GEOLOGY AND GEOMORPHOLOGY OF THE MOUNT NOORAT VOLCANIC COMPLEX

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Mount Noorat is a prominent volcano in the Victorian Volcanic Plains (VVP) with an extraordinarily regular crater. The complex of which it is part displays much of the variation in volcanic features that occurs in the Newer Volcanics Province as a whole.

The Newer Volcanics Province is a major region of volcanism that reaches from Melbourne in the east to west of Mount Gambier in South Australia, and includes the VVP and numerous volcanoes and valley flows in the Central Highlands. At 23,000 km^2, it is one of the largest volcanic provinces of its type in the world. Its sister volcano, Budj Bim (or Mt Eccles), located south of Hamilton, and an associated lava flow which reaches the coast near Tyrendarra, has recently been declared part of a World Heritage Area for its major volcanological and archaeological significance.

Geologists have been studying Mt Noorat since the 19th century. Two of the most detailed investigations were by honours students, Ian Stone (1972) and Shane Papworth (1991) from The University of Melbourne and La Trobe University, respectively. This past work is summarised here, but as new techniques are applied to Mt Noorat, we can expect parts of the story to change.

Two terms in the title, *geology* and *geomorphology*, warrant clarification. Geomorphology refers to the expression as landforms of features in the landscape. Mt Noorat is an example of a particular type of landform, a volcanic cone. The geology of a region is the aggregate of all the earth materials and structures in the region. Geology and geomorphology are also fields of science, concerned with the study of the Earth generally and of its surficial features, respectively.

[Figure 1: a, Map showing location of Newer Volcanics Province in south-eastern Australia. b, Map of Newer Volcanics Province showing location of places and volcanic features named in text. Also shown is the approximate northern limit of significant groundwater aquifers. [See Cas et al. 2016, fig. 4a]]

Why volcanism in south-eastern Australia?

The Newer Volcanics Province occurs *within* the Australian tectonic plate. Most volcanism occurs near the edge of tectonic plates, so that volcanic products like those in the Newer Volcanics Province warrant a particular name – *intraplate volcanics*. *Plate-boundary* volcanism is readily understood as related either to rifting, where plates split and pull apart, or to subduction, where one plate dives beneath another. Some *intraplate* volcanism, e.g. Hawaii, can be confidently assigned to the presence of a “hot spot”, where a hot plume of magma derived from the mantle below the Earth’s crust reaches the surface. However, in the case of the Newer Volcanics Province, it appears that volcanism arises primarily from the melting of deep-seated rocks beneath south-eastern Australia as a response to two main factors. First, abrupt increases in the thickness of the *lithosphere* (Earth’s crust plus upper mantle) here favours the development of convection cells of hot, malleable rock in the mantle just below the lithosphere. Second, compression at the New Zealand margin of the Australian plate causes buckling of the plate beneath south-eastern Australia. Buckling eases the pressure on the mantle and results in melting of a portion of the rock there. The resultant magma makes its way to the surface along ancient faults which help to localise eruptions. In the case of Mt Noorat, it sits above the greatest discontinuity in Victoria’s geology. This is the Moyston Fault, exposed at Moyston (just east of the Grampians) and buried beneath the Otway Basin in the Noorat area. The Moyston Fault is oriented roughly north-south and juxtaposes major geological bodies known as the Delamerian Fold Belt to the west and the Lachlan Fold Belt (east). This and other major buried faults act as a kind of plumbing system that directs magma through the crust to the surface.

[Figure 2: Illustration of the *edge-driven* convection model in the context of south-eastern Australia. Mt Noorat is the volcanic product of convection of ductile mantle rock adjacent to an abrupt thickening of the lithosphere, formation of magma, and eruption. [See Heath et al. 2020 and Demidjuk et al. 2007]]

[Figure 3: a, Map showing relation of New Zealand, straddling boundary of Australian and Pacific tectonic plates, to south-eastern part of Australian continent. b, Map showing major geological features of south-eastern mainland Australia, including Delamerian Fold Belt, Lachlan Fold Belt, Grampians, Otway Basin, Murray Basin, and Moyston and some other faults, together with the location of Mt Noorat. [See Cas et al. 2016, fig. 1a]]

What is the Newer Volcanics Province?

