Paleomagnetic record of basaltic volcanism from Pukaki and Onepoto maar lake cores, Auckland Volcanic Field, New Zealand

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Abstract

The Auckland Volcanic Field contains several maars that formed after the last interglacial and subsequently filled with sediment. Two of these maars, Pukaki and Onepoto, were recently cored as part of the Auckland Maar Lakes Project. The tephra stratigraphy of the cores indicates that sediment accumulated relatively slowly in both maars until the Holocene when ocean waters breached the craters and they filled up quite rapidly. Using u-channels, we collected 23 m of pre-Holocene lacustrine sediment from the Pukaki 1-01 core and 15 m from the Onepoto core. Paleomagnetic measurements were performed on these at the University of California, Davis. Environmental magnetic records from both cores provide insights in particular about the eruptive history of the Auckland Volcanic Field. The lack of a tephrostratigraphic control in the lower portion of the cores, and the lack of similar trends in the magnetic parameters, prevented a complete core correlation. The main finding is that local basaltic tephra layers visible in the cores show up as spikes in the concentration dependent magnetic parameters, suggesting that other spikes represent tephra layers that are not as easily discerned.

Keywords Environmental magnetism; Pukaki; Onepoto; Auckland Volcanic Field; maars; ash deposits

INTRODUCTION

Environmental magnetism has been widely used for studying environmental processes in lacustrine sequences. Many techniques have been developed to determine the nature of the magnetic material in sediments (Thompson & Oldfield 1986; Oldfield 1991; Verosub & Roberts 1995), and these provide powerful and rapid tools for detecting changes in the concentration, mineralogy, and grain size distribution of the magnetic grains (Thompson et al. 1980). One parameter, magnetic susceptibility, has been shown to be particularly useful for detecting the presence of tephra layers in lacustrine sequences. In fact, tephra layers are often rich in ferromagnetic material, which shows up as peaks in magnetic susceptibility (e.g., Oldfield et al. 1978, 1983; Oldfield 1988; Lozano-Garcia et al. 1993). In New Zealand, environmental magnetism has already been used successfully to study the processes that control sedimentation in Lakes Tutira and Waikopiro near Hawke Bay, and cores from Lake Tutira have also been correlated using the magnetic susceptibility peaks as indicators of storm pulses (Turner 1997).

In this project, we studied cores of lacustrine sequences from two maars in the Auckland Volcanic Field (AVF), Pukaki and Onepoto (Fig. 1). The cores were collected in February 2001 and November 2000, respectively, as part of a project in collaboration with several organisations, including the University of Auckland, Victoria University of Wellington, the University of California, Davis, and the New Zealand Institute of Geological and Nuclear Sciences. The lacustrine sequence from Pukaki maar was 25 m long and spanned the interval from c. 7.5-9.5 ka to c. 80-100 ka; the core from Onepoto maar was 16.7 m long and spanned the interval from c. 8.5 ka to older than 45-69 ka (Shane & Hovered 2002). We used environmental magnetic methods to look for evidence of basaltic volcanism, which is not easily detected by other chemical or physical techniques. Our results provide new information about the eruptive history of the AVF during the late Glacial period in New Zealand.

BACKGROUND

The Last Glacial Maximum (c. 25-15 ka, McGlone 1988; McGlone et al. 1993) was not particularly severe in the North Island of New Zealand. During that time, small valley glaciers and small ice caps existed on volcanoes and mountain ranges in the southern and central part, respectively, of the island (McArthur & Shepherd 1990; Newnham et al. 1999). Nevertheless, severe fluvial and wind erosion occured over much of the region (Pillans et al. 1993). A recent palynological study from the Auckland Isthmus identified the period c. 23-16.5 ka as a “second phase” of the Last Glacial Maximum, resulting in contraction of the forest, expansion of shrubs and grassland, and dominance of more open landscape. During this second phase the climate became cool and dry and run-off decreased (Sandiford et al. 2002). Evidence from the northern part of the island suggests that precipitation rather than temperature was the primary cause of vegetation change (Newnham 1999). The onset of warmer conditions, as evidenced by the spread of podocarp forest, occurred c. 14.5 ka ago (Newnham et al. 1989). A pollen record from Pukaki maar shows that the change to warmer conditions occurred as early as c. 18 ka ago (Sandiford et al. 2003).

For the North Island, only the record of silicic and andesitic volcanism for the last 64 ka is well established (Shane 2000). That record is obtained primarily from tephra beds consisting of nonconsolidated pyroclastic ejecta derived from the acidic magma sources in the central North Island, more than 100 km from the AVF. The main sources are the Taupo Volcanic Centre (TVC), Okataina Volcanic Centre (OVC), Taranaki volcano (Tk), and Tongariro Volcanic Centre (TgVC) (Sandiford et al. 2001; Shane & Hoverd 2002). A summary of the stratigraphy and chronology of silicic tephra in New Zealand was published by Froggatt & Lowe (1990), and recently additional tephrostratigraphic information was obtained from geochemical analyses of cores from maar craters in the AVF (Sandiford et al. 2001; Shane & Hoverd 2002; Shane 2005; Molloy et al. 2009). However, little information is available about the history of the basaltic eruptions in the AVF, and there little evidence of a spatial or temporal trend of this activity, making it difficult to predict future eruptions (Shane & Smith 2000; Edbrooke et al. 2003).

