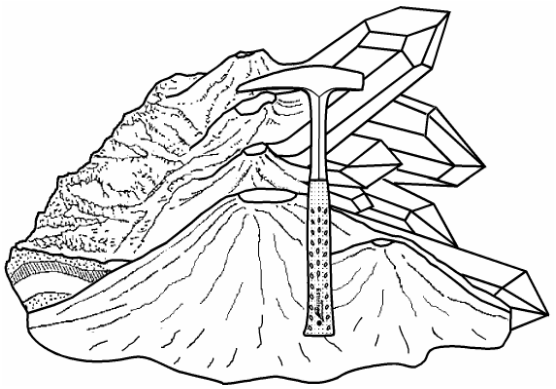


Geocene

Auckland GeoClub Magazine
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PANMURE BASIN TUFF RING

Bruce W. Hayward, Helen Holzer, Hugh R. Grenfell

One fine Sunday morning in July 2006, a group of 13 GeoClubbers descended on Panmure Basin, Auckland, to investigate the theory that the dip of tuff beds on the inner slopes of the tuff ring should be consistently in towards the crater.

Panmure Basin is one of Auckland Volcanic Field's maar craters (Fig. 1) surrounded by a 25 m high tuff ring. Radiocarbon dating on wood buried beneath Panmure Basin tuff has dated the time of eruption at ~27,000 yrs BP (McDougall et al., 1969).



Fig. 1. Oblique aerial photograph of Panmure Basin looking east, 1994.

Our measurements on the strike and dip of well-exposed tuff beds around the intertidal edge of Panmure Basin (Fig. 2) show that about half our observations conformed to the inwards-dipping expectations. The dips varied between 5 and 40˚, the highest of these (>30˚) were probably too steep to have been the original slopes on which the tuff was deposited.

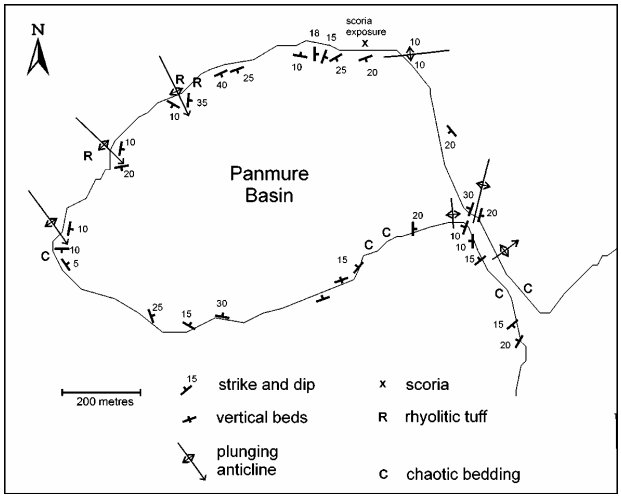


Fig. 2. Strike and dip of tuff beds exposed intertidally around the edge of Panmure Basin.

They may have been over-steepened by slumping of tuff blocks into the crater. This is probably also the explanation for the 10˚ outwards dip on tuff beds on the central northern side of the basin (Fig. 2). There are three places on the western to north-western side of the basin where the tuff beds form anticlines with NW to NNW axes. In two of these places, we found that the core of these apparent anticlines was composed of weathered light-coloured rhyolitic siltstone or tuff. From these observations we infer that the rhyolitic tuff forms the local basement underneath the Panmure Basin tuff and that it had a gently rolling surface topography. Instead of being structurally folded anticlines, the tuff has draped over three low, NW-trending ridges of weathered rhyolitic rocks. In this part of the Basin, at least, the thickness of tuff on the inside of the crater wall is extremely thin.

Clearly much of the shape on the north-western side is due to explosive activity rather than construction of a tuff ring. The reverse may be true on the south-east side, where most of the peninsula between the basin and the Tamaki Estuary seems to be composed of tuff (Kermode, 1992). The cliffs on either side of the outlet channel through the northern end of this peninsula, show that its structure is not simple either. A prominent anticline is exposed on the east side of the entrance near where it enters the basin. The core of this anticline is composed of slumped blocks of tuff that are unconformably draped by the anticline beds.

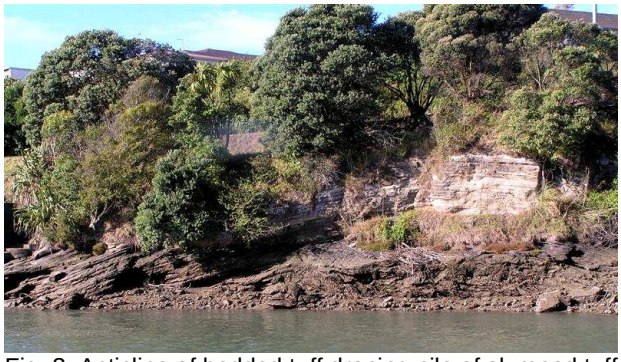


Fig. 3. Anticline of bedded tuff draping pile of slumped tuff at the entrance to Panmure Basin.

The explanation here must be that there was slumping back into the crater during eruptions and the later ash was draped over a mound of slumped tuff. A similar explanation may explain a smaller anticline just under the supports of the walking bridge over the entrance channel on its eastern bank. Slumping may also account for some of the other dip reversals exposed in the banks of the entrance channel.



