Seventeen minutes that shook the Earth

A geomorphologic approach to the interpretation of the King's Trough Complex, North-East Atlantic.

Lars G. Franzén[1]
Gustaf D. Nelhans[2,*]

[1] Physical Geography, Department of Earth Sciences, University of Gothenburg, P.O. Box 460, SE-405 30 Göteborg, Sweden, tel. +46-31-7861958. fax. +46-31-7861986
[2] Department of History of Ideas and Theory of Science, University of Gothenburg, P.O. Box 200, SE-405 30 Göteborg, Sweden

* This author was responsible for image processing

Correspondence and requests for material should be addressed to L.G.F. (lars@gvc.gu.se) or G.D.N. (gustaf.nelhans@theorysc.gu.se)

1. Abstract

The King's Trough Complex (KTC) of the North-East Atlantic is believed to have a cometary impact origin. The episode is in much similar to the Comet Shoemaker-Levy 9 event on Jupiter 1994. With the King's Trough event, a dense swarm of bodies, hit the Atlantic ocean with an extremely low angle of incidence (<5°). On their course, coming from WNW relative to the Earth, the swarm of impactors ricocheted on the sea bottom, thus creating the complex of troughs and ridges e.g. King's Trough, Peake and Freen Deeps and Palmer Ridge. A geomorphological interpretation indicates a total of 12 separate funnelling marks, formed within a probable time lapse of 17 minutes. The impactors' fate after ricocheting is unknown, they might have returned into space, or they might have landed on the Earth. The tsunamis following an event of this dignity must have flooded large parts of Western Europe and Africa, the back-swash resulting in the formation of several submarine canyons on adjacent shelves. Tsunami generated currents might also explain major sediment hiatuses and mega-ripples found on the ocean floor. Two different ages of this event are discussed; at c. 28 Ma at the Rupelian/Chattian shift (the Early/Late Oligocene boundary) and c. 16-18 Ma at the Burgigalian/Langhian shift (at the Early/Middle Miocene boundary or somewhat earlier). If we are proven right, the KTC would be included among the largest impact structures yet found on the Earth. It is clear that any set of impact events capable of penetrating deep water to form structures of the size of this complex would have required bolides comparable to the largest among the terrestrial impact record.

2. Keywords: King's Trough Complex, submarine impact structure, north-east Atlantic, Oligoscene, Miocene

3. Introduction

The possible effects of cosmic impacts in the history of the Earth, on geology and the evolution of life has been a major topic to scientists from many fields during the last decades, initiated by the first suggestion of an impact origin for the Cretaceous-Tertiary (K-T) extinction (Alvarez *et al.*, 1980). Since the first proposals were laid down, there have been studies of more K-T sites, of other major extinctions, and of new ideas about the environmental responses to impacts and their biological consequences, beyond the original concept of a year of darkness and starvation (Chapman, 1989). While the Alvarez hypothesis assumed that the mass extinction was caused by the impact of one single asteroid or comet c.10 km across (Swisher *et al*., 1992), many scientists today thinks there were multiple events, not a sole event at Chixalub (e.g. Keller, 2003; Keller *et al*., 2003)

Even if there is little knowledge on modern impact events such as the Tunguska of 1908 (e.g. Bronshten, 1999; Chyba *et al.,* 1993), historical and archaeological research has recently considered impacts as possible causes for cultural downturns in the past, e.g. during the Bronze Age, which was highlighted during the Cambridge Conference of 1997 (Peiser *et al*., 1998). This and several recent monographs such as Baillie’s (Baillie, 1999) reflect the rapidly increasing common interest regarding these questions.

While the vast majority of impact craters have been reported from land, the probability of an ocean impact is much greater. Statistically, roughly three out of four impacts on the Earth's surface should occur in the oceans. The imbalance in distribution pattern of known impact structures has several reasons. One is obvious; the lack of available detailed bathysmetric data. Another is crater morphology. Comparison of the impact structures and related deposits with those on land and shallow target depths, show several major differences of which the most significant is the absence of an elevated crater rim. Instead the crater perimeter is bewelled and eroded because of the impact induced bottom currents and turbulent, resurge water flow into the crater formed. This process reworks most of the fall-out breccia back into the crater cavity where it accumulates in much larger thickness than in impact craters on land (Jansa-Lubomir, 1993; Ormö, 1998). Maybe this material would even be enough to conceal a central peak. In addition to this, normal sedimentation and related processes such as slumping and sliding of sediments would smoothen out possible impact traces over time. While most work on ocean impact cratering is made on old structures, which are uplifted and easily studied on land e.g. Ormö’s (1998), only few studies have been made on known structures in the deep ocean. Some recent examples are e.g. the Chesapeake Bay impact crater (e.g. Powars *et al*., 1993; McHugh *et al*., 1997; Glass, 2004), Toms Canyon impact crater on the New Jersey outer continental shelf (Poag *et al.*, 1993; Poag and Poppe, 1998); The Early Cambrian Neugrund Structure in the Gulf of Finland, Baltic Sea (Suuroja and Suuroja, 2000), the Miocene craters of the Timor Sea (Gorter and Glikson, 2000; Gorter *et al*., 2002), the Late Jurassic Mjølnir impact structure in Barents Sea (Dypvik *et al*., 1996; Dypvik and Jansa, 2003), the Bedout End-Permian impact crater offshore north-western Australia (Becker *et al.,* 2004) and a proposed large K/T impact crater in the Gulf of Maine (Abbot and Manzer, 2003). Only one impact into 4-5 km deep ocean is known, that of the Eltanin asteroid into the Bellinghousen Sea southwest of Chile (Gersonde and Kyte, 2001; Kettrup *et al*., 2002).

4. Description of King's Trough Complex area

The enigmatic King's Trough Complex (KTC), which is situated c. 400 km NNE of the Azores (Fig.1), is a major feature of the oceanic part of the Eurasian plate. It consists of a series of parallel or sub-parallel throughs totalling more than 400 km linked en echelon by cols and flanked by ridges, giving rise to a relative relief of more than 3500 m. After first being described by Laughton (1965), the formation of this complex has been a matter of debate. It has been interpreted as: a NNE-SSW compression (Matthews *et al*., 1969), a compressional boundary with some subsequent vertical motion around 45-38 Ma (Le Pichon and Sibuet, 1971), a short-lived plate boundary around 27 Ma (Cann, 1971) while Williams and McKenzie (Williams and McKenzie, 1971) thought its formation began with the elimination of a bend in the Mid-Atlantic Ridge axis around 56 Ma. Laughton *et al.* (1975) concluded that the KTC didn't appear to be a part of a structure zone but rather the result from tectonic activity remote from present plate boundaries, with no topographic evidence for a direct connection with the northward movement of Iberia.

