遠征北極—深海中的生痕化石證據

Expedition to the Arctic: Evidence from the Sediment Core

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地球的最北邊是一片荒涼且寒冷的水域—北極海，北極海中的沉積物可以用來研究高緯度地區的古氣候與環境演變，是極為珍貴的材料，但它們得來不易。科學家們必須忍受著嚴寒，在冰天雪地中乘著破冰船前往北極海鑽探海底岩芯進行分析。在仔細審視這些珍貴的岩芯時，我們發現一層獨特的灰色沉積物，它與下方沉積物之間有明顯的切面，指示著突然的環境變化，而切面之上並無發現任何生物存在的證據，然而其之下卻有密集的生物活動遺跡，以及代表生物逃脫的生痕化石。這會是指示過去曾經發生一次冰堰塞湖潰堤事件，而將生活在北極海海底沉積物裡的生物活埋的證據嗎？

北極海下，不為人知的故事

北極海位於地球的最北端，是五大洋之中最小最淺的海洋，它被北美大陸與歐亞大陸所包圍，對外僅有狹窄的白令海峽及弗拉姆海峽分別與太平洋、大西洋相連（圖1），且海洋表面長年有浮冰覆蓋，使得北極海成為相對封閉的海洋。這些得天獨厚的條件，讓北極海能夠較不受外來的干擾、持續且穩定地記錄著地球的古氣候變化。

關於古氣候的研究，除了可以運用雪花壓實而形成的冰芯來研究裡面的液態或氣泡成分組成，沈降在海床上的沉積物也是非常好的研究材料。遠古至今，海納百川，大海接收來自四面八方的沉積物，收藏著最完整的古環境和氣候變遷紀錄。在破冰船上利用鑽探機具從海床下鑽取而出的深海沉積物樣本，我們稱之為「岩芯」（圖2 a-b）。北極海的岩芯和湖泊岩芯、石筍一樣，有著深淺分明的紋層；這些紋層隨著年代的推演，向上層層堆疊沉積，每一層都忠實的記錄著古氣候變化的訊息。

科學家們來回仔細觀察這來之不易的岩芯，除了看得到層理分明的紋層之外，還有一個很特別的區塊—那是一層底部邊界清晰的灰色泥層（圖2 e）。這層灰色的泥層，無論在顏色或成分都與其他紋層不

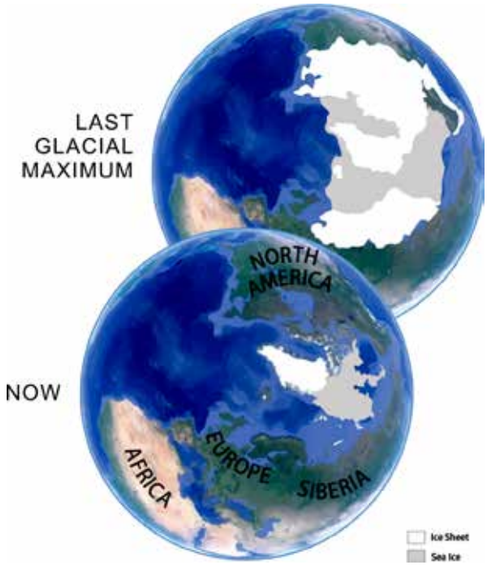

圖1　北極海俯視圖。圖中分別為現今和末次冰盛期（Last Glacial Maximum）時北半球的冰川位置（白色）與海冰分佈（灰色）之示意圖。
Figure 1. A top view of the Arctic Ocean showing ice distribution during the Last Glacial Maximum and during modern times. The white area represents ice sheet distribution, while the gray area shows sea ice distribution.

The Arctic is one of the most climatically sensitive and rapidly changing regions on the planet. In studying sediments on the Arctic seafloor, to investigate how the Arctic has responded to climate change in the geologic past, scientists discovered an intriguing, distinct layer of grey sediments in the deep-sea cores. The layer has a sharp lower boundary, suggesting an abrupt change in sedimentation, and the layer itself is void of signs of animal activities, while the layer directly underneath shows evidence of a rich bottom fauna. Could this be evidence for a giant ice-dammed lake, which catastrophically emptied into the Arctic Ocean and buried the creatures living on the seafloor at the end of a previous glacial period?

