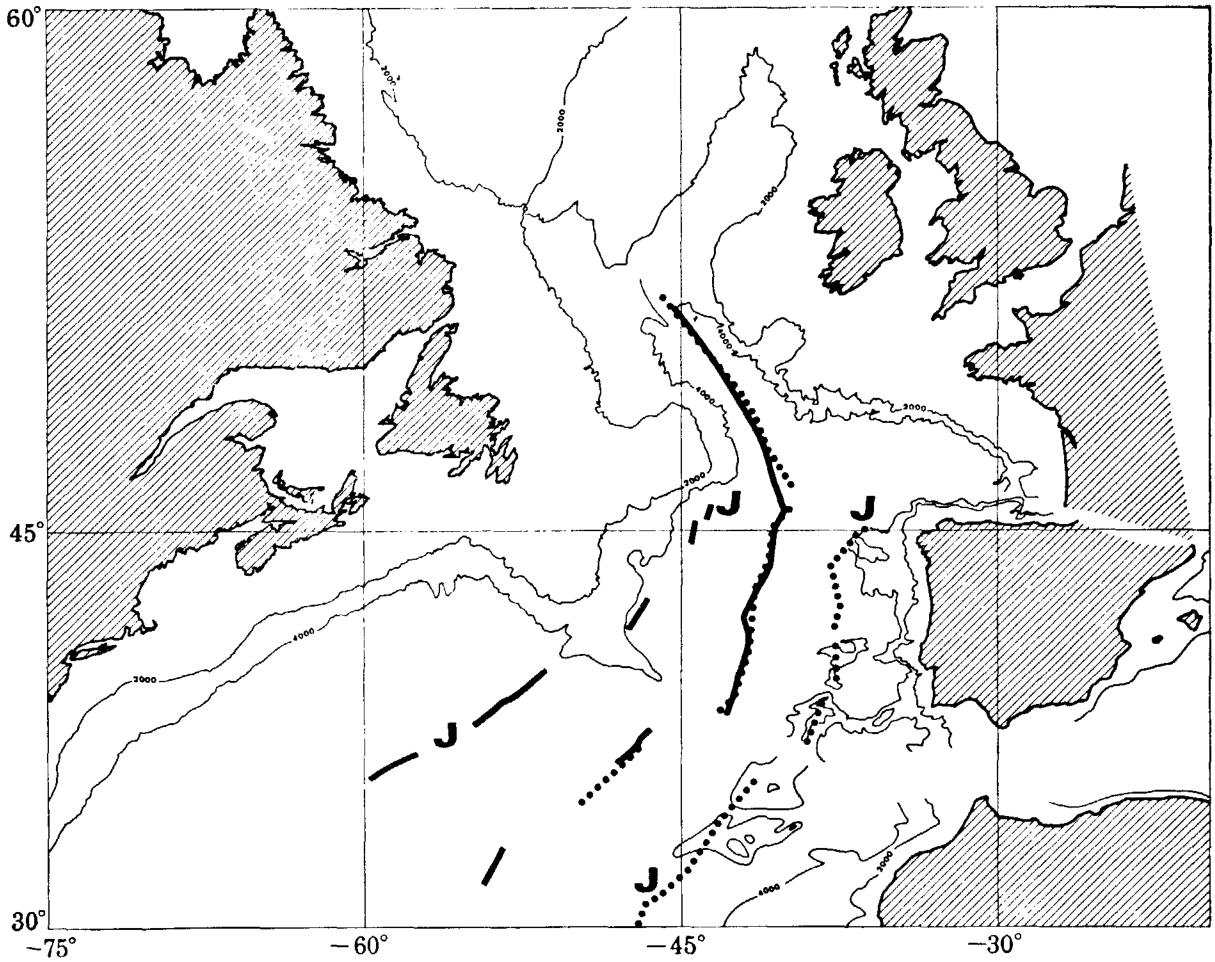

FIGURE 5. Reconstruction of the position of continents at the time of anomaly 34 (Upper Santonian). Bathymetric contours in metres. America is kept fixed. Magnetic anomalies J and A 34 in dotted line on the eastern side and in continuous line on the western side of the North Atlantic. With the conventions of Le Pichon *et al.* (1973), parameters of rotation are: Europe/North America, 63.0° N, 149.3° E, −19.0; Iberian Peninsula/North America, 82.8° N 121.3° E, −22.6°.

