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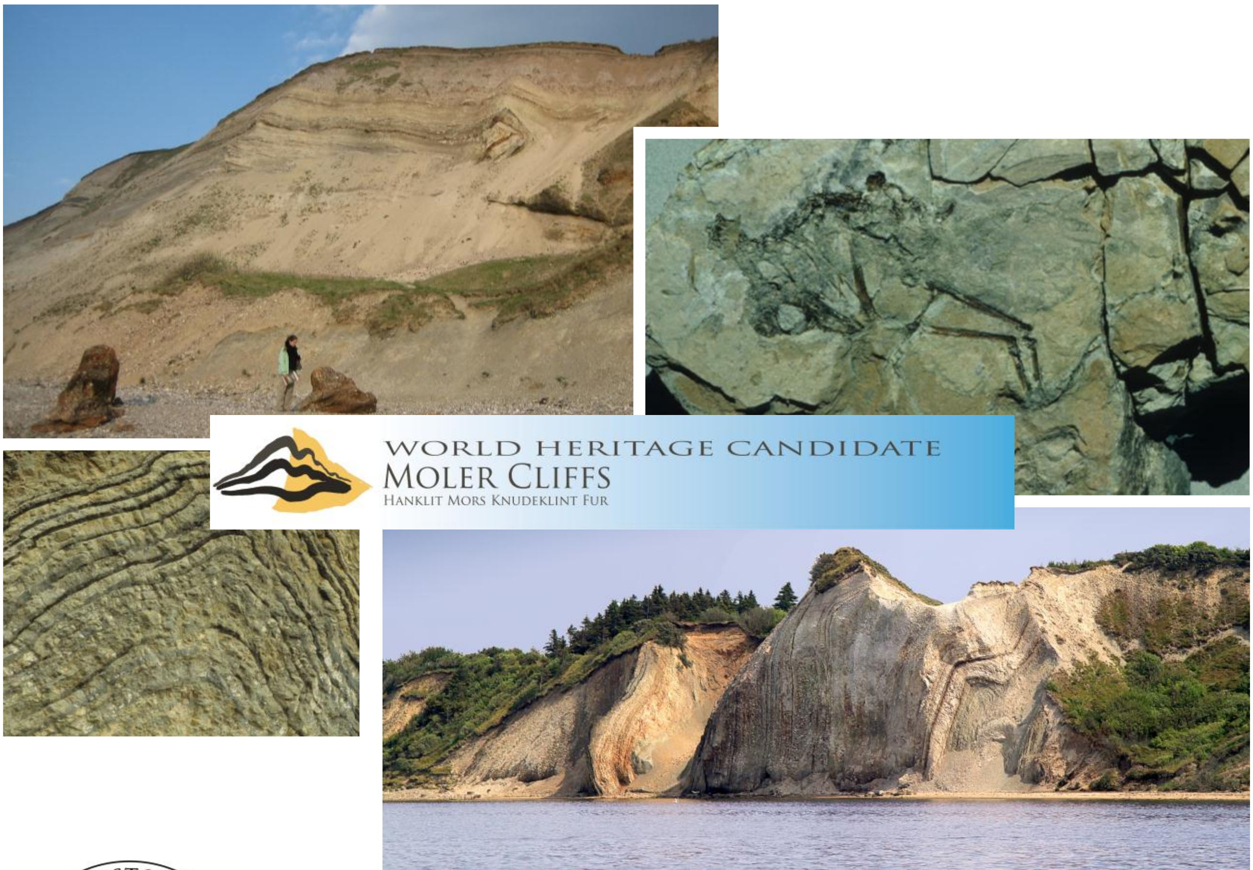

DE NATIONALE GEOLOGISKE UNDERSØGELSER FOR
DANMARK OG GRØNLAND, KLIMA- OG ENERGIMINISTERIET

Preface

In 2009 the Moler Cliffs were placed on the Danish list of tentative sites for the UNESCO list of World Heritage Sites. In the following years a description of the Moler Cliffs, their scientific importance and unique combination of earth-science elements, was prepared, in order to qualify a submission of the Moler Cliffs under natural criteria viii according to the Operational Guidelines. Two sites, Hanklit (Island of Mors) and Knudeklint (Island of Fur), are appointed as the main representatives of the Moler Cliffs, which aspire to be admitted to UNESCO"S list of World Heritage Sites. The two sites comprise a serial national property.

„Moler" is the local, Danish name for a marine Eocene diatomite, which is exposed in coastal cliffs in the western part of Limfjorden, northern Denmark. The Moler Cliffs expose sections through glaciotectonic complexes comprising pale yellow diatomite (Moler) interbedded with dark grey layers of volcanic ash and overlain by Quaternary sediments. The ash layers record the dramatic volcanic eruptions during the early break–up of the continents bordering the North Atlantic Ocean c. 56 Ma (million years ago).

The diatomite is an exceptional preservation lagerstätte for a range of Eocene fossils, including birds, turtles, insects, fish and plants. The palaeontological importance of the strata in the Moler Cliffs is that they were deposited in an environment, which preserved the fossils very well, hence the term „Fossil Lagerstätte". These fossils are significant because they represent faunas and floras documenting the responses to the brief greenhouse event termed the Paleocene–Eocene Thermal Maximum (PETM). The PETM occurred only 10 million years after the mass-extinction at the Cretaceous–Tertiary boundary.

The Moler Cliffs expose sections through glaciotectonic complexes characterized by folds and thrusts. These structures are enhanced by the black layers of volcanic ash interbedded in the pale yellow diatomite. The glaciotectonic deformation elevated the Eocene strata to their present position above sea level and created the hilly landscape, which is so characteristic of the moler area.

The Moler Cliffs are attractive to the public due to their scenic beauty as well as their unique features. The combination of sediments, ash layers, fossils and deformation structures is not known from other outcrops of Early Eocene strata. In addition the Moler Cliffs are of significant interest for scientists investigating the North Sea Basin and the North Atlantic Igneous Province.

The comparative analysis documents the unique features and scientific importance of the Moler Cliffs and concludes that the sites Hanklit and Knudeklint may be admitted to UNESCO"S World Heritage List under the criteria viii. The combination of three elements referring to criteria viii is considered important: (1) the property records an important geodynamic event, (2) the property includes a palaeontological site, and (3) the property display the unique framework of folds and thrusts created during glacial processes.

Dueholm Kloster, Nykøbing Mors, June 1, 2012……………………………………………………………

Per Noe
Project leader

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Introduction

Two outstanding Moler Cliffs, Hanklit on Mors and Knudeklint on Fur, have been selected as the serial national property to be nominated as a World Heritage Site. Additional cliffs with exposures of moler are found along the coasts of the islands Fur and Mors, as well as in Himmerland and Thy, respectively (see map Fig. 1). These supplementary localities add to the outstanding universal value of the Moler Cliffs.

Moler is a marine clayey diatomite, which was deposited in the eastern part of the North Sea during the Early Eocene, and is formally designated the Fur Formation. The formation is c. 60 m thick and contains 187 numbered layers of volcanic ash, as well as a wealth of terrestrial and marine fossils. O.B. Bøggild (1918) numbered the ash layers –39 to +140. Later field work has discovered a few additional ash layers: –18b, –19a, –19b, –21a, –21b –21c, –21d and –29a (Gry 1940, Larsen *et al*. 2003). The volcanic ash layers record dramatic eruptions during the early break–up of the Laurentian-Eurasian continental margins bordering the North Atlantic Ocean c. 56 Ma (million years ago). The volcanic glass, which is the main constituent of the ash layers, is very well preserved in the diatomite, which allows detailed investigations of the petrology of the ash layers. The volcanic ash layers are known from a large area, but are generally strongly weathered or devitrified.

It is no coincidence that both volcanic ash layers and numerous, well preserved fossils occur in the same diatomite succession. Diatoms are siliceous algae, and they were deposited on the sea floor in large quantities, which affected the chemistry of the bottom water conditions in two ways. The abundance of opal frustules from the diatoms resulted in a pore water chemistry, which protected the volcanic glass from devitrification. In addition the decomposition of organic matter from the diatoms resulted in a large consumption of oxygen from the bottom water. This led to anoxic conditions, which preserved dead animals as perfect fossils.

Regional geological setting and global correlation

The geological features to be observed in the Moler Cliffs (volcanic ash layers, marine and terrestrial fossil assemblages, as well as glaciotectonic structures) are determined by the geographical position of Denmark. Its geological setting is locally related to the North Sea Basin, which is a continental shelf basin developed as a tectonic depression between the British Islands and the continental northern Europe. The regional geological setting includes the geotectonic features such as the margin of the North Atlantic, and the mountains of Scandinavia, where the Scandinavian ice cap formed during the Quaternary.

The focus on this comparative analysis is global as regards the changes in fossil assemblages during and immediately after the PETM. The focus is on the northern hemisphere as regards the glaciotectonic complexes, as such complexes of Quaternary age are best known from the areas adjacent to the ice shields in Scandinavia and North America. The focus is regional as regards the volcanism linked to the opening of the North Atlantic Ocean.

Main criteria for the evaluation of sites to be compared with the Moler Cliffs

The Moler Cliffs are proposed in accordance with criterion viii: outstanding example representing major stages of Earth‟s history, including the record of life, and documentation of significant geological processes in development of landforms. The importance/significance of the Moler Cliffs should not be judged from a single criterion. Their unique features derive from the three main sources: I: the volcanic ash layers representing the Early Eocene continental break up preceding the formation of the North Atlantic Ocean, II: The fossil assemblage documenting the development of fauna and flora during and immediately after the PETM Greenhouse event, and III: The outstanding glaciotectonic complexes recording the ice advance dynamics in the second half of the Pleistocene period. The comparative analysis considers these three themes separately in the succeeding chapters.

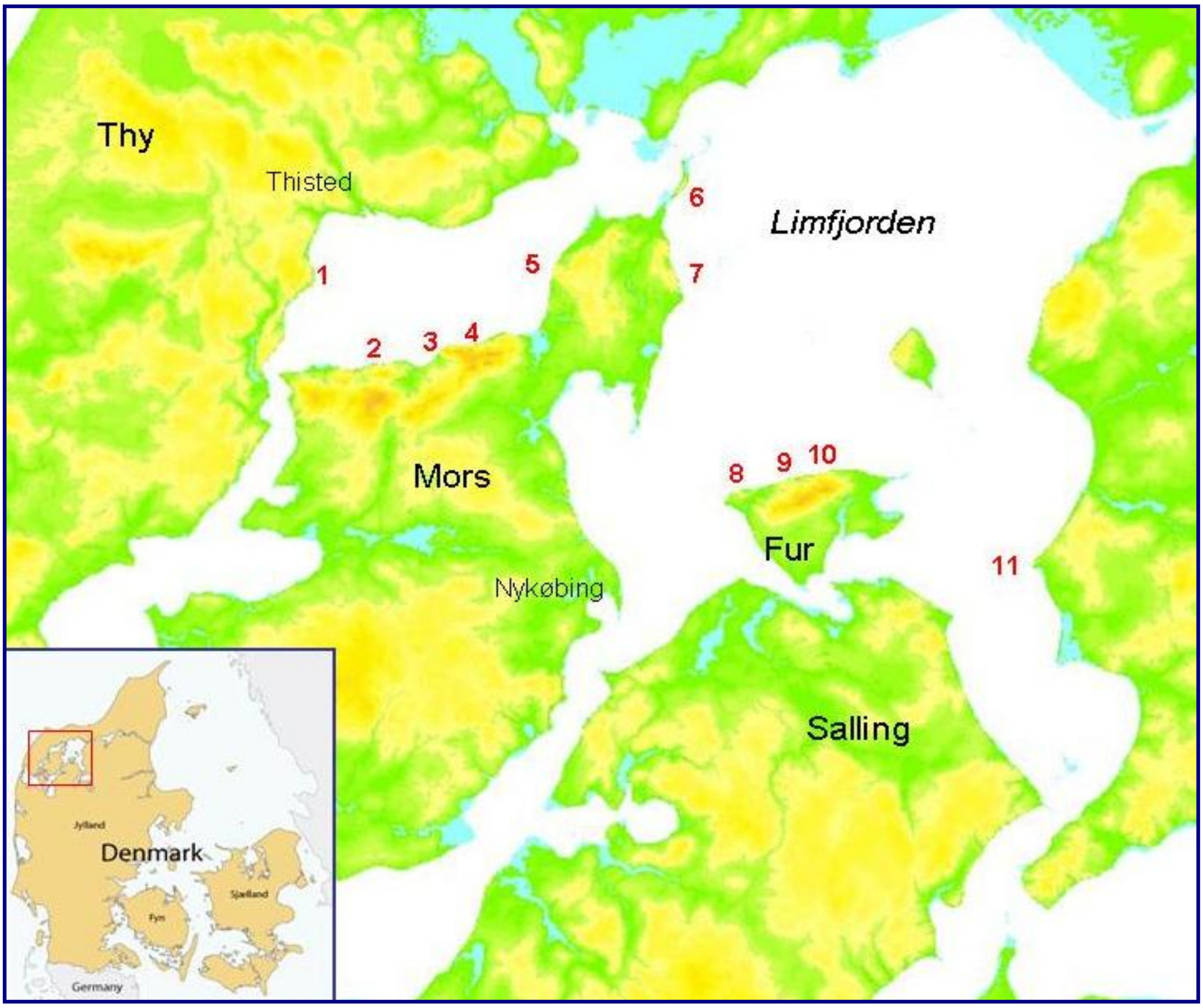


Figure 1. *Map of the moler cliffs in the western part of the Limfjorden. Number 3 is the location of Hanklit on the island Mors, and number 8 is Knudeklint on island Fur. To the west number 1 is the Silstrup Hoved cliff in Thy. Nnumber 2 and 4 are Svaleklit and Salgjerhøj, respectively west and east of Hanklit, and on the northernmost part of Mors number 5 is Skærbæk, 6 is Feggeklit, and 7 is Ejerslev Cliff. On Fur two cliffs are situated east of Knudeklit, namelig Stolleklint,9, and Østklint, 10. In Himmerland number 11 locates Ertebøl Hoved.*

The volcanic ash layers, evidence of the break-up of the North Atlantic – an important geodynamic event

The North Atlantic Ocean is relatively young and the initial formation of ocean crust commenced during the magneto-chron 24, 55–56 million years ago. At that time the North Atlantic igneous province (NAIP) comprised eruption centres in East Greenland, Scotland, Northern Ireland and along the shelf including the Shetland and Faroe Islands. The NAIP includes the basaltic and picritic lavas of Baffin Bay and West Greenland, the ≈7 km thick predominantly tholeiitic lava flow sequences of the Blosseville Kyst of East Greenland, the seaward-dipping reflectors of the Greenland and northwest European volcanic rifted margins; the Faroe Islands and the British Tertiary basaltic lavas, and the aseismic ridges connecting Iceland to either margin of the central Northeast Atlantic. The total area of NAIP is 1.3 x 10^6 km^2 (Eldholm & Grue 1994), and the total volume is 5–10 x 10^6 km^3 (Eldholm & Grue 1994, White & McKenzie 1989, Holbrook *et al*. 2001, Storey *et al*. 2007) (Fig. 2).

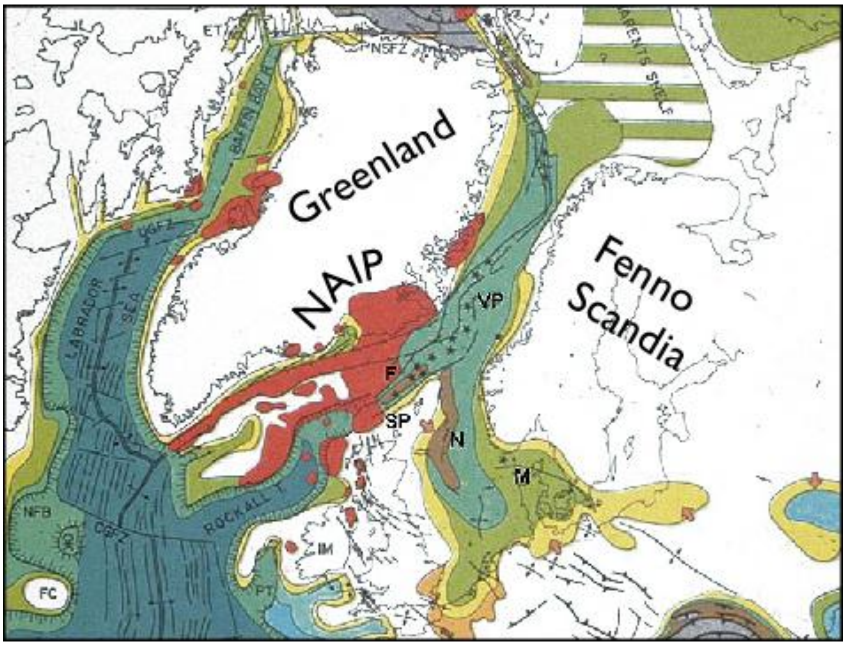


Figure 2. *Map of the North Atlantic Igneous Province (NAIP) indicated by red colour, and its relation to the generally setting of ocean, shelf areas and continent configuration in the earliest Eocene. F is the position of the Faeroe Islands, M is location of the moler area, N locates the North Sea, SP the Sheetland Plateau and VP the Vøring Plateau.*
From Ziegler (1988).

The initial activity of the NAIP consisted of continental volcanic eruptions (Larsen *et al*. 1999, 2003, Storey *et al*. 2007) and related rifting of the continental crust (Storey *et al*. 2007b, Hansen *et al*. 2009). Thick piles of lava flows accumulated in East Greenland and at the Faroe Islands. As the eruption sites moved seawards they were flooded, and the resulting explosive phreatic eruptions generated huge volumes of volcanic ash. The effect of intrusion of water into a crater was also seen during the eruption from Eyafjalla Jökull on Iceland, which generated sufficient amounts of volcanic ash to affect air traffic in Northwest Europe in 2010. The ash from the NAIP spread over large parts of northern Europe, and the ash layers have been recognized in numerous wells in the North Sea, in DSDP hole 550 southwest of Ireland, and at several localities in England, Austria, Germany and Denmark. After a few million years the main eruption centres were again above sea level and generated only small amounts of volcanic ash. Other parts of the Mid–Atlantic Ridge were located at so great water depths that no airborne volcanic ash was produced. The spreading of the North Atlantic Ocean is an ongoing process, and the UNESCO World Heritage property Surtsey in Iceland is a striking example of the continued volcanic activity associated with the Icelandic Hot Spot.

Geochemical analyses of the 187 numbered ash layers in the Fur Formation at Limfjorden and analyses of the known intrusions in the NAIP clearly indicates that the volcanic centers initially were distributed along a broad S-N trending zone, which eventually defined the continental margins. This is exemplified by the igneous complexes in East Greenland and Scotland. However, more "in-land" continental intrusions are known to have existed, such as the granitic intrusion on the island of Lundy in the Bristol Channel off the coast of SW-England. It has a geochemical composition similar to the rhyolitic ash layer –33 in the ash layer succession in the Moler Cliffs at Limfjorden. A similar correlation exists between ash layers –21 to –17 and the Gardiner igneous complex in East Greenland (Larsen *et al*. 2003, Storey *et al*. 2007).

Figure 3. *Ash layer ÷17 is a very characteristic bed, about 4 cm thick with a bright orange yellow colour. It is radiometrically dated to 55,5 Ma, and its source is interpreted to be from the peralkaline intrusions in East Greenland. It is in the Moler Cliffs located in the lower part of the Fur Formation. Note that the trowel for scale is placed at the ash layer ÷17 and that the diatomite change from being bioturbated, structureless below the ash layer to be finely laminated above the layer.*

An important marker bed for correlations within the NAIP is ash layer –17 (Fig. 2), which has a distinct mineralogical and geochemical composition (Pedersen *et al*. 1975, Larsen *et al*. 2003). Knox (1985) recognized ash layer –17 in several wells in the North Sea as well as on the Atlantic shelf (Goban Spur) and demonstrated its value for correlation and its wide geographical distribution. Ash layer –17 was subsequently recognized as interbedded with subaerial lava flows in the Skrænterne Formation in East Greenland (Heister *et al*. 2001, Storey *et al*. 2007). Radiometric datings confirm the correlation of the Skrænterne Formation Tuff with ash layer –17 in Northwest Europe. In East Greenland the volcanic succession shows that the Skrænterne Formation Tuff was erupted after the onset of massive flood basalt volcanism but within the error of estimated continental break-up time (Storey *et al*. 2007).

The ash layers in the Moler Cliffs are numbered from –39 to +140 (Bøggild 1918). Most of the ash layers with negative numbers represent the continental break-up. During the active rifting large volumes of ash were emanated, which are represented by the positive ash layers, most of which are of a tholeiitic basaltic composition. A notable exception is ash layer +19, which is 20 cm thick and andesitic (Fig. 4).

A surge in magma production, coupled with the eruption of mid-ocean ridge basalt (MORB)–like flows in the upper part of the Milne Land Formation flood basalts in East Greenland indicate that the early stages of „Rift to Drift" occurred at 55.5 ± 0.3 Ma (Storey *et a*l. 2007).Charles *et al*. (2012) dated PETM based on U–PB dating of zircon in tuff layer within PETM in the Longyearbyen section. ^{206}Pb/^{238}U date of 55.785 ± 0.034(0.066)[0.086] Ma which results in a numerical age of 55.728–55.964 Ma for the Paleocene/Eocene boundary.