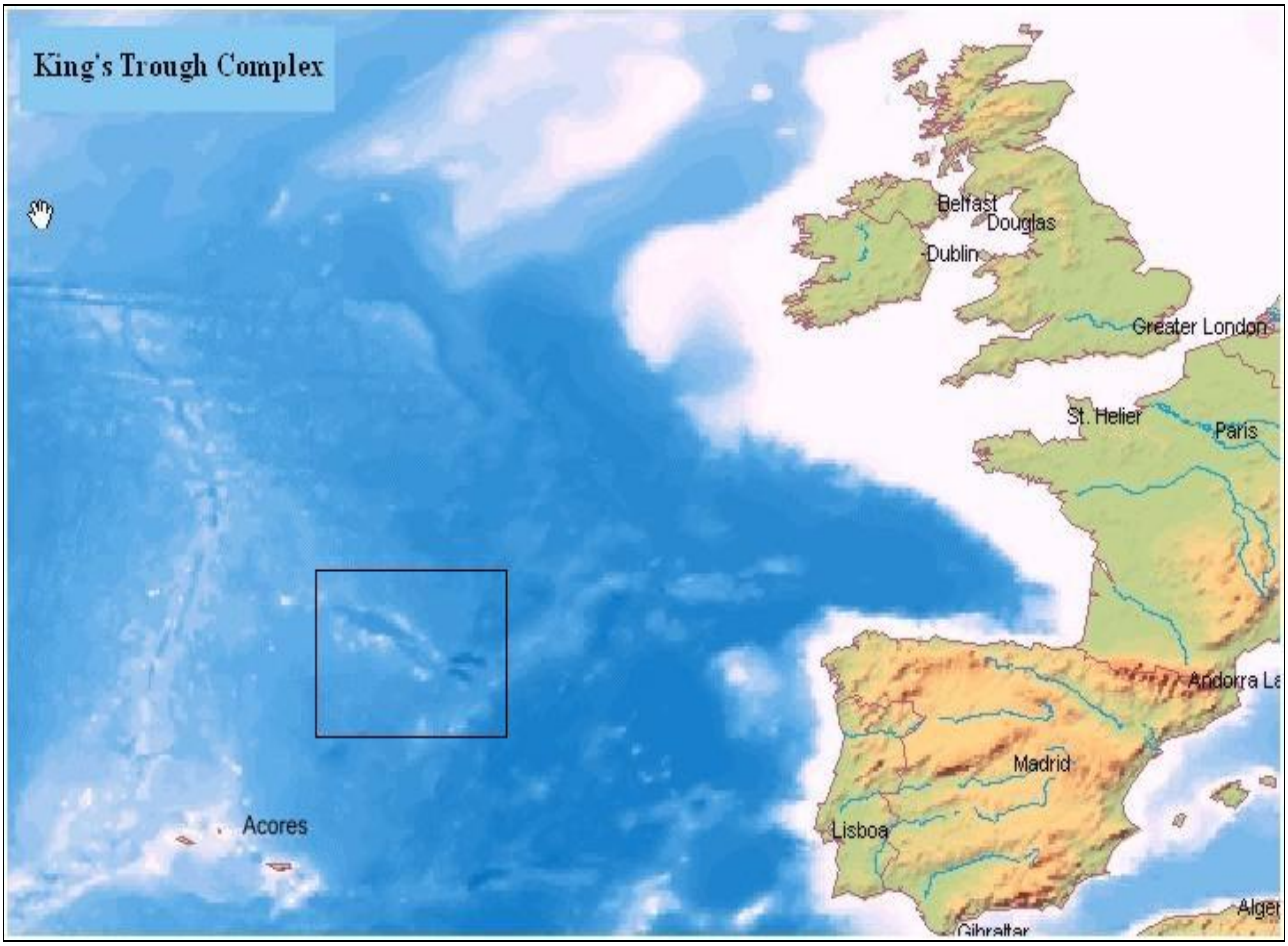

Figure 1. King's Trough Complex position in the NE Atlantic – an overview.

Vogt and Avery (1974) concluded that increased mantle plume discharge around 26 Ma caused formation of a new plate boundary, whereas Grimaud *et al.* (1982) *suggested* that King's Trough could be a transform fault. According to Grimaud *et al*. (1982) the unusual features of Peake and Freen Deeps may have developed along a different set of boundaries between the Iberian and European plates that evolved subsequently to the observed Late Eocene configuration. Alternatively, they were older structures rejuvenated by the distant Miocene convergence of the African and

European plates. Based on seismic refraction and gravity results Searle and Whitmarsh (1978) suggested that the ridges in the complex was formed by unusually voluminous volcanism at a small hot-spot situated on the Mid Atlantic Ridge from the time of magnetic anomaly c. 56 Ma at least until c.21 Ma. This latter idea was later supported by Kidd *et al*. (1982), which concluded that the detailed morphology and geological sequence at King's Trough agreed best with this hypothesis. Kidd *et al.* (1982) gave a possible age of the formation of about 32 to 16-20 Ma. Later Kidd and Ramsay (1987) suggested that KTC was generated by a combination of initial spreading from an elevated part of the Mid-Atlantic Ridge, an uplift that was associated with igneous intrusion and volcanicity at appr. 32 Ma, and a period of extensional subsidence and rifting between 16 and 20 Ma. Based on spectral analysis of a gravity and topography profile across King's Trough, Louden (1983) concluded that the topography is regionally compensated on lithosphere older than 20 Ma, which meant that the feature formed away from the Mid-ocean Ridge no earlier than the late Oligocene. It was further suggested that the formation was not coincident with the rotation of an Iberian plate to build the Pyrenees (45-38 Ma) (Le Pichon and Sibuet, 1971), unless that orogenic activity continued longer than presently thought. The KTC has also been interpreted as the plate boundary between Iberia and Eurasia 18-6 million years ago (Roest and Shrivastava, 1991), later as a reactivated pseudo-fault of a propagating rift created by extensional motion across this plate boundary from 17 to 9(6) Ma (Shrivastava and Roest, 1992). In the latest work, to our knowledge, Mello *et al*. (1999) claimed the KTC to be a remnant of a hotspot that existed at the North America-Africa-Eurasia triple junction between 59 and 26 Ma.

King's Trough itself is a flat-bottomed valley approximately 320 km long trending NW-SE. No sediments are being found on the flanking slopes (Kidd and Ramsay, 1987). The K/Ar ages of the dredged basalts (52±6 Ma) and the magnetic ages of basement recorded, about 50 Ma seem compatible according to Kidd and Ramsay (1987). Lowermost Miocene chalks were the youngest dredge haul material recovered at King's Trough Axis. Figure 3 shows a SW/NE seismic reflection profile over King's Trough. The other two depressions, **Peake** and **Freen Deeps** are two smaller throughs east of King's Trough. Seismic reflection records show that underneath about 700 m of sediments the basement lies at a depth greater than 6600 m in Peake Deep and 6000 m in Freen Deep (Matthews *et al*., 1969). **Palmer Ridge** is an asymmetrical ridge with its steep slope facing south, dividing Peake and Freen Deeps in the eastern part of the complex, which rises to a minimum depth of 2433 m. The crest is almost horizontal and remains within 34 m of 3110 m. An apparently continuos outcrop of serpentinite develop along the crest may mark the axis of an elongated serpentine intrusion which uplifted and tilted the overlying rock to form a broadly anticline structure (Ramsay, 1970). Cann and Funnel (1967) suggested that the emplacement of the serpentinite accompanied by the uplift of Palmer Ridge occurred at appr. 26 Ma based on the K/Ar ages obtained from three retrograde amphiboles (29, 21 and 27 Ma). (Peake and Freen Deeps, as well as Palmer Ridge, according to unconfirmed hearsay, were named after three different British biscuit brands, by the DSDP ship crew). Other prominent and named features of the complex are Antialtair Seamount situated on the southern flank of King's Trough and Crumb Seamount situated on the plain SW Antialtair Seamount. Antialtair Seamount is the highest spot of the southern flanking ridge, reaching to c. 500 f m b.s.l. whereas Crumb Seamount is one in a group of five with their crests reaching c. 2000 m b.s.l.

