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K/Ar AGE ESTIMATE OF THE PLIOCENE-PLEISTOCENE BOUNDARY IN NEW ZEALAND

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ABSTRACT. On the west coast of the Auckland Province in the North Island, New Zealand, basalts occur which on stratigraphic evidence appear to lie close to the climatically defined Pliocene-Pleistocene boundary. Samples of basalt from two localities have been dated by the potassium-argon method and yield concordant ages of 2.4 to 2.6 million years. Basalts, from one locality, that are younger than the base of the Pleistocene give dates of 2.4 ± 0.1 million years. Preliminary paleomagnetic measurements indicate that the rocks have normal polarity, which places further restrictions on the minimum age of the boundary at approximately 2.5 million years. Hence the Pliocene-Pleistocene boundary as accepted in New Zealand appears to have an age of about 2.5 million years.

INTRODUCTION

Purpose.—In this paper we report potassium argon dates on volcanic rocks which, from stratigraphic evidence, are considered to lie approximately at the Pliocene-Pleistocene boundary as accepted (defined) in New Zealand.

Pliocene-Pleistocene review.—Two definitions of the Pliocene-Pleistocene boundary in current use may or may not be equivalent (compare, Flint, 1965). One definition is based upon evolutionary changes in organisms, and the other utilizes the first appearance of climatic deterioration in the Late Tertiary. This cooling produced widespread glaciation which in turn caused fluctuations of sealevel and fauna and flora migration. Sedimentary rocks deposited in both continental and marine environments may also show evidence of the cooling.

In discussing the definition of the base of the Pleistocene Flint (1965) regarded the appearance of the first general climatic cooling as possibly more useful than the biological changes in organisms that occurred in this relatively short interval of geological time.

Commonly the age of the Pliocene-Pleistocene boundary has been assumed to be about one million years (compare, Kulp, 1961), but some workers, particularly in New Zealand (for example, Suggate, 1963), have argued that this is too short a time for the geological events which occurred in the Pleistocene. Revised age estimates for the Pliocene-Pleistocene boundary ranging from 1.5 to 3.0 million years have been made by a number of workers (Evernden and Curtis, 1965; Ericson, Ewing, and Wollin, 1964; Opdyke and others, 1966; McDougall and Wensink, 1966; Curry, 1966).

NEW ZEALAND GEOLOGIC SETTING

Pliocene-Pleistocene stratigraphy.—Gage (1961) summarized the stratigraphic record in New Zealand and its bearing on the base of the Pleistocene. The oldest glacial deposits known from Upper Cenozoic

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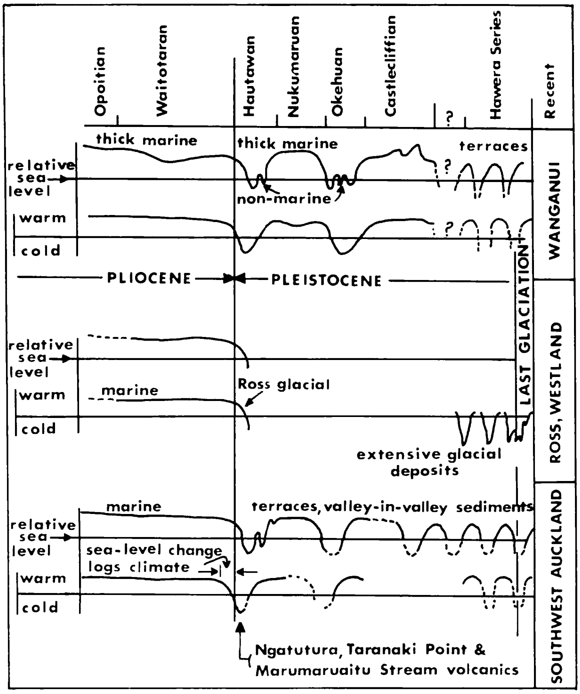

Fig. 1. New Zealand climate and sealevel relationships with time.