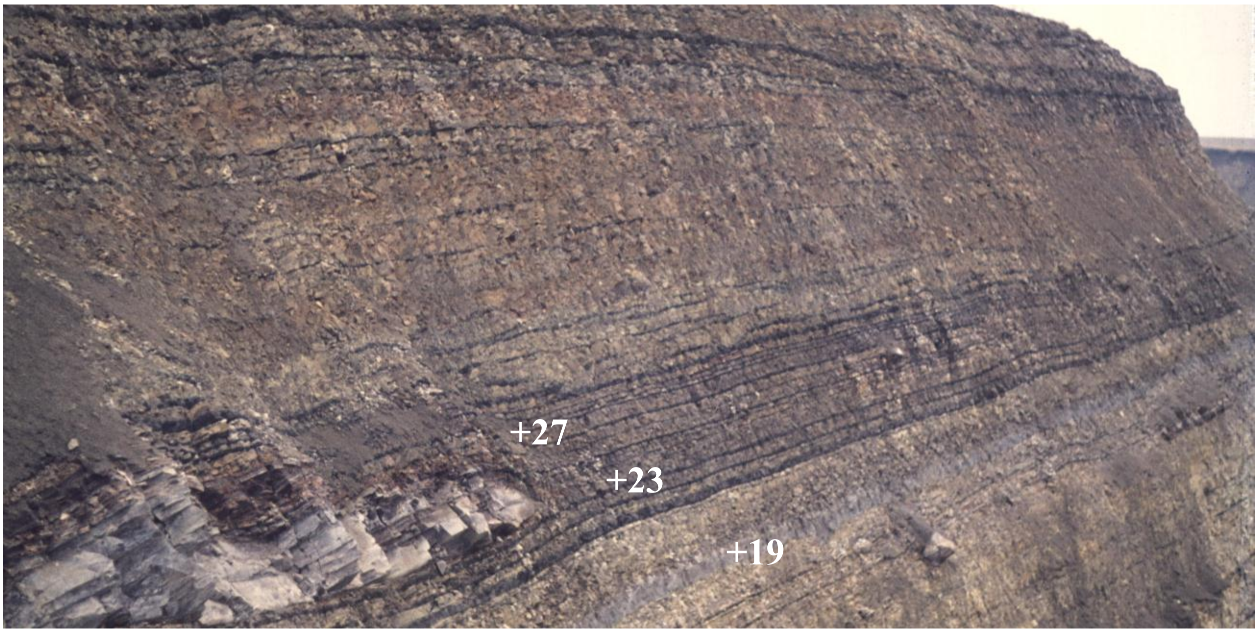


Figure 4. *In the succession of positive ash layers the ash bed +19 is the most outstanding with its grey colour and a thickness of 20 cm. Note the calcareous concretion between ash layers +23 and +27. In the calcareous concretions the preservation of the volcanic glass is almost perfect. The composition of ash layer +19 isandesitic whereas the blac ash layers above are all of tholiitic basaltic composition.*

PETM	Stratigraphic succession at Fur	East Greenland
	Ash layers in the Knudshoved Member of the Røsnæs Ler Formation. The volcanic glass is devitrified, chemical composition not known.	Continued upwelling of magma, either above sea level (Proto-Icelancis hot spot) or deep-water marine eruptions. Decreasing production of volcanic ash.
	Ash layer +19 is a thick layer of andesitic composition, which has been recognized regionally. It was dated to 54.09±0.14 Ma (Chambers *et al*. 2003).	
	Ash layers +1 to +140 of basaltic composition, similar to MORB–lavas (Larsen *et al*. 2003).	Upwelling of magma, eruption sites in shallow water, phreatic eruptions. Formation of oceanic crust began at 55.5±0.3 Ma (Storey *et al*. 2007).
	Ash layer –17 is a regional marker bed and has been dated to 55.12±0.12(Storey *et al*. 2007), calibrated to 55.39±0.12 Ma. Previously ash layer –17 was dated to 54.52 ± 0.05 Ma (Chambers *et al*. 2003).	Ash layer –17 is deposited in the Skrænterne Formation (subaerial lava flows). The tuff is dated to 55.6±0.1x Ma (Storey *et al*. 2007).
Upper boundary of PETM	Dinoflagellates and C–isotope values indicate the end of PETM close to **ash layer –19b**	Rømer Fjord Formation
	The lower part of the Fur Formation (with **ash layers –33 to –19b**) was deposited during PETM	Geike Plateau Formation
Basis of PETM dated as 55.93 Ma (Westerhold *et al*. 2007)	Top of Stolleklint Ler located between **ash layers –33 and –34**.	
	Basis of PETM corresponds to basis of Stolleklint Ler, occasionally exposed west of Stolleklint	
The P/E boundary dated as 55.827 ±0.086 Ma or 55.831 ±0.086 Ma (Charles et al. 2012).		
		Milne Land Formation. The upper part of the formation comprises Fe-Ti basalts and MORB-like flows, reflecting the early stage of „Rift to Drift"
		Nansen Fjord Formation

Table 1. *PETM was a global greenhouse event defining the Paleocene/Eocene boundary. In the Moler Cliffs the Stolleklint Ler and the lower part of the Fur Formation was deposited during the PETM. The table shows the stratigraphic setting of PETM and its position relative to the sedimentary succession in the Moler Cliffs represented by the outcrops on Fur.The Moler Cliffs represents a distal position relative to the source of volcanic ash. For comparison the right column indicates the contemporaneous strata deposited in a proximal position, namely East Greenland. In sedimentary successions the PETM is identified by negative C–isotope values, high TOC values and the abundant occurrence of the dinoflagellate Apectodinium.*

The Paleocene-Eocene Thermal Maximum, PETM

The Paleocene-Eocene Thermal Maximum (PETM) is an extreme, global greenhouse event, which marks the beginning of the Eocene Epoch. It lasted for less than c. 200,000 years (Röhl *et al.* 2007; Westerhold *et al.* 2009; McInerney & Wing 2011) and is recognized worldwide as a geochemical anomaly (a C-isotope excursion) in both terrestrial and marine deposits. This anomaly has therefore been selected as the Paleocene/Eocene boundary (Aubry & Ouda 2003, Gradstein *et al*. 2004). The base of PETM (and of the Eocene) has been dated to 55.9 Ma (Westerhold *et al*. 2009).Fossils of marine benthic foraminifera have recorded the temperature through $\delta^{18}O$-isotopes from their shells, indicating a temperature increase of ocean bottom waters of 5-7 °C at high latitudes and 4-5 °C at mid-level latitudes (Schmitz *et al.* 2004; Gingerich 2006). Temperatures remained high during the following million years of the „Early Eocene Climatic Optimum" (Zachos *et al.* 2001).

In Denmark the base of PETM corresponds to the base of the Stolleklint Ler, a dark grey laminated mudstone, while the upper, gradational, boundary of PETM is located within the lower part of the Fur Formation (Table 1). The uppermost part of the Stolleklint Ler is exposed in Knudeklint, and more exposures may be found at Stolleklint, one of the Moler Cliffs on the north coast of Fur. The Stolleklint Ler and the Fur Formation preserve diverse and abundant fossil fauna and floras from the PETM and the period immediately after. The relationship between PETM and the succession of volcanic ash layers in the Moler Cliffs is shown in Table 1. The lithostratigraphic correlation of formations at the Paleocene/Eocene transition is listed in Table 2.

Causes for the PETM

PETM was probably triggered by greenhouse gases released during the intense igneous activity linked to the opening of the North Atlantic. This event coincides with palaeomagnetic anomaly C24r (Larsen *et al.* 2003). It has been suggested that the gases generated by magma interaction, mainly sill intrusions, with basin-filling carbon-rich sedimentary rocks were the source to the greenhouse effect, although the detailed mechanisms and contributions are still discussed (Svensen *et al*. 2004, Storey *et al*. 2007, McInerney & Wing 2011).
The PETM is not accompanied by any significant mass-extinction (McInerney & Wing 2011).

Figure 5. *The heterotrophic dinoflagellate Apectodinium is a significant microfossil appearing during the Paleocene/Eocene Thermal Maximum about 55.8 Ma ago. The size of the species is ca. 100 µm in lengt. Photo Claus Heilmann-Clausen.*

Chronostratigraphy Series	Stage	Biozones P	NP	Danish Basin NW	SE	North Sea Basin	London & Hampshire Basins	Mons Basin	Paris Basin
Lower Eocene (*pars*)	Ypresian	P6b	11	Røsnæs Clay Fm.		Horda Fm.	London Clay Fm.	Kortrijk Fm.	Epernay Fm.
						Balder Fm.			
	Sparnacian*	P6a	10	Fur Fm. (A)	Ølst Fm.		Harwich Fm.		
		P5		CIE	(A)	Sele Fm. (A)	Woolwich & Reading fms. CIE (A)	Tienen Fm. CIE (A)	Soissonnais Fm. (A) Vaugirard Fm. Mortemer Fm. CIE (A)
Upper Paleocene (*pars*)	Thanetian		9	Østerrende Clay*		Lista Fm.	Upnor Fm.	Bois Gilles Fm.	Bracheux Fm.

Table 2. **L***ithostratigraphic correlation and age of geological formations at the Paleocene/Eocene transition in the various Europe. Shaded areas indicate hiati; Fm= Formation;* (**A**)*= Apectodinium acme present;* **CIE***= Carbon Isotope present; *= informal units. Compiled from Ellison et al. (1994, 1996, Ali & Jolley (1996), Mitlehner (1996), Schmitz et al. (1996), Heilmann-Clausen & Schmitz (2000), Smith (2000), Aubrey et al. (2005), Schiøler et al. (2007).*

Significance of the earliest Eocene fossil records

Coincident with, and probably related to the PETM, are several turnovers in the global flora and fauna, marine as well as terrestrial, and documented by fossils worldwide (Kelly *et al*. 1996, Crouch *et al*. 2001, Gingerich 2006, McInerney & Wing 2011). Turnovers represent relative changes in faunal and floral composition and relative abundance of taxa, as well as their evolutionary rates, where new taxonomic groups appear and flourish, while old groups are replaced or diminish in importance. The only major marine extinction event at the PETM resulted in the extinction of 50% of benthic foraminifera species (Kennett & Stott 1991).

Microfossils worldwide record a massive turnover among planktic foraminifera and dinoflagellate species. Significantly, an almost global abundance peak and great expansion of geographic range of the heterotrophic dinoflagellate *Apectodinium* has been recorded. This biostratigraphic event is termed the "Apectodinium acme" and its duration is used to constrain the PETM event (Kelly *et al*. 1996, Crouch et al. 2001, McInerney & Wing 2011). Terrestrial biodiversity was also afflicted by the rapid global warming. Fossil and geological evidence from around the world indicate the PETM is marked by a brief drying event and increased seasonality recorded by fossil plants, after which wetter conditions reappeared (McInerney & Wing 2011). Some mammal groups went extinct but three other mammal groups; artiodactyls, perissodactyls and primates (:APP taxa), appeared suddenly and simultaneously in North America and Asia at the initiation of the Eocene Epoch (Gingerich 2003, 2006; McInerney & Wing, 2011). The same pattern was recovered in Europe. Here the appearance of the APP taxa coincides with extinctions among multituberculates and condylarths (Legendre & Hartenberger 1992).

Interestingly, detailed fossil records may also reveal a physiological response to the PETM warming. There is evidence of concurrent dwarfing among unrelated mammal groups, and most early representatives of the above-mentioned APP taxa were small. The cause of this "dwarfing" is currently unknown, but it has been speculated to be the result of the increased levels of atmospheric CO2, which would have lowered the nutritional value of plants and limited the size of herbivores. It has been further proposed that the dwarfing process could have increased the rate of evolution of mammals, through an evolutionary „bottleneck", facilitating the rapid evolution and speciation of the APP taxa in a few thousand generations (Gingerich 2006).

Significance of the glaciotectonic complexes formed during the Pleistocene glaciations

The dominant impact during the Pleistocene period is the repeated cycles of glaciations. These glaciations had a dominant influence on the formation of the landscape on the northern hemisphere. In the mountainous areas the accumulated ice spread towards the lowlands resulting in gletscher erosion of the mountains creating their peaked topography. In the lowland the eroded material accumulated, and when the ice advanced over the lowlands the landscapes were modulated to form the characteristic glacial geomorphology. The most scenic element of this geomorphology is the ice-shoved hills consisting of a system of arc-formed composite ridges (Aber & Ber 2007). The ridges were formed during proglacial thrusting of the bedrocks in front of the advancing ice margin. The morphology of the hills indicates the direction of the push from the ice margin. However, the ice-shoved hills do not generally represent the stationary line of the ice sheet, i.e. the line along which the ice terminated and from where it finally melted back. The up-thrusting of the ridges were the result of the forces impacted on the deposits in the foreland, when the ice was still advancing and consequently had the greatest power of deforming the proglacial beds (Fig. 6). The framework and internal structure of a composite hill system is referred to as a glaciotectonic complex (Pedersen 2005).

Figure 6. *A glaciotectonic complex is formed by up-thrusting of the ridges composed by the deposits in the foreland. In the present example from Northeast Greenland (Caroline Mathildes Alps) the ice is still advancing and deforming the proglacial beds.*

The maximum extend of the ice sheets in North America and Europe are mapped out on the basis of the distribution of the tills from the various ice sheet advances. During the Pleistocene period the duration of the ice ages increase coinciding with the pattern of the Milankowitch cycles. In the middle of the Pleistocene (1.2-0.8 Ma) the 100 ka starts to dominate, which caused cold periods to be hard enough for big continental ice sheets to build up (Ehlers et al. 2011, Pedersen 2012). This is regarded to be the reason for the former ice sheets in Elsterian and Saalian to have had the largest extend on the Laurentian and Eurasian continents (Figs 7 and 8). However, the impact of the last Weichselain (Wisconsian) ice age is much more dominant, in particular the deformations related to the ice advances taking place during the Last Glacial Maximum (30-20 Ka).

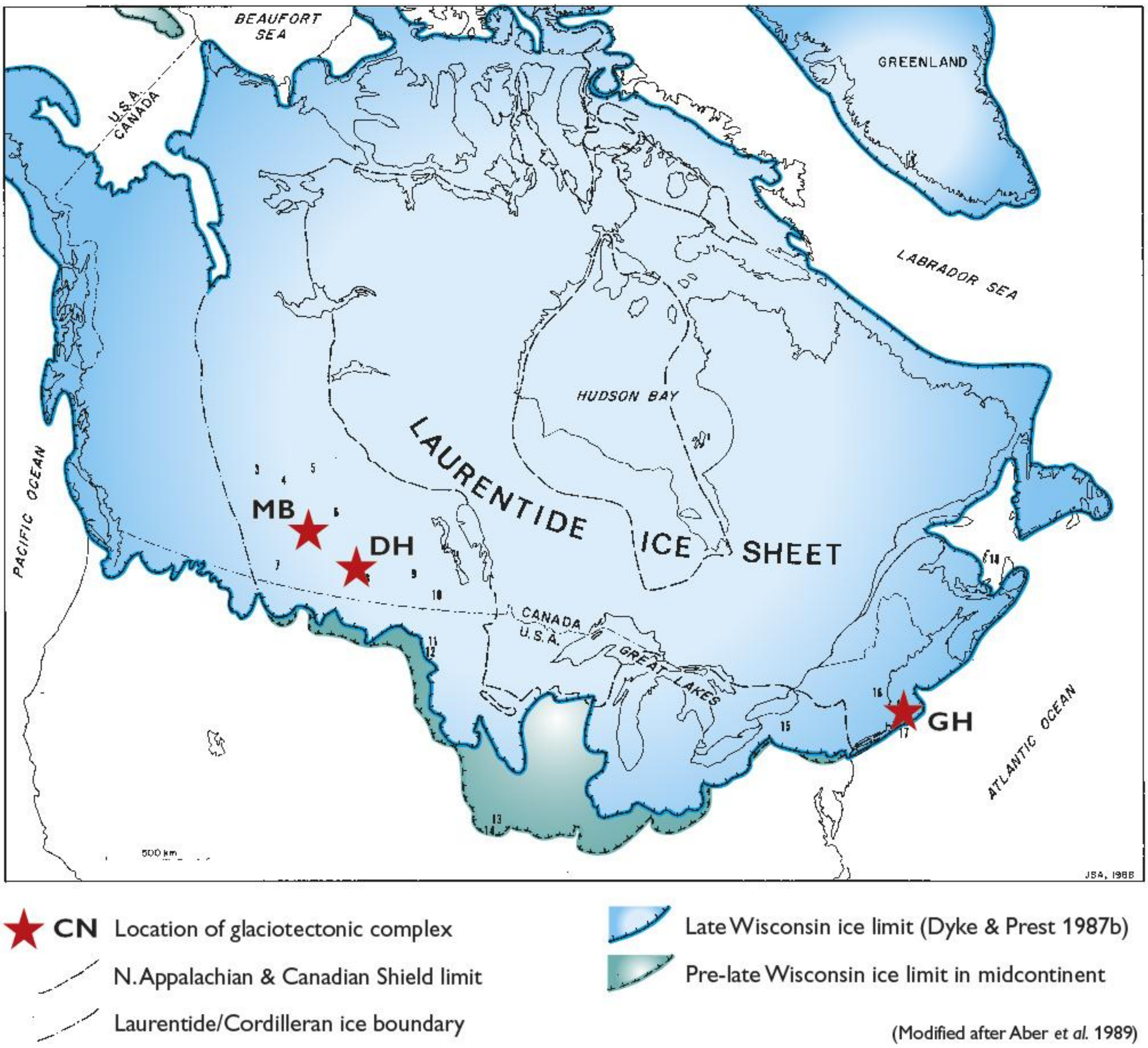
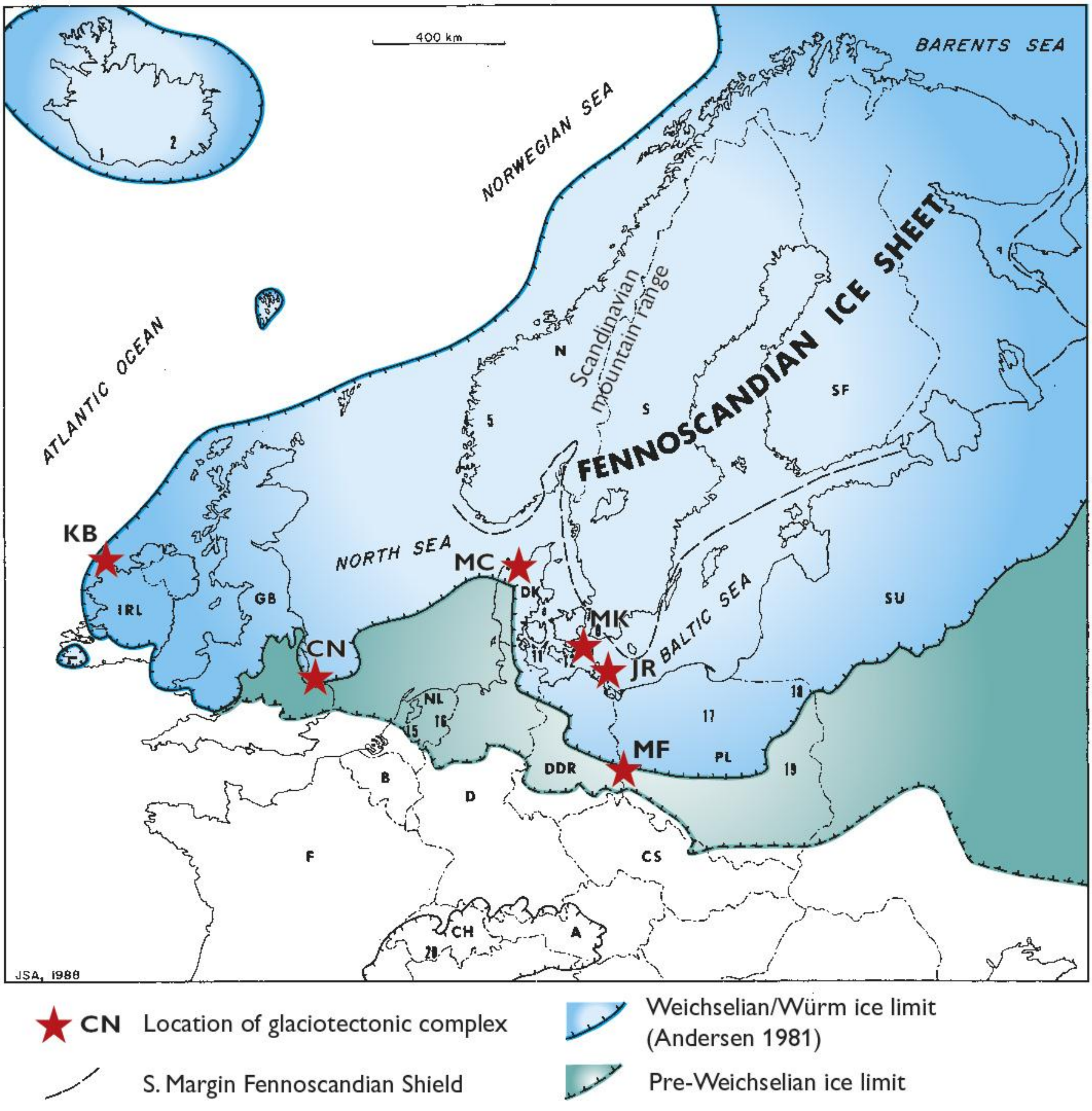


Figure 7. *Map of the ice coverage in North America during the Pleistocene glaciations. The sites of glaciotectonic complexes focused on in the comparative analysis are marked by asterix with the following annotaions MB= Mud Buttes, DH=Dirth Hills and GH=Gay Head.*

The moler cliffs at Limfjorden have all been affected by glaciotectonic deformations. If the Fur Formation had not been glaciotectonically up-thrust it would still have been situated below the surface and only known from well record. However, the internal architecture of the glaciotectonic complexes is a fascinating subject, which has not yet been represented as an UNESCO World Heritage Site. Attention is thus paid to this special type of natural property to be considered sufficient important to be nominated to the list of candidates.



(Modified after Aber *et al.* 1989)

Figure 8. *Map of the ice coverage in Northern Europe during the Pleistocene glaciations. The sites of glaciotectonic complexes focused on in the comparative analysis are marked by asterix with the following annotaions KB= Killala Bay, northwestern Ireland; CN=Cromer, Norfolk northeast coast; MC=The Moler Cliffs Hanklit and Knudeklint, northern Denmark; MK= Møns Klint, southeastern Denmark; JR=Jasmund.east coast of the German island Rüge; MF= Muskauer Faltenbogen at the southern part of the boundary between Germany and Poland.*

Assessment criteria

The comparative analysis aims at verifying the quality of the proposed property. The Moler Cliffs constitute a serial national property, and the cliffs and the geological formations possess the unique quality of being of poly-scientific value within the branch of earth sciences. There are no geological settings in the world, which contains the same combinations of earth science aspects ranging from the production of marine diatoms over preservation of volcanic ash layers documenting a large scale geotectonic event, an exeptional record of terrestrial fauna and floras mixed with the well preserved representatives of the life in the sea, to the fascinating evidences of the landscape creation in the formerly glaciated land areas of the northern hemisphere. It has thus been necessary to prepare the comparative analysis within three separate fields: the Early Eocne volcanic ash layers, the record of the earliest Eocene life evolution, and finally the structural geology of glaciotectonic complexes. A number of other fields might have been suggested, for example comparative sites with clayey marine diatomites or occurrences of crystal pseudomorphs after ikaite (impressive crystal rosettes of calcium carbonate). However, the three fields suggested are the important identities that place the Moler Cliffs in focus as a universal geoscience property.