5. An alternative explanation to the formation of the King's Trough Complex

While the formation of KTC, so far, has been attributed to endogen forces such as plate movements or volcanism, the recently arisen interest in ocean impacts, as exemplified above, gave us the impulse to examine the KTC in the context of a possible impact origin. We realize that our suggestion here is provocative, but we want at least to ventilate the possibility in a scientific forum.

From the bathymetric data available, e.g. the map of the bathymetry of the Northeast Atlantic *“Mid-Atlantic Ridge to Southwest Europe – Sheet 3”* presented by Laughton, Roberts and Graves (1975) as an appendix in an issue of Deep-Sea Research, the KTC stands out as a unique elongated feature with it’s parallel troughs and ridges stretching from NW to SE in the area between the Iberian peninsula and the Mid-Atlantic Ridge. Even if the forms presented in this way is intriguing and incites the imagination, this two-dimensional presentation could not be used for any thorough interpretations.

We hence decided to use modern techniques to visualize this form which is practically inaccessible due to its size, and to the great water depths at which it is situated. The best raw material offered was a contour line map presented as an appendix in the DSDP 94 report of 1987, along with a smaller contour line map over the area around Peake and Freen deeps presented by Davis and Jones (1971).

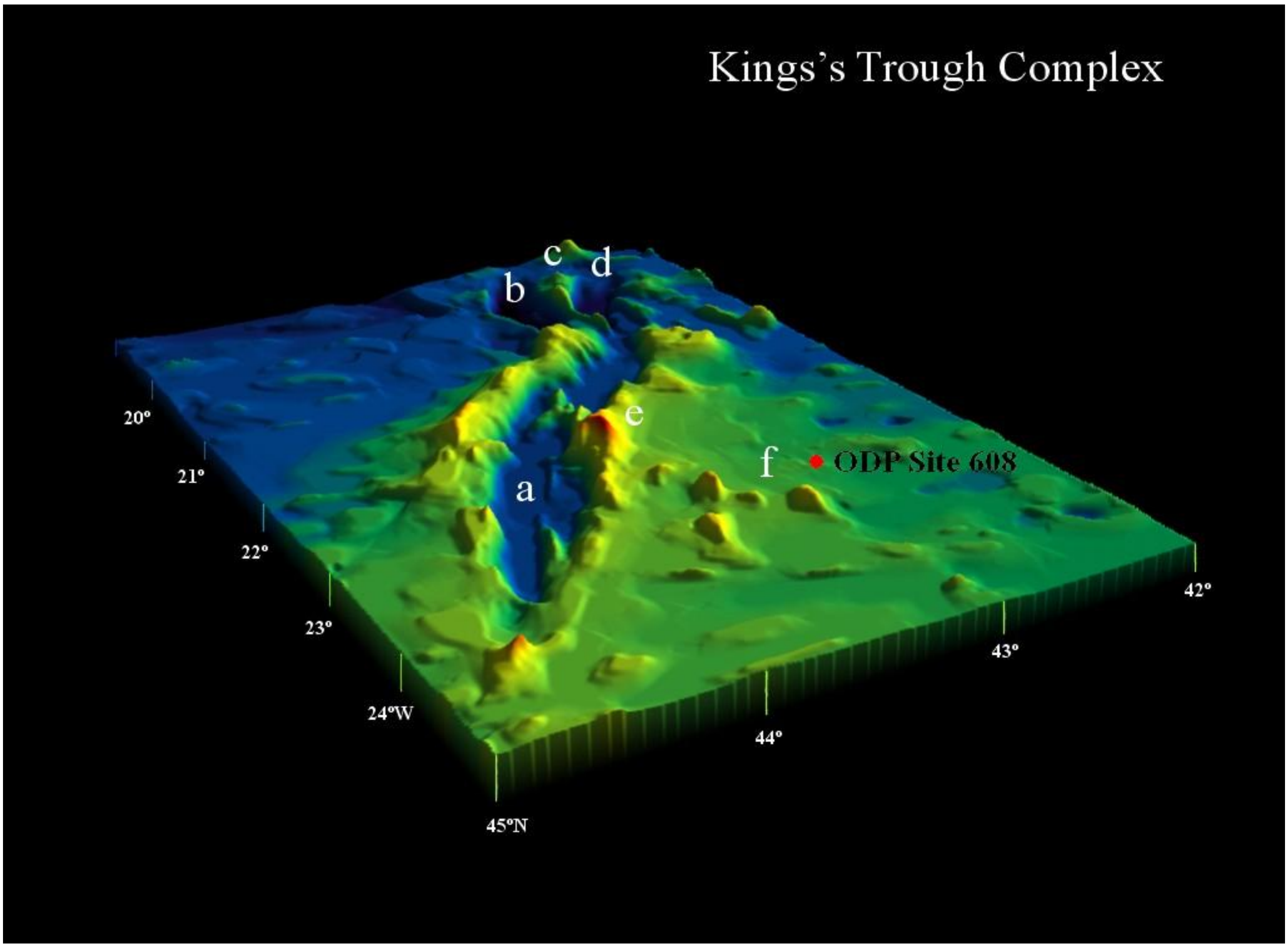

Figure 2. 3D-image of King’s Trough Complex as seen from direction of incoming objects. Letters refer to major features of the complex and other morphological features possibly associated with the King’s Trough impact event: a/ Kings Trough, main trough, b/ Peake Deep, c/ Palmer Ridge, d/ Freen Deep, e/ Antialtair Seamount, f/ Crumb Seamount Vertical magnification 500 per cent.

The 3D images shown in various figures here are based on the digitising of these two topographical images. Figure 4 shows the contour lines along with one of the 3D-images made. Although the isolines on bathymetric maps are based on manual interpolations from sounded depth profiles they must be regarded the most reliable base available for further interpretation. The digitalisation was made with a very high resolution, on scanned and strongly enlarged copies of the maps. Digitalisation was made on 18 different sub-units with *CartaLinx*™and various steps on and off were made with *Surfer*™*, Idrisi* ™and *3DEM* ™ ending up in a final raster version. Interpolation between isolines was made by kriging in Surfer™. The final images were constructed in *3DEM*™, which also allowed animations and fly over possibilities.

5.1 Interpretation

The 3D images produced allowed us to look at the formation from any direction in all planes, angle of incident light, angle of observation (altitude) and vertical magnification of the terrain. The default value used on the images shown here is 500 per cent.