successions in New Zealand are tillites that conformably overlie marine beds of the Waitotaran Stage (N.Z. time-stratigraphic code; see Fleming, 1962) in the Ross area of the west coast of the South Island (Gage, 1945). A lignite bed at the base of the tillites contains a cool-climate flora identified by Couper and McQueen (1954) as belonging to the Hautawan Stage[1] (see fig. 1). Hence there exists in the New Zealand stratigraphic record a clearly defined association between deposition of glacial deposits and the strong climatic deterioration, bringing to a close a period of climatic stability that had existed throughout the Upper Tertiary (Fleming, 1962). Fleming (1953) suggested that the climatic cooling recognized in the very thick Upper Cenozoic succession around Wanganui, which commenced at the close of Waitotaran time in New Zealand, provides reasonable grounds for drawing the Pliocene-Pleistocene boundary between the Waitotaran and Hautawan Stages.

Region dated—General.—The volcanic rocks used for dating in this study are associated with flat-lying Upper Cenozoic sediments (shallow marine, littoral, and eolian) exposed in cliffs at several places along the west coast of Auckland Province, North Island of New Zealand. The successions contain a number of formations separated by erosional

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[1] The name Hautawan is used throughout (after Fleming, 1962) in preference to the older Lower Nukumaruan.

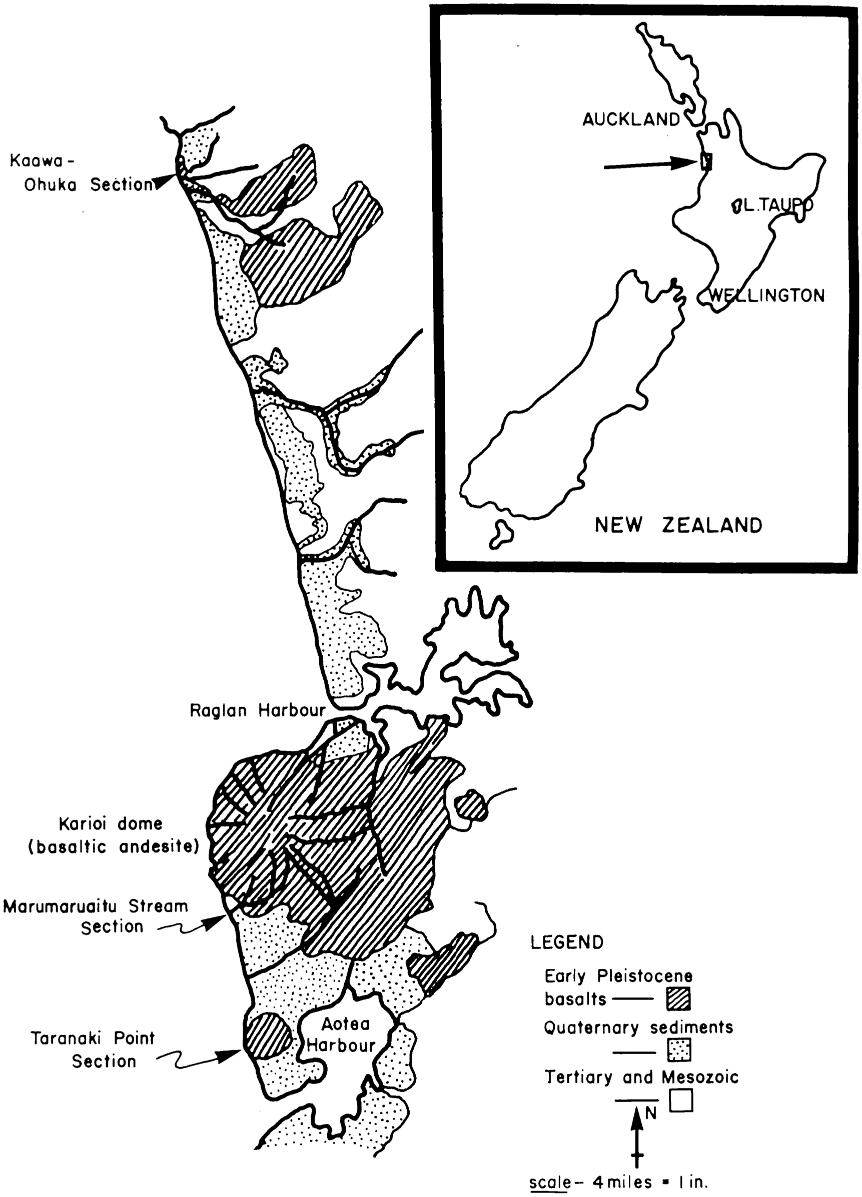

Fig. 2. Location of Kaawa-Ohuka, Taranaki Point, and Marumaruaitu Stream sections.

unconformities. From the stratigraphy a number of large-scale oscillations of sealevel have been deduced; these commenced in the Late Cenozoic and continued until the present day (Brothers, 1954; Chappell, ms). Palynologic evidence suggests that these sealevel fluctuations are associated with climatic oscillations (Couper and McQueen, 1954; Harris, *in* Chappell, ms). The cycles are thought to be glacioeustatic and may be correlated with those of the Wanganui and Ross areas.

At several localities, sections occur which appear to contain the geologic record of the commencement of the first oscillation and also contain evidence for the climatic conditions that existed searlier. Basaltic lavas occur within a number of cliff sections, and the stratigraphy suggests that these lavas were erupted shortly after the first climatic deterioration and associated fall in sealevel. Hence, if the interpretation of the stratigraphy is correct, we may hope by dating the lavas to estimate the age of the base of the Pleistocene in New Zealand.

