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Exotic Grains in a Core from Cornwall, NY – Do They Have an Impact Source?

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We have found seven discrete layers in a bog core from Cornwall, NY about 80 km away from the Atlantic Ocean. All but two layers contain material that is unlikely to be locally derived. In most cases, the material in the layers has been transported thousands of kilometers from its source area. Six out of the seven layers are difficult to explain except through impact processes. If all of these layers are derived from impacts that produced craters, the data imply a very high impact rate during late Holocene time. In addition, we have been able to associate two of the impact ejecta layers with dated tsunami events that span the Atlantic Ocean. If this discovery is validated by further research, it implies a much larger tsunami hazard in the Atlantic Ocean than previously reported.

Keywords: sedimentation rate, sediment transport, scanning electron microscope (SEM) analysis, impact ejecta layer, impact hypothesis during late Holocene time, tsunami hazard in the Atlantic Ocean.

Introduction

Impact ejecta travel thousands of kilometers away from their source crater. They are deposited within seconds to minutes of the impact event [11]. If impact ejecta could be discerned within cores with rapid sedimentation rates, they would constitute marker horizons with geologically instantaneous ages. In this paper, we discuss seven layers from a bog core with a sedimentation rate of ~100 cm per 1000 years. In each case, some component of the layer suggests transport over long distances. Each layer also contains components that are suggestive of impact. However, a confirmation of the impact origin and the source crater for each layer is still in progress.

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Background

In 2006, we used a piston corer to take a core from Tamarack Pond in Black Rock Forest near Cornwall, NY. Tamarack Pond is an artificial lake that was a bog until about 100 years ago. Approximately 1 km away, an earlier core from Sutherland Pond is known to have a sedimentation rate of about 100 cm per thousand years [22]. We are interested in determining if Tamarack Pond also had a similar sedimentation rate and geological history.

In our initial studies, we sampled for pollen and found that the sedimentation rate was similar to that of the Sutherland Pond core. We then searched for datable seeds and twigs. These were used to define a dated stratigraphy for the Tamarack Pond core [13]. We found that the sedimentation rate for the upper part of the core was identical within error to that of the previously dated Sutherland Pond core. The lower part of the Tamarack Pond core had no material that could be dated. Therefore, we extrapolate our ages downward assuming that the sedimentation rate is the same as that in Sutherland Pond.

Regional Geological Setting

The area around Tamarack Pond consists of Proterozoic age rocks of the Hudson Highlands. With the exception of a few granites and pegmatites, most of the rocks are hornblende-granulite grade gneisses [3]. None of the rocks have fossils. There are no active volcanoes in the area. The closest source of glassy volcanic rocks of Holocene age is the volcanic arc in the Caribbean. Tamarack Pond is on a local topographic high with low relief. Thus, there is no expectation of any long distance of sediment transport sourced from younger rocks.

Laboratory Methods

We took our core sample on an island mat of vegetation in the center of Tamarack Pond (Fig. 1). The upper 260 cm of the «core» contained only water. To avoid transposition errors, we have retained our original estimates of depth. Thus, the top of the sediment layer and the 2006 A.D. age horizon is at 260 cm depth.

Samples were processed in two different ways. Our initial samples were taken at 10 cm intervals. They were burned in an oven at 400°C and then sieved with stainless steel sieves and dried in an oven at 60°C. Our samples for dating and pollen analysis were not burned but were sieved in stainless steel sieves and dried in an oven at 60°C. The sieved samples were divided into 3 different size fractions: >150 µm, >63 µm, and >38 µm. We also kept all sieving residues. The two largest size fractions were examined optically with a microscope with a maximum magnification of 110 times. Interesting grains that did not look detrital were selected for examination with a scanning electron microscope.

The scanning electron microscope (SEM) analysis consisted of two parts. We first examined the samples using an FEI XL30 ESEM in both secondary and backscatter modes. Secondly, we used the EDAX energy dispersive X-ray analyzer (EDS) to determine the composition of the sample. We combined all of this data to determine the origin of each grain.

Layer A. 350-355 cm. Corrected ^{14}C Age: 1006±67 A.D.

This layer contains four grains that appear either distally transported and/or impact related. The first is a fresh basaltic glass shard with no vesicles (Fig. 2). The nearest source of basaltic glass from recent volcanism is either along the mid-Atlantic spreading ridge (2800 km away) or in the western

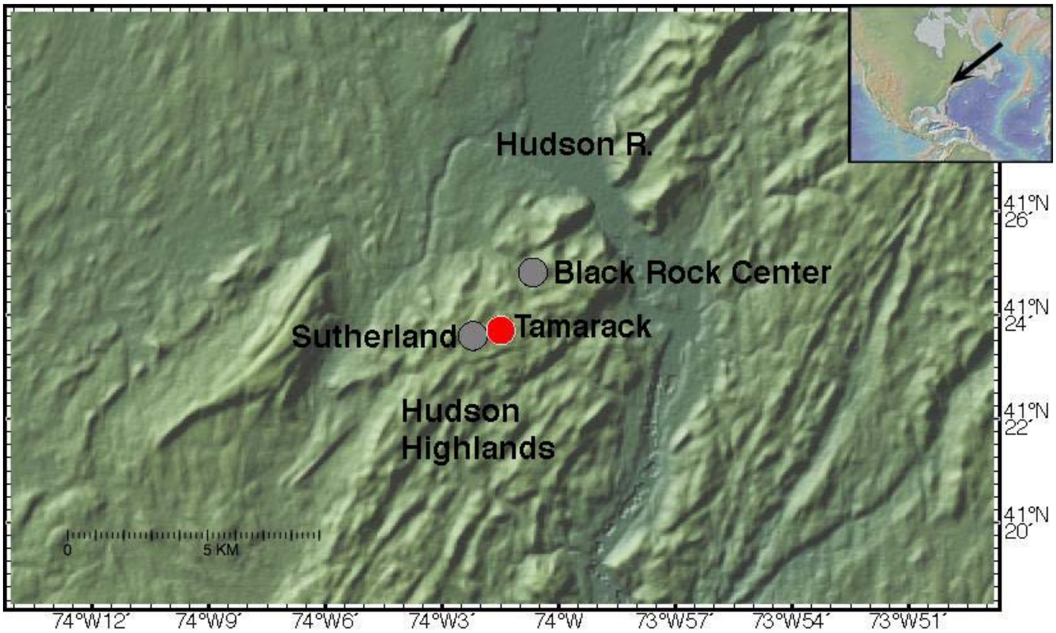

Fig. 1. Location map. Inset. Location of Black Rock Forest relative to east coast of North America. Large map: Red circle: Location of Tamarack Pond. Gray circles: Locations of Sutherland Pond and central administration building of Black Rock forest in Cornwall, NY. Black Rock forest is in the Hudson Highlands just west of the Hudson River. Image from Geomapapp. Layer A. 350-355 cm. Corrected ^{14}C Age: 1006±67 A.D

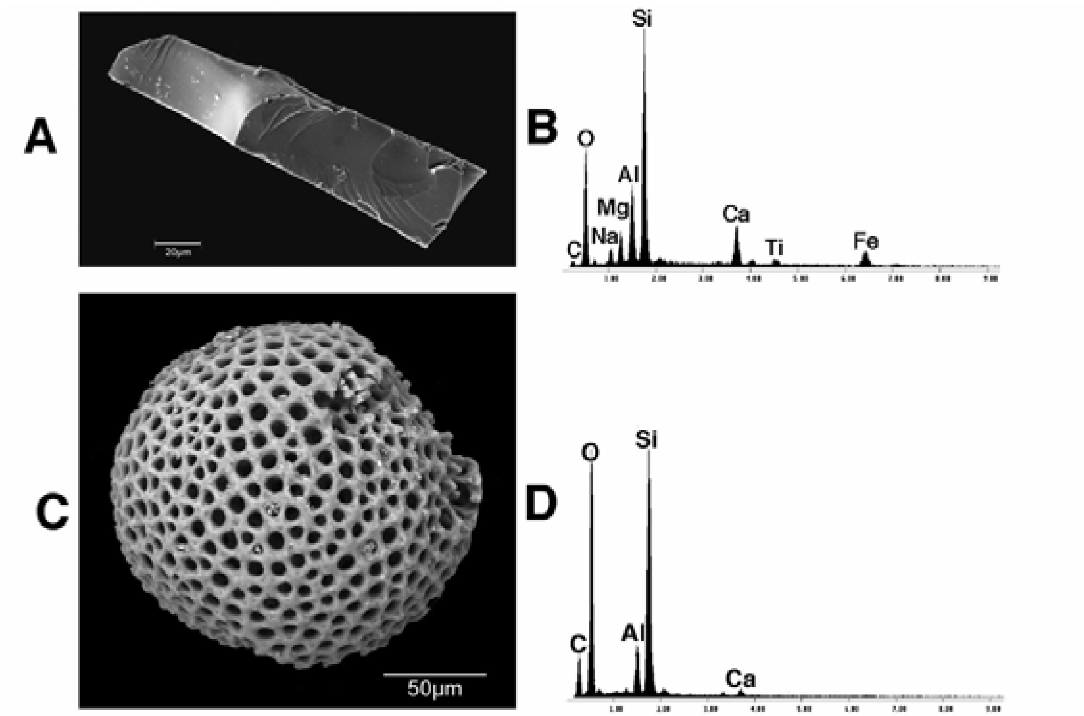

Fig. 2. Fresh basaltic glass shard and radiolarian. A. SEM image of glass shard. Note curved broken surfaces which are characteristic of glass. B. X-ray analysis (EDS) of surface of glass shard. Composition does not match that of any mineral. It does match the composition of basaltic glass. C. Radiolarian-species is not identifiable but the genus is Cenosphaera. D. Analysis of the surface of the radiolarian showing that is dominantly composed of SiO_2. The minor Al, Ca, and C peaks may be from material coating the radiolarian test