Judging from the form of the different units of the KTC showing up in the model we must assume that, if we are dealing with an impact event in the first place, it must have been a multiple oblique one, with an extremely low angle of incidence, close to parallel with Earth’s surface. There are three possible basic lines of interpretation i.e.; (1) the impactors were originally one body which went into orbit around the Earth, was pulled apart by tidal forces and impacted as a string of pearls; (2) the event was caused by a already formed train of bodies which came in collision course with Earth and impacted although it almost passed us by; (3) a combination of 1 and 2 i.e. the event was caused by an object approaching the Earth. When it came within the distance of the Roche limit tidal forces pulled it apart. The remaining smaller fragments impacted before going into orbit, within a relatively short time interval. The limited spreading of craters, almost on line, favours explanation 1 and 3, while in the second scenario, assuming it was something like the Shoemaker-Levy, there would have been a greater time lapse between the different impacts. Another aspect favouring scenario three is the craters’ forms (Fig.5) i.e. the easterly features seem to be deeper and shorter while the westerly are shallower and longer. If the impactors' train was in orbit they would all appear with about the same basic shape. With this we propose the following (numbers referred to in Figure 5 are in the interpreted order of impact); Orbiting around the Sun the Earth approached a large object on a collision course. When they got close enough to each other, the object was caught by Earth’s gravitation and was pulled apart by tidal forces when it arrived within the range of the Roche limit, forming a train of smaller objects. Compared to the Comet Shoemaker-Levy 9 event the fragments were fairly close to each other, implying a relatively recent separation from the original body. Relative to Earth, travelling at the speed of c. 30 kms^{-1} (assuming an object relatively still in space the Earth’s orbital speed around the Sun could be set at 30 kms^{-1}) the first body in this train hit in the western part of Freen Deep area funnelling this trench (1). Only a few moments later a second body hit the western part of Peake Deep, the northern rim already formed by the Freen Deep impactor possibly altering the direction of this body while bouncing, at a more northerly course. A third much smaller body deformed the western part of the Peake Deep giving it a “banana shape” and formed the small crater (3). Another possible way to explain the bent shape of Peake and Freen Deeps, as discussed below, is rifting, i.e. a displacement relative towards north of Freen and Peake deeps, the rifting zone being quite wide. The Earth rotation, 0.46 kms^{-1} in direction from the swarm, made the following members of the train hit gradually more to the west and at a gradually levelled angle of incidence. The fourth impactor hit SW of Freen Deep. The next four impactors (5-8) created the eastern part of King’s Trough while bodies 9, 10 and 11 funnelled the main trench. The last member of the train, probably one of the smaller pieces in this group, slightly deformed the entrance rim in the westernmost part of the complex (12). The chain of seamounts surrounding the complex e.g. Antialtair Seamount (Fig 2e) in the south would represent the funnelling ridges of the event. Crumb Seamounts (Fig.2f) and other features with a positive form situated on the plains surrounding the complex may have been formed by funnelling debris thrown off the impact zone. From a time perspective, and assuming that the train came in as a straight line, Earth rotation speed of 0.46 kms^{-1} limits **the duration of the whole event at c. 17 minutes.** The impactors' funnelling speed at relative c. 30 kms^{-1} allow us to calculate the formation time of the longest individual trench in the King's Trough unit at c. 5 seconds. The impactors' "total passage time" sums up a c. 16 s. Looking at the ellipsoid trenches formed one could assume that all objects but a possible few bounced off. Their further destinies are unknown, some of them might finally have landed on the Earth, and others might have bounced back into space.

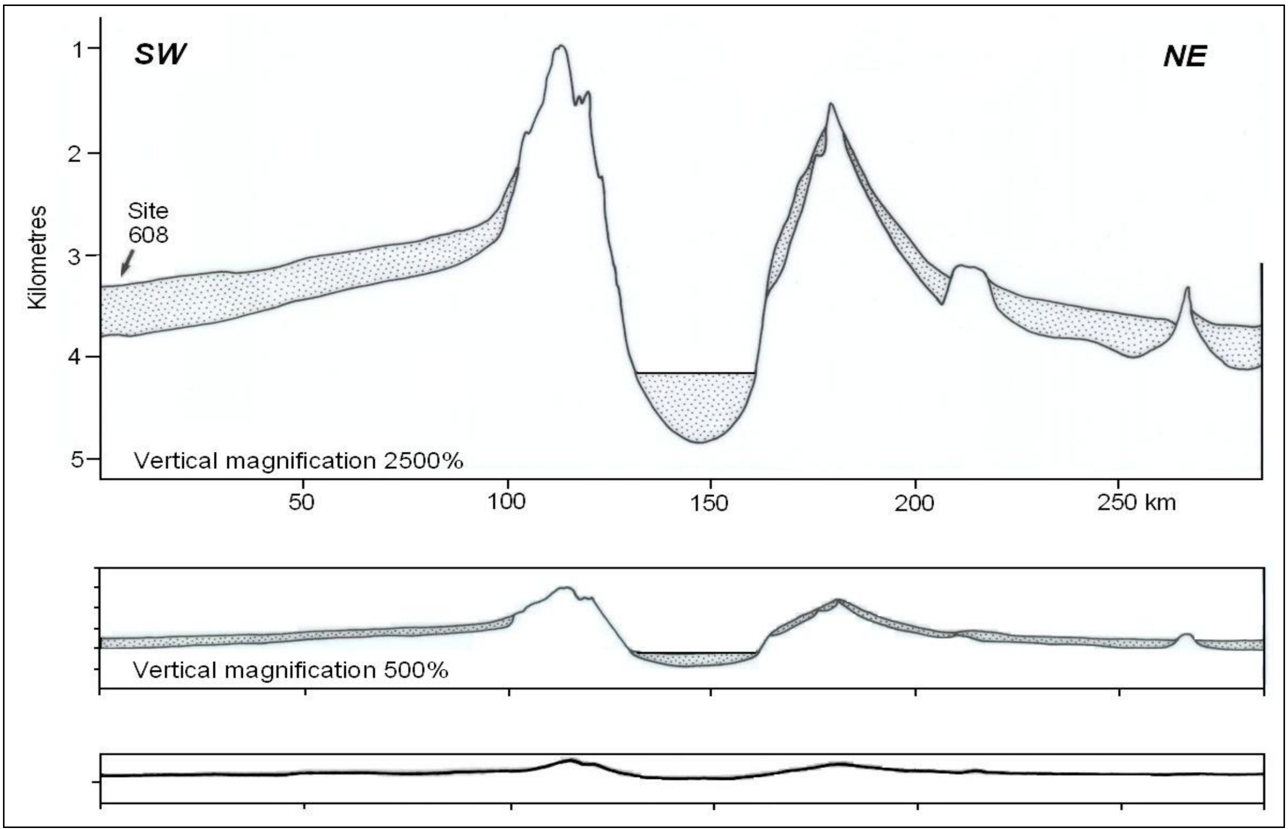

Figure 3 - SW-NE seismic reflection profile of the King's Trough complex from 42°45' N, 23°05' W (SW) to 44°55' N, 21°05' W (NE) showing the location of Site 608 (Reworked from Kidd and Ramsay, 1987, Fig.2).