GEOLOGY OF THE DATED SECTIONS

Introduction.—Originally basalts from three sections were chosen for dating: Kaawa-Ohuka, Taranaki Point, and Marumaruaitu Stream (fig. 2). Unfortunately the Ngatutura Basalt from the Kaawa-Ohuka area proved unsuitable for dating. The basalt showed extensive deuteric alteration and also contained inclusions of ultramafic nodules. Nevertheless because of the stratigraphic importance of the Ngatutura Basalt a considerable effort was made to date several samples. The results were not reproducible and ranged from 1.0 to 2.3 million years both within and between samples. This was due, at least in part, to the high contamination by air argon. Also, the possibility of some variable excess argon contribution has not yet been excluded. Hence these data have been rejected. Basalts from the two other sections were much more favorable for dating, and apparently reliable reproducible results were obtained.

Although the Ngatutura Basalt was unsuitable for dating, a brief discussion of the stratigraphy at Kaawa-Ohuka is necessary because the other two sections are more easily understood by correlation with this section. Stratigraphic relations within the Kaawa-Ohuka section are most completely described by Kear (1957), who also summarized the work of the numerous previous writers. The section is illustrated in figure 3 and table 1. With reference to the stratigraphic definition of the base of the Pleistocene, the critical elements of the succession are, first, the characteristics of the Kaawa Formation and, second, the relationship between the uppermost member of the Kaawa Formation and the Ngatutura Volcanics.

Kaawa-Ohuka coastal section.—The Kaawa Formation was deposited on a flat, comparatively extensive surface of marine planation cut across Oligocene sediments of the Te Kuiti and Waikawau Groups. The basal member of the Kaawa Formation is the Kaawa Shellbed which passes gradationally into Kaawa Sandstone both laterally and vertically. The shellbed contains a very rich molluscan fauna studied by Laws (1950), who reported 203 molluscan genera indicating a depositional water depth of 10 to 15 fathoms. Laws (1950) considered its age to be