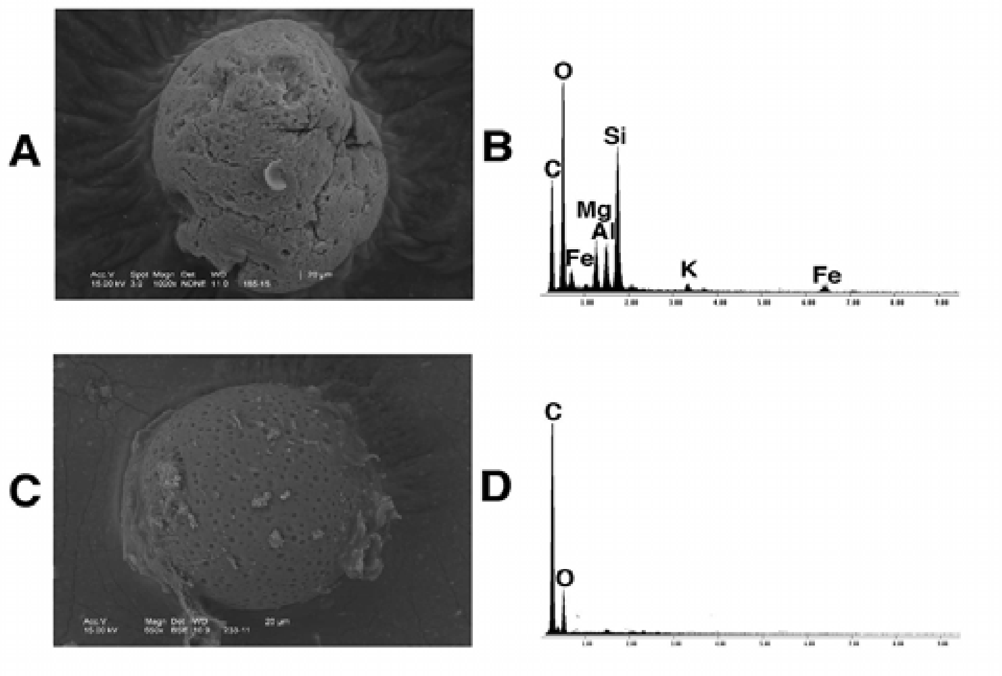

Fig. 3. Glauconite microfossil cast and C rich spherule. A. Microfossil cast composed of glauconite clay. The cast is green in color. B. X-ray analysis (EDAX) of the composition of the microfossil cast. C. Perfectly round, vesicular spherule. D. X-ray analysis (EDAX) of the composition of the spherule

United States (3700 away). The nearest Caribbean volcano is 2600 km away but Caribbean volcanic glass is generally more silicic than basalt. Thus, we infer that if this basaltic glass is volcanic in origin, it has been transported a minimum distance of 2800 km.

The second grain is a radiolarian belonging to the genus Cenosphaera (James Hayes, written comm.). Cenosphaera is most commonly found in the mid-high latitudes 40°-50° N and 40°-50°S or in upwelling areas. It is very uncommon in the tropics [21].

The third grain is a glauconitic microfossil cast (Fig. 3). Close-ups of the grain show that it has morphology like that of other clay minerals. The compositional analysis matches the composition of glauconite. The last grain is a vesicular, perfectly round Carbon-rich spherule with a smooth surface in between the holes. Round, vesicular C-rich spherules have been found in the impact ejecta layer from the younger Dryas [12].

Discussion of Origin of Layer A

Two of the components of layer A are of undoubted marine origin. Glauconite casts form exclusively in the marine environment, either within marine microfossils or as a replacement of faecal pellets. Glauconite is considered to be so unstable that it cannot survive reworking [31]. The glauconite we have found is a microfossil cast, most probably of a foraminifer. The radiolarian is also of marine origin and is most probably from 40° to 50° N or an upwelling region in the North Atlantic. A third component of layer A is a basaltic glass. Because the glass has no vesicles and no significant potassium, it is unlikely to come from a continental basalt flow or an arc volcano. As basalt is deeply buried on older oceanic crust, the most probable nearby sources are the mid-Atlantic ridge or thinly sedimented oceanic crust. If we look for marine sediments in the Atlantic that contain both glauconite and radiolarians, are

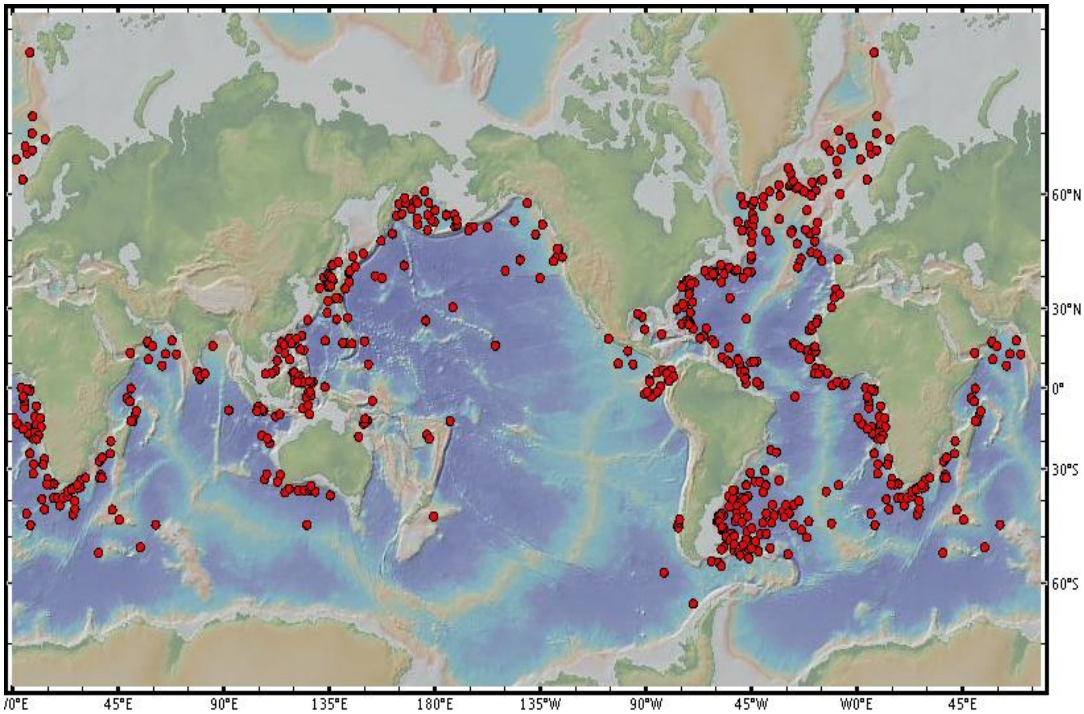

Fig. 4. Locations of marine sediment cores containing both radiolarians and glauconite (source of data, Lamont core curator Rusty Lotti)

between 40° and 50° N, and are close to a mid-ocean ridge, there are only three sites with the correct sedimentary assemblage and geographic location (Fig. 4). These sites are approximately 3800 to 4000 km away from Black Rock Forest.

Because these locations are so far away from Black Rock Forest, the only viable method for transporting the material to Black Rock Forest is an impact event. This hypothesis would fit with the inclusion of a perfectly round carbon spherule with a smooth surface in layer A. In known impact ejecta layers, there are many perfectly round spherules with smooth surfaces of varying compositions [9, 23, 33]. The perfect roundness and smoothness of impact spherules is the result of solidification in a vacuum or near vacuum produced by the impact. The carbon spherules in layer A closely resemble carbon impact spherules from the impact ejecta layer of the younger Dryas [12]. The impact hypothesis has several testable predictions. Because the impact must have been relatively large in order to produce a discernable ejecta layer over 3700 km from the source area of its marine components, it should also have produced a tsunami. Therefore, we have searched the geological record for a tsunami in the Atlantic sometime between 939 A. D. and 1073 A.D.

Tsunami in the Atlantic between 939 A.D. and 1073 A.D.

We have found tsunami events with the right age range in two locations. The first tsunami event has a known age of Sept 28, 1014 A.D [8, 16]. This event is reported in several different historical sources (Fig. 5). From the Anglo-Saxon chronicle «and in this year on St. Michaels mass eve came the great sea flood widely through this country and ran up so far as it had never done before and drowned many vils and of mankind a countless number».

Table 1. Locations and Azimuths to Tsunami Sources for Events circa 1014 A.D

Location	Max_Age, AD	Min_Age, A.D.	Azimuth	Lat.	Lon
Curacao-N	893	1028	N45E	12.37618	-69.12700
Curacao-N	906	1045	N45E	12.39583	-69.15107
Porth Cwyfan	>1180	>1460	S47W	53.19125	-4.50448
Porth Terfyn	>1180	>1460	S43W	53.18437	-4.46661
Mounts Bay	1014	1014	unknown	50.12142	-5.47675
Kent	1014	1014	unknown	51.11491	1.32091
Sussex	1014	1014	unknown	50.82057	-0.16187
Hampshire	1014	1014	unknown	50.81342	-1.22543

The second tsunami event is in the Lesser Antilles. Two ^{14}C dates of a tsunami (Table 1) have the right age range to match the age of layer A [27]. The tsunami came in from the northeast of the Lesser Antilles [29], consistent with a source northeast of the Lesser Antilles.

White circle: source area with glauconite and radiolarians in marine sediment that also has young basalt close to the surface. Blue circle: Location of Black Rock Forest. Yellow circles: Locations of tsunami deposits that are circa 1014 A.D. (Caribbean) or have an exact calendar year date of September 28, 1014 A.D. (Great Britain). Arrows: Inferred direction to tsunami source derived from the elongation direction of tsunami boulder deposits.

