GEOSCIENCES 09

Annual Conference
Oamaru, NZ

FIELD TRIP 5

WAIAREKA-DEBORAH VOLCANICS – VOLCANOES OF THE PALEOGENE SHELF

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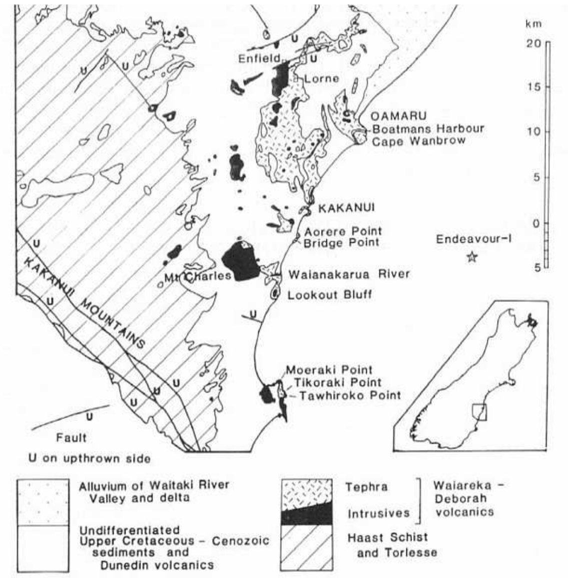
Introduction

Participants in this trip will visit a few of the volcanoes erupted on submerged continental crust of New Zealand's Oligocene shelf. They are part of the Waiareka-Deborah Group, which has been inferred to represent between a few tens and a couple of hundred km^3 of magma (Coombs et al., 1986), with most of the volume in intrusions. It is one of a number of Cenozoic intraplate volcanic successions that have developed almost continuously on the South Island since the end of Cretaceous rifting (Hoernle et al., 2006).

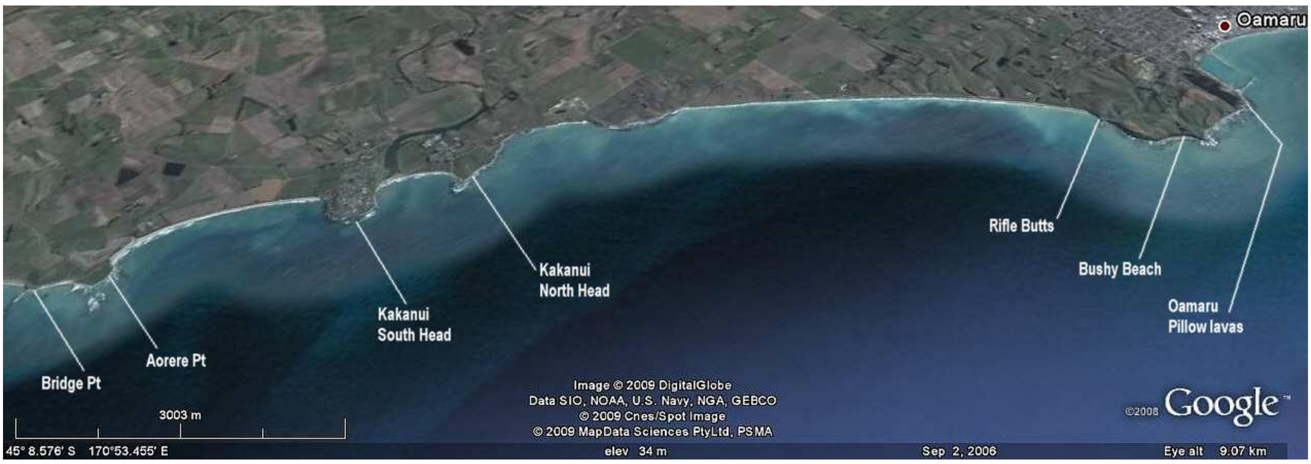


Three sites will be visited, with possible variations depending on participant interest and beach accessibility. The first will be the Kakanui Mineral Breccia and related deposits at Kakanui South Head. It has been subject of a number of studies focused on mantle-derived minerals, but our focus will be on the style of eruption represented by bedded and unbedded volcaniclastic deposits.

Stop 2, tide and waves permitting, will be at Bridge Point, where the succession of deposits has been described as resulting from a "Surtla type" eruption, i.e. one generally like that of Surtsey but which ceased before building the volcano above the surface.

Our third and final stop will be at the Oamaru volcano, where we will park at the penguin centre and walk along Graves' Track to the well-known pillow locality. This should be near low tide, and if possible we continue onward to view an thin-bedded sequence of ambiguous origin, then return to the carpark via the shoreface. This will take us through a series of bedded volcaniclastic deposits, through pillow lavas, to hyaloclastite breccias just below the penguin parade and one-time carpark area.

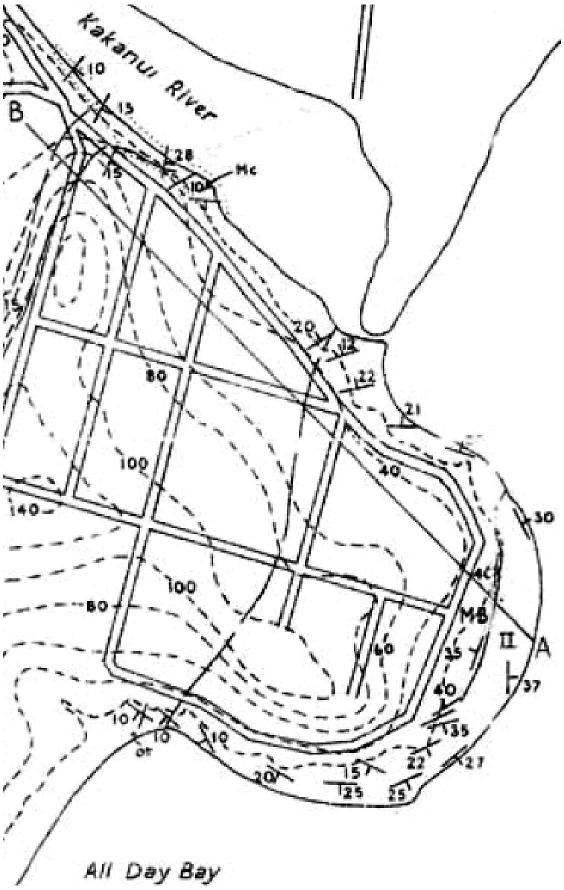
We will return to the Opera House early enough to be ready for the evening BBQ pickup.



