香港地質大爆炸
Hong Kong's Big Bang

糧船灣超級火山的故事
The Discovery of High Island SUPERVOLCANO

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前言 FOREWORD

香港地質調查組經過數十年細緻而深入的地質勘測工作及研究，於2008年下旬發現香港可能坐落於遠古的巨大火山。其後，該組再進行四年的深入研究，證實上述驚人發現，並於國際科學期刊發表論文，確認位於香港東南面的糧船灣超級火山。

這發現於2012年吸引了本地及海外傳媒的廣泛注意，而本地學術團體、大學及學校亦紛紛表示希望作深入認識。此事亦令公眾進一步關注香港聯合國教科文組織世界地質公園展示香港的地質遺產，當中包括糧船灣火山超級噴發所產生的龐大火山產物。

為提升公眾對香港地質的興趣，並提供實用參考資料，我們以雙語編寫這本以發現香港超級火山為藍本的通俗地質學書籍，希望啟發香港有志於科學探索的年輕一代研讀地球科學，從而認識我們的自然世界並作出貢獻。

這裡述說的故事，猶如一次歷時數十載的地質發現之旅，將一幅巨大拼圖拼湊成形。這些拼圖零片早於一百年前已經出現，其後經歷代地質學家多年孕育和發展，直到近期才成功湊成一幅連貫完整的圖像。

本書由土力工程處香港地質調查組撰寫，與同由香港地質調查組編寫的《***香港地質－四億年的旅程***》屬同一系列，藉此向公眾介紹香港地質。我們期望兩書能為大眾帶來饒富趣味而又能增長知識的閱讀體驗。

Following decades of meticulous geological mapping and studies undertaken by the Hong Kong Geological Survey, an astounding discovery in late 2008 revealed that Hong Kong might be sitting in the bowel of an ancient monster volcano. It took the ensuing four years of detailed study to verify this astonishing revelation, which culminated in the publication of a scientific paper in an international journal describing the High Island supervolcano in southeastern Hong Kong.

The finding attracted widespread local and international media interest in 2012, as well as attention from local learned societies, universities and schools eager to learn the story behind the discovery. In addition, the event put into sharp focus the unique attributes of the Hong Kong UNESCO Global Geopark, which showcases Hong Kong's geological heritage, including the colossal volcanic product of the High Island supereruption.

In order to further stimulate interest in Hong Kong's geological landscape, and provide a useful reference for interested members of the public, it was considered worthwhile to produce a geological book written at an introductory level, in both Chinese and English, featuring the story behind the discovery of Hong Kong's supervolcano. It is hoped that this story will inspire Hong Kong's young scientific minds to consider studying Earth Sciences, and to envisage the potential contribution they can make toward understanding our natural world.

The story presented here likens the voyage of geological discovery over decades of scientific investigation to the assembly of interlocking pieces of a gigantic jigsaw puzzle. Some pieces of the puzzle began their incubation almost a century ago, later to be nurtured and developed over the years by generations of geologists. Final slotting in of the pieces to create the complete picture only occurred very recently.

This book has been written by the Hong Kong Geological Survey, Geotechnical Engineering Office. It has been designed as a companion to the book entitled: ***Hong Kong Geology – A 400-million year journey***, also produced by the Hong Kong Geological Survey, which provides a popular account of Hong Kong's geology. We hope they will make an interesting and informative read.

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土木工程拓展署
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2018年12月

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December 2018

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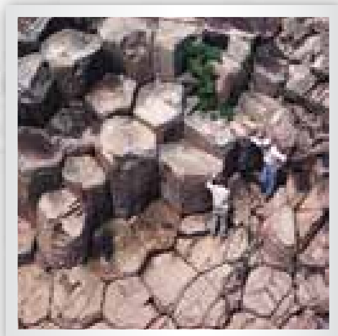
序 PROLOGUE

自十九世紀以來，歷代地質學家便對覆蓋香港東部大部分地區的六角岩柱著迷。早期的自然學家認識到這些岩組極似北愛爾蘭巨人堤道的六角岩柱，但規模更大。香港的岩柱最初被認為同樣是由玄武質熔岩組成，岩石成分富鎂和鐵。不過，經仔細研究後，便發現這些岩柱的化學成分截然不同。它們不是玄武岩，而是由流紋質火山灰固化成的凝灰岩，二氧化矽和鋁的含量很高。

但是，如此龐大的火山岩柱群是如何形成的問題仍懸疑未解。什麼類型的火山可以產生如此巨大的凝灰岩體？火山什麼時候噴發？火山在哪裡？火山噴發期間發生了什麼事？人類或恐龍見證了火山的噴發嗎？這些有趣的問題，乃至更多的疑問，正是我們要講述的故事核心所在。



地質發現就像在事前不知道圖像全貌的情況下去完成巨大的拼圖。一開始，拼圖零片的含義還不很清楚，彼此之間看似沒有關係。但是，經過漫長而刻苦的努力，拼圖被逐漸拼湊成形，圖像就顯露出來。在這個拼圖遊戲中，每一項地質證據就像拼圖的零片，必須經過細緻入微的研究，方可獲得。

長時間的野外考察、數以百計的地球化學分析、全面的地球物理研究，以及數十個岩石樣本的年齡測定，每項工作都構成這幅拼圖的一小塊零片，最終湊成一幅連貫的圖像。過程中，地質學家運用了幾個世紀以來從科學研究中得到的各種基本地質概念和原理，同時依靠想像力和推理，試圖把這些拼圖的零片準確無誤地拼合在一起。

Since the 19th century, generations of geologists have been fascinated by the hexagonal rock columns that cover a large area of eastern Hong Kong. The early naturalists recognised that these rock formations bore a striking resemblance to the hexagonal columns forming the Giant's Causeway in Northern Ireland, but on a larger scale. The rock unit was initially thought to be made of the same type of volcanic rock called "basalt lava". However, closer examination soon revealed that the columns in eastern Hong Kong were made of a very different composition. Instead of basalt lava, which is a magnesium- and iron-rich rock, the columns are composed of solidified rhyolitic ash, known as tuff, which has a high silica and aluminium content.

But the question remained as to how such a voluminous volcanic unit could have been formed. What type of volcano could have produced this gigantic ash body? When did the eruption occur and where was the volcano? What happened during the volcanic eruption? Were humans there to witness the event? Or even dinosaurs? The answer to these intriguing questions and many more lie at the centre of our story.

Geological discovery is akin to solving a huge jigsaw puzzle without knowing the full picture in advance. At the start, the pieces of the puzzle are poorly defined, and show little relationship to each other. But as the pieces are shaped and moulded, and slowly and painstakingly assembled, the image reveals itself. The pieces of the puzzle in our case comprise pieces of geological evidence, which becomes available through meticulous investigation.

Many hours of fieldwork, hundreds of geochemical analyses, a comprehensive set of geophysical studies, and detailed age-dating of tens of rock samples. Each forms just one small piece of the jigsaw puzzle, which will eventually interconnect to form a coherent picture. While trying to put the pieces together, geologists apply fundamental geological concepts and principles, developed over centuries of scientific investigation. At the same time they rely on imagination and powers of deduction to ensure the correct interlocking fit.

岩石的分佈
DISTRIBUTION OF ROCKS

香港地質測繪
GEOLOGICAL MAPPING OF HONG KONG

推斷某地區的地質歷史，必須先收集各種資料，然後逐步分析及合併成串連的事件。對地質學家來說，這需要多年細緻而有系統的勘測工作，還要極大的耐心。香港超級火山的發現，是經過多年的團隊合作才完成，而我們早在1980年代已展開的地質測繪工作，為這項發現奠下基礎。

地質調查的首要工作，是收集關於各種岩石分佈的資料。一般而言，須通過長時間的實地考察和實驗室試驗等工作，綜合資料以繪製地質圖。地質圖亦在若干程度上反映了地質學家依據實地考察和當時其他證據而得出對地質歷史的認識。

自十九世紀以來，許多人都對香港地質調查作出了貢獻。第一次全港性的地質調查是在上世紀初由一群加拿大地質學家進行。他們在1936年出版了首幅地質圖，比例為1:84,480。地質圖顯示了火成岩、沉積岩組，以及表土沉積物的主要分佈狀況，但沒有描述斷層、褶皺或其他地質構造。

這些空白的地質構造資料由兩名來自英國的地質學家填補。他們於1971年完成了兩幅1:50,000比例的地質圖，記錄了火山岩、深成岩和沉積岩之間的主要分區，並且顯示如層理和節理等地質構造的走向和傾角。

香港地質調查組於1982年成立。當時由四至六名測繪地質學家組成，每位地質學家負責繪製一至兩幅特定地質圖。在1984年至1996年的12年間，共製作了15幅1:20,000比例的地質圖，進一步增潤了本港火山岩地層和花崗岩侵入史。

全港1:20,000比例的地質圖準確標示了本港主要岩石類型的分佈。地質圖顯示，「古老」的沉積岩在新界北部及吐露港區域附近出現，而「年輕」的沉積岩則在新界東北部附近的

To unravel the geological history of a region, one must begin by gathering various pieces of information, and then to slowly fit these together into a chain of events. For geologists this requires years of meticulous and systematic surveying, and immense patience. The discovery of Hong Kong's supervolcano took years of team effort and was underpinned back in the 1980s by systematic geological mapping.

The very first piece of geological information that geologists normally gather from an area is the distribution of various rock types. This is usually done by geological surveys, which involve hours and hours of field and laboratory work, and preparation of geological maps. These geological maps inevitably reflect some degree of the geologists' interpretation of the geological history based on their field observations and other evidence available at the time the maps were produced.

Numerous individuals have contributed to the geological surveying of Hong Kong since the 19th century. The first territory-wide geological survey was carried out in the early 20th century by a group of Canadian geologists, resulting in the publication of the first geological map in 1936 at a scale of 1:84,480. The map showed the main distribution of igneous and sedimentary rock groups, as well as the superficial deposits, but no portrayal of faults, folds, or other geological structures.

This was remedied in 1971 when two 1:50,000-scale map sheets were completed by two geologists from the United Kingdom. The set included major divisions among the volcanic, plutonic and sedimentary rocks alongside the geological structures, such as strike and dip of bedding and rock joints.

The Hong Kong Geological Survey was established in 1982. Over the course of 12 years, from 1984 to 1996, fifteen 1:20,000-scale geological maps, displaying further refinements to the volcanic stratigraphy and intrusion history, were produced. At that time, there was a team of four to six mapping geologists, with each geologist responsible for one or two particular map sheets.

By the time the 1:20,000-scale geological maps were completed, an accurate picture of the distribution of the major rock types in Hong Kong had been established. This showed that "old" sedimentary rocks were exposed in the northern New Territories and around the Tolo Harbour area, and "young" sedimentary rocks were exposed in the

大鵬灣(如赤洲、鴨洲和坪洲)出現。然而，香港的岩石大部分是通過岩漿冷卻和凝固而形成的火成岩，佔全港岩石露頭百分之八十五，火山岩佔大約百分之五十，這些岩石與火山噴發直接相關，其餘百分之三十五為花崗質岩石，由火山底下的岩漿凝固結晶而成。

在1:20,000比例的地質圖上，火山岩分為地層單元，並歸類成岩組及岩組群(稱為火山岩群)。相比之下，花崗岩只根據其晶體大小(粗粒、中粒或細粒)簡單分類。當時我們對不同類型的花崗質岩石所知甚少，亦未嘗試將花崗質岩石分組或弄清其與火山岩的關係。實地觀察結果顯示，花崗岩較火山岩年輕。

northeastern New Territories around Mirs Bay, such as Port Island, Ap Chau and Ping Chau. However, most of the outcrop area of Hong Kong (85%) comprised igneous rocks formed through cooling and solidification of magma. About 50% of the igneous rocks are made of volcanic rocks, which means these rocks were once directly associated with volcanoes, and 35% are made of granitic rocks, which represent the crystallised roots of the volcanoes.

As the volcanic rocks are stratigraphical units, they were divided into named formations, and families of formations (known as Volcanic Groups), on the 1:20,000-scale geological maps. In contrast, little was known about the different types of granitic rocks and their relationship to the volcanic rocks. The granites were simply classified according to crystal size (coarse, medium or fine). Field observations showed the granites were younger than the volcanic rocks, but no attempt was made to group the granites or correlate them with the volcanic rocks.

到了1990年代中後期，我們繪製出各種花崗岩的界線，並根據接觸關係確定了花崗岩之間的相對年齡，繼而把各種花崗質岩石分成大型的侵入單元，稱為深成岩體。給岩體命名的方法，與火山岩群命名的方法相同，花崗岩體也被歸類為花崗質岩套。

於2000年出版的1:100,000比例的地質圖(圖1-1)對火山岩地層詳加分類並顯示深成岩侵入史，其中包括對岩套和岩體、火山岩群和岩組的命名。此時，拼圖遊戲的第一塊零片已然確定，但它在拼圖中的位置仍是未知數。

During the mid- to late-1990s, the boundaries of the different types of granites were mapped out, and their relative ages were established based on contact relationships. The granitic rocks were assigned to a number of large, single intrusive units called “plutons”. Names were given to the plutons in the same way that names were given to the different volcanic units. The granite plutons were also grouped into families (known as Granitic Suites).

The 1:100,000-scale geological map (Figure 1-1), published in 2000, showed detailed subdivision of the volcanic stratigraphy and plutonic history including naming of suites and plutons, volcanic groups and formations. Thus, the first piece of our jigsaw puzzle had been defined but its position in the big picture was not known.

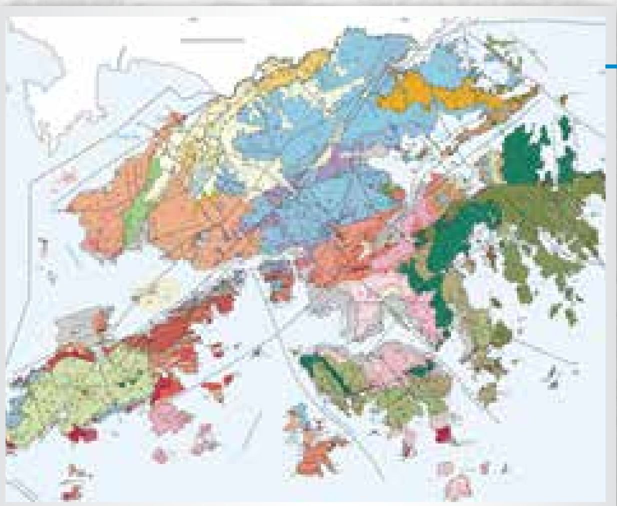


圖1-1. 於2000年出版的1:100,000比例香港地質圖
Figure 1-1. Extract from a 1:100,000-scale geological map of Hong Kong published in 2000

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火成岩及火山類型

IGNEOUS ROCKS AND TYPES OF VOLCANO

那麼，火成岩是如何形成的呢？火成岩由來自地球深處的岩漿凝固而成(圖1-2)。

So, how are igneous rocks formed? Igneous rocks are formed from solidified magma (i.e. molten rock) that originates from deep within the Earth (Figure 1-2).

侵入岩，或稱深成岩，是當岩漿上升期間被困於地球深處，導致冷卻過程非常緩慢，往往歷時數千或百萬年才得以完全凝固。緩慢的冷卻過程，給予個別礦物足夠時間結晶，形成體積相對較大的晶體。侵入岩一般擁有較粗粒的岩理及互鎖的礦物。花崗岩是香港最常見的侵入岩。

Intrusive, or plutonic, igneous rocks are formed when rising magma is trapped deep within the Earth, where it cools very slowly over many thousands or millions of years. Slow cooling allows sufficient time for individual mineral grains to grow and form relatively large crystals. Intrusive rocks have a coarse-grained texture with interlocking crystals. Granite is the most common intrusive rock in Hong Kong.

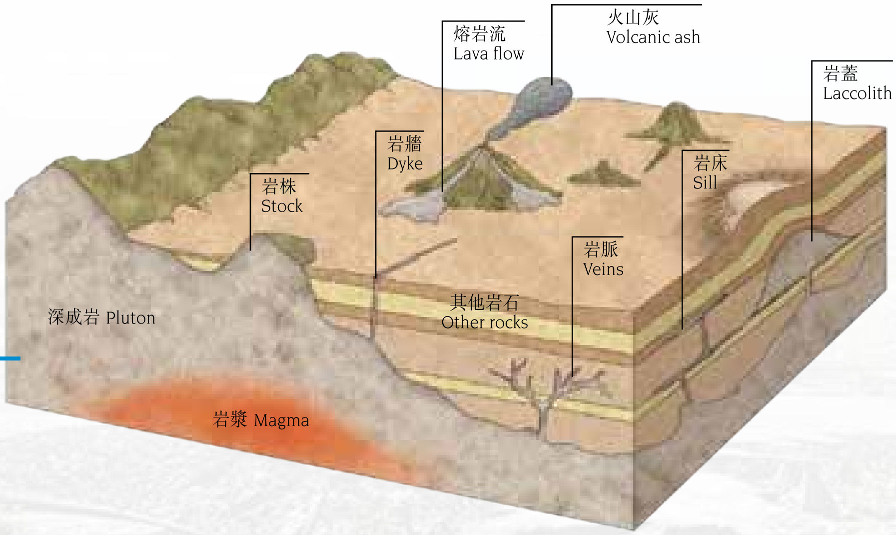


圖1-2. 各種火成岩的形態
Figure 1-2. Various forms of igneous rock

噴出岩，或稱火山岩，是當岩漿向上湧出噴發，並在地面或非常接近地球表面冷卻而形成。噴出的岩漿暴露於溫度較低的大氣層，其冷卻及凝固速度相對較快，因而形成岩理較幼的噴出性火成岩。熔岩及凝灰岩是兩種常見的火山岩。凝灰岩是由火山灰凝固而成。

Extrusive, or volcanic, igneous rocks are produced when magma is erupted at, or very near, the Earth's surface. The erupted magma cools and solidifies relatively quickly when it is exposed to the cooler temperatures of the atmosphere, resulting in forming a fine-grained texture. Lava and tuff are two common volcanic rocks. Tuff is solidified ash.