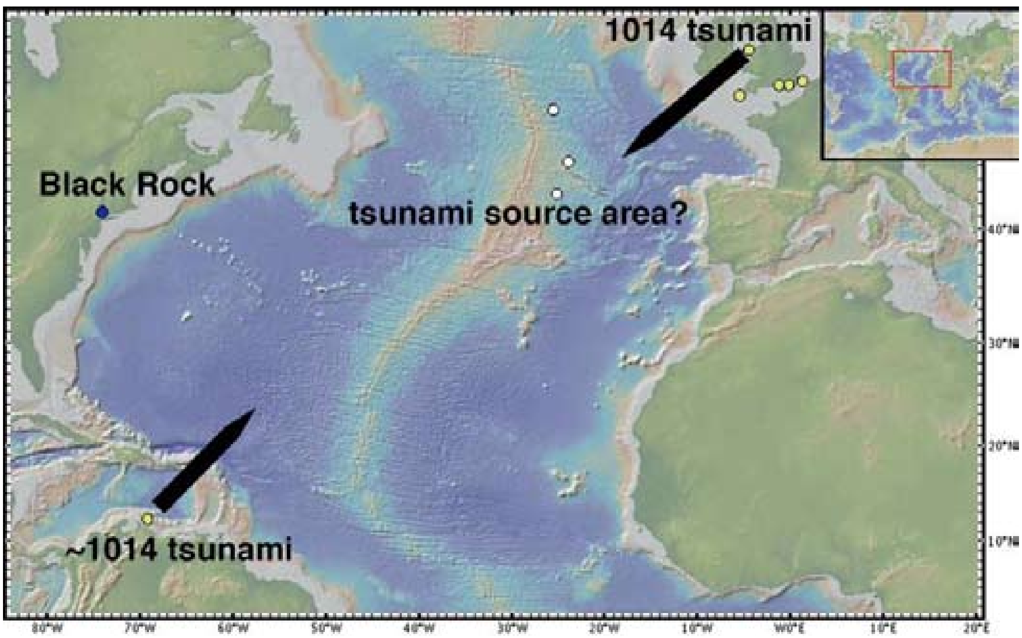

Fig. 5. Proposed source area of transported layer in Black Rock forest and locations of 1014 A.D. or circa 1014 A.D. tsunami layers

Discussion of Tsunami Data

Of the three possible impact sites, the northernmost site would not produce a tsunami in the English Channel area. Either one of the other two possible impact sites could have provided a source for the two known tsunami events on opposite sides of the Atlantic that occurred about

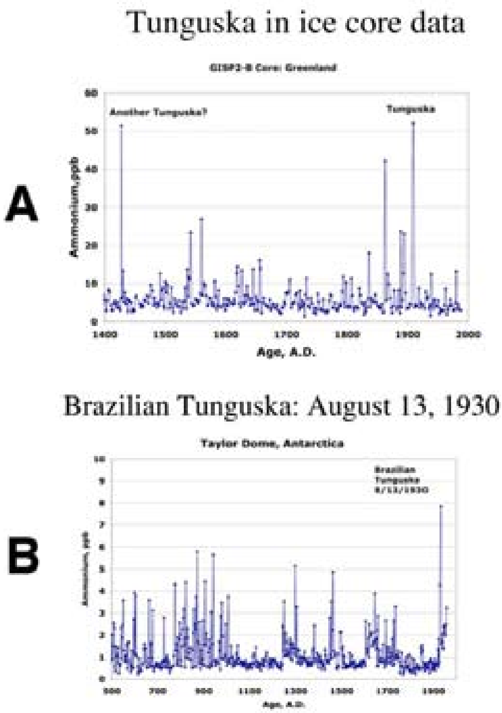

Fig. 6. Ammonium values in ice core samples. A: Ammonium values in the GISP2 ice core from Greenland [24, 34]. B: Ammonium values in the Taylor dome ice core from Antarctica [25]

1000 years ago. There is also a lack of tsunami deposits that are circa 1000 B.P. near Lisbon, Portugal. The bay in Lisbon faces southwest and contains tsunami deposits that are roughly the age of the 1775 earthquake and an older set of deposits that are roughly 2440±50 B.P. in age [30]. The lack of tsunami deposits that are circa 1000 years old near Lisbon can be explained if the source for the 1014 A.D. tsunami was somewhat north of the latitude of Lisbon (38.7°N). The tsunami data are therefore consistent with the hypothesis of an impact into the North Atlantic above 40°N but cannot prove it.

Ice Core Data and the Impact Hypothesis

An impact origin for the tsunami in Great Britain in 1014 A.D. is proposed based on its association with a prominent ammonium anomaly in the GRIP ice core [6]. The youngest prominent ammonium anomaly in the GISP2 ice core is the same age as the Tunguska impact event (Fig. 6A) [4, 28, 35]. We have also found a prominent ammonium anomaly in the Taylor Dome ice core that occurs at the same time (August 13.1930) as an impact event in Brazil, South America [5] (Fig. 6B). Thus, we infer that some ammonium anomalies in ice cores were produced by impact events.

Conclusions: Layer A

A core from Tamarack Pond in Cornwall, NY has a layer containing a transported radiolarian in association with a glauconite microfossil cast, low-K basaltic glass, and a perfectly round, smooth carbon spherule. There are three LDEO cores in the north Atlantic near the ridge crest that could be close to the source of this layer. Because these cores are all at least 3700 km away from Cornwall, NY, an impact into the Atlantic is the only viable method of transport of glauconite, radiolarians, and basaltic glass to Black Rock Forest.

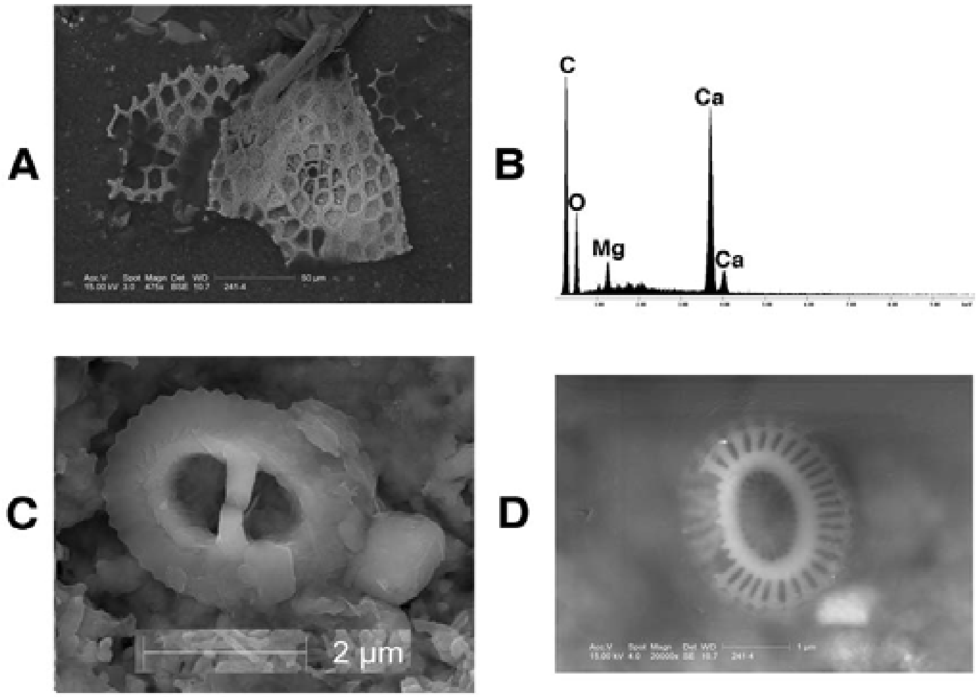

Fig. 7. Red coral with coccoliths in its interstices. A: SEM photomicrograph of red coral. B: X-ray analysis of the composition of the red coral. C: SEM photomicrograph of coccolith from the interstices of the red coral. Species: Gephyrocapsa oceanica. D: SEM photomicrograph of second coccolith from the interstices of the red coral. Species: Emiliana huxleyi

The temporal correlation of circa 1014 A.D. tsunami events in the Caribbean and Great Britain with the age of layer A provides further support for our Atlantic impact hypothesis. The azimuths of the tsunami sources for both events are consistent with a source area that is located close to two of our three proposed impact sites. The results are encouraging but not definitive. A search for a crater candidate must be undertaken near our proposed impact sites and the presence of thick layers of impact ejecta close to any crater candidates should then be investigated. In addition, future work on the solid fraction of the 1014 A.D. horizon in the GISP2 core should show the presence of impact ejecta that includes marine components. Nevertheless, our initial work is intriguing and a follow up should be vigorously pursued.

Layer B. 382-384 cm. Age: 925±76 A.D.

This layer contains at least one undoubtedly transported component, a red coral fragment with two coccoliths trapped in its cells (Fig. 7).

There is no red coral in the Atlantic Ocean near Black Rock Forest. Red coral is found predominantly in the Mediterranean Sea. However, the closest location with red coral is the Cape Verde Islands. One of the coccoliths is Gephyrocapsa. The angle between the long axis of Gephyrocapsa and the orientation of the bridge across the middle is called the bridge angle. The bridge angle varies as a function of the temperature in which the coccolith precipitated. Bridge angles greater than 56 degrees denote equatorial associations [7]. The Gephyrocapsa in Fig. 7 is Gephyrocapsa Equatorial. Gephyrocapsa Equatorial lives at latitudes between 17°N and 17°S [7].

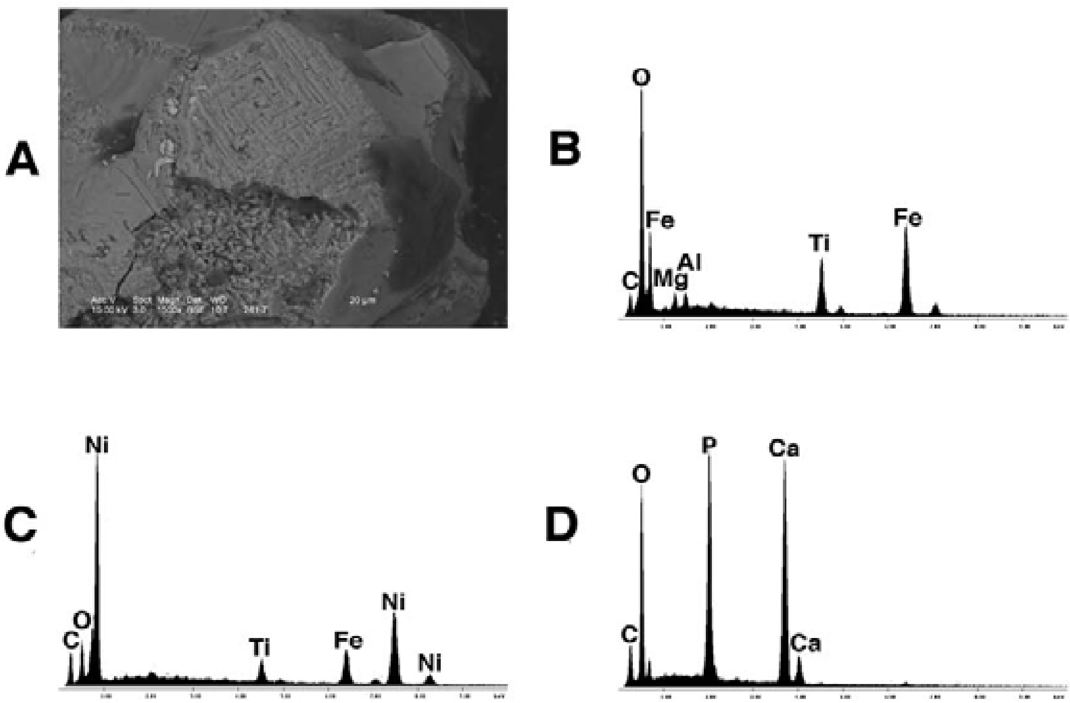

Fig. 8. Ilmenite grain with usual texture and splashed on Ni metal and calcium phosphate. The Ni metal appears as the bright drops on the upper left side of the image. A: SEM photomicrograph of ilmenite grain. B: X-ray analysis of composition of ilmenite grain. Some Mg and Al are included in the structure and this is unusual. C. X-ray analysis of the composition of the splashed on Ni metal. The Fe and Ti peaks are from the surrounding ilmenite grain. All of the oxygen can be accounted for by the ilmenite. Thus, the Ni is likely to be Ni metal rather than Ni oxide. D: X-ray analysis of splashed on Ca phosphate