Stop 1: Kakanui Mineral Breccia

Mineralogically distinctive lapilli tuffs of the Kakanui Mineral Breccia comprise mostly thin-bedded deposits that are crosscut and onlapped at the eastern end of South Head by a small zone of chaotic unbedded tuff breccia. Around the Head to the north and east, the thin-bedded pyroclastic deposits pass upward into reworked and calcareous sedimentary deposits formed in relatively shallow water. Similar lapilli-tuff beds crop out for another km or so north, with varied bedding orientations suggesting multiple local eruptive sites.

Dickey (1966) separated the Mineral Breccia unit (MB on map below left) from another volcaniclastic unit in which garnets and other exotic mantle-derived minerals are sparse or absent (II on the map).



Bedding is well-developed around South Head, with beds along the eastern shore of the head dipping outward from land, and these dips are coupled with a semi-circular reef around the headland.

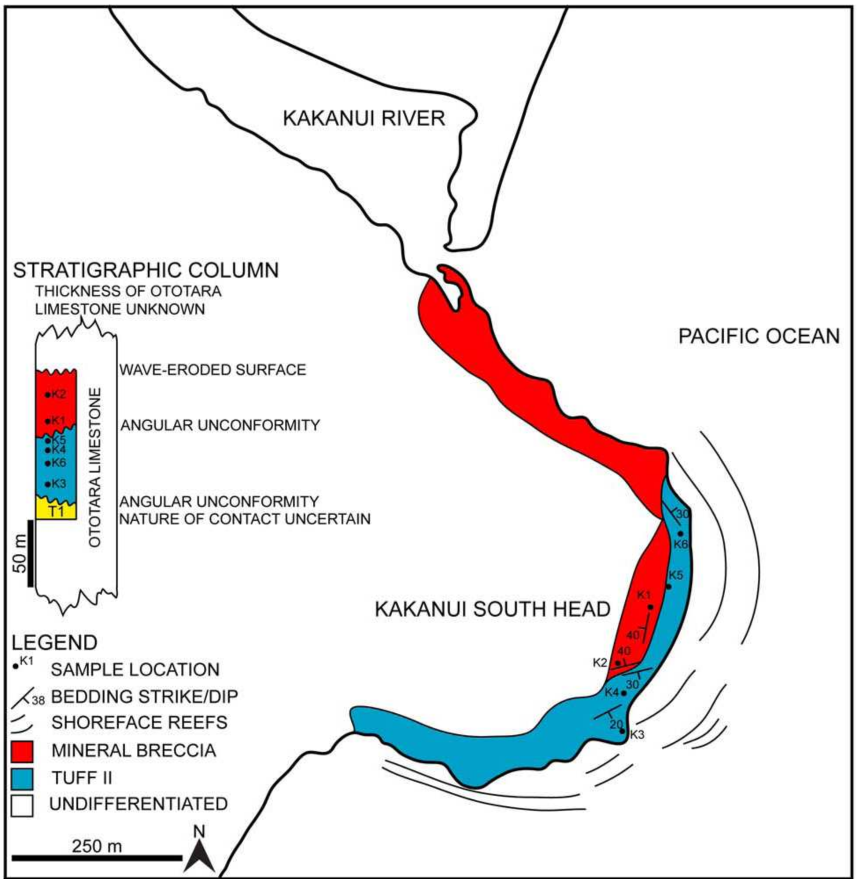
Further west on the north shore, this pattern breaks down, with older beds of Dickey's Tuff I returning to the typical shallow eastward dip of sedimentary rocks in this region.

Landward of these tuff beds on the east edge of the southern headland the Mineral Breccia is exposed. This unit includes a body of structureless tuff breccia near where the 35-degree westward dip is measured on the contact between them, and where bedding is present it dips westward, toward the inferred source vent.

As part of an internal exercise for a 4th year paper, Matt Sagar produced an updated and colorised version of Dickey's map, and locates 6 samples collected for the exercise.

The photograph at right is taken from site K6 on Sagar's map, loooking NNW, and slows decimetre-thick beds in the "tuff II" unit of Dickey.

Despite the name, the Mineral Breccia rarely has sufficient coarse clasts to qualify as a breccia; most consists of lapilli tuff. Larger fragments include irregular cored bombs that were shaped by ductile deformation (below). These do not show evidence for having welded together or to other fragments, indicated that they had chilled surfaces and had perhaps largely solidified prior to deposition.