火山通常在聚合性板塊邊緣出現，例如被稱為「火環」的環太平洋火圈(圖1-3)。

Volcanoes are commonly found at convergent plate margins, such as the "Ring of Fire" (Figure 1-3) around the Pacific Ocean basin.

常見的火山類型有三種，包括盾狀火山、層狀火山和破火山口火山。它們在不同的板塊環境下產生，而各種火山的形成，也視乎岩漿成分而定。

Three common types of volcanoes, including shield volcanoes, stratovolcanoes and caldera-type volcanoes, occur in various tectonic settings. The formation of various types of volcanoes also depends on the magma composition.

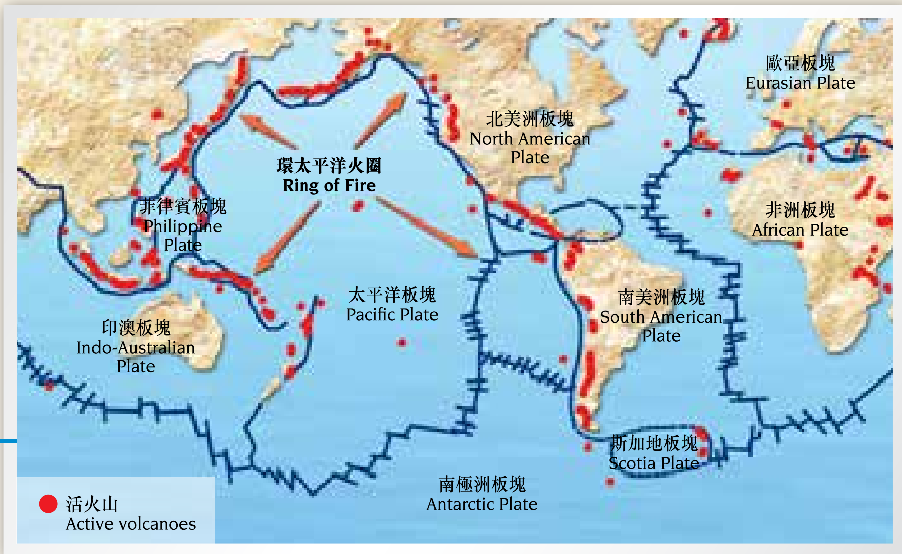
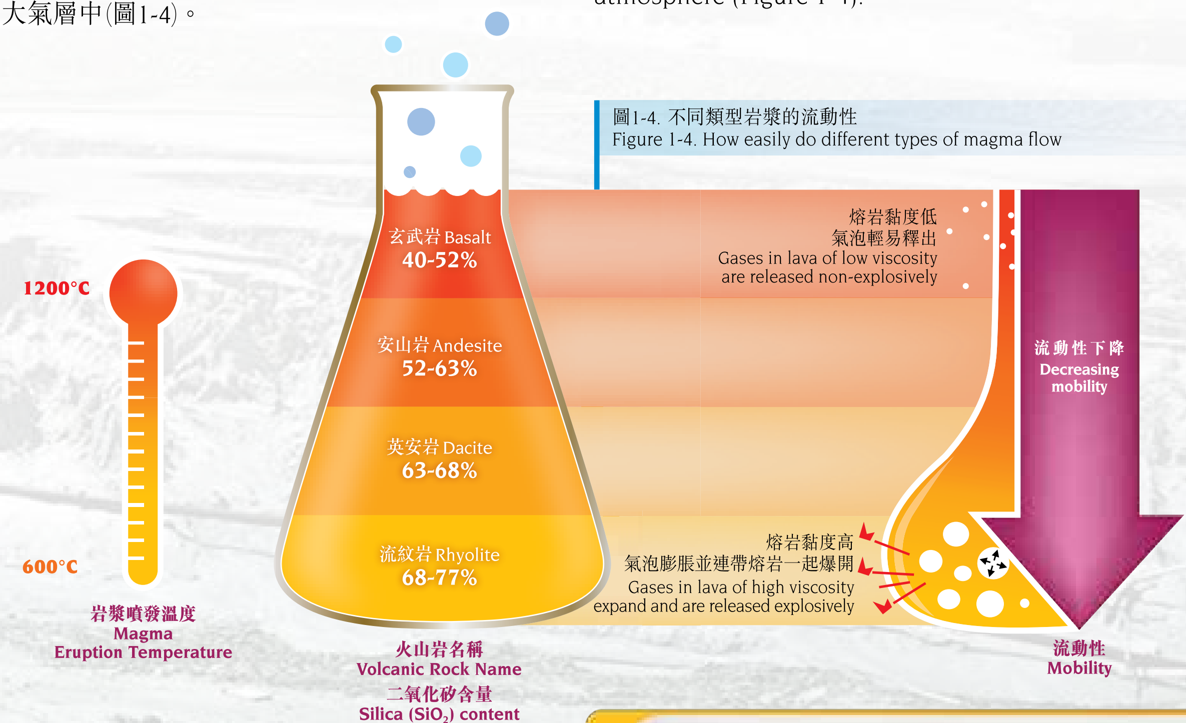


圖1-3. 活火山、板塊及「環太平洋火圈」
Figure 1-3. Active volcanoes, tectonic plates and the "Ring of Fire"

地質學家通常根據二氧化矽含量把岩漿分類。低二氧化矽岩漿(即二氧化矽的含重量為45-65%)具較高的流動性，岩漿中的氣體在到達地表時，可相對輕易地從中釋出，如夏威夷熔岩流。即溶解的氣體以水蒸氣氣泡的形式出現，然後從岩漿中非爆炸性地排出，釋放到大氣層中(圖1-4)。

Geologists generally classify magma in terms of its silica content. Low-silica magmas (i.e. SiO_2 = 45-65 wt%), such as the lava flows in Hawaii, are runny, and any trapped gases can escape relatively easily from the magmas when they reach the surface. That is, as magma comes to the surface, the dissolved gases come out of solution in the form of vapour, which are then released non-explosively into the atmosphere (Figure 1-4).

圖1-4. 不同類型岩漿的流動性
Figure 1-4. How easily do different types of magma flow



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相比之下，具有較高二氧化矽含量(即二氧化矽的含重量為65-77%)的岩漿非常黏稠且黏滯，不易流動。當黏稠的岩漿通過地殼上升時，岩漿中不斷膨脹的氣泡很難逃逸。最終，當氣泡膨脹到不能再被包含在岩漿時，會連帶岩漿一起爆開。這過程把岩漿和其中的晶體砸碎，岩漿碎片驟冷就變成細玻璃質顆粒，即火山灰。這些火山灰是火山噴發時升到大氣層中巨大火山灰雲柱的主要成分。部分火山灰雲柱可能坍塌並沿地面流動，稱為火山灰流。

香港的火山岩絕大部分為流紋質成分，主要由破火山口型火山猛烈噴發的火山灰組成。

By contrast, magmas with relatively high-silica content (i.e. SiO_2 = 65-77 wt%), are very sticky and viscous and do not flow well. When the sticky magma ascends through the crust, the developing bubbles in the magma have great difficulty in escaping. Eventually, the bubbles can no longer be contained in the magma as they expand to bursting, at which point the magma literally blows itself apart, shattering any crystals and liquid, and which quenches into fine glass particles as volcanic ash. These are the main components of the giant ash clouds that rise into the atmosphere forming an eruption column, and which may partially collapse and flow out along the surface.

The volcanic rocks in Hong Kong are predominantly rhyolitic in composition and consist mainly of ash. These rocks were formed by violent eruptions of volcanic ash from caldera-type volcanoes.

圖1-5. 岩漿
Figure 1-5. Magma

資料匣 BOX

什麼是岩漿？
What is Magma?

岩漿的主要成分包括高溫混合的矽酸鹽物質(岩漿)、水和溶解氣體。岩漿內還可能含有在岩漿上升到地面時冷卻而形成的晶體及岩石碎片。在地球深處，岩漿處於高壓之下，其中的氣體溶解在岩漿中。

Magma consists of a high temperature mixture of silicate material (magmatic liquid), water and dissolved gases. It may also contain crystals formed during cooling of the magma, or rock fragments incorporated into the magma, during ascent toward the Earth's surface. Deep in the Earth, the magma is under high pressure, and the gases within it are dissolved in the melt.

資料匣 BOX

地質學家如何量度火山噴發的威力？
How do geologists measure the violence of a volcanic eruption?

火山爆發指數(VEI)是根據火山噴出物體積將火山噴發的猛烈程度進行分級。這個指數利用對數刻度，情況有點像地震震級。VEI＝0的火山噴發表示岩漿連續流出，跟夏威夷基拉韋亞火山的噴發相似。1991年菲律賓的皮納圖博火山噴發屬VEI＝6，1815年印尼的坦博拉火山噴發屬VEI＝7。超級噴發屬VEI＝8或更高，值得慶幸的是，超級噴發極為罕見，平均而言，大約每隔一萬至十萬年才發生一次。至於超大型(>2,500立方公里)的火山噴發，通常每十萬至二十萬年才發生一次。

Geologists have a logarithmic scale (a bit like an earthquake magnitude scale) by which they classify the violence of a volcanic eruption based on volume of ejected materials. It's called the Volcanic Explosivity Index (or VEI). A volcano of VEI = 0, would be something similar to continuous outpouring of magma such as from Kilauea volcano in Hawaii. A VEI = 6 was the 1991 Pinatubo eruption in the Philippines, and a VEI = 7 was the 1815 Tambora eruption in Indonesia. Supereruptions have a VEI = 8 or higher. Thankfully, the frequency of such supereruptions is, on average, only about once every 10,000 to 100,000 years. The very big ones (>2,500 km^3) are usually once every 100,000 to 200,000 years, so they are extremely rare events.

圖1-6. 火山爆發指數
Figure 1-6. Volcanic Explosivity Index (VEI)

火山管道系統
VOLCANIC PLUMBING SYSTEM

火山噴發期間，岩漿從地底通過火山通道噴出，產生熔岩或火山灰。岩漿庫和火山通道被統稱為火山管道系統(圖1-7)。

岩漿有時不會上升到地表，而是被困在地下，並緩慢地結晶形成侵入岩。因此，花崗質深成岩體一直被認為是火山系統中未曾噴發的岩漿，相當於已經凝固的岩漿庫。

During volcanic eruptions, magma is expelled from below the Earth's surface through volcanic vents, producing lava or volcanic ash. The magma chamber and the vents are collectively known as the volcanic plumbing system (Figure 1-7).

Sometimes, the molten rocks in the magma chamber do not erupt to the surface, but are trapped in the ground and crystallise slowly to form intrusive rocks. The granitic plutons are therefore considered to be the non-erupted counterpart of the volcanic rocks, representing the frozen magma chamber that fed a volcano.

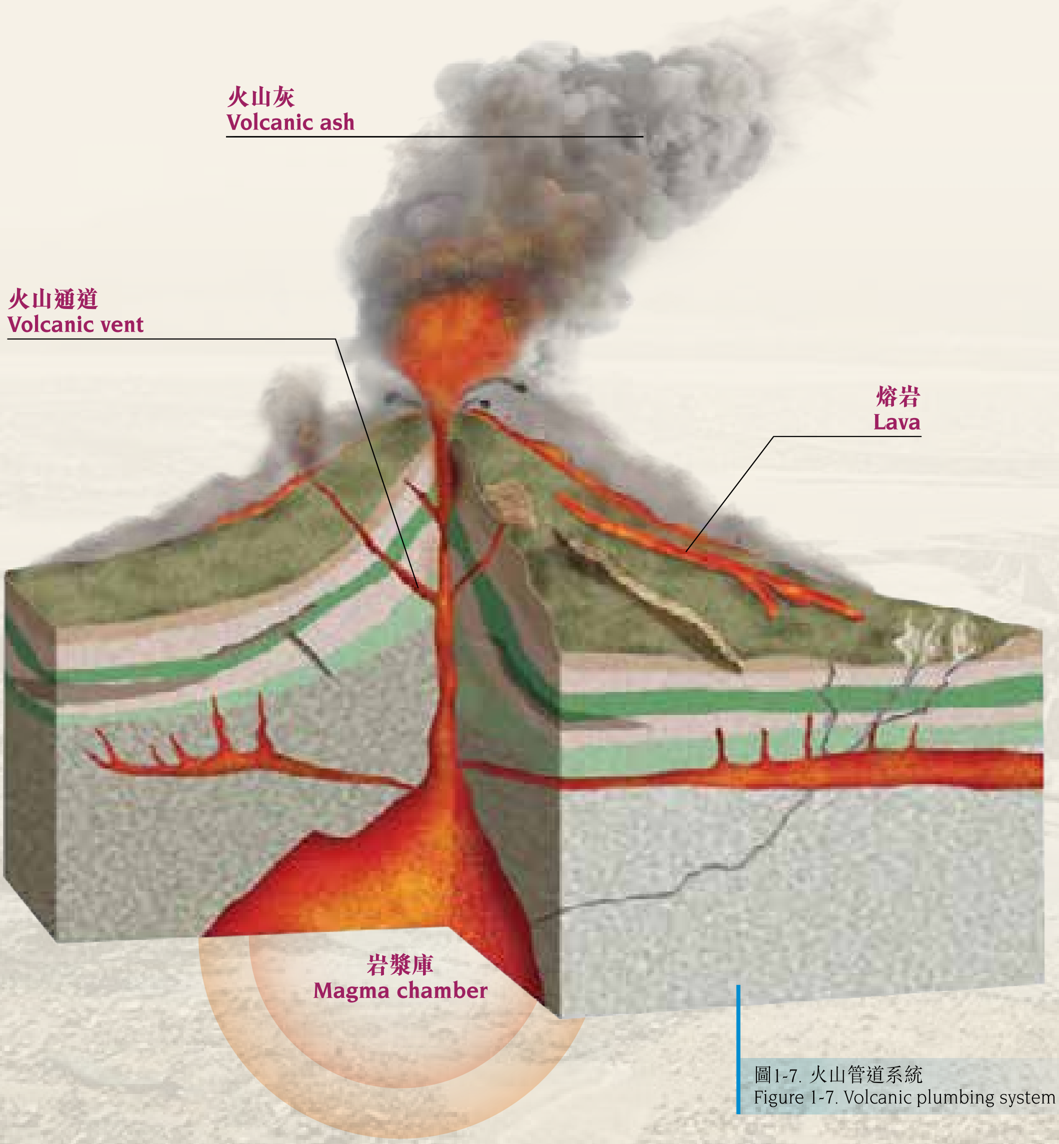


圖1-7. 火山管道系統
Figure 1-7. Volcanic plumbing system

火山岩和花崗岩的配對
PAIRING OF VOLCANIC AND GRANITIC ROCKS

香港岩漿岩的年齡和地球化學特徵

AGES AND GEOCHEMISTRY OF MAGMATIC ROCKS IN HONG KONG

拼圖的第二塊零片，是火山岩群與花崗質岩套的相互關係。首步是通過放射性年齡測定來確定岩石的年齡。

在1970年代進行的放射性年齡測定顯示，香港火山岩的年齡大約為一億五千四百萬年，而花崗岩則為一億四千三百萬年至一億一千七百萬年。這些早期測試結果參差，誤差較大。直到1990年代中期，新開發利用鋯石進行的放射性定齡法能夠更精準地測定岩石的年齡。

因此，我們將火山岩和花崗質岩石分組後，決定展開有系統的年齡測定研究(圖2-1)。研究揭示了令人驚訝的結果，因為火山岩和花崗質岩石都可分為四個明顯不同的年齡組別，而每組火山岩可與一組花崗質岩石配成一對，組成四對獨特的火山岩–花崗岩組合。我們對年齡測定結果大感詫異，於是決定對岩石進行廣泛的地球化學評估，以觀察這四對火山岩–花崗岩組合能否從其化學成分反映出來。

The second piece of our jigsaw puzzle was the correlation of the volcanic groups and granitic suites. The first step in the process was to determine the precise ages of the rocks by radiometric dating.

Back in the 1970s, early radiometric dating work claimed that the volcanic rocks in Hong Kong were around 154 million years old, and granites ranged from 143 to 117 million years old. These early attempts yielded mixed results with large errors. However, in the mid-1990s, a new radiometric method of dating zircon minerals was developed, meaning that ages could be determined with much greater precision and accuracy.

Consequently, following the grouping of the magmatic rocks into families, it was decided to carry out a systematic age dating study (Figure 2-1). The results of dating revealed a surprising pattern in the rocks because the volcanic and granitic rocks could be grouped into four distinct age categories, and each category had its unique combination of volcanic-granitic assemblages. The geologists were so amazed with this age pattern that they decided to carry out an extensive geochemical assessment of the rocks to see whether the same groupings were reflected by their geochemical composition.