5.2 Dating the event

From the sediment record two possible age candidates stand out as possible candidates i.e. at c. 26-28 Ma at the Rupelian/Chattian shift (the Early/Late Oligocene boundary or somewhat later) and c. 16-18 Ma at the Burgigalian/Langhian shift (the Early/Middle Miocene boundary or somewhat earlier). A compilation of available data was made by Kidd and Ramsay (1987) where they divided the complex into three sub units: (a) King's Trough Axis, (b) Palmer Ridge and (c) King's Trough Flank. Dates from King's Trough Axis mainly included dredged material such as basalts, hyaloclastite, trachytes, and volcanic tuffs and ashes. Whereas the dredged basalts gained K-Ar ages of 52±6 Ma, the trachytes dated at around 32 Ma and the tuffs and ashes were inferred to be slightly younger than these were. At Palmer Ridge several dredge hauls were made mainly on the southern flank towards Freen Deep. Besides chalks in the hauls, there were other *in situ* rock types such as basalts, amphiboles, serpentines, gabbros, and volcanic ashes.

Among the material dredged from Palmer Ridge, Cann (1971) reports specimens with various grade of metamorphosis. Although Cann points out that dates from metamorphosed rocks are more reliable than igneous rocks formed in the ocean, being more stable relative to seawater he does not discuss the grade of metamorphosis as a possible source of error. The large number of unmetamorphosed and partly metamorphosed rocks found at Palmer Ridge point in the direction of a very short event, the metamorphic effect visible only for a few centimetres beyond which the rock is unmetamorphosed. Dating from such material would most likely be very uncertain showing up with higher ages than the actual event of metamorphosis event i.e. an insufficient "zeroing" of the K-Ar clock of minerals used for analysis.

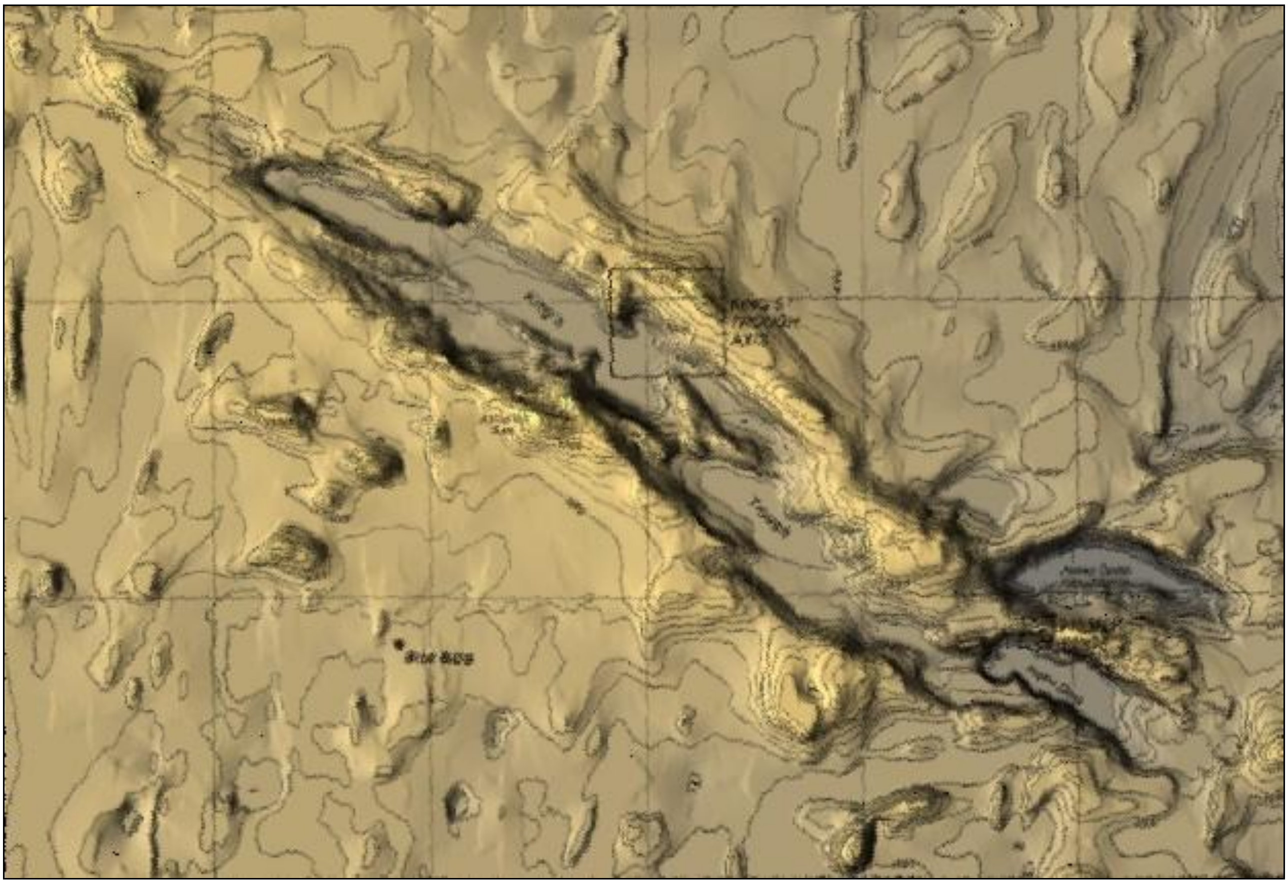

Figure 4. Bathymetry of King's Trough Complex, overlaid on 3D-image. The 3D images shown in various figures here are based on the digitising of the bathymetric image presented as an appendix in the ODP 94, publication of 1987. Vertical magnification 500 per cent.

5.3 Sedimentary evidence

The most striking/conspicuous evidential sign is found in Site 608 which is probably the most complete Tertiary-to-Recent section drilled in this part of the North-Atlantic. Site 608 of the Ocean Drilling Project (ODP), is situated some 100 km south of King's Trough (Fig.2). The record of events of Site 608 depicts volcanicity, a major hiatus, and sediment instability, all of which were believed to be related to tectonic events at the trough axis (Kidd and Ramsay, 1987). The stratigraphic record starting at the basement, (c. 500 m sub-bottom depth, a basalt which has been dated at 52 Ma) begins with middle Eocene marly nanno chalks with volcanics. The upper Eocene sequence is containing volcaniclastic turbidites and graded volcanic ash beds, and the lithology clearly indicates rather rapid deposition of sediment. The sandy lower parts of the graded ash beds consist mainly of tuff clasts. The clasts are moderately to well rounded, indicated substantial current transport. The graded beds were interpreted as turbidite deposits transported from an upslope location. In the core, several intervals were identified where remobilization and redeposition of the chalk had taken place. The graded volcanic beds are overlaid by a chalk breccia of Late Oligocene, which has been interpreted as a debris flow deposit. Above this at c.462 m there is a 9.5 m hiatus, defined in both the lithology, magnetostratigraphy (Clement and Robinson, 1987) and biostratigraphy, representing a time interval of up to 9.7 Ma (Upper Eocene/lower Oligocene) (Ruddiman *et al*., 1987), but no others at the sampling density used (Baldauf *et al*., 1987). Immediately above the hiatus is an interval of marly nannofossil chalk with flaser structures and a chalk conglomerate, displaying soft-sediment deformation structures, that was interpreted as consisting of debris flows. The hiatus was interpreted as to be of tectonic origin, because it is recorded as an angular unconformity in seismic profiles and may be correlated with a regional volcanic event (Shipboard Scientific Party, 1987). At 375-369 m sub-bottom another chalk breccia is found interpreted as debris flow material. Above this breccia between 370 and 320 m high-angle faults with a few millimetres displacement are common in the beds. The fault planes generally have slickenside surfaces (Hill, 1987).