The message from the Arctic

The Arctic Ocean is the coldest and most desolate ocean on Earth. It is unique amongst the world's oceans due to the perennial sea-ice cover, abundant freshwater input, and limited exchange to the Global oceans through the Bering and Fram Straits (Figure 1). It is also changing more rapidly in response to global climate change than many of the other oceans of the world.

Marine sediment cores allow scientists to reconstruct past environmental conditions in the Arctic. This is because terrigenous material is being eroded and transported by rivers into the ocean. In theory, the seafloor acts as a huge archive that records environmental changes of the surrounding land masses. Scientists challenge the extreme conditions of the Arctic using icebreakers to slowly travel through thick sea ice, and reach as far as the North Pole, in the center of the Arctic Ocean. Geologists then use coring tools to sample invaluable sections of sediments from the seafloor (Figure 2 a-b). The different layers in the sediment contain pieces of information on how the climate and the environment in the Arctic have changed through warmer and colder periods of the past.

When investigating some of these sediment cores, scientists observed a distinct gray colored layer with a sharp lower boundary, which was deposited during the last glacial cycle (Figure 2 e). The color and composition of this layer was distinctly different from surrounding sediments, and the sharp lower boundary suggested a sudden change in sedimentation. These observations raised several questions: How does this layer form? What caused this apparently abrupt event? If this was a large and previously unknown event, how did it influence the Arctic Ocean and the global climate system?

Marine sediment analysis – What X-ray radiographs can tell

After the sediment cores were retrieved from the seafloor, they were split into two halves: one half is routinely archived for future research, and the other half was analyzed using a variety of techniques. One efficient way to study marine sediments is through X-ray radiography (Figure 2 c-f), which operates using

一樣；將岩芯剖半之後，從剖面更可以清楚的看見，這層灰色泥層的底部邊界平整，清楚的與下方的沉積物分隔開來！到底是什麼原因形成了這一層特別的灰色泥層？它是否暗示這片看似寧靜的北極海曾經發生過什麼不為人知的大事件？它對北極海以及全球氣候又曾經帶來什麼樣的影響呢？我們將隨著科學家的研究，一起在岩芯中尋找線索、破解謎團！

X光分析岩芯紋層

科學家在破冰船上除了對抗酷寒之外，也忙著定位鑽探位置與準備工作。當岩芯樣本一被鑽取上來之後，研究人員會在破冰船上將岩芯剖半，一半存放起來用作日後研究，另一半則分裝到一個個平板狀的塑膠盒內；這麼做除了方便運送和存放外，也是為了後續進行的X光掃描做準備（圖2 c-f）。

就像去醫院骨科照X光片的原理一樣，物體密度較高處（如骨頭）在X光片上會顯示成白色，密度較低處（如肌肉）則會顯示成灰色或黑色。透過檢視這些岩芯的X光片（圖2 g），我們可以觀察到幾個有趣的現象，例如：沉積物中出現許多白色的小圓點、成層且重複出現的紋層，和生活在沉積物中的生物所留下來的痕跡。小圓點是冰川從陸地所搬運而來的碎石，由於密度高於周圍的沉積物，在X光片上就顯得特別亮且突出；紋層是懸浮物質慢慢水平沉積在海底而形成，規律地記錄著所有環境與氣候變化。除此之外，還有在岩芯剖面上肉眼不容易觀察到、但在X光片上顯得迂迴曲折的生痕化石，它們通常是小型生物在海底下覓食、移動、鑽洞或逃脫時留下的痕跡。