Assessment criteria for evaluating Early Eocene ash layer sites

The property, consisting of the Hanklit and Knudeklint Moler Cliffs, is of universal value due to the ash layer record, which documents the development of the North Atlantic Igneous Province in the Early Eocene. The property to be nominated meets three of the thirteen themes proposed by Dingwall *et al*. (2005):

- The site provides evidence of the igneous development that records the onset of continental break-up and initiation of sea floor spreading (theme 1)
- The volcanic ash layers are clearly identified and represent a continuous succession mirroring the activity of a volcanic province (theme 2).
- The stratigraphy of the site is well documented (theme 4)

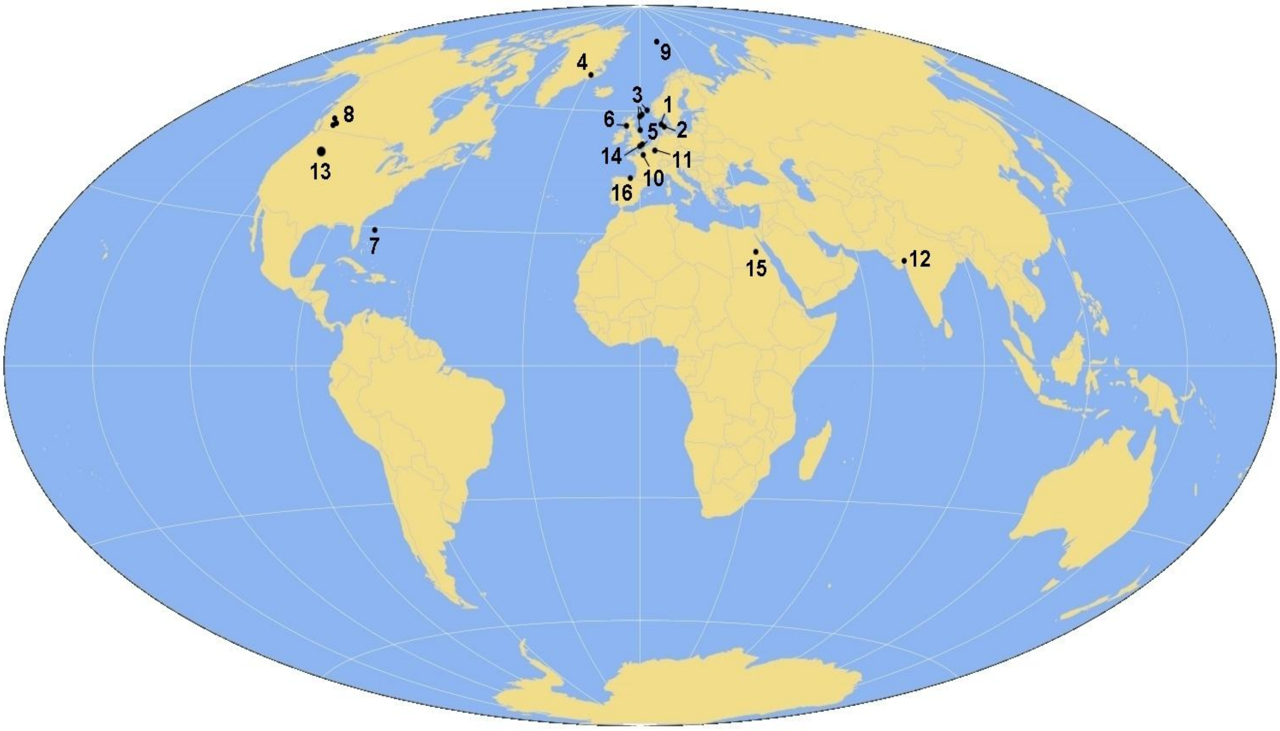


Figure 9. *World map showing Early Eocene ash layer or fossiliferous localities included in the comparative analysis. 1: Fur Formation, 2: Ølst Formation, 3: North Sea boreholes, 4: Skrænterne Formation, 5: Harwich Formation, 6: Isle of Rùm, 7: Blake Nose, 8: Kamloops Group, 9: Frysjaodden Formation, Svalbard, 10: Soisonnais Formation, 11: Tienen Formation, 12: Cambay Shale Formation, 13: Willwood Formation, 14: Woolwich Formation, 15: Esna Formation, 16: Zumaia deposits (Map from freeworldmaps.net).*

Consequently the following five criteria are suggested as important in the comparative analysis:

1. The succession should be continuous
2. The geochemistry of the volcanic ash layers should be documented and described in sufficient detail to allow comparison with volcanic rocks or other ash layer successions
3. The volcanic ash layers should represent original air-borne tephra, which has not been redeposited in the sedimentary environment
4. The volcanic ash should be of earliest Eocene age
5. The locality with volcanic ash layers should be accessible and well exposed along a sustained outcrop, such as a coastal cliff, a river side, a protected road cut, a reclaimed pit with cross-sections protected by legislations or a similar accessible locality.

The volcanic ash layers exposed in the Moler Cliffs at Hanklit and Knudeklint are described and compared to a number of Early Eocene ash layer successions. These are presented in Table 3 and described in the paragraphs below.

Locality	Lithostratigrph	Country	No. layers	Original tephra	Redepos.	Chem	Sediment	Age	Access.	Importance
Moler Cliffs Hanklit Knudeklint	Røsnæs Clay Fm Fur Fm Ølst Fm (Stolleklint Clay)	DK	187	Well reserved	No	Yes	Diatomite, Laminated, Marine w. fossils	Earliest Eocene	yes	Large
Ølst clay pit Road-cutting at Ølst	Ølst Formation	DK	187	Poorly preserved	No	??	Clay	Earliest Eocene	yes	Stratigraphic
Herne Bay	Oldhaven beds	UK		Mostly altered	No				yes	Stratigraphic
	Harwich Formation	UK						Earliest Eocene	yes	
Wrabness	Harwich Formation	UK	44	Completely altered Montmorr.					yes	
Walton-on-the-Naze	Harwich Formation	UK							yes	
Cores in North Sea	Balder Formation?	UK	>200					Earliest Eocene	no	Scientific
Cores in North Sea	Balder Formation Sele Formation	Norway	>400					Earliest Eocene	no	Scientific
Gronau Nunatak	Skrænterne Fm	East Greenland						Earliest Eocene		
Rum	Rum central igneous complex	Scotland UK	Few, Discon-tinuous		no	Rhyoda citic		?	yes	Local, unlikely to have a potential for regional correlation
Blake Nose off Florida	radiolarian ooze, well-preserved tests.	USA	>50,few mm to 5 cm thick	Largely unaltered	yes volcaniclastic turbidites	Dacitic rhyoda-citic	Hemipelagic, calcareous oozes, chalks, and marls	Eocene	no	
Horsefly outcrop	Kamloops Group	Canada BC	thin	?	?		Laminated Diatomaceous, Lacustrine w. fossils	Early Eocene, EECO, slightly younger than the Fur Fm	Large?	

Table 3. *List of outcrops with volcanic ash layers of earliest Eocene age.*

Assessment criteria for evaluating the Early Eocene fossil assemblages

Fossil sites and geological formations meeting the main criteria

In order to properly understand the biotic changes, which the global ecosystems underwent during the PETM global warming event, it is necessary to find geological sections and formations, which preserve and record aspects of biodiversity before, during, and in the immediate aftermath of the event. Additionally, fossils must be present in abundance and their preservation must be good enough to allow clear taxonomic identification. Finally, the formations should record as broad a biodiversity as possible, including micro- and macrofossils, flora and fauna, as well as terrestrial and/or marine biotas. Additionally, the sections and formation chosen to represent may have the characteristics of a *Konservat-lagerstätte*. Usually, only the hard parts of living organisms such as shell or bone are preserved as fossils. Soft tissue, such as muscle, skin, feathers or fur rots away or dissolves before it can be preferred. However, *Konservat-lagerstätte* represents unique depositional environments, where exceptional conditions have resulted in the preservation of soft tissue from fossils (Seilacher *et al.* 1985). As *Konservat-lagerstätte* also preserve the remnants of completely soft-bodied animals, plants and the soft tissue of other groups, these have proven exceedingly important in the understaidng of the evolution and history of life on Earth. Examples of *Konservat-lagerstätte* which have been inscribed as UNESCO World heritage sites are the Burgess Shale (part of the Canadian Rocky Mountain Parks world heritage site), which preserve 540 million-year-old soft bodied organisms; Miguasha National Park site in Canada with 370 million-year-old-fossil fishes documenting the ancestors of land-living tetrapods; and the Messel Pit site in Germany, which preserves an exceptional snapshot of terrestrial biodiversity during the middle of the Eocene epoch, 47 million years ago.

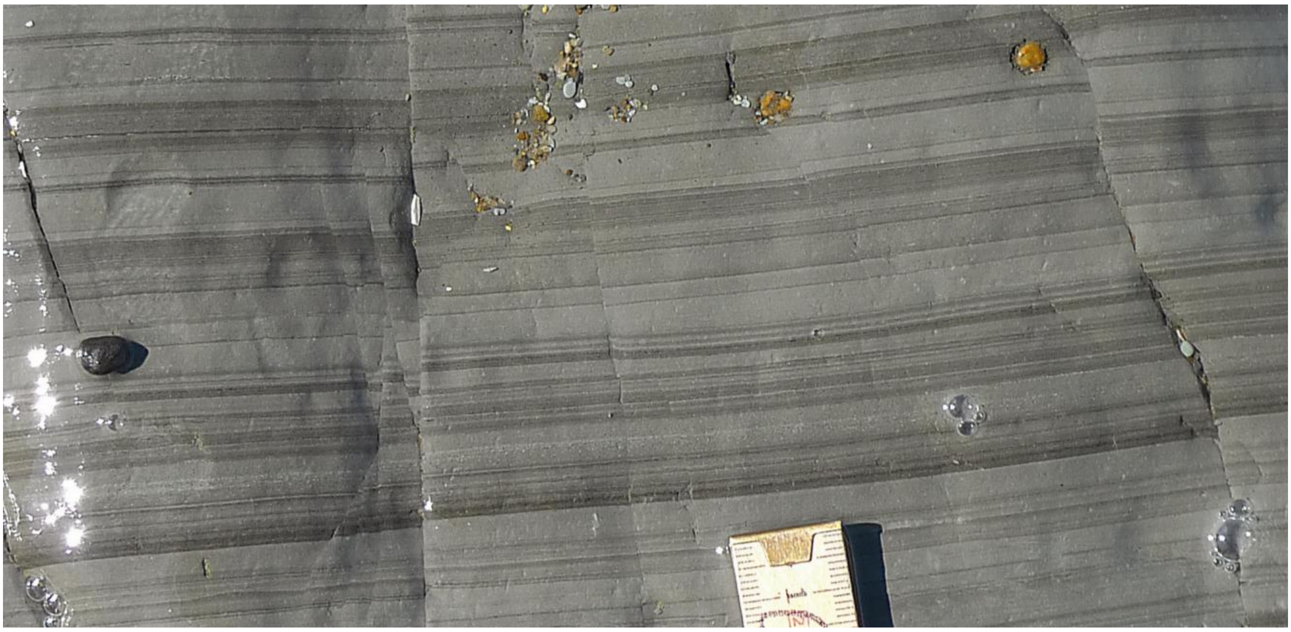


Figure 10. *The finely laminated clay representing the PETM unit at the north coast of the islandFur. Photo C. Heilmann-Clausen.*

As studies indicate that evolution and faunal turnover was extremely rapid during the PETM (Gingerich 2003, 2006), the comparative analysis is only interested in localities that record the environment during and immediately after the PETM event. Therefore, the comparative “time window” will be narrowed to the few million years immediately after the event. Thus only geological sites and formations, which have been stratigraphically correlated to marine plankton microfssil zones P5-P6b; marine calcareous nannoplankton zones NP9-10; European Palaeogene mammal fossil zones MP 7; Bumbanian Asian Land Mammal Age; early Wasatchian North American Land Mammal Age; or the informal “Sparnacian” European chronostratigraphic stage.

The property to be nominated for documenting the record and evolution of life during and immediately after the PETM should cover two of the thirteen themes proposed by Dingwall *et al.* (2005): It must be a stratigraphically well-constrained formation (theme 4) (Fig. 9) preserving and documenting the history of life through an abundant and diverse fossil content (theme 5). Therefore, the following three main criteria for the comparative analysis are suggested:

1. The formation shall be stratigraphically well-constrained and include evidence for the presence of the PETM within, or have a documentable direct link to the PETM by being either directly correlated to, or superpositioned on, another formation containing geologic evidence for the PETM.
2. The formation should contain a high diversity of fossils, simultaneously documenting several biotic groups.
3. The formation should contain well-preserved fossils meriting it the description of a *Konservat-lagerstätte*.

It is the practice of world heritage nomination to concern specific geographic sites. However, for practical purposes this comparative analysis will consider not only the fossils recovered from a specific geological site, but is extended to cover the known fossil record from the geological formation, which the fossil site(s) are representative of. This is done to highlight the full picture of biodiversity, which the geological formation shows and to take into consideration the potential for further studies and future fossil discoveries at each site. These can be reliably predicted from discoveries made at other localities preserving the exact same geological formation.

Over 140 localities containing the PETM are currently known from around the world (McInerney & Wing, 2011: Supplemental Table 1). However, many of these are subsurface drilling sites unavailable to the general public, or only preserve a limited sample of biodiversity by virtue of having few fossil groups. Therefore these have been *a priori* rejected for detailed comparison with the Fur Formation. Instead five formations from around the world recording the most significantly diverse assemblage of fossil biodiversity have been selected for in-depth comparison below: Soisonnais Formation (France), Tienen Formation (Belgium), Willwood Formation (USA), Woolwich Formation (United Kingdom) and Cambay Shale Formation (India). Additionally, two notable formations, which have been of significant scientific importance in constraining the Paleocene-Eocene boundary, proven relevant for global correlation and understanding the events of the PETM event have been included for comparative purposes: Esna Formation (Egypt), and (Spain).

Assessment criteria for evaluating sites of Pleistocene glaciotectonic complexes

The nominated site belongs to Earth‟s history which defined by IUCN as a subset of geological features (Dingwall *et al*. 2005), which are represented by phenomena that record important events in the past development of the planet such as:

- Tectonic and structural features
- Ice ages and global patterns of continental ice-sheet expansion and recession

The analysis compares outstanding glaciotectonic complexes documenting the ice advance dynamics in the second half of the Pleistocene period. The following four criteria are suggested:

1) The candidate for this group of sites should be a site well exposed along a sustained outcrop, such as a coastal cliff, a river side, a protected road cut, a reclaimed pit with cross-sections protected by legislations or a similar accessible locality.
2) The site should be a representative locus for a geomorphic system of an ice advance. In other words, the site should be located in a focus point of ice shoved hill landscape or composite parallel-ridge landscape.
3) The candidate should have a research record documenting its scientific value. The scientific work should document the relations ship displaced bedrock (pre-Quaternary formations) and the glacial stratigraphy (the glaciodynamic set up). Only complexes involving up-thrust bedrocks are regarded as sufficiently dramatic to attracting attention, and glaciotectonic complexes involving only deformed Quaternary deposits are thus excluded.
4) The documentation should contain a constructed profile, a balanced cross section, a detailed description of internal framework, and an interpretation of the progressive glaciotectonic deformation.

Examples of sites which, although impressive, are excluded due to the criteria:

- Rubjerg Knude Glaciotectonic Complex, northern Denmark (Pedersen 2005) – the most carefully analysed glaciotectonic complex in the world, but includes only late Quaternary deposits,
- Risting Klint glaciotectonic section, Langeland central Denmark (Sjørring *et al.* 1982) – a well known classic locality, which only contains 130 000 year old Quaternary deposits.
- Bovbjerg, cross-section of the Main Stationary Line, western Denmark (Pedersen *et al.* 1988) – the complex is fameous for its loction at the Weichselian MSL, but includes only Quaternary deposits.
- Utrecht Ridges, Netherlands (Wateren 1992) – deformed Quaternary sediments known from sand pits.
- Elblag Upland, northern Poland (Makowska 1995) – Extensive glaciotectonic terrain including deformed Tertiary units , but only known from clay pits and drilling data below surface exposure.
- Peski, western Belarus (Karabanov 2000) – Cretaceous chalk sheets forming impressive glaciotectonic complex, but only exposed in chalk pits.
- Fanø Bugt, eastern North Sea (Andersen 2004) – cross-section only identified on seismic sections supported by drilling data from the seabed off the Danish west coast.

Description of earliest Eocene volcanic ash layer sites

Fur Formation ash layers in Moler Cliffs, the Hanklit and Knudeklint sites

The importance of the preservation of volcanic glass

The volcanic ash layers exposed in the Moler Cliffs are known from outcrops in Denmark, England and from numerous oil exploration wells in the North Sea. In most of the region the volcanic ash is interbedded with clays and is consequently are heavily altered. Major-element analyses of bulk ash samples often show hydration and leaching to such an extent that the original chemical composition of the ash is unrecognizable (Madirazza & Fregerslev 1969; Malm *et al*. 1984; Morton & Knox 1990). In contrast the volcanic glass is fresh where it is interbedded in the diatomite (Bøggild 1918, Larsen *et al.* 2003) (Fig. 10), and it is possible to determine major-element data from microprobe analyses (Pedersen *et al*. 1975; Morton *et al*. 1988a) and to determine glass inclusions in feldspar crystals (Morton & Knox 1990). In the altered ash layers it is still possible to obtain useful data on immobile elements such as Ti, P, Zr, Nb, and Y from analysis of bulk ashes (Malm *et al*. 1984; Morton & Evans 1988; Morton & Knox 1990; Haaland *et al*. 2000, Larsen *et al*. 2003). Radiometric datings of the ash layers has been focused on ash layers –17 and +19. Swisher & Knox (1993) obtained $^{40}Ar/^{39}Ar$ ages of 53.7 ± 0.1 Ma and 53.2 ± 0.5 Ma. Berggren *et al*. (1995) gives an age of 55.0 Ma for ash layer –17 (quoted as 54.5 Ma by Knox 1997). Ash layer –17 was dated to 54.52 ± 0.05 Ma (Chambers *et al.* 2003). Recently –17 has been dated to 55.12 ± 0.12 Ma by Storey *et al*. (2007). Please note that $^{40}Ar/^{39}Ar$ ages are given relative to a standard (the Fish Canyon Tuff). New determinations of the age of the standard affects the calibrated ages of ash layer –17.

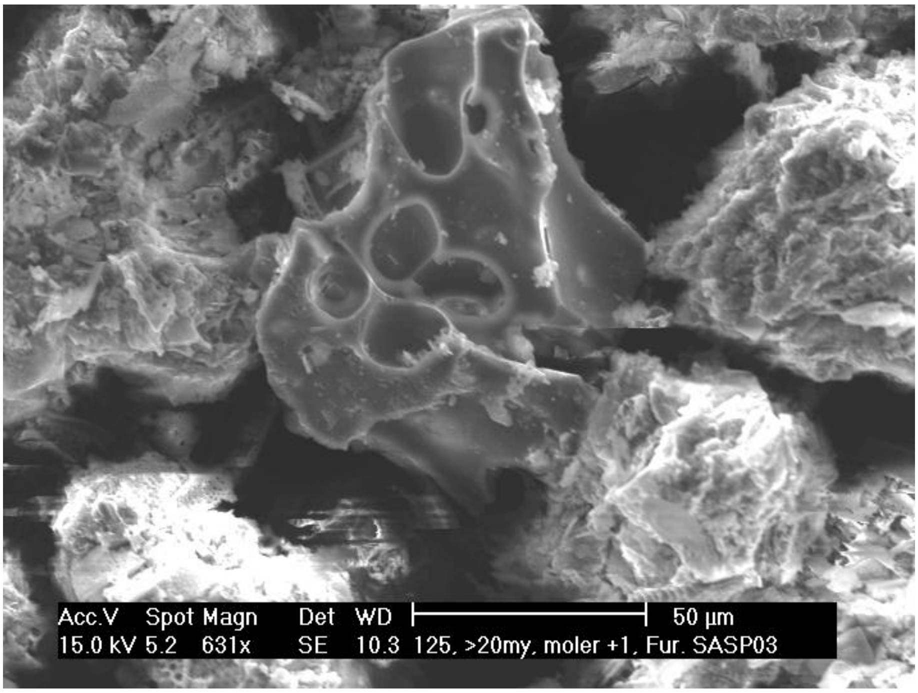


Figure 11. *A scanning electron microphoto of a well preserved vesicular grain of volcanic glass from a sample of the basaltic ash layer +1 in the Fur Formation from the site Knudeklint on Fur.*

Chemical analyses of volcanic ash from the Fur Formation

Larsen *et al*. (2003) analysed the chemical composition (main elements and trace elements) in a total of 104 samples from *c*. 77 different Danish ash layers and two samples from Germany. The ash layers were sampled in the Fur Formation, and if possible in calcareous concretions formed during early diagenesis (Pedersen & Buchardt 1996). Comparison demonstrated that the carbonate-cemented ash layers contain much less clay than the non-cemented samples, and the grain size distribution is different with many more small particles because these have not been turned into clay (Larsen *et al*. 2003). This shows that although the volcanic glass is well preserved in the diatomite, it is even better preserved in the calcareous concretions. The content of volatiles is an indication of the amount of weathering and alteration of the volcanic ash, and the lowest amounts of volatiles were found in samples from the carbonate concretions indicating that the volcanic ash outside the concretions had been subjected to seafloor weathering and other alterations (Larsen *et al*. 2003). In the undersaturated phonolitic to trachytic layer −17, the glass is extensively leached and hydrated (Pedersen *et al*. 1975), and fresh glass is only found in melt inclusions in sanidine (L. Heister, personal communication to Larsen *et al*. 2003).

Magma types and comparisons

Various magma types in the Danish ash series are identified and characterized (Bøggild 1918, Larsen *et al*. 2003). In the positive series both major and trace elements are relatively undisturbed. They are evolved, Fe–Ti-rich tholeiitic basalts, which originated from one single igneous suite (Larsen *et al*. 2003), and are very similar to the ferrobasalts in the Tertiary lava pile in Iceland (Wood, 1978; Flower *et al*., 1982). In comparison the Tertiary flood basalt successions in East Greenland and the Faroe Islands contain a few ferrobasalts which are less enriched than the Danish ashes (Larsen *et a*l. 1989; Hald & Waagstein 1984). The best likeness is found in lavas of the youngest formation in East Greenland, the post-breakup Igtertivâ Formation. Similar rocks are not known from the British part of the province (Larsen *et al*. 2003).

