Constructing a temporal eruption record for the Auckland Volcanic Field via Bayesian age reconciliation

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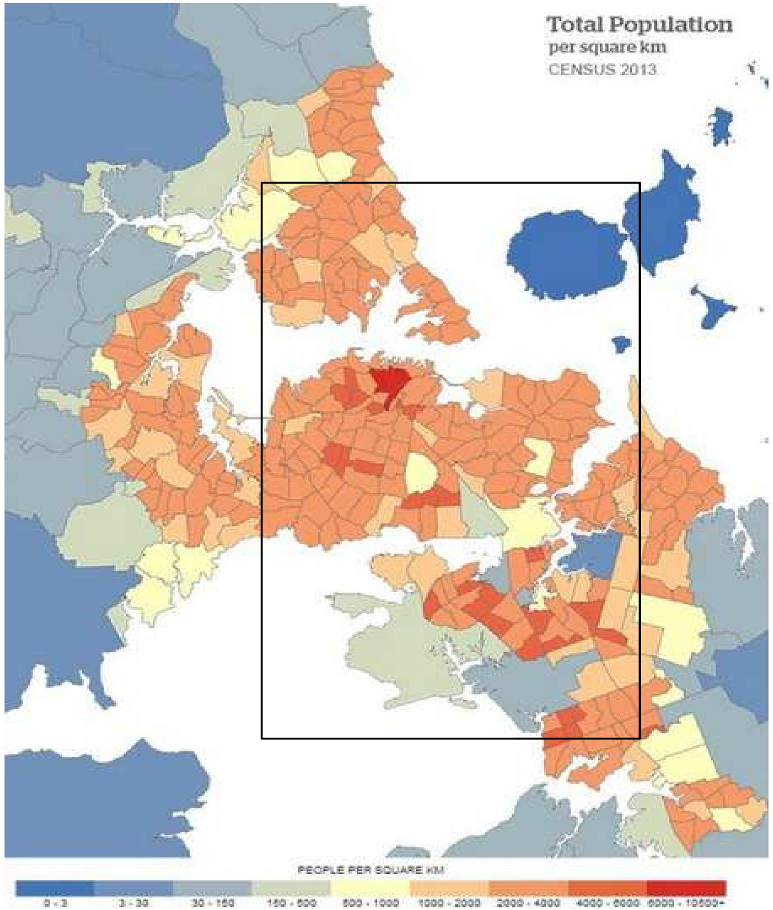
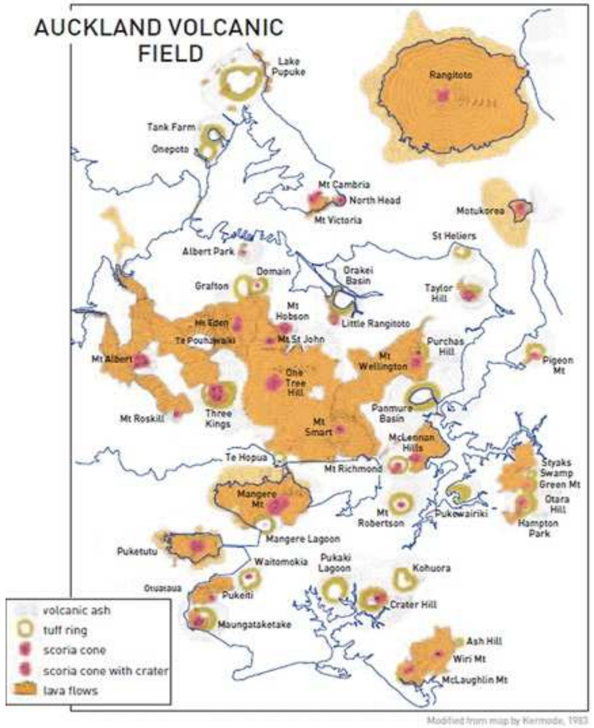
The Auckland Volcanic Field





High population density, lifelines narrowly constrained

- **<u>WHERE</u>** is the next eruption likely to be?

Spatio-temporal hazard estimates

Monogenetic volcanic fields have multiple volcanoes; a new eruption is expected to create a new volcano. Events are infrequent.

For land-use and emergency planning purposes:

where is the next eruption *likely* to be?

In short time frame, answered(?) by monitoring data (seismicity, gas, ...)

What about in a period of repose?