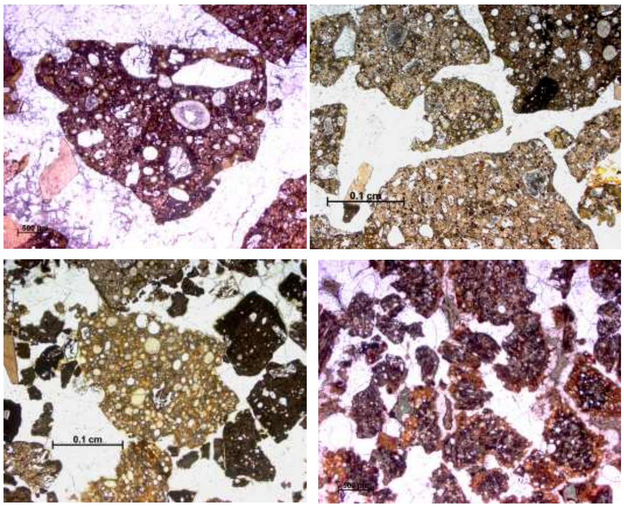


Geological map and stratigraphic column showing the distribution, structure and estimated thicknesses of, and relationships between, the Deborah Volcanics and Ototara Limestone, sample locations, and shoreface reefs visible in satellite imagery within the coastal section visited at Kakanui Head South (constructed from field observations, Dickey (1968) and Google Earth). Stratigraphic positions of samples are relative only, not absolute.

Bedding within the Mineral Breccia ranges from poorly to very well developed, with conspicuous thinly bedded deposits at the northeastern corner of South Head.

Note the subtle bedding discordances and lateral wedging of thin beds that indicate deposition from currents. Bedding in these and similar deposits is interpreted to have formed during the eruption from *eruption fed density currents.* The term was introduced (White, 1996) to express the inference that during construction of a subaqueous pyroclastic edifice, the waterlain deposits forming it are both deposited initially from material ejected into the water column during the eruption, and that this material is not "reworked" in the process of being transported to the depositional surface. Deposits of eruption-fed density currents are primary pyroclastic rocks. (White and Houghton, 2006)

Glassy juvenile fragments range from opaque tachylitic ones to translucent palagonite-altered grains that were originally sideromelane glass. Vesicle populations are fairly diverse, with a range of both total vesicularity and vesicle shapes and sizes, both within single fragments and among the fragment population. The top two photomicrographs show vesicular pyroclasts in the Mineral Breccia at Sagar's K1 site, the other two from lapilli tuff of the "tuff II" unit at sites K4 and K6.



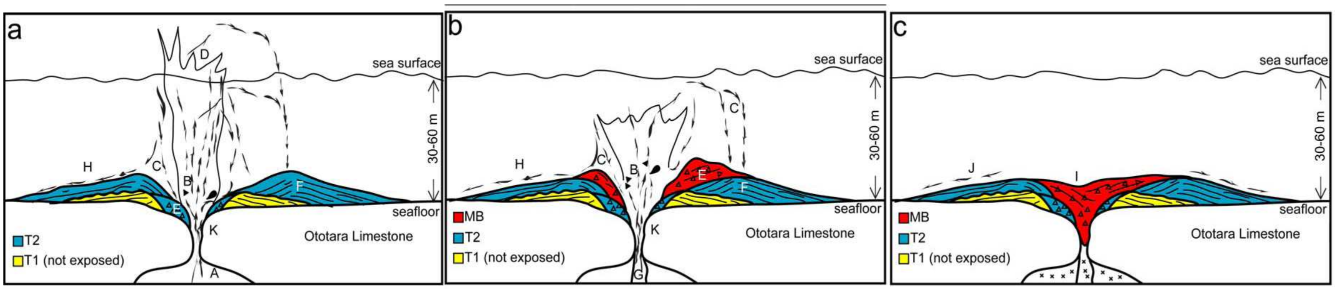
A recent study (Corcoran and Moore, 2008) examined the overall depositional setting and development of the volcanic centre at South Head. A shelf-depth eruptive setting is confirmed from fossiliferous over- and underlying sedimentary rocks, and a surtseyan style of eruption is inferred.

	Specimen #			
Species	OU52312B	OU49352A	OU49352B	OU49322
SiO_2	45.52	44.56	44.17	45.53
TiO_2	2.36	2.55	3.22	2.28
Al_2O_3	15.72	17.77	16.48	16.5
FeO*	11.19	11.34	10.31	10.06
MnO	0.19	0.24	0.17	0.21
MgO	3.57	3.47	4.03	3.48
CaO	8.86	9.75	10.59	9.86
Na_2O	5.83	6.57	5.11	5.68
K_2O	1.9	3.68	2.73	3.17
P_2O_5	1.01	0.84	0.98	1.36
Total	96.15	100.77	97.79	98.13

Average electron microprobe analyses of alkalic glass from the Mineral Breccia Member of the Deborah Volcanics, Kakanui (OU49352A, OU49352B & OU49322), and Waiareka Volcanics, Cape Wanbrow (OU52312B) (Coombs, Cas et al. 1986; Coombs and Reay 1986) are given at left.

Mantle megacrysts in the Mineral Breccia often have smooth, shiny exteriors ("polished"), and include pyrope garnet, omphacitic pyroxene, kaersutite, anorthoclase, ilmenite, chrome diopside, apatite, spinel and phlogopitic biotite. Xenoliths include lherzolite, pyroxenite, garnet pyroxenites ("eclogites") and a range of granulites (Coombs et al., 1986).