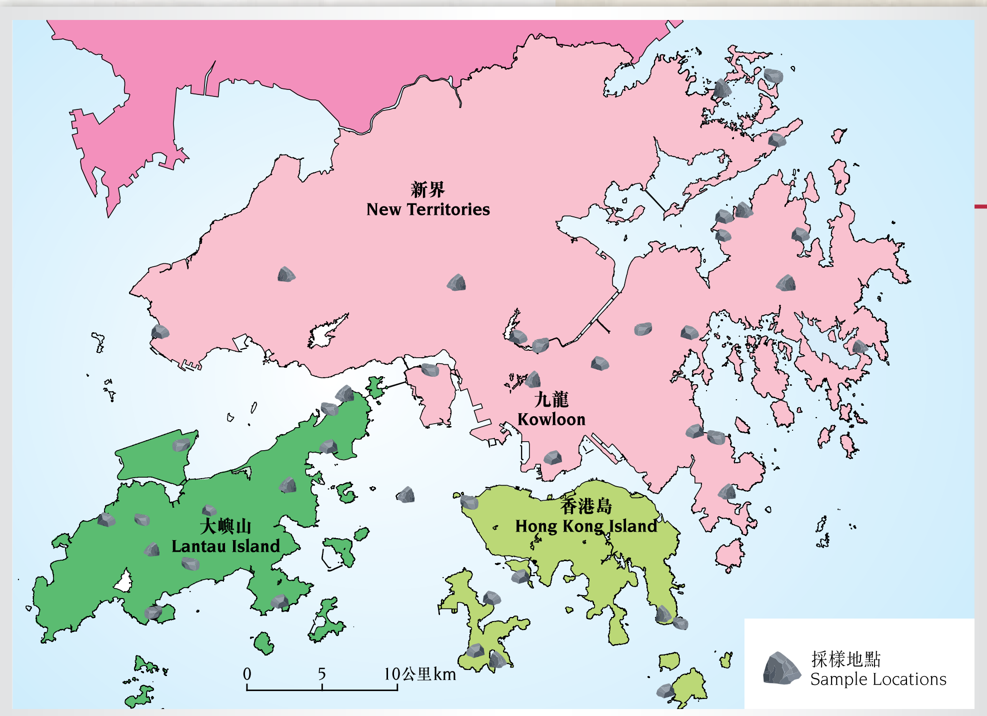


圖2-1. 年齡測定研究的採樣地點
Figure 2-1. Sample locations for age dating study

資料匣 BOX

地質學家如何確定岩石的年齡？
How do geologists determine the age of a rock?

你可能會問，地質學家如何測定岩石的年齡？地質學家使用各種放射性年齡測定方法，當中以鈾–鉛同位素測定法最為普遍使用。簡單來説，同位素具有正常數量的質子和電子，但有不同數量的中子。放射性元素如鈾的同位素是不穩定的(稱為母同位素)，並通過釋放能量而衰變成更穩定的鉛同位素(稱為子同位素)。每個同位素都有特定的衰變率和半衰期。岩石中含有同位素的礦物一旦形成，礦物中的母同位素就開始衰變，產生子同位素，而半衰期是指母同位素由初始時的數量衰變至一半時所需的時間。通過測定礦物中母子同位素的比例，便可以計算礦物的年齡，從而知悉岩石的年齡。

You may ask, how do geologists date the rocks? Well, geologists use a variety of radiometric methods; the most favoured being the uranium-lead isotope system. In simple terms, isotopes are atoms of an element with a normal number of protons and electrons but a different number of neutrons. Isotopes of radioactive elements, such as uranium (known as the parent isotope), are unstable and decay to a more stable isotope of lead (known as the daughter isotope) by releasing energy. The rate of decay and half-life of isotopes is constant, and unique to each particular isotope. Once a mineral is formed, the parent isotope in the mineral begins to decay to produce a daughter isotope. The time required for half of the parent isotope to decay to daughter isotope is called "half-life". By counting the ratio of parent to daughter isotopes in a mineral, the age of the mineral, and hence the rock bearing them, can be determined.

鈾鉛同位素年齡測定
U-Pb Isotopic Dating

於花崗質岩漿中結晶的鋯石含有不穩定的鈾(U)原子，並於鋯石結晶後開始以特定的衰變率衰變成鉛(Pb)。透過量度鈾(母同位素)和鉛(子同位素)的比例便可計算礦物，即岩石的年齡。

Zircon minerals crystallising in a granitic magma incorporate the unstable radioactive uranium isotope. By measuring the ratio of the parent uranium isotope to the daughter lead isotope, and knowing the half-life of the radioactive uranium isotope, the age of the mineral since it first crystallised, and hence the rock, can be determined.

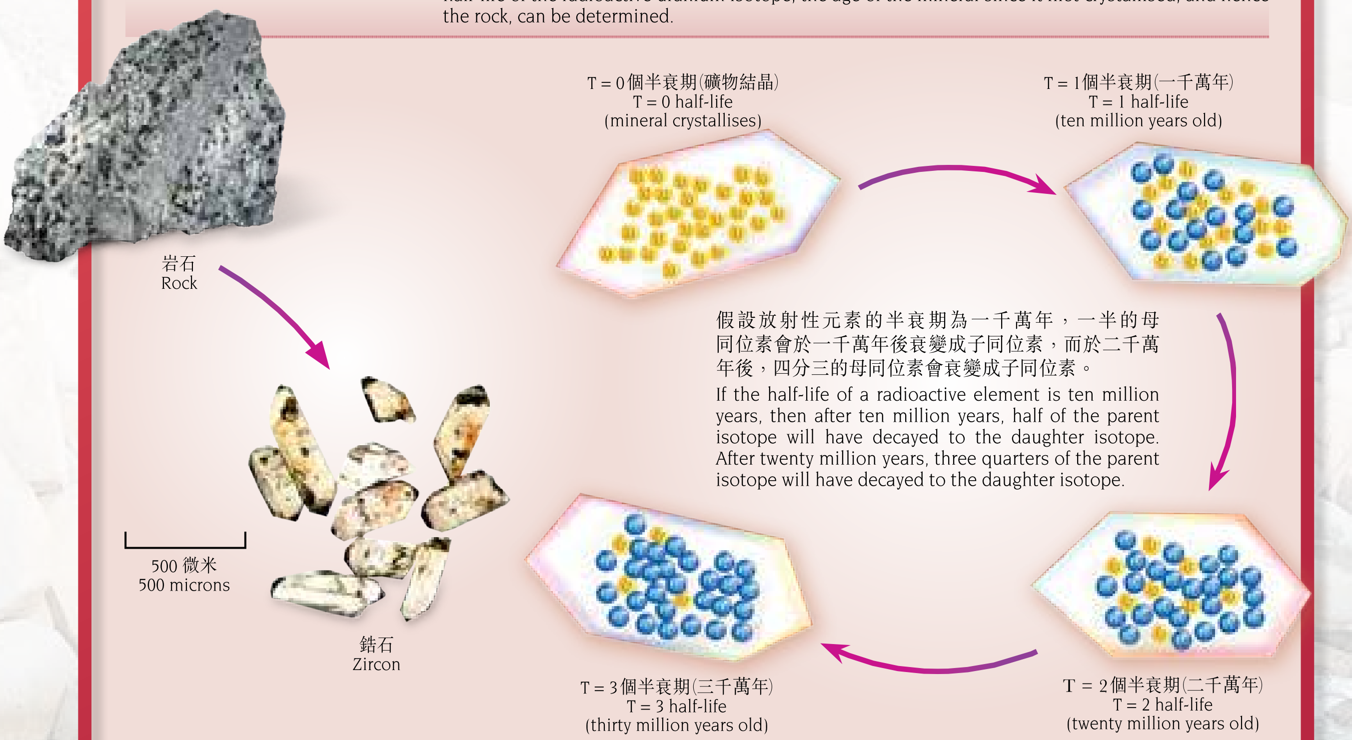


圖2-2. 放射性年齡測定
Figure 2-2. Radiometric dating

資料匣 BOX

地質年代解釋
Geological time explained

我們有需要了解地質年代的巨大跨度。地質學家口中所說皆以數百萬年為單位，其實就像我們大多數人所說的年度一樣。因此，在地質學上一百萬到幾千萬年前的岩石是「年輕的」；而幾億到幾十億年的岩石，在地質學上才算是「古老」。有一個簡單的方法，可以幫助我們理解地質年代的巨大跨度，我們可以把整個地球的歷史(即四十五億七千萬年)看作一天(即時鐘的24小時)(圖2-3)。地殼在地球形成後的大約二十四秒(即大約一百三十萬年後)開始形成。地球表面最古老的岩石(約四十二億八千萬年前)，是在地球形成之後大約一小時三十一分鐘出現。現在快速向前行22個小時到深夜，地球形成後約23個小時，第一隻鳥類出現。而現代人則在午夜前4秒鐘出現。

We need to understand the immensity of geological time. Geologists talk in millions of years, the same way most people talk in years. So, rocks from one to tens of millions of years old are geologically "young", whereas rocks from hundreds to thousands of millions of years old, are geologically "old". A convenient way to think about the immensity of geological time, is if we picture the whole of the Earth's history (i.e. 4.57 billion years) as one day (i.e. 24 hours of a clock) (Figure 2-3). The Earth's crust begins to develop at about twenty-four seconds after formation of the Earth (i.e. about 1.3 million years after formation). The oldest rocks found at the Earth's surface (about 4,280 million years ago) appear at about one hour and thirty-one minutes after the formation of the Earth. Fast forward now by 22 hours into the late evening, and at about 23 hours after the formation of the Earth, the first bird appears. Modern man appears 4 seconds before midnight.

地球化學分組
GEOCHEMICAL GROUPINGS

我們對香港各區大約1,000個火山岩和花崗岩類樣本進行了化學分析。本港大多數火成岩的二氧化矽含重量為65-77%。除鈉、鋁、鉀等主要元素外，岩石中還含有次要和微量元素。在研究火山岩和花崗質岩石的地球化學特徵時，我們再次發現兩者之間有一系列令人意想不到的關係，就是四對火山岩–花崗岩組合的年齡分組與地球化學分組一致(圖2-4)。

我們的下一個任務，就是要確定四對火山岩–花崗岩組合的地理分佈。

Approximately 1,000 volcanic and granitic rock samples from all over Hong Kong were analysed for their chemical composition. In Hong Kong, most of the igneous rocks contain between 65% and 77% by weight of silica. Apart from the major elements such as sodium, aluminium and potassium, the rocks also contain minor and trace elements. The geochemical characteristics of the volcanic and granitic rocks were examined, and, once again, an astonishing set of relationships emerged. It was found that the geochemical groupings matched the age groupings (Figure 2-4).

The next task was to determine the geographic distribution of the four volcanic and granitic rock groupings.

圖2-3. 將四十五億七千萬年看作一天計算
Figure 2-3. 4.57 billion years in one day

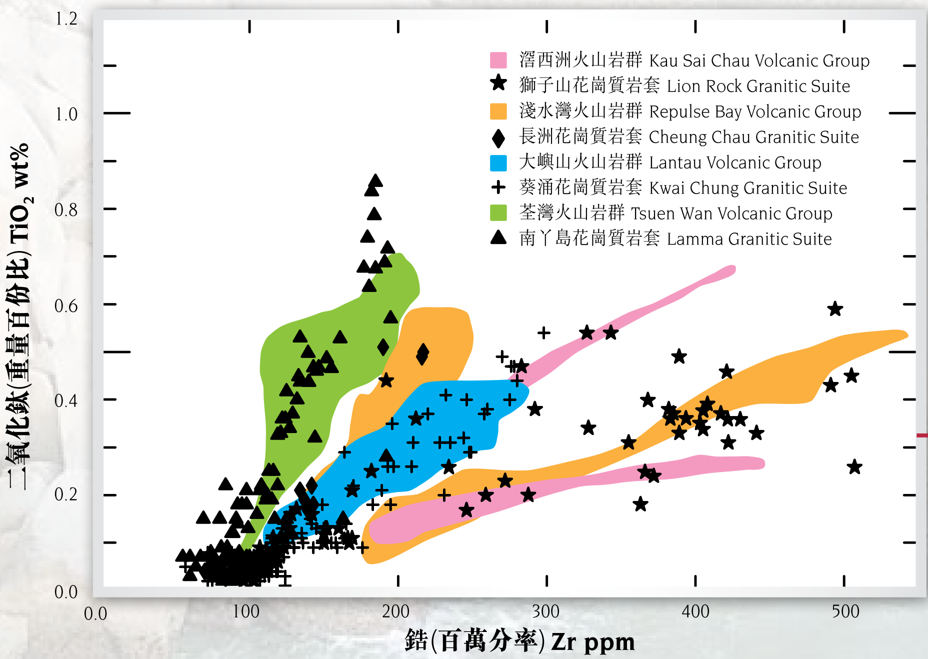


圖2-4. 地球化學分析顯示火山岩群與花崗質岩套的關係
Figure 2-4. Geochemical plot showing the relationships between volcanic groups and granitic suites

四個火山岩–花崗岩組合
FOUR VOLCANIC – GRANITIC ASSEMBLAGES

四組火山岩–花崗岩的關係
RELATIONSHIPS OF THE FOUR VOLCANIC – GRANITIC ASSEMBLAGES

我們根據岩石的年齡和地球化學成分，將本港的火山岩和花崗質岩石分成四個年齡和地球化學成分分明的組合，並進行了顏色編碼，繪製出一幅地質圖(圖2-5)。我們很快便發現，最古老的火山岩–花崗岩組合主要分佈在本港的西北部，下一個岩石組合位於中部，東南部則是兩個最年輕的火山岩–花崗岩組合。似乎火山岩和花崗岩組合的岩石成分和年齡看來是有系統地向東南方向遞進的。

我們意識到，在新界中部、大嶼山西部和西貢地區的火山岩和花崗岩組合，可能由各自的破火山口型火山系統產生。因此，香港在中生代晚期曾出現大約二千五百萬年的火山活動期。這是九十年代中後期我們對香港地質理解的重大突破。

The volcanic and granitic rocks were grouped into four pairs of discrete ages and geochemical composition and colour-coded on a map (Figure 2-5). It soon emerged that the oldest grouping lay mostly in the northwest of Hong Kong, the next grouping in the middle, and the two youngest groupings in the southeast. So it looked like there was a systematic southeastward progression in composition and age among the paired volcanic-granitic assemblages.

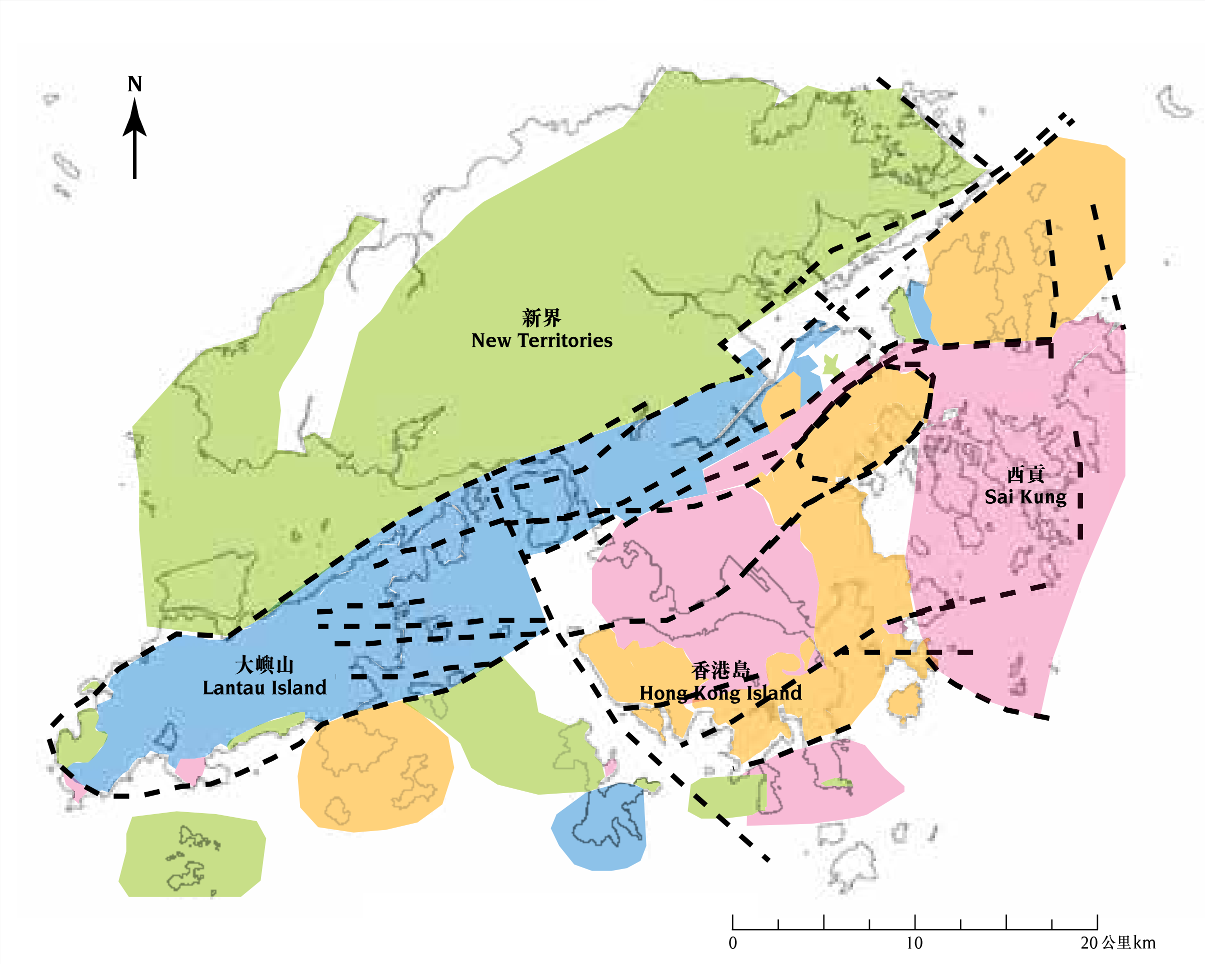
It was recognised that individual pairs of volcanic and granitic rocks were probably generated from separate caldera-type volcanic systems in the central part of the New Territories, western part of Lantau Island and in the Sai Kung area. Thus, an approximately 25-million-year period of volcanic activity was recorded in Hong Kong back in the late Mesozoic Era. This was a major breakthrough in our understanding of Hong Kong geology back in mid-to late-1990s.