The layer also contains at least one definite piece of impact ejecta, an ilmenite grain with splashed on Ni metal and splashed on Ca phosphate (Fig. 8). In addition, the layer contains one partially dissolved and apparently melted foraminiferal fossil of a type that lives in brackish water. This layer is discussed in more detail in a separate publication (Gerard-Little et al., in preparation).

Layer C. 452-454 cm. Age: 28±92 B.C. (120 B.C to 64 A.D.)

This layer contains glauconite rosettes on a glassy looking fragment, basaltic glass with lens shaped fractures, a quartz grain with tiny micrometer scale Sn-rich silicate spherules in holes in the surface, and titanomagnetite grains with odd craters on their surfaces (Fig. 9, 10, 11). Glauconite rosettes have been found in continental basalts on the surface of cracks in basalt or on open weathering surfaces [17]. In one case, glauconite rosettes were discovered on the surface of samples from a borehole in basalt [18]. The metamorphic grade of the basalt is extremely low. Basaltic glass with lens shaped fractures has not been reported elsewhere, to our knowledge. We found three Sn-rich silicate spherules from an unknown source on the surface of the quartz grain. The surface of the titanomagnetite grain is extremely fresh, and it cannot have been exposed to weathering for any length of time. The craters in the titanomagnetite grain are similar to craters produced by high speed projectiles.

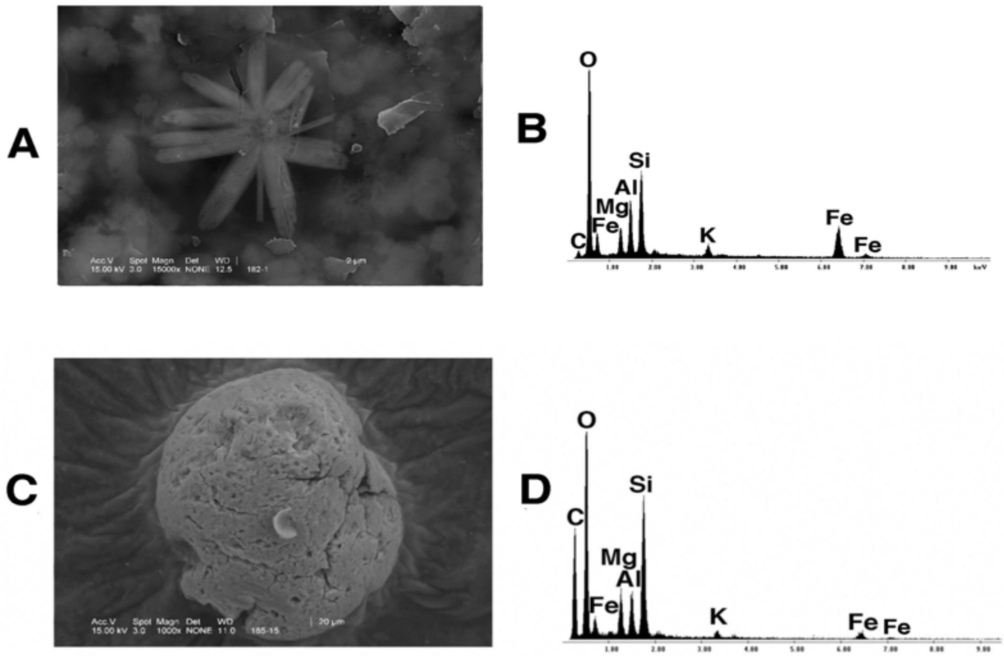

Fig. 9. Comparison of glauconite in two different forms. A: Glauconite rosette on top surface of rock fragment from Layer C. B: X-ray analysis of glauconite rosette to left. C: Microfossil cast composed of glauconite from layer A. D. X-ray analysis of glauconite cast to left. Note in particular the three iron peaks in both X-ray analyses

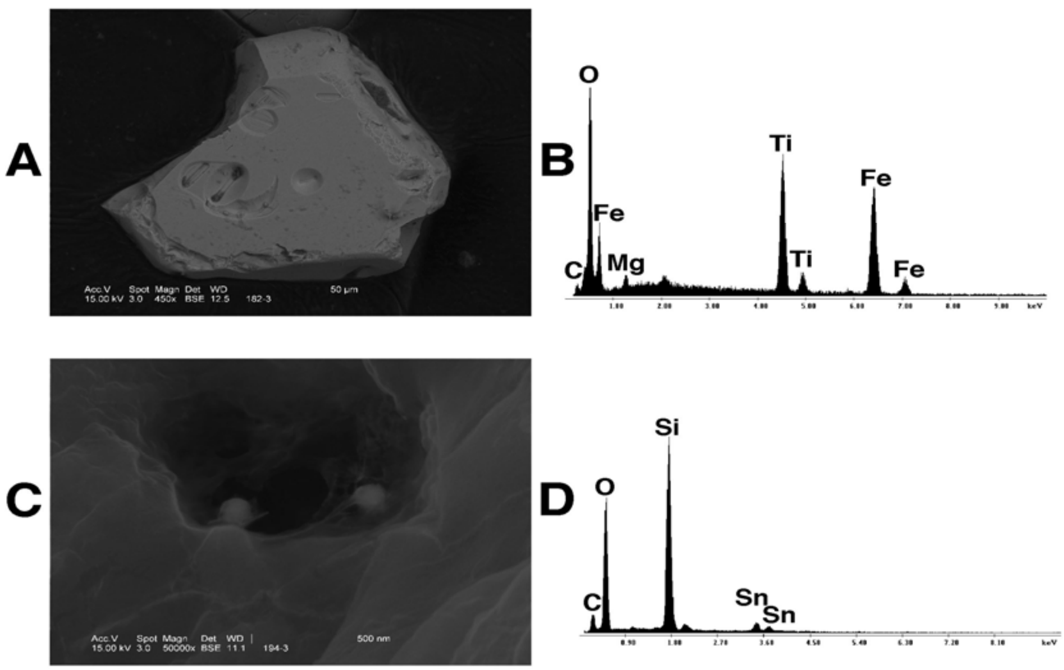

Fig. 10. Unusual components of layer C. A: Ilmenite grain with unusual craters on its surface. B: X ray analysis of ilmenite. C: Sn-rich silicate spherules in hole in quartz grain. D: X-ray analysis of spherules

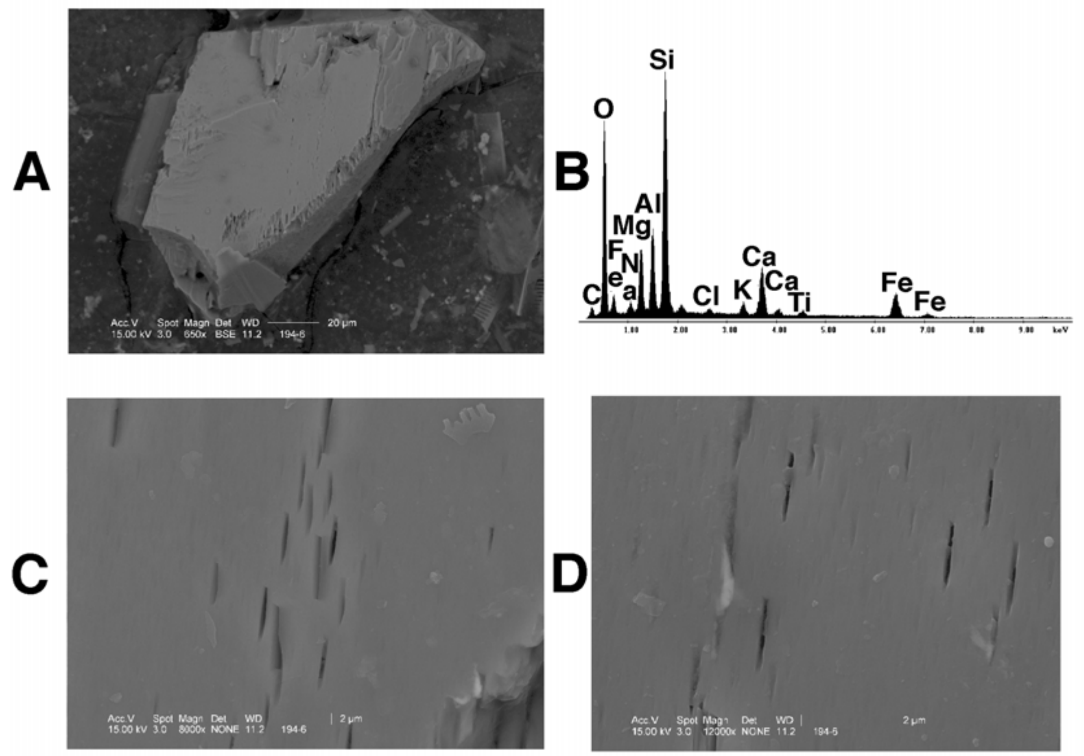

Fig. 11. Basaltic glass with lens-shaped fractures. A. Entire grain showing conchoidally fractured, fresh surfaces. There is no apparent cleavage. B. X-ray analysis of the grain in A showing a composition like that of typical basaltic glass. C and D. Close ups of the lens shaped fractures in the surface of the glass. Note that the length to width ratio of the fractures is about 10 to 1 with width measured at the center of the fractures