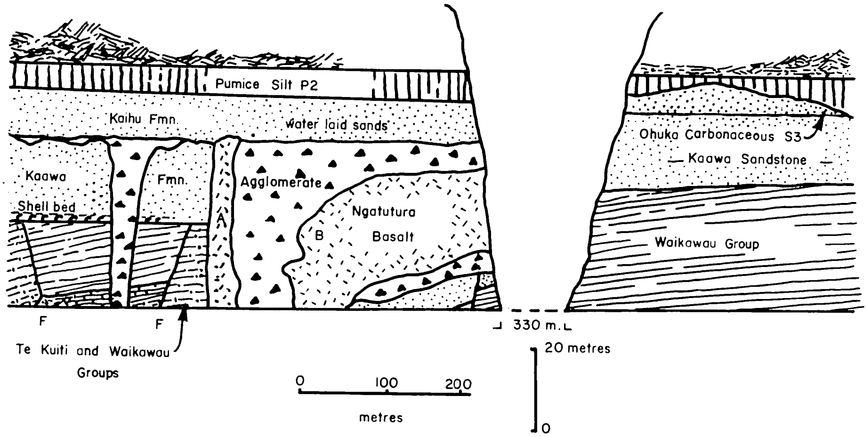

Fig. 3. Kaawa-Ohuka geologic cross-section.

Opoitian (Lower-Mid Pliocene). The climate was considered similar to that of the present day.

The Kaawa Sandstone passes upward gradationally into the Ohuka Carbonaceous Sandstone, representing a change from quiet-water marine deposition to a littoral environment. Floral analyses, by Couper and McQueen (1954), of samples from the Ohuka Carbonaceous Sandstone showed that the plant-microfossil population was almost identical with that found in modern cores taken in Milford Sound (west coast of South Island, N.Z.), which is 8° farther south. They tentatively assigned a Lower Pleistocene (Hautawan) age to the material. The important result is that the indicated cool climate is the earliest known from the Upper Cenozoic deposits of the southwest Auckland region and is correlated with the first cooling recognized in the very thick Upper Cenozoic succession in the Wanganui region described by Fleming (1953). The stratigraphic age of this cooling is Hautawan (Fleming, 1953; 1962), and hence Couper and McQueen's suggested age is vindicated.

In the section (fig. 3) basalt agglomerates fill narrow valleys cut into the Kaawa Formation and older formations, and basalts intrude both the agglomerate and Tertiary rocks. An erosion surface truncates basalts and Kaawa Formation alike (fig. 3). The overlying Kaihu Formation consists of estuarine and eolian beds; very regular pumice-silt beds constitute reliable marker horizons within this formation. A peat sample taken from the lowest pumice-silt horizon was considered by Couper (*in* Kear, 1957) to indicate a Nukumaruan age and a climate similar to today's.

Taranaki Point section.—A sequence (Chappell, ms) similar to that at Kaawa-Ohuka is exposed in a cliff section 32 miles farther south (fig. 4 and table 1). Although the Kaawa Shellbed is not present in the Kaawa Formation at Taranaki Point, there is a complete correla-

TABLE 1

Stratigraphic correlations between the Ngatutura, Taranaki Point, and Marumaruaitu Stream sections

Rock unit			NZ time-rock unit (stage) (nomenclature after Fleming, 1962)	Epoch
Ngatutura	Taranaki Point	Marumaruaitu Stream		
Kaihu Formation			Nukumaruan	
	erosional unconformity			
		Olivine basalt flow		Lowest Pleistocene
Ngatutura volcanics	Manuaitu Basalt	Boulder bed		
Ohuka carbonaceous sandstone	Carbonaceous sandstone	Basaltic andesite	Hautawan	
Kaawa Sandstone			Waitotaran	Upper Pliocene
Kaawa Shellbed			Opitian and possibly younger	Mid
	angular unconformity			
Kaikawau and Te Kuiti Group				Oligocene

tion in lithology and contained mineral suites. The carbonaceous beach sand (point *X*, fig. 4) contains a flora identified by Harris (*in* Chappell, ms) as representing a climate much cooler than today's and similar to that inferred from the Ohuka Carbonaceous Sandstone in the Kaawa section, determined by Couper and McQueen (1954). Although containing no floral species that became extinct specifically in Hautawan time, the carbonaceous sandstone in the Taranaki Point section is identified as Hautawan because it contains the record of the first cooling