兩個火山岩和花崗岩組合的空間重疊
SPATIAL OVERLAP OF THE TWO YOUNGER GROUPS

本港東南部兩個較年輕的火山岩和花崗岩組合(即圖2-5中滘西洲火山岩群–獅子山花崗質岩套和淺水灣火山岩群–長洲花崗質岩套)似乎在地理位置上有所重疊。岩石形成的正確次序還有待研究。地質學家稱之為構建地層剖面。意即將各岩層的序列拼接在一起，並從最古老到最年輕的岩層正確地排列出來。正確的岩層序列有助瞭解地層結構，以及兩個岩石組合何以在空間分佈上有所重疊。

The two youngest groups (i.e. the Kau Sai Chau Volcanic Group – Lion Rock Granitic Suite and the Repulse Bay Volcanic Group – Cheung Chau Granitic Suite in Figure 2-5) appeared to overlap geographically in southeastern Hong Kong. Somehow, an orderly sequence of events had to be worked out. Geologists call this constructing a stratigraphic section. That means piecing various layered rock sequences together and placing them into a correct order from oldest to youngest. Knowing the correct rock sequence can help with understanding the stratigraphy and why there is an apparent overlap in spatial distribution.

圖2-5. 火山岩群和花崗質岩套的年齡組別和分佈
Figure 2-5. Age grouping and distribution of volcanic groups and granitic suites



斷層 Faults

較年輕 Younger

較古老 Older

一億四千萬年前
140 million years ago

滘西洲火山岩群 – 獅子山花崗質岩套
Kau Sai Chau Volcanic Group - Lion Rock Granitic Suite

一億四千三百萬年前
143 million years ago

淺水灣火山岩群 – 長洲花崗質岩套
Repulse Bay Volcanic Group - Cheung Chau Granitic Suite

一億四千六百萬年前
146 million years ago

大嶼山火山岩群 – 葵涌花崗質岩套
Lantau Volcanic Group - Kwai Chung Granitic Suite

一億六千四百萬至一億六千萬年前
164-160 million years ago

荃灣火山岩群 – 南丫島花崗質岩套
Tsuen Wan Volcanic Group - Lamma Granitic Suite

重建地層柱狀剖面圖
RECONSTRUCTING A STRATIGRAPHIC COLUMN

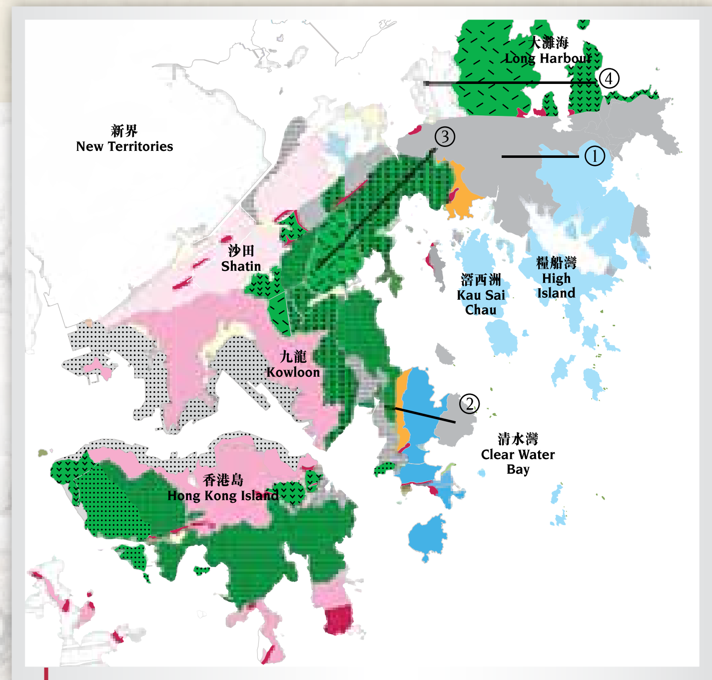
重建連續地層剖面
RECONSTRUCTING A CONTINUOUS STRATIGRAPHIC SECTION

兩個較年輕火山岩群的分佈狀況看來非常奇怪。在西貢北部、東九龍及港島南部的岩層是由斷層分隔成數個岩石分段。這些斷層的走向跟香港西北面的斷層不同。要在兩個最年輕的岩石群組中找到完整的地層剖面並不容易。然而，憑著岩石的精確年齡及地球化學特徵，我們便能夠將這些隔斷的岩石分段按時間順序排列出來，為這兩個火山岩群建立完整的序列(圖2-6)，並從而發現兩個較年輕的火山岩群中間被170米厚的沉積岩層所分隔(即圖2-6中橙色位置)。

然而，不同岩石分段和岩石群組的斷層和整體結構仍然令人大惑不解。

There seemed to be a very odd distribution of rocks of the two youngest volcanic groups. The rocks are separated by faults into several blocks in northern Sai Kung, eastern Kowloon and southern Hong Kong Island. The faults separating these rock blocks are of a different orientation to those in the northwestern parts of Hong Kong. Finding a complete stratigraphic section within the two youngest groups was not easy. However, with the advantage of some precise ages on the rocks and their geochemical characteristics, it became possible to piece these separated rock blocks into an orderly sequence from oldest to youngest and erect a complete sequence for the two groups (Figure 2-6). Volcanic rocks of the two groups were separated by a 170 m thick layer of sedimentary rocks (i.e. those in orange colour in Figure 2-6).

However, the faults and overall structure of the different blocks and groups of rocks remained puzzling.



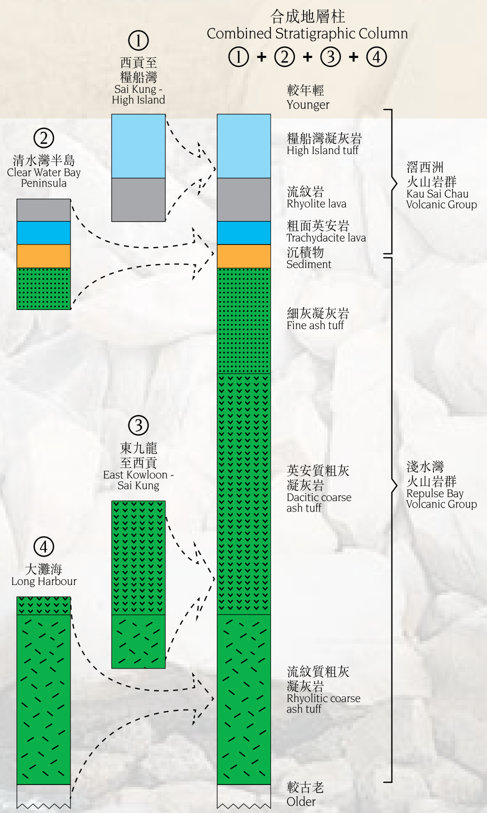
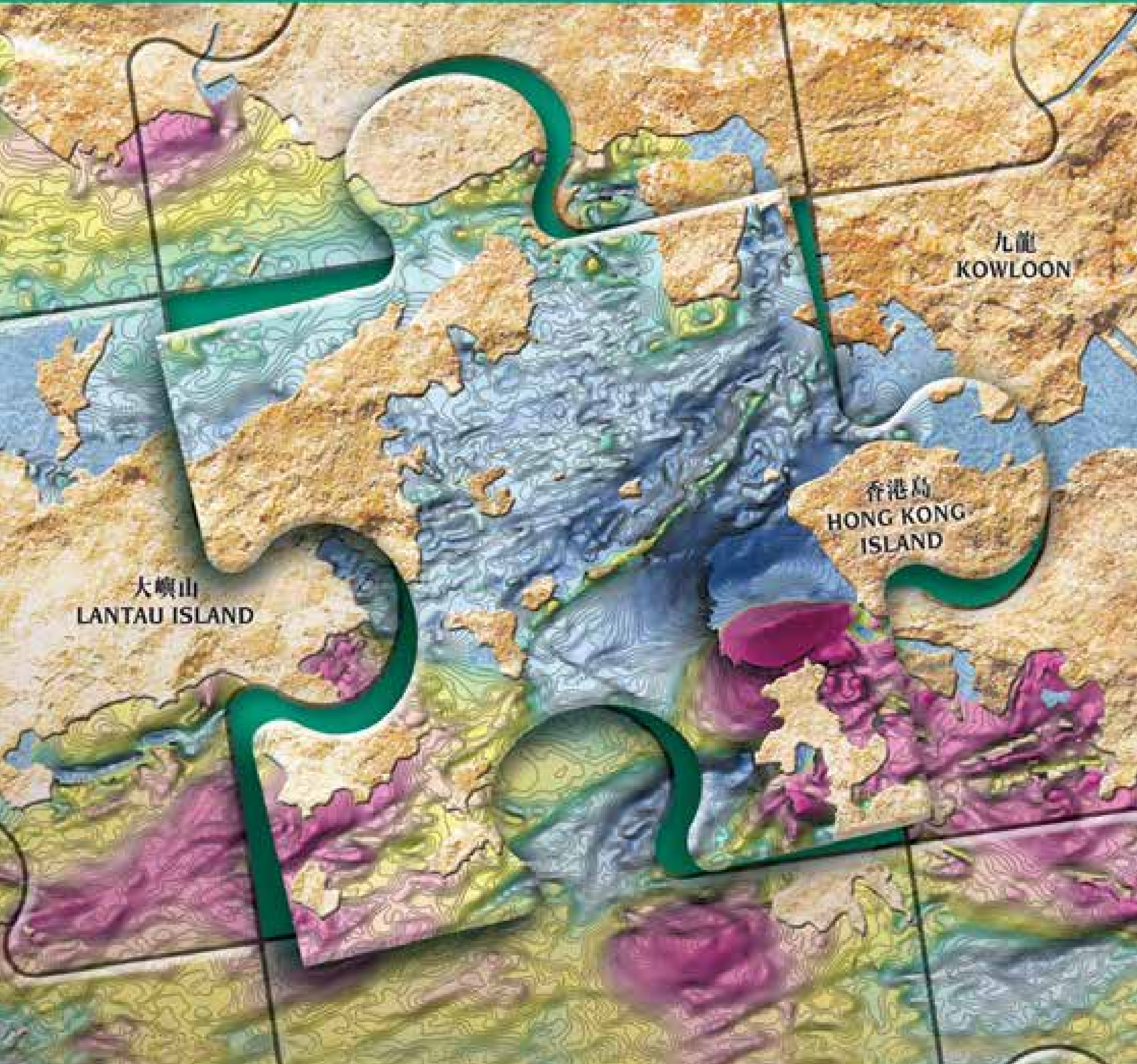


圖2-6. 重建兩個最年輕的火山岩群的地層
Figure 2-6. Stratigraphic reconstruction of the two youngest volcanic groups

地球物理勘測揭示的地質構造

GEOLOGICAL STRUCTURES AS REVEALED BY GEOPHYSICAL SURVEYS



陸上和近海地質構造
ONSHORE AND OFFSHORE GEOLOGICAL STRUCTURES

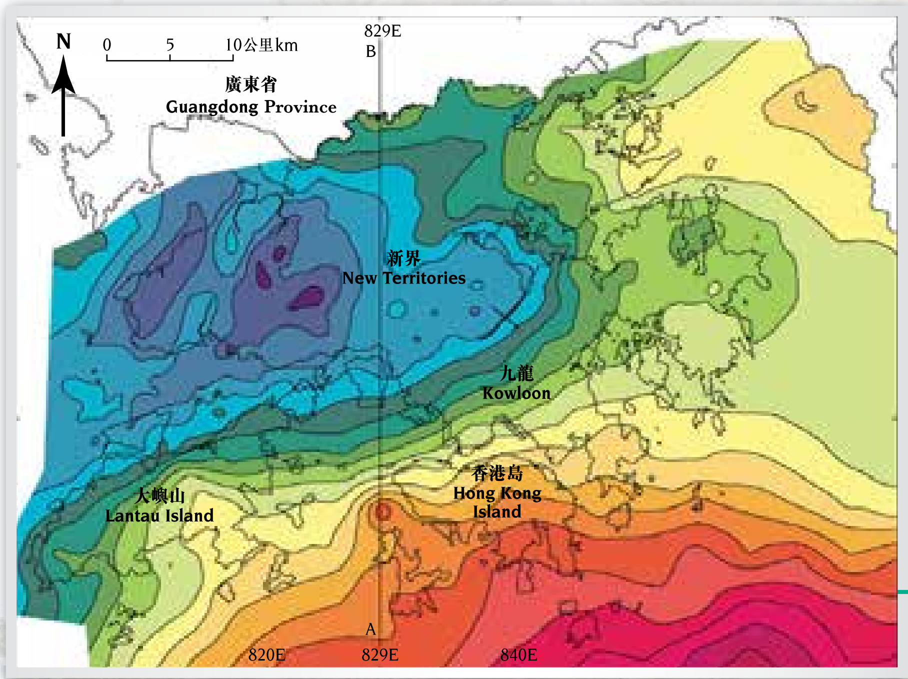
地球物理學揭示隱藏的地質構造
GEOPHYSICS REVEALS HIDDEN STRUCTURES

為解開這一部分的謎團，我們利用各種地球物理學的方法來識別隱藏在深處的地質構造。這是拼圖的第三塊零片。

地球物理學將物理學的原理應用於地球研究，其中包括磁場和重力場調查。九十年代初，本港進行了一次重力調查，以探索深層地殼構造(圖3-1)。同時，還進行了數次海洋磁場調查，以確定在陸地上一些地質特徵(如斷層)於近海的延續位置。我們將這些地球物理學調查結果整合在一起，得出一幅全香港的複合圖。同時，我們把數學方法應用到重力數據上，以識別5-10公里深的上中部地殼之間的隱藏構造，及隱藏在5公里以內的上層地殼構造。得出的複合圖顯示，在香港東南地區，斷層走向是由北向南和由東向西；至於在香港西北地區，斷層主要呈東北向，以及西北向。

In order to solve this part of the riddle, geophysical methods were applied to identify structures hidden deep within the Earth. This is the third piece of our jigsaw puzzle.

Geophysics applies the principles of physics to the study of the Earth, including the surveys of magnetic and gravitational fields. A gravity survey of Hong Kong was carried out in the early 1990s to explore the deep crustal structure (Figure 3-1). At about the same time, a number of marine magnetic surveys were conducted to identify the offshore continuation of mapped onshore features, such as faults. The magnetic surveys were pieced together to produce a single territory-wide composite map. Coincidentally, a mathematical technique was applied to the gravity data that enabled identification of hidden structures in the upper-middle crust, between 5-10 km deep, and in the upper crust down to a depth of 5 km. The resulting map showed that in southeastern Hong Kong, fault structures were oriented north-south and east-west, whereas in the northwest of Hong Kong they were mainly oriented northeast-southwest, and northwest-southeast.