Discussion-Layer C

Some sort of catastrophic explosion must have produced the glass and the fractured titanomagnetite. The basaltic glass has discernable K in it and could be derived from an explosive volcanic eruption. The closest volcanoes that produce K-rich glass are in the Caribbean, over 2600 km away. However, Caribbean volcanism is typically more silica rich than basalt. The closest volcanoes producing basaltic rocks are near the mid-Atlantic ridge, about 2900 km away [32]. Microprobe work on the chemistry of the basaltic glass is needed to determine its probable source area (Fig. 11). The Sn-rich silicate spherules resemble impact spherules but are not definitive due to their small size. If they are impact related the Sn may be derived from the impactor. Impact ejecta from presumed cometary impactors have enrichments in Sn, Sb, and Pb [20], all elements with low melting points that are thought to be enriched in comets. Thus, the presence of Sn does not necessarily tell us anything about the chemistry of the source rocks for this layer. The glauconite rosettes are derived from basalt that has never experienced high-grade metamorphism. With the data we have so far, the materials in this layer could be either from a continental impact event or a large explosive volcanic eruption. If the layer is from a continental impact event, it could be derived from a local impact site in the Triassic basalts of the Newark group. If so, the extremely small diameters of the spherules imply a very small source crater only a few meters in diameter. Alternatively, if the layer is derived from an explosive volcanic eruption, it must have traveled over 2600 km from its source volcano.

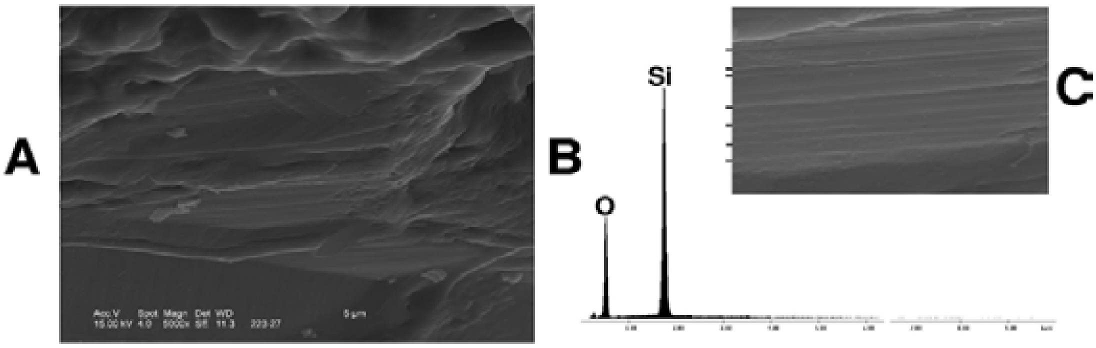

Fig. 12. Possible shocked quartz grain (unpolished). A: SEM image of surface of the grain. Three directions of planar features are visible. The spacing between the planar fractures is less than a micron, one defining characteristic of shock lamellae. B: X-ray analysis of the composition of the grain. C: Enlargement of the best-resolved planar features in Fig. A. Edges of the best resolved planar features are delineated by lines on the left side of the image. The height of the image is equal to a distance of 3.1 micrometers. The planar features in this image have a spacing of much less than 1 micrometer and thus are clearly PDFs resulting from shock metamorphism [19] rather than metamorphic deformation features

Layer D. 490-494 cm. Age: 327±113 B.C.

This layer contains two possible shocked quartz grains (Fig. 12). One of the two grains with shocked quartz also has glauconite. The origin of the grains in this layer is unknown. In theory, the planar features in the grain are PDFs, as their spacing is much less than 1 micrometer [19]. However, the mainstream impact community will not accept these grains as shocked quartz unless the grains are imaged in a polished thin section. More grains need to be characterized to pin down the source location and origin of the layer. The layer has the same age within error as the Chiemgau impact crater field. It also has the same age within error as a tsunami layer in the Hudson [14] that contains the following shocked minerals: impact diamond (lonsdaleite), shocked olivine, and shocked limonite [10]. So far, shocked quartz has not been found in the tsunami layer. Our papers devoted to the tsunami layer and the confirmed shocked minerals in the layer are in preparation.

Layer E. 522-524 cm. Age: 605±97 B.C.

This layer contains a high-Mg carbonate microfossil (Fig. 13). It also contains a glass with a composition similar to Mg-rich pyroxene or basalt and a glass with a composition similar to albite feldspar (Fig. 14). The latter glass appears vesicular but only in some areas. The layer also contains an optically translucent grain with a surface that appears vesiculated in some places. The grain has an average composition akin to marine clay but has abundant bright material, a combination of Ni and Fe, on the surface. The Si in the sample can account for all of the minor oxygen in the analysis.

Discussion Layer E.

The combination of components in layer E (Figs. 13, 14, 15, 16) suggests an impact into an oceanic area, possessing a basaltic substrate covered by a thin layer of clay rich sediment. Some of the basaltic glass (Fig. 14) has a small percentage of K so it is most likely from a source that is not on a mid-ocean ridge. The very high Ni content of the material splashed onto the clear grain in Fig. 15, and its

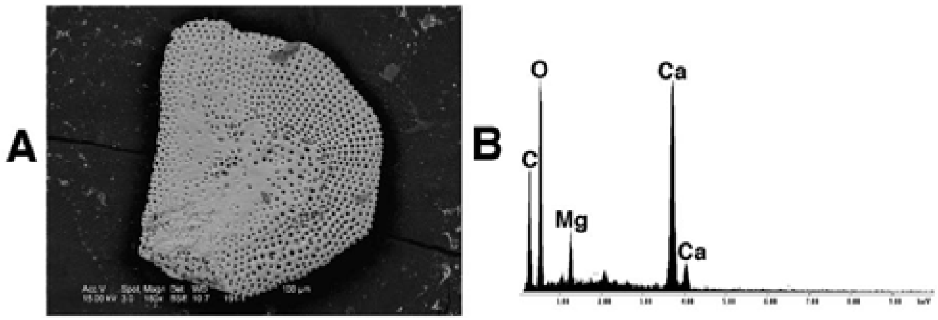

Fig. 13. Marine carbonate fossil. A: SEM image of marine fossil. B: X-ray analysis of composition of fossil. Note that there is a strong Mg peak, consistent with either aragonite or high Mg calcite. The carbonate contains about 26 mol% Mg

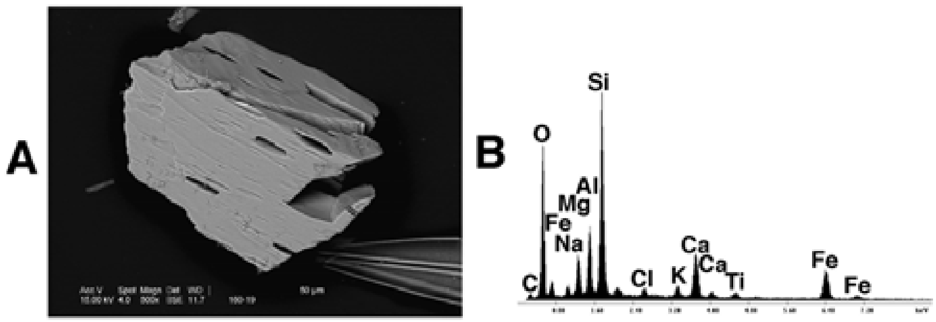

Fig. 14. Basaltic glass with lens-shaped fractures. A: SEM image of black basaltic glass with lens shaped fractures. B: X-ray analysis of composition of the glass

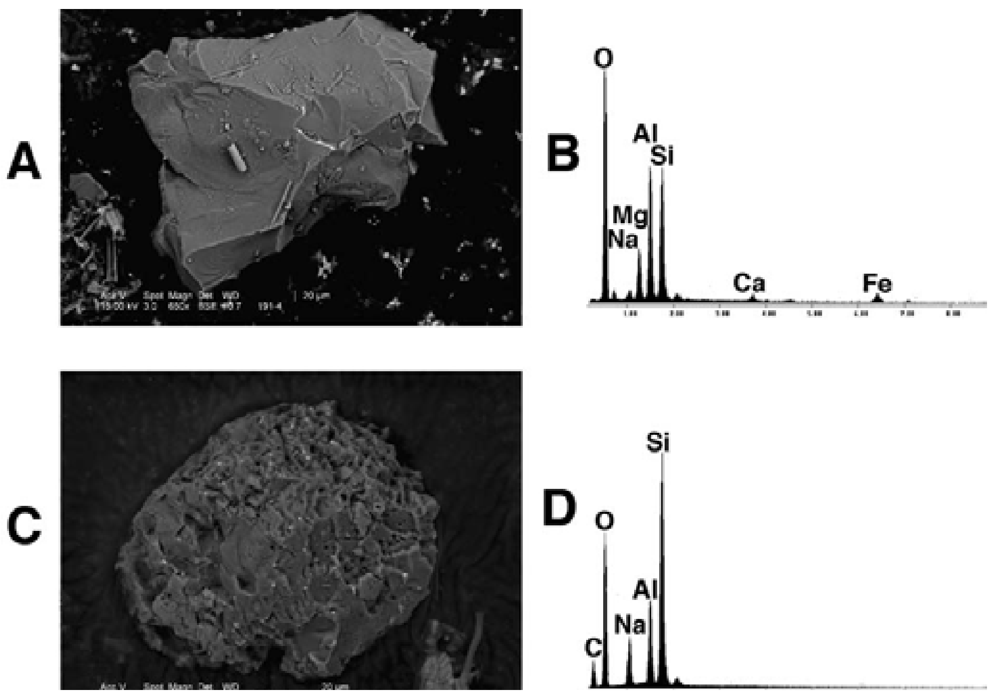

Fig. 15. Glass Grains. A: SEM image of grain with conchoidal fracture. B: X-ray analysis of composition of the grain in A. C: SEM image of grain with conchoidal fracture. Parts of the grain appear vesiculated. D: X-ray analysis of the composition of grain in C