The Newer Volcanics Province is the region, largely in central and western Victoria but reaching into South Australia, that displays the products of volcanism of the last five million years or more. Those products belong to a geological unit called the Newer Volcanic Group which is found from Melbourne in the east to west of Mt Gambier, South Australia; and from near Maldon in the Central Highlands in the north to the coast at Port Fairy and Portland and offshore at Lady Julia Percy Island. The rocks making up the Newer Volcanics Province are mostly of bluestone (solid basalt), but include fragmental volcanics such as scoria and ash. The landscape of the Newer Volcanics Provinces is strongly influenced by the pre-volcanic topography. In the Central Highlands, erupted lavas flowed down deep river valleys, so that the resultant bluestone bodies occur as long, narrow geological units. In addition, explosive eruptions resulted in a high density of volcanic cones. In the Otway Basin to the south and west, though, the pre-volcanic relief was much less pronounced, which allowed most lava flows to spread over broad areas and give rise to near-flat volcanic plains. The lava flows strongly disrupted the pre-basaltic drainage system, as a result of which hundreds of lakes formed, including Australia's largest permanent lake, Lake Corangamite, which is visible from Mt Noorat. Again, subordinate in volume to the lava flows but striking features of the landscapes, volcanic cones and craters are the product of explosive eruptions.

Mt Noorat as a feature in the landscape

Whereas some volcanoes in the Newer Volcanics Province are simple in form, others are complex. Mt Elephant, north-east of Mt Noorat, is a prominent volcano, one with a conical shape and a large crater, which formed during a single eruption. Mt Noorat, too, is a volcanic cone with a very regular crater, but it is part of a volcanic complex developed during a series of eruptions. Thus, while Mt Noorat is the most obvious landform in the Noorat complex, there are several other landforms present, including low mounds, small craters and tuff rings and lava flows. Earlier features in the complex, such as the tuff rings, are obscured by later ones. Quarries adjacent to Mt Noorat are exposing and extracting fragmental volcanic products mainly from the tuff ring. The Noorat complex covers 42 km^2, much of which is low-relief lava plain.

[Figure 4: Selection of photographs of landforms, including aerial/satellite of Mt Noorat and surrounds]

Tuff rings

Tuff rings are low, ring-like features that surround certain types of volcanic craters. The craters, known as *maars*, are the result of explosive excavation of rocks at and below the former land surface. The Newer Volcanics Province contains about forty maar-tuff ring complexes, including some of the largest in the world, such as Tower Hill and Lake Purrumbete. Some of the rock- and magma-derived fragments (tuff) from the eruption build up at the edges of a maar to form a tuff ring. Careful mapping at Noorat has shown that, in fact, two tuff rings exist and intersect, just as the maars they are associated with intersect. The formation of the maars and tuff rings represents the first stage of the Noorat volcanic complex. Later stages have buried most of it, including all of the maars, so it requires one's imagination to remove Mt Noorat and to picture the maars beneath it, one slightly north of the other, but nevertheless intersecting. An impression of one of the tuff rings can be gained by following the road from Noorat toward the north on the western flank of Mt Noorat, where the rise is due to the presence of the tuff ring. Even here, the tuff ring is covered by black scoria from a later eruption, as Molan's quarry shows. The southern tuff ring is roughly circular and about 2 km in diameter while the northern one is about 800 m across and of uncertain shape.

[Figure 5: Map of the Noorat volcanic complex showing the distribution of buried tuff rings, scoria complex and lava flows. This is based on the work of Shane Papworth (1991) who was a student at La Trobe University.]