Probability forecast: estimate the *hazard* $\lambda(x)$ such that the probability of an event in the neighbourhood of x , (i.e., $y:||y-x|| < \Delta x$) ~ $\lambda(x) \pi (\Delta x)^2$

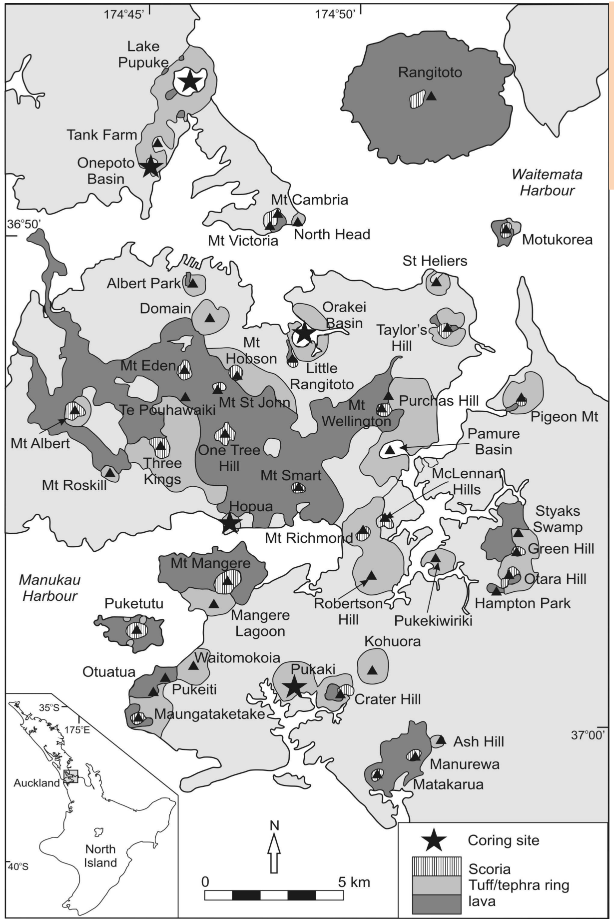
We know the spatial locations of (most) vents

Look for spatial patterns (events are more likely to occur `near' previous events?)

BUT! Want PRESENT DAY hazard

Does the pattern change over time?

The Auckland Volcanic Field



51(?) small basaltic volcanoes

young (~250,000 years)

Most recent eruption ~600 years ago

Data:

- Stratigraphy, ~33 vents constrained in at least one direction
- Age determinations
  - Paleomagnetism ~5+ vents
  - C14, ~13 vents
  - Tephrostratigraphy, 22+ tephra in 5 locations
  - Ar-Ar, ~4 vents
  - Thermoluminesence, 2 vents
  - K-Ar, unreliable due to excess Ar
- Relative geomorphology or weathering

Decreasing reliability

Also: known vent locations, reasonable volume data (Allen and Smith 1994; Kereszturi et al. 2013)

A Monte Carlo sample of age-orderings

By reverse engineering the tephra dispersal, Bebbington and Cronin (2011, 2012) constructed ***feasible*** age-orderings.

Laschamp magnetic excursion

No **apparent spatio-temporal structure**, but plenty of both temporal and spatial structure

Mono Lake magnetic excursion

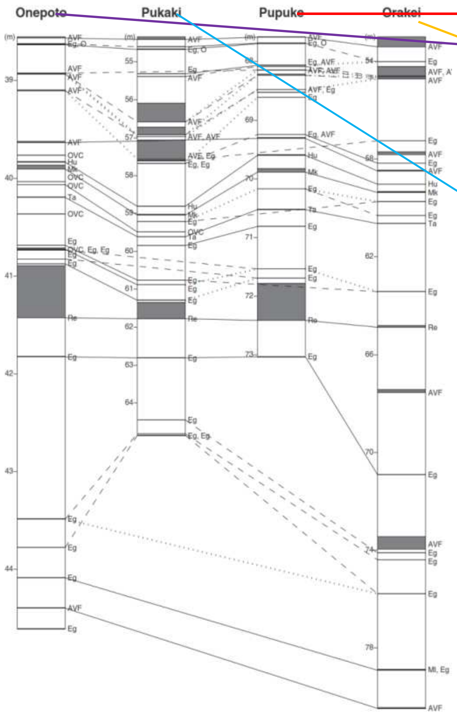
But can we find the **MOST LIKELY** age-ordering?

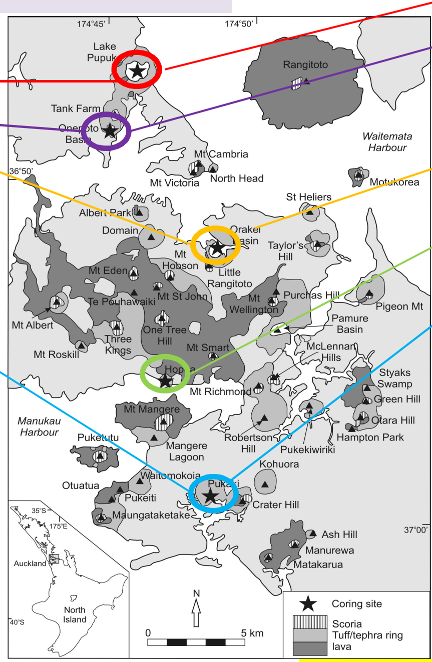
Name	Mean Age (ka)	Age Error (ka)	Min Order	Max Order
Onepoto Basin	248.4	27.8	1	7
Albert Park	229.8	39.5	1	7
……	……	……	……	……
St Heliers	185.0	52.8	2	9
Te Pouhawaiki	152.9	70.3	1	34
……	……	……	……	……
Mt St John	54.8	4.6	10	13
Maungataketake	41.4	0.4	13	15
Otuataua	41.4	0.4	14	16
McLennan Hills	40.1	1.2	13	16
One Tree Hill	34.9	0.7	16	18
……	……	……	……	……
Hopua Basin	32.3	0.4	19	26
Puketutu	31.9	0.3	22	27
Wiri Mountain	31.9	0.3	21	28
Mt Richmond	31.7	0.3	21	28
Taylors Hill	31.7	0.3	21	28
Crater Hill	31.6	0.3	23	28
North Head	31.2	0.1	27	29
……	……	……	……	……