It is not always possible to determine the original igneous compositions of the ash layers in the negative series due to severe alteration combined with extreme compositions. Layers −11, −12, and −13 are only comparable with nepheline normative basalts in East Greenland. The original melts for these ash layers must have been alkali basalts (Larsen *et al*. 2003).

Strongly alkaline to peralkaline rocks are represented by ashlayers −17 to −20, and −17 has been used for radiometric age determination. Layer −17 contains crystals of sanidine, Mg–kataphorite, titan-aegirine, ilmenite, perovskite, and sphene alongside lithic fragments and granulite-facies orthopyroxenes, and is thus polymict (Pedersen *et al*. 1975; Rønsbo *et al*. 1977). These authors judged the erupted magma to be a peralkaline phonolite or trachyte that had picked up earlier solidified rocks in a high-level volcanic complex of nephelinitic affinity, possibly a peralkaline phonolite. The high peaks for Nb and Zr have been found in ash layer Sele 70, in borehole BGS 81/46a in the North Sea (Morton and Knox, 1990). The only other North Atlantic rocks with similarly high Nb and Zr peaks are from East Greenland and comprise a few dykes in the Gardiner complex, and a dyke and a tuff layer in the flood basalts in northern Blosseville Kyst. Heister *et al*.

(2001) correlated the East Greenland tuff layer directly with layer ─17 and suggested that both originated in the Gardiner complex (Fig. 12).

Layers ─18 and ─18a probably originated from alkaline rhyolitic magmas, comparable to the lavas from the Myggbugta Complex, NE Greenland, or the rhyolite dykes from Lundy, Britain (Fig. 12).
The two samples of layer ─19a and three samples of layer ─19b show a fair amount of internal variation. In East Greenland, similar rocks form dykes in the Gardiner complex, lavas of the Prinsen af Wales Bjerge Formation, Kangerlussuaq, and lavas and plugs in the Nunatak areas in NE Greenland. Similar rocks are not known from the European side of the North Atlantic. Intermediate alkaline rocks: layers ─19, ─19c, and ─20 lack similar rocks in the North Atlantic.

Contaminated trachytes or dacites are represented by ashlayers ─15,─21, and ─21b. They resemble found for trachyte lavas (benmoreites) from Mull, or trachyte dykes from Lundy. A very similar pattern is found in dacite lavas from the Darwin complex. Ash layer ─21a is geochemically similar to alkali basaltic dykes in the Gardiner complex and lavas in the Prinsen af Wales Bjerge Formation, East Greenland. Old and less enriched basaltic ash layers (─22, ─24, ─26, (─27), ─28, ─29a, ─34, and ─35) do not match rocks within the North Atlantic Igneous Province. The „closest" matches are a basalt fromMull, and a basalt from East Iceland. Layer ─33 is a subalkaline rhyolite and shows striking resemblances to the Lundy granite or some peraluminous rhyolites from Antrim (Larsen *et al*. 2003).

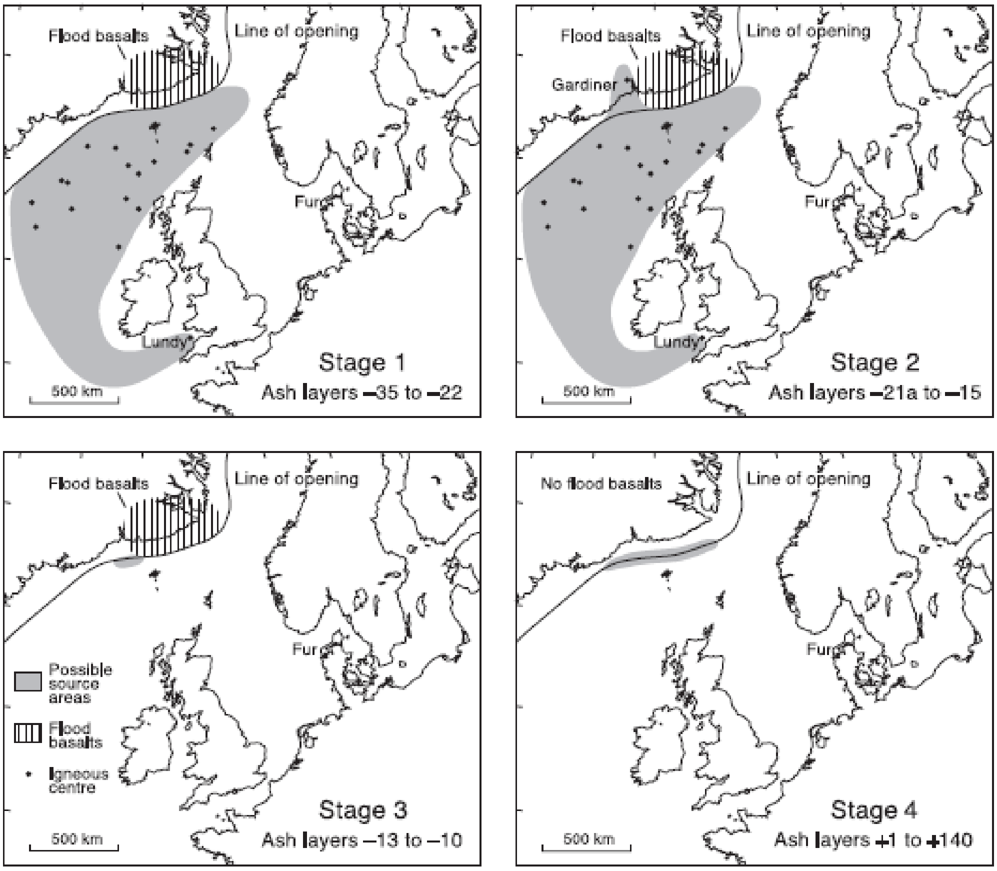


Figure 12. *The source area for the four stages of igneous activity recorded in the Fur Formation.From Larsen et al. 2003.*

Ash layer Stratigraphy

Knox & Morton (1988) and Knox (1997) distinguished three phases of ash deposition in the North Sea. Phase 1 is early, and synchronous with the main volcanism in the British Isles from where the ashes were probably derived. Coeval ash layers in Denmark should be situated in the Holmehus Clay Formation and the Kerteminde Marl (Heilmann-Clausen *et al*. 1985) but are inconspicuous and easily be overlooked (C. Heilmann-Clausen, personal communication to Larsen *et al*. 2003).

Phase 2 comprises several sub-phases.

- Phase 2a (or 2.1 and 2.2a) comprises the negative ash series in Denmark and the Sele Formation in the North Sea.
- Phase 2b (or 2.2b) comprises the positive ash series in Denmark and the Balder Formation in the North Sea. Phase 2b is the phase of paroxysmal activity.
- Phase 2c (or 2.2c) and phase 2d (or 3) comprise sporadic ash layers in the younger sediments and are also represented in Denmark in the Røsnæs Clay Formation (Heilmann-Clausen *et al*. 1985, Knox 1997).

Thus, the ash layers in the Moler Cliffs represent eruption sites, which were active *c*. 56–54 Ma ago. This is the time of formation of the major part of the flood basalt succession in East Greenland and the middle and upper lava formations in the Faroes (Storey *et a*l. 1996; Larsen *et al*. 1999, Waagstein *et al*. 2002). There was also volcanism on the Vøring Plateau (Sinton *et al*. 1998). The basaltic activity in the British Isles was extinct by this time (Chambers & Pringle 2001), whereas some acid centres were active, among these the Mourne Mountains and Slieve Gullion in Ireland (around 56 Ma, Gamble *et al*. 1999), and Lundy, St. Kilda, and Rockall (all around 55 Ma, Mussett *et al*. 1988; Ritchie *et al*. 1999). On the shelf, the igneous centres of Darwin and Erlend were active, Darwin at 55–56 Ma (Sinton *et al*. 1998) and Erlend probably around the same time (Ritchie *et al*. 1999; Jolley & Bell 2002). There are more than 20 igneous centers on the shelf and some of these were probably active.

Consequently there is circumstantial evidence pointing to sources for the Danish ashes in the Faroe–Greenland area. This requires transport distances of at least 1100 km to Fur, 1200–1600 km to the deposits in SE England and northern Germany, and about 2000 km to deposits in Austria. In comparison to these distances, younger ash layers from the whole age range Eocene to Holocene in drill and piston cores in the North Atlantic have been interpreted as sourced from Iceland, even in cores at distances of up to 1500 km from Iceland. In recent times, ash from the 1875 eruption of Askja in central Iceland fell in a 0.5-cm thick layer in Stockholm, 1700 km away (Thoroddsen, 1925, pp. 208–209). Thus, it seems realistic that some of the Palaeogene ash deposits could be sourced from as far away as East Greenland. Pedersen *et al*. (1975) recognized four stages of volcanic activity in the Danish ashes and probable source areas were identified by Larsen *et al*. (2003) (Fig. 12). The sedimentlogical log locating the ash layers in the Fur Formation is shown in Fig. 13.

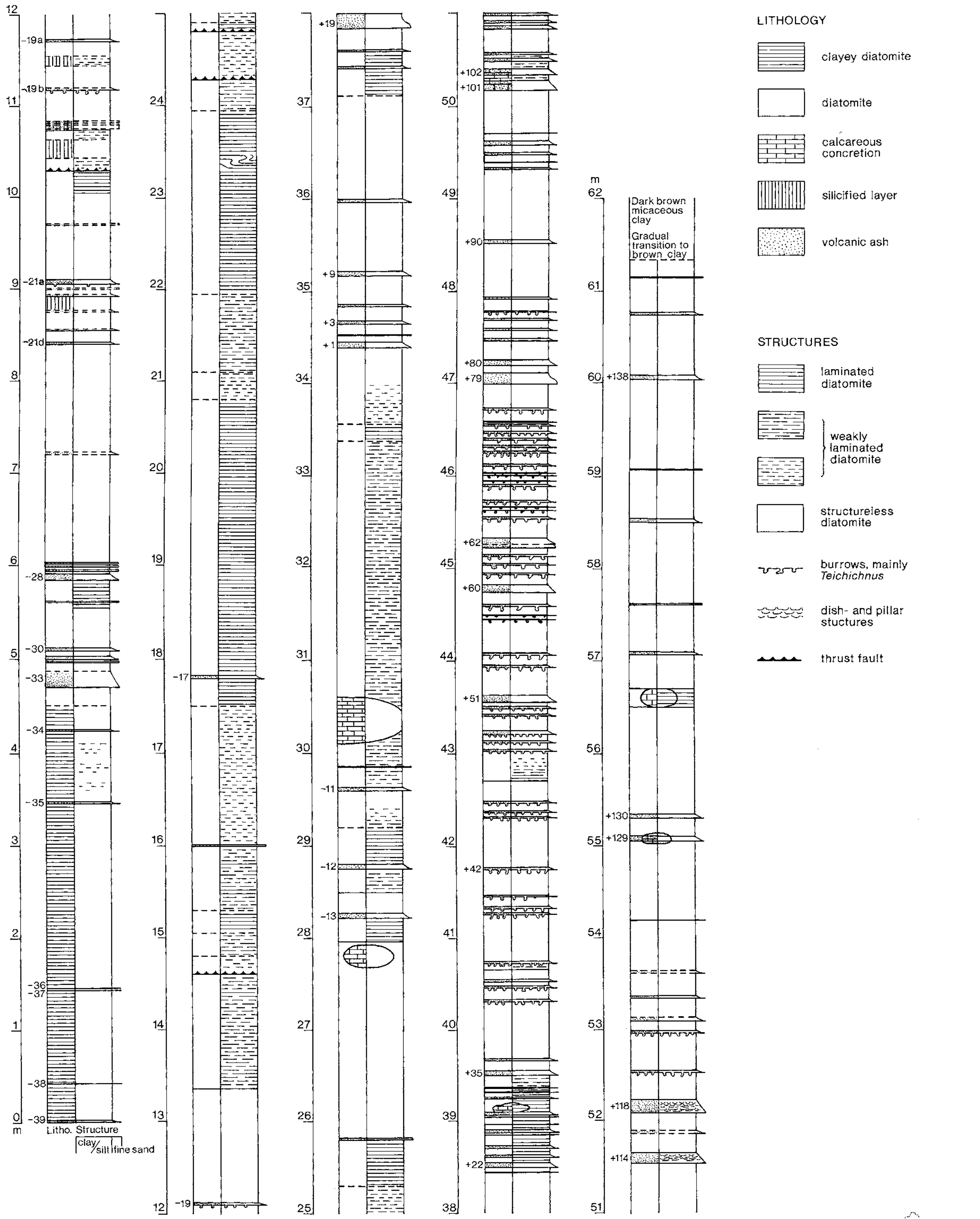


Figure 13. *Sedimentological log of the Fur Formation attached with numbers of the prominent ash layers. Note that there is a negative and a positve numbering of the ash layers after Bøggild (1918, and the measures in meters are given relative to the 0- point seattled at ash layer -39 at the base of the formation as defined by Pedersen & Surlyk (1983).*

The four stages of volcanic activity in the Danish ashes recognized by Pedersen *et al*. (1975) are related to the following source areas by Larsen *et al*. (2003) (Fig. 12):

- Stage 1. Basalts and peraluminous rhyolite, layers (−39?) −35 to −22: sources on the NW European shelf such as the Lundy (peraluminous rhyolite), Darwin, Erlend, or non-analysed complexes.
- Stage 2. Trachytes, rhyolites, alkali basalts, nephelinites, and phonolite, layers −21b to −15: sources on the NW European shelf and in East Greenland. The suite of strongly alkaline layers could all have originated from a nephelinitic volcanic complex such as the Gardiner igneous centre in East Greenland.
- Stage 3. Alkali basalts, layers −13, −12, −11, may be the products of a failed or propagating part of the opening rift.
- Stage 4. Tholeiitic ferrobasalts and rhyolites, layers +1 to +140, represent a cataclysmic stage sourced from a gigantic volcanic system representing the nascent Proto-Iceland within the opening ocean.

The thick succession of subaerial lavas in East Greenland occurred during stage 1–2 and probably stage 3. The cataclysmic character of stage 4 can be understood if the areas of extremely high magma production at this time moved away from the continent and into the sea-covered opening rift, thus switching the bulk of volcanism from effusive to explosive. When Proto-Iceland finally emerged, the explosive activity abated again (Larsen *et a*l. 2003).

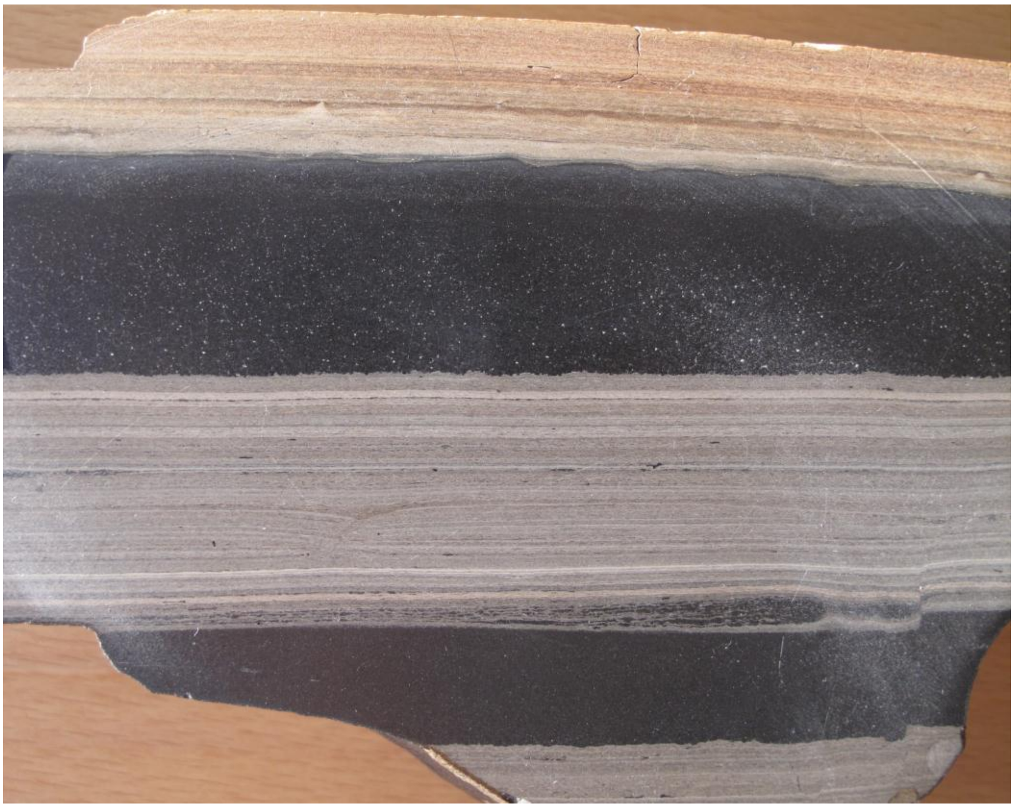


Figure 14. *The preservation of ash layers in calcareous concretion provides very good conditions for the chemical analysis of the volcanic ash. The photo displays ash layer +26 and +27, the latter almost 3 cm thick. Note the graded bedding of the ash particles which indicates the air-borne transport and gravity separation of particles in water column during sedimentation.*

Summary

- 187 numbered layers of volcanic ash (between –39 and +140) is found in the Moler Cliffs
- The ash was deposited by settling of air-borne particles.
- The volcanic glass is generally well preserved and the chemistry is well documented (Larsen *et al*. 2003), which allows interpretation of eruption areas and correlation of ash layer –17 with the Gardiner Igneous Complex in East Greenland.
- The lowest degree of alteration is found in calcareous concretions
- The majority of volcanic ash layers are interbedded in a clayey diatomite (Moler), but ash layers –39 to –34 are interbedded in the clayey Stolleklint Ler (see Fig. 13). The Knudeklint locality also includes a number of ash layers in the Knudshoved Member (basal part of the Røsnæs Clay Formation) (Heilmann-Clausen 1982, Heilmann-Clausen *et al*. 1985).
- The base of the Stolleklint Ler coincides with the base of the PETM, which provides a link between this global palaeoclimatic event and the volcanic activity in the North Atlantic.
- The ash layers are accessible in the Moler cliffs such as Hanklit and Knudeklint. Due to the contrast in between the sandy, predominantly dark grey volcanic ash and the pale diatomite the ash layers are very prominent in the Moler Cliffs.

Main points for comparative analysis

- 187 numbered layers are found in the Moler Cliffs
- The ash layers are well-preserved and thoroughly studied and demonstrate the development of the NAIP during the earliest Eocene
- Most ash layers are interbedded in a marine clayey diatomite (Moler) of earliest Eocene age and consist of air-borne material
- The ash layers are linked to the PETM
- The ash layers are accessible to the public at the sites Hanklit and Knudeklint, as well as at other localities.

The references listed below are those which have contributed with new data on the volcanic ash layers. The numerous publications which mention the ash layers are not included. The references are listed in chronological order.

Forchhammer 1835, Printz 1885, Bøggild 1903, Ussing 1904, Gagel 1907, Bøggild 1918, Andersen 1937a, 1937b, 1938, Gry 1940, Norin 1940, Noe-Nygaard 1967, Sharma 1969, 1970, Flodén 1973, Åm 1973, Pedersen *et al*. 1975, Rønsbo *et al*. 1977, Pedersen & Surlyk 1977, Pedersen & Jørgensen 1981, Jensen & Langnes 1992, Berggren *et al*. 1995, Kjaer & Heilmann-Clausen 1996, Knox 1997, Chambers *et al*. 2003, Larsen *et al*. 2003, Storey *et a*l. 2007, Knox *et al*. 2010.

The number of references exceeds 25 convincingly documenting the scientific importance of the ash layers in the Fur Formation exposed at Hanklit and Knudeklint.

Volcanic ash layers from the Ølst Formation, Denmark

The Ølst Formation consists of fine-grained marine clay and is known from various outcrops in Denmark (Heilmann-Clausen *et al*. 1985). It has its name from the type locality in eastern Jutland, and is correlated to the Sele Formation and the lower part of the Balder Formation in the North Sea (Schiøler *et al*. 2007). The succession of volcanic ash layers known from the Fur Formation were described from the Ølst area by Bøggild (1918), Andersen (1937), Nielsen & Heilmann-Clausen (1988). The volcanic glass is strongly altered, and the ash layers are consequently less suited for chemical analyses. The volcanic ash layers still constitute important isochronous marker beds and allow detailed correlation between occurrences of the earliest Eocene deposits in Denmark. Interbedding between diatomite and clay is seen in the Harre Borehole in Jutland (Nielsen 1994), and is also known from exploration wells in the North Sea (Thomsen & Danielsen 1995, Danielsen & Thomsen 1997).

Figure 15. *The Ølst Formation is exposed in the Leca-clay pits in central Jutland, Denmark. The Leca factory is seen in the background behind the excavated hill.*

Main points for comparative analysis

- The volcanic ash layers known from the Fur Formation (Moler Cliffs) are all recognized
- The volcanic glass is strongly altered
- The volcanic ash is interbedded in fine-grained marine clay (Ølst Formation)
- The volcanic ash layers are accessible in the clay pit and at a few landslide affected coastal cliffs at Djursland, eastern Jutland, Denmark.

References

Bøggild 1918, Andersen 1937a, b, 1938, 1944, Nielsen 1974, Heilmann-Clausen *et al*. 1985, Nielsen & Heilmann-Clausen 1988, Knox 1994, Nielsen 1994, Schmitz *et al*. 2004.

Volcanic ash layers in the North Sea boreholes

Latest Paleocene and earliest Eocene ash layers occur in the North Sea mainly in the Sele and Balder Formations but ash layers are also known from the Lista Formation as well as the lower part of the Horda Formation (for lithostratigraphy see Table 2). The series of ash layers is known from many wells in the North Sea, but the individual layers can‟t be resolved by geophysical methods (petrophysical logs). Consequently the ash layers are only known from relatively few cored sections (Malm *et al*. 1984, Morton & Knox 1990). Four stages in Gash layer deposition were distinguished by Jacques & Thouvenin (1975), Knox & Morton (1983) and Larsen *et al.* (2003) (see chapter above).

The ash layers in the Sele Formation correspond to the negative ash layers in the Fur Formation and the Stolleklint Ler, which is the basal part of the Ølst Formation (Table 3). The high number of ash layers known from the Balder Formation corresponds to the positive ash layers in the Fur Formation. The ashes in the North Sea have basaltic affinities but the degree of alteration is considerably greater than in the ashes found in the Fur Formation.