Scoria complex

The most prominent features of Noorat's landscape belong to the scoria complex, sometimes called *nested cones*, which formed as the second stage of the Noorat volcanic complex. *Scoria* is a type of volcanic rock that has numerous gas bubbles in it. It may pile up during a volcanic eruption to form a scoria cone. Mt Noorat is a scoria cone, as are many other volcanoes in western Victoria, such as Mt Elephant and Mt Buninyong. Imagine Mt Noorat forming as a jet of magma and gas shot into the air at a hole in the ground surface, or *vent*, now marked by its spectacular crater. The magma cooled rapidly in the air and fell back to earth as solid scoria which built up around the vent. Lesser cones with vents and mounds of scoria occur around Mt Noorat, all within the perimeters of the older maar craters. The minor scoria features formed during small eruptions. Mt Noorat's crater is about 160 m deep and its rim rises to 170 m above the surrounding plain. While the crater is everywhere steep, a rock exposure high on the north-eastern wall of the crater is near-vertical. This is due to the *welding* of the constituent volcanic fragments, meaning that the fragments were still very hot and molten when they fell out of the sky, and fused to form a solid mass. Such a process occurs when *fire-fountains* – modest sprays of fragmented magma shot into the air – develop.

Lava flows

Youngest component of the Noorat volcanic complex is a group of lava flows on the north, south and eastern sides of Mt Noorat. The largest is the northern flow, which extends about 7 km north of Mt Noorat and covers about 30 km^2. It displays a variety of surficial features. Close to the eruption point on the northern side of Mt Noorat is a field of stony rises, which is a very rough volcanic landscape marked by the presence of pressure mounds (*tumuli*), depressions and lava channels with paired levee banks. Further north, such landforms disappear and the lava surface becomes smooth.

Geology of Mt Noorat

Mt Noorat is a pile of the products of one of the many eruptions at the site of the Noorat volcanic complex. According to *superposition*, one of the foundational principles of the science of geology, other eruptive materials that are buried by Mt Noorat must be older than the latter.

What is the character, firstly, of the eruptive products that form Mt Noorat? Examples of those products can be seen on the soil surface, in engineering scrapes and in one major outcrop high on the wall of the crater. They are examples of tephra, the fragmental products of explosive eruptions. Tephra is divided into three classes based on size: ash (<2 mm), lapilli (2-64 mm) and blocks and bombs (>64 mm). At Mt Noorat, it appears the tephra is quite coarse, being dominated by coarse lapilli and blocks and bombs. The bombs are of particular fascination. They show streamlined shapes, which indicates that they were semi-molten when they were thrown into the air, spun through the air as they cooled, and then landed adjacent to the crater. The largest bombs are 2 m in diameter. Whatever their size, the fragments have the composition of basalt, which is typically a dark, very finely crystalline volcanic rock. Some tephra fragments contain smaller, often green fragments surrounded by dark basalt. A useful name for fragments of green or other colours is *xenolith*, meaning "foreign rock". Xenoliths are of special interest because they are samples of the mantle or lower crust below south-eastern Australia, and have been intensively studied to improve our understanding of those deep regions. Green xenoliths are dominated by the mineral, olivine.

Some of the tephra from the Mt Noorat eruption clearly failed to cool much when it was thrown into the air. It was still hot enough when it landed on the rim of the volcano to fuse with other still-molten fragments. The result is a rampart on the eastern side of the crater that contains lapilli, blocks and bombs welded into a solid mass.