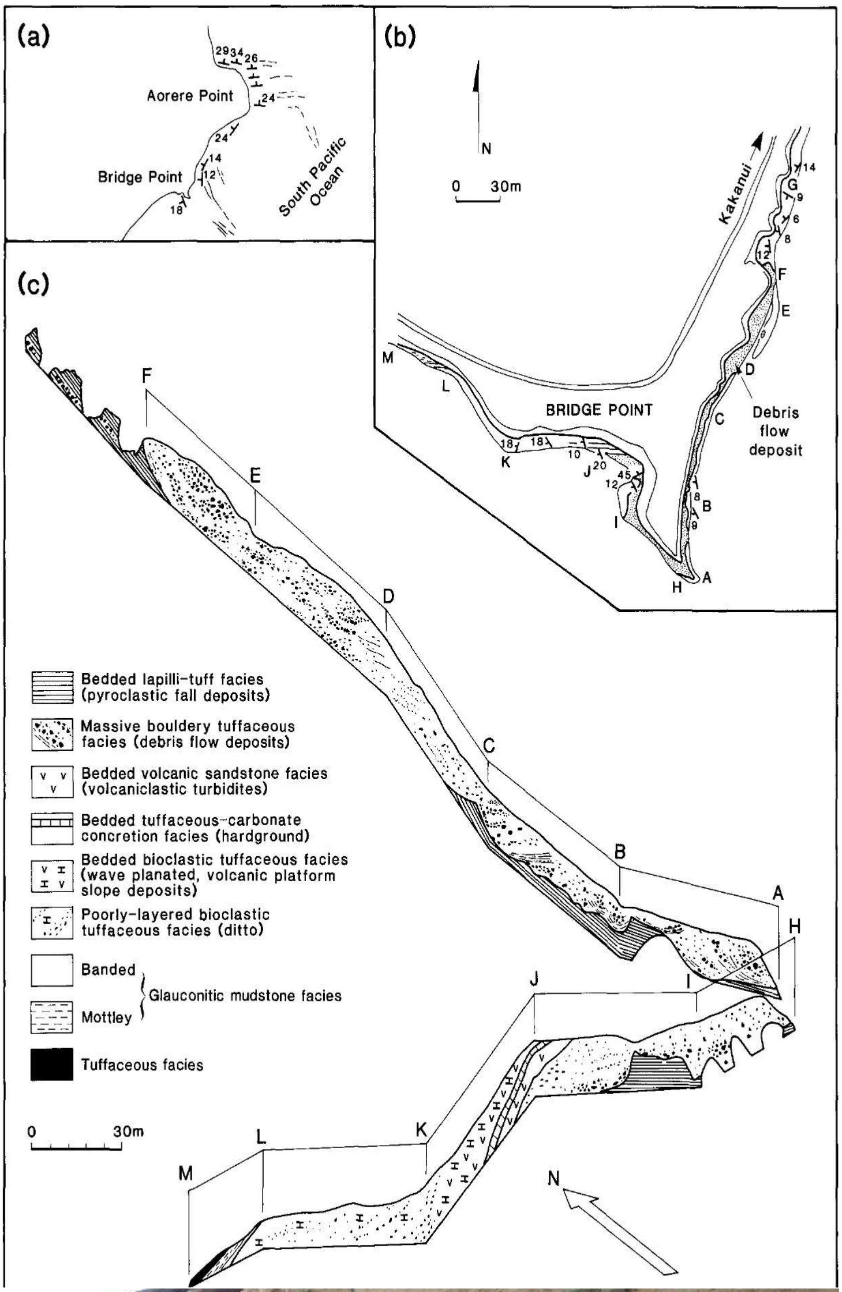
Borrowing again from Matt Sagar's 2008 report, the figure and caption below summarise a number of good observations about the eruption products and depositional processes represented at South Head.



Diagrammatic cross-sections depicting construction of the Kakanui South Head edifice. No relative or absolute scale implied. (a–b) A: Stagnation in small shallow magma chamber or conduit, and/or slow ascent rate of the volatile-rich basanitic T2 parent melt allowed non-explosive degassing, which produced poorly vesicular tachylite. CO_2 exsolved at greater depth than H_2O. B: Ballistic dispersal of large xenoliths, blocks, bombs, medium–coarse lapilli and megacrysts formed massive–crudely bedded chaotic lapilli tuff-breccia proximal to the vent (E). C: Fall-out and density currents and grain flows formed directly from collapsing eruption columns deposited graded beds on the slopes of the edifice (F) and within the vent (E). D: Some tephra jets penetrated the sea surface. E & F: An angular unconformity separates the MB and T2. G: Volatile-rich nephelenitic MB magma ascended rapidly carrying dense mantle xenoliths plus megacrysts, and fragments to produce angular, blocky, vesicular sideromelane lapilli. CO2 exsolved at greater depth than H2O. H: Grain and debris flows initiated via edifice over-steepening during eruptions and wave-action re-deposited the primary volcaniclastic sediments. K: Magma fragmentation occurred at the seafloor via BISE due to excessive water:magma ratios and inundation of the vent. A steam cupola, aided by the volatile-rich nature of the magmas, insulated the eruption columns permitting tachylite, and bombs to form. (c) I: Wave-eroded surface cut into the top of the Deborah Volcanics, caused removal of the emergent upper portion of the edifice, which may have existed. J: Reworking of the edifice continued principally due to wave-action following cessation of volcanism.

Stop 2: Bridge Point

Bridge Point is a relatively small outcrop area that is the subject of two papers initiated when Ray Cas spent a sabbatical at Otago (Cas and Landis, 1987; Cas et al., 1989). Hoernle et al. (2006) report a date of 39.5 +/- 1.8 Ma ($^{40}Ar/^{39}Ar$, step heating) from Bridge Point.



The first of the two papers focuses on the prominent debris-flow deposit indicated in frame b of figure 2 in Cas et al (1989).

We plan to drop onto the beach between Aorere Point and Bridge Point, then walk south and work our way back to the north.

The debris-flow deposit is exposed near the southern end of the outcrops before the natural bridge. It overlies in the south a series of thin-bedded lapilli tuff not dissimilar in terms of bedding style to what we've seen at Kakanui South Head. Above an erosional subplanar contact, a single ~ 2 m thick layer has a largely unstratified interior. Punctuating this layer a a few locations are curved channel-form strata that are interpreted to represent shear banding along the edges of U-shaped domains of plug-flow within the overall debris-flow or debris-flow deposit . The multiple layers indicate progressive migration of the plug-flow (Cas and Landis, 1987), and record a type of lateral-accretion surface.