Fig. 4. Large fusiform basaltic bomb exposed in tuff beds on the north shore of Panmure Basin.

The tuff beds are best exposed and most easily accessible at low tide on the east shore of the basin, just south of the outlet channel. Here the ash also contains blocks and bombs of primary basalt (Fig. 3) and Waitemata Sandstone. The latter group have been blasted free from the wall of the vent and thrown high in the air, landing with an impact sag in the soft surrounding ash.



Fig. 5. Impact depressions of volcanic bombs that landed in soft tuff, seen in the cliffs on the west side of the entrance channel into Panmure Basin.

An unusual exposure of bedded fine scoria occurs next to the path around the lagoon on the north side. This scoria clearly overlies Panmure Basin tuff and forms the surface deposits that form the low ridge that extends slightly into the crater beneath the end of Cleary Rd. This scoria has been interpreted as being wind-blown from Mt Wellington, which erupted ~9,000 yrs ago (Kermode et al., 1992). This inference seems reasonable, as this is the closest point on the edge of Panmure Basin to Mt Wellington, which is located 1 km due north of this exposure, and there is a high mound between Cleary Rd and Panmure roundabout that is probably also built up from scoria. Another plausible explanation for this scoria could be that it came from a small scoria cone that was a late phase eruption of Panmure Basin volcano, just like the small scoria cones within explosion craters in the Domain, Three Kings, Crater Hill, Waitomokia, Mangere Lagoon and other Auckland volcanoes. There is no surface expression of such a cone within Panmure Basin, so if it exists at all it would be buried beneath the marine mud of the crater floor. After writing this note, we read Newspaper reports in Feb 2008, that suggest that such a scoria cone may have been encountered while coring the sediment in the basin by GNS and Auckland University geologists.

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NORTH HEAD VOLCANO

Bruce Hayward, Peter Daymond-King and Rhiannon Daymond-King

One cold, windy Sunday morning in July 2007, seventeen Geoclubbers gathered in the carpark at North Head. Armed with base maps, clip boards, torches and compasses they spent the next 4 hours exploring and mapping the structure of North Head volcano (Fig. 1), both inside (in the tunnels) and out.



Fig. 1. Oblique aerial photograph of North Head, 1994 from the east. Note the NNE-striking ribs of tuff on the northern shore (right).

Questions to be addressed included: how much of the volcano we see today is composed of tuff and how much of scoria; where was the centre of the tuff ring and did it coincide with the scoria cone vent; and what caused the complexities in the tuff ring on the northern side?

Charles Heaphy (1860) showed North Head as a scoria cone on his geological sketch map of the Auckland District, 1857, but did not describe it.

Ferdinand von Hochstetter clearly crossed the Waitemata by boat in 1859 and visited North Head as he provided a detailed description (Hochstetter, 1864; Fleming, 1959) and cross-section (Fig. 2). Features seen in 1859 and no longer visible include "a shallow depression indicating the crater" on the top of the scoria cone, "the volcanic bombs found on its surface, regularly pear-shaped or lemon-shaped bombs with their apices spirally turned", and "a small lava flow emerged in a westerly direction and is lost in a swamp."

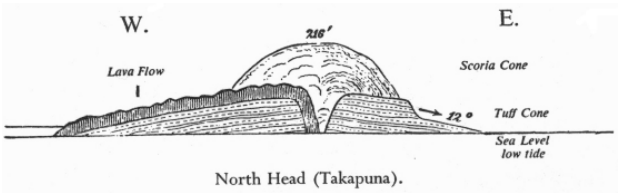


Fig. 2. Geological cross-section of North Head, as interpreted by Hochstetter (1864).

One hundred year later, Ernie Searle (1959) described North Head as a compound scoria cone mound with earlier explosive activity building a compact tuff cone. Between North Head and the ridge of Waitemata Sandstone at Takapuna Head, Searle mapped a 3 m high terrace of beach sand that he inferred accumulated during the early Holocene high sea level period, then known as the Flandrian Transgression.

Les Kermode (1992) mapped North Head at 1:50,000 showing everything within one sq cm with no room to show any structure. The scoria capping the tuff ring with a small flow to the west were shown. The beach ridge linking North Head to Takapuna Head is shown as a 200-300 m wide belt extending north-west behind Cheltenham. The remaining flat land between North Head and Mt Victoria is shown to have been low-lying swamp that has been reclaimed in European times. Kermode et al. (1992) conclude that, despite some quarrying and extensive tunnelling associated with North Head's use as a defensive fort, "the original shape is little changed".

Our mapping (Fig. 3) showed that only the upper 20 m (or about top third) of North Head is composed of scoria, although it extends lower down the west side, where the remains of a small quarry is located. There was insufficient exposure of the scoria to determine whether the present mound has quaquaversal dips and still retains the shape of the original scoria cone or not. We did note, however, that stratification of the oldest layers of scoria on the south-east side of the cone paralleled the 22° dip of the underlying tuff (Fig. 3). One exposure near the top of the scoria cone on the south-west side is of a 5 m width of 0.3 m+ thick rootless lava flow, inferred to have formed by fountaining lava being erupted so hot that it was still liquid when it landed.