Beneath the tephra of the Mt Noorat eruption is an older deposit of tephra of very different character. This material makes up the tuff rings, constructed during the first eruptions of the Noorat volcanic complex. While not accessible to the public, the older tephra is exposed in quarries at the western foot of Mt Noorat. It is distinctly layered, and dips gently away from the volcanic complex, that is, toward the west in the quarries. It is buff-coloured and consists of a mix of ash and lapilli. Non-magmatic (*lithic*) components of the tuff rings include fossils (foraminifers) from the muddy limestone (Gellibrand Marl) that underlies much of the volcanic plain. Other lithics are limestone, clay, iron-oxide grains and older basalt, ranging in size to 2 m. Lee's quarry on the north-western side of Mt Noorat exposes a series of reverse faults in the tuff ring which thrust slices of tuff-ring and basaltic fallout tephra radially outward from the buried maar. This deformation is likely to be due to heaving of the near-surface deposits as magma moved upward.
Technical note: The deposits of the tuff rings are dominated by the following texturally defined classes, or facies: massive ash, planar-stratified ash, planar lapilli and diffuse lapilli; and lesser cross-stratified and clast lapilli facies, with rare occurrences of accretionary lapilli indicating a brief phase of very wet eruption. Sedimentary structures include abundant planar stratification, graded bedding and rare cross stratification, ripples and dunes, as well as enigmatic polygonal cracks. Basalt of the scoria cones and the lava flows, as well as the basaltic component of the tuff rings, typically displays phenocrysts of olivine, lesser clinopyroxene and minor orthopyroxene, the last derived from xenoliths. Its groundmass consists of volcanic glass, plagioclase, clinopyroxene, magnetite [opaque oxide??] and trace apatite. In places, scoria is palagonitic (featuring hydrated glass), which implies localised alteration by steam. Xenoliths are predominantly spinel lherzolite, together with wehrlite, websterite and pyroxenite. The broad composition of the magmatic products is basalt, but more particularly is alkalic (nepheline hawaiite to hawaiite). In this, the Noorat complex's composition is similar to that of many of the scoria cones and maars of western Victoria, and contrasts with the tholeiitic to transitional composition of the generally somewhat older plains lava flows.

[Figure 6: photographs of exposures and individual tephra specimens from (i) the Mt Noorat eruption and (ii) the earlier phreatomagmatic eruption.]

Age of Mt Noorat

Mt Noorat erupted almost precisely 100,000 years ago. Geochronologists, scientists who determine the age of earth materials, at The University of Melbourne used the argon-argon ($^{40}Ar/^{39}Ar$) technique to garner this age.

Nevertheless, not all products of the eruption yield the age of the eruption. Xenoliths are typically much older, with ages including tens and hundreds of millions of years. Some basaltic blocks in the Noorat volcanic complex have been dated at nearly 600,000 years, suggesting that they come from much older lava flows that lie beneath the complex.

Volcanology and Mt Noorat

The Newer Volcanics Province, as a whole, and the Noorat volcanic complex, in particular, show a range of volcanic landforms and deposits that reflect a variety of eruption styles. Important variables affecting eruption styles include the amount of gas in the erupting magma and the amount of water in the rocks the magma rises through.

Gas and volcanic eruptions

Most magma contains at least some dissolved gas. As magma rises from the mantle and lower crust toward the surface, the pressure from the overlying rocks decreases. This may allow some of the gas to come out of solution and form bubbles. However, if the proportion of gas is small, the magma is likely to come to the surface and be erupted quietly in the form of lava flows. The generally flat lava plains of the Newer Volcanics Province formed in this way and consist of dense basalt or vesicular basalt (basalt with bubbles in it).

If enough gas exsolves from the magma, however, the volume of gas may be so great as to allow the suspension of blebs of magma in the gas. This process is known as *fragmentation* of the magma. The gas provides a thrust like that in a jet engine and drives the suspended magma toward the surface. The result is an explosive eruption that shoots fragmented magma and magmatic gases into the air. The air rapidly cools the magma fragments, and they may be solid by the time they fall back to the surface. If so, they build up as a pile of tephra around the crater, in the form of a cone. However, if the slope of the cone becomes too steep, a portion of the tephra pile collapses. The final slope does not exceed the *angle of repose*, which is the maximum angle at which friction between tephra particles is able to support the pile. Mt Noorat itself formed largely in this way. However, it is clear that, for part of the Mt Noorat eruption, the volcanic fragments that fell from the eruption column were still very hot and molten when they landed on the growing cone. When still molten, the fragments, in this case called *spatter*, are able to fuse and, in some cases, then flow as lava. The near-vertical outcrops on the eastern side of Mt Noorat's crater are very steep because molten fragments fused and then cooled to form a spatter rampart.