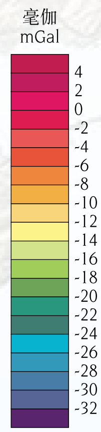
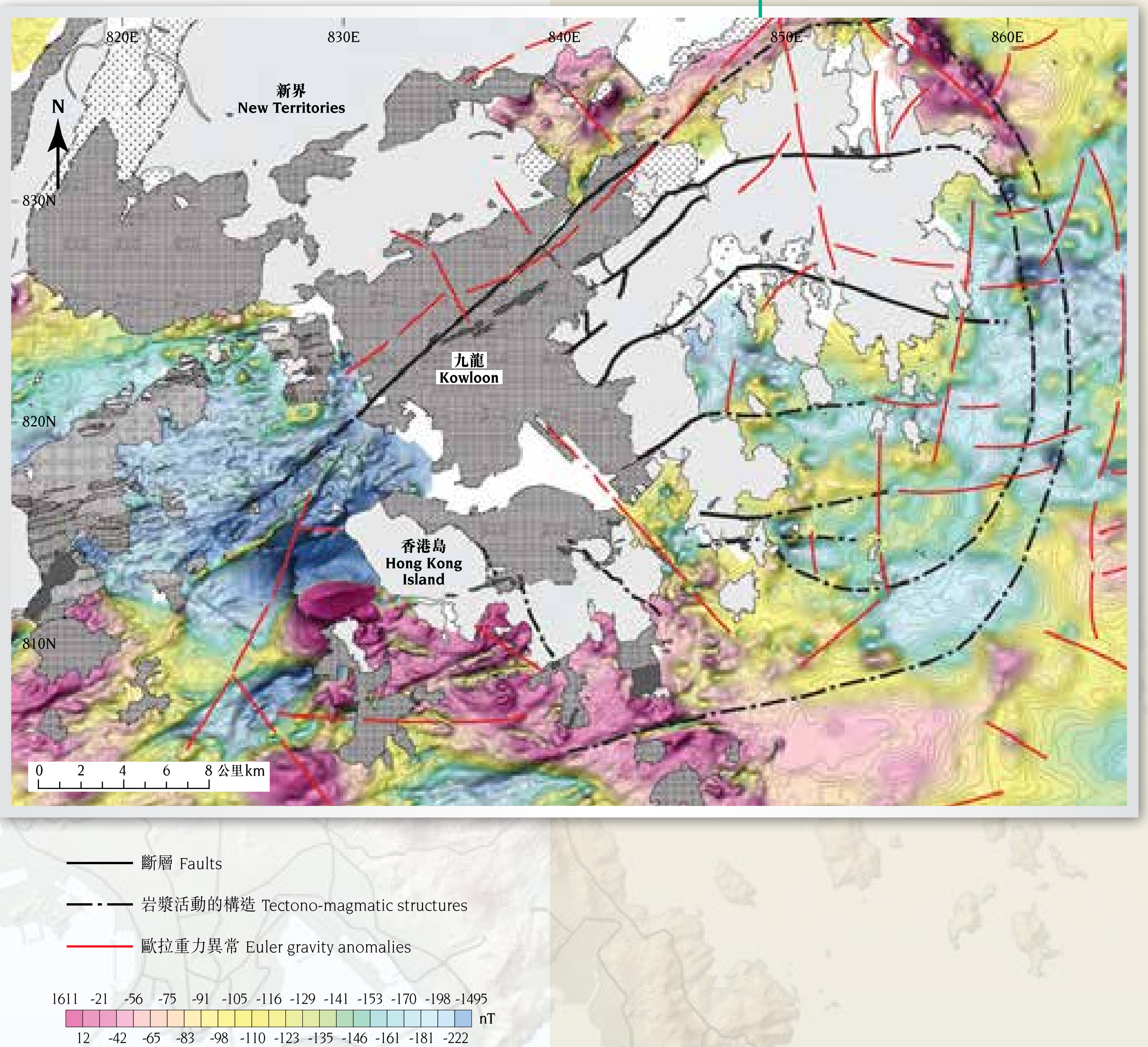


圖3-1. 香港布格重力異常圖
Figure 3-1. Bouguer gravity anomaly map of Hong Kong

然而，以上種種如何有助理解本港東南地區岩漿岩群組重疊的疑問呢？我們完成進一步的地球化學和年齡測定之後，將所有地球物理數據、岩組的分佈，以及地質構造的資料整合到同一張圖上(圖3-2)。

But how did all this contribute toward understanding why the magmatic groups in the southeast overlapped? Following further investigations involving geochemistry and age dating, all the geophysical data, mapped rock units and geological structures were combined in a single map (Figure 3-2).

圖3-2. 磁力異常圖及重力數據
Figure 3-2. Magnetic anomaly map and gravity data



以國際地磁參考場為基準之剩餘磁力異常圖：未調查地區無色
Residual Magnetic Anomaly Map based on the International Geomagnetic Reference Field (IGRF): unsurveyed areas are uncoloured

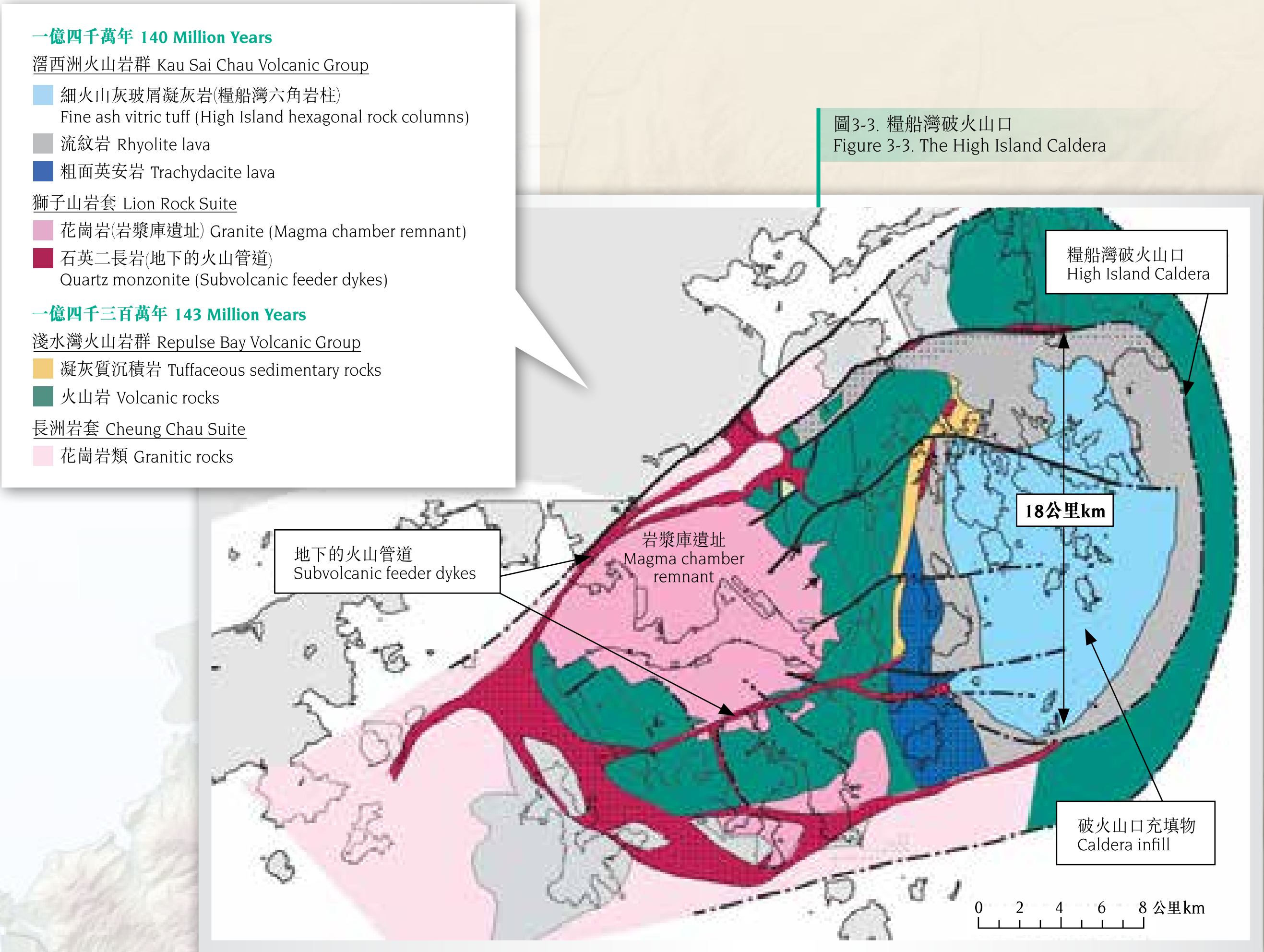
發現糧船灣破火山口
DISCOVERY OF THE HIGH ISLAND CALDERA

整合證據
COMBINING THE EVIDENCE

一旦在地質圖加上重力及地磁數據，我們有驚人的發現－這是「恍然大悟」的一刻。整合的地質圖顯示了本港東南地區火山管道系統的橫切面，從地殼表面的火山岩到岩漿庫內的深處。西貢的火山岩是破火山口火山的頂部，而九龍及港島北部的花崗岩則代表火山底下已凍結的岩漿庫。我們正看著傾側了的火山管道系統，經過數百萬年來的侵蝕而展現出來(圖3-3)。

Once the geological map data, and gravity and magnetic data had been added, a staggering discovery was made – this was the "aha" moment. The map revealed the cross-section of a volcanic plumbing system in southeast Hong Kong, from volcanic rocks at the surface to deep within the magma chamber. The volcanic rocks in Sai Kung represent the top of a caldera volcano, and the granites in Kowloon and the northern part of Hong Kong Island represent the frozen magma chamber underneath the volcano. The geologists were looking at a volcanic plumbing system lying on its side; erosion over millions of years had revealed this exposure (Figure 3-3).

圖3-3. 糧船灣破火山口
Figure 3-3. The High Island Caldera



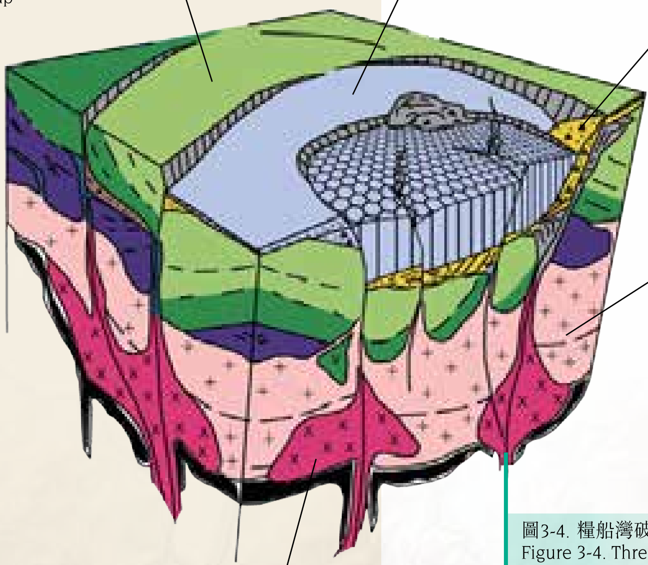


圖3-4. 糧船灣破火山口三維模型
Figure 3-4. Three-dimensional block diagram of the High Island Caldera

我們以地質調查和地球物理學的方法揭示的一系列斷層，代表破火山口邊緣的環狀構造。根據對環狀構造的辨識，我們估計糧船灣破火山口的直徑至少為18公里。因此，我們不僅看到地表上破火山口的環狀構造，還可以看到環狀斷層延伸到地底的岩漿庫。換句話說，這揭示了火山岩與地底岩漿庫和火山管道之間的連接關係(圖3-4)。

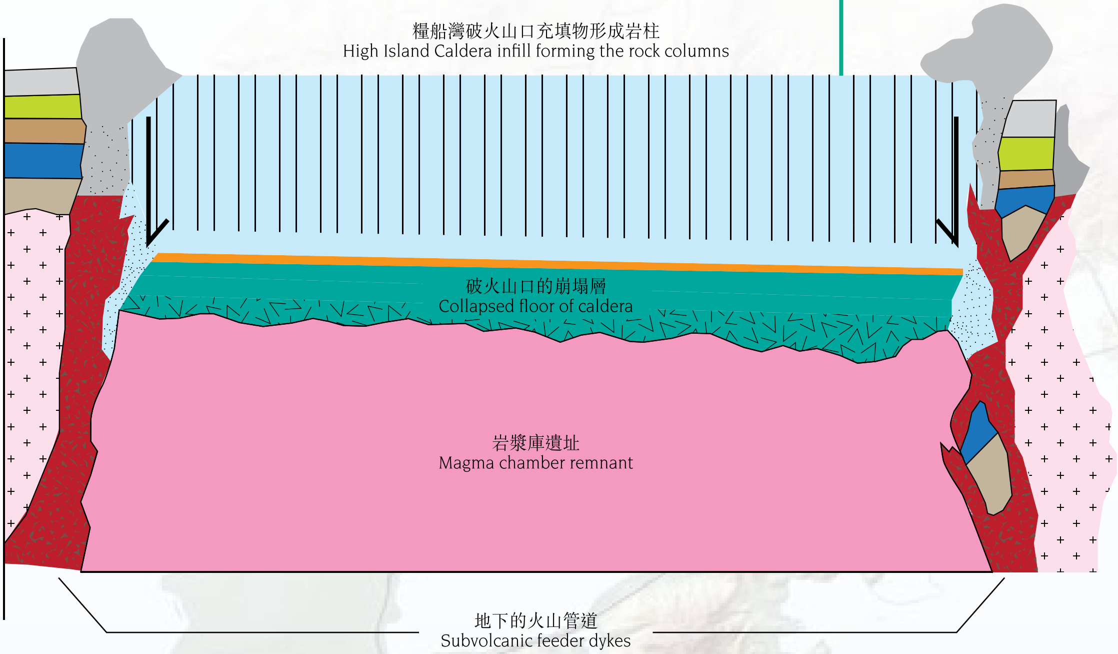
The series of faults, as revealed by surface mapping and geophysical methods, represent the caldera-bounding ring structure. Based on the identification of the ring structure, we can estimate the diameter of the High Island Caldera to be at least 18 km. So instead of just seeing the caldera ring structure at the surface, we can see the continuation of the ring faults deep into the underlying magma chamber. In other words, the connection between the volcanic rock at the surface and its feeder dykes from the underlying magma chamber was revealed (Figure 3-4).

火山管道系統和地殼剖面
VOLCANIC PLUMBING SYSTEM AND CRUSTAL SECTION

將火山管道系統的不同部分整合在一起，就揭示了火山全貌。我們最初以為，兩個重疊的火山岩群屬於相同的破火山口系統，但很明顯，這個解釋未免過於簡單。火山岩分段的分佈以前被解釋為沿斷層的側向移動，但現在被認為是沿「環狀斷層」垂直的幾公里位移(圖3-5)。這些斷層是岩漿注入的管道，正是破火山口崩塌時所形成的構造。在這個岩層序列中間夾有170米厚沉積物，似乎標誌著破火山口發展歷史上的間斷時期，分隔開一億四千三百萬年的淺水灣火山岩群與一億四千萬年的滘西洲火山岩群。

Piecing together the different parts of the volcanic plumbing system enabled the full picture of the volcano to be revealed. It was at first thought that the two overlapping younger volcanic groups belonged to the same caldera system, but it became obvious that this explanation was too simple. What previously had been interpreted as lateral offsets of rock blocks along faults, were now seen to be “ring faults” of several kilometres of vertical displacement (Figure 3-5). Along these faults were injections of magmas, exactly what we would expect from a collapsed caldera structure. The 170 m-thick sedimentary unit sandwiched in the sequence seemed to mark a hiatus in the caldera development history, separating the 143-million-year-old Repulse Bay Volcanic Group from the 140-million-year-old Kau Sai Chau Volcanic Group.

圖3-5. 糧船灣破火山口橫切面示意圖
Figure 3-5. Schematic cross-section of the High Island Caldera



糧船灣火山的噴發規模
SIZE OF THE HIGH ISLAND ERUPTION

糧船灣火山噴發的規模究竟有多大？
HOW BIG WAS THE HIGH ISLAND ERUPTION?

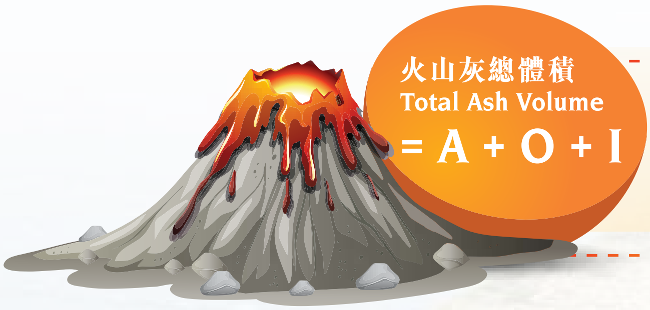
這是拼圖的第四塊零片。於西貢東部大規模的柱狀火山岩，一直被認為與單一次的災難性噴發相關。這火山灰層顯然是破火山口形成時最終災難性噴發的產物。我們下一步是要確定噴發的規模。

為計算噴發出的火山灰總量，地質學家需要考慮火山噴發時產生的三種主要火山灰沉積物。首先是噴射到大氣層之中，而隨後沉積下降的火山落灰；第二，從火山噴出沿著地面流動的火山灰，稱作火山灰流；最後是噴出後回落到破火山口凹陷的火山灰，稱為破火山口內部的火山灰(圖4-1)。

就古老的破火山口火山而言，要計算這些噴發物的體積並不容易，因為大部分火山灰已經被侵蝕。然而，地質學家從現代破火山口火山噴發得到線索。通過對現代火山進行詳細研究，地質學家得悉火山落灰、火山灰流和破火山口內部的火山灰的體積是大致相同的。倘若其中一種主要火山灰沉積物的體積可以直接測量，其他兩種火山灰沉積物的體積就可以從中估算出來，從而計算出火山灰的總噴發體積。

This is the fourth piece of our jigsaw puzzle. The remarkably large size and thickness of the columnar jointed tuff in eastern Sai Kung had previously been associated with a single catastrophic eruption. But it became apparent that this ash was the product of the final cataclysmic caldera-forming eruption. The next step was to determine the size of the eruption.

In order to calculate the total volume of ash erupted, it is necessary to take into account three main ash deposits from a volcanic eruption; first, the ash erupted into the atmosphere and subsequently deposited as the ash fallout component; second, the ash that flows out of the volcano along the ground known as outflow ash component; and finally, the ash that falls back into and fills up the caldera depression, called the intracaldera ash component (Figure 4-1).