We noted that tunnels in the loose scoria were constructed by digging trenches, lining them with concrete and building a concrete roof before backfilling over the top. Tunnels constructed through the underlying, more cohesive tuff were dug by usual tunnelling methods and mostly left unlined.

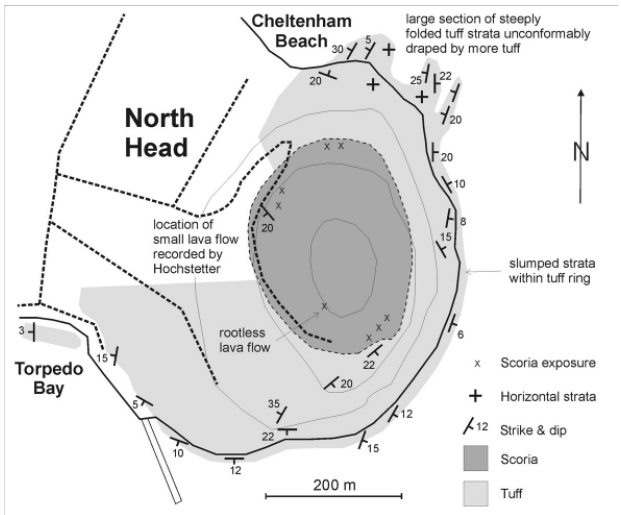


Fig. 3. Geological map and of North Head prepared during GeoClub visit, 2007.

We concluded that most of North Head is composed of tuff with beds dipping outwards at 5-22° around its south-west to north-east slopes (Fig.

3, 4). This confirms an eruption centre near the centre of present day North Head. A reversal of dip was seen in the wall of an access tunnel on the southern side (Fig. 3) and is inferred to be a result of a partial failure of the tuff cone slope during eruptions. Another convincing example of penecontemporaneous slumping within the tuff cone is present low on the eastern slopes (Fig. 3).



Fig. 4. East-dipping bedding planes form the shore-platform around the east side of North Head.

Intertidally in Torpedo Bay the tuff beds flatten off, providing evidence that the tuff cone did not extend much further west than it does at present. Today's south-west and west lower slopes of North Head approximate the original tuff cone's slopes. On the east and north-east sides however, marine erosion has cut 200-300 m into the tuff cone creating 30-40 m high cliffs.

On the northern shore, there are three remarkable ridges of bedded tuff extending NNE out into the harbour, parallel to their strike. Beds in the two eastern ridges define an anticline-syncline couplet with the beds broken brittlely across the tighter parts of the folds. This structure does not extend SSW along strike through to the south side of the tuff ring and seems to be confined to the north. Younger tuff beds high in the northern cliffs appear to be horizontal or dipping north as would be expected on the outer northern slope of the tuff ring. It would seem that these NNE-striking structures were produced during construction of the tuff ring, but if they were a result of downslope collapse and sliding of tuff beds, the folds should strike parallel to the slope (EW) and not perpendicular to it. So we have no explanation for what is present. Suggestions please?

Thus our field mapping answered two of our three original questions, but there is still one outstanding.

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NORTHLAND ALLOCHTHON-RELATED SLOPE FAILURES WITHIN THE WAITEMATA GROUP

Jill Kenny

At the Geological Society of New Zealand Conference in Tauranga, 2007, I presented a poster (Kenny 2007) demonstrating large-scale block faults that I believe exist in Auckland, even though they are not represented on published regional maps (Kermode 1992, Edbrooke 2001). I inferred block faulting using offsets of the only marker horizon in the region that can actually be followed – the "late Miocene" eroded surface on Waitemata Group rocks (Kermode 1992). This year, I have revised my thoughts about the E- to NE-trending faults and the arc-shaped faults (Kenny in press), exploring the possibility that they may be sub-horizontal in orientation, and associated with emplacement of slices of allochthonous (Waitemata Group) material – a situation with which I was familiar from my work on the East Coast Allochthon near Ruatoria (Kenny 1980, 1984, 1986). Geocene 3 provides a means to demonstrate my ideas on a map coloured according to topography of the peneplained and subsequently deeply dissected surface of the Waitemata Group (Figure 1). The accompanying text develops the hypothesis that many of the faults are sub-horizontal. This should be read in conjunction with the more detailed analysis in the latest GSNZ Newsletter (Kenny in press).

Figure 1 shows three distinct fault trends.
1) The Auckland, North Shore and Waitakere City regions are dominated by a series of ridges, often arc-shaped, with steep south-facing gradients and gentle northern slopes. These are interpreted to be arc-shaped sub-horizontal faults (Kenny in press). They appear to fan out from an area just north of Albany, which corresponds with the southern toe of the Northland Allochthon (Hayward 1993). Best examples are the asymmetrical ridges in the vicinity of Lucas and Hellyers Creeks, Greenhithe.

2) South of the Auckland isthmus I have interpreted the ENE-trending faults (Kenny 2007) as being the eastern extensions of splay faults from offshore west coast (Edbrooke 2001).

3) NNW faults truncate both of these trends.