The AVF contains about 50 volcanic centres formed by phreatomagmatic basaltic eruptions that occurred simultaneously and occasionally, as at Onepoto, were followed by, lava extrusion. These eruptions resulted in the formation of a circular crater with a low rim, called a maar, surrounded by ash, lapilli, and tuff ring deposits. The erupted material is olivine basalt, typically covering c. 100 km^2. Most of the events were associated with the two largest volcanoes, Rangitoto and One Tree Hill. They have produced almost 60% of the total volume of lava. The age of the onset of the activity in the AVF is still uncertain, but thermoluminescence dating implies it could be more than 141 ka (Kermode 1992 and references therein). Recent thermoluminescence dating of volcanic ejecta underlying the lacustrine sediments in Pukaki maar shows that it was active c. 124.6 ka ago (Rieser 2001).

Pukaki and Onepoto maars are located in the southern and northern part of the AVF, respectively (Fig. 1). They were occupied by lakes in late Pleistocene to early Holocene and so their basal deposits are lacustrine in nature. However, as sea level rose in the mid Holocene, both maars were breached and then filled rapidly with marine sediments. Many tephra layers, mainly silicic in composition, have been identified by means of visual and microscope observations in the sedimentary sequences in the maars. A tephrostratigraphic description of the upper part of the lacustrine sequence from Pukaki maar, obtained from a previous core and spanning the interval from 6.6 to 28 ka has been published (Sandiford et al. 2001). Preliminary results from multidisciplinary studies on the Pukaki core that we studied (Drillhole 1-01) were reported by Dickinson (2001). Also Hagg & Augustinus (2003) compiled a tephrostratigraphic report on 80 tephra layers from the Onepoto lacustrine sequence that spans the interval from c. 9.5 to > 50 ka. Estimates of the average sedimentation rate for the Onepoto sequence have been provided by Shane & Hoverd (2002) and Shane & Sandiford (2003). These data made it possible to correlate part of the Onepoto core to the upper part of the older core from Pukaki maar

(Shane & Hoverd 2002) and then to correlate these to the recently studied cores from Pupuke, Orakei, and Hopua maars (Molloy et al. 2009).

METHODS

Samples were collected from the relevant piston-cored segments of both lacustrine sequences using u-channels, which are plastic containers with a square (2 x 2 cm) cross-section. The u-channels were measured at the UC Davis Paleomagnetism Laboratory. The natural remanent magnetisation (NRM), anhysteretic remanent magnetisation (ARM), and low field magnetic susceptibility (κ) were measured every 1-cm using a 2G Enterprises Model 755R cryogenic magnetometer system. The magnetic susceptibility was also measured at the same spatial resolution using a Bartington field surface probe.

ARM was imposed by applying an alternating magnetic field with an amplitude of 100 mT with a superimposed bias field of 50 μT. The NRM and ARM were AF demagnetised up to 60 mT in 9 and 7 steps respectively. Magnetisation measurements were made after each demagnetisation step.

Various magnetic parameters were used to assess the concentration, grain size, and mineralogy of the magnetic grains in the Pukaki and Onepoto cores. NRM and ARM intensity, and magnetic susceptibility, are all measures of the concentration of magnetic material. The magnetic susceptibility also responds to the presence of paramagnetic and superparamagnetic minerals providing additional information about the nature of the magnetic fraction. Because ARM is more sensitive to the presence of finer grained (single-domain (SD)) magnetite while magnetic susceptibility is more sensitive to the presence of coarser grained (multi-domain (MD)) magnetite and superparamagnetic (SPM) magnetite (less than 20 nm in grain size) as well, the ratio ARM/κ provides information about relative magnetic grain size. The ARM_{30mT}/ ARM ratio (where ARM_{30mT} is the ARM intensity remaining after demagnetisation at 30 mT), which reflects the resistance to demagnetisation, is a measure of the coercive force of the magnetic carriers.

In both of the studied cores, there were inconsistencies between actual and driller's lengths of the runs. This required the use of a corrected depth scale. For Pukaki maar, the sediment expanded significantly after drilling, causing apparent overlap between sequential runs which are each about 1.5 m in length. For this reason the original depth scale used by Pepper (2001) was corrected by applying a uniform compression to each run in order to restore the driller's length (Turner et al. 2001).

For Onepoto maar, the uncertainties concerned not only the length but also the vertical position of the runs reported by the drillers. The sequence also contained numerous gaps due to loss of material between sequential core runs. Therefore, we used the corrected depth scale developed by Hagg (2003) in which these factors were taken in account. For this scale, all depths are referred to the marine-fresh water boundary which corresponds to a depth of ϕ m.