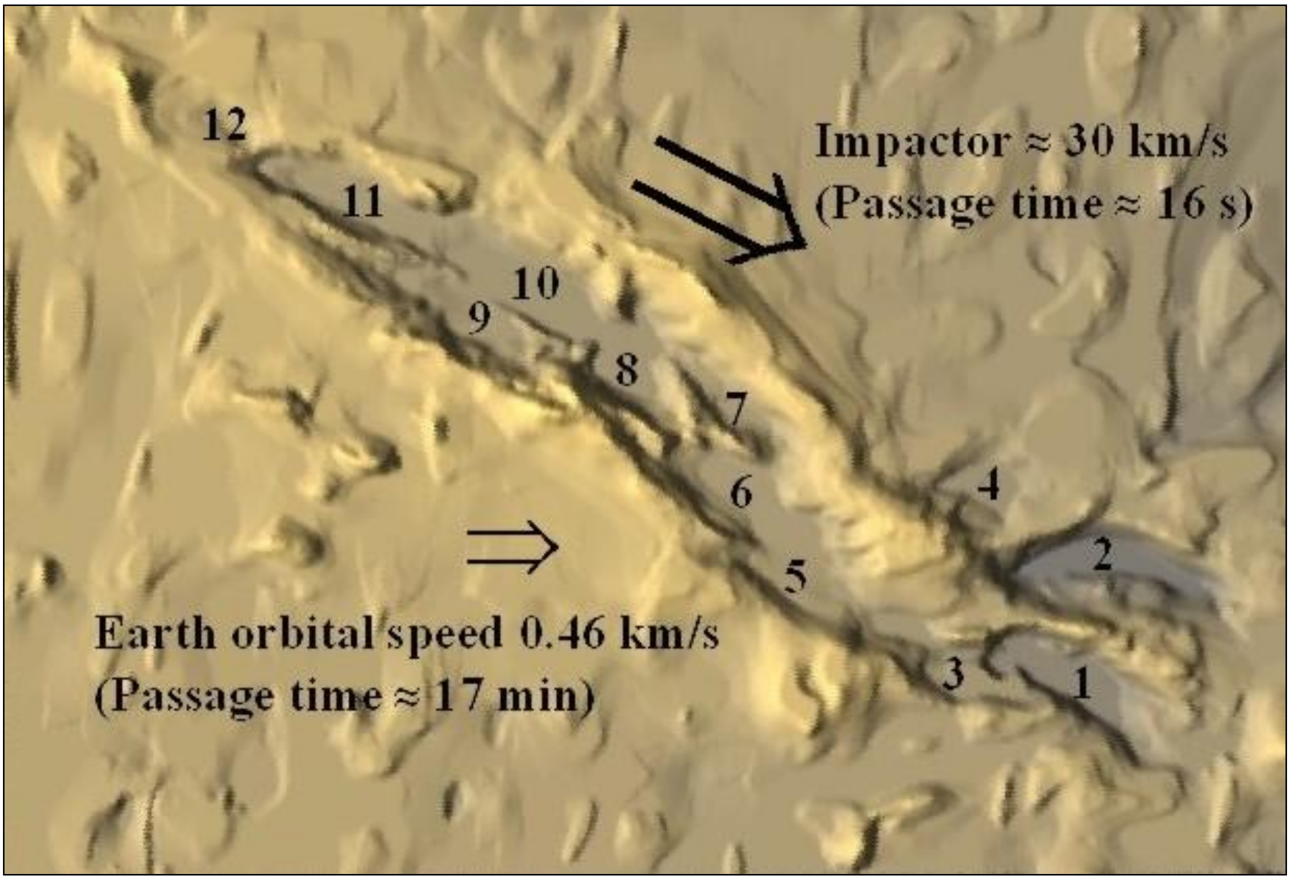

Figure 5. 3D-image over the complex, showing impactors' speed and direction, Earth orbital speed and direction, timing of event, and the assumed order of impact (1-12). Vertical magnification 500 per cent.

Sedimentation rates over this early Miocene period averaged 10 m*Ma^{-1}, except for the latest part (until c.320 m) when the sedimentation rate was only 8.5 m/Ma. At sub bottom depths of c.320-270 m the sediment, corresponding to middle is frequently brecciated (Clement and Robinson, 1987). Throughout the middle Miocene, the site was obviously more tectonic stable than during early Miocene, and the sedimentation rate averaged at 19 m*Ma^{-1}, almost twice the rates in the lower parts of the sequence. According to Ruddiman *et al*. (1987) this appears to be accounted for by evidence of local reworking and signs of slope sedimentation with turbidites and major reworking of foraminifers, although the vertical transport distances for displaced material must not have been great. Regarding the large hiatus, the mere lack of 9.5 m of sediments raises questions if they were lost or if they were never there in the first place?

6. Discussion

The size and form of an impact crater depends upon the size and velocity of the impactor, the incidence angle, and the nature of the surface on which the object impacts. The probability of an exactly vertical impact is very small. Although some impacts may be almost vertical, the most probable angle of impact of a randomly incident projectile is 45 degrees. Oblique incidence of the projectile is thus an important facet of impact cratering. All but the most oblique hypervelocity impacts (<10°) produce circular craters. Phenomena such as ricochet of the projectile, elongated craters, and downrange streaks, however, may appear at very low angles of incidence (Melosh, 1989). The production of elongated troughs by oblique impacts is problematic. Elongated or elliptical craters may form where two or more craters in a swarm overlap, but the likelihood of thus forming a series of troughs with a long axis more than double the width is extremely small. In general, experiments and computer modelling show that a low angle of impact does have a strong influence on the distribution of ejecta but little on the shape of the crater except at near-grazing incidies (<5° from horizontal). Examples of craters on land produced by low angle impacts include the cluster of small craters at Campo del Cielo (Cassidy, 1968) where elongated craters are interpreted as low velocity penetration funnels rather than equidimensional explosion basins. The shallow elongate depressions formed in low strength loess at the Rio Cuarto crater field (Schultz and Lianza, 1992; Schultz et al., 1994) though up to 4 by 1 km in plan, have rimes less than 10 m high and are no more than 10 m deep. The Schultz and Lianza claim has recently been toned down since it was found that the described depressions were only few in a large field of similar elongated depressions which have now been claimed to be formed by wind erosion (Bland *et al*., 2001). The question, regarding an exogenic or endogenic formation mechanism, of the Rio Cuarto structures, is still open. In any case, even if oblique craters are rare, the ocean floors might hide numerous impact structures just waiting to be found, including oblique touchdown marks.