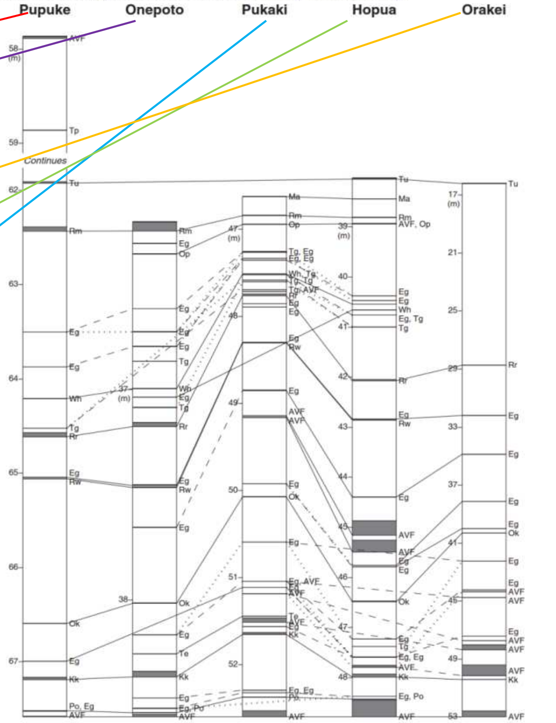
Maar Tephra Thicknesses

Figure 3. Stratigraphy of post-29 cal ka BP tephra layers. Dotted lines show the tephra correlations from Molloy et al. (2009). Dashed lines show the correlations returned by our procedure when the non-linearity constant defined in Eq. (1) equals 0.5 ka. Solid lines show correlations consistent between our arrangement and that of Molloy et al. (2009).

Molloy et al. (2009), Green et al. (2014)





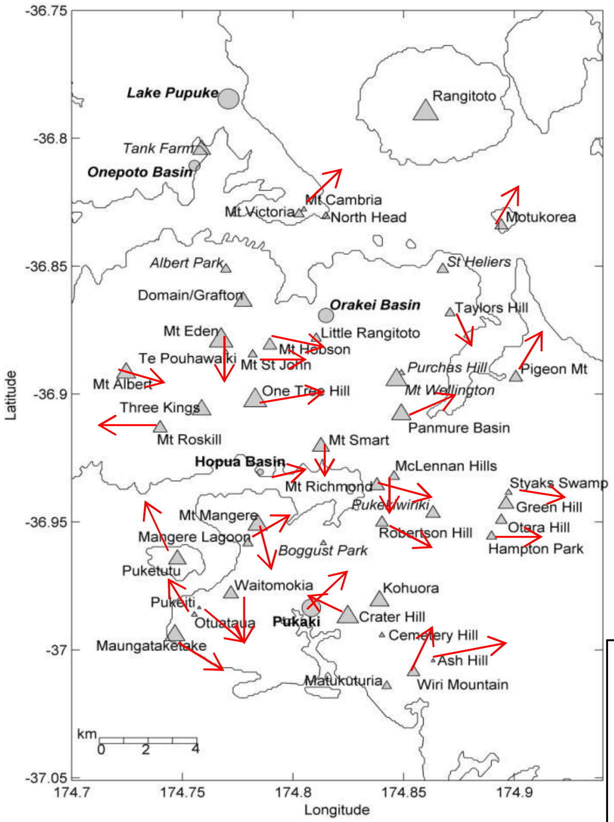


22 or 23 distinct AVF tephras

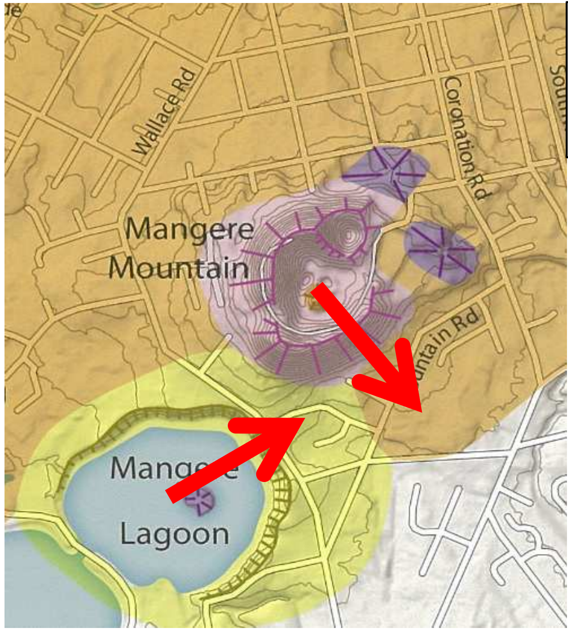
- at from 1 to 5 locations, with age distributions and thicknesses
- interspersed with 10 dated rhyolitic marker tephras

Figure 4. Stratigraphy of pre-29 cal ka BP tephra layers. Dotted lines show the tephra correlations from Molloy et al. (2009). Dashed lines show the correlations returned by our procedure when the non-linearity constant defined in Eq. (1) equals 0.5 ka. Solid lines show correlations consistent between our arrangement and that of Molloy et al. (2009).