RESULTS

In both cores, the NRM intensities are strong and generally show uni-vectorial decay to the origin during AF demagnetisation. Based on an average coercivity (ARM_{30mT}/ ARM) of 0.4, we consider the NRM direction at 30 mT as representing the characteristic remanent magnetisation (ChRM). This suggests that magnetite is the main magnetic carrier and that magnetically hard minerals, such as hematite, are not present to any significant extent. However, at this demagnetisation level (and almost all others) many of the declinations are to the south in the co-ordinate system of the u-channels. Such a result is anomalous and suggests that the sediment in many segments has been remagnetised, possibly by a drilling-induced remanence or more probably by some aspects of the core-splitting procedure. The inclinations are variable, which might indicate partial remagnetisation; however, shallow positive values can be distinguished clearly in both of the cores.

We computed the Koenigsberger ratio Q, defined as the ratio of the remanent magnetisation to the induced magnetization, using the International Geomagnetic Reference Field (IGRF) value (54,000 nT = 42.99 A/m) in the area of Auckland. The background Q-value is < 1 at both the sites; on the whole, the Q-value is higher in the Pukaki core (ranging from 0.03 to 90) than in Onepoto core (ranging from 0.01 to 5). The values greater than 1 correspond to high NRM intensity peaks in both cores and to the upper part of Pukaki core, and the bottom of Onepoto core. In these intervals the more stable SD/pseudo-single domain (PSD) grains of magnetite are dominant over the less stable SPM and MD grains.

Pukaki

In Fig. 2A we show the magnetic parameters of the lacustrine sequence from the Pukaki core. The pattern of the ChRM and ARM intensities is very similar. High values characterise the interval between 50.7 and 58.5 m, then the intensities become low down-core until 73 m where the ChRM intensity quickly rises. Magnetic susceptibility is high in two intervals: between 53 and 59 m and between 63 and 69 m. In particular, below 64.6 m, some spikes are >200 x 10^{-5} SI, such as the intervals between 64.74 and 64.89 m where κ reaches c. 700 x 10^{-5} SI, and between 67.53 and 68.97 m (see also table 1 in Turner et al. 2001).

In contrast, the ChRM and ARM intensities both show peaks in the upper part of the core, for example, at 54.59, 55.80, and 57.86 m. Both κ and NRM increase below 73 m where there is a transition to volcanic debris.

In the interval between 50.7 and 54.25 m, the grain size parameter, ARM/κ, shows peaks which mirror those seen in the ChRM intensity. Otherwise this parameter decreases until c. 57 m where it is then mostly constant until the bottom of the record. The ARM_{30mT}/ ARM shows a gradual decrease down-core from a maximum at c. 52 m to a minimum at c. 66 m.

In general, these parameters indicate a high concentration of magnetic remanence carriers in the upper part of the core. The high values of ARM/κ ratio suggests that the higher concentrations are associated with finer grains. This conclusion is consistent with the decrease in coercive force downcore which indicates that in the lower portion, MD grains are more common than the SD grains that predominate in the upper portion.

The simplest conclusion that can be drawn from these observations is that increases in the relative concentration of magnetic material correspond to periods of major volcanic activity. On the other hand, a comparison of the magnetic records from Pukaki maar with a preliminary tephrostratigraphy of distal silicic and andesitic tephra (Alloway 2001; Shane 2005) does not show any clear correlation. In addition, four prominent silicic tephra present in the core, the Rotoma Tephra at 49.10 m (8.5 ka based on ^{14}C; Froggatt & Lowe 1990), the Rotorua Tephra at 49.82 m (13.1 ka based on ^{14}C; Froggatt & Lowe 1990), the Kawakawa Tephra at 54.87 m (22.6 ka based on ^{14}C; Froggatt & Lowe 1990), and the Rotoehu Tephra between 62.9 and 64.35 m (64 ka based on K-Ar; Wilson et al. 1992), do not have a distinct magnetic signature.

We suggest that local basaltic tephra, rather than distal silicic and andesitic tephra, is the the primary determinant of the high values of magnetic susceptibility, ChRM, and ARM intensity. This inference is supported by the correspondence with basaltic tephra already identified in the core from Pukaki maar. This correspondence was first discussed by Turner et al. (2001), and in Table 1 we show 25 additional features that probably represent basaltic tephra. In many cases the magnetic features do not correspond to visible tephra layers, which makes them useful for detecting basaltic eruptions.

Onepoto

Figure 2B illustrates the magnetic parameters of the lacustrine sequence from Onepoto maar. The magnetic susceptibility, ChRM and ARM intensity, and the ARM/κ show low and rather constant values down to c. 15 m. Toward the bottom of the core the parameters increase, indicating a higher concentration of the magnetic minerals that correlates with basaltic detritus identified by Shane & Hoverd (2002). Such a correlation requires that section 29 be shifted down-core by c. 1 m which is consistent with the conclusion drawn by Hagg (2003) concerning the loss of material at the top of that section.