Much of the Waitemata Group consists of near-horizontal undulating strata, interrupted by minor local faulting (Chappell 1963, High 1975, Kermode 1992), and rare highly deformed intervals associated with laharic Parnell Grit emplacement (Ballance 1974, Allen 2004). At other localities the Waitemata Group contains highly contorted zones up to 100 m thick, interpreted as being the result of syn-sedimentary or pene-contemporaneous slumping in a tectonically active subsiding basin (Gregory 1969, Spörli 1989, Hayward 1993, Isaac *et al*. 1994, Allen 2004, Spörli & Rowland 2007).

Hayward (1982, 1993) has inferred catastrophic sub-seafloor slope failures slumping from the Silverdale area southwards as far as Albany. If the sub-horizontal E- to NE-trending faults and the arc-shaped faults in Figure 1 represent imbricate slices of dislocated, disrupted Waitemata Group sediments, and if these slices represent zones of slumping, then the catastrophic slope failures reached much further than Albany, perhaps fanning outwards more than 30 km from Albany as far as Henderson in the southwest and Howick in the southeast. Many more slumps are undoubtedly present on smaller scales, represented by smaller asymmetric ridges across the landscape.

Widespread asymmetric folds within the deformed imbricate slices verge mainly south, but in the southern region of the basin folds verge east (Spörli 1989, Spörli & Rowland 2007). This evidence corroborates the patterns seen in Figure 1, extending southward migration of Northland Allochthon-related sub-seafloor slumping into the Auckland area.

The sub-seafloor failures at the toe of the Northland Allochthon affected the mid Waitemata Group sedimentary pile in the north of the study area in the middle to late Otaian (Hayward 1993). Deposition of Waitemata sediments continued through the early Miocene and was followed by a period of uplift and erosion that formed the "late Miocene" (Kermode 1992) or Pliocene (Ballance 1968) eroded Waitemata surface.

In the south of the study area this peneplain surface was disrupted by "post-Early Miocene (Edbrooke 2001, p.51) block faulting, which formed a series of east-trending horst and graben features (High 1975, 1977, Berry 1986, Omerod 1989, Petch *et al*. 1991).

The imbricate slope failures and the block faults have been truncated by N- to NNW-trending normal faults, most of which are down-thrown to the west. They are probably related to the NNW-trending regional faults which display NE-SW extension (Spörli & Rowlands 2007), such as the Drury, Wairoa and Waikopua Faults, inferred to be of middle to late Miocene age (Spörli 1989, Edbrooke 2001), and to the NNW-trending Hauraki rift zone to the east (Hochstein & Nixon 1979).