In the photo at right, the debris-flow deposit is overlain by 2-3 m of loess. The accretion surfaces are visible near the left of the photo, with a domain of coarser-grained debris further to the right marking a second such plug-flow domain.

At the northern end of these Bridge Point outcrops is a coarse breccia containing apparent fluidally-deformed bombs as well as blocks of bedded tuff and other volcanic rock (photo below). This may be a separate debris-flow deposit, or it may be the edge of a vent-filling deposit, which would help explain the fluidal fragments and coarse overall nature.

Around to the southwest side of Bridge Point, which will be visited by the other mid-conference trip, the volcaniclastic succession is overlain by glauconitic and bioclastic deposits.

Aorere Point to the north is interpreted to represent deposits underlying those exposed at Bridge Point as shown at right (Cas et al., 1989).

If we have time, we will take a quick look at the Aorere Point deposits, which are consistently thin-bedded and rather monotonous in appearance.

The overall sequence of development at Bridge Point is illustrated below (Fig. 9; Cas et al., 1989).

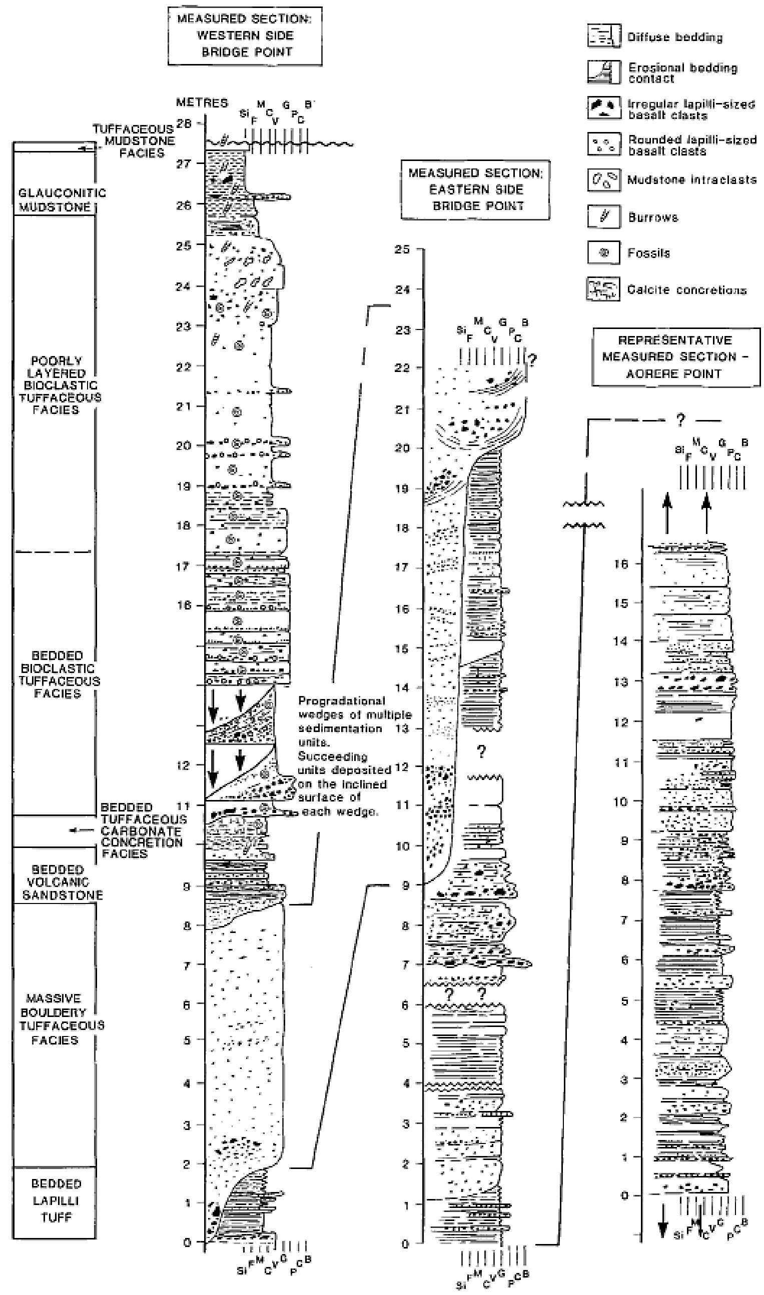
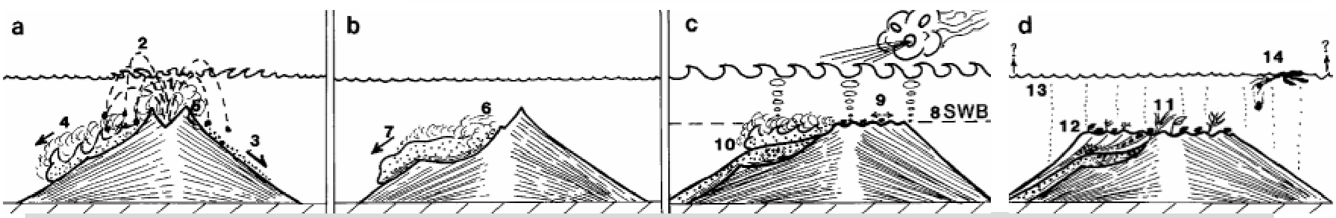


Fig. 9 a–d. Schematic representation of the principal stages of development of the Bridge Point-Aorere Point, Surtla-type, Surtseyan volcano; *1* Shallow subaqueous eruption; *2* Rare subaerial tephra jets; *3* Downslope grain flow; *4* Turbidity currents; *5* Local eddies & working; *6* Sector collapse; *7* Grain-dominant debris flow; *8* SWB-Storm wave-base; *9* Wave-planation & reworking of edifice top; *10* Redeposition; *11* Colonisation of platform; *12* Platform widened by growth of talus ramps; *13* Pelagic sedimentation; *14* Floating holdfasts of kelp



Stop 3: Boatman's Harbour, Oamaru volcano

The volcanic edifice at Oamaru is larger and more complex than the other two seen today. Its stratigraphy has played a role in regional studies (Gage, 1957), but no overall study of its volcanology has yet been published.