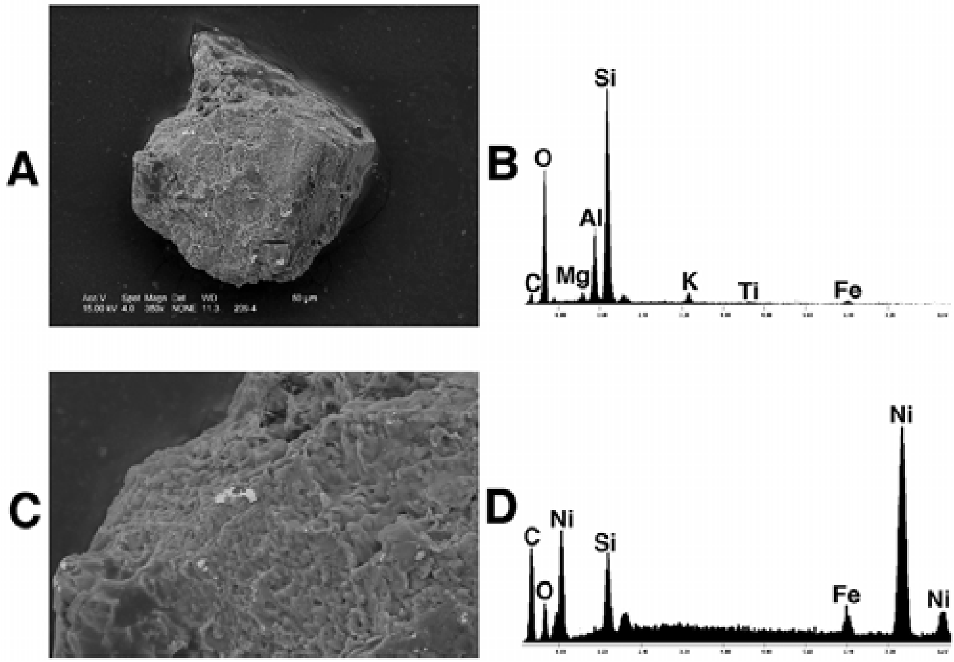

Fig. 16. Metal on Clear Grain. A. SEM backscatter image of entire grain. B. X-ray analysis of composition of grain matrix. C. SEM backscatter detail of grain showing melted, vesiculated surface and bright material of higher atomic number splashed on surface. D. X-ray analysis of composition of bright material (includes contribution from surrounding matrix)

apparent lack of oxygen, suggest an event that vaporized and reduced extraterrestrial material. The high Mg content of the marine fossil suggests a marine platform in very shallow water. The closest marine platform is Bermuda, over 1200 km away. However, basalt is not exposed near the surface in Bermuda; it is deeply buried by the subsidence of the islands over time. Because we are seeing fresh basaltic glass, the source area most likely has very thin sediment cover over a basalt layer. The high Mg content of the marine fossils precludes a source on most of the crest of the mid-Atlantic ridge, as it is too deep for aragonite or high Mg calcite to be stable. Taking these factors into account, the next most plausible source is near a marine hotspot or volcanic arc in the tropics. The closest hotspot islands in the tropics are the Canary Islands, over 5100 km away. The closest volcanic arc is in the Caribbean, over 2600 km away.

The size of the grains we have found is relatively large. Making an analogy to the average size of shocked quartz grains versus distance from the K/T impact site, the source area for Layer E should be within 9000 km of Black Rock forest [26].

The hypothesis of an impact near the Canary Islands or in the Caribbean around 600 B.C. can be tested further by looking for tsunami deposits of that age in Spain, Portugal and the Caribbean. Using ages determined by electron spin resonance dating (ESR), there is one tsunami deposit of that age on the Caribbean island of Curacao. The tsunami source is NE of Curacao, either in the Atlantic or in the Caribbean arc. An older tsunami deposit from Portugal has an uncorrected ^{14}C age of 2440±50 B.P. This age overlaps with the uncorrected ^{14}C age of the tsunami deposit in Curacao of 2511±43 B.P. Thus, it is possible that all of the ages are derived from the same tsunamigenic event. If so, the tsunami source is somewhere in the northern tropical Atlantic Ocean or the Caribbean arc.

Layer F. 542-544 cm. Age: 794±83 B.C.

Layer F contains a carbonate fossil from the ocean, glasses of many types, mineral grains and an iron chloride spherule. The carbonate fossil is high in Mg, implying a source in shallow water at low latitudes (Fig. 17). The glasses range in composition from high-Na silicic glass to high-Mg basaltic glass (Fig. 18). There are mineral grains as well. Fig. 19 (A, B) shows a translucent pink grain with conchoidal fracture. It is most probably Mg rich garnet (pyrope) from a relatively high-grade terrane. Fig. 19 (C, D) is of a black glassy looking mineral with relatively high K, Al, and Si. It most resembles K-feldspar but the black appearance and minor Fe and Mg are typical of glass. Part of the grain is pulled back like the lid of a sardine can. The glass in Fig. 20 is basaltic glass. It has a pyrite spherule that is indenting and making a track in it. Fig. 21 shows a perfectly smooth FeCl spherule containing small amounts of Cr and Ni.

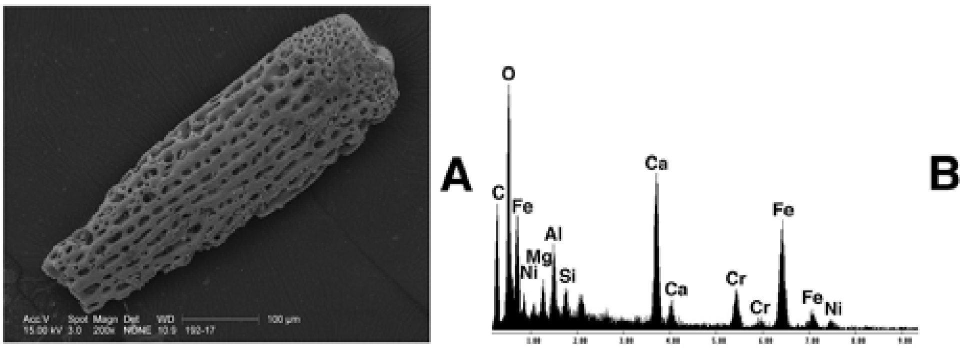

Fig. 17. High Mg carbonate fragment. A: SEM image of submarine fossil. B: X-ray analysis of surface of fossil near metal contamination from stainless steel sieve

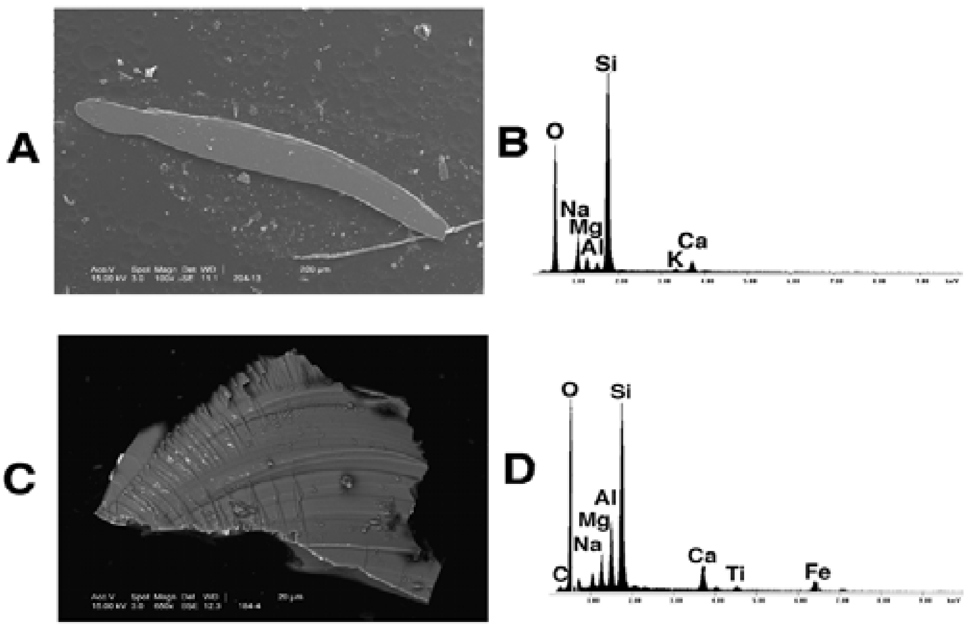

Fig. 18. Conchoidally fractured grains that appear to be glass. A: SEM image of optically clear glass shard. B: X-ray analysis of the composition of the glass shard. C: Optically clear greenish grain with conchoidal fracture and gouges. D: X-ray analysis of the composition of C

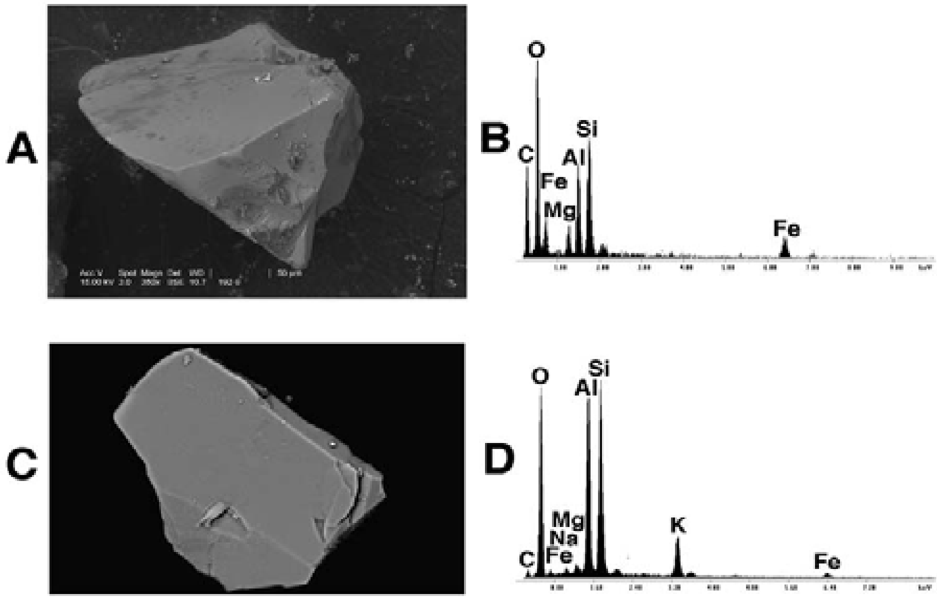

Fig. 19. Possible mineral grains. A: Optically clear pink grain with conchoidal fracture. B: X-ray analysis of the composition of the grain in A. C: Optically clear grain with section pealed back like sardine can. D: X-ray analysis of the composition of the grain in C