Eruptive Tephra Volumes and Directions



Bold = cored maars
Italics = too old
Symbol size ~ volume$^{1/3}$
Arrow = dispersal axis



Dispersal axis in line with highest point on the rim

Volumes: Allen and Smith (1994), Kereszturi et al (2013)

Directions: Hayward et al. (2011)

Prior age distributions

Volcanic Risk Solutions — Massey University

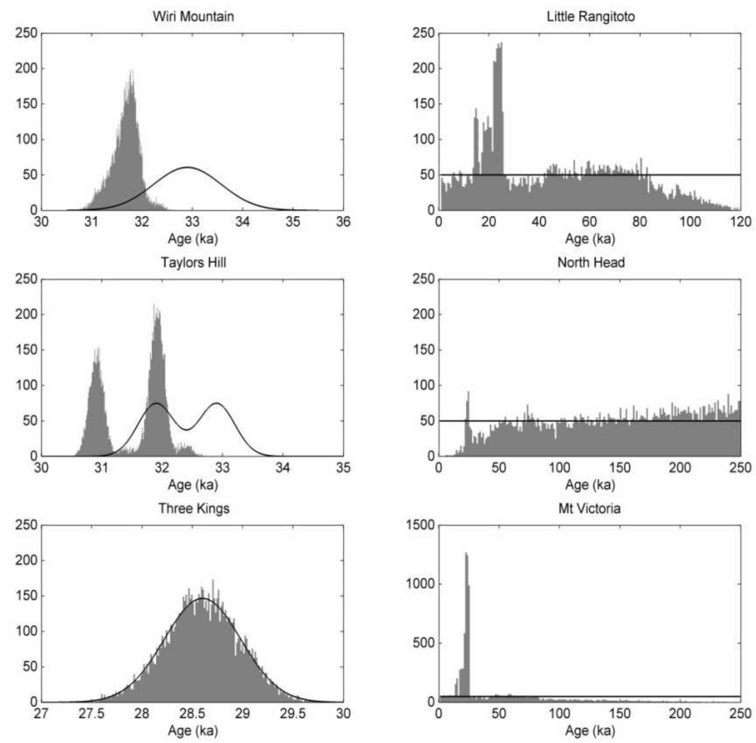
Age determinations

Volcano	Age (ka)	Dating method	References
Ash Hill	31.80 ± 0.16	^{14}C	Hayward (2008a)
Boggust Park	> 130	Sea level	Hayward et al. (2011a)
Crater Hill	33.33 ± 0.67	^{14}C	Searle (1965)
Domain	> 60	^{14}C	Grenfell and Kenny (1995)
Green Hill	199.83 ± 8.98	^{14}C methanol	Sameshima (1990)
Hampton Park	26.60 ± 8.10	$^{40}Ar/^{39}Ar$	Cassata et al. (2008)
Hopua	> 29	Oldest tephra	Molloy et al. (2009)
	< 33	Age of lava at base	Lindsay and Leonard (2009)
Kohuora	34.02 ± 0.27	^{14}C	Searle (1965); Grant-Taylor and Rafter (1971)
McLennan Hills	42.60 ± 3.80	$^{40}Ar/^{39}Ar$	Cassata et al. (2008)
Maungataketake	39.99 ± 0.53	^{14}C	Fergusson et al. (1959); Grant-Taylor and Rafter (1963); Polach et al. (1969); McDougall et al. (1969)
Motukorea	> 7	Sea level	Bryner (1991)
Mt. Albert	> 30	^{14}C	Fergusson et al. (1959); Grant-Taylor and Rafter (1963)
Mt. Eden	28.39 ± 0.35	^{14}C	East and George (2003)
Mt. Mangere	21.94 ± 0.40	^{14}C	Searle (1959, 1965); Grant-Taylor and Rafter (1971)
Onepoto Basin	> 99.5	Oldest tephra	Molloy et al. (2009); Green et al. (2014)
Orakei Basin	> 83.1	Oldest tephra	Molloy et al. (2009)
	< 120	Sea level	Hayward, pers. comm.
Panmure Basin	31.73 ± 0.17	^{14}C	Fergusson et al. (1959); Grant-Taylor and Rafter (1963); Polach et al. (1969); McDougall et al. (1969)
Pukaki	> 67	Oldest tephra	Molloy et al. (2009)
Puketutu	33.60 ± 3.70	$^{40}Ar/^{39}Ar$	Cassata et al. (2008)
Pukewairiki	> 130	Sea level	Lindsay and Leonard (2009)
Pupuke	207 ± 6	$^{40}Ar/^{39}Ar$	Cassata et al. (2008)
Roberston Hill	29.90 ± 0.60	^{14}C	Sandiford et al. (2002)
Three Kings	28.59 ± 0.38	^{14}C	Eade (2009)
Wiri Mountain	32.88 ± 0.67	^{14}C	Searle (1965); Grant-Taylor and Rafter (1971)