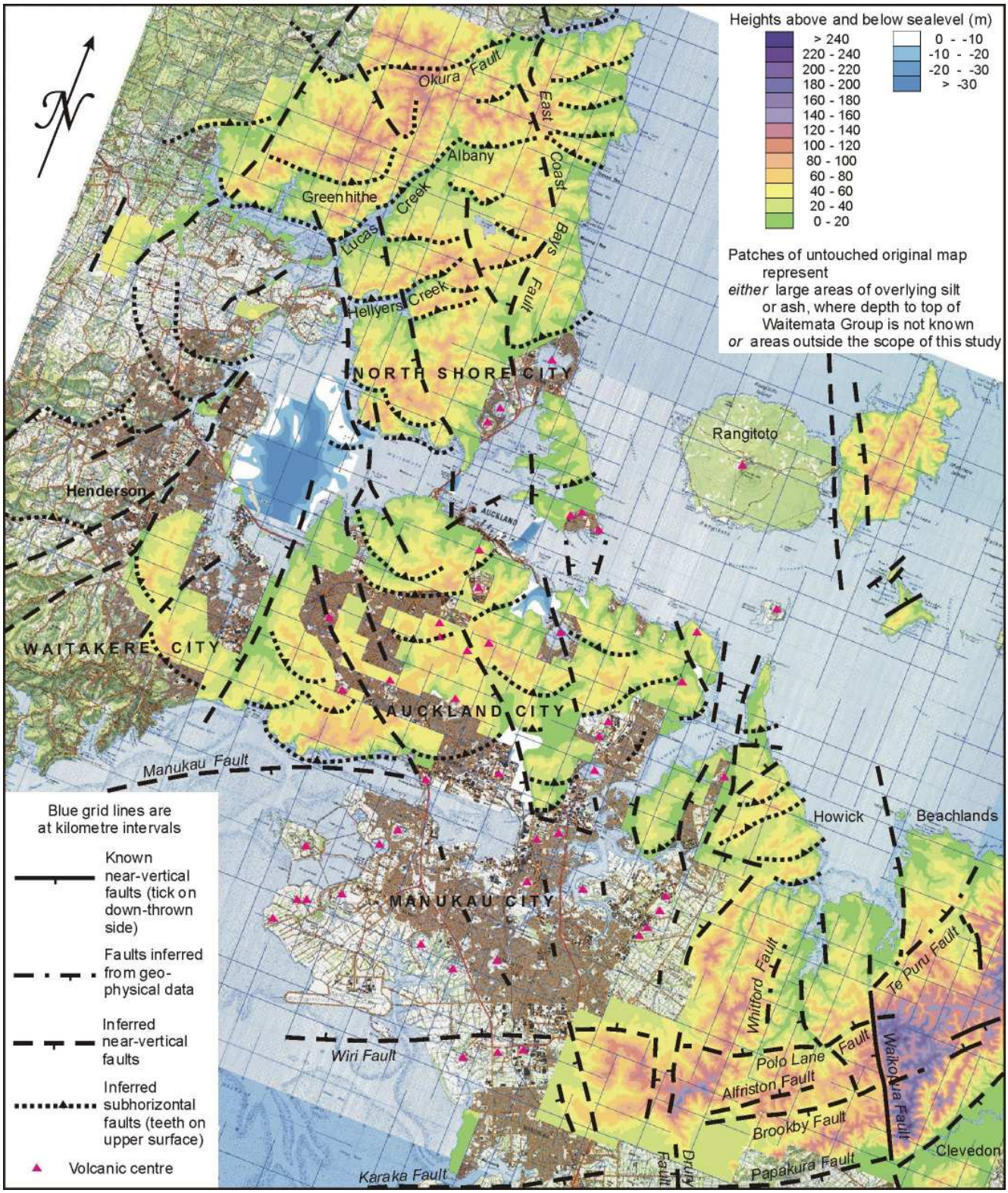


Fig1: Areas of known erosion surface of Waitemata Group superimposed on street map of Auckland area (some areas of greywacke also coloured).

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ASH HILL VOLCANO, WIRI

Bruce W. Hayward



Fig. 1. Aerial view of Ash Hill (crater circled) from the north west in 1994. x marks location of 2006 earthworks.

One of the least well known of Auckland's young basalt volcanoes is Ash Hill in Wiri (Fig. 1). It is not shown on Hochstetter's (1864) map of the volcanoes of Auckland, and appears to have been first recognised and named by Searle (1961) after nearby Ash Rd, which was named for the ash trees and not volcanic ash (Kermode et al., 1992). Oral tradition records that it was first noticed by Ernie Searle and Nick Brothers, when they flew over the area in a small aeroplane as part of Searle's research for his 1961 report.

Searle (1961, p.241) describes it as the "site of a minor phreatic eruption that built a tuff cone with a small explosive crater". There is no indication whether Searle ever saw any actual tuff exposure or whether his description was purely based on the geomorphology of a small, shallow (125 m diameter) crater surrounded by a slightly raised mound, particularly on the north and east sides. Kermode et al. (1991) report that the crater is "at least 30 m deep" and "has been infilled by peat and organic mud". This alludes to unpublished results of drilling that was undertaken at Ash Hill at the time it was being developed as an industrial subdivision.

Today it is very difficult to locate the remains of Ash Hill volcano, and I am indebted to the late Les Kermode for pointing it out to us during an Auckland Geology Club trip in 1994. The crater lies beneath the truck park and backyard of an industrial site on the east side of Ash Rd and the low mound around it is best seen beyond to the north and east. The crater-fill sediments are now capped with fill and some of the surrounding tuff ring was apparently flattened during industrial subdivision. Early in 2006, I was alerted by local geology enthusiast John Smith, to some earthworks being undertaken on a property next to a petrol station in Wiri-Station Rd. In preparing the building site, a large flat terrace was cut out of part of the northern slopes of Ash Hill's tuff ring.

Cuttings at the south and west sides of the terrace exposed a section through the tuff ring deposits and underlying Pleistocene rhyolitic sediment. It showed that the lower part of the tuff ring was an original topographic rise composed of Pleistocene sediment and that the erupted tuff formed a deposit just 2-3 m thick burying a fossil soil and small trees (Fig. 2).



Fig. 2. Cutting showing rhyolitic sediment overlain by black soil, peat and buried small trees beneath 2 m of massive lithic tuff, Wiri Station Rd.

The tuff deposit was typical of that which accumulates close to an explosive vent with subrounded to subangular blocks and cobbles of country rock sitting in a matrix of comminuted sediment (Fig. 3).



Fig. 3. Cutting showing massive lithic tuff deposit of Ash Hill with blocks of Waitemata Sandstone and Pleistocene sediment and small dark pebbles of basalt. Glasses case for scale.

The blocks included Waitemata Sandstone and Pleistocene peat and rhyolitic tuff. A significant component of the pebble-sized clasts was angular pieces of dark basalt. This clearly shows that Ash Hill was not just a hydrothermal eruption caused by superheated groundwater bursting out in an explosive steam eruption but that magma was involved. Presumably the magma rose up along this conduit and on encountering cold groundwater several large explosive eruptions ensued, throwing out a large quantity of the overlying country rock and a little bit of the basalt magma. It could well have been the product of an offshoot conduit from the much larger Wiri Mt volcanic eruptions, just 1 km to the south-west. Thus I am satisfied that Ash Hill can indeed be called one of Auckland's, all be it smaller, volcanoes.

Age

A sample of a small in-situ tree directly beneath the Ash Hill tuff was collected for radiocarbon dating (WK21120). The University of Waikato Radiocarbon Dating Laboratory returned a conventional age of 27,065 +/- 199 radiocarbon years BP, which is converted by the CalPal package to 31,800+/-159 calendar years BP. This age is close to those previously obtained from wood underlying flows or tuff in a number of other Manukau volcanoes (all ages in radiocarbon years, Searle, 1965), including nearby Wiri Mt (28,300+/-690 yrs BP) and Maungataketake (29,000+/-1500 yrs BP). Shane et al. (2005) also recorded a 1.5 m thick pulse of basaltic tephra in the nearby (5 km to the north-west) Pukaki Lagoon crater lake sequence at about 32,000 cal yrs BP. Thus Ash Hill quite likely erupted in association with Wiri Mt and at about the same time as several other Manukau volcanic centres.