The ARM_{30mT}/ ARM shows there are no substantial variations in coercive force. As was found in the Pukaki core, the magnetic susceptibility, ChRM intensity, and ARM intensity records are characterised by spikes that are believed to indicate basaltic volcanic tephra. The frequency of the spikes increases below 11 m, which probably indicates a period of major volcanic activity (Fig. 3). We have identified a total of 36 magnetic features which are shown in Table 2. The use of the corrected depth scale allowed us to compare our results to the available tephrostratigraphy (Shane & Hoverd 2002; Hagg & Augustinus 2003). Only a few of the numerous silicic and andesitic tephra, such as Rotoma and Kawakawa Tephra, stand out in the magnetic data, again indicating that we are looking at a record of local basaltic volcanism.

DISCUSSION AND CONCLUSIONS

In both sequences, the behavior of the ChRM and the ARM is consistent with magnetite as the primary magnetic carrier.

Based on the magnetic susceptibility, and the ChRM and ARM intensities, we identified several short intervals of increased concentration of magnetic minerals that we associate with increased basaltic volcanism in the AVF. In the Pukaki core, we also identified two periods of higher volcanic activity that correspond also to periods of low biogenic productivity (Dunbar et al. 2001).

In the Pukaki core, the general up-core decrease in magnetic grain size and increase in coercive force could be associated with migration of eruptive centres in the AVF away from Pukaki maar. On the other hand, a high concentration of fine magnetic grains occurs between Kawakawa and Rotorua Tephra (between c. 22.6 and 13.1 ka). Because of the lack of data from a 1 m interval right below the Rotorua Tephra, we can not precisely constrain the upper part of this interval, although it clearly spans the Last Glacial Maximum (c. 25-15 ka). Although the last glaciation in the North Island of New Zealand was less strong than in the South Island, eolian transport played an important role at this time (Pillans et al. 1993; Newnham et al. 1999) with a landscape that consisted of beech forest of varying extent within a predominantly shrubland/grassland environment (Sandiford et al. 2003). While wind conditions may have been responsible for some of the grain size variation observed in the Pukaki core, we believe that this was not the primary factor. It is also possible that magnetite dissolution favored by an organic-rich environment and reducing conditions contributed to decrease the coercive force of the magnetic grains with depth due to preferential dissolution of SD grains during early diagenesis (Turner, 1997; Karlin, 1990).

In the studied sequences, most silicic and andesitic tephra do not have a clear magnetic signature. For this reason, we interpret the magnetic spikes as arising from local basaltic eruptions. The paucity of ferromagnesian minerals in acidic tephra was previously noted during study of the upper part of the older Pukaki core (Sandiford et al. 2001). This phenomenon can be caused by the distance from the source area (central North Island) or by post-depositional processes, such as the dissolution of magnetite in silicic tephra layers (Hodder et al. 1991).

In the Onepoto core, the Rotoma, Kawakawa, and a few other acidic tephra produced features in the magnetic record. The ferromagnetic components of these tephra were apparently preserved, despite the fact that the Onepoto maar is located in the northern part of AVF at a significantly greater distance from the area source (central North Island) than Pukaki maar. Perhaps for some local environmental reason, there was less magnetite dissolution in these specific intervals. But, in general, higher sedimentation rates and higher magnitudes of remanent magnetisation characterise the Pukaki lacustrine sequence compared to the one from Onepoto. This probably depends on local environmental conditions (e.g., climatic conditions, lake floor geometry, and instability of the crater rims) which contribute to the preservation of the tephra layers and of the magnetic minerals therein. The smaller number of tephra preserved in Onepoto may be related to these factors and to a more distal location of this site from the volcanic centres. Two prominent magnetic features appear in the Onepoto core, one just below the Kawakawa Tephra and another at 9.16 m (indicated with number 3 and 13 in Fig. 3 and table 2). The former feature has been identified visually as a basaltic tephra by Shane & Hoverd (2002). We think these features are both basaltic tephra probably from a near source.

Also in the Onepoto sequence, we infer that most of the magnetic features are caused by local basaltic tephra. The maar was probably dominated by a quiet sedimentation environment, interrupted mainly by the deposition of tephra. A period of major volcanic activity occurs below 11 m in this core. The sudden increase in the concentration of the magnetic material at the bottom of the core corresponds to an interval of abundant weathered basaltic detritus.

The lack of corresponding features in the magnetic records from the two cores does not allow us to use the magnetic data for inter-core correlation. We also cannot use the record of magnetic directions since it is likely that significant remagnetisation has occurred. Otherwise we might have been able to detect the Laschamp and Mono Lake geomagnetic excursions which have been identified in lava flows from the AVF (Cassata et al. 2008). Nonetheless, we provide evidence for a much greater number of possible basaltic events in the AVF than has previously been detected. In the time interval constrained by the Rotoehu (64 ka) and Rotoma (8.5 ka) Tephra, for Pukaki core, we observe a mean frequency of basaltic events of one per c. 1000 yr. This observation though speculative, particularly because of uncertainties concerning the age of the Rotoehu Tephra (Shane & Sandiford 2003; Molloy et al. 2009), implies that previous attempts to compute the frequency of local events, such as that proposed by Sandiford et al. (2001) using Pukaki maar, need to be treated with caution. This issue has recently been discussed by Molloy et al. (2009) who have also considered the preservation of the tephra and the fact that microscopic tephra layers (< 0.5 mm) likely present in the cores are usually not identified. These considerations compound the problems with simple frequency models for the AVF arising from uncertainties in tephra age and from grouped tephra (Shane & Hoverd 2002; Edbrooke et al. 2003).