A succession of volcanic and volcaniclastic beds are exposed in seacliffs along Graves Track, and can be examined at low tide. On this trip we will first walk along the track and descend to examine the pillow lavas exposed between 100 and 150 m on the column above. If there is time, we will walk downsection to the surge cross-bedded facies, then double back and follow the shoreline upsection from the lower pillows through the pillow breccia facies.

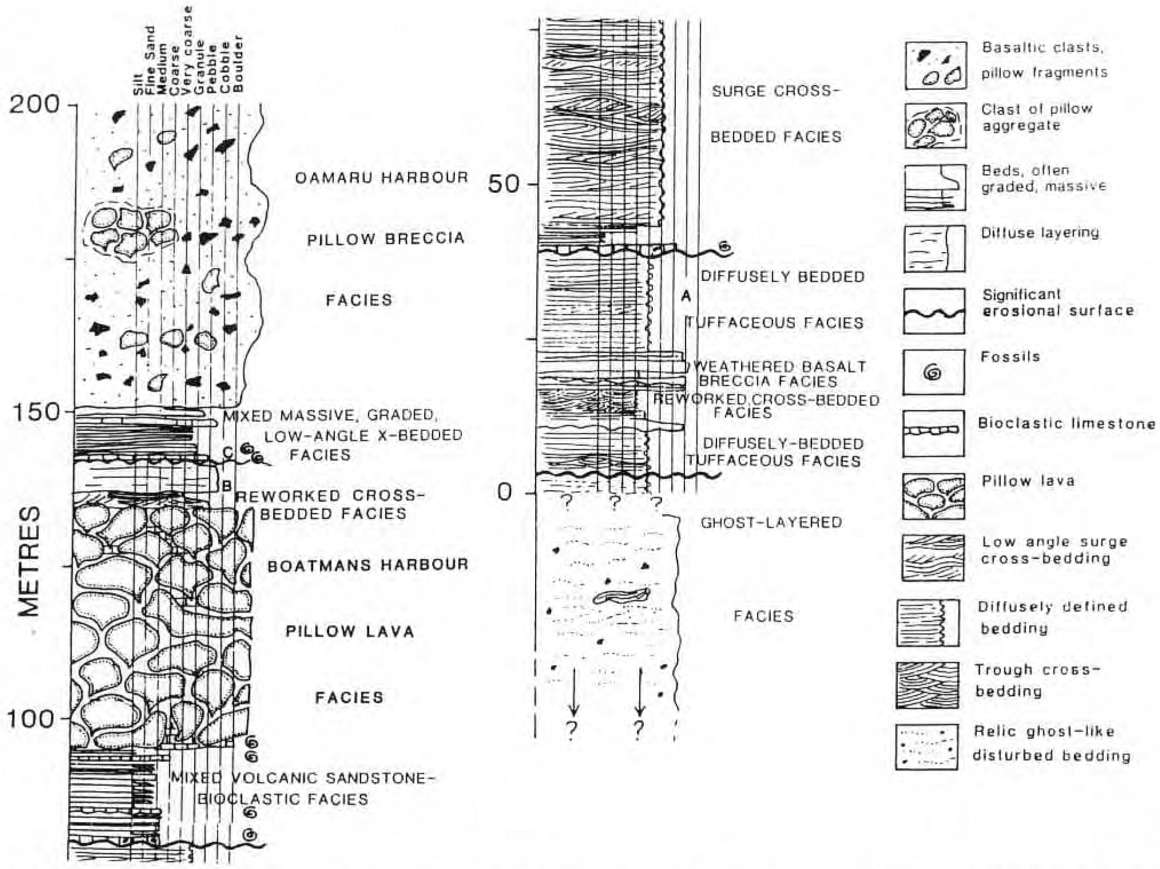


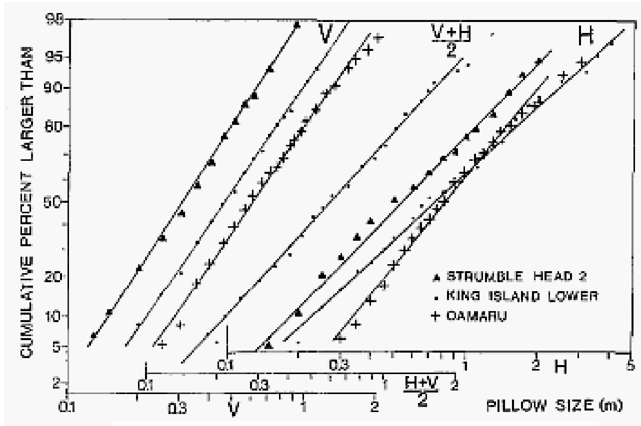
Fig. 2—Stratigraphic column, Waiareka-Deborah volcanics, Cape Wanbrow-Boatmans Harbour-Oamaru Harbour Board Quary section, North Otago. A. B. Basanitic cobbles and lapilli, lherzolite nodules and high-alumina clinopyroxene megacrysts. C. Fine-grained basanitic tuff.

The Boatmans Harbour pillow lavas are spectacularly exposed, and have featured more than once in volcanological studies. Walker (1992) included them in a quantitative study of pillow morphology.