Stratigraphy

Stratigraphy	References
Ash Hill $>$ Wiri Mountain	
Green Hill $>$ Styaks Swamp	Sibson (1968)
Kohuora $>$ Crater Hill	
Mangere Lagoon $>$ Mt Mangere	Kermode and Heron (1992)
Mt Albert $>$ Mt Roskill	Searle (1962)
Mt Eden $>$ Mt Hobson	
Mt Mangere $>$ Mt Smart	Kermode and Heron (1992)
Mt Roskill $>$ Three Kings	Allen and Smith (1994)
Mt St John $>$ Three Kings	Eade (2009)
North Head $>$ Mt Victoria	
One Tree Hill $>$ Hopua	Allen and Smith (1994)
One Tree Hill $>$ Mt Eden	
One Tree Hill $>$ Mt Mangere	Hayward (2008b)
One Tree Hill $>$ Mt Smart	Searle (1962); Hayward (2008b)
One Tree Hill $>$ Three Kings	Hayward (2008b)
Orakei Basin $>$ Little Rangitoto	Kermode et al. (1992)
Pukeiti $>$ Otuataua	Searle (1959)
Te Pouhawaiki $>$ Mt Eden	Affleck et al. (2001)
Waitomokia $>$ Pukeiti	Searle (1959)
Wiri Mountain $>$ Matukutureia	
Cemetery Hill $\geq$ Crater Hill	Nemeth, pers. comm.
Otara Hill $\geq$ Hampton Park	Cassidy and Locke (2010)
Maungataketake $\geq$ Otuataua	Cassidy and Locke (2010)
Mt. Cambria $=$ Mt Victoria	

'Known' ages and stratigraphy combined with paleomagnetic (e.g. Mono Lake) constraints to simulate 10,000 feasible age sequences



Tephra attenuation

Expected thickness, with wind

wind speed

dispersal axis

column height term

$$\hat{T}_{ik}(r_{ik}, \xi_{ik}) = \gamma_i \exp\{-(\beta U) r_{ik}[1 - \cos(\xi_{ik} - \phi_i)]\} r_{ik}^{-\alpha}$$

without wind

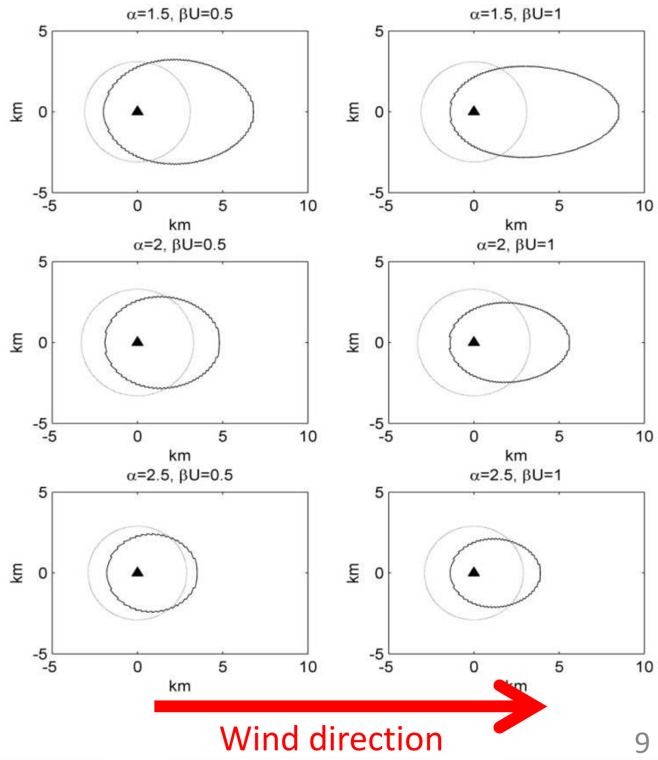
$$\hat{T}_{ik}(r_{ik}, \xi_{ik}) = \gamma_i r_{ik}^{-\alpha}.$$

distance

azimuth

Gonzalez-Mellado & De la Cruz Reyna (2010) ; Kawabata et al. (2013)

Actual thickness has lognormal distribution with given mean and coefficient of variation 0.5