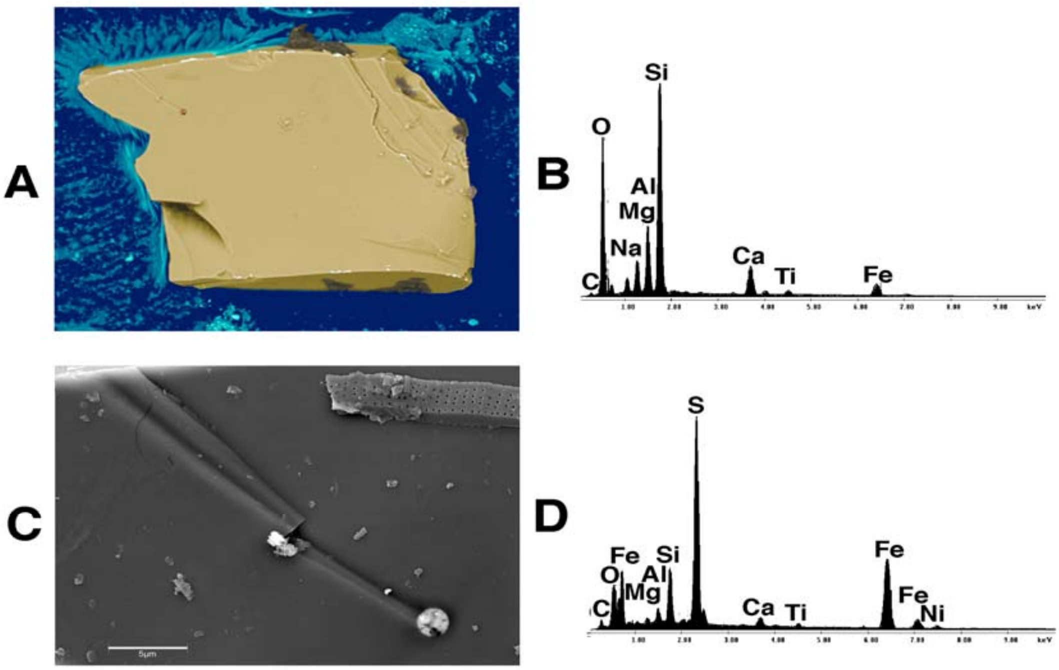

Fig. 20. Pyrite spherule indenting basaltic glass. A: SEM image of entire grain. Pyrite spherule is colored red. B: X-ray analysis of the composition of the glass. C: Close up of iron sulfide spherule indenting glass. The pyrite is following a single track. The offset of the track is an optical illusion. D: X-ray analysis of the composition of the spherule

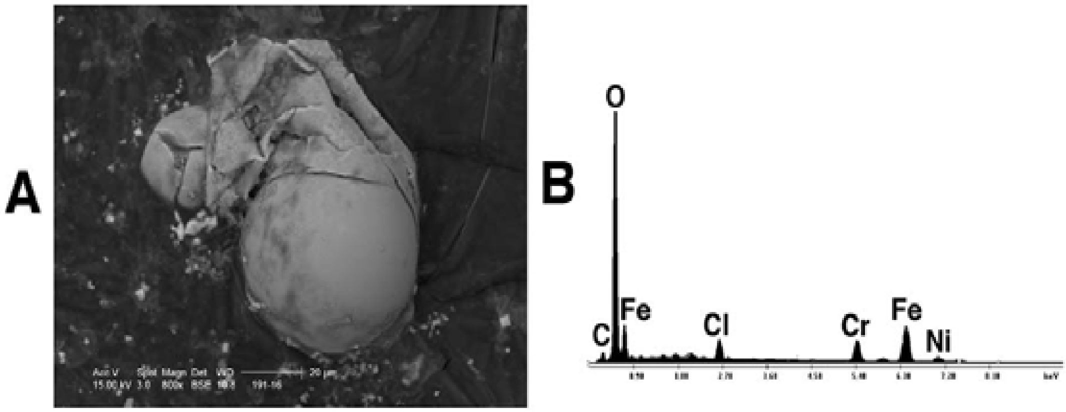

Fig. 21. Iron chloride impact spherule. A: SEM image of smooth, perfectly round iron chloride spherule. B: X-ray analysis of composition of the spherule. Note the Fe, Cr and Ni peaks

Discussion: Layer F

Many unusual features of this layer are most consistent with an impact event. Iron chloride is a common alteration product of meteoritic iron. However, an iron chloride spherule with a perfectly smooth surface cannot be a simple ablation product of a fireball or a small meteorite. Cosmic spherules do not contain large amounts of Cl. If the Cl was added by alteration in situ, the alteration should also have roughened the surface of the spherule. The Ni in the iron chloride spherule provides further evidence of an impact origin. The basaltic glass that is being indented by an iron sulfide spherule is not volcanic glass. The formation of an indentation track without breaking the grain or the spherule requires the indentor to have a very high speed. In addition, the iron sulfide spherule contains a small amount of Ni. As far as we know, this sort of feature has never been observed in volcanic ejecta. The K-rich grain that has been peeled back like the cover of a sardine can is also hard to explain with normal earth surface processes. However, the high speeds and shock deformation that accompany impacts can produce fluid like deformation of solid material. The most unusual features of this layer can all be interpreted as impact ejecta.

The layer also contains material that is geologically normal but is out of place in a fresh water bog. For example, Mg rich carbonates are typically found in tropical oceans, not in the ocean near New York City. The New York area has no active volcanoes, making the presence of fresh glass unusual as well. None of the fresh glass is vesicular. There is no pumice and the glass has highly variable chemistry. All of these features are most consistent with material transported to this location by an impact rather than a volcanic eruption.

There are several lines of evidence leading to the conclusion that the impact was under the ocean. First, there is the presence of a transported marine fossil from a tropical location. Second, an impact spherule composed of iron chloride would be most likely to form in an oceanic impact where there is an ample supply of Cl. We have never heard of anyone finding such a spherule before. As most impacts that have been studied are continental, this is consistent with our inferences about the oceanic origin of the iron Cl spherule.

There is one piece of data that seems at odds with an oceanic impact. This is the occurrence of a broken garnet grain of pyrope composition. This is the one grain that might be locally derived from the

Hudson Highlands or glacial debris. It has probably not been transported for a great distance, as it is not rounded and it has a very fresh broken surface. The fresh conchoidal fractures on the grain surface might be from frost weathering. Because, the origin of the grain of pyrope is equivocal, it cannot be used to infer the location of the impact source.

Conclusions-Layer F

Layer F most likely originated from an impact into the ocean between 30°N and 30°S, where calcareous organisms with high Mg contents are abundant. There are no known tsunami layers of this age in the Atlantic Ocean. The spectacular nature of the deposits suggests a large impact. The time series of tsunami activity from western Australia shows a peak at 785±100 B.C. [8]. The direction to the source for this tsunami is to the northeast of Australia. Thus, the most probable location of this impact is in the tropical Pacific Ocean. Because many of the grains we have found are larger than 150 micrometers in diameter, we use the data of [26] to infer that the impact source was within 9000 km of Black Rock Forest. This rules out an impact source in the western Pacific or the Tasman Sea.

We have found chevrons in Hawaii that point to a site to the northeast of the Hawaiian Islands. We interpret chevrons as tsunami deposits produced by point sources, i.e. landslides, impacts or volcanic eruptions. Chevrons cannot form as the result of a tsunami generated by a line source such as a large subduction zone earthquake. The chevrons we have found in Hawaii are the only chevrons in the Pacific that point to a possible tropical point source of tsunami. There are several sites along the coast of Baja California that have shallow carbonate platforms and thin sediment cover over basalt. These are our candidate source areas for the impact event. This source area would explain why we have such a spectacular deposit in North America.

Layer G. 562-564 cm. Age: 1082±99 B.C.

Layer G contains 6 shards of glass. None of the glass shards have vesicles and none have the appearance of volcanic glass. The most unusual of the glass shards is shown above. The surface of the glass contains three marine microfossils entombed in the glass. The microfossils have some relief and are not flat on the surface of the glass. Because the fossils appear like coccoliths, we infer they have been silicified as they were entombed in the glass. Coccoliths are normally composed of calcium carbonate.

Discussion: Layer G

So far as we know, no submarine volcanic eruption has ever been observed to produce silicified marine microfossils. Recent experimental work on impact ejecta from South America has found that organic matter can only be preserved in glass if temperatures are ~1600°C [23]. If temperatures are lower, the organic matter will burn up. We infer that the similar temperatures would be required to preserve silicified coccoliths. If so, the glass fragment above (Fig. 22) could only have formed during an impact.

There are no Holocene lavas extruded at temperatures above 1600°C. Thus, the most likely explanation is that the silicified coccoliths formed during a submarine impact.