Water and volcanic eruptions

Sometime magma rises toward the surface through host rock that contains substantial quantities of water. This is groundwater which is stored in pores and fractures in the host (country) rock. Magma, of course, is very hot, with the temperature of basaltic magma exceeding 1000°C. If it comes into contact with groundwater, the water *flashes* – that is, it converts instantaneously to superheated vapour. The sudden and enormous increase in fluid pressure in the country rock may cause a tremendous explosion that excavates a crater (maar) at the surface. The Mt Noorat complex includes two maars which are buried by the later fragmental cone. Tower Hill, between Warrnambool and Port Fairy, is one of the largest maars in the world; while Lake Purrumbete, east of Camperdown, is Victoria's best preserved maar; and Camperdown's Lake Bullenmerri-Lake Gnotuk-Mt Leura complex is a major system of maars and scoria cones. We can understand the early phases of the Mt Noorat complex's history by referring to Tower Hill and Lake Purrumbete. In both cases, the central crater is surrounded by a low ring, called a *tuff ring*. Tuff is a consolidated deposit of tephra, that is, fragmental material blown radially out of the crater during the groundwater explosion. It is likely to contain a mix of magmatic fragments and comminuted country rock, the latter being much lighter in colour in the Newer Volcanics Province than the former. The tephra is carried from the crater by a combination of ballistic transport (through the air) and transport in a *base surge*. A base surge is a ground-hugging flow of tephra and gas that travels a short distance from the maar and is responsible for formation of the tuff ring. Exposures through the tuff ring, such as in quarries, show that the tephra is distinctly layered, reflecting a pulsatory mode of deposition. The Noorat volcanic complex includes a tuff ring that was buried by later eruptions, but which is being exploited in quarries just west of Mt Noorat. The tuff ring's presence makes it clear that interaction between magma and groundwater was an important part of the history of the Noorat complex. The fine grain of the tephra in the tuff ring means that fragmentation was intense, and that plenty of groundwater was involved.

Maars are the surface expression of larger structures called *diatremes*. Diatremes are funnel-shaped bodies of disturbed country rock and tephra that narrow downward to where they meet a feeder dyke consisting of solidified magma. In some cases, dykes are found within a diatreme, and may form a ring around the margin of the maar, in which case they are called *ring dykes*. As magma is fed upward to meet water-saturated rock and explode, not only is tephra ejected into the atmosphere, but collapse takes place to form the diatreme. Such explosions and collapse may be repeated, as has clearly happened in the Noorat volcanic complex to form a double maar. The feeder to the first-formed maar was probably blocked by collapse of the host rock followed by establishment of a new feeder a short distance away. Also at Noorat, some dykes reached the surface to form the final-stage lava flows, with much lesser involvement of gas.

[Figure 7: a, Model of a maar with tuff ring in vertical section, perhaps like the maars of the Noorat volcanic complex, which are now largely buried beneath later deposits. The maar lies above a diatreme, that is, a zone of faulted and fractured host rock deformed by explosive volcanism as magma superheated groundwater in the host rock. The diatreme is a zone of collapse, on the order of 2-3 km deep, which passes downward into a feeder dyke. [See Lorenz 1986]. b, Representation of a violent eruption that produces a maar, a tuff ring and a diatreme. Hot magma meets a layer of rock saturated with abundant groundwater which flashes (that is, is instantaneously converted to gas). The enormous increase in pressure blows out a crater, and fragments both host rock and magma to produce tephra. A tuff ring forms largely from the tephra deposited from a ground-hugging base surge. [See KellerLynn 2015]]