Likelihood Equations

Includes terms for observed thickness, not observed (but should have been!) thicknesses, difference in ages, and the presence of rhyolitic marker tephras …

$$u_{ijk}(T_{jk}) = \begin{cases} \frac{1}{T_{jk}\sqrt{2\pi\sigma^2{}_N}} \exp\left[-\frac{(\log T_{jk} - \mu_{N_{ik}})^2}{2\sigma_N^2}\right], & T_{jk} > 0 \\ \frac{1}{\sqrt{2\pi\sigma_N^2}} \int_0^{0.05} \frac{1}{t} \exp\left\{-\frac{[\log(t) - \mu_{N_{ik}}]^2}{2\sigma_N^2}\right\} \mathrm{d}t, & T_{jk} = 0 \\ 1, & T_{jk} = \mathrm{NA}, \end{cases}$$

$$v_{ik}^n(T_{jk}) = \begin{cases} \frac{1}{\sqrt{2\pi\sigma_N^2}} \int_0^{0.05} t^{-1} \exp\left\{-\frac{[\log(t) - \mu_{N_{ik}}]^2}{2\sigma_N^2}\right\} \mathrm{d}t, & s_i^n \in C_k \\ 1, & \text{otherwise}, \end{cases}$$

$$f_j^n(s_i^n) = \frac{1}{\sqrt{2\pi\sigma_j^2}} \exp\left[-\frac{(s_i^n - \mu_j)^2}{2\sigma_j^2}\right]$$

$$g_{j,j^*}^n(s_i^n) = \begin{cases} Pr(j^* < s_i^n) = \frac{1}{\sqrt{2\pi\sigma_{j^*}^2}} \int_{-\infty}^{s_i^n} \exp\left[-\frac{(t-\mu_{j^*})^2}{2\sigma_{j^*}^2}\right] \mathrm{d}t, & \text{AVF} j \text{ older than } j^* \\ Pr(j^* > s_i^n) = 1 - \frac{1}{\sqrt{2\pi\sigma_{j^*}^2}} \int_{-\infty}^{s_i^n} \exp\left[-\frac{(t-\mu_{j^*})^2}{2\sigma_{j^*}^2}\right] \mathrm{d}t, & \text{otherwise}, \end{cases}$$

$$\log L_{ij}^n = \begin{cases} \sum_{k=1}^5 \log u_{ijk}(T_{jk}) + \log f_j^n(s_i^n) + \sum_{j^*=1}^{10} \log g_{j,j^*}^n(s_i^n) & j = \{1, \ldots, 20\} \\ \sum_{k=1}^5 \log v_{ik}^n(T_{jk}) & j = 0, \end{cases}$$

Solved by linear programming:

$$\log L^n = \sum_{i=1}^{41} \sum_{j=1}^{20} x_{ij}^n \left[\sum_{k=1}^{5} \log u_{ijk}(T_{jk}) + \log f_j^n(s_i^n) + \sum_{j^*=1}^{10} \log g_{j,j^*}^n(s_i^n)\right] + \sum_{i=1}^{41} \sum_{k=1}^{5} x_{i0}^n \log v_{ik}^n(T_{jk}).$$

with constraints for stratigraphy, etc.

$$\sum_{i=1}^{41} (ix_{i,j+1}^n - ix_{ij}^n) > 0, \forall j = 1, \ldots, 19.$$

Results, βU=0.5, α=2

Table 6: Marginal posterior probabilities for a volcano to have produced a given tephra for the baseline scenario with $\alpha = 2.0, \beta U = 0.5$. The global best arrangement is indicated by bold type.