Locality UK Well 16/7a-2 (northern North Sea)

The entire, 25‒30 m thick succession of mudstone with interbedded tephras was cored. More than 200 graded tephras greater than 0.5 cm thick were identified, as well as many thinner layers (214 tephra layers in the Balder Formation and 9 layers in the Sele Formation) (Morton & Knox 1990).

BGS Borehole 81/46A (southern North Sea, offshore Yorkshire)

Both the Balder and Sele Formations were cored, 74 tephras have been identified, the majority (62) in the Balder Formatin. One ash layer is correlated to +19 in the Fur Fm based on feldspar composition (Morton & Knox 1990).

Norwegian Well 25/8-1 and 25/10-1(northern North Sea)

The well is continuously cored through the lower part of the Balder Formation and the entire Sele Formation into the Lista Formation. A total of 117 tephra layers were identified (101 in the Balder + 16 in the Sele Formation) (Morton & Knox 1990). The well 25/10-1 has been described by Ræstad (1976) and Ræstad & Prestvik (1982) and should include more than 430 ash layers over an interval of 100 feet. They are divided into three subphases of volcanic activity (Malm *et al*. 1984).

Norwegian Well 30/2-1 (north Viking Graben)

The main tuff zone within the Balder Formation is 47 m thick in the well and was examined in a 16 m long core. The core contains 168 tuff beds of which 49 are less than 1 cm thick. The ash layers are interbedded in laminated mudstones containing pyritized diatom frustules (Malm *et al*. 1984). Thin sections show that the ash particles commonly contain spherical vugs and morphologies comparable with those produced during Surtseyan type eruptions. XRD-analyses show, however, that the tuff beds are composed mainly of clay minerals, and the volcanic glass is thus altered (also shown by the high values of „loss on ignition"). The chemical composition of 17 tuff layers suggest that they represent TiO_2- and FeO-rich basalts (Malm *et al.* 1984).

Results

- In three of the wells mentioned above an ash layer has been found which is correlated to −17 in the Fur Formation, but the list of cores with volcanic ash layers is not complete.
- Analyses of the tephras from 16/7a-2, 81/46A and 30/2-1 show a significant degree of hydration of the ash and alteration of volcanic glass to smectite. In comparison the Danish ashes (in diatomite) are much less altered (Larsen *et al*. 2003).
- The majority of the Balder tephras are tholeiitic, while the Sele Fm contains tephras of more variable composition. The same pattern is reported from the Fur Fm (Pedersen *et al*. 1975, Larsen *et al*. 2003).
- The number of ash layers varies between the wells indicating the ash clouds from individual eruptions may have been geographically restricted.
- The ash layers are more closely spaced in the North Sea cores than in the Fur Formation. This reflects either that the wells are located closer to the eruption sites or that the rate of sedimentation was lower.

Main points for comparative analysis

- The ash layer succession is the same as the one known from the Fur Formation and must originate from the same source area
- The ash layers in the North Sea sediments are altered
- The ash layers are inaccessible to the public

References

The list of references below does not claim to be complete. Emphasis is here on the publications from 1975–1990, during which period the „volcanic ash marker" was established as a regional marker horizon in the North Sea Basin. Jacqué & Thouvenin 1975, Knox & Harland 1979, Malm *et al*. 1984, Knox & Morton 1988, Morton & Knox 1990, Schiøler *et al*. 2007, Knox *et al*. 2010.

The Skrænterne Formation Tuff, East Greenland

Locality Gronau West Nunatak, East Greenland

Pyroclastic deposits (= volcanic ash) are interbedded with subaerial lavas in a thick volcanic succession at Gronau West Nunatak in East Greenland (Heister *et al*. 2001, Storey *et al*. 2007). Of special interest is one tuff bed (the Gronau alkaline pyroclastic tuff, termed the Skrænterne Formation Tuff in Storey *et al*. 2007).

The alkaline pyroclastic tuff occurs at 2565 m a.s.l. and is 5-10 cm thick. The tuff is interbedded conformably between subaerial lavas of plagioclase-phyric and picritic composition. The tuff layer contains unaltered Na-rich sanidine feldspar crystals as well as volcanic glass that has been altered to a greenish montmorillonitic groundmass. The sanidine crystals are used for radiometric dating of the tuff, and the latest age of 55.12$\pm$0.12 Ma was published by Storey *et al*. (2007).
At least 20 intrusive subvolcanic and plutonic complexes have been identified in the early Tertiary igneous province of East Greenland. The majority of them can be eliminated as possible sources for the Gronau West Nunatak Tuff. The best match with respect to both age and composition is with the Gardiner Complex.
The tuff is mineralogically and geochemically similar to the intrusive Gardiner Complex, and is also very similar in composition and age to ash layer ─17 from the Fur Formation (Heister *et al*. 2001, Storey *et al*. 2007), se also Table xx (PETM relative to Danish ash layers).
It is proposed that a Plinian-scale eruption led to wide dispersal distances (>1000 km) of the tuff. This implies a high eruption column, which must have supplied both ash and volatiles to the troposphere and/or stratosphere. The CO_2 production associated with the Gardiner eruption has not been estimated, but it is known from modern carbonatite volcanoes that they may potentially supply a large pulse of CO_2 to the atmosphere during a relatively short eruption time (a contribution to PETM ?).

Main points for comparative analysis

- The Gronau West Nunatak is inaccessible to the public
- The Gronau alkaline pyroclastic tuff (=the Skrænterne Formation Tuff) may be the result of an explosive (Plinian) eruption at the Gardiner complex
- This tuff is probably equivalent to ash layer -17 in the Fur Formation. This provides evidence for the long distance transport of volcanic ash.
- The tuff is only slightly altered and is not redeposited.

References

Heister *et al*. 2001, Chambers *et al*. 2003, Storey *et al*. 2007.

Hawich Formation volcanic ash layers in the UK

The lithostratigraphy of southeastern UK is shown in Table 2. Volcanic ash layers are known from a number of outcrops and boreholes (Knox & Ellison 1979, Knox 1978, 1983, Knox *et al*. 2010). The presence of a volcanic ash deposit in the London Clay of East Anglia was first reported by Elliott (1971). The ash layer was recognized within a concretionary calcite bed referred to as the „Harwich Stone Band‟. Elliott concluded that the ash was a distal representative of the „ash-series‟ of the Danish Mo-clay. This correlation is confirmed and it is shown that the Harwich Stone Band ash is itself one of a succession of more than 40 ash layers occurring in SE England. The Harwich Stone Band lies approximately 6.5 m from the base of the London Clay.

Any significant concentration of volcanic ash in the sediments of southeast England is likely to be related to the main Balder Formation phase of volcanism, with only minor traces of the preceding and following phases (Knox & Harland 1979). The ash-bearing beds are absent from the Crystal Palace Borehole of southeast London where clays of the Walton Member rest directly on the Woolwich Beds. West of London the ash-bearing beds reappear at Harefield, but only the upper division is represented. In the Bunker's Hill and Shamblehurst Boreholes ash-bearing beds are absent, and here the „basement bed" appers to be younger (Knox 1983).Three of the best exposures are briefly described below:

- Herne Bay (Oldhaven Beds, former lithostratigraphy, present part of Harwich Formation)
- Walton-on-the-Naze (Harwich Member, now Harwich Formation. Equivalent to the Balder Fm)
- Wrabness (London Clay Formation, equivalent to the Horda Formation and thus too young)

References

Whitaker 1872, Burrows & Holland 1896, Ward 1977, Knox & Ellison 1979, Knox 1979, 1983, Morton & Knox 1990,

Figure 16. *The clayey cliff at Walton-on-the-Naze, southeast UK, is one of the sites, where the Harwich Formation is cropping out. Due to the clayey nature of the cliff, the exposure of the formation is often hampered by landslides.*

Herne Bay, Oldhaven beds

At Herne Bay most of the section is occupied by the Oldhaven Beds. Ash particles of apparent direct air-fall origin are relatively abundant in the Oldhaven Beds. The volcanic grains are well preserved but form only a small proportion of the sand fraction (1-5 %). The ash particles recorded from the Oldhaven Beds are closely comparable with those encountered in the Harwich Member of East Anglia. Few grains show fractured vesicular outlines and the isotropic groundmass has disseminated pyrite and minute feldspar laths. These relatively unaltered grains are accompanied by strongly altered grains consisting of yellow-green, low birefringent smectitic clay.

Points for the comparative analysis

- Air-fall volcanic ash layers are observed in the Oldhaven beds
- These ash layers are correlated to those in the Balder Formation (the positive series in Denmark)
- The volcanic grains, apparently, never constitute more than 15% of a sample
- A large proportion of the volcanic grains are altered.

The Harwich Member

The Harwich Member of East Anglia comprises detrital beds and discrete ash layers.

Altered particles are, noticeably, restricted to the detrital beds. The interbedded detrital siltstones and mudstones may also contain „unaltered" particles.

The discrete ash layers consist either of 'unaltered' particles (found in calcite-cemented portions) or have been converted to colourless smectite. „Unaltered" particles are absent from the uppermost sandy unit of the Harwich Member, which lacks discrete ash layers (Knox & Ellison 1979), although altered ash particles continue up into this unit. The ability to distinguish active pyroclastic deposition by means of the petrography of included ash particles is of considerable value in the correlation of the Harwich Member with beds further to the south.

Figure 17. *The exposure at Wrabness where the clayey formation contains smectitizesed tuff layers equivalente to the ash layers in the Fur Formation*

Wrabness (Stour estuary, SE England)

The cliff at Wrabness (Fig. 16.) on the southern shore of the Stour estuary is a Site of Special Scientific Interest (SSSI). The section at Wrabness includes the „Harwich Stone Band" and more than 15 m of the overlying beds, all of which are tuff-bearing except the top 5 m. Up to a metre of the beds below the Stone Band are exposed in the low cliffs south of Shotley; the remainder of the sequence described below was obtained from an IGS borehole at Shotley Gate [TM 24393460] (Knox & Ellison 1979).

The upper ash-bearing division includes the Stone Band and the overlying clays; it is relatively sand-free and lacks intensive bioturbation, so that up to 34 ash layers are more or less continuous. The lower division is more silty, sandy and bioturbated, so that the ash layers are poorly defined and locally indistinguishable. Up to 10 ash layers are observed, but the abundance of disseminated ash in the lower division indicates that the original number of ash falls was much greater.

The ash layers are most distinctive on weathered surfaces, where they appear cream to yellow-brown in contrast to the associated grey-brown clays; on fresh surfaces they appear dark blue-grey. In the upper division they are more or less continuous within the limits of any one exposure but may show a marked variation in thickness. The more uniform layers range from less than 10mm to about 80 mm in thickness. Internal structures include graded bedding (well displayed in the Stone Band tuff) and more commonly horizontal lamination or cross-lamination. Tuffs displaying the latter two structures include variable amounts of detrital sand and silt, indicating reworking of the primary ash deposits.

The ashes have mostly undergone total alteration to montmorillonite with variable amounts of pyrite; vestiges of pyroclastic texture are, however, visible in both hand specimen and thin section. The alteration has locally been inhibited by early calcite cementation. In the cemented tuffs a well-defined pyroclastic texture is retained; the particles consist mostly of devitrified glass, sometimes with vesicular texture, and lava with microlitic feldspars (Knox & Ellison 1979).

Points for the comparative analysis

- 44 ash layers are observed in the section at Wrabness
- Most ash layers are completely altered to montmorillonite
- The ash layers are most distinctive on weathered surfaces (as colour changes)
- The ash layers are correlated to those in the Balder Formation (the positive series in Denmark).

Isle of Rum rhyodacitic volcanic ash layers, Scotland

The opening phase of the Paleocene volcano and intrusive complex preserved on the Isle of Rum (Scotland) features a caldera, which are exposed in two areas on the island. Logs through the caldera-infill breccias, sandstones and felsite that covered the caldera floor reveal that the caldera existed, and was being infilled by collapse breccias slumping from the caldera walls, before any magma reached the surface. The caldera-fill sediments and tuffs are overlain by ignimbrites (Troll *et al*. 2000).

Thin-bedded (and discontinuous) lithic and crystal tuffs overlie the breccias. Breccias formed after the first eruptions contain volcanic components, which range from glass shards, coated lapilli, scoria and felsic clasts to plagioclase crystal fragments derived from the crystal tuff. Three units of tuffs are distinguished. The pyroclastic deposits are small-volume deposits generated by violent eruptions before and between depositions of ignimbrites (Troll *et al*. 2000).

Points for the comparative analysis

- The tuff is rhyodacitic, not basaltic
- Volumes of ash was apparently small and the tuff layers are discontinuous
- The tuffs form a small part of the succession
- The tuffs are unlikely to have a potential for regional correlation

Blake Nose off Florida

Ash layers in Eocene ooze, with up to 50% radiolarians (opal tests well preserved). Air-fall ash layers, as well as redeposited ash (volcaniclastic turbidites).

Five wells were drilled at the Blake Nose off Florida during Deep Sea Drilling Project Leg 171B. More than 50 discrete volcanic ash layers are interbedded in hemipelagic sediments of Eocene age: yellowish to greenish calcareous oozes, chalks, and marls with variable proportions of calcareous nannofossils and foraminifers and with a significant percentage of siliceous microfossils (radiolarians, sponge spicules, minor diatoms). Clay content generally increases downcore, and there are occasional intercalations of porcellanite and chert (Norris *et al.*1998). The Eocene ash layers, which range in thickness from millimeters to more than 5 cm are composed of largely unaltered volcanic glass. The dacitic-rhyodacitic composition of most ash layers suggests a provenance from a calc-alkaline volcanic source in the Caribbean Island arc (Reicherter & Pletsch 1998).

Well-preserved radiolarian tests occasionally constitute >50% of the sediment. These ash layers are often strongly bioturbated and are interpreted as formed by direct settling of air-fall deposits through the water column.Other ash layers were interpreted as volcaniclastic turbidite deposits (Reicherter and Pletsch, 1998).

Main points for comparative analysis

- Ash layers not accessible for public
- The ash layers are redeposited or strongly bioturbated

Kamloops Group volcanic ash layers, British Columbia, Canada

A volcanic arc that extended over much of south-central British Columbia contributed large volumes of volcaniclastic sediment and volcanic flows to the fossiliferous Eocene basins. Mount Boucherie is an Eocene dacite dome flanked by fluvial and lacustrine strata of the Eocene White Lake Formation close to the Okanagan Lake. Between eruptive episodes, a diverse variety of fluvial and lacustrine sediments were deposited. Air-borne as well as redeposited volcanic ash layers occur in diatomaceous lacustrine deposits of Early Eocene age (EECO = Early Eocene Climatic Optimum). The lacustrine strata contain a rich fauna of insects and fishe as well as a fossil flora.

The Kamloops Group is a succession of Lower to Middle Eocene volcanic and sedimentary rocks found throughout south-central British Columbia (Dawson 1895, Ewing 1981; Breitsprecher et al. 2000; Breitsprecher 2002). At the type locality near Kamloops, it is composed of the lower Tranquille and upper Dewdrop Flats formations (Ewing 1981). Widespread volcanic flows and breccias of the Kamloops Group and correlative rocks overlie Eocene fluvial and lacustrine sediments. In the Princeton area Eocene volcanic rocks of the Cedar Formation are overlain by Eocene sedimentary strata of the Allenby Formation (Read 2000).

Horsefly outcrops. The sedimentary rocks contain thin interbeds of tuffaceous material. Massive tuffaceous interbeds within the varved sediments may have been caused by local volcanic eruptions; thinner tephra layers were probably redeposited during episodic storms that swept accumulated material from the watershed into the lake (Mustoe 2005). The volcanic ash is interbedded in a laminated sediment where couplets of diatomite laminae alternating with organic-rich laminae are interpreted as annual (varves).

Falkland site. The Falkland site (Smith 2009, 2011) is located within a small outcrop of a rhyolite ash member of the Tranquille Formation that includes a minor shale element. Breitsprecher (2002) described this as a syn-volcanic sedimentary facies. Directly overlying the Falkland fossil locality is a massive to crudely bedded volcaniclastic breccia informally designated the Estekwalan breccia unit of the Tranquille Formation (Breitsprecher 2002). Directly beneath and surrounding the Falkland fossil beds are andesite and basalt lava flows and mudflows of the Dewdrop Flats and Tranquille Formations (Thompson and Beatty 2004). The Falkland site has been dated using U–Pb analysis of zircons from interbedded ash layers as 50.61 ± 0.16 Ma (Moss *et al*. 2005), placing it near the end of the EECO (Smith *et al*. 2009).

Points for the comparative analysis

- The volcanic activity belong to a volcanic arc
- The Canadian volcanism is not basaltic
- The ash layers are of local extent
- Ash layers are thin, interbedded in laminated diatomaceous sediments
- The sediments are rich in fossils (insects, fish, macroplant fossils)
- The sedimentary succession represents a lacustrine environment (non marine!)
- The age of the deposits is Early Eocene (EECO), slightly younger than the Fur Formation
- The climate was warm, EECO

Frysjaodden Formation ash layers, Spitsbergen, Svalbard

Charles *et al*. (2012) document a U-Pb (zircon) date from a bentonite layer within the PETM CIE from the Longyearbyen section in the Central Basin of Spitsbergen. They combine this date with cyclostratigraphic datasets, from both the Longyearbyen section (Harding *et al*., 2011) and core BH9/05 (drilled near Sveagruva, Spitsbergen (Dypvik *et al*. 2011) to constrain the age of the P/E boundary.

The study localities are located in the Palaeogene Central Basin of Spitsbergen. A comprehensive overview of the stratigraphy of the Central Basin and the other Palaeogene successions on Spitsbergen is given by Dallman *et al*. (1999), Harland (1997) and references therein.

Two sections were studied: the Longyearbyen outcrop section and core BH9/05. At Longyearbyen the PETM lies within the Gilsonryggen Member of the Frysjaodden Formation (Harding *et al*. 2011), a unit of

around 250 m of homogeneous mudstones. Two conspicuous bentonite horizons occur at 10.90 and 14.60 m above the top 141 of the Hollendardalen Formation, within the PETM CIE (Charles *et al*. 2012).
The Frysjaodden Formation is identified from 551-110 m depth in core BH9/05 (Dypvik *et al*. 2011), drilled NW of the town of Sveagruva near Urdkollbreen. Two bentonite horizons are lying at 517.20 and 511.10 metres depth respectively (Charles *et al*. 2012).

The lower bentonite layer in the Longyearbyen section contain zircons, and ten analyses yielded $^{206}Pb/^{238}$236 U dates between 57.08 and 55.71 Ma. The five youngest analyses yielding a weighted mean $^{206}Pb/^{238}$249 U date of 55.785 ±0.034 (0.066)[0.086] Ma (Charles *et al*. 2012).

The P/E boundary is defined as the base of the PETM CIE (*Dupuis et al*., 2003). In order to constrain the age of the P/E boundary, the relative duration between the dated bentonite horizon and the onset of the PETM CIE is required. Taking into account both the cyclostratigraphic options and their uncertainty, together with the uncertainty from the radio-isotopic dating of sample of SB01-1, they derive at an age range of 55.728-55.964 Ma for the P/E boundary (Charles *et al*. 2012).

Main points for comparative analysis

- Ash layers not easily accessible for public
- The ash layers are altered, but exhibit important zircon-date records

Micellaneous sites

Ash layers from the Atlantic margin

Deep Sea Drilling Project Leg 550 encountered volcanic ash layers of earliest Eocene age at Goban Spur (southwest of Ireland) and in the Bay of Biscay. The recognition of ash layers –17 and +19 (from ther Danish ash layer succession in the Moler cliffs) was a major break-through in the understanding of the position of the ash producing volcanoes, and the ash layers potential for regional stratigraphic correlation (Knox 1985).

Central American eruptiv evnt

Sigurdsson *et al*. (2000) recorded a significant explosive volcanic event in Central America during the ODP Leg 165 investigation in the Carribian Sea. The oldest explosive volcanic phase is considered Early Eocene (c. 50 Ma) and the ash layers are interpreted as having originated from the Cayman ridge. The Carribian ash layer record of explosive episodes (volcanic ash layers) is claimed to be the largest and most complete recovered to date.

The Miocene succession includes ignimbrites and these have attracted much interest. Apparently the Early Eocene volcanic eruptions are some million years younger than the ash layers interbedded in the Moler Cliffs.

Descriptions of Early Eocene formations and their fossil records

Fur Formation, Denmark – Marine section

Age

The Fur Formation is of earliest Eocene (Ypresian) age. This has been confirmed by a $^{39}Ar/^{40}Ar$-date of 55.12 Ma obtained from the -17 ash layer in the formation (Storey *et al.* 2007). Combined with earlier $^{39}Ar/^{40}Ar$-dates (Chambers *et al.* 2003), the entire Fur Formation probably spans the age interval of 55-54 Ma. Additionally, the CIE and the *Apectodinium* acme marking the Paleocene/Eocene boundary has been identified in the underlying Stolleklint Clay Member of the Ølst Formation (Heilmann-Clausen & Schmitz 2000; Schmitz *et al.* 2004), with which the Fur Formation is stratigraphically continuous (Pedersen & Surlyk 1983). The *Apectodinium* acme has also been recovered in the lowermost part of the Fur Formation, up to the stratigraphic level of ash layer -19, and thus records the latter part of the PETM event (Willumsen 2004).

Geographic description of the sites

The Fur Formation is readily available at several coastal cliffs and open pit mines in the western part of the Limfjord area in northern Denmark (Pedersen & Surlyk 1983).

Lithology and palaeoenvironment

The Fur Formation is an approximately 60 meters thick, fine-grained diatomite, with occasional nodules and/or horizons cemented by calcite and including numerous volcanic ash layers (Pedersen & Surlyk 1983). The carbonate nodules and horizons have been shown to have formed through bacterial decomposition of organic materials within the sediment (Pedersen & Buchardt 1996).

The sediments are interpreted as having been deposited in a region of intensive local upwelling in the North Sea basin, where nutrient-rich bottom water resulted in extraordinary blooms of diatoms. Most of the formation was deposited at water depths below storm wave base, under anoxic or slightly dysoxic bottom conditions. Within certain horizons calcareous carbonate concretions occur, sometimes in more-or-less continuous layers (Pedersen & Surlyk 1983).