破火山口火山噴發的火山灰組成部分
Ash components of a caldera eruption

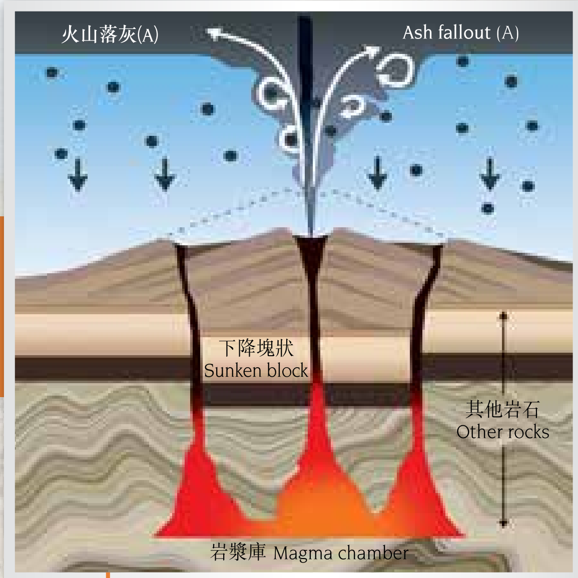


圖4-1a. 火山落灰
Figure 4-1a. Ash fallout

不過，由於火山落灰沉積較為鬆散，其密度不及破火山口內部的火山灰和火山灰流。因此地質學家還需要考慮這三類火山灰沉積物的不同密度，以計算出火山灰的「稠密岩石等量」體積。火山落灰的「稠密岩石等量」體積在較合理的推算下只有其它火山噴發物的約三分之一。

對於糧船灣破火山口火山噴發，我們只能考慮破火山口內部的火山灰，即糧船灣組凝灰岩，因為這是糧船灣噴發留下的唯一產物。要計算其體積，需要估計破火山口原本的直徑，以及火山口內部的火山灰的厚度。基於對破火山口環狀斷層的識別，估計糧船灣破火山口的直徑至少為18公里(圖3-3)。由於無法得知多少火山岩已經被侵蝕，保守估計破火山口內部的火山灰的厚度有一公里。基於上述資料，我們能夠用簡單的數學方法計算出糧船灣組凝灰岩的體積。

火山落灰(A)、火山灰流(O)和破火山口內部的火山灰(I)是三種主要火山灰組成成分。
Ash fallout (A), outflow ash (O) and intracaldera ash (I) are the three main ash components.

It is not easy to measure these components from ancient caldera eruptions because much of the ash has eroded away. However, modern caldera eruptions can provide clues, and detailed study of modern volcanoes shows that the volumes of the ash fallout, outflow ash and intracaldera ash components are roughly similar. When the volume of one of the components can be measured directly, then the volumes of the other two components can be estimated, and an estimate calculated for the total volume of ash erupted.

However, the ash density needed to be taken into consideration. Therefore, we calculated a "dense rock equivalent" (DRE) volume of ash erupted. Since the ash fallout component is likely to be less dense than the intracaldera ash and outflow ash components, a better approximation is that ash fallout component is about one-third the volume of the other components.

In the Hong Kong case, we could only take into account the intracaldera ash, as the solitary material preserved from the High Island eruption. To measure the volume of this required an estimate of the original diameter of the caldera, plus the thickness of the ash layer. Based on identification of the ring faults, the diameter was estimated to be at least 18 km across (Figure 3-3). Next, the minimum exposed thickness of the intracaldera ash unit was measured, based on geological mapping. This estimation gave a conservative thickness of 1 km for the unit, because it is not known how much material had already been eroded. At this point, a volume was calculated using simple mathematics.

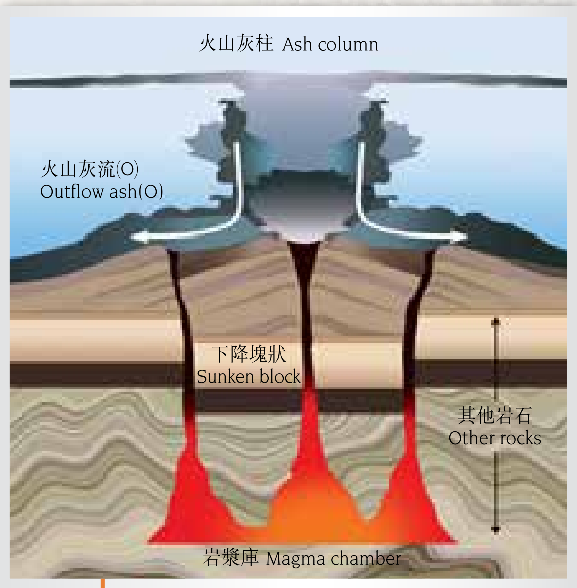


圖4-1b. 火山灰流
Figure 4-1b. Outflow ash

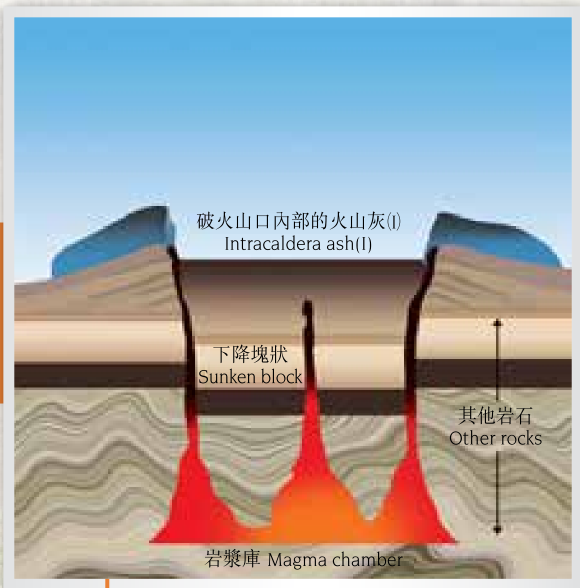


圖4-1c. 破火山口內部的火山灰
Figure 4-1c. Intracaldera ash

西貢的六角岩柱(即糧船灣凝灰岩)是由糧船灣火山噴發產生的破火山口內部的火山灰凝固而成。根據實驗室直接測試的結果，糧船灣凝灰岩(固化火山灰)的密度約為2,430公斤/立方米，與其他成分相類的凝灰岩的密度相若，其「稠密岩石等量」體積約為250立方公里。由於火山灰流的體積與此數值相約，故在體積估算中可先將此值乘二。最難估算的體積成分是火山落灰。根據對成分相類的現代破火山口火山的體積估算，估計糧船灣火山噴發時火山落灰的「稠密岩石等量」體積最小約為70立方公里。

如將上述三個成分相加，糧船灣火山噴發的「稠密岩石等量」總體積至少為570立方公里。我們基於對現代火山的研究，假設鬆散的

In the case of the High Island eruption, the intracaldera ash has solidified into the hexagonal rock columns. The density of the High Island tuff (solidified ash) from the High Island Caldera was measured directly in the laboratory at about 2,430 kg/m^3, which is comparable to the density of tuff of similar composition. The DRE volume within the High Island Caldera was calculated to be about 250 km^3. Doubling this value takes into account the DRE volume of the outflow component. The most difficult volume component to estimate is the ash fallout. Based on volume estimates made on modern caldera volcanoes of similar composition, it was estimated that the minimum volume of DRE ash fallout for the High Island eruption was about 70 km^3.

Adding up all three components gave an estimated total DRE volume of 570 km^3 for the High Island eruption, which, as a minimum, places it firmly within the supereruption category. We assume from studies of modern volcanoes that the unconsolidated intracaldera and outflow ash

資料匣 BOX

地質學家如何界定火山噴發量？
How do geologists define the volume of a volcanic eruption?

地質學家以兩種方式來界定火山噴發量：以「火山灰」的體積計算，即假定噴發出來的火山物質全是鬆散未凝固的火山灰的總體積；或以「稠密岩石等量」體積計算，即假定噴發出來的火山物質全被轉化為岩石的總體積。實際上，火山噴發出來的物質中通常混合了鬆散的火山灰和已凝固的火山岩。然而，在古代噴發的火山沉積物當中，幾乎所有的火山灰都已經被轉化為岩石。為了解火山灰的轉換過程，想像一下，從鬆散的火山灰中將所有空氣吸出，使火山灰的體積減少，則留下的「稠密岩石等量」會小於原來的未凝固火山灰體積的一半。

There are two ways in which the volume of a volcanic eruption can be defined: either by “ash” volume, which is the total volume of erupted material assuming that it is all loose, unconsolidated ash; or the equivalent volume of “ash” if it was converted into rock, known as the “dense rock equivalent” (DRE) volume. In reality, there is usually a mixture of both loose ash and fused or welded ash in volcanic deposits. However, in ancient deposits from eruptions, virtually all the unconsolidated ash materials are converted into rock. To understand the conversion process, imagine sucking all the air out of the loose material so the volume of ash is reduced, leaving a DRE that is less than half the original, unconsolidated ash volume.

破火山口內部的火山灰及火山灰流的密度為1,100公斤/立方米，而鬆散的火山落灰的密度為700公斤/立方米。基於這些假設，我們便可以將糧船灣火山噴發的「稠密岩石等量」體積轉換成鬆散狀態下火山灰的體積。破火山口內部的火山灰加上火山灰流的體積大約是1,100立方公里，而火山落灰體積為大約240立方公里，所以估計糧船灣火山的火山灰總噴發量超過1,300立方公里。相當於整個香港遭超過1,100米厚的火山灰覆蓋！

由於地質學家對超級火山所下的定義指產生過至少一次爆炸性超級噴發的火山，因此糧船灣火山亦可稱為糧船灣超級火山！

components had a density of about 1,100 kg/m^3, while the unconsolidated ash fallout component had a density of about 700 kg/m^3. Based on these assumptions, converting the outflow ash and intracaldera ash DRE volumes to unconsolidated ash would result in a combined volume of approximately 1,100 km^3, while the DRE ash fallout volume would roughly equal 240 km^3. This gives an estimated total unconsolidated ash volume of over 1,300 km^3. This amount is equivalent to covering the whole of Hong Kong with ash to a depth of over 1,100m.

As geologists define a supervolcano as having produced at least one explosive supereruption, then the volcano that produced the High Island supereruption can now be called the High Island Supervolcano!

圖4-2. 假設大型吸塵機將空氣抽走並將鬆散的火山灰轉化成稠密的岩石
Figure 4-2. Imagine a large vacuum cleaner sucking out the air of loose ash and turning it into dense rock

資料匣 BOX

什麼是超級噴發？
What is a supereruption?

要算得上超級噴發，噴發出來的岩漿重量必須至少為一千萬億公斤(即1,000,000,000,000,000公斤)。此外，噴出的火山灰體積必須至少為1,000立方公里，這相當於把大約50萬個香港大球場填滿火山灰！如果我們設法把火山灰中所有空氣吸走，「稠密岩石等量」體積會減少到約400立方公里，相當於將約20萬個香港大球場填滿火山岩！

To qualify as a supereruption, the weight of magma erupted must be at least one quadrillion kg (i.e. 1,000,000,000,000,000 kg). Also, the volume of ash erupted must be at least 1,000 km^3. This is equivalent to about 500,000 Hong Kong Stadiums full of ash! If we managed to suck all the air out of the ash, this would reduce to a DRE volume of about 400 km^3 – equivalent to about 200,000 Hong Kong Stadiums full of rock!

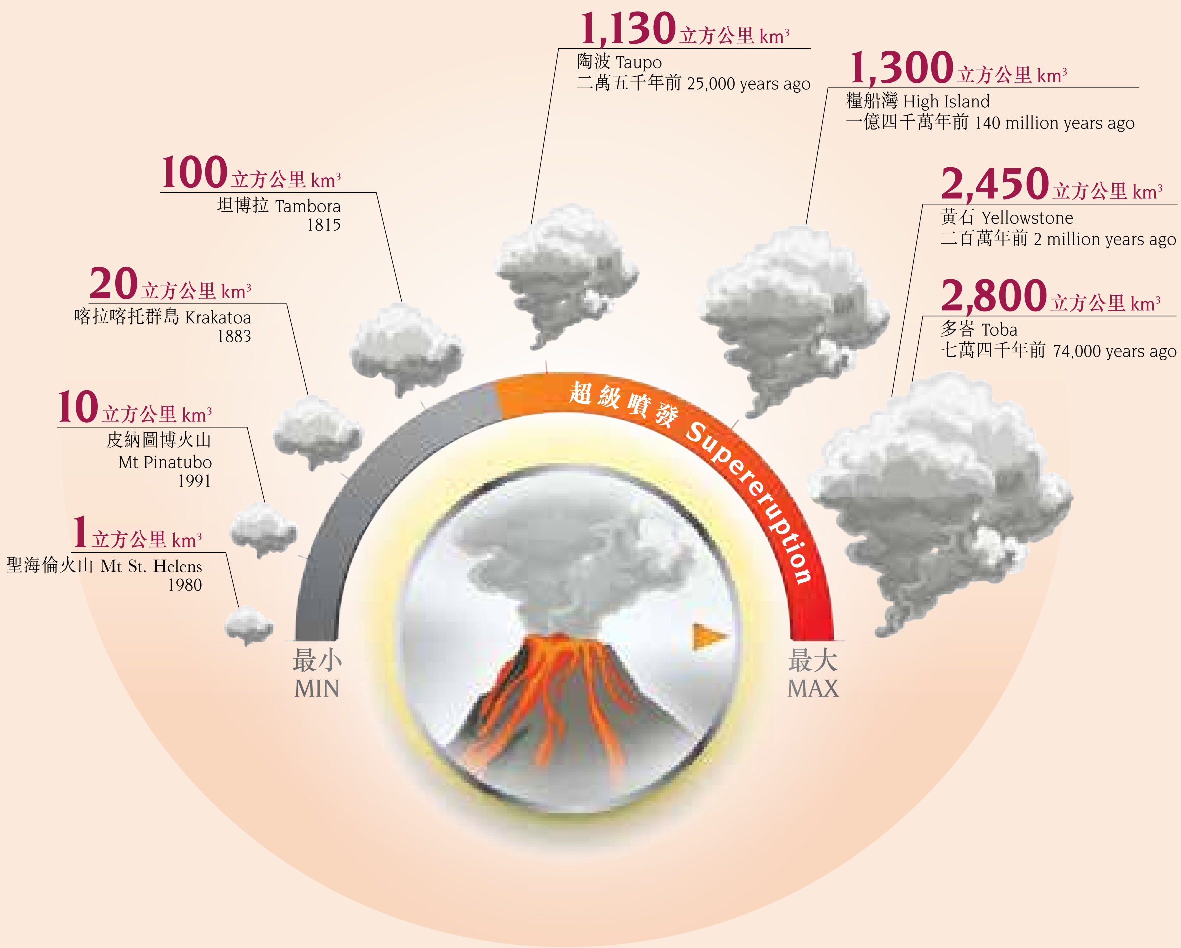


圖4-3. 超級噴發的火山灰體積
Figure 4-3. Ash volume of a supereruption

在人類歷史上最大的火山噴發也不足以跟超級噴發的規模相提並論。例如，1980年美國華盛頓州的聖海倫火山噴發，火山灰體積估計約為1立方公里。菲律賓的皮納圖博火山於1991年噴發，估計火山灰體積為10立方公里。於1883年噴發的印尼爪哇西部的喀拉喀托群島火山，火山灰體積估計為20立方公里。在印尼松巴哇島上的坦博拉火山，是近一千年來已知最大型的火山噴發事件，估計火山灰體積為100立方公里。不過，這些噴發都未達超級噴發的規模(圖4-4)。

要算得上大噴發，要以數量級增加噴發火山灰的體積。火山灰體積為1,000立方公里的超級噴發所釋放出的總能量，估計相當於大約 6.3×10^{18} 焦耳，即等於大約10萬個原子彈或15億噸黃色炸藥所釋放的能量！

The biggest volcanic eruptions recorded in human history do not come close to the size of a supereruption. For example, the eruption of Mount St. Helens volcano in 1980, in Washington State, U.S.A., had an estimated ash volume of about 1 km^3. Mount Pinatubo in the Philippines, which erupted in 1991, had an estimated ash volume of 10 km^3. Krakatoa, west of Java in Indonesia, which erupted in 1883, had an estimated ash volume of 20 km^3. Tambora volcano, on the island of Sumbawa, Indonesia, was the largest known eruption in the last millennia, with an estimated ash volume of 100 km^3. But none of these eruptions can be considered superscale (Figure 4-4).

To enter the big league, an increase in order of magnitude of erupted ash volume is required. The total amount of energy released in a supereruption with ash volume of 1,000 km^3 is estimated to be equivalent to about 6.3 exajoule. In layman's terms, this energy equals about 100,000 atomic bombs, or 1.5 billion tonnes of TNT!

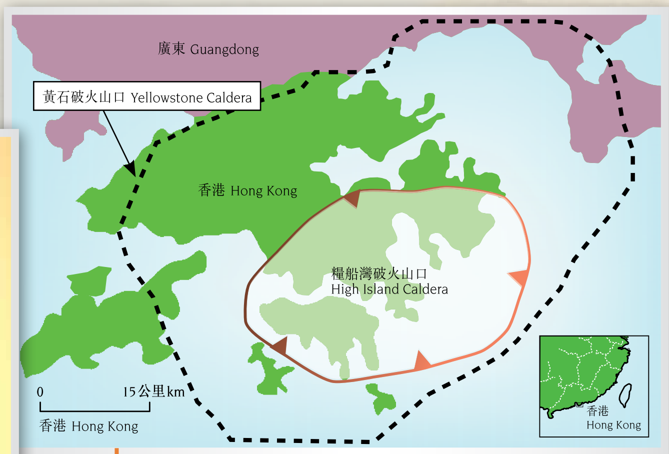
圖4-4. 主要火山噴發的位置
Figure 4-4. Locations of major volcanic eruptions

糧船灣超級噴發的規模如何與其他超級噴發相比？

HOW DOES THE SIZE OF THE HIGH ISLAND SUPERERUPTION COMPARE WITH OTHER KNOWN SUPERERUPTIONS?