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BRIDGE PROTECTS ST KENTIGERN CLIFF SECTION

Bruce Hayward and Anna Sandiford

In February 2007 a group of Geoclubbers revisited the St Kentigern cliff peat cliff section that had recently been made much more easily accessible. The opening of a new coastal walkway in Pakuranga in March 2007 marked a new era in earth science conservation in New Zealand. The walkway was a long awaited extension of the Rotary Walkway which wends its way alongside the Tamaki Estuary from Farm Cove and now reaches the Pakuranga Highway opposite the Pakuranga shopping mall. The walkway extension was held up for many years by St Kentigern College who refused permission to let Manukau City Council and the local Rotary Club to route some of the path across some of its land around the bottom of its playing fields. A compromise was eventually reached where the proposed walkway was to be sited atop a new 1-2 m high mudcrete embankment to be constructed around the base of the sea cliffs at the foot of the St Kentigern property. St Kentigern College contributed to its construction because the embankment also doubled as an erosion protection barrier. The only impediment to this new plan was that an important geological feature was exposed in part of the cliffs and was scheduled for protection on the Manukau District Plan. After negotiations with the Geological Society, it was agreed that a substantial wooden bridge would be constructed across the front of a 10 m wide section of cliff. This would allow the high tide access to slowly erode away at the base of the cliff, as it would naturally, removing weathered material and keeping the exposed strata relatively fresh, clean and visible. If the embankment had been built across the face, some of the section would have been buried and that above would have quickly weathered to clay and become hidden by vegetation.

The construction of a bridge is an innovative solution to an unusual problem and as such is a New Zealand first, although similar structures have been built overseas to protect important geological features. The St Kentigern's bridge now provides easy access to view an important slice of Auckland's and Pakuranga's ancient history. A nearby sign explains some of its significance. The rock strata seen in the cliff provide the most complete record of Auckland's geography, changing forest cover and the impact of major volcanic ash showers, during the period one to one and a quarter million years ago.

At beach level in the bottom of the exposed section are the remains of a fossilised forest with branches, and small tree stumps with roots extending down into the underlying volcanic ash. This one and a quarter million year old forest grew at the head of the ancestral Tamaki River valley at a time when sea level was lower than today. At that time the Tamaki River flowed south and west through Westfield and past Onehunga to join the Manukau Harbour River valley. The river only reversed its flow about 50,000 yrs ago when Mt Richmond and McLennan Hills volcanoes erupted and blocked the route through to the Manukau.

The black peat that buries the forest, tells us that the trees were drowned and killed by the formation of a swamp. The overlying 5 m of strata consists of black peat, brown organic mud, and light-coloured volcanic ash, all of which were deposited in this swamp or shallow lake over the following 250,000 years. British palynologist Anna Sandiford has undertaken detailed studies of the fossil pollen and spores in 100 samples through this sequence. Her results document the vegetation of this part of Auckland through three Ice Ages and the intervening warm periods. The site was a swamp fringed by *Sphagnum* moss, sedges, umbrella ferns and cushion plants. During the three warm periods the swamp was surrounded by an angiosperm-conifer forest dominated by pohutukawa, kahikatea, maire, tanekaha, kauri, rimu, totara and tree ferns, indicative of a moist, frost-free, coastal environment. During the cold Ice Age periods, sea level was lower, the coast further away, and the tall-tree forest was reduced with establishment of silver and red beech and more numerous shrubs (e.g. *Coprosma*, *Hebe*). The pollen record also shows that the volcanic ash falls felled many of the tall trees and there was a temporary increase in plants commonly associated with forest disturbance, such as manuka, taupata, tussock and grassland, until the tall forest grew back again.