Fossil content

The fossil assemblage of the Fur Formation is extremely diverse; containing both micro- and macrofossils, as well as sampling both marine and terrestrial environments. The chief fossil microflora are marine diatoms, which make up upwards of 60% of the sediment (Pedersen *et al.* 2004). Additionally dinoflagellates, terrestrial spores and pollen have been reported, along with silicoflagellates and radiolarians (Heilmann-Clausen 1995, Mitlehner 1996, Willumsen 2004). The macrofossil assemblage is dominated by marine bony fish (Bonde 1966, 1982, 1997, 2008) and terrestrial insects (Rust 1999, 2000; Rust & Andersen 1999; Rust *et al.* 1999, 2008), but includes terrestrial plants (Bonde 1987), terrestrial birds (Lindow & Dyke 2006, Mayr &

Bertelli 2011), marine and terrestrial turtles (Nielsen 1959, 1963, Madsen 2011) as well as a few invertebrate bivalves, snails and crustaceans (Bonde 1987, Petersen 1997, Garassino & Jakobsen 2005).

The Fur Formation is well-known internationally from three-dimensionally preserved, articulated vertebrate fossils and insects. Furthermore, its taphonomy indicates it is a *Konservat-lagerstätte*, an area of exceptional fossil preservation (Dyke & Lindow 2009). Fossil preservation of feathers (as melanosome grains) and other soft tissue, which is extremely rare on a global scale, has been described from birds and bony fish (Lindow & Dyke 2007, Vinther *et al.* 2008; Lindgren *et al.* 2012). Finally, certain levels of the diatomite contain abundant trace fossils (Pedersen 1981, Pedersen and Surlyk 1983).

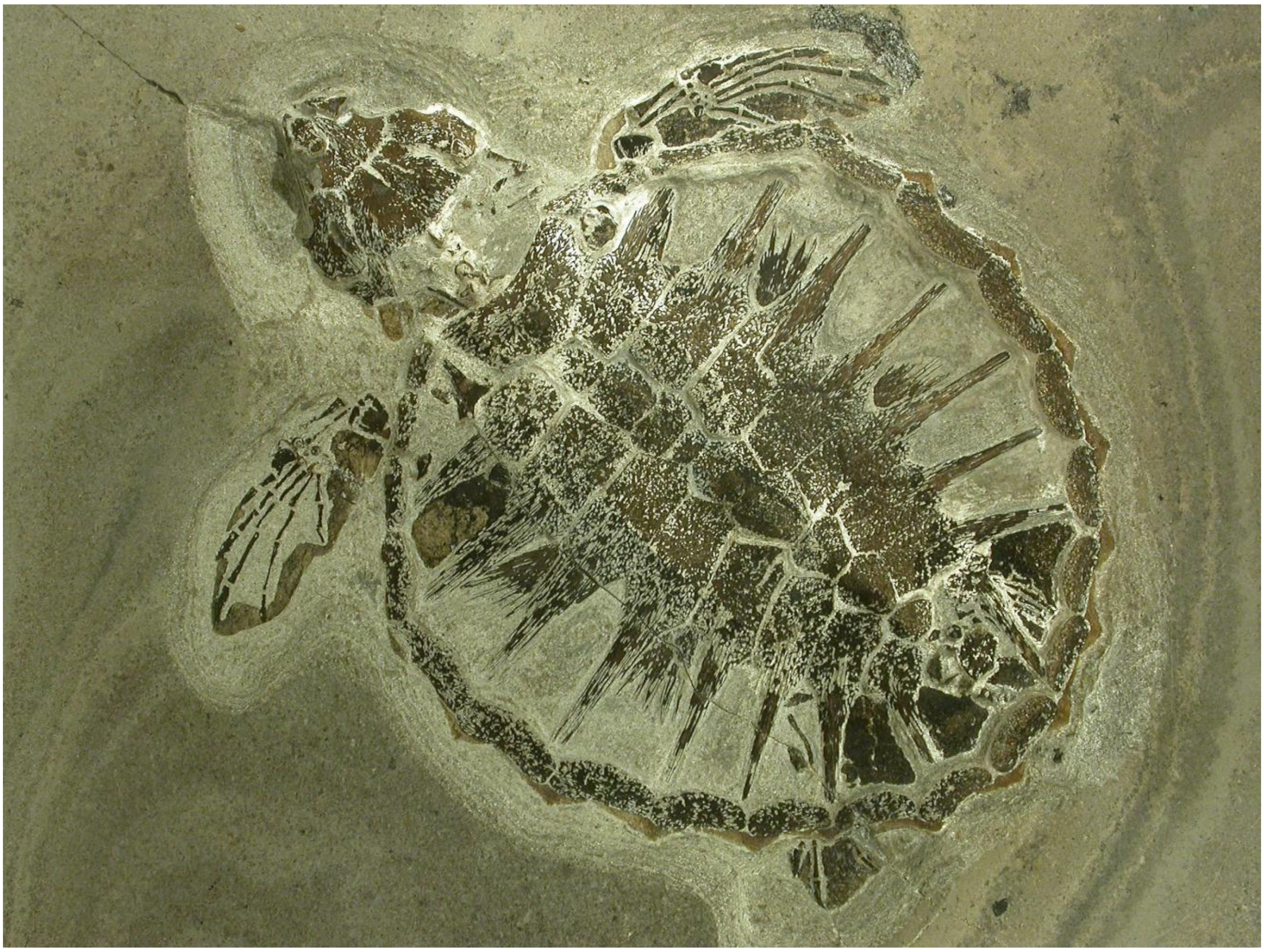


Figure 18. *This fossil is probably the best preserved young sea turtle in the world. It is 10 cm in size and even the web of the flipper can be recognized. It was found in the Fur Formation on northern Mors.*

Significance of the site

The deposits of the Fur Formation provide the single most comprehensive insight into the biodiversity during and immediately after the PETM event. It is an internationally exceptional fossil site with exquisite preservation of elements from both marine (microflora and -fauna, fish and turtles) and terrestrial ecosystems (pollen and spores, plants, insects and birds). Additionally, the Fur Formation produces fully articulated skeletons and soft tissue such as feathers.

The Fur Formation can be, and has been, correlated to other fossil-bearing sections worldwide, and represents a continuous sedimentary record across PETM event, when combined with the underlying Stolleklint Clay Member of the Ølst Formation. This section also contains well-preserved fossils, and preliminary studies indicate major differences in the fish faunas between the Stolleklint Member and the Fur Formation (Bonde 1997). This has important implications for potential future studies addressing turnovers in marine fish ecosystems at the time of the PETM global warming event.

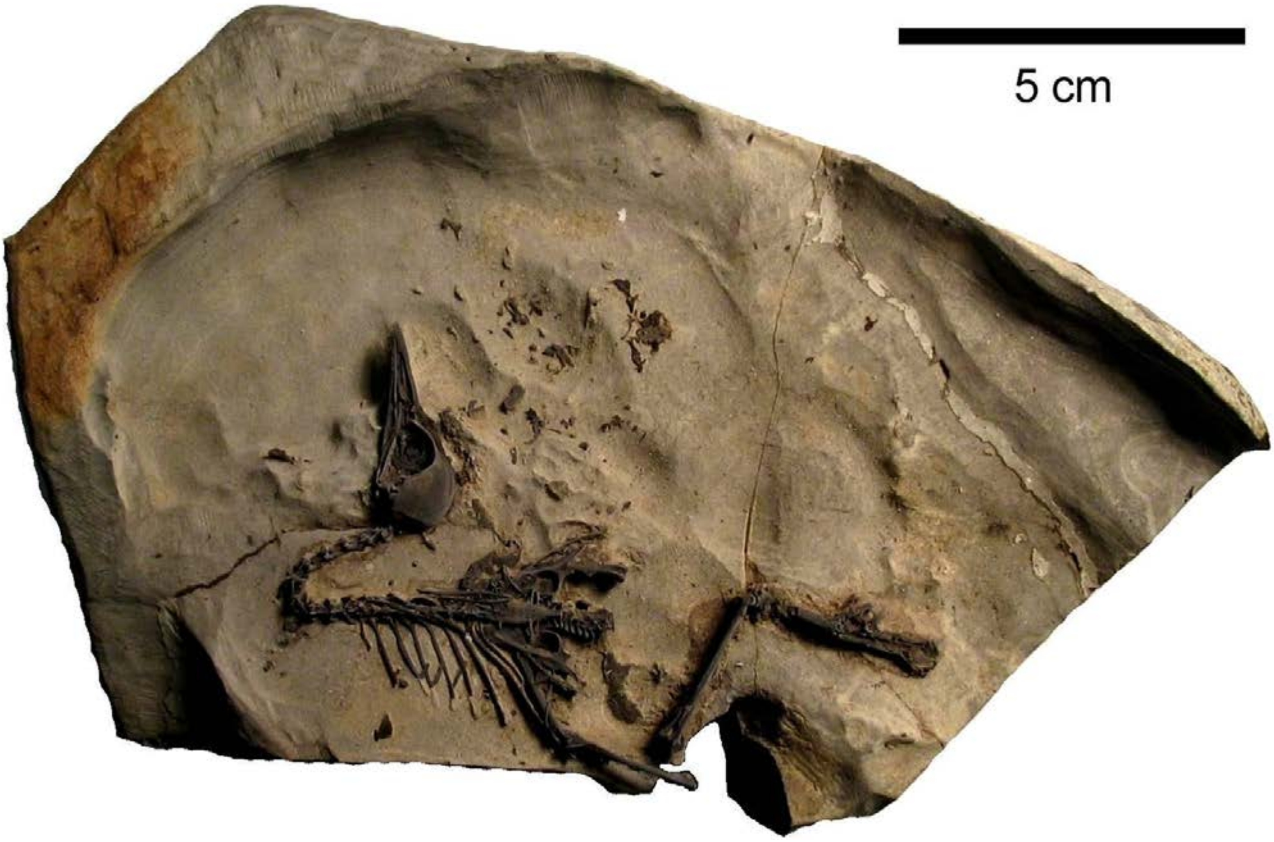


Figure 19. *The Fur Formation is especially well known for the fossils of birds. This very well preserved skeleton of a bird (Morsavis sedilis) is the oldest known species representing the sea gulls and waders. However, the construction of its feet indicates that it in contrast to its present relatives was more adjusted to live in the woods.*

Soisonnais Formation, Paris Basin, France – marine and terrestrial sections

Age

The Soisonnais Formation is earliest Eocene based on dinoflagellates (Zone W1), charophyte algae (*Peckichara disermas* zone) and is referrable to European Paleogene Mammal Zone MP7 based on the composition of the mammal fauna (Nel *et al.* 1999). At the Sotteville-sur-Mer locality in Normandy, the Soisonnais Formation overlies the Mortemer Formation, which contains the CIE (Smith *et al.* 2011).

Geographic description of sites

The Soisonnais Formation crops out throughout the central Paris Basin and on the Normandy coast (Smith *et al.* 2011). The main site at Le Quesnoy is situated near Houdancourt in the Oise Department of northern France. Here two fossil-bearing subsites are known, each representing a fossil channel infill (Nel *et al.* 1999).

Lithology and palaeoenvironment

The layers of the Soisonnais Formation are well-bedded clays, silts and sands with some shell layers and lignites. The average thickness of the entire formation is 10 meters (Aubry *et al.* 2005). The Soisonnais deposits represent open marine environments (Craquelins Member); a tidal environment (upper Vauxbuin Member; Ailly Member), tidally influenced marine marshes (Vexin Member), and terrestrial environments with lakes and swamps (lower Vauxbuin Member), while the deposits at le Quesnoy have been interpreted as being deposited in a forested fluvio-lacustrine environment under a warm, seasonally wet climate, based on preliminary analysis of plants, vertebrates and arthropods by Nel *et al.* (1999).

Fossil content

The Vauxbuin Member preserves dinoflagellates, charophytes, marine bivalves and some plant remains. From the Vexin Member come dinoflagellates, foraminifera, ostracodes, marine bivalves and fish remains (Aubry *et al.* 2005). The Le Quesnoy locality has yielded fossil-bearing amber, a diverse flora of fossil pollen, fruits and well-preserved plant fossils, as well as more than 20,000 arthropod specimens in amber representing 300 taxa of which 79 species had been described by 2009; thousands of teeth, scales and bones of freshwater fish; amphibians; 22 taxa of reptiles; and 24 taxa of mammals (Nel *et al.* 1999, Jacques & de Franceschi 2005, Dutheil *et al.* 2006, Brasero *et al.* 2009). Additionally, the amber has preserved soft tissue such as mammal hair, bird feathers, skin casts and spider webs (Nel *et al.* 1999).

Significance of the formation

The Soisonnais Formation preserves one of the World‟s most diverse earliest Eocene fauna and flora. It encompasses numerous depositional environments, and has been regionally correlated to the Woolwich and Reading Formations of the Hampshire-London basins and the Tienen Formation of Belgium (Aubry *et al.*

2005). The deposits at the Le Quesnoy site are remarkable for a great diversity, numbers and exceptional preservation of arthropods, from an important time period which is otherwise devoid of fossiliferous amber deposits. Some fossil insects preserved in amber are the oldest known representatives of their lineages and their excellent state of preservation merits the designation *Konservat-lagerstätte* for these fossils (Nel *et al.* 2004a,b, Brasero *et al.* 2009). Additionally, the flora shows similarities to the early Eocene of the Paris basin, while the fauna is similar to that of the Dormaal Sand Member of the Tienen Formation in Belgium (Nel *et al.* 1999). Studies of fruit endocarps have confirmed the presence of a megathermal climate in Europe in the lowermost Eocene (Jacques & de Franceschi 2005).

Tienen Formation, Mons Basin, Belgium – terrestrial and marine sections

Age

Latest Paleocene - Earliest Eocene. The Dormaal Sand Member of the formation is the type section for European Paleogene Mammal Zone MP7 and has been interpreted as deposited prior to the CIE, with a suggested age of 55.8-55.5 Ma (Smith 2000). The CIE as well as the *Apectodinium* acme has been recovered from sediments referred to the Tienen Formation in the Kallo borehole (Steurbaut *et al.* 2003). Fossil wood-bearing strata at Hoegaarden have been referred to the PETM (Fairon-Demaret *et al.* 2003).

Geographic description of sites

The Tienen Formation occurs throughout northern Belgium and the eastern part of Mons Basin (Fairon-Demaret *et al.* 2003). Five major outcrops are known: Dormaal (vertebrate fossils), Orp-le-Grand, Hoegaarden (fossil tree stumps), Erquelinnes and Leval (fossil plants), of which Dormaal is the most intensely studied (Smith, 2000). In addition more than 30 fossil localities dating to the Paleocene-Eocene transition are known from Belgium, but most are small or boreholes (Fairon-Demaret & Smith 2002). The Dormaal Sand Formation stratotype locality is located between the towns of Tienen and Sint-Truiden in eastern Belgium (Fairon-Demaret & Smith 2002). The Goudberg-Hoegaarden section is a rail and motorway-side cut located 3 kilometers southwest of the city of Tienen (Fairon-Demaret *et al.* 2003).

Lithology and palaeoenvironment

The basal Dormaal Sand Member is a series of thin layers of pebbly sand beds, interbedded with lignitic and clayey sands with a total thickness of less than 1 (one) meter (Fairon-Demaret & Smith 2002). The middle part of the Tienen formation exposed at Goudberg-Hoegaarden consists of fine sands and silt some meters thick, with a lignitic, fossil tree-bearing horizon (Fairon-Demaret *et al.* 2003).

The Dormaal Sand Member has been interpreted as a fluvio-lagoonal environment deposited in a large valley during a marine lowstand; specifically the paleoenvironment was a warm humid climate or subtropical forest with dry and wet periods, revealed through combined analysis of plant, mammal and microfaunal fossils

(Smith 2000). The strata in the Goudberg-Hoegaarden section have been interpreted as an assemblage of fluviatile, lacustrine and peat swamp environments (Fairon-Demaret *et al.* 2003).

Fossil content

The Tienen Formation Dormaal Sand Member contains a very diverse and rich fauna of terrestrial mammals, snakes, lizards, birds, crocodiles, amphibians and fishes (Fairon-Demaret & Smith 2002). Terrestrial mammals are represented by around 14,000 teeth identified to 55 taxa (Smith 2000). Furthermore, 47 taxa of shark have been identified from teeth (Gaudant & Smith 2008). A small number of badly-preserved fruit and seeds have been recovered and identified from the Dormaal Sand Member (Fairon-Demaret & Smith 2002). An angiosperm leaf assemblage is known from Leval, while the younger Goudberg-Hoegaarden section from the middle part of the Tienen Formationen revealed hundreds of fossil tree stumps preserved *in situ*, but almost completely lacks microfossils (Fairon-Demaret *et al.* 2003). Although hardly any microfossils have been recovered from terrestrial exposures of the formation, an assemblage of dinoflagellates, as well as a marine and terrestrial palynoflora has been recovered from sediments in the Kallo borehole, which are correlatable to the Tienen Formation (Steurbaut *et al.* 2003).

Significance of the site

The Dormaal Sand Member has been extensively excavated for fossils since the 1880‟es and displays a rich and diverse flora and fauna dating to the PETM. It is also of great stratigraphic importance as the type section for reference level MP7 of the European Paleogene with more than 50 terrestrial mammal taxa identified (Schmidt-Kittler 1987, Smith 2000, Fairon-Demaret & Smith 2002). A number of mammal genera show strong affinities with Northern European and North American faunas of the same age, less so with faunas from Southern Europe and Asia, and the Tienen formation can thus be correlated to several formations in North America and Europe (Smith 2000).

Cambay Shale Formation, Vastan Lignite Mine, India – marine and terrestrial sections

Age

The age of the Cambay Shale Formation is currently disputed. The largest body of work describes the sections exposed at the Vastan Lignite Mine locality as possibly latest Paleocene and reaching into the Early Eocene based on dinoflagellates (latest NP9 to possibly lower NP12; latest P5- to early P7) (Garg *et al.* 2008). However, this date has been challenged recently by a taxonomic re-analysis of foraminifers of the genus *Nummulites*, which imply a much younger age for the entire main section, referring it instead to biozones NP12 (entire) and uppermost P6 to P7 (Punekar & Saraswati 2010; see also Rust *et al.* 2010).

Additionally, a CIE assumed to be representing the second Eocene Thermal Maximum (ETM2: ca. 53.7 Ma) has been identified in strata immediately above the Cambay Shale Formation (Clementz *et al.* 2011).

Geographic description of sites

The Cambay Shale Formation outcrops in several areas around the Gulf of Cambay in western India; the main locality for fossils from the Cambay shale is the Vastan Lignite mine, which is located 30 kilometers northeast of the city of Surat. Here, some 200 meters of sediments belonging to the Formation overlie the older volcanics of the Deccan Traps (Garg *et al.* 2008).

Lithology and palaeoenvironment

Sediments of the Cambay Shale Formation consist of carbonaceous greenish-grey shales and lignites, interbedded with carbonates. The deposits have been interpreted as being deposited in marine bays, tidal creeks and coastal marches during a large-scale marine transgression of western India during the Paleocene-Eocene (Garg *et al.* 2008).

Fossil content

The shales of the lower, informally-named Succession A are devoid of macrofossils, but marine molluscs are common in the upper levels with four shell carbonate horizons also containing nummulitid foraminifers, as well as a sparse dinoflagellate assemblage collected from a few horizons (Garg *et al.* 2008). There is a very high diversity of vertebrates including sharks, teleost fish, reptiles, turtles, birds and especially mammals represented by isolated, but diagnosable bones and teeth (Rana *et al.* 2004, Prasad & Bajpai 2008, Bajpai *et al.* 2009, Rose *et al.* 2009, Mayr *et al.* 2010, Clementz *et al.* 2011). Finally, a very diverse and well-preserved insect fauna of 700 specimens preserved in amber and representing approximately 55 families and more than 100 species has recently been reported (Rust *et al.* 2010). The state of preservation of these insects merits the formation the designation of *Konservat-lagerstätte* for the amber fossils.

Significance of the site

The fossils of the Cambay Shale Formation is the earliest known record of Cenozoic reptiles, mammals and birds from the Indian subcontinent. Additionally, the mammal fauna has links to both Europe and southeast Asia and may provide important clues to dating the plate tectonic collision between Asia and the Indian subcontinent (Rose *et al.*, 2009; Clementz *et al.*, 2011), while bird fossils show a possible connection to Europe (Mayr *et al.*, 2010). The recently-reported amber insect fauna is a unique record of fully tropical palaeoenvironment otherwise not known from the Paleogene, and displays taxonomic ties to Eocene of Europe as well as the Miocene-recent of tropical America and Australasia (Rust *et al.*, 2010).

Willwood Formation, Bighorn and Clarks Fork Basins, Wyoming and Montana, USA – terrestrial sections

Age

The Willwood Formation is latest Paleocene – Early Eocene in age, based on the presence of mammalian fossil referable to the Clarkforkian and Wasatchian North American Land Mammal Ages (NALMAs). It contains the CIE and has an estimated age of 55,5 to 53 million years (Bowen *et al.* 2001; Gingerich 2003; Clyde *et al.* 2007).

Geographic description of sites

The Willwood Formation and is comprised of several well-exposed fossil localities with a lateral persistence of several kilometers in badlands and canyons, which can be reached by car and foot from Powell, Wyoming. The main Polecat Bench exposures are located about 8-10 kilometres north and west of Powell. Outside Polecat Bench, the fossil-bearing Paleocene and lower Eocene strata extend for around 20 km to the west across the Clarks Fork Basin, as well as 120 km to the southeast through the entire Bighorn Basin (Gingerich, 2003).

Lithology and palaeoenvironment

The Willwood Formation consist of red, yellow-brown and purple mudstones and mudrocks, which have been interpreted as channels, channel fills, floodplain palaeosols and swamps, deposited in an environment small fluvial systems in subsiding intermontane basins (Kraus 2001, Wing *et al.* 2005). More than 700 meters of the Willwood Formation are exposed at the Polecat Bench section (Gingerich 2003). Plant fossils indicate that during the PETM climate in the basin rapidly warmed 5 to 10 °C and the environment shifted from a humid to a drier environment during the PETM, gradually becoming more humid afterwards (Wing *et al.* 2005).

Fossil content

Vertebrate fossils are represented by bones or teeth sieved from sediments. More than 150 mammalian species represented by more than 40,000 thousand specimens have been collected (Gingerich, 2003; Wing *et al.* 2005; Chew *et al.* 2009). Other vertebrate fossils include fish scales and reptile bones (Gingerich 2003, 2006), a very diverse turtle fauna (Holroyd *et al.* 2001), and a number of bird fossils (Houde, 1988, Mayr 2009). Invertebrates are represented by non-marine snails (Hartman & Roth 1998). More than 25,000 palynomorphs have been collected in the Paleocene-Eocene of the Bighorn Basin (Wing *et al.* 2005), endocarps ("fruit stones") are abundant in the Wa-0 interval marking the CIE (Gingerich 2003),; all-in-all 398 specimens of plant megafossils representing 29 morphospecies have been collected in a stratigraphic interval spanning the PETM, but approximately 30,000 megafossil specimens are known from Paleocene-Eocene localities across the entire Bighorn Basin (Wing *et al.* 2005); ichnofossils are abundant and very diverse (Smith *et al.* 2008).