糧船灣超級噴發與紐西蘭陶波火山區的超級噴發，在成分及板塊構造環境方面有非常相似之處。在過去二百萬年間，陶波火山區超級噴發所產生的火山灰量，是地球上最高的地區之一。陶波火山最年輕一次的超級噴發是二萬五千四百年前，噴出的火山灰體積約為1,130立方公里，略少於計算得出的糧船灣超級噴發的火山灰量，而陶波火山破火山口的面積亦似乎較小。此外，與陶波火山鄰近的瓦卡馬魯破火山口相比，糧船灣破火山口僅略小一些。瓦卡馬魯火山大約在三十三萬年前噴發，噴出1,500立方公里的火山灰。如果我們將位於美國懷俄明州黃石火山的破火山口重疊在糧船灣破火山口之上，那麼我們就可以看到後者的面積僅為673平方公里，而巨型的黃石火山系統的面積是3,885平方公里，將兩者相比，真是小巫見大巫(圖4-5)。這並不奇怪，因為從黃石破火山口噴發的火山灰量幾乎是糧船灣破火山口的兩倍。這些比較顯示，糧船灣破火山口的大小與其他體積和規模相若的超級火山破火山口的大小是大致相同的。

Compositionally, and in terms of its plate tectonic setting, the High Island supereruption has remarkable similarities with supereruptions from the Taupo Volcanic Zone, New Zealand. This region is one of the most productive on the Earth in terms of volumes of ash produced from supereruptions over the last two million years. As mentioned earlier, the youngest supereruption known is from the Taupo Volcano 25,400 years ago. The volume of ash erupted is about 1,130 km^3, slightly less than that calculated for the High Island supereruption. However, the size of the Taupo caldera appears to be somewhat smaller. By contrast, compared with the size of the neighbouring Whakamaru caldera, which erupted 1,500 km^3 of ash about 330,000 years ago, the High Island Caldera is only slightly smaller. If we superimpose the size of the Yellowstone Caldera, located in Wyoming, U.S.A., on the High Island Caldera we can see how the latter, at 673 km^2, is completely dwarfed by the gigantic Yellowstone system, at 3,885 km^2. This is not surprising, as the volume of materials erupted from the Yellowstone Caldera is known to be almost double that of the High Island Caldera (Figure 4-5). The key point of these comparisons is to show that the size of the High Island Caldera is roughly the same as other supervolcano calderas of similar volume and scale.



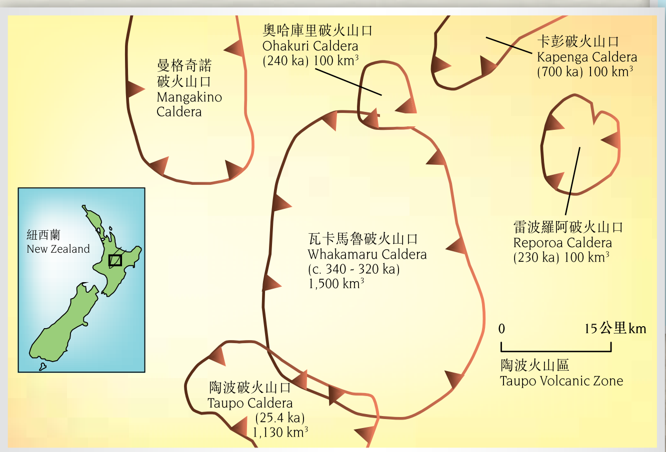


圖4-5. 糧船灣破火山口跟陶波、瓦卡馬魯和黃石破火山口對比
Figure 4-5. Size of the High Island Caldera compared with Taupo, Whakamaru caldera, and Yellowstone Caldera

在一億四千萬年前發生的香港糧船灣火山噴發，估計噴出了1,300立方公里的火山灰，所以我們可以頗有把握地將之列入超級噴發的行列，但是還有真正「超級」的超級噴發，那就是美國懷俄明州的黃石破火山口火山噴發。其中一次規模最大的噴發發生在二百萬年前，火山灰體積約達2,500立方公里。另一次巨型級超級噴發於七萬四千年前發生在印尼蘇門答臘島多峇湖，噴出的火山灰體積估計為2,800立方公里。這次噴發產生了全球性的廣泛影響，有科學家認為它引起了人類進化中的「人口瓶頸」現象。不過，其中一次已知的最大超級噴發是美國科羅拉多州的拉加里塔火山，在大約二千七百八十萬年前發生，產生的火山灰估計達5,000立方公里，大致相當於美國密歇根湖的儲水量。

With an estimated 1,300 km^3 of ash ejected, the High Island volcanic outburst in Hong Kong 140 million years ago comes comfortably into the supereruption class, but then there are the truly "super" supereruptions. Yellowstone Volcano in Wyoming has produced a number of supereruptions; one of the largest took place nearly two million years ago, with a volume of about 2,500 km^3 of ash. Another giant supereruption occurred at what is now Lake Toba in Sumatra, Indonesia, 74,000 years ago. The volume estimated for this eruption is about 2,800 km^3 of erupted ash. Such was the global impact of this eruption, that many scientists believe it caused a "population bottleneck" in human evolution. But one of the largest of all known supereruptions came from La Garita volcano in Colorado, U.S.A. About 27.8 million years ago, the La Garita supereruption produced an estimated 5,000 km^3 of ash – a volume that is roughly equivalent to the amount of water in Lake Michigan.

什麼類型的火山產生超級噴發？
WHAT TYPES OF VOLCANOES PRODUCE SUPERERUPTIONS?

這是一個重要的問題，因為只有特定類型的火山，才能產生真正的巨大噴發。大多數人想到火山時，腦海中馬上就會出現經典的火山形狀，一個具有中央噴道向上翹的錐體，如日本的富士山。這類火山被稱為層狀火山，因為它們是由一層層連續的火山灰和熔岩積聚起來的，火山灰和熔岩大部分從中央噴道噴出。如果火山下面的岩漿庫發展得足夠大，那麼一次大噴發就可能從岩漿庫噴出大量的岩漿。這樣火山山體便會被破壞，然後岩漿沿著一個近環形的破裂系統而不是中央噴道溢出。當破火山口火山崩塌至下面的岩漿庫時，就會有巨大的噴發。這類型火山稱為破火山口火山，因為它看起來形狀像大鍋。世界各地有許多現代破火山口火山的例子，它們都呈環形，在火山中央的凹陷處通常被湖水填滿(圖4-6)。

This is an important question, because only certain types of volcanoes produce the truly gargantuan eruptions. When most people think about volcanoes, they immediately picture in their minds the classic volcano shape: an upturned cone with a central vent, like Mount Fuji in Japan. This is known as a stratovolcano because it is built up of consecutive layers of ash and lava erupted mostly from a central vent. But if the magma chamber beneath the volcano grows large enough, a big eruption may drain out sufficiently voluminous magma from the chamber and undermine the volcano to a point where it collapses in on itself. Magma then escapes along a subcircular fracture system rather than a central conduit. These are known as caldera volcanoes because they look a bit like a cauldron in shape. There are many examples of modern caldera volcanoes around the world, and they all have a ring-shape to them, often with a lake filling the central depression (Figure 4-6). At some point in their history of activity, the central part of the volcano has collapsed into the underlying magma chamber. When this happens, a colossal eruption occurs.

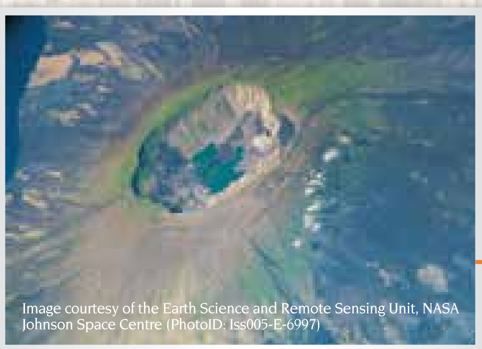


Image courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Centre (PhotoID: Iss005-E-6997)

圖4-6. 加拉帕戈斯群島的拉昆布雷活火山破火山口
Figure 4-6. Collapsed caldera of active La Cumbre Volcano, Galapagos

破火山口噴發大多不會達到超級噴發規模。這需要一些非常特殊的條件，才可以發展成超級噴發。首先，需要有巨大而持久的熱源來形成上層地殼(0-5公里深)中的岩漿。第二，地殼必須有容納大量岩漿的空間。第三，要有合適的岩漿成分。第四，要有觸發噴發的因素，這可能是內部因素，如岩漿超壓；或外部因素，如較熱的岩漿注入到岩漿庫的底部。

爆炸性超級噴發主要由含大量溶解氣體的高二氧化矽岩漿產生。這些有利超級噴發的岩漿成分通常在大陸地殼而不是海洋地殼中出現，並且通常位於聚合性板塊邊緣，亦即是海洋地殼被擠迫在大陸地殼之下的板塊邊緣。這些環境提供了超級噴發所需的三大條件。首先是俯衝板塊提供的熱源。當板塊俯衝時，它熔化和脫水，並產生液體傳遞到上覆的地幔中，令地幔熔化。這過程形成岩漿並注入到上覆的大陸地殼。第二是有利的拉張構造環境，為形成的岩漿創造了空間。第三，岩漿由厚厚的大陸地殼融化而產生，具有高二氧化矽成分。

超級噴發也可能在大陸的中間發生，例如黃石火山，在那裏地幔中有連續上升的熱源，稱為「地幔熱點」。

由於地形受廣泛侵蝕，古代超級火山的破火山口往往難以識別。陶波火山是最年輕的超級火山，用衛星圖像可以看到破火山口形成的陶波湖(圖4-7)。然而，更古老的超級破火山口火山，就更難以察覺了。

Most caldera eruptions are not superscale. To develop a supereruption requires some very special circumstances. First of all, there needs to be a huge and sustained heat source to cook up the molten magma in the upper crust (0-5 km deep). Second, there must be space for a crustal reservoir to accommodate the vast volume of magma. Third, the magma needs to be the right composition. And fourth, there needs to be an eruption trigger: this might be an internal factor, such as magma overpressure, or an external factor, such as injection of a hotter magma into the base of the magma chamber.

Explosive supereruptions are mainly generated by high-silica magmas containing a high degree of dissolved gas. These favourable compositions are usually found within the continental crust rather than oceanic crust and are usually located at convergent plate boundaries, where the oceanic crust is being forced beneath the continental crust. These settings provide three conditions needed for a supereruption. First, is a heat source, which is provided by the descending plate; as it descends, it melts and dewaters, generating fluids that rise into the overlying mantle, causing it in turn to melt and be injected into the overriding continental crust. Second, is a favourable extensional environment that creates space for the resulting magma. And third is the existence of the high-silica magma composition – a result of the melting of thick continental crust.

Supereruptions may also take place in the middle of continents where there is continuous upwelling of heat from the mantle (called a "mantle hot-spot"), as in the case of Yellowstone Volcano.

Ancient supervolcano calderas are not always easy to recognise because of extensive erosion of the landscape. The youngest supervolcano caldera spotted using satellite imagery is Lake Taupo (Figure 4-7). However, the older the supervolcano, the more difficult it is to detect.


圖片來源：NASA World Wind
Source: NASA World Wind

圖4-7. 位於紐西蘭陶波湖最年輕的超級噴發地點
Figure 4-7. Lake Taupo, NZ, location of the youngest known supereruption

糧船灣超級噴發
THE HIGH ISLAND SUPERERUPTION

糧船灣超級噴發
THE HIGH ISLAND SUPERERUPTION

超級噴發的先兆
SUPERERUPTION PRECURSORS

糧船灣破火山口實際上由兩個重疊的岩漿系統組合而成。年代較久遠的系統在大約一億四千三百萬年前開始發展，斷斷續續的噴發最終導致了大約一百萬年後的巨大破火山口崩塌事件。我們不知道這次噴發事件是否超級噴發，但是確實知道龐大的地殼塊陷落至下方的岩漿庫。糧船灣破火山口的火山管道系統也有可能在這個時候形成。在破火山口形成之後，凹陷的位置演變成了一個湖泊。在七十萬年期間，湖底積累了約170米厚的沉積物。在一億四千一百萬年前，火山活動再度活躍，由湖底噴發，並可能伴隨強烈噴發，逐漸形成了一座露出湖面的火山穹頂。這個火山穹頂的噴發管道與先前一億四千三百萬年的火山岩漿系統相同。然後，在大約一億四千一百萬年前，在破火山口北部環狀斷層的噴發管道上發生了一次大噴發，噴出熾熱的火山灰，這便是不久之後發生的糧船灣超級噴發的先兆。

The High Island Caldera is actually a combination of two overlapping magmatic systems. The older system began developing about 143 million years ago, and culminated with a huge caldera collapse event about 1 million years later. We do not know if there was a supereruption, but we do know that there was colossal foundering of crustal blocks into an underlying magma chamber. It is also likely that the volcanic plumbing system of the High Island Caldera was established at this time. Following the caldera formation, a lake developed within the depression. Over about 700,000 years, approximately 170 m of sediment accumulated on the lake floor. Renewed activity commenced about 141 million years ago and was marked by an eruption on the lakebed, and the gradual building up of a volcanic dome above the water level, possibly accompanied by violent eruptions. The feeder vent used for this volcanic dome was the same as that for the 143-million-year-old magmatic system. Then, at about 141 million years ago, there was a major eruption of hot ash from a vent on the northern caldera ring fault. This was the precursor to the High Island supereruption, which followed shortly afterward.

糧船灣超級噴發是如何展開的？
HOW MIGHT THE HIGH ISLAND SUPERERUPTION HAVE UNFOLDED?

我們現在知道，在糧船灣超級噴發前夕，岩漿庫內可能因有較熱的岩漿從底部注入而得到額外的熱能，令岩漿庫內大量的高二氧化矽岩漿隨時噴發。我們從近代的超級火山系統比較得知，這個岩漿庫可能用了幾十年乃至幾萬年時間，才可積累這麼多可噴發的岩漿。

糧船灣超級噴發的主要火山管道，似乎位於靠近破火山口南邊的環狀斷層，可能利用了早期火山穹頂相同的噴發管道。火山開始噴發後，之前崩塌的地殼塊似乎沿著北部和南部的環狀斷層構造進一步崩塌。由於岩漿庫給淘空，

We now know that immediately prior to the High Island supereruption, there was probably an increase in heat input within the magma chamber. The additional heat is thought to have come from the injection of hot magma into the base of the magma chamber that had been assembling a huge volume of silica-rich magma ready to erupt. Based on comparison with more recent supervolcano systems, however, it seems that accumulation of the eruptible magma within the chamber could have taken anything from a few tens of years to several ten thousands of years.

The main feeder vent for the High Island supereruption seems to be located close to the southern caldera ring fault, possibly exploiting the same conduit as the earlier volcanic dome. Once the eruption got underway, it seems

破火山口的地殼塊因失去支撐而下陷，結果從破火山口邊緣引發巨大滑坡，滑坡碎片轟然撞向破火山口的地塊。這些大型滑坡的碎片其後被上公里厚的熾熱火山灰覆蓋，填滿了新形成的火山凹陷。

there was further collapse of previously deeply foundered crustal blocks along the northern and southern ring fault structures. As the floor of the caldera was undermined by the evacuating magma chamber, huge landslides triggered from the now unsupported caldera sides sent debris crashing across the subsiding floor. This mega-landslide debris was then overlain by volcanic ash falling back into the newly generated depression, filling it up with kilometre-thick scorching hot ash.

糧船灣超級噴發持續了多久？

HOW LONG DID THE HIGH ISLAND SUPERERUPTION LAST?

糧船灣超級噴發可能持續了數周至數月，甚至乎數年，但我們並無相關確鑿證據。不過，根據噴發率的理論上限值(1.1×10⁶立方米/秒)，這次超級噴發的時間最短可能只歷時13天。這就是說在13天內，持續不斷地每秒噴出可填滿440個奧林匹克游泳池的火山灰！更有可能的情況是，噴發在數周或數月內，經歷了由盛到衰的過程，跟在現代爆炸性噴發如皮納圖博火山所觀察到的情況相似(圖5-1)。噴發的噪音會是如雷鳴一般，而持續爆炸所產生的震波相信會帶來災難性的破壞。

The eruption may have lasted from a few weeks to several months, possibly even years. We really have no firm evidence for the duration of the High Island supereruption. However, based on the theoretical upper limit for the eruption rate (1.1 x 10^6 m^3 per second), the minimum time of the eruption could have been little as 13 days. But this would have meant evacuating an estimated 440 Olympic swimming pools full of ash per second continuously over those 13 days! It is more likely that the eruption waxed and waned over a number of weeks or months, as has been observed in modern explosive eruptions, such as Mount Pinatubo (Figure 5-1). The noise from the eruption would have been thunderous, and the shockwaves generated from the ongoing blasts would have been unsurvivable.