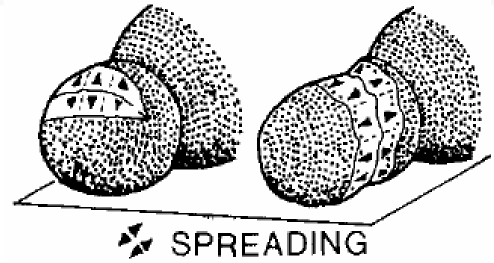
	Compn.	H				V					N
		Md	16	84	aver	Md	16	84	5	aver	
K. Oamaru	alk. bas.	0.78	0.42	1.61	1.11	0.56	0.34	1.04	0.24	0.70	194

(H, dimension parallel with base/top of pillowed flow; V, dimension at right angles to H; *16, 84, 5,* dimensions at the 16, 84 and 5 percentile; *average*, arithmetic average; *N* number of pillows measured)

Walker's study concluded, among other things, that the size distribution of pillows at Oamaru, and elsewhere, follows an approximately lognormal distribution. For Oamaru he plotted pillow height (thickness), with the distribution actually having two distinct lognormal slopes as seen at right.



He noted multiple rinds, but disagreed with the analysis of Kawachi and Pringle (1988; see below), interpreting the multiple rinds as artifacts of outcrops randomly coinciding with spreading joins, at which an old rind is split and a new one develops on the fresh surface as shown at right.



Kawachi and Pringle (1988) had previously studied in some detail the chilled rinds on the pillows, many of which show multiple, or nested, rinds. Their interpretation is that the multiple rinds represent more-complicated series of events involving pillow-tube inflation with accumulation of exsolved gases in the pillow, gas-condensation, tube collapse, and inward thrusting of hardened rind. Their diagrams are much nicer than Walker's…

Kawachi and Pringle: Pillow multiple-rind structure

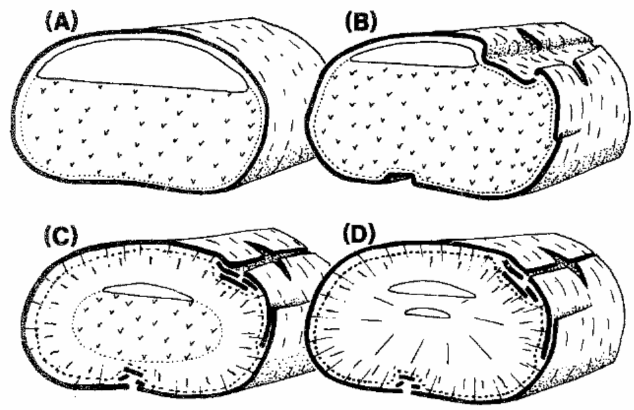
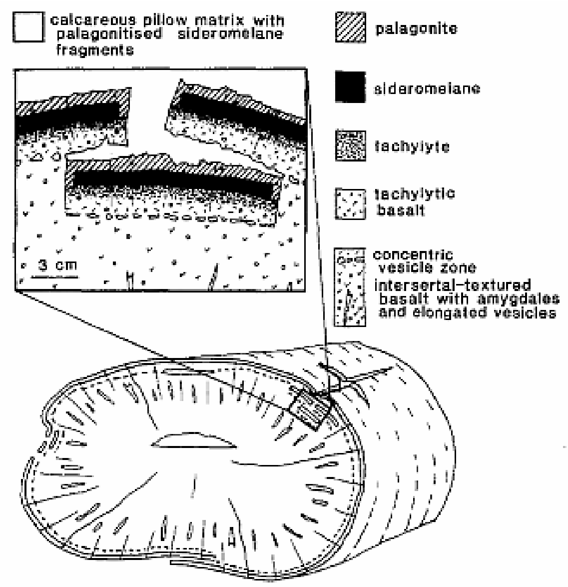


Fig. 3 A–D. Development of multiple-rind structure in a pillow in successive stages from **A** to **D**; **A** After sideromelane skin is formed, exsolved gases from molten lava accumulate at top part of pillow; **B** As water vapor condenses, implosion causes inward-buckling and thrusting of rind at top, sides, and bottom of pillow. Buckled rind forms depressions on surface of pillow. These depressions form both parallel and normal to elongation of pillow (cf. Fig. 2E). Interior of pillow is still molten. Implosion and resulting inward-buckling and thrusting are repeated until gas exsolution and condensation diminish, and the skin becomes too thick to buckle. Inward-buckled rind breaks at weak places such as radial joints. Some gaps completely close, but some are filled with interstitial calcareous material (Fig. 1); **C** Interior of pillow solidified except for core. Small gas chamber remains. Concentric zone of small vesicles forms around pillow in tachylytic basalt. Radially arranged pencil-size elongated ("pipe") vesicles form inside concentric vesicle zone. Radial joints extend further inward as solidification progresses; **D** Pillow completely solidified. Successive stages of solidification may be shown by a series of flat-bottomed gas chambers and different radial joint systems



Downsection from these pillows is the surge-bedded lithofacies indicated in the column by Coombs et al. (1989). Base surges are low-concentration gas-particle flows identified at historic phreatomagmatic eruptions such as that of Taal (Moore et al., 1966). One of their definining and most notable features is their ability to move across water, so the presence of surge deposits in a presumed subaqueous deposit is highly anomalous. Because base-surges and other "surges" are defined as low-concentration flows, and the interstitial fluid is gas, they will *never* have a density greater than water; subaqueous deposition seems an impossibility. Another volcano at which subaqueous deposition by base-surges was inferred (Wohletz and Sheridan, 1983) was later restudied, and the surge-like bedforms reinterpreted as combined-flow bedforms resulting from eruption-fed density currents interacting with surface waves (White, 1996). Here, the bedding shows all the characteristics of true "surge" deposits; low sweeping dunes with, critically, form-draping and locally internal strata consisting of fine-ash deposits. These are a characteristic feature of phreatomagmaic surge deposits in subaerial settings. In subaqueous currents, fines are partitioned into the current tails and largely bypass sloping depositional surfaces. Warm currents carrying fines can segregate them even more effectively into buoyant plumes that decouple from the currents (Cantelli et al., 2008).