Significance of the site

The terrestrial Paleocene-Eocene record at Polecat Bench section contains the CIE and records the attendant PETM event (Bowen *et al.* 2001). An excellent detailed stratigraphic resolution of fossil finds has been used to document faunal turnover and attendant dwarfing amongst mammals during the PETM event; the transition between the Clarkforkian and Wasatchian North American Land Mammal Ages (NALMAs) (Gingerich 2003, 2006, Chew 2009); changes in turtle faunal composition (Holroyd *et al.* 2001). In addition plants fossil document rapid floral turnover and environmental change (Wing *et al.* 2005).

Woolwich Formation, Hampshire & London Basins, England – marine sections

Age

The Woolwich Formation is of earliest Eocene age and records the *Apectodinium* acme (Ellison *et al.* 1996, King 2006). The CIE has been identified in the Cobham Lignite Bed, which underlies part of the formation at the Scalers Hill locality in Kent, England (Ali & Jolley 1996, Ellison *et al.* 1994, Collinson *et al.* 2007).

Geographic description of sites

The Woolwich Formation occurs throughout southeast England, with a few available exposures, such as the type section at Charlton in southeast London and Lower Upnor Pit in Kent, although the formation is also locally exposed in East Anglia (Ellison *et al.* 1994, King 2006).

Lithology and palaeoenvironment

The Woolwich Formation consists of dark grey to grey-brown organic-rich shelly clays with heterolithic sediments, sand beds and coarse-material channels. The lower 2 meters is composed of brackish water shells, while there is a „*Paludina* limestone bed" in the top. Occasional, thin lignites are found within the formation. All together, the formation reaches thicknesses of up to 14.5 meter, with an average of 11-12 meters (Ellison *et al.* 1994).

The formation is interpreted to have been deposited in a low-energy marine setting with some freshwater influences (Ellison *et al.* 1994, King 2006).

Fossil content

The palynoflora is varied and rich, although calcareous nannofossils are absent (Ellison *et al.* 1994). Bivalves are present, primarily oyster beds and abundant *Corbicula* clams at some levels. Vertebrates are represented by shark's teeth referable to a few species, as well as fragments of bony fish teeth and bones (Ward 1980). Trace fossils such as *Thalassinoides* burrow systems are abundant in some levels (King 2006).

Significance of the site

The *Apectodinium* acme is present in the Woolwich Formation referring it to the time of the PETM. On a local scale, the lower and middle Woolwich formation is correlatable to the Reading Formation, which contains the CIE is its continental facies equivalent (Ellison *et al.* 1994, Collinson *et al.* 2007). Together the two formations form the lowermost Eocene of the Hampshire and London Basins, and have been correlated to the deposits of the Paris and Mons Basins in continental Europe (e.g. Smith 2000, Aubry *et al.* 2005). Additionally, macroinvertebrate fossil assemblages from the PETM are extremely rare and have so far gone without description (Ivany & Sessa 2010), so the rich shell beds of the Woolwich Formation would provide an opportunity for further studies.

Esna Formation, Dababiya, Egypt – marine sections

Age

The Esna Formation is earliest Eocene in age and contains the CIE, while spanning the nannoplankton NP8/NP9 zonal boundary up to including NP11 and possibly NP12; foraminifera zones P4 to P7 (Aubry *et al.* 2007).

Geographic description of sites

The Dababiya quarry site is located 35 km south of Luxor in Egypt, and is easily reached by car. The section is laterally exposed in an area of approximately 0.5 * 0.5 kilometers. Sediments of the Esna Formation and associated deposits are exposed throughout northeastern Egypt and the Western Desert (Aubry *et al.* 2007).

Lithology and palaeoenvironment

The formation consists of Eocene limestones, marls and shales with phosphatic nodules. All together, the vertical thickness in the sections at Dababiya is around ~160 meters. The depositional environment of the Esna Formation has been interpreted as outer neritic to upper bathyal (Ernst *et al.* 2006, Aubry *et al.* 2007).

Fossil content

The formation contains “abundant and well-preserved” microfossils of foraminifers, dinoflagellates, and calcareous nannoplankton; coprolites are numerous in some levels (Aubry *et al.* 2007). High numbers of fossilized parts of fishes (bones, teeth, jaws, scales) are present immediately above CIE layers, but become absent a few meters above. Finally, trace fossils in the shape of bioturbation and burrows present (Ernst *et al.* 2006).

Significance of the site

The GSSP for the base of the Eocene is fixed at the base of the El Mahmiya Member of the Esna Formation at the locality. The locality presents and unbroken sedimentary record across the Paleocene-Eocene boundary, as well as recording the global Carbon Isotope Excursion (CIE) related to the Paleocene-Eocene Thermal Maximum (PETM), as well as the turnover in marine nannoplankton (Aubry *et al.* 2007). For this reason, the Dababiya Quarry is on the tentative list of UNESCO world heritage sites.

Zumaia deposits, Basque Basin, Spain – marine sections

Age

The deposits at the Zumaia locality have not been formally assigned to a geological formation. They span the Paleocene-Eocene boundary, with the CIE clearly identified. It spans the nannoplankton zones NP7+8 to NP10, as well as planktonic foraminifera zones P5 to P6a (Schmitz *et al.* 1997, Baceta *et al.* 2000).

Geographic description of the site

The Zumaia deposits are located approximately 20 kilometers west of the city of San Sebastian in the Gipuzkoa province of northern Spain. The locality situated in a sea-cliff on the Itzurun beach below the town of Zumaia, with strongly inclined strata (Baceta *et al.* 2000). A section with similar deposits from the Basque Basin occurs at the Trabakua Pass in northern Spain, but studies indicate that the sediments here have been subject to deep burial diagenesis (Baceta *et al.* 2000)

Lithology and palaeoenvironment

The Paleocene-Eocene boundary sediments at Zumaia are alternating layers of gray and green limestones, marly limestones and marlstones. The Paleocene-Eocene boundary is marked by a 0,3 meters thick marlstone bed overlain by four meters of claystones. All together, the entire section at Zumaia has a total thickness of more than 80 meters (Baceta *et al.* 2000). The deposits have been interpreted as hemipelagic sediments interbedded with thin turbidite layers and the depositional environment is interpreted as outer marine with a depositional depth around 1,000 meters (Baceta *et al.* 2000, Dinarès-Turell *et al.* 2002).

Fossil content

The formation contains planktic and benthic foraminifers, as well as calcareous nannoplankton (Schmitz *et al.* 1997, Alegret *et al.* 2009).

Significance of the site

The deposits in the Zumaia section are widely recognised as one of the most complete and depositionally expanded marine sections for studying the Paleocene-Eocene boundary transition. It was therefore a prospective GSSP for the base of the Eocene (Dinarès-Turell *et al.* 2002, Schmitz *et al.* 2004). Here the unbroken sedimentary record across the Paleocene-Eocene boundary records the global Carbon Isotope Excursion (CIE), the benthic foraminifera extinction event and turnovers in marine nannoplankton at the PETM, as well as a solid geochemical, magnetostratigraphic and cyclostratigraphic records (Schmitz *et al.* 1997, Dinarès-Turell *et al.* 2002, Schmitz *et al.* 2004).

Figure 20. *One of the most common fish fossils in the Fur Formation is the barbudo, Polymixiid. The fossil is 12 cm long and was preserved withour matrix between the fish bones in a calcareous concretion near ash layer +15.*

Description of sites representing the Pleistocene glaciotectonic complexes

Sites meeting the four main criteria

Glaciotectonic complex	Country	Age of deformation
Moler cliffs Limfjorden	Denmark	Weichselian
Møns Klint	Denmark	Weichselian
Rügen	Germany	Weichselian
Aquinnah, Martha‟s Vineyard	USA	Wisconsin
Mud Buttes	Canada	Wisconsin
Dirt Hills & Cactus Hills	Canada	Wisconsin (and earlier)
Cromer Beach, Norfolk	United Kingdom	Middle Pleistocene
Killala Bay	Ireland	Late Pleistocene
Muskauer-Faltenborgen	Poland-Germany	Middle Pleistocene

Table 4. *The table summarises the sites considered in the comparative analysis. Note that Weichselian and Wisconsin are both late Pleistocene. Middle Pleistocene is in general referred to the Elsterian glacial age. However, some stratigraphic uncertainties remains to be solved in the correlation from marine isotope stages (MIS) and terrestrial glacial deposits.*

Moler Cliffs, Limfjorden, northern Denmark

The Moler Cliffs at Limfjorden comprises 11 well described cliff sections displaying glaciotectonic complexes (Fig. 1). Among these two are selected for representing the property to be nominated for the candidate list of the UNESCO World Heritages: the Hanklit and the Knudeklint. Both cliffs have a long record of investigations, a profile have been constructed for both cliffs, and balanced cross-section constructions have been carried out for the structural complex to perform a basis for a dynamic interpretation of their sequential formation. Both cliffs represent a cross-section through a composite ridges system, which morphologic can be recognised over an area of 20 km^2. The cliffs are easy accessible by a walking distance from at parking place near the shore. The coastal cliff profiles have along record of sustainability being informatively exposed for more than 75 years.

Hanklit north coast of Mors

Hanklit is a 60 m high coastal cliff section, more than 500 m long (Fig. 6). It is located at the north coast of the island of Mors, northern Denmark (Fig. 5). Its most impressive structure is a thrust sheet with a hanging-wall anticline displaced 300 m along a gentle dipping thrust fault. This thrust sheet is the middle one in the complex comprising three large sheets displaced piggy-back on each other.

The stratigraphy of the thrust sheets constitutes about 40 m of the Fur Formation (Eocene diatomite with volcanic ash layers) overlain by 15-20 m glacial deposits of Weichselian age (Gry 1940, Klint & Pedersen 1995). A detailed structural analysis including a profile and a balanced cross-section is provided by Klint & Pedersen (1995). The Hanklit profile represents a cross-section through the proximal part of a 3 x 10 km^2 wide arc-formed composite ridge system pushed up by the Norwegian Ice Advance about 28.000 years ago.

The composite ridge system stands out as marked hills in the glacial morphological landscape of Mors. The highest point on Mors, Salgjerhøj 89 m above sea level, is located in the central eastern part of the hilly complex. Beyond Salgjerhøj an additional moler cliff is located, and to the west of Hanklit cliff section trends parallel to the fold axis, whereas cross-section perpendicular to the fold axes can be seen in a minor number of clay pits.

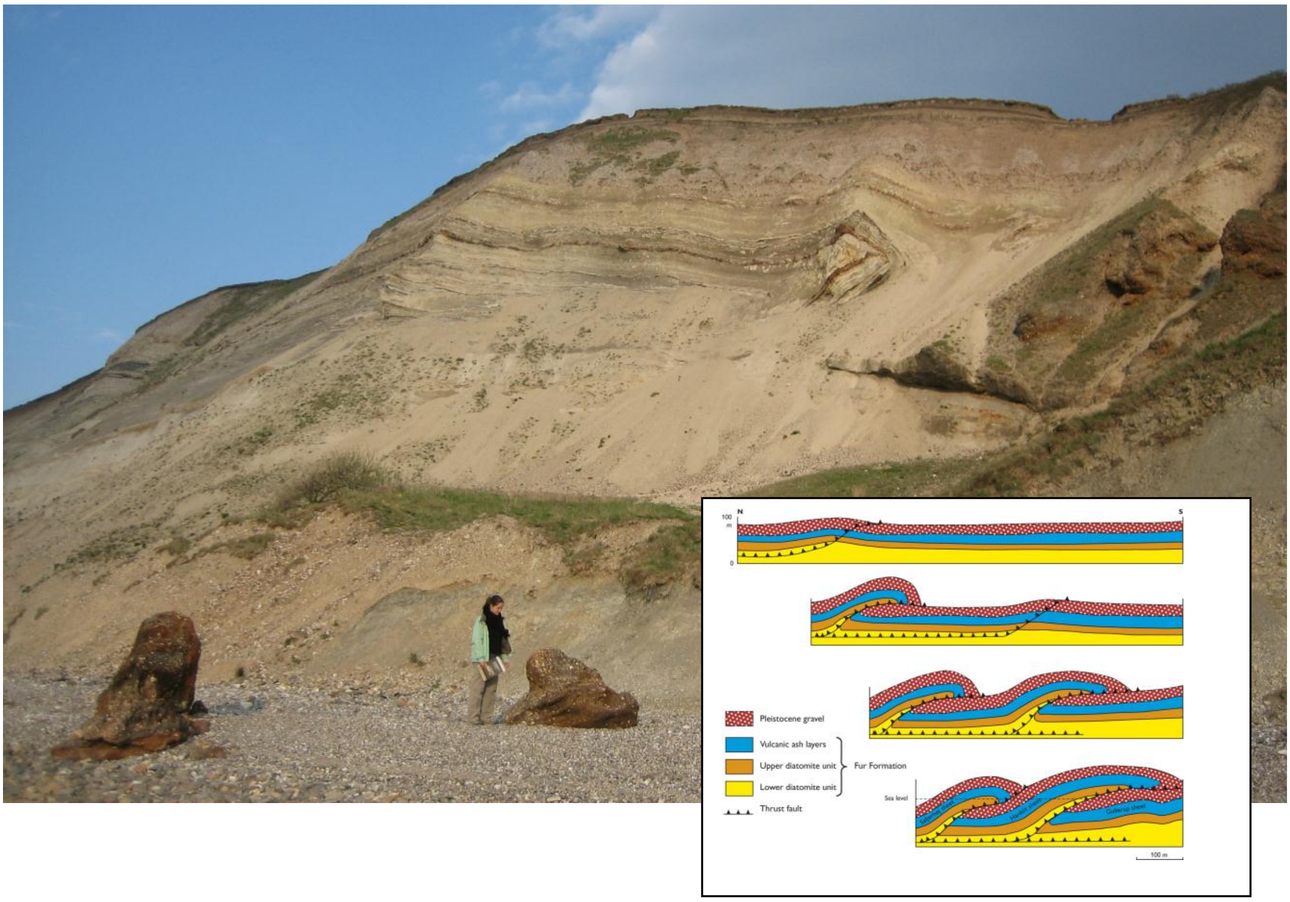


Figure 21. *The frontal part of the Hanklit thrust sheet comprising the Eocene Fur Formation forms an impressive hanging-wall anticline, which was displaced for abot 300 m along a thrust fault above outwash plain deposits. The diagram in the lower right corner illustrates the dynamic development.*

Knudeklint northwestern corner of Fur

Knudeklint is a 35 m high coastal cliff on the NW-corner of the island of Fur situated in the central part of Limfjorden, northern Denmark (Fig. 5). The profile is about 1 km long and contains seven larger thrust sheet with the Early Eocene Fur Formation as the dominant lithological unit (Gry 1940, 1965,). The most impressive structure is the large-scale folded thrust-sheet at the transition from the proximal to the distal part of the complex. This structure comprises two anticlines separated with an upright, tight syncline. In the core of the syncline the youngest Eocene beds records the upper boundary of the Fur Formation, whereas the lower boundary of the Fur Formation crops out along the hanging-wall ramp limiting the distal anticline (Pedersen 2000, 2011).

Due to the well represented stratigraphic record of the complete succession of the Fur Formation, the Knudeklint is the type locality of the Fur Formation. The deformation of the glaciotectonic complex on Fur took place during the Norwegian Ice Advance about 28.000 years ago (Pedersen 2011). A succession of 8-10 m glaciofluvial sand and gravel was carried piggy-back on the thrust sheets. This sand unit represents a proglacial outwash deposit, which in the foreland of the glaciotectonic complex fill out a former tunnel-valley more than 60 m deep. The advancing ice pushed the thrust sheets up in a composite ridge system creating the hilly northern part of the Fur island.

Figure 22. *The Knudeklint comprises a folded complex with two anticlines separated by an upright syncline. The folded unit comprises the 60 m thick Fur Formation, which visitors can work pass and study in the beds vertical position.The site is naturally the type locality of the Fur Formation.*

Møns Klint southeastern Denmark

Møns Klint is an about 100 m high coastal cliff located along the east coast of the island Møn in the south-eastern part of Denmark. The coastal cliff is about 5 km long and comprises 15 thrust sheets of white Cretaceous chalk. On top of the chalk, Upper Maastrichtian of age (ca. 66 Ma), a succession of two Weichselian tills inter-layered by glaciolacustrine and –fluvial deposits caps the thrust sheets. This resulted in a morphology characterised by white cliffs separated by vegetation rich gullies created in the soft Quaternary sediments.

The Møns Klint is a classic glaciotectonic site, which has been known for more than 150 years. The cross-section published by Puggaard (1851) was performed in a copper engraving, which has been reproduced in several publications ever since. The deformation was one of the youngest Weichselian events caused by the Baltic Ice Advance about 18.000 years ago, and the complex was furthermore superimposed by a recessive ice advance close to the termination of the ice age (Pedersen 2000, Pedersen & Gravesen 2009).

The southern part of the coastal cliff displays a cross-section of the structures perpendicular to the main strike of thrust faults, and the composite ridges can be followed along strike for about 5 km inland. The highest point in the complex is 143 m above sea level. The geomorphology of the hills is to some extent covered by woods, but the footpath along the edge of the cliff is famous for its scenic views. A natural centre has recently been established on top of the cliff.

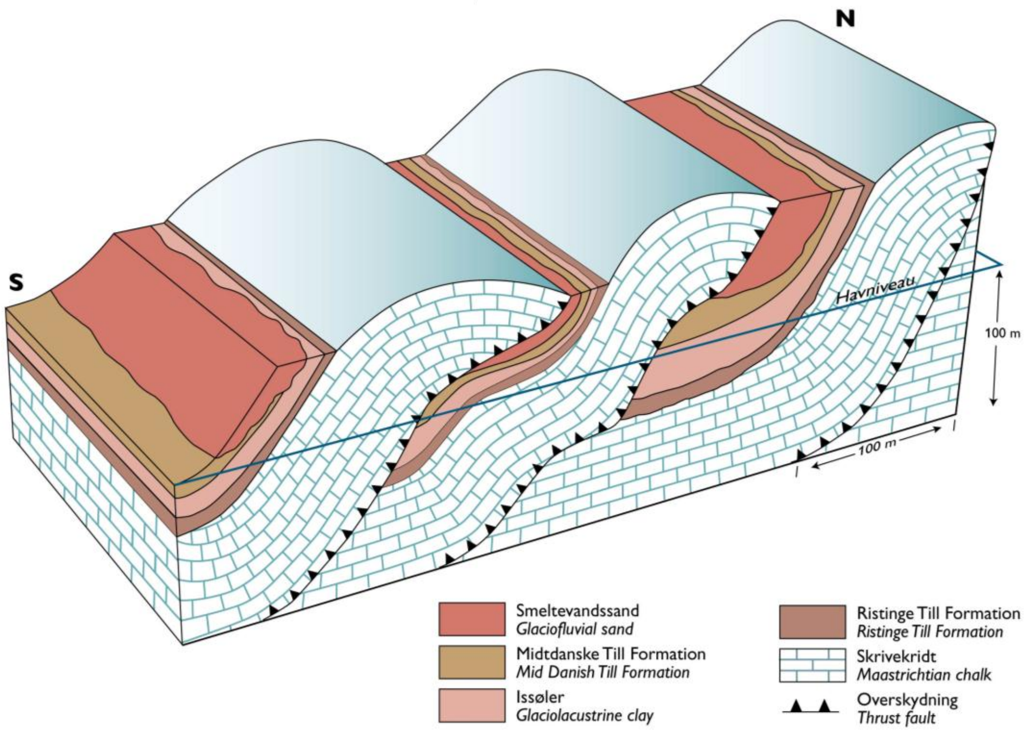


Figure 23. *Block diagram illustrating the framework of the thrust fault structures in the southern part of the Møns Klint glaciotectonic complex. From Pedersen & Gravesen (2009).*

Figure 24. *The scenic view of the three chalk thrus sheets illustrated in the block diagram in Fig. 23. Note that the Quaternary deposits on the back of the chalk unit and below the thrust fault of the overriding thrust sheet developed erosional gullies covered by vegetation.*

Jasmund east coast of Rügen, Germany.

The glaciotectonic complex at Rügen is located in the Jasmund National Park with the nature exhibition center Köningsstuhl in the hilly woods about a kilometer from the coastal cliff on the Island Rügen, which is an island in the Baltic Sea, NE Germany. Exposed cross sections are accessible along the more than 20 km long coastal cliff of the peninsula Jasmund and the Kap Arkona in the NE and N part of Rügen. The cliffs are up to 100 m high and the pre-Quaternary unit comprises Maastrichtian (Upper Cretaceous) chalk. The thrust sheets constitutes about 90 m Cretqaceous chalk and about 40 m Pleistocene glacibene sediments (Ludwig 2011). The chalk cliffs at Rügen have repeatedly been compared to the glaciotectonic complex at Møns Klint, Denmark (Johnstrup 1874, Slater 1927, Gripp 1947, Ludwig 2005, 2011). The chalk stratigraphy is similar and the glaciotectonic deformation is referred to the same late Weichselian event. However, the structures at Rügen have always been regarded as a more complex architecture, which in general is interpreted as the effect of an interlobate compression (Gripp 1947, Ludwig 2011). The compression was in the NE directed towards the southwest, and in the SE it was directed towards the west or westnorthwest. An alternative model for the interpretation could be a superimposed deformation, first with a glaciotectonic displacement caused by the Swedish Ice advance (Brandenburg Stadium), secondly superimposed by the deformation caused by the Baltic Ice advance about 17.000 years BP (Pedersen 2000, Stephan 2001, Pedersen 2005). The glaciodynamic origin is still discussed with a number og suggestions for Neotectonic and gletscher dynamic models. Although Ludwig‟s (2005, 2001) presentations of cross sections documents the structure of the glaciotectonic complex at Rügen, a detailed structural analysis with application of balanced cross section construction has not been prepared.

Figure 25. *Two thrust sheet of upper Cretaceous chalk are separated by a unit of Weichselian glacial deposits. Note the hanging-wall anticline nicely outlined by the flint beds in thrust sheet to the left. The coastal cliff at Jasmund, east coast of Rügen, northern Germany.*

Gay Head Cliff on Martha's Vineyard, Massachusetts, USA.