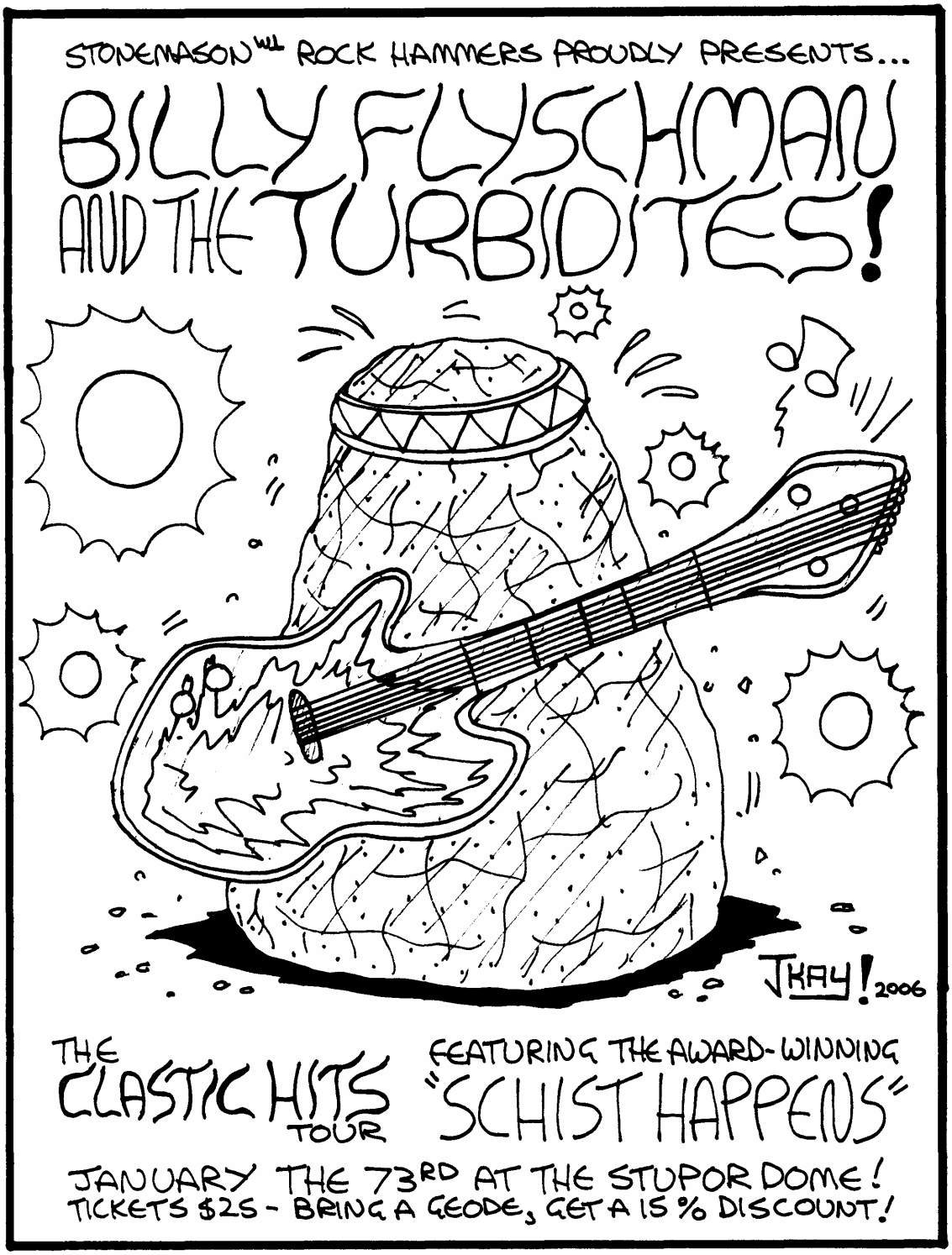
Photo: This special wooden bridge has been built to protect the view of the unique sequence of peat, fossil forest, and volcanic ash showers in the St Kentigern College cliffs.

Light-coloured volcanic ash in the sequence is rhyolitic in composition and came from numerous large eruptions in the centre of the North Island, around Mangakino. Some of the 1-10 cm ash beds within the peat are direct air-fall deposits from ash blown 300 km northwest from a huge eruption, like that which later that formed Lake Taupo.

A 20-50 cm thick bed of brilliant white, fine pumice ash was emplaced as a hot ignimbrite flow - a fast-moving cloud of hot ash, fine pumice, water

vapour and other gases, that race across the ground incinerating and burying everything in its path. This ignimbrite mantles much of southern Auckland in deposits up to 5 m thick. It was undoubtedly one of the largest eruptions ever to occur in New Zealand.

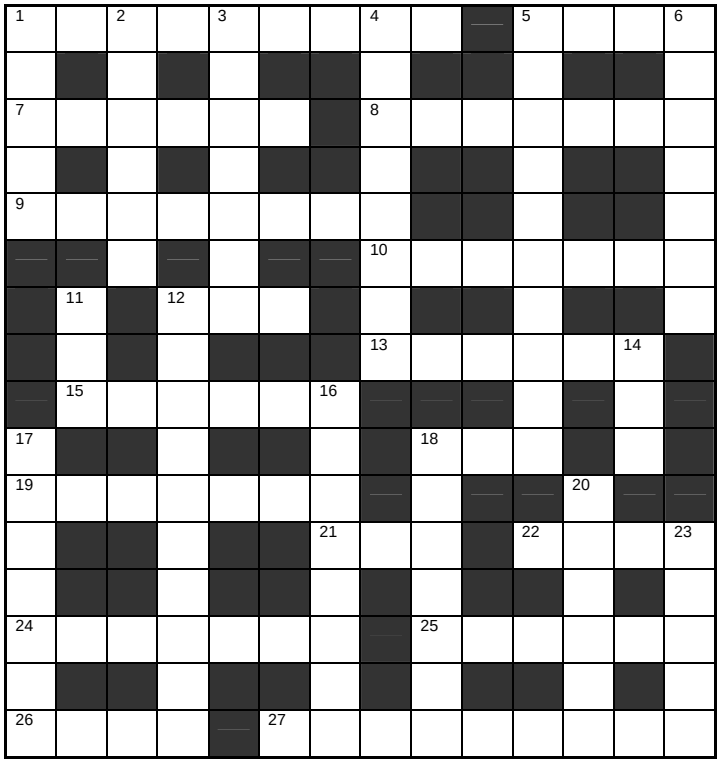
Until now, this important page of Auckland's history could only be viewed by those prepared to plod through the Tamaki Estuary mud to get there (as GeoClub members did 6 years ago). Now that the new walkway and bridge provide easy access, it is likely to become an important destination for science and geography classes from nearby schools.