By definition, the J anomaly is associated with topographic features (Pitman & Talwani 1972) such as the Tore–Madeira rise on the eastern side of the North Atlantic and the 'J anomaly ridge', south of Grand Banks and the Newfoundland fracture zone. Ballard *et al.* (1976) have proposed that these J anomaly twin features were associated with an Azores-like hot spot. The formation of these twin structural features, whatever their invoked mode of formation, would have modified both the tectonic evolution of the nearby continental margins and the style of sedimentation. This can explain the change in sedimentation type from the Aptian graded sequences emplaced by turbidity currents to the Albian dark shales and also the presence of the main seismic discontinuity between acoustic formations 4 and 3 (figure 2). Note that the dark shales are deposited on the Armorican margin during Middle Aptian (Montadert *et al.* 1976) perhaps because the connection between the Iberian abyssal plain and the Bay of Biscay was not established north and south of the Flemish Cap – Galicia Bank structural feature at the time of anomaly J.

Since Uppermost Aptian the western continental margin of the Iberian peninsula globally subsided because of vertical cooling of the lithosphere as the accreting boundary move away towards the west.

(*d*) *Anomaly* 34: *a step in the opening of the North Atlantic*

The trend and length of anomalies 34 on each side of the North Atlantic have been defined by numerous data. Between the Charlie–Gibbs fracture zone and the Azores–Gibraltar line, it is impossible, using the constraints of these two fracture zones, to match the corresponding plate boundaries at the time of anomaly 34 (Upper Santonian in the Van Hinte Scale (1976)). On the other hand, Le Pichon & Sibuet (1971) have examined the kinematics of the Eocene episode of compression between the Iberian and European plates and have shown that the boundary between the two plates extended west of the Pyrenees, along the Spanish marginal trench to end west of King's Trough at the triple point junction. Consequently, the positions of anomalies 34 on each side of this plate boundary have been shifted after their creation. Segments of anomalies 34, located north and south of the Charcot and Biscay Seamounts, have been unambiguously matched with anomaly 34 on the American side by using the trend constraints of the Charlie–Gibbs fracture zone and the Azores–Gibraltar line. One of the main kinematic implications is that at the time of anomaly 34, the Bay of Biscay was not completely created, which is supported by the fact that anomalies 34 and 33 might be present in the central part of the Bay of Biscay (Williams 1975; Sibuet *et al.* 1979).

In Upper Santonian the open sea is well developed south of the Charlie–Gibbs fracture zone (53° N). The sudden arrival of primary minerals formed in upstream soils (illite, chlorite, sandy silicate, kaolinite) from Upper Santonian to Lower Maestrichtian at least is probably due to the supply of minerals inherited from high latitudes and transported by the just established north–south oceanic circulation (Chamley *et al.* 1979). This oceanic circulation could have been established at the time of the early opening of the Labrador Sea (Le Pichon *et al.* 1971 *b*) that is at the time of anomaly 34.

6. Conclusion

The early kinematic evolution of the Atlantic, north of the Azores–Gibraltar line, provides strong constraints on the shape and size variations of oceanic basins and also about their possible connections and the establishment of oceanic circulation through time. The general results of Leg 47b have been integrated within a tentative reconstruction of the positions of the continents at the times of anomalies 34 (Upper Santonian) and M0 (Upper Aptian) and have been related to the early history of the North Atlantic opening. The last movements of subsidence and tilting of blocks associated with the so-called Upper Jurassic – early Cretaceous tensional episode have been dated as Uppermost Aptian at the level of site 398. Then, the beginning of true seafloor spreading in the northern Atlantic is dated as Uppermost Aptian and the connection of the North Atlantic ocean with the Labrador sea seems to have been established in Santonian times.