Possible Correlation to Climate Downturns

Three of the seven layers in Fig. 22 have roughly the same age as prominent climate downturns (Fig. 23, Table 2). Layers D, C and G have ages that roughly match those of climate downturns at 41

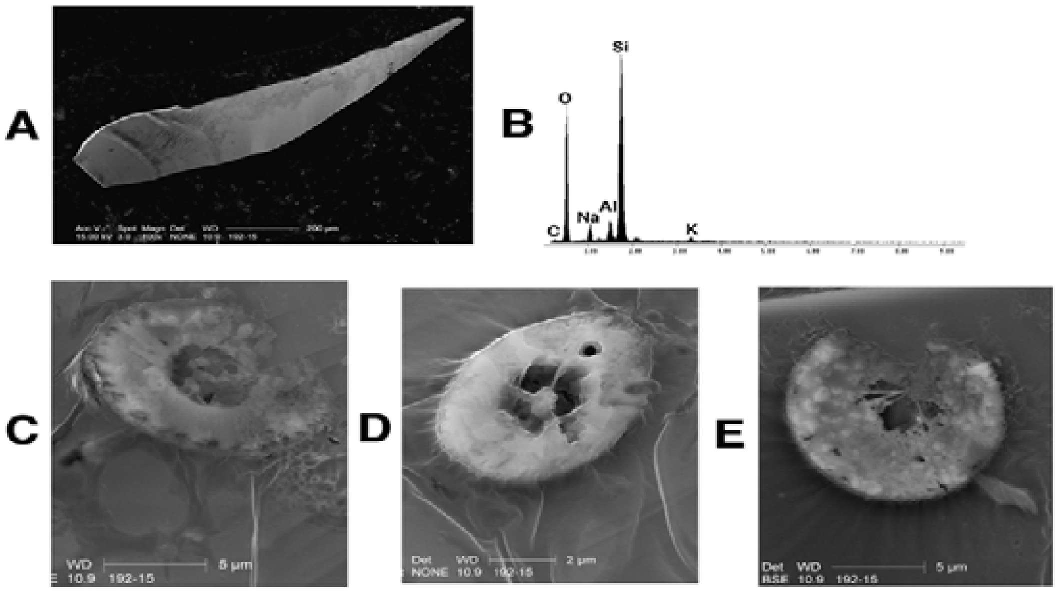

Fig. 22. Glass shard with embedded silicified coccoliths. A. SEM image of entire glass shard. B. X-ray analysis of glass shard. C, D and E. Embedded silicified cocoliths

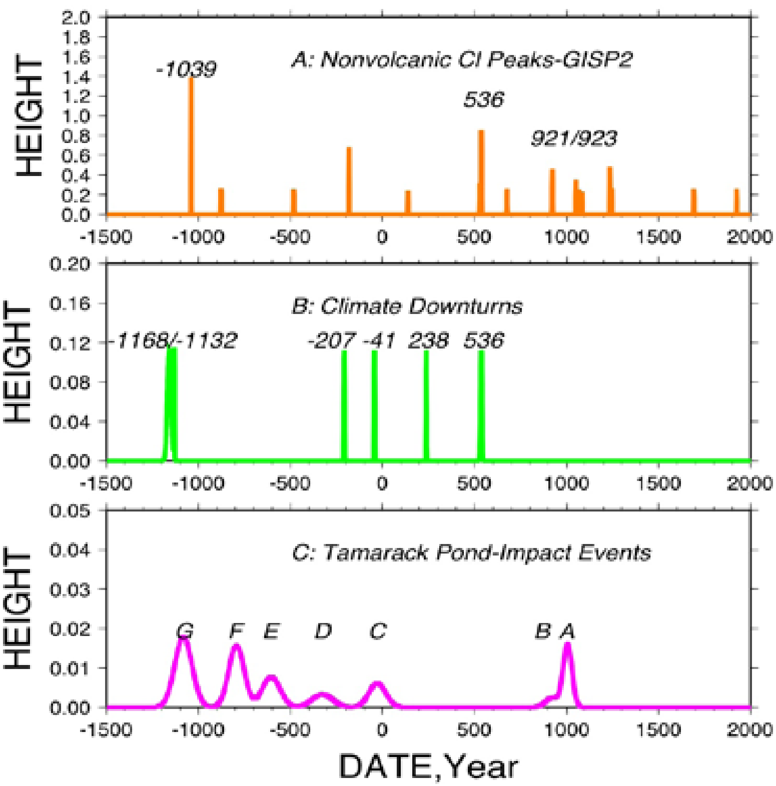

Fig. 23. Time series of impact events compared to nonvolcanic Cl anomalies and climate downturns. A: Nonvolcanic Cl anomalies in the GISP2 ice core. B: Prominent climate downturns proposed by Mike Baillie based on the analysis of tree ring records. All are proposed to have an extraterrestrial source. C: Discrete impact layers identified so far in the Tamarack Pond core

Table 2. Layers in Tamarack Pond Core vs. Climate Downturn and Tsunami Events

Layer Name	Age	Climate Downturn?	Regional Tsunami?
A	1006±67 A.D.	No	Yes, Atlantic
B	925±76 A.D.	No (nonvolcanic Cl)	No
C	28±92 B.C	Yes	No
D	327±113 B.C.	Yes	No (local tsunami)
E	606±97 B.C.	No	Yes, Atlantic
F	794±83 B.C.	No	Yes, Pacific?
G	1082±99 B.C.	Yes	No

B.C., 207 B.C. and 1132 B.C. However, much more work remains before any of these layers can be linked unequivocally to a climate downturn.

Layer B has an age that roughly matches nonvolcanic Cl anomalies at 921 and 923 A.D. in the GISP2 ice core. This is important because the largest nonvolcanic Cl anomaly in the last 2000 years is at 536 A.D. The nonvolcanic Cl anomaly at 536 A.D. corresponds to a time of greatly increased input of impact ejecta into the GISP2 ice core [2]. The increased input of impact ejecta matches the time of a dust veil event that lasted from March 536 until August of 537. Thus, at least one nonvolcanic Cl anomaly and climate downturn can be linked precisely to impact ejecta. The present data is intriguing but cannot prove that impacts produced the climate downturns at 41 B.C., 207 B.C. and 1132 B.C. In the short term, more work is needed to more fully characterize each layer in the Tamarack Pond Core and also to pinpoint the depths of maximum concentration of impact ejecta. In the long term, all of the layers must be located and precisely dated within ice core samples.

Relationship to Tsunami

The layers that we have not been able to relate to climate downturns or nonvolcanic Cl anomalies are those that have the same age as regional tsunamis. Two of the postulated tsunamis are in the Atlantic and might represent smaller impact events. If the third tsunami started in the eastern Pacific and reached Australia, it should have been quite large. We do not know why the third event did not produce a climate downturn. Perhaps it occurred in relatively deep water and produced less dust to cloud the atmosphere. Clearly the water depth of impacts is important. If we assume that most of these impactors are just barely big enough to produce a crater, an impactor that hits deep water should produce less atmospheric dust and more water vapor. A tsunami originating from a deep-water impact event will have a greater initial wave height and is more likely to travel long distances without significant attenuation. Thus, the inverse relationship we see between climate downturns and regionally significant tsunami makes sense in terms of the amount of dust generated by shallow water impacts compared to deep-water impacts. Because we infer a very high Holocene impact rate compared to the long-term rate of impacts, the simplest assumption to make is that most impactors are «small», just above the threshold size needed to generate widely dispersed atmospheric dust.

Further testing of the relationship to tsunami will require searches for impact ejecta within tsunami layers. We have found evidence of impact ejecta within a local tsunami layer in the Hudson River that is circa 300 B.C. [10]. This layer contains impact diamonds and shocked minerals. The impact ejecta were found in layers deposited below mean sea level. Particularly in the Atlantic, tsunami layers from bogs and marine cores need to be routinely examined for impact ejecta. Only then can we determine how many tsunami events are produced by impacts.

Summary of Results

The seven youngest layers in a bog core from Cornwall NY all contain exotic components that did not form in the Proterozoic age basement of Black Rock Forest. Six out of the seven layers contain material that is difficult to explain except with an impact event. The youngest layer, layer A, contains probable impact glass, an equatorial radiolarian, a probable impact spherule, and a glauconite fossil cast. It is also temporally associated with an ammonium anomaly in the GRIP ice core and tsunami deposits in Great Britain and the Caribbean. It may have a calendar year age of 1014 A.D., the age of the ammonium anomaly and the tsunami event in Great Britain. Layer B contains transported red coral and a grain with native Ni on its surface. Layer C contains glauconite rosettes, a fresh glass fragment, tiny Sn-rich silicate spherules, and titanomagnetite with odd craters on its surface. This layer may have a local source from a small impact or it may have a distal volcanic source. Layer D contains possible shocked quartz grains that must be further verified. One of the quartz grains appears to be associated with glauconite. This layer could have a local or distal source. Layer E contains a transported marine microfossil from the tropical ocean, a basaltic glass, and an albite feldspar or albite rich glass. It also contains a glassy grain with splashed-on Ni metal. All of these components suggest a tropical source. Layer E has the same age as tsunami deposits in Portugal and Curacao. It may have originated from an impact into the tropical Atlantic. Layer F contains a rich variety of material that is likely to be impact-related: an Fe chloride impact spherule with trace Ni, impact glass indented by a pyrite spherule with trace Ni, and numerous other glasses. It also contains a high Mg carbonate fossil that was transported from the tropical ocean. Based on its rich assemblage of material and data on point sources of tsunami in the Pacific, its probable source area is in the eastern tropical Pacific. Layer G contains silicified coccoliths entombed in impact glass. It most likely formed during a low latitude impact event. Most of our data suggests long distance transport of exotic material, in particular fresh glass, marine fossils, Ni rich material, and possible impact spherules. However, we have not yet identified unequivocal shocked minerals or impact diamonds in any of these layers in the Tamarack Pond core. This will be required to convince the mainstream impact community that we have found impact ejecta. Our results are tantalizing and exciting, but are still equivocal.

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Необычные частицы в пробах из Корнвала, штат Нью-Йорк – имеют ли они импактное происхождение?

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Мы обнаружили семь отдельных прослоек в пробах донных осадков из Корнвала, штат Нью-Йорк, расположенных около 80 км от Атлантического океана. Все прослойки пробы, кроме двух, содержали материал, который вряд ли является местным. В большинстве случаев этот материал в прослойках перенесен за тысячи километров от района их возникновения. Шесть из семи прослоек трудно объяснить, исключив импактный процесс. Если все эти прослойки получены от импактных воздействий в результате возникновения кратеров, то эти данные подразумевают очень высокие частоты импактных воздействий в период позднего голоцена. Кроме того, мы смогли связать две прослойки, содержащие частицы от импактных воздействий, с данными о цунами, которые охватывали Атлантический океан. Если это открытие подтвердится дальнейшими исследованиями, то это подразумевает гораздо большую опасность цунами в Атлантическом океане, чем сообщалось ранее.

Ключевые слова: скорость осадконакопления, транспорт наносов, анализ с помощью сканирующего электронного микроскопа (СЭМ), прослойка с включениями вещества импактной природы, гипотеза импактных воздействий в позднем голоцене, опасность цунами в Атлантическом океане.