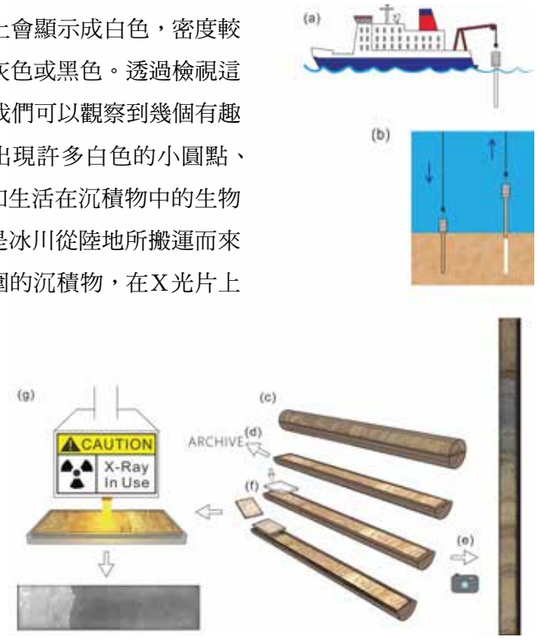

圖2 海洋岩芯採集與分裝樣本之流程示意圖。(a)–(b)破冰船把鑽探機具放入海中並在海底取得岩芯後，會繼續在船上進行樣本分裝。(c)把岩芯剖半，(d)一半儲存於岩芯資料庫，(e)另一半作為實驗用途，但會先將岩芯表面拍照存檔，(f)然後再分裝至塑膠盒內，(g)最後利用X光掃描進行分析。

Figure 2. Simplified diagram showing the process of collecting marine sediment cores. (a)–(b) The icebreaker uses the coring tool to obtain sediment core from the seafloor, then continues the sampling onboard. (c) The core is then split into two halves. (d) One half is archived. (e) The second half is used for X-ray analysis, but first a digital image is taken. (f) A thin sediment slab is cut out with the help of a plastic box. (g) Finally, the slab is X-rayed and the image can be used for analysis.

動物的脫逃？

觀察這層灰色泥層的X光片，可以看到下部邊界十分清晰，邊界上下的組成成分也非常不一樣（圖3）：邊界之下只有零星幾顆碎石，並可以觀察到明顯的生物擾動痕跡，其中一些岩芯的邊界之下，還能看見垂直方向的逃脫型生痕化石；邊界之上則是大量的小碎石摻雜在沉積物之中，且並無明顯的生物擾動痕跡。隨著岩芯往上觀察，形成的年代越來越年輕，碎石的數量逐漸減少，而生痕化石又再度出現。

the same principle as when taking an X-ray at the hospital. Higher density of some objects, like bones or rocks, will show up as white color, while objects with lower density, like muscles or mud, are evidenced by gray or black colors.

If we look at the radiographs of the cores (Figure 2 g), we can see three distinct features: small white spots, stacked horizontal layers, and the twisting and turning traces left by organisms living inside the sediment. The small white spots are pebbles called ice-rafted debris, which is terrigenous material so large that it must have been transported by floating pieces of ice, such as ice floes or icebergs, and then deposited in the ocean when the ice melted. The stack of layers formed when material suspended in the ocean slowly deposited on the seafloor. This kind of orderly sediment is the one best suited to record the surrounding environmental and climate changes. The twisting and turning trace fossils are not easily observed in the soft marine sediment, but are clearly visible in the radiographs. Because the trace fossils record the behaviors of the animals in the sediment, they can reveal what activities the animals were engaging in, such as moving, feeding, boring, escaping etc.

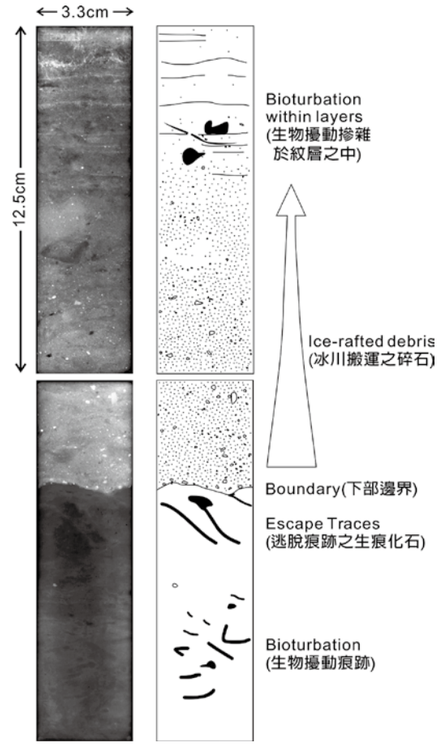

圖3 灰色泥層的X光片與對照解說圖

Figure 3. The radiographs of the gray layer on the left, with its description on the right.