All of the previous interpretations on the formation of the KTC include internal factors, where volcanism seems the most cherished candidate. From a geological point of view the major argument against a volcanic origin, is the depth of the trenches, above all Freen and Peake Deeps with their bottoms 1000-2000 metres below the adjacent sea bottom level. Volcanism is generally associated with positive landforms i.e. volcanic cones normally reach far over their surroundings. If we accept hot spot volcanism below a prograding sea bottom, we would most likely end up with a chain of volcanoes and not a series of deep trenches surrounded by rimlike chains of narrow seamounts. If these trenches were the result of seafloor extension there would likely be one major depression and not 15 smaller lenslike trenches such is the case here, unless there are some very local and special sink mechanisms involved, such as collapsed volcanic calderas. According to Miles and Kidd (1987) magnetic data do not indicate extension across the complex, during formation nor during any later rifting, and Matthews *et al.* (1969) ruled out the caldera background. If spreading occurred it must have taken place within the King's Trough axis itself, since there is no evidence for it on either flank (Miles and Kidd, 1987). According to Matthews *et al*. (1969) seismic refraction results in the Freen-Peake area shows no thinning of the crust under the deeps although the Moho may be depressed by 2 km. Matthews *et al.* further claim that models consistent with gravity and seismic information suggest there is a dense block in the upper mantle of this area. If we put this latter information in context with a possible impact scenario the Freen-Peake area might not represent the tracks of two different impactors but a more "normal" impact structure. If generalised, Freen and Peake Deeps could both be parts of a larger more or less circular impact structure, where Palmer Ridge makes up for an elongated central peak. The dense block in the upper mantle might be remains of an impactor train member which did not ricochet but penetrated through the thin oceanic crust. The distribution of magnetic anomalies within the KTC are shown in Figure 6. This map is a reworked detail from a map of magnetic anomalies in the Northeast Atlantic Ocean (Verhoef *et al*., 1986).

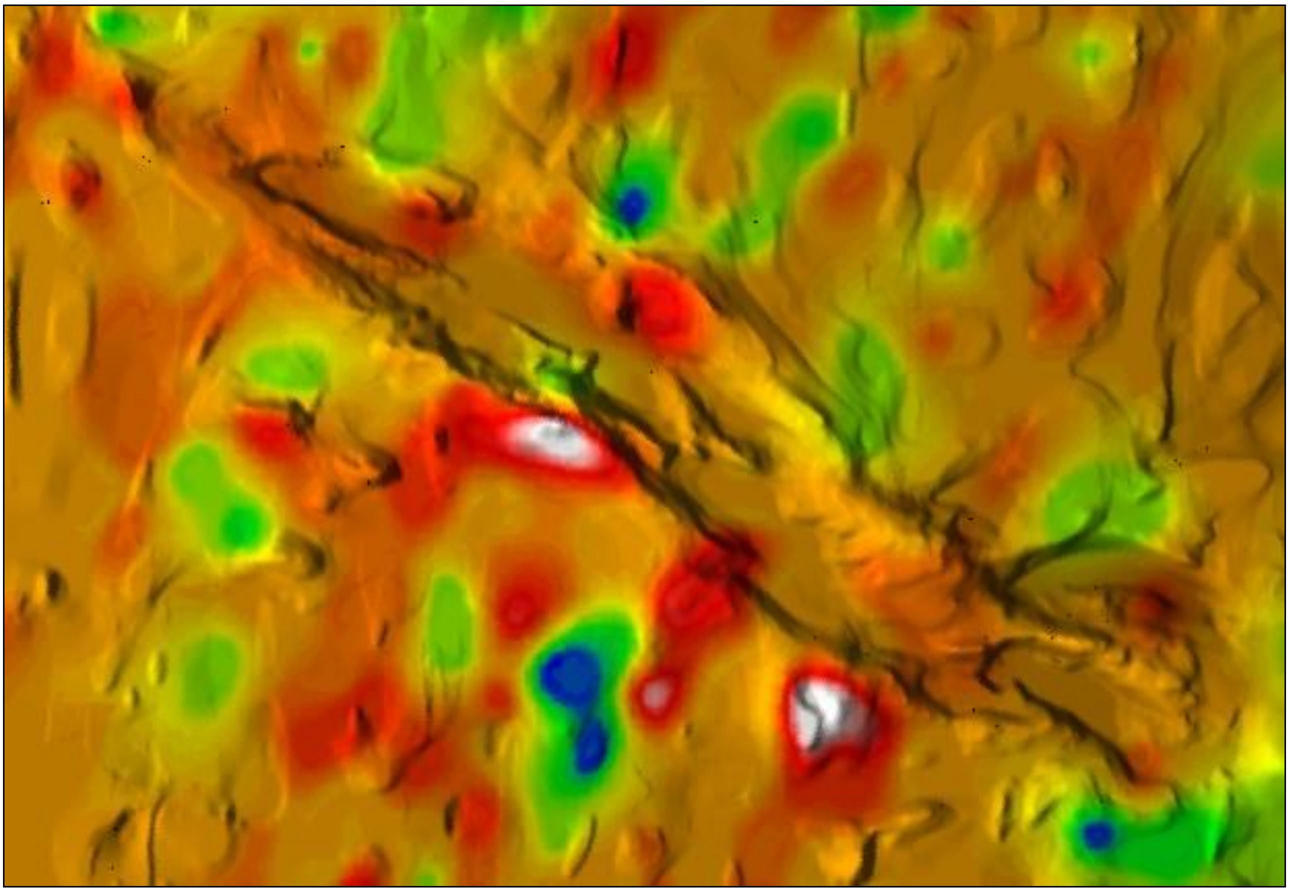

Figure 6. Magnetic anomalies of the King's Trough Complex area overlaid on 3D-image. Reworked detail from Verhoef et al. (1986). Approximate values of colour coding (nT) (white >100 (strong positive anomaly), red 50-100, orange 50 to -50, green -50 to -100 and blue <-100 (strong negative anomaly).

From formation timing aspect Miles and Kidd (1987) concluded that the formation of the Eocene Crust of King's Trough was separate from the formation of the Trough, during the Miocene.

Another conspicuous feature with this complex regards sediments. While the sediment thickness within the major basins in the region is in excess of 1 km (Kidd and Ramsay, 1987), the general sediment thickness in the major trough itself is only about 75% of that outside. This was interpreted as either being a result of the trough itself being formed later or that the bottom depth is situated below the Carbonate Compensating Depth (CCD). Observations in Peake or Freen Deeps supports this latter idea (Davies and Jones, 1971). Looking at Figure 3 and using this section as a representative for the King's Trough the mean sediment depth could be calculated at 660 m by dividing the sediment section area by its length. Knowing that the relatively steep slopes flanking both sides of the trough are more or less sediment-free, we could assume that the sediments within these slopes have either slided, slumped or been transported to the trough bottom by turbidity currents. At this particular section the crest-to-crest distance is 70 km. If we distribute the sediment layers found within the trough evenly on these crest-to-crest distance, assuming there has been no losses owing to horizontal transport, we find that they would make up for an average of 300 m. We further assume that some of these external sediments were formed at much shallower depth, above CCD and that they were rapidly deposited and covered with a layer of clay before a significant amount of solution could take burial after downslope transport (Davies and Jones, 1971). Finally assuming that external carbonate-rich sediments roughly make up for 90-95% of the total (the external deposition section width make up for 46 km or 66% of the total of 70 km) a correction factor of 1.11-1.05 for the 300 m calculated above could be used, to estimate the theoretical depth if all sediments had been formed above CCD. Thus we get a mean theoretical sediment depth of 315-330 m, a figure which could be used, along with Core 608 described above, for a rough dating of the formation of the trough, i.e. c.320 m or the earliest part of Middle Miocene. On ridges and terraces in the complex, flanking the deep basins, where sediments occur, they are normally up to around 300 m deep (Davies and Jones, 1971) ranging in age from middle Miocene to present day (Cann, 1971) supporting the above calculations.