Volcano	Tephra (AVF0 = 'unmatched')																				
	AVF0	AVF1	AVF2	AVF3	AVF4	AVF5	AVF6	AVF7	AVF8	AVF9	AVF10	AVF11	AVF12	AVF13	AVF14	AVF15	AVF16	AVF17	AVF18	AVF19	AVF20
Ash Hill	.8011					.0004	.1612	.0373													
Cemetery Hill	[illegible]				.0002	.0170	.1326	.1716	**.5343**	.1106	.0008										
Crater Hill	0					.0001	.0150	.0068	.2779	**.5690**	.1301	.0011									
Domain	.7589	**.1326**	.0870	.0215																	
Green Hill	.0102	.0007	.0031	.0162	.0255	.0160	.0059	.0003	.0004	.0037	.0376	.0164	.0555	**.1900**	.1223	.1029	.0775	.0874	.1098	.0878	.0308
Hampton Park	.3939					.0001								.0648	.1480	**.1912**	.1051	.0693	.0167	.0070	.0039
Hopua Basin	.8042			.0003		.0639	.0499	.0359	.0003	.0021	.0413	.0021									
Kohuora	.0001	.0001	.0018	.0171	**.8610**	.0656	.0514	.0010	.0010												
Little Rangitoto	.0440	.1987	**.1923**	.1444	.0215	.0117	.0013	.0009	.0008	.0025	.0133	.0056	.0182	.0497	.0383	.0288	.0208	.0317	.0488	.0530	.0737
Mangere Lagoon	.7382	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			
Matukutureia	.0209									.0008	.0076	.0032	.0067	.1381	.1007	.0861	.0683	.0642	.0950	.2123	.1961
Maungataketake	.9943	.0012		.0034		.0002	.0009														
McLennan Hills	.9259		.0162	.0435		.0128	.0009	.0007													
Motukorea	.9494	.0023	.0007	.0002		.0019					.0006			.0065	.0008	.0029	.0021	.0276	.0010	.0016	.0024
Mt Albert	.8857	.0585	.0360	.0184	.0007	.0005	.0001				.0001										
Mt Cambria	.7322	.0105	.0238	.0175	.0035	.0083					.0050			.0329	.0103	.0492	.0156	**.0888**	.0012	.0011	.0001
Mt Eden	.0442									.0006	.0363	.3759	**.5430**								
Mt Hobson	.1233										.0002	.0038	.0184	.1215	.0880	.0743	.0609	.0841	**.1128**	.1302	.1825
Mt Mangere	.0095													.0048	.0431	.1439	**.3543**	.3037	.1366	.0041	
Mt Richmond	.7783					.0013	.0717	.1487													
Mt Roskill	.9408	.0185	.0261	.0022	.0001	.0067	.0001	.0004			.0051										
Mt Smart	.0099														.0004	.0050	.0266	.0786	.2761	**.3807**	.2227
Mt St John	.7185	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]									
Mt Victoria	.1755	.0696	.0735	.0718	.0136	.0070	.0030	.0001	.0001	.0018	.0043	.0050	.0076	.1063	.1252	.0652	.0846	.0173	.0773	.0382	.0530
North Head	.7306	.1006	.0624	.0508	.0077	.0036	.0004	.0001	.0001	.0003	.0050	.0015	.0050	.0112	.0062	.0041	.0028	.0026	.0019	.0015	.0016
One Tree Hill	.6754	.0843	.1248	.0981	.0023	.0109	.0009	.0002	.0001	.0003	.0018	.0009									
Otara Hill	.0057	.0004	.0006	.0075	.0052	.0030	.0020			.0008	.0073	.0040	.0112	.2147	**.2664**	.1806	.1282	.0605	.0686	.0251	.0082
Otuataua	.6472	.0065	.0601	**.2341**	.0477	.0040	.0002	.0002													
Panmure Basin	.1300		.0001	.0004	.0004	**.7081**	.0807	.0568		.0004	.0231										
Pigeon Mountain	.7722	.0307	.0443	.0358	.0005	.0047					.0062			.0225	.0122	.0161	.0074	.0281	.0039	.0036	.0118
Pukaki	[illegible]	.0886																			
Pukeiti	1																				
Puketutu	[illegible]				.0006	.0033	.0383	.0496	.1623	.2245	**.4942**	.0002									
Robertson Hill	.9995						.0005														
Styaks Swamp	.5310													.0116	.0165	.0339	.0362	.0535	.0503	.0538	**.2132**
Taylors Hill	.5495			.0001		.0198	**.2255**	.2043			.0008										
Te Pouhawaiki	.7341	.0941	.0740	.0702	.0079	.0063	.0011	.0003	.0003	.0004	.0087	.0026									
Three Kings	0									.0032	.0954	**.5717**	.3297								
Waitomokia	1																				
Wiri Mountain	[illegible]					.0023	.1535	**.2843**	.0224	.0783	.0647										

- Three Kings (large volume, central, good age) one of AVF 9-12
- Crater Hill (large, good age, azimuth towards maar) also always matched
- Green Hill, Little Rangitoto, Mt Victoria, North Head can match any tephra
- Pukeiti, Waitomokia don't match any tephra

Find *most likely* ***global*** arrangement with another linear program …

Best overall arrangments

Table 7: Best global arrangement of assigning Volcano i to AVF tephra j. Scenarios are outlined in the sensitivity analysis section. The six parameter sets are (A = $\{\alpha = 1.5, \beta U = 0.5\}$; B = $\{\alpha = 2, \beta U = 0.5\}$; C = $\{\alpha = 2.5, \beta U = 0.5\}$; D = $\{\alpha = 1.5, \beta U = 1\}$; E = $\{\alpha = 2, \beta U = 1\}$; F = $\{\alpha = 2.5, \beta U = 1\}$). Bold type indicates scenario-determined identifications.

Tephra	Volcano	Scenario				
		Baseline	Maungataketake and North Head older	Three Kings is AVF9	Three Kings is AVF10	AVF9 split in two
AVF1	Little Rangitoto	ADEF		ACDEF	All	ACDEF
	Otuataua		DEF			
	Domain	BC	ABC	B		B
AVF2	One Tree Hill	ADEF	All	ACDEF	All	ACDEF
	Little Rangitoto	BC		B		B
AVF3	Otuataua	All		All	All	All
	Little Rangitoto		All			
AVF4	Kohuora	All	All	All	All	All
AVF5	Panmure Basin	All	All	All	All	All
AVF6	Ash Hill	DEF	DEF			EF
	Taylors Hill	ABC	ABC		DEF	ABCD
	Wiri Mountain			AB	ABC	
	Crater Hill			CDE		
	Cemetery Hill			F		
AVF7	Wiri Mountain	All	All	CDEF	EF	BCDEF
	Cemetery Hill			AB	ABCD	A
AVF8	Cemetery Hill	All	All			BCDEF
	Crater Hill			AB	All	A
	Puketutu			CDEF		
AVF9	Crater Hill	All	All			
	Three Kings			**All**		
	Puketutu				All	
AVF9A	Wiri Mountain					A
	Crater Hill					BCDEF
AVF9B	Puketutu					All
AVF10	Puketutu	All	All			
	Robertson Hill			ABC		
	Hopua			DEF		All
	Three Kings				**All**	
AVF11	Three Kings	ABC	ABC			ABC
	Mt Eden	DEF	DEF	DEF		DEF
	Hopua			ABC	All	
AVF12	Mt Eden	ABC	ABC	ABC	All	ABC
	Three Kings	DEF	DEF			DEF
	Green Hill			DEF		
AVF13	Green Hill	All	All	ABC	All	All
	Mt Hobson			DEF		
AVF14	Otara Hill	All	All	All	All	All
AVF15	Hampton Park	All	All	All	All	All
AVF16	Mt Mangere	All	CDEF	All	All	All
	Matukutureia		AB			
AVF17	Mt Cambria	All		BCDEF	All	All
	Mt Mangere		AB			
	Mt Hobson		CDEF	A		
AVF18	Mt Hobson	AB	AB		A	AB
	Mt Smart	CDEF	CDEF	All	BCDEF	CDEF
AVF19	Mt Smart	AB	AB		A	AB
	Matukutureia	CDEF	CDEF	All	BCDEF	CDEF
AVF20	Styaks Swamp	All	All	All	All	All