Basaltic eruptions probably represent the greatest threat to the city of Auckland, and our study shows that the frequency of such events may have been significantly underestimated. This has serious consequences for hazard and risk assessment in the Auckland area (e.g., Magill & Blong 2005a, b).

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Fig. 1 Location map of the Pukaki and Onepoto maars in Auckland Volcanic Field. *Inset*: Location map of North Island. OVC is Okataina Volcanic Centre; TVC is Taupo Volcanic Centre; TgVC is Tongariro Volcanic Centre; TaVZ is Taranaki Volcanic Zone.

Fig. 2 Magnetic susceptibility, ChRM intensity and inclination, ARM intensity, ARM/κ, and ARM_{30mT}/ ARM parameters for Pukaki 1-01 (A) and Onepoto (B) cores. The columns on the right show the depth of the main magnetic features and of important volcanic tephra. See Tables 1 and 2 for major details. The errors associated with the magnetic susceptibility are less than 2 % of the measured values. They only become significant in the intervals where the values approach the resolution of the instrument (2×10^{-6} SI) where they produce a corresponding increase in the errors associated with the ARM/κ values.

Fig. 3 Magnetic susceptibility, ChRM, and ARM intensity for Onepoto core. The main magnetic features are identified with numbers reported also in Table 2. On the left is indicated a period of probably major volcanic activity in the AVF.

Table 1 Magnetic signatures from NRM and ARM intensity records for Pukaki core not shown in Turner et al. (2001). Lithological description from Dickinson (2001).

Table 2 Magnetic signatures and lithological description for the Onepoto core. Identified tephra from Shane & Hoverd (2002).

Table 1

Core Sections	Corrected depth (m)	Description
33	51.32-51.37	
34	51.42	clay with sections of a darker color
34	51.63-51.68	clay with sections of a darker color
34	51.82	
34	51.99	
34	52.14	
34	52.25	
34	52.35	
34	52.42	
35	53.53-53.60	
37	56.87-56.89	tephra? Very dark gray
38	57.91-57.98	fine silt, very dark gray
38	58.14-58.23	fine silt, very dark gray
38	58.26-58.32	fine silt, very dark gray
38	58.54-58.56	fine silt, very dark gray
40	60.44-60.53	laminated sediment
41	61.9	basaltic tephra
41	62.87	white fine silty tephra
42	63.36	fine sand, tephra
43	64.83	
45	67.20-67.49	basaltic tephra at 67.20 m
46	68.39	
46	68.54	
46	68.84	
46	69.37-69.53	tephra layers

Table 2

	Core Sections	Corrected depth (m)	Tephra	Description
0	21A	0.21-0.25	Rotoma	white, 4 cm thickness
1	21A	0.64	basaltic tephra?	
2	22A	2.32-2.34	Kawakawa	white, 2.5 cm thickness
3	22A	2.51	121AVF	
4	22B	2.82	basaltic tephra?	
5	23	3.9	Tahuna	
6	24	5.12-5.14	95Tk	pink, 2 cm thickness
7	24	5.90	basaltic tephra?	
8	25A	6.71	basaltic tephra?	
9	25A	7.00	basaltic tephra?	
10	25A	7.45	basaltic tephra?	
11	25A	7.62	basaltic tephra?	
12	25A	8.06	basaltic tephra?	
13	26A	9.16	basaltic tephra?	
14	26A	9.41	basaltic tephra?	
15	26A	10.31	basaltic tephra?	
16	27A	11.27	basaltic tephra?	
17	27A	11.36	basaltic tephra?	
18	27A	11.43	basaltic tephra?	
19	27A	11.66	71TK	pink, 2 cm thickness
20	27A	11.78	70TK	
21	27A	11.81	basaltic tephra?	
22	27A	11.96	68TK	
23	27A	12.2	67Tk	
24	27A	12.26	basaltic tephra?	
25	27A	12.32	basaltic tephra?	
26	27B	12.58	61TK	
27	28	13.21	basaltic tephra?	
28	28	13.48	basaltic tephra?	
29	28	13.84	basaltic tephra?	
30	28	14.09	basaltic tephra?	
31	28	14.44	basaltic tephra?	
32	29	14.69	basaltic tephra?	
33	29	14.81	basaltic tephra?	
34	29	14.91-14.93	41TVZ	white, 2 cm thickness
35	29	15.32-15.37	30TK-?	pink, 2 mm thickness

AVF = Auckland Volcanic Field, Tk = Taranaki volcano, and TVZ= Taupo Volcanic Centre.