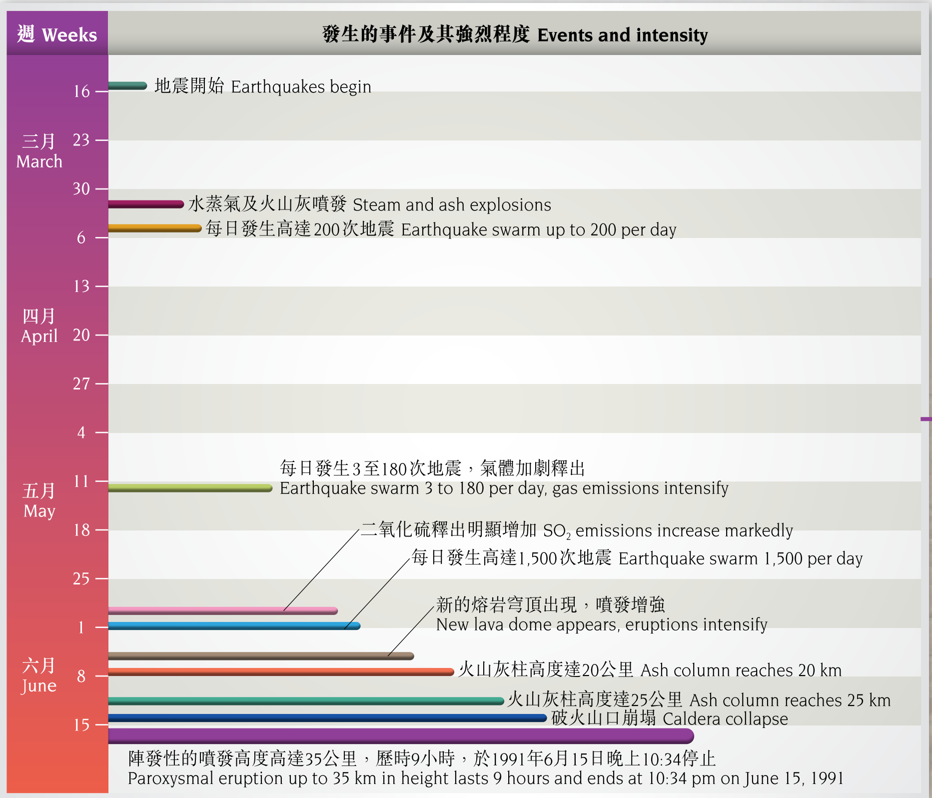


圖5-1. 1991年6月15日菲律賓皮納圖博火山噴發的事件時間表
Figure 5-1. Timeline of events leading to the June 15, 1991 eruption of Mount Pinatubo Philippines

糧船灣凝灰岩
THE HIGH ISLAND TUFF

糧船灣超級噴發產生的柱狀節理凝灰岩(糧船灣凝灰岩)的成分非常均勻，屬高二氧化矽(二氧化矽含重量76-77%)流紋岩質。在地質學上，這種岩石被稱為含晶屑的細火山灰玻屑凝灰岩。這表示凝灰岩由非常精細的玻璃質火山灰組成。重要的是，鑑於糧船灣凝灰岩的二氧化矽含量高，其原本流紋質岩漿的高黏度性會阻礙岩漿流到離火山較遠的距離。只有在爆炸性噴發時所產生的火山灰，方可使流紋質岩漿快速而大量地噴發到地面。

The columnar-jointed solidified ash of the High Island supereruption (High Island tuff) is remarkably uniform in composition and has a high-silica (SiO_2 = 76-77 wt%) rhyolite chemistry. Geologically, the rock is described as a crystal-bearing, fine ash vitric tuff. That means the tuff is made up of very fine, glassy volcanic ash. Importantly, given the high silica content of the High Island tuff, the high viscosity of the original rhyolitic magma would have prevented it from flowing any significant distance from the volcano. In order for the rhyolitic magma to have been emplaced quickly and voluminously, it must have erupted explosively, producing volcanic ash.

在噴發時，玻璃質火山灰會非常熾熱(約800°C)，當火山灰碰到地面時，會與其他晶體和浮石碎片熔融在一起。由於火山灰的重量，這些緻密的火山灰熔融物全部被壓縮在一起，過程稱為壓實作用，形成被拉長、透鏡狀的浮石碎片條紋，稱為條紋斑狀結構。火山灰沉積後，由於火山灰緩慢地冷卻，還有氣體和水溶液的循環，使有些晶體得以生長。這過程稱為脫玻化作用，即玻璃質火山碎片轉變成細微的晶粒。

火山灰沉積後額外的晶體生長也可能在岩漿氣體從壓縮的浮石碎片排出的時候發生，過程稱為氣相結晶作用。在某些地方，徹底的脫玻化和氣相結晶作用，會幾乎將原來的條紋斑狀結構破壞殆盡。

糧船灣凝灰岩含有肉眼可見，直徑通常為1-2毫米的晶體，也有晶狀良好的粉紅色鹼性長石、較大粒的石英和白色斜長石的碎片，還有浮石碎片和小量黑雲母晶體(圖5-2及圖5-3)。深色基質由非常細粒(<0.06毫米)的晶體組成，它們曾經是玻璃質顆粒或碎片。由於在火山噴發期間，晶體中夾雜的氣體快速膨脹，造成晶體爆炸，使凝灰岩中的許多石英和長石晶體生成凹槽或空心的輪廓。這些特徵清楚表明，西貢的柱狀節理岩石是由火山灰凝固而成，而非流紋岩熔岩。

圖5-2. 糧船灣凝灰岩樣本
Figure 5-2. Hand specimen of High Island tuff

At the time of eruption, the glassy ash particles were so hot (approx. 800˚C) that they fused together with other crystals and pumice fragments on impact with the ground. Compaction, due to the weight of ash, compressed it all together, forming a streaked appearance containing drawn out lenticular-shaped pumice fragments – this is known as a eutaxitic fabric. After ash deposition, some crystal growth occurred due to the slow cooling and circulation of gas and aqueous solutions. This process, known as devitrification, turned the glassy volcanic shards into fine crystal particles.

Additional post-depositional crystal growth, called vapour-phase crystallisation, might also have occurred during the expulsion of magmatic gas from some compressed pumice fragments. In places, the devitrification and vapour-phase crystallisation has been so complete that the original eutaxitic fabric has almost been completely destroyed.

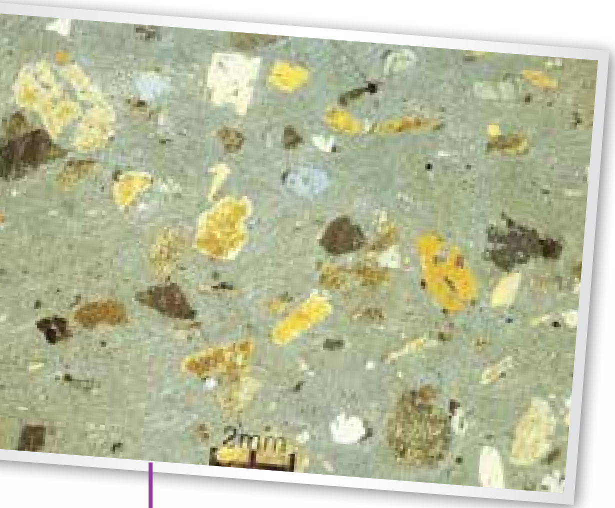


圖5-3. 糧船灣凝灰岩薄片
Figure 5-3. Rock thin section of High Island tuff

Crystals visible to the naked eye, typically 1-2 mm in diameter, are composed of well-shaped, pink alkali feldspar, with some larger broken fragments of quartz and white plagioclase feldspar, and there are also pumice fragments and minor biotite crystals (Figure 5-2 & Figure 5-3). The dark coloured matrix, or groundmass, is composed of very fine-grained (<0.06 mm) crystals that were once glassy particles, or shards. Many of the quartz and feldspar crystals in the tuff have strongly embayed outlines as a result of the rapid expansion of trapped gas in the crystals that caused them to explode during the eruption. These features strongly indicate that the columnar-jointed rock at Sai Kung is made of solidified ash and not rhyolite lava.

六角形岩柱如何形成？
HOW DID THE HEXAGONAL ROCK COLUMNS FORM?

通過對西貢凝灰岩(固化火山灰)岩柱高度精確的測定，糧船灣超級噴發已確定為一億四千萬年前發生。凝灰岩驚人的規模和厚度與單次災難性的破火山口噴發有關。估計火山灰在崩塌的破火山口盆地中存積。

破火山口地塊通常被認為是近乎垂直地崩塌(非完全垂直)，填塞在破火山口盆地中的火山灰本來是水平地存積。隨著火山灰在盆地中冷卻收縮，形成從上到下由冷卻表面擴展的冷卻節理。它們之所以會形成六邊形的形態，是因為要最有效地釋放拉伸應力(圖5-4)。

High-precision dating of the columnar-jointed tuff (solidified ash) at Sai Kung puts the age of the High Island supereruption at 140 million years. The amazing size and thickness of this solidified ash was related to a single, catastrophic, caldera-forming eruption. The volcanic ash is thought to have pooled within the collapsed caldera depression.

Collapse of the caldera floor is generally thought to be subvertical (that is, not quite vertical), and any ash trapped in the resultant depression would have filled up horizontally. As the ash cooled in the depression, thermal contraction caused cooling joints to form which then propagated down perpendicular to the cooling surface. These cooling joints formed in hexagonal pattern because this is the most efficient arrangement for releasing tensile stress (Figure 5-4).

圖5-4. 冷卻收縮而形成的柱狀節理，從冷卻面成直角向下發展
Figure 5-4. Columnar joints formed by thermal contraction propagated down perpendicular to the cooling surface

在西貢東部，凝灰岩六角柱一致地向東傾斜約20°，是什麼原因導致六角狀岩柱明顯傾斜？傾斜是何時發生的？一個有趣的觀察是，這些岩柱通常向傾斜方向上彎曲(圖5-5)。這表明彎曲可能是在火山灰冷卻和柱狀節理形成期間發生的。糧船灣破火山口內的火山岩總體上都朝相同方向傾斜。然而，由更早期岩漿活動形成的岩石似乎都直立在破火山口邊界之外。這再次表明，六角狀岩柱明顯的傾斜不是由區域性地殼撓曲所致，而是完全在破火山口盆地內發生。最有可能的解釋是，破火山口地塊發生不對稱崩塌，使破火山口地塊東部較其他位置更深地跌入岩漿庫。破火山口地塊的不對稱崩塌，可能導致冷卻中的火山灰因其自身重量下滑塌，從而導致某部分六角岩柱的彎曲現象。

In eastern Sai Kung, the hexagonal columns of solidified ash are tilted consistently at about 20° toward the east. So what may have caused the apparent tilting of the columns and when might this have happened? One interesting observation is that the columns are commonly bent in the direction of tilting (Figure 5-5). This suggests that the bending may have occurred during cooling and formation of the columns. All volcanic rocks within the High Island Caldera are tilted in broadly the same direction. However, that belonging to earlier magmatic events appears upright outside the boundaries of the caldera. This again suggests that the apparent tilting is not a regional crustal warping, but rather developed entirely within the caldera depression itself. The most likely explanation is that the collapse of the caldera floor occurred asymmetrically, so that the eastern section of the caldera floor fell deeper into the magma chamber than others. The asymmetric collapse of the caldera floor may have caused the slumping of cooling ash under its own weight, leading to the bending of the columns.

圖5-5. 萬宜水庫東壩傾斜及彎曲的岩柱
Figure 5-5. Tilted and bended columns at East Dam, High Island Reservoir

糧船灣超級噴發如何影響到地球的其他地方？

HOW MIGHT THE SUPERERUPTION HAVE AFFECTED THE REST OF THE PLANET?

糧船灣超級噴發產生的火山灰，可能貫穿高空55公里處的平流層。通過跟黃石(二百萬年前；圖5-6)和陶波(二萬五千四百年前；圖5-7)

Ash from the High Island supereruption could have penetrated as far as 55 km up into the stratosphere. By comparing the size of the eruption to measured ash fallout deposits from both the Yellowstone (2M years ago; Figure 5-6)

圖5-6. 二百萬年前黃石火山超級噴發火山灰降落的範圍
Figure 5-6. Extent of ash fall from 2M years Yellowstone supereruption

這兩次超級噴發的火山灰沉積物的規模比較，我們可以估計，糧船灣超級噴發的火山灰很可能影響到很大範圍的區域，包括華南地區，並延伸達數百公里。距離火山半徑100公里內，火山灰層平均厚度約為40米，而破火山口盆地中的火山灰更可能深達數百米。

在火山100公里的半徑範圍內，生物可能全遭滅絕。火山灰雲籠罩大氣層數周，乃至數月。大量的硫磺氣體，主要是二氧化硫(SO_2)，可能被釋放到大氣層中。這些氣體水化並產生硫酸雨，可能會損及所有有幸在原先火山噴發中倖免於難的生物。全球氣候可能會受到重大影響，估計北半球平均氣溫會下降達10攝氏度，足以引發迷你的冰河時期，全球冬季會持續數十年，所有位處赤道的森林都會在嚴寒環境下消失。

and Taupo supereruptions (25,400 years ago; Figure 5-7), we can estimate that the ash would likely have affected a large area, including much of southern China to the west, and extending several hundreds of kilometres to the east. Within a 100 km radius of the volcano, this layer would have been on average around 40 m thick, and deposits in depressions could have been as much as several hundreds of metres deep.

Every living thing within this 100 km radius would have been destroyed. The ash cloud would have remained in the atmosphere for weeks, and possibly months. Vast amounts of sulphur gases, mainly sulphur dioxide (SO_2), would have been released into the atmosphere. These gases would have hydrated, bringing sulphuric acid raining down on any living organism fortunate enough to have survived the original blast. The global climate would have been significantly affected, with a predicted lowering of average temperature of up to 10 degrees Celsius in the northern hemisphere. This is more than enough to induce a mini ice-age. The resulting global winter would have lasted for decades, and all equatorial forests would have been wiped out by the freezing conditions.

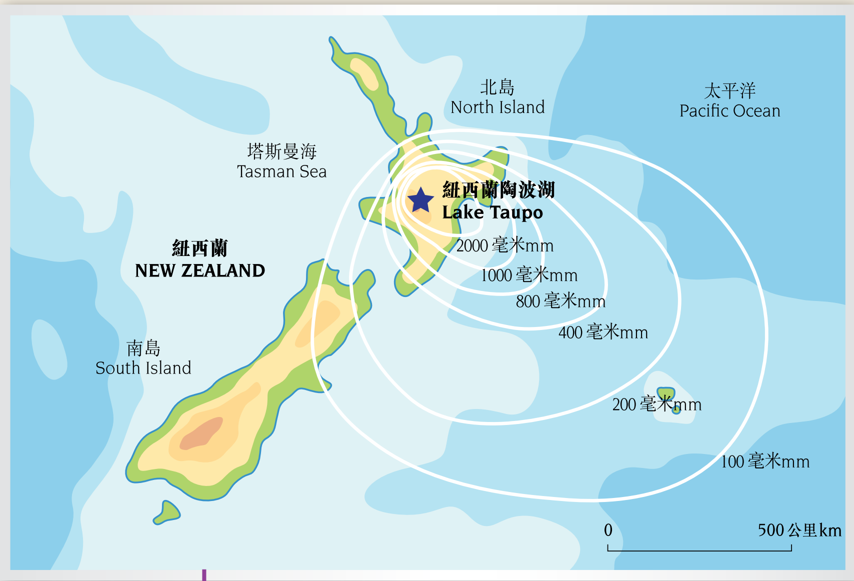


圖5-7. 二萬五千四百年前於陶波火山的奧魯阿努伊超級噴發火山灰降落的範圍
Figure 5-7. Extent of ash fall from the 25,400 years Oruanui supereruption from Taupo volcano

糧船灣超級噴發的後果
AFTERMATH OF THE SUPERERUPTION

在糧船灣破火山口崩塌後，似乎仍有若干殘餘岩漿活動，因而形成各種火山穹頂和花崗質侵入岩。然而，從那時起，本港似乎再也沒有經歷過另一次重大的火山噴發。實際上，糧船灣破火山口的崩塌，標誌了香港地區二千五百萬年火山活動歷史的終結。自那以後，再無發生大型火山噴發，而在不久的將來，也不太可能發生。倘若今天發生這樣的噴發，後果會難以想像。地質學家正積極研究過往的巨型噴發現象，以其更深入了解及有效預測未來的類似事件，以及其對全球氣候的潛在影響。

Immediately after the High Island Caldera collapse, there seems to have been some residual magmatic activity that formed various volcanic domes and granitic intrusions. Since then, however, Hong Kong does not appear to have experienced another major volcanic eruption. Effectively, the High Island Caldera collapse signalled the end of a 25-million-year history of volcanic activities in the Hong Kong region. There has not been a major eruption since, and one is most unlikely in the near future. Should such an eruption occur today, the consequences are too frightening to imagine. Scientists are actively researching these past giant eruptions to better understand and predict similar events in the future, and their potential impact on the global climate.

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科學發現是漫長而艱辛的旅程，終點往往難以預見。整個過程猶如拼湊一幅巨大的拼圖，直至到了關鍵一刻圖像終於顯露出來。《***香港地質大爆炸－糧船灣超級火山的故事***》以通俗的方式講解這個科學發現旅程。本書先記述成就精彩發現的拼圖零片，其後則闡釋糧船灣超級噴發的體積、性質和對遠古環境的可能影響。此書與早前出版的《***香港地質－四億年的旅程***》屬同一系列，旨在為對香港地質有興趣的大眾，提供實用參考資料。

The road to scientific discovery is often long and arduous, with no obvious end in sight. Gradually, akin to assembling pieces of a concealed jigsaw puzzle, an image emerges until there is a pivotal moment when a complete picture is revealed. ***Hong Kong's Big Bang – The Discovery of High Island Supervolcano*** describes such a scientific journey. Written at an introductory level, the first chapters describe the building blocks of the jigsaw puzzle that led to an amazing discovery. The later chapters define the size, nature and possible palaeo-environmental impacts of the High Island supereruption. The book is intended as a useful reference for members of the public interested in Hong Kong geology, and complements an earlier book giving an overview of Hong Kong's geology: ***Hong Kong Geology – A 400-million year journey.***

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