V. Renard and X. Le Pichon critically reviewed the manuscript and made helpful suggestions.

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Reprinted from Nature, Vol. 281, No. 5728, pp. 209-211, September 20 1979

ART N° 474
Contribution COB N° 656

Basaltic pillars in collapsed lava-pools on the deep ocean floor

J. Francheteau*, T. Juteau† & C. Rangin‡

* Centre Océanologique de Bretagne, BP 337, 29273, Brest Cedex
† Université Louis Pasteur, Strasbourg
‡ Université Pierre et Marie Curie, Paris, France

Observations of peculiar volcanic objects, made by a submersible on the deep sea floor at a depth of about 2,600 m at and near the axis of the East Pacific Rise during the CYAMEX expedition as part of the RITA Project[1] are presented here. Two basic types of flow forms were observed within the crestal area of the East Pacific Rise: pillow flows and fluid lavas, the latter sometimes overlying massive flows. The East Pacific Rise at 21° N comprises an axial, unfaulted extrusion zone bordered by an extension zone characterised by faulting[2,3]. Pillow flows occupy the innermost or extrusion zone and constitute small elongated volcanic highs. Fluid lavas tend to occur at the edge of the adjacent extension zone in bathymetric lows controlled by normal faults or steep primary slopes of constructional highs. In the 50 × 200 m lows which border the extrusion zone the fluid lava is smooth and lobate surfaces which represent the upper surface of the flow are locally collapsed and reveal the internal structure of the fluid lavas. Where the roof collapse is extensive, layered columnar features are visible and volcanic layering can be seen against the flank of the bordering volcanic highs (Figs 1–3). Similar features have been reported from the Galapagos Rift[4]. The diameter of the approximately cylindrical pillars ranges from 0.5 to 2 m. Some pillars are made of multiple coalescent cylinders. The tops of the pillars are glassy, funnel-shaped and always widening upwards. The pillars were presumed to be hollow from several observations of gashes or openings in the vertical walls of the pillars. This was demonstrated during dive CY 78–19 to the south where a small pillar was toppled by CYANA and subsequent examination revealed a circular canal along the axis of the pillar. The outer surface of the pillars is marked by centimetre-thick glassy, subhorizontal ledges extending several centimetres from the outer vertical surface of the pillars (Figs 2–4). The ledges are spaced every 2–5 cm and show small lava stalactites hanging on the underside of the ledges. Examination of large layered fragments of pillars recovered by CYANA demonstrated that the layering is only a surface feature as it does not extend through the basaltic mass of the pillars. The apparent layering is due to glass ledges adhering to a vertical basaltic pipe. In some rare instances the pillar outer surface showed no ledges and instead a smooth surface corrugated with vertical grooves. Some pillars are inclined or slightly curved; others get narrower towards the base. The pillars are almost totally aphyric and have the same bulk composition as other lava types recovered in the axial zone of the East Pacific Rise at 21° N (ref. 5).

Fig. 1 General landscape: pillars within collapsed lava pond.

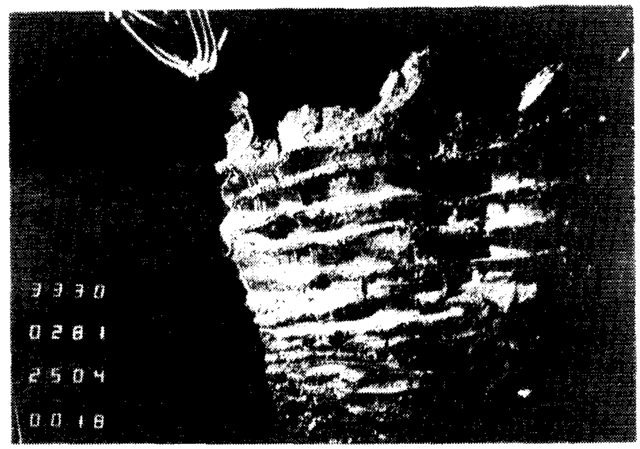

Fig. 2 Detail of a pillar showing the centimetric pseudo layering, with thin and darker salient glass layers projecting from the basaltic surface of the pillar.

The pillars occur in forest-like arrangement (Fig. 3). Their spacing ranges from 0.5 to 3 m and sometimes they coal c. building walls, especially near the edges of the depressions. However, the pillars are not confined to the edges. The flanks of the lows show large segments of undisrupted glass ledges analogous to those observed on the pillar surfaces. In one case (dive CY 78–19) where the fluid flows partially filled a graben, the layered lateral margin could be seen to represent a chilled, 5–10 cm-thick wall plated against the truncated pillow basalts of the normal fault scarp. The chilled margin was partially detached from the scarp surface.