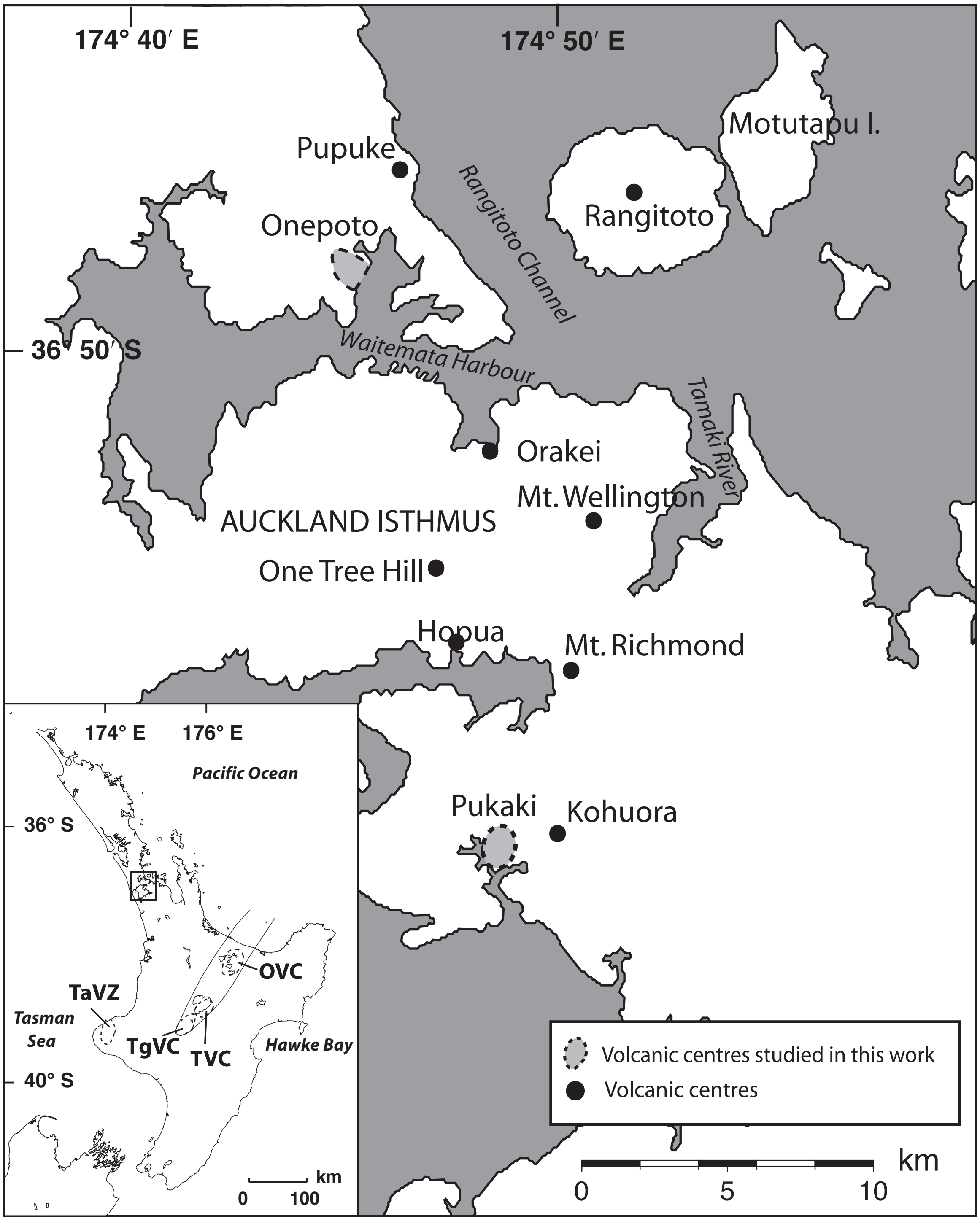

Figure 1

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A