Complex development

The Noorat volcanic complex, despite the marked variety of its landforms and deposits, formed rapidly – over months or a few years – and with no major time breaks. The initial maar-diatreme stage, with its massive explosions, was due to the generation of large volumes of gas as magma heated groundwater. As the amount of available groundwater progressively diminished, the scoria cones and mounds and then lava flows formed. The eruption of abundant scoria implies the present of sufficient gas to fragment the magma. Even as part of this stage, several phases can be identified, which are named for their similarity to the styles of eruption that have been witnessed at eruptions in other parts of the world. Mt Noorat itself is the product of a *micro-plinian* eruption, similar to but less intense than the eruption of Mt Vesuvius, Italy, in 79 AD that was observed by Pliny the Younger. A micro-plinian eruption has a stable, buoyant eruption column that is sustained for a significant duration. With a declining proportion of gas, eruptions became intermittent and the height of the eruption column decreased. The spatter ramparts at Mt Noorat result from fire-fountaining, characteristic of strombolian and hawaiian styles of eruptions. Mt Stromboli is an island volcano off the coast of Sicily and Hawaii is part of a chain of volcanoes, most now extinct and submerged, in the northern Pacific Ocean.

Soil development

The many millenia since the eruptions that formed the Noorat volcanic complex are ample to allow the formation of soil upon the volcanic parent materials. Water is a critical agent of soil development, and the highly permeable nature of most of the Noorat complex's volcanic products means that its near-surface part alters (*weathers*) very quickly to soil. Basaltic parent materials, like those at Mt Noorat and throughout the Newer Volcanics Province, release abundant nutrients when they weather. The resultant soils are very fertile and form the basis of a rich agricultural industry.

Soils on Mt Noorat are mostly red, indicating that they are well drained. This means that oxygen, often carried by water, has ready access to the materials immediately below the surface. The red colour reflects the presence of oxidised iron minerals, the iron being derived from the parent volcanics, in which the iron is in a reduced chemical state and occurs in green or grey minerals. That is, the colour change represents oxidation of the parent material during weathering. Where an exposure shows a complete profile from the soil down to the unaltered parent material, a pronounced colour change marks the weathering front. Above the weathering front is pink or red soil while below is dark grey basalt generally in the form of tephra. Weathering of the parent converts reduced iron to oxidised iron.

While the boundary between the soil and the parent material is mostly subhorizontal, in places narrow zones of oxidised material project downward into the parent. These are visible only in vertical exposures. They represent extensions of the weathering zone where oxygen has been transported to greater depth and altered the parent material. What has enabled this to happen? The roots of trees grow to substantial depths below the land surface, and provide a pathway for water and oxygen to reach greater depths. The resultant features are known as root channels. In some cases, carbon dioxide derived from the atmosphere and particularly from the soil reacts with calcium ions in soil waters that is leached from the parent volcanics and precipitates as calcium carbonate ($CaCO_3$). This may occur preferentially in the root channels after the roots have rotted out. In such cases the $CaCO_3$ aggregate mimics the shape of the original root, and is called a root cast.

Terracettes

A notable feature of the soils in the crater of Mt Noorat is the presence of many apparently near-horizontal lines. These are the effects of minor slope failures, where units of soil roughly a metre thick have slumped. Slumping involves slippage of a segment of soil on a slope, accompanied by rotation. The effect at Mt Noorat is to produce a step-like topography up the wall of the crater, and the name given to the features – terracettes – reflects that topography. The surface of each terracette is roughly horizontal, and cattle grazing in the crater preferentially walk along the tops of them – but do not create them.

[Figure 8. Soil development on Noorat volcanic complex.]