Non-collapsed glassy upper surfaces of fluid lavas surrounding the fields of pillars show that in the depressions, the thickness of the lobate fluid lava roof is about 10 cm. The horizontal dimension of the lobes is of the same order as the pillar spacing and pillars provide roof support at the junction between adjacent lobes. The geometry of the lobate roof junction is analogous to that of the funnel-shaped pillar tops. Pieces of the lobate roof are commonly preserved around the fluid lava depressions and also where they form bridges between adjacent pillars. In most cases the lava pool appears to be concave upward with a slight (a few metres) depression in the middle of the pool with respect to the edges.

The seafloor around the pillars is strewn by rubble made up of pillar fragments and roof slabs. A deeply incised rille-like canyon was observed near the axis of the fluid–lava depression.

These observations lead us to the following interpretations (Figs 5 and 6):

(1) The fluid lavas fill a preexisting depression either controlled by faulting or by adjacent constructional highs. This is proved by inspection of the lateral contact and by the contrast in lava freshness between the fill and the adjacent pillows. The remarkable fluidity of the lavas cannot be ascribed to chemical differences or to temperature of extrusion. It probably reflects the large volume of outpouring which could in turn be a function of a very high spreading rate over a short time span.

(2) The seawater which is trapped in the crust under the fluid lava pool is heated and expands (by a factor of 20 for a temperature of 800 °C at a depth of 2,600 m (see ref. 6), forcing its way up through the molten lava in a series of vertical conduits (J. Moore, personal communication) (Fig. 5). The walls of the conduits will be quenched at the boundary between the rising water and the hotter magma. The conduit walls will grow outward from the inner glassy walls of the conduits with time. This explains the hollow pillars found by CYANA. A similar

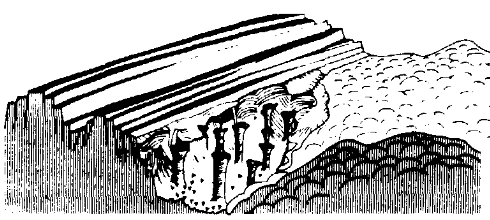

Fig. 3 Lava pool after roof collapse showing basaltic pillars at the boundary of the unfractured extrusion zone (on the right). The pillars are about 10–15 m high.

explanation has been put forward by Fuller[7] and Waters[8] to account for the existence of vertical cavities (spiracles) that cut massive lava on the Columbia River Plateau. These authors proposed that water vapour and other gases surge upward into liquid lava that covers marshy ground.

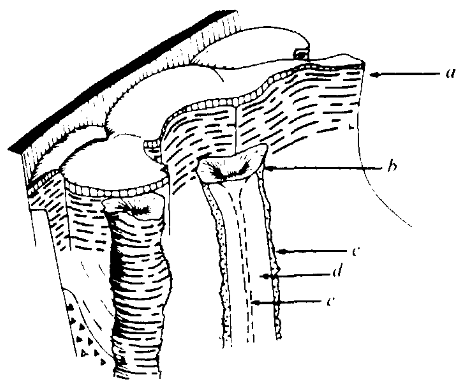

Fig. 4 Detail of basaltic pillar and of edge of magma pool. *a*, Pillar attached to the edge of the pool and capped by smooth lobate fluid lava. *b*, Pillar: funnel-shaped widening upwards Pillar cross-section showing: *c*, lava cooling ledges on outer margin; *d*, massive lava inside pillar wall; *e*, hollow conduit inside pillar.

(3) Before any extensive crystallisation takes place, the lava pool is drained rapidly in successive stages (Fig. 6). This leaves 'bath-tub' rings around the 'cold walls' present in the depression. This includes the pillars and the edges of the pool. This accounts for the apparent layering shown by the pillar samples. The rille-like canyon seen on the floor of the pool may be a drain path. Finally down-drag of either the roof or the outer rigid carapace of the pillars can scrape vertical grooves on the still plastic interior and explain the smooth corrugated outer surfaces of some pillars. A similar mechanism has been proposed by Moore and Richter[9] to explain the vertical striations on the surface of Hawaïan tree moulds.