The trapped animals underneath

Now, let's look at a radiograph of the gray layer (Figure 3). In this example, we can see the very sharp lower boundary, and the composition of the sediment below and above this boundary show striking differences. Below the boundary, there is only little ice-rafted debris (small stones) within the sediment, while bioturbation or trace fossils are abundant. In at least one core, a long-curved trace opening upward lies just below the boundary, suggesting that it is an escape trace formed when the animal tried to avoid being buried by the coarse sediment being deposit on top of it. Above the boundary, the sediment contains large amounts of ice-rafted debris, and there are no signs of bioturbation or trace fossils. However, if we continue looking up along the core, the amount of ice-rafted debris gradually decreases, and bioturbation returns.

This sequence suggests that when the gray layer was deposited, something dramatic happened! Something must have changed the marine environment completely at that time. One hypothesis is that a huge flood occurred, delivering vast amounts of fresh water and sedi-

這樣的過程可能暗示灰色泥層形成時，環境突然改變了！例如大型的洪水事件把沉積物與大量洪水帶入北極海，如此強大的水流不但侵蝕海底表面，並迫使居住在海底沉積物中的生物必須往下或向四周逃脫。這場洪水所帶來的大量沉積物繼續堆積在侵蝕面之上，海底慢慢回復到之前平靜的狀態，漸漸地再度吸引生物群落。如此大型的災難發生在高緯度地區內，極可能指示著一次冰堰塞湖的潰堤事件。

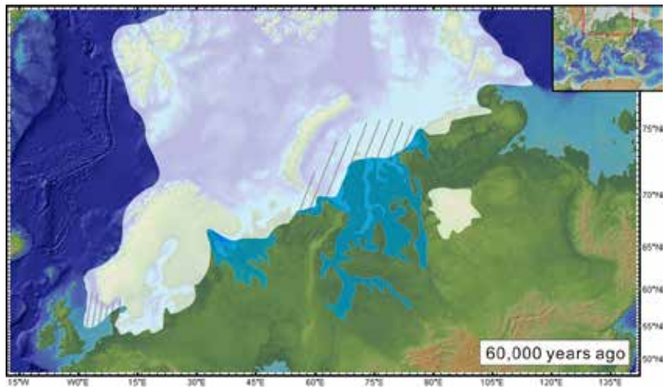

圖4　6萬年前西西伯利亞平原上冰堰塞湖（圖中央藍色區塊）與冰川（白色）之位置，圖修改自Mangerud et al., 2004和Svendsen et al., 2004。

Figure 4. The location of the ice-dammed lakes (blue area in the middle) and the ice sheet (white area) in northern Eurasia 60,000 years ago (modified from Mangerud et al., 2004 and Svendsen et al., 2004).

科學家的看法

根據歐亞大陸北部冰川歷史的研究，地質學家在西伯利亞內陸發現許多湖泊沉積物以及湖岸的沉積構造，證明這裡過去曾經存在過內陸湖泊。這些湖泊的形成是因為過去西伯利亞北面巨大的冰川把往北流的河流都擋住了，使得河水在冰川前的低地匯積成湖泊，這類湖泊稱為冰堰塞湖（ice-dammed lake）。地質學家指出，在不同時期西伯利亞北部冰堰塞湖的大小都不一樣，但它們絕對可以媲美現今世界上最大的湖泊：裏海（面積37萬1,000平方公里）。而當時最大的湖泊甚至是今天裏海面積的兩倍！但這麼大量的水體最終會因為無處宣洩而潰堤，引發浩大的洪水事件。科學家認為，在北極海岩芯中發現這些灰色泥層下部如此平整的邊界極有可能是大型洩洪事件所造成的。形成原因或許與6萬年前威赫塞爾冰期（Weichselian glaciation）中期時，位於西西伯利亞平原（West Siberian Plain）廣闊的冰堰塞湖洩洪有關（圖4）。這次的洩洪事件造成大量湖水湧入北極海，使得原本在海底下棲息的生物必須逃向別處，因此留下了這些擾動痕跡與生痕化石。