Summary of the history of the Noorat volcanic complex

Large volumes of basaltic lava had spread across western Victoria's plains well before the eruptions that formed the Noorat volcanic complex took place. The Noorat complex developed 100,000 years ago in three stages:

1. Violent interaction took place between rising magma and groundwater in rock aquifers. Successive explosions created two intersecting maar craters. Finely fragmented magma and host rock were blown out of the craters, a portion to be deposited as tuff rings at the crater margins.
2. As the amount of groundwater available to interact with the magma diminished, the eruption became less violent. Nevertheless, sufficient gas was present to fragment the magma and project it into the atmosphere, from which it returned to earth as scoria. The proportion of host rock being erupted, though, was minimal. Scoria cones and mounds, including the magnificent cone and crater of Mt Noorat, formed. As the amount of gas continued to decline, so too did the vigour of the eruption. Fire fountaining and the formation of spatter ramparts high on the crater wall were transitional to the final volcanic stage.
3. Quiet eruption of lavas from the ring fractures below the complex led to the formation of several lava flows, some largely featureless but the northern one developing a stony-rise topography in places.
4. The subsequent 100,000 years has resulted in the formation of a soil profile on the volcanic products. Minerals and glass in the volcanic materials react and interact with the atmosphere and plants and are altered to clays and other new minerals.

Conclusion

Mt Noorat is a particularly attractive example of the hundreds of eruption points that exist in the Newer Volcanics Province of south-eastern Australia. It is on the site of three different types of eruptions, each of which resulted in a different suite of landforms and volcanic products. Mt Noorat's well formed cone and crater are the most eye-catching of these, but understanding the full history of the Noorat volcanic complex requires inquiry into the maars, tuff rings, lava flows and dykes that are also present. The walking trail on Mt Noorat provides a superb view of a substantial portion of the NVP and beyond it to the Otway Ranges to the east and the Grampians (north).

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Appendix. Terminology.

Some technical terms that geologists apply to the landforms, deposits and processes associated with the Newer Volcanics Province are listed and defined below.

ash the fine fraction (grains <2 mm diameter) of tephra
base surge a radially moving, ground-hugging mixture of magmatic and host-rock fragments derived from an eruption involving the interaction of magma and groundwater
bleb

blocks   the coarse fraction (grains >64 mm diameter) of tephra, where the grains are angular
bombs   the coarse fraction (grains >64 mm diameter) of tephra, where the grains are streamlined because they were viscous and underwent shaping during flight
diatreme   funnel-shaped faulted complex formed as a result of explosive interaction between magma and groundwater, and consequent collapse; in plan view, the faults typically have a ring-like pattern and may be intruded by magma to form dykes
dykes   relatively narrow bodies of igneous rock formed when magma is injected into host rock
lapilli   the intermediate fraction (grains 2-64 mm diameter) of tephra
lava   molten rock after eruption
lithics particles in tephra derived from the fragmentation of older rock
maar   a crater formed as a result of an eruption involving the interaction of magma and groundwater; at the surface above a diatreme
magma   molten rock prior to eruption
magmatic eruption   an eruption the products of which are virtually all derived from magma
phreatic eruption   an eruption involving interaction with groundwater where the products are virtually all from host rock
phreatomagmatic eruption   an eruption involving interaction with groundwater where the products are of mixed derivation, from magma and from host rock
pyroclastic   (of) fragmental material generated during a volcanic eruption
scoria
spatter   pyroclastics that remained fluid as they fell back to Earth after eruption, and may fuse
superposition   the placement of successive geological layers, one upon another
tephra   a deposit of fragmental material derived from a volcanic eruption
tuff   a consolidated deposit of fragmental material derived from a volcanic eruption
vesicles   gas bubbles in volcanic rock
welding   the fusing of viscous magma fragments to form a solid rock
xenolith   a rock fragment in volcanic or other igneous rock that is derived from a different source such as the host rock to the parent magma