7. Possible effects of this impact

The little knowledge on oblique impacts allows us merely to guess the magnitude of possible effects at this event. The large number of fragments involved awakes the assumption of an original body with a low tensile strength, such as a comet, which are supposed to split more easily under the influence of tidal forces, than a stony or metallic object. The knowledge of cometary impacts is probably even more restricted. Nevertheless the impact power of frozen gases and liquids would only by short to that of a denser object; however, impact products would differ to a large extent.

Among the physical signs, the most natural consequence of any ocean impact would be the shockwave induced tsunami. The backwash from one or several tsunamis wave would most probably have put its signature to surrounding coastal areas and continental shelves. Tsunami effects would also affect shallower areas in the ocean i.e. seamounts, island rises and other positive ocean bottom features. One would expect tsunami generated currents to erode top sediments and hence lithological gaps or hiatuses would show up. A compilation of the ODP material for the Atlantic comes up with striking unconformities regarding the time span discussed i.e. major hiatuses occur in several sites in the Early Tertiary and the hiatuses are most commonly found in drilling sites near the coast or on elevated places on the ocean floor. In some cases Late Early to Early Middle Miocene lies immediately on top of Eocene to late Cretaceous, often with an intermediate mixed layer and sometimes with seismic reflector forming the bottommost layer of the younger sequence in others there is a hiatus of just a few Ma. Some examples; Leg 11 of the NW Atlantic (Lancelot *et al*., 1972); Walvis Ridge Seamount of SE Atlantic (Pearch-Nielsen, 1977); Gorringe Bank of ODP Site 120 of NE Atlantic (Ryan, 1973); The Rockall Plateau region of the North Atlantic (Baldauf, 1987); ODP Leg 159 of Eastern Equatorial Atlantic, Ivorian basin (Schellpeper and Watkins, 1998). Dolan (1987) emphasises the presence of a wide spread Late Early to Early Middle Miocene hiatus throughout the eastern North Atlantic during this time interval, but suggests increased bottom-water circulation as a possible explanation. Shor and Poore (1979) conclude that the deep circulation of the eastern North Atlantic did not attain its present configuration until at least the early Miocene. A somewhat controversial question is thus awoke; Did the suggested impact event trigger off an altered circulation followed by a general cooling as suggested by Thomas (Thomas, 1987).

Keller and Barron (1983) in their compilation of Miocene deep-sea hiatuses marks an Early Miocene hiatus, the NH1, of around 20-18 Ma perhaps the most significant erosional event during the Miocene. According to Keller and Barron (1983) this hiatus has a world-wide distribution in both middle and low latitudes, and only a few deep-sea sequences are complete during this interval. The timing of this event is put towards the end of this period i.e. around 18 Ma. Another hiatus NH2 occurs at c. 16-15 Ma. NH2 occurs in deep as well as shallow sedimentary sequences and is suggested to be associated with a short, fast rise and fall of the eustatic sea level (Vail and Hardenbol, 1979). The most likely explanation to increased erosion, according to Keller and Barron (1983) is currents changed by tectonic uplift, or initiation of Norwegian Overflow water.

Large tsunami waves single and/or repeated such as would have been expected after a multiple ocean impact event are expected to reach far inland, the backwash water masses bringing large amounts of soils and weathering debris back to the ocean. In the shelves the sudden sea level equilibrium changes would trigger submarine sliding and slumping of sediments perhaps large enough to clear out sediments from, or even create, submarine canyons such as the Nazare, Tagus, Sado, Cap Brenton, Cap Ferret, and the Cayar canyons on the Iberian Peninsula the canyons on the canyons on the southern parts of the Celtic Shelf and canyons on the NW African shelf. Regarding the Cap Ferret canyon in the Bay of Biscay, Coumes *et al*. (1982), by the interpretation of seismic reflection profiles, concluded that the canyon formed by deep cutting into the Miocene, and older deposits. Other phenomena that could be associated with tsunamis, after an impact of the magnitude proposed here, are giant sedimentary ridges or "mega-ripples" such as those that could be seen west of Vigo Seamount in the 'strait' between Vasco da Gama and Vigo Seamounts (Group Galice, 1979).

8. Conclusions

While most of the tracks from impacts are still known from land, many remain unknown and hidden from discovery by great ocean depths. Only a handful of these marine impacts are yet recovered and described in the literature. Elongated impact tracks from oblique impacts, or impact funnelling which is proposed here, are even scarcer.

With the geomorphological interpretation made here we cannot exclude that the KTC was formed by an impact event. On the contrary there are many indicators favouring this interpretation.

The relative moderate sediment depths, of King's Trough, Peake and Freen Deeps and their immediate surroundings, indicate that sedimentation started long after sedimentation in more distant areas with equal basal rock age. A simple model compensating for carbonate loss showed that sedimentation in the depressions, with mean sub bottom sediment depths of 315-330 m, commenced around the Early/Middle Miocene boundary at c.15 Ma. The chalk breccias and the high angle faults occurring below 320 m sub bottom in Core 608 indicate deformation. This, and the sub-horizontal shear which was interpreted as *"...differential compaction on a regional scale."* by Hill (1987), could equally be explained by straight or oblique horizontal mechanical shear caused by the impactor while funnelling King's Trough. The sudden increase in sedimentation rates in Core 608, the deposition of turbidites and major reworking of foraminifers as indicated from the beginning of Middle Miocene indicate downslope transport, **necessarily, and logically, demanding a nearby slope**. This, along with other indicators such as sediment hiatuses, in spite of the major hiatus and the dates of metamorphosed rocks found in the dredge hauls, makes us propose in the first place, that the deep basins and high ridges of the KTC were formed at the Early/Middle Miocene boundary or somewhat before.

Benthic $\delta^{18}O$ isotope measurements achieved from the Ocean Drilling Program (Miller *et al*., 1987) show rapid and distinctly falling temperatures at the beginning of Middle Miocene. It could not be excluded that an event of this magnitude could have had a decisive impact on the climate development (Clube and Napier, 1976). In this respect, this event could have given a first impulse for the initiation of the present Pleistocene ice age.

If we are proven right, the KTC would be included among the largest impact structures yet found on the Earth. It is clear that any set of impact events capable of penetrating deep water to form structures of the size of this complex would have required bolides comparable to the largest among the terrestrial impact record. Hopefully, more thorough studies of the sedimentological record in the area, or findings of tektites which could be associated with this event, could help us to resolve this enigma.

9. Final remarks

According to hearsay the different forms in the KTC was named by the ship-crew of one of the ODP vessels. The names were taken from two famous British biscuit makers - *Peake-Freen's* and *Huntley & Palmer.* Whether the name of *Huntley* was used or not is unknown, no form on the bathymetric maps has this name, nor in the literature.

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