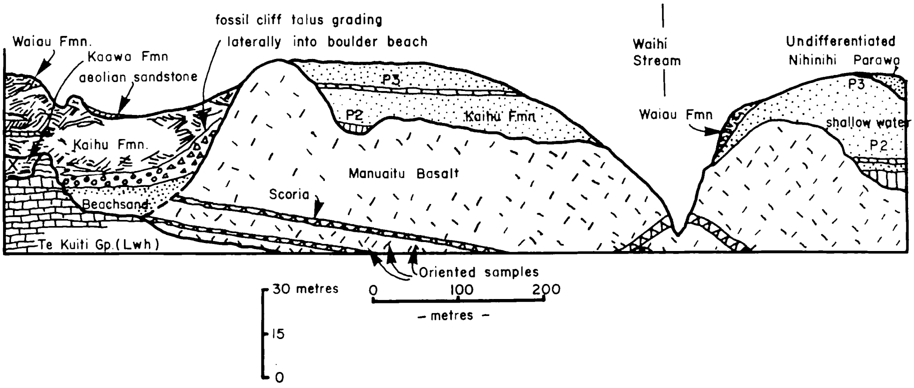

Fig. 4. Taranaki Point geologic cross-section.

and because of complete similarity in lithology and stratigraphy with Kaawa-Ohuka.

The overlying Kaihu Formation is correlated directly with the succession at Kaawa by virtue of pumice-silt marker beds and contains a Nukumaruan warm-climate flora. The dated rocks (Manuaitu basalts—fig. 4) are basalt flows filling a broad valley in Tertiary rocks (which include the Kaawa Formation), and the basalts, in turn, are cut by an erosion surface and are buried beneath the Kaihu Formation. The fact that the flows are terrestrial (that is, no pillow structure or glassy selvages; very regularly and in places coarsely jointed) suggests that they were emplaced during the post-Kaawa marine regression. The basalts are thought definitely to be younger than the Kaawa Formation because of the absence of any basaltic detritus in the Kaawa marine sand and overlying carbonaceous sand. This is compared with the later basaltic Kaihu sand, which contains 30 percent titanomagnetite.

Samples were collected from several separate flows; however, the stratigraphic relationship of the flow at the Waihi Stream mouth to flows of the same basalt formation just to the north was obscure. This area at the stream mouth showed strong spheroidal weathering as opposed to the platy structure of the flows just to the north.

Marumaruaitu Stream section.—The third locality from which samples for dating were taken is the mouth of Marumaruaitu Stream, seven miles north of Taranaki Point (figs. 1, 5; and table 1). Two sets of samples were collected from lava flows which lie respectively above and below a boulder bed at least 20 meters thick (fig. 5). The sub-horizontal massive basaltic andesite lying beneath the boulder bed appears to be an early flow of Karioi Volcano, whereas the basalts of the upper flows probably came from a local center. Sediments of the Kaihu Formation mantle the section, and the altitude of the pumice-silt marker beds (deposited in very shallow water) is the same as in the other two sec-

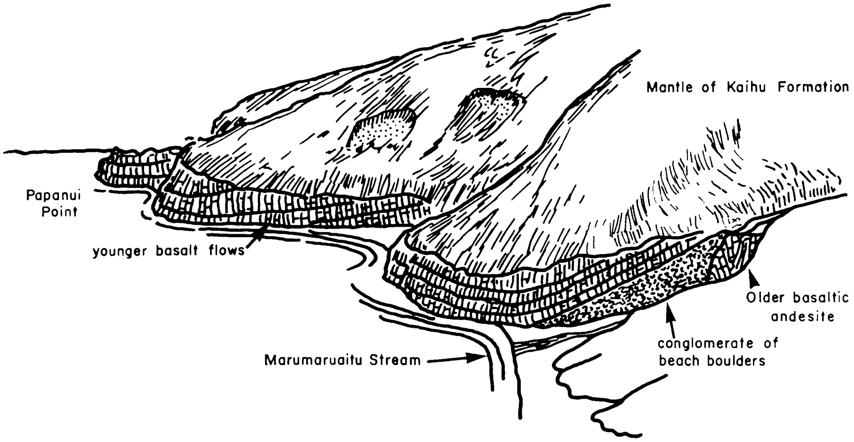

Fig. 5. Marumaruaitu Stream geologic cross-section.

tions described, indicating that there has been no differential movement between them.