"Billy Flyschman"
Cartoon by Jon Kay

GEOPUZZLES Rhiannon Daymond-King

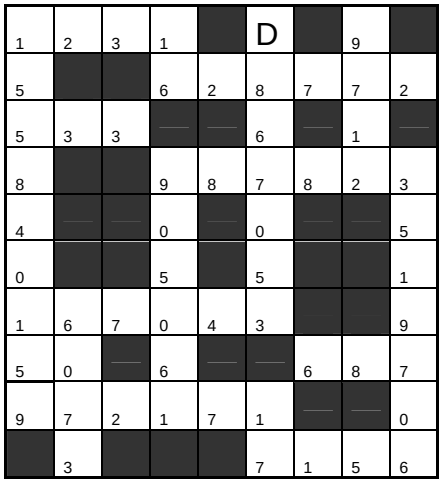
CROSSWORD



DOWN
1. A thin layer which represents annual deposition
2. Formed of rock, or fragments of rock
3. Where detritus had been removed by wind action
4. Essential micronutrient, semimetal similar to sulphur
5. Processes occurring in sediment after deposition, before metamorphosis
6. Spherical to elliptical lumps of rock common in soils and evaporites
11. A valuable or semi-precious stone, cut or shaped for display
12. A regular polyhedron with eight equilateral triangle faces
14. A first order geological time unit
16. A good display piece of mineral/fossil, or a particular sample
17. On or along the continental edge of a large basin, sea or ocean
18. A deep part of the ocean, from 2-6 km below sea level
20. A basic, ionic salt of a Group I or II metal
23. A single, small fragment of rock or other material; the orientation of many such.

ACROSS
1. The action of lava and ash issuing through the crust
5. Relative direction towards centre of earth; hilly rolling grassland
7. Mineral forming fibrous needle-like inclusions in other minerals, esp. quartz
8. Found or designated in a particular place or time
9. Material being expelled from deposit or depositional source
10. A trace fossil footprint, usually of a land animal or bird.
12. Unusual; not divisible by two; irregular occurrence
13. Silicate inner shell of the Earth between Mohorovicic and Gutenberg Discontinuities
15. Basic units of length in the International System of Units
18. A chain of volcanic islands or mountains formed by subduction during plate tectonics
19. Being on continental crust; on land, away from the ocean
21. A small, low-elevation, sandy island formed on the surface of coral reefs
22. Magma that has cooled in the neck of a volcanic cone, often left behind by erosion
24. An actinide element, used with or instead of uranium in dating and nuclear fuel
25. Internally consistent layers of rock; bands of different coloured or textured materials
26. Dip, or other gently sloping orientation of rock layers, or a fold hinge
27. A small amount of any material trapped inside a mineral or crystal during its formation

TAKE 5 #3



Each number corresponds with a letter. To work out the crossword, replace the 10 numbers with letters. Key: 8=U.

GEOWORDOKU

Fill the grid so every column, every row and every 3x3 box contains the full nine letters of the word (They can be in any order). There is only one solution to each.

Word: AMPHIBOLE

A M H	P O	O M A P
I B	I B E H A	L A
P E L M	M O	H I B

Word: PLUTONICS

S N 	I C P O	 U L N
O U C S	N I T	I L N O
O C S	C P I N	 I S

WORD CHANGING
Turn one Geology word into another!
Change only one letter each time, to make a new word. Each letter change must be to a word in English. (no foreign words, or names; e.g. John cannot follow join, but coin can.)
EXAMPLE: dusk to dawn
dusk, dust, must, most, moot, moon, mown, down, *dawn* (A Dreaming Week, by Carol Ann Duffy)

Change ROCK to CLAY
Change LEAD to GOLD! (Be an old fashioned alchemist!)

WORD MATCHING
Find a word that can precede crystal, fall, flour and salt.

WORDFIND

P	A	L	Y	N	O	L	O	G	Y	K
E	Y	T	T	R	I	U	M	L	A	A
R	A	R	E	A	E	C	A	R	T	O
M	D	O	O	L	F	M	S	E	C	L
E	R	U	C	C	R	T	E	S	N	I
A	O	G	E	O	L	O	G	Y	I	N
B	C	H	N	V	A	A	A	E	T	O
L	E	V	E	E	P	L	S	G	X	T
E	R	O	S	I	O	N	U	T	E	A
A	E	O	N	T	C	A	P	M	I	R
P	A	G	E	G	A	V	A	E	L	C

This WordFind contains these 35 words. They can be found in any direction - left, right, up, down, or diagonal - but the words are always in a straight line.

aeon	extinct	opal
alcove	flood	page
alum	gaping	palynology
arc	geology	permeable
area	geyser	pyroclastic
clast	impact	rare
cleavage	inset	record
coal	kaolin	sages
craton	karst	trace
day	leap	trough
eocene	levee	yttrium
erosion	normal	