(4) Solidification of the fluid lava against the cold wall at the bottom of the pool would help to maintain pillars in position after collapse of the roof.

Thus tall, near vertical and hollow pillars with rings of glassy ledges are found in dense arrangement within fossil pools of fluid lava. They are interpreted as the fossil witnesses of both

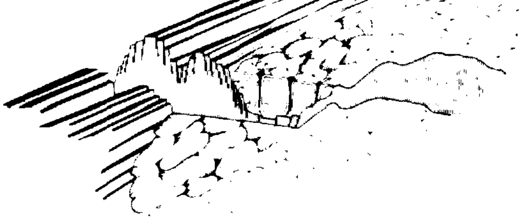

Fig. 5 Reconstruction of magma pool before the draining of lavas and roof collapse. The arrows at the pool surface represent escape of water.

temporary liquid magma pools which can fill topographic lows and smoth the ridge topography, and of the rhythmic nature and rapidity of the magma pool withdrawal. When drain-off is prevented or when it proceeds too slowly, massive lavas are created.

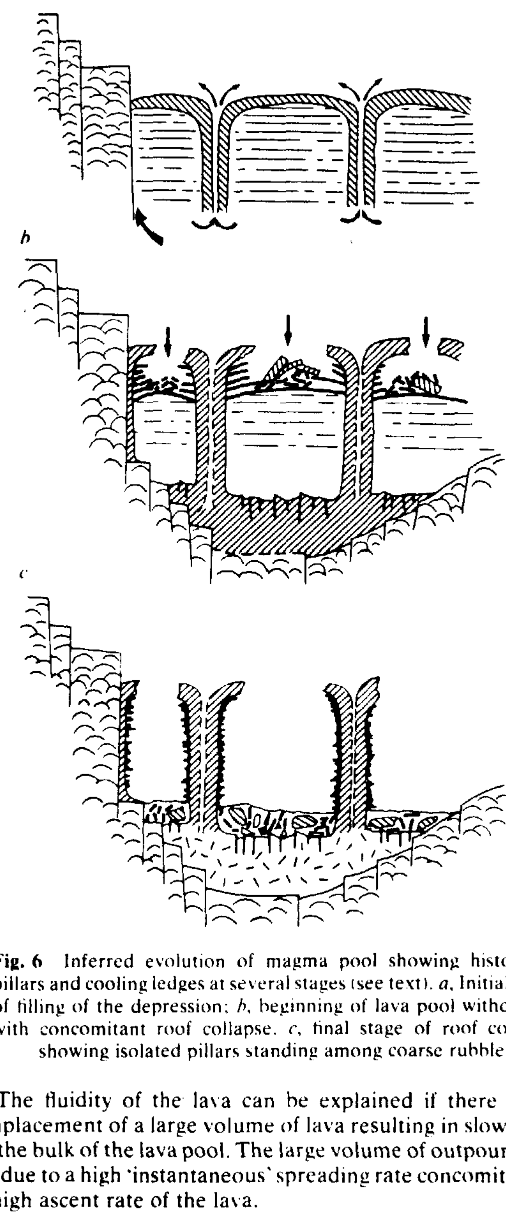

Fig. 6 Inferred evolution of magma pool showing history of pillars and cooling ledges at several stages (see text). *a*, Initial stage of filling of the depression; *b*, beginning of lava pool withdrawal with concomitant roof collapse. *c*, final stage of roof collapse showing isolated pillars standing among coarse rubble.

The fluidity of the lava can be explained if there is rapid emplacement of a large volume of lava resulting in slow cooling of the bulk of the lava pool. The large volume of outpouring may be due to a high 'instantaneous' spreading rate concomitant with a high ascent rate of the lava.

The observations at 21° N show that the size of lava pools increases southward along the axis and thus that the fluid lava regime in the south is predominant over the pillow lava regime. This suggests that instantaneous rates of spreading may be variable along the strike of the mid-ocean ridge.

Received 27 April; accepted 30 July 1979

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Printed in Great Britain by Macmillan Production Ltd., Basingstoke, Hampshire