In examining the surge-bedded deposits here, an important possibility for consideration is that they may have been formed subaerially, but then relocated by partial flank collapse of the volcanic edifice to a subaqueous final resting place. Another possibility is that the unconformity separating them from the overlying bioclastic deposits and then pillow lavas was initiated subaerially, and the surge-bedded facies formed on an emergent part of the volcano.

The last stretch on the walk back will take us across a sedimentary interval that marks the break originally defined between the Waiareka and the Deborah volcanics. Coombs et al. (1989) made a case that these tuffaceous to bioclastic deposits of the Ototara Limestone are unreliable as a regional separation between volcanic units, and introduced the Waiareka-Deborah Volcanics as a unit.

Upsection from the limestone and volcaniclastic sediments showing evidence of wave reworking is a complex suite of pillow lava, pillow breccia (e.g. image below) and hyaloclastite.

The sequence attracted the attention of Doug Lewis (Lewis, 1973) because it is cut by clastic dikes. They are, specifically, bioclastic, and the fossils comprising the dikes are *younger* than the rocks that they cut, with at least one containing an Awamoan (Lower Miocene) assemblage. The dikes also show evidence of polyphase emplacement.

More-recent work by students at Otago under supervision by R. Ewan Fordyce have confirmed the presence of microfossils in the dikes that are younger than the ages of rocks that they cut, not only at Boatmans Harbour but at other sites in eastern Otago.

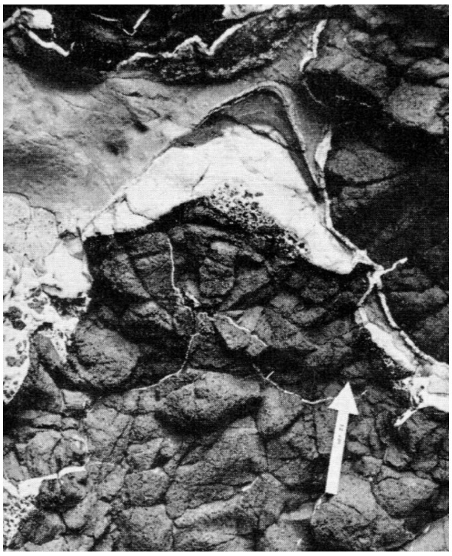
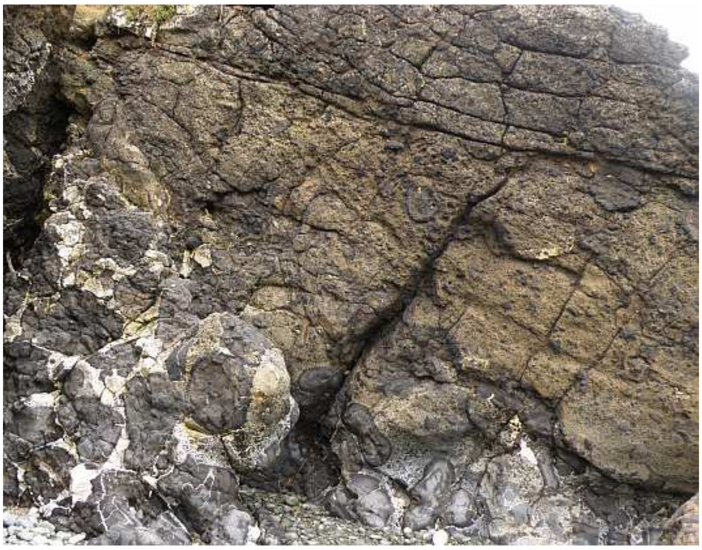


Fig. 10. – Polyphase infillings of the interstices amongst pillow lavas between the Quarry and Boatmans Harbour on Cape Wanbrow (553647). Note particularly the heirarchy of talus cones (close-up view); four generations can be readily recognised, beginning at the base with fragments of volcanics set in sparry (recrystallized) calcite and ending with a thin light grey biosparite (more of which fills the lower third of the large subjacent-left interstice). The upper surfaces of the second and fourth generation limestones appear corroded as if partially dissolved between times of infilling. A fifth (youngest) generation of infilling comprises the grey-green muddy sand that surrounds the apex of the cone and fills the large interstice to its left. Multiphase infillings with subhorizontal layers can be detected in other interstices, both in and out of the view of the photographs. The black muddy generation which can be seen in the talus cone has no analogue in any dike that I observed, and it may reflect weathering products of the lavas which filtered down between episodes of dike infilling. The arrow is 12 cm long.

In addition to clastic dikes, the interstices of a pillow section within this sequence drew Lewis' attention (1973; right).

We will, if possible, spend some time examining this interstitial material to see if the inference of geopetal infilling of long-enduring cavities between pillows is fully supported. There are two questions, the first simply whether the textures are indeed geopetal ones, indicative of cavity-filling deposition. The second, should we be satisfied that the bioclastic material infiltrated interstitial spaces following pillow emplacement, is whether the millions of years of time implied for the infilling is required by the deposit features. What would the alternative? Emplacement of pillows on a soft carbonate substrate, either as lavas that "loaded" into the sediment, or as partly intrusive pillows. In this case, many of the lava-sediment relationships would be broadly *peperitic* (Skilling et al., 2002).



Above and below these pillows are pillow breccias and related hyaloclastic deposits of dense glassy fragments, all probably formed by interaction of effusive basaltic magma or lava with water along or near the shoreline.

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