Mono Lake Excursion (rows AVF6 Ash Hill to AVF10 Puketutu)

Scenarios

- Maungataketake ~ 87.4 ± 2.4 ka, North Head > 80 ka
- Three Kings is AVF 9 or AVF 10
- AVF 9 (thick in N and S, thin in middle) is actually 2 distinct tephras

6 Conditions

Wind: DEF > ABC

Column height: AD > BE > DF

Results do not change if CV is doubled to better represent certain massively thick tephras.

Conclusions

Table 8: Comparison of event order models

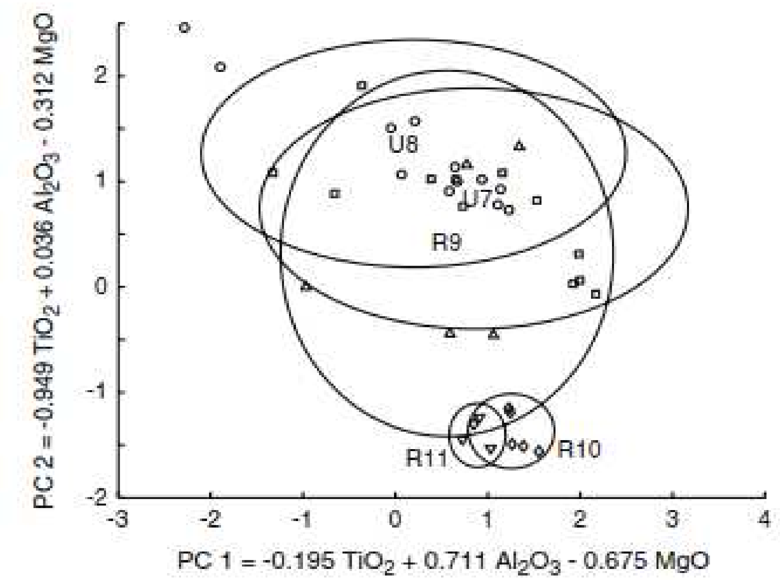
Tephra	Baseline model, this work	Bebbington and Cronin (2012)
AVF1	Little Rangitoto/Domain	Pukaki
AVF2	One Tree Hill/Little Rangitoto	Domain
AVF3	Otuataua	Mt St John
AVF4	Kohuora	One Tree Hill
AVF5	Panmure Basin	Motukorea
AVF6	Taylors Hill / Ash Hill	Kohuora
AVF7	Wiri Mountain	Crater Hill
AVF8	Cemetery Hill	Puketutu
AVF9	Crater Hill	Hopua Basin
AVF10	Puketutu	North Head
AVF11	Three Kings / Mt Eden	Panmure Basin
AVF12	Three Kings / Mt Eden	Three Kings
AVF13	Green Hill	Mt Eden
AVF14	Otara Hill	Mt Hobson
AVF15	Hampton Park	Little Rangitoto
AVF16	Mt Mangere	Pigeon Mountain
AVF17	Mt Cambria	Mangere Lagoon
AVF18	Mt Hobson / Mt Smart	Mt Mangere
AVF19	Mt Smart / Matakutureia	Mt Smart
AVF20	Styaks Swamp	Styaks Swamp

- Taylors Hill was most likely the first of the Mono Lake volcanoes to erupt.
- Almost all of the large volume volcanoes are allocated.
  - Maungataketake and Mt Roskill have unfavourable directions.
  - Mt Albert has large volume and good dispersal axis, but only age data is > 35 ka

Future Work

Incorporate geochemistry of sources and deposits

- Additional likelihood penalty if the source and deposit geochemistry differs



Describe multi-element geochemistry by multivariate Gaussian distribution (e.g., in 2-D an ellipse)

- Can use principle components to reduce dimensionality
- Need data to quantify whatever systematic bias and heteroscedasticity exists between lava/scoria/tuff and tephra geochemistry.

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