但如此大量的淡水在極短時間內流入北極海到底會造成什麼影響？是否也像末次冰期時北美大陸上的冰川融水流入北大西洋而影響海洋環流，繼而引發新仙女木事件（Younger Dryas）這樣大尺度的氣候變化？這個答案目前還不得而知，只能仰賴科學家們在一次又一次前往北極的破冰船上，尋找更多的線索…

延伸閱讀—新仙女木事件（The Younger Dryas）

新仙女木事件是地球歷史上著名的氣候突變事件，指的是距今1萬2,800年至1萬1,500年前一次短暫的全球氣溫驟降事件，當時地球剛經歷完末次冰盛期（Last Glacial Maximum），在逐漸暖化的過程中發生了「氣候反彈」，而造成這次的小冰期。這次驟冷事件的命名來自於在該時期歐洲低緯度地區發現了仙女木（寒帶地區的標誌植物）的花粉，顯示當時全球氣溫的下降。

ment into the Arctic Ocean. The strong current associated with this event eroded the seafloor, and the animal underneath was imprisoned by rapid deposition of the covering sediment. After this dramatic event, sedimentation gradually returned to normal and animals colonized the seafloor again. Such a dramatic event in the Arctic region can most likely be related to an outburst flood from an ice-dammed lake that formed during the growth of terrestrial ice sheets during a past glacial period.

What the Quaternary geologist thinks – An ice-dammed lake drainage?

This scenario is actually supported by research on the history of the Eurasian ice sheet. Geologists have found lake shoreline structures and lake sediment in the Siberian hinterland, demonstrating the existence of huge lakes in the past. These lakes formed when the expanding ice sheet blocked the rivers from reaching the Arctic Ocean, resulting in the formation of huge ice-dammed lakes with the potential to result in massive outburst floods. The lakes were of different sizes, and the largest could have been greater than the largest lake today: the Caspian Sea, which has a surface area of 371,000 km^2. A sudden change in the configuration of the ice sheet during melting could generate an enormous outburst flood. Therefore, some geologists believe that the enigmatic gray layer in Arctic sediments was caused by a sudden outburst of an ice-dammed lake that happened during the Middle Weichselian glaciation, about 60,000 years ago. This ice-dammed lake was probably located on the West Siberian Plain where the ice sheet blocked the Siberian rivers' route to the North (Figure 4). An event of this size must have contributed large amounts of fresh water and lake sediment into the Arctic Ocean. This rapid input of sediment to the seafloor was clearly bad for the organisms living in and on the seafloor, as demonstrated by the escape traces found in some cores.

However, could such tremendous amount of fresh water flushed into the Arctic Ocean in a geologically short time also have had an effect on the climate? For comparison, water from a glacial lake in North America that formed during the Last Glacial Maximum was later released into the Atlantic Ocean during the deglaciation. This fresh water disturbed global thermohaline circulation and is believed to be associated with the Younger Dryas cooling event. However, would the Siberian outburst cause the same result as the Younger Dryas event, or was it a more local event? The answer is open to speculation unless we find solid evidence to show that the layer actually came from Siberia.

Additional reading - The Younger Dryas

The Younger Dryas, a global cold event that lasted from 12,800 to 11,500 years ago, is a climatic rebound that happened when the Earth's climate was gradually warming after the last ice age. It is named after a glacial tundra indicator wildflower *Dryas octopetala*, which was widespread and replaced the forest in the north during this time.