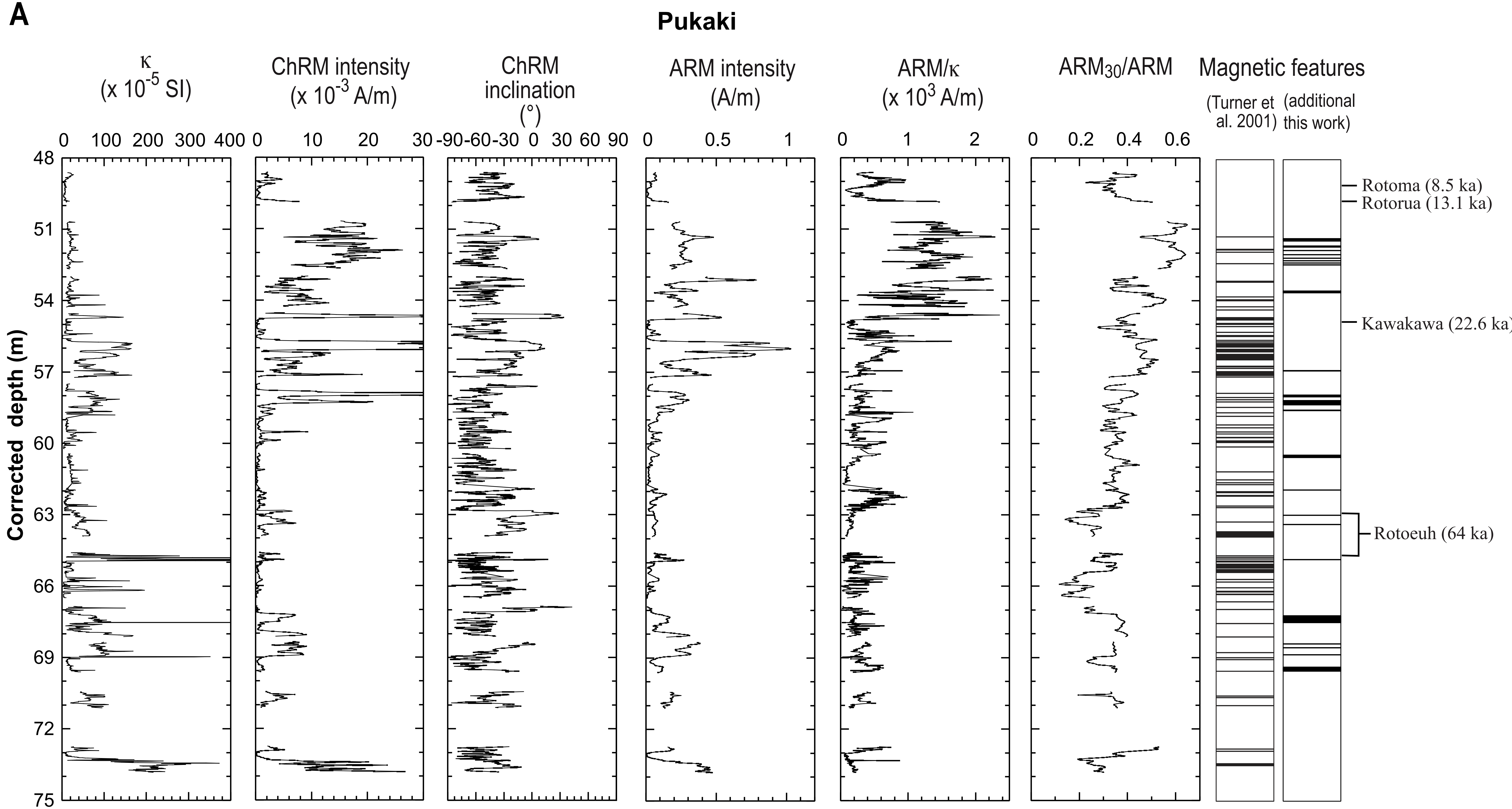

Figure 2A

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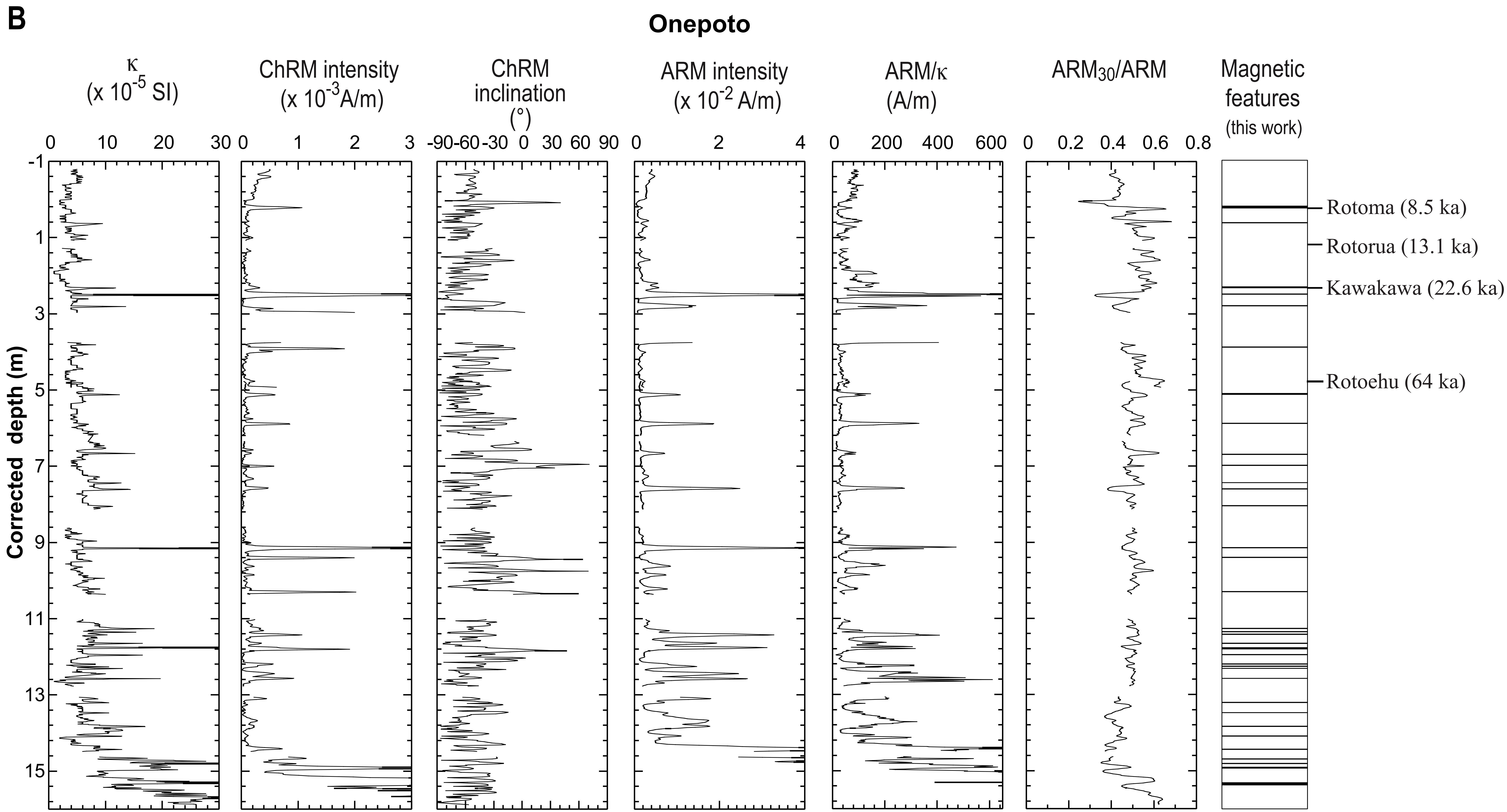