The Gay Head Cliff is a ca. 45 m high coastal cliff exposed at the western end of the island Martha‟s Vineyard, Massuchusetts, USA. The cliff section is about one kilometre long and comprises about 5 thrust sheets, which have been overturned folded towards the south. The stratigraphic unit comprises upper Cretaceous silt and sand with intervals of white kaolinite and black lignite layers as well as red plastic clays. The Cretaceous beds are overlain by Miocene glauconitic sand and a layer of lower Pleistocene conglomerate (Kaye 1964, 1980).

The complex consists of 20-30 m thick thrust sheets, which are folded in a complicated framework. The complex represents a cross-section through the Aquinnah cupola hill, with the highest point about 85 m above sea level. The deformation of the complex took place during the glacial advance in the late Wisconsin about 28-24.000 years ago (Ridge 2004).

The cross-section of the Gay Head Cliff glaciotectonic complex was sketched by Woodworth (1897) at a time when a glaciotectonic origin of the structures in the cliff were generally accepted (Aber & Ber 2007). Later constructions of the cross-section was published by Kaye (1980), but detailed structural investigations with construction of balanced cross-section have not been performed.

Figure 26. *The cliff exposed at the western end of the island Martha's Vineyard, Massuchusetts, USA display a cross sections of the Aquinnah glacial terrain. The ice sheet deforming the cliff was directed from the mainland seen in the horizon towards the Atlantic Ocean behind the viewer of the cliff. The cross section of the cliff was described under the locality named Gay Head Cliff by Kay (1980).*

Mud Buttes, Alberta, Canada

The Mud Buttes are a group of low hills 2 km long 800 m wide popping up from the main plane to form 50 m high hills in the southern part of Alberta, Canada. The erosion in a number of gullies has formed badlands exposing cross section through the glaciotectonic complex. The bedrock displaced in the complex comprises the upper Cretaceous Belly River Formation (Green 1972). According to the local tourist brochures the Mud Buttes is the most spectacular glaciotectonic complex on the North American continent.

The glaciotectonic complex Mud Buttes was first described by Hopkins (1923). A detailed structural description was given by Slater (1927), who distinguished 3 deformation zones or structural units. These were reinterpreted to comprise 4 thrust sheets comprising upper Cretaceous sand and clayey sand with ironstone markers. The thrust sheets are all deformed proglacially from the east–northeast during the main Wisconsin ice advance about 20.000 years BP (Fenton *et al.* 1993).

The structural description performed by (Fenton *et al.* 1993) is very adequate. However, detailed interpretation of the dynamic development based on a balanced cross section construction has not been prepared.

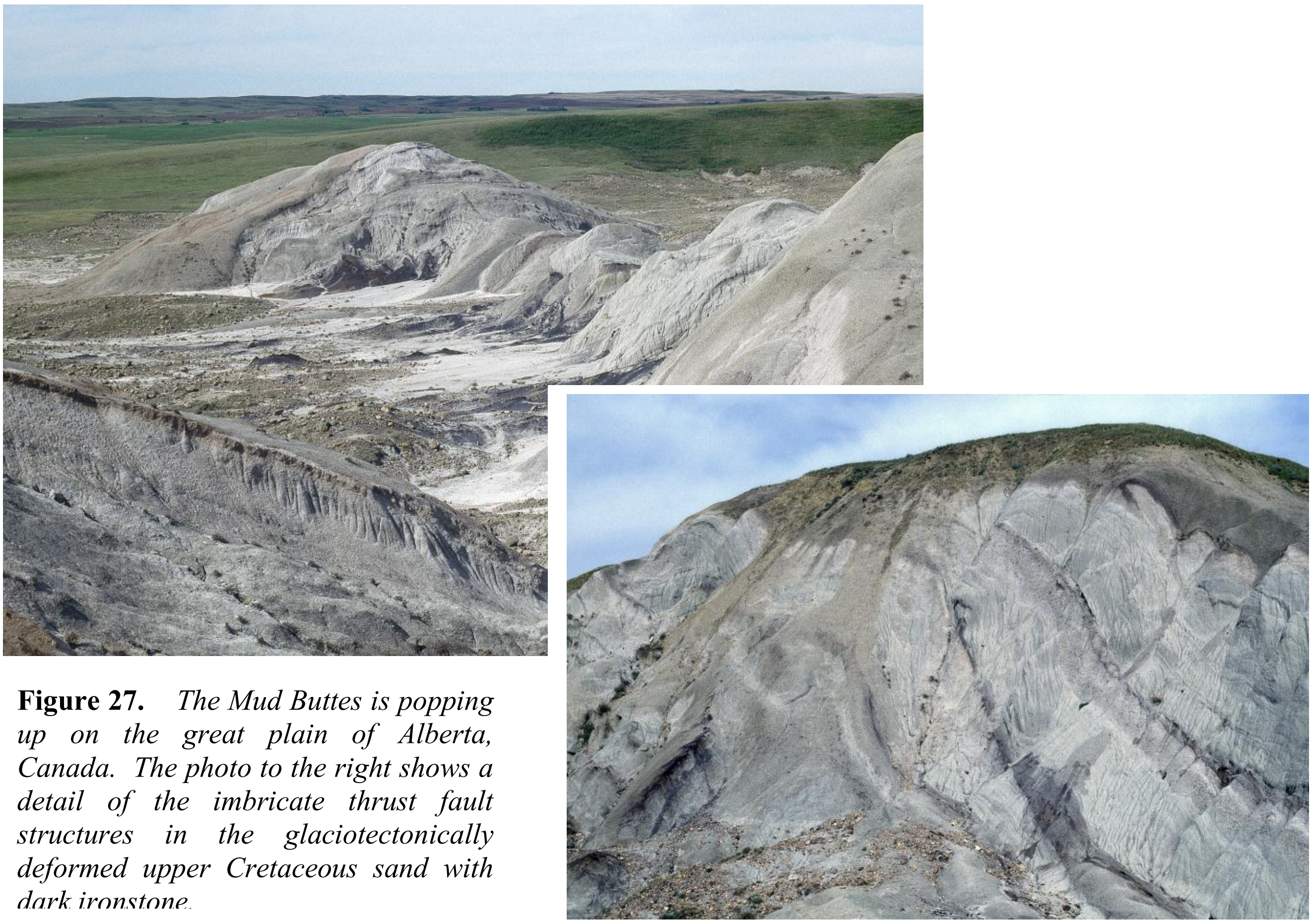


Figure 27. *The Mud Buttes is popping up on the great plain of Alberta, Canada. The photo to the right shows a detail of the imbricate thrust fault structures in the glaciotectonically deformed upper Cretaceous sand with dark ironstone.*

Dirt Hills and Cactus Hills, Saskatchewan, Canada

One of the most impressive horse-shoe hill complexes is the Dirt Hills in southern Saskatchewan, Canada (Aber *et al.* 1989). The hills occupies and area of 20x20 km^2, and comprises up-thrust sheets of upper Cretaceous sands and clayey sandstone, which are distributed in distal positioned Dirt Hills arc and the proximal Cactus Hills arc. The thrust sheets reach a maximum thickness of about 90 m, and they are generalle pushed up from an ice advance directed from the NE towards SW (Aber 1993). The structural analysis of the complex indicates that the core of the complex was generated by an early glacial event respecting the primary structures of the bedrock geology (Kupsch 1962). The most recent dating of the deformation supports the model that the complex was formed by a mega surge during a readvance of the Laurentian Ice Sheet in the latest part of the Pleistocene, probably around 13.000 years BP (Aber & Ber 2007).

The Dirt Hills and Cactus Hills are an outstanding example of glacialmorphological landscape created during a dramatic ice sheet dynamic. The composite ridges complex is in scale and geomorphic expression comparable to the composite ridges of the Bjergby Arc in the core of which Hanklit is located (Aber & Ber 2007). Despite the detailed analysis provided by Aber (1993) a structural analysis including the construction of glaciotectonic cross sections has not been carried out, probably because the scarcity of reasonable exposures of cross sections. One of the exposed cross sections is the road cut shown in Fig. 27.

Figure 28. *Structural cross section in a road cut thorough the Dirt Hills, Saskatchewan.The bedrocks thrust up in composite ridges comprises upper Cretaceous sand and clayey sandstone.*

Cromer Beach, Norfolk, United Kingdom

The north coast of Norfolk is the fameous site for chalk sheets to have been thrust up towards the south and southwest in East Anglia. The site is here included in the term Cromer Beach, but it includes a series of localities distributed along the northeast coast of Norfolk from Weybourne furthest to the NW over

Sherringham, Runtorn, Cromer, Overstrand, Sidestrand, Trimingham, Bacton and Happisburgh to the SE, a distance of about 30 km. A number of glaciotectonic studies have been published about the glacial deposits including the rafts of Upper Cretaceous chalk (Banham 1975, 1988, Hart 1990, Hart & Boulton 1991, Lee & Phillips 2008, Lee 2009, Burke *et al.* 2009). The timing of the glaciotectonic deformation is closely related to the dating of tills overlaying the chalk rafts and participating in the deformation, and tills truncating the glaciotectonic structures. The most prominent glacial event affecting Norfolk is the North Sea Drift which resulted in deposition of Scandinavian erratics in the Cromer Tills (Burke *et al.* 2009). The ice advance was directected from the north to northeast and took place in the earlier part of the Saalian glaciation, which is tentatively correlated to MIS 10 and dated to about 350 000 years BP (Lee 2009).

Unfourtunately the main strike of the coastal cliff is parallel to the strike of structural elements such as bedding and thrust plans. It is therefore difficult to present a continous structural cross section perpendicular to the fold axes of the hanging-wall anticlines. The structural analysis of Burke *et al.* (2009) is very impressive, but it also demonstrates the complexity of the glaciotectonic structures. These were already interpreted to be the combination of proglacial deformation and the formation of raft-carrying glacitectonites by Banham (1975) and Hart (1990), which contributes to the difficulty of presenting a model for the formation of the Cromer complex.

Figure 29. *Two thrust sheets with hanging-wall anticlines outlined in upper Cretaceous chalk surrounded by Cromer Tills are instructively exposed at the locality Sidestrand, Norfolk.*

Killala Bay, northwest Ireland

The glacially dislocated bedrock unit at the coasts of Killala Bay belongs to the oldest pre-Quaternary rock units deformed by glacial tectonics. The bedrock here comprises Carboniferous limestone, sandstones and shales, which have have been displaced in thrust sheets (Warren 1991). Among the structures recognized are hanging-wall anticlines folded in beds of the Carboniferous successions. These have a thickness of up to 8 m, whereas the overlain till unit have thickness of up to 30 m. In general the displacement is towards the north and northwest in the direction of the ice sheet flow from the source in the central Ireland (Warren 1991). The correlation of the internal structures in the glaciotectonic complex with the surface geomorphology is not very clear, and the terrain is described as a combination of kames and drumlins with only few relations to the internal structures of the glaciotectonic architecture.

The structures present at Killala Bay are very impressive. However, detailed analysis including measured cross sections has not been performed. In many aspects the glaciotectonic deformation can be compared to the Hanklit thrust fault.

Figure 30. *Glaciotectonically deformed Carboniferous limestone, sandstones and shales occur in the Killala Bay complex, northern Ireland. Note the hanging-wall anticline to the right in the thrust sheet in the middle of the section. The thickness of this thrust sheet is about 5 m.The thrusting was towards theAtlantic Sea to the northwest (to the right in the photo) and caused by the ice sheet advance in the late Pleistocene.*

Muskauer Faltenbogen, border between Poland and Germany

One of the most impressive ice-shoved hill complexes in Europe is the Muskauer Faltenbogen Arc complex on the border between Poland and Germany (Kupetz 1997, Kupetz *et al*. 2004). This landscape has already been appointed a position on list of the UNESCOs World Heritage Cultural Landscapes. The property Muskauer Park is located in the vicinity of the most distal composite ridge in the horse-shoe formed hilly landscape. According to Aber & Ber (2007) this composite ridges complex is in many aspects compareable to the Dirt Hills and Cactus Hills in Saskatchewan. The complexes are of the same size (20x20 km^2), the arc formed shapes are similar with three major zones recognizeable. However, the age of the complexes could not be more different. While the Dirt Hills and Cactus Hills represent a surge from the last glaciation, the Muskauer Faltenborgen Arc represents one of the oldest recognized complexes being created during the Elsterian glaciation (Ehlers *et al.* 2011). Thus the complex represents the southernmost mega-scale expression of the extent of the Scandinavian Ice Sheet (Fig. 8), which is instructively documented by the occurrence of indicator boulders from the basement of the Danish island of Bornholm (Kupetz *et al*. 2004). The pre-Quaternary bedrock deformed during the glaciotectonics comprises Miocene lignites and sand deposits.

The Muskauer Faltenbogen Arc Complex might have been a good candidate representing a Pleistocene glaciotectonic complex. However, the majorities of the composite ridges are destroyed by excavation of lignites and have been left as water filled ponds, and due to the reclaiming of the area all structural cross sections have been erased. Furthermore, a detailed dynamic analysis based on balanced cross sections is not provided.

Summary of assessment

Comparative assessment of Early Eocene ash layer sites

The assessment of sites representing Early Eocene ash layers is summarized in Table 3 (p. 20). Due to the five criteria (p. 19) the sites can be grouped in three categories:

1. Large importance with all criteria satisfied
2. Important with some criteria satisfied
3. Although important the site is inaccessible to public

It is obvious that all the sites of offshore boreholes are important, but can never be regarded as a heritage site and they belong consequently to category 3. The same conclusion can be made about the Skrænterne Formation in East Greenland, which is only accessible in connection with expensive, scientific expeditions.

The accessible geological localities on land are Horsefly in Canada, Rum in Scotland, the localities of the Harwich Formation in East Anglia in UK, and Danish sites with volcanic ash layer. The first two of these are insignificant in connection with regional and global stratigraphy and can only be regarded as being of local importance, therefore characterized as category 2 sites. The sites in eastern UK have important stratigraphic significance, but the record of ash layers is only half the numbers as known from the North Sea and the Danish sites. Moreover, the volcanic glass suffers from being altered to smectite and the sites are assessed to be category 2.

Finally two sites are left in category 1, namely the Ølst site in central Denmark, and the Moler Cliffs in northern Denmark. The Ølst beds have been recognized in road cuts. However, these have never been protected as geo-sites. The Leca clay pit in Ølst is still an active site for raw material excavation and is not suitable for public access. Furthermore, the volcanic glass is strongly devitrified and the ash layers have been transformed into bentonites.

Due to the comparative analysis the Moler Cliffs are outstanding as the accessible sites for experience of a succession of well preserved and easily recognizable volcanic ash layers. The succession documents an outstanding tectonic event that took place 55 million years ago, when the North Atlantic Igneous Province initiated the creation of the North Atlantic Ocean.

Comparative assessment of Early Eocene fossil assemblages

In order to quantitatively compare the fossil biodiversity of the various geological formations selected for study, a scoring system is employed in the comparative analysis (see Table 5). For each formation, a point is gained if a specific group has been documented as fossil from its deposits. Additionally, groups are noted and scored as either marine (M) or terrestrial (T). The following overall groupings of fossils are employed in the analysis:

Microfauna: dinoflagellates (M, T), foraminifera (M), radiolarians (M), silicoflagellates (M), ostracod crustaceans (M, T)
Microflora: calcareous nannoplankton (M), charophytes (M, T), diatoms (M, T), pollen (T), spores (T),
Invertebrate macrofauna: bivalves (M, T), brachiopods (M), echinoderms (M), snails (M, T)
Vertebrate macrofauna: sharks (M), bony fish (M, T), amphibians (T), reptiles (M, T), turtles (M, T), mammals (T), birds (M, T)
Macroflora: fruits (T), plants (M, T), trees (T)
Arthropods: crustaceans (M, T), insects (T), scorpions (T), spiders (T)
Trace fossils: traces of animal activity (M, T)

Finally, if the preservation of one or more fossil groups is of a exceptional quality, which merits it to be designation Konservat-lagerstätte, this is noted.

Each fossil group present in the formation yields one point in the scoring system, as does the designation of Konservat-lagerstätte. These points are then combined in the most right hand column of Table 5 on page 67, so that formations recording the highest taxonomic diversity also score the highest amount of points in the analysis. The formations are ranked in the table, with the ones containing the greatest number of groups ranked first.

The Fur Formation ranks highest due to the presence of several terrestrial groups in an otherwise marine environment and the Konservat-lagerstätten quality of its soft tissue preservation. Similarly the two next-highest formations (Soisonnais and Tienen) rank highly, because they include a combination of marine and terrestrial environments in their deposits.

Formation	Age	Depositional environment	Microfauna	Microflora	Invertebrate macrofauna	Vertebrate macrofauna	Macroflora	Arthropods	Trace fossils	Konservat-lagerstätte	Points
Fur	earliest Eocene $^{39}Ar/^{40}Ar$-date: 55-54 Ma; *Apectodinium* acme	Marine	M	M & T	M	M & T	T	T	M	Yes	10
Soisonnais	earliest Eocene MP7; *Apectodinium* acme	Terrestrial & Marine	M	T	T & M	T	T	T		Yes	8
Tienen	Latest Paleocene-earliest Eocene; CIE; MP7; *Apectodinium* acme	Terrestrial & Marine	M	M & T		T & M	T		T		7
Cambay Shale	?latest Paleocene-Early Eocene ?P5-P7; ?NP9-NP12; underlies ETM2	Marine & Terrestrial	M		M	T & M		T		Yes	6
Willwood	latest Paleocene-Early Eocene CIE; Clarkforkian-Wasatchian NALMA	Terrestrial		T	T	T	T		T		5
Woolwich	earliest Eocene *Apectodinium* acme, overlies CIE	Marine	M	M	M	M			M		5
Esna	latest Paleocene-earliest Eocene CIE, NP9-NP11, P4-P7	Marine	M	M		M			M		4*
Zumaia deposits	latest Paleocene-earliest Eocene CIE, NP7-10, P5-6a	Marine	M	M							2*

Table 5. *Formations listed according to presence of major fossil groups (M = marine biota; T = terrestrial biota) and quality of fossil preservation. Formations whose points value has an asterisk (*) added, have played a significant scientific importance in constraining the Paleocene-Eocene boundary, and the events of the PETM.*

Comparative assessment of glaciotectonic sites

In the most recent geo-scientific textbook on glaciotectonics (Aber & Ber 2007) the Moler Cliffs and their surrounding terrain occupy the most substantial part. Thus the structural geology and geomorphology of the moler sites and the landscapes on Mors and Fur are preliminary ranged in the class of outstanding geosites. Except Killala Bay the other sites are also included in the textbook by Aber & Ber (2007) or in its predecessor Aber *et al.* (1989), and their importances are ranged in the following order: Møns Klint, Dirt Hills and Cactus Hills, Aquinnah, Rügen, Muskauer Faltenbogen, Cromer Beach and Mud Buttes. This it not indicating that these sites are the most outstanding glaciotectonic sites, but due to the listed criteria, which only includes complexes deforming pre-Quaternary bedrock, some of the best sites are not considered in the assessment, like the Rubjerg Knude Glaciotectonic Complex, Denmark (Pedersen 2005).

In the comparative analysis the assessment of Muskauer Faltenbogen is rangeed in the third category (lowest of three) due to the bad condition of cross sections and the destruction of geomorphic features by the former lignite excavation. The Killala bay is also in a third category due to its poor scientific records.

The Mud Buttes is regarded as a category two site. It is impressive, but it is not outstanding compared to the scientific record. The Dirt Hills and Cactus Hills is a geosite of outstanding geomorphology, but compared to the accessible coherent structural cross sections it must be ranged as a category two.

The chalk cliffs at Cromer Beach, Rügen and Møns Klint are all outstanding and undoubtly category one sites. However, the number of structural details that can be recognized in the moler cliffs due to the beautifull preservation of the continuous bedding is outstanding amongst glaciotectonic complexes. This is the convincing reason for the large number of highly qualified structural analyses that have been carried out on the moler cliffs.

Conclusions

The analysis of the geo-sites to be compared with the Moler Cliffs Hanklit on Mors and Fur Knudeklint on Fur has been carried out by assessment of three different aspects of geo-scientific qualifications. Each of these aspects has been evaluated by a separated comparative analysis. The first comparative analysis focuses on the geo-sites documenting large volcanic eruption centers recorded in a marine succession of well preserved ash layers, in particular sites contributing to the evidences of tectonic events, here exemplified by the North Atlantic Igneous Provins. The second comparative analysis focuses on the aspect of fossil preservation and records of the life and evolution in the earliest Eocene about 55 million years BP. This palaeontological aspect includes additionally the special record of the development of the Paleocene/Eocene Thermal Maximum (PETM), which was a significant greenhouse event. The third comparative analysis brings the glaciotectonic features displayed in the Moler Cliffs into a broad frame of glaciotectonic complexes, which demonstrate the revolutionary modulation of the landscape due to advancing of ice sheets during the glaciation of the Northern Hemisphere in the past two million years.

The bases for the comparative analyses have been defining three sets of criteria, which signify the specific values attached to the three aspects. In the assessment of the Eocene volcanic ash layers it has been emphasized that the succession should be continuous, there should be well documented series of geochemical analyses of individual ash layers, the ash layers should represent primary ash falls (not redeposited grain flows), and the ash layers should be easily identifiable in accessible cliff sections. According to the comparative analysis the Moler Cliffs are the best qualified property for the documenting and satisfaction of the assessment criteria.

In the assessment of the Eocene fossil assemblages the following criteria were emphasized: Firstly the stratigraphy of the site for fossil collection should be well-constrained and include evidence of a direct link to the PETM. Secondly the formation should contain a high diversity of fossils, which also demands for simultaneously documenting several biotic groups. Thirdly the formation in focus should contain so well-preserved fossils that it can be characterised as a *Konservat-lagerstätte*. The Fur Formation is judged the best qualified compared to the formations nominated for assessment.

The assessment criteria for evaluating the best Pleistocene glaciotectonic complex focused on the preservation and sustainability of the outcrops. Furthermore the complex should form part of a glacial-geomorphic landscape, which internal structures should be documented in the site. Finally a structural analysis of the glaciotectonic features must be available in published literature. According to the analysis the Moler Cliffs stand out as one of the most classic areas for documenting structural analysis of glaciotectonic complexes. Furthermore their easy accessibility makes them unique, and the experience of the hilly landscape representing the ice-shoved composite ridges is a scenic pleasure.

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