Figure 2B

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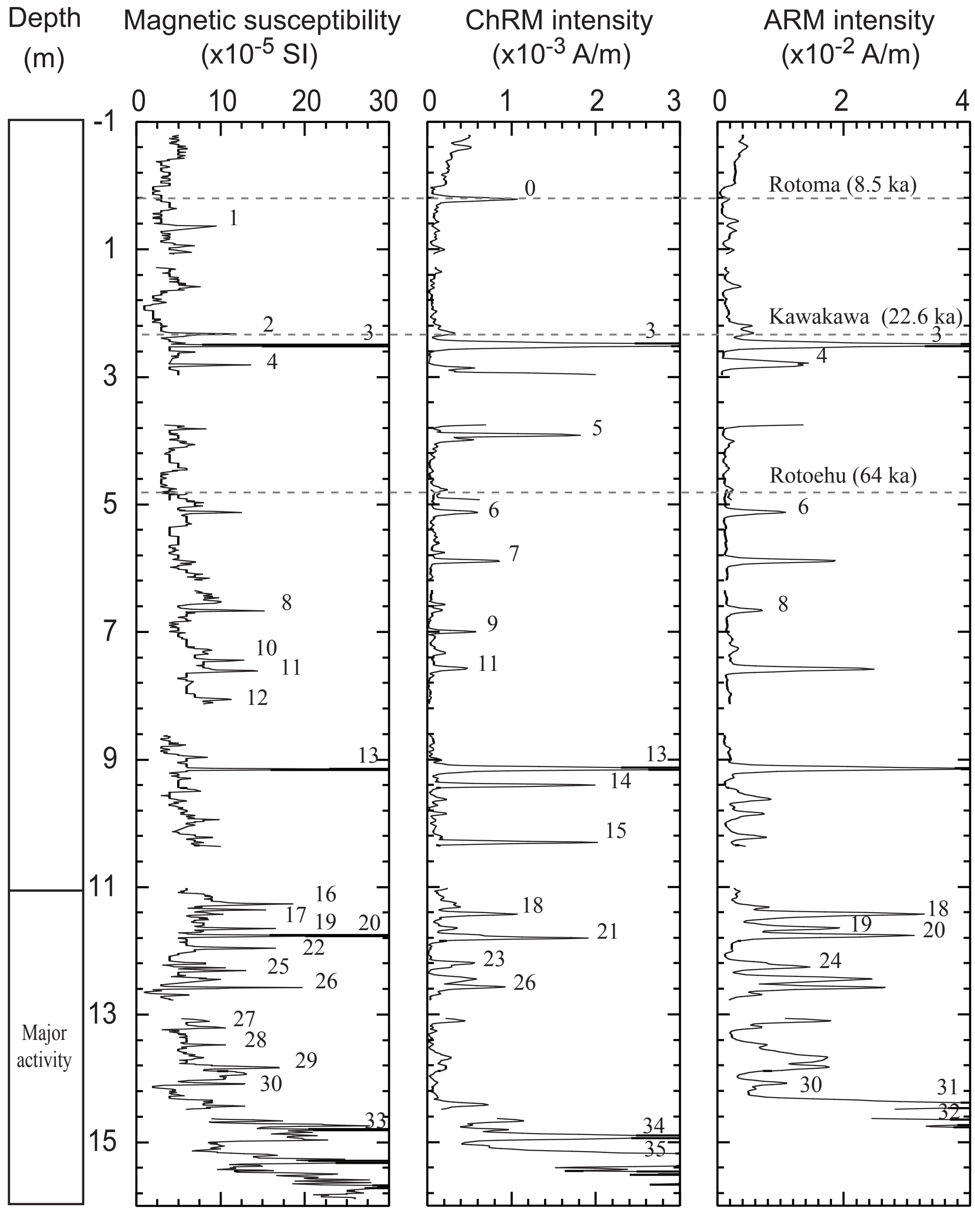

Figure 3

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