Although the Kaawa Formation is not present, the oldest flow (that is, the basaltic andesite) is post-Kaawa, as Pliocene sealevel was demonstrably more than 40 feet higher than the top of the flow (compare fig. 5), which is terrestrial (that is, no pillow structure or glassy selvages; regularly and coarsely jointed), and hence this flow was erupted after the marine regression which terminated Pliocene sedimentation. A cliff was then cut into the lava (fig. 5), and a thick beach boulder bed accumulated during the subsequent transgression, which achieved a relative sealevel of at least +60 feet (with respect to the present sealevel datum). The clean, planar surface of the overlying olivine-basalt lavas, together with a lack of glassy selvage, no "steam explosion" traces, and regular columnar joints extending down to the interface, is taken as indication that the lavas flowed over a dry surface. This means that there was an interruption to the overall positive movement of the Kaihu Transgression, and the altitude of the pumice-silt marker beds in the Kaihu Formation suggests that this was a marine regression rather than a local uplift. The younger basalts of Papanui Point then are younger than the base of the Pleistocene.

K/Ar AGE DETERMINATION

Technique.—The laboratory techniques used have been described in detail (McDougall, 1964, 1966). In this study all samples were analyzed in whole-rock form. Argon content was determined by fusing the sample under high vacuum, admitting a small, accurately known amount of argon 38 tracer, and then measuring this purified mixture statically on a Reynolds type mass spectrometer. From the relative concentrations of the mass 36, 38, and 40 isotopes the amount of radiogenic argon was calculated. Potassium was analyzed in duplicate by flame photometry (Cooper, 1963) using a lithium standard solution with sodium buffer. Results are given in table 2, and details of the samples are listed in the appendix. Duplicate potassium analysis generally agree to better than 1 percent. Replicate argon determinations agree to about 4 percent or better. The overall accuracy is probably ± 5 percent decreasing in those samples with high air correction (greater than 80 percent) to ± 7 percent, excluding uncertainties in the decay constants.

Sample requirements.—When dating any rocks by K/Ar (particularly whole-rock samples) great care must be taken in the selection of samples. The rock must be free from weathering and/or alteration. Fine-grained alteration products may not retain radiogenic argon even at normal temperatures, resulting in a younger than real age. However, recent evidence suggests that provided the alteration is deuteric reliable dates may still be obtained from such rocks (Amaral and others, 1966; McDougall and Wensink, 1966). Also, when dating young rocks (less than 5 m. y.) the relative amount of radiogenic argon compared to the amount of argon contributed from the air often can be quite small. Thus, at high air Ar^{40} correction values the error in measuring the small radiogenic component is magnified so that reproducibility becomes difficult or, in extreme cases, impossible.

The only real confidence test available is that based on consistency between replicate measurements on a given sample and between results on samples where relative ages are known from stratigraphy.

Very few of the samples collected from the areas discussed were ideal for dating because of the presence of some alteration in the groundmass (see app.); however, the consistency of the results on different samples and the good agreement between replicate determinations suggests that the measured ages probably approach the true age closely. In all cases the ages can be regarded as reliable minimum values.

Taranaki Point discussion.—GA 2044 (2.50 m.y. avg) and GA 2045 (2.53 m.y. avg) are from the northern half of the Manuaitu Basalt outcrop with GA 2045 being approximately 2 flows higher stratigraphically (fig. 5). Statistically, their average ages are indistinguishable. GA 2042 (2.60 m.y. avg) from the Waihi Stream mouth, although apparently older than the other two samples, could be considered as similar after noting their individual-run values. However, in the field the exact relationship of this flow to the flows from which GA 2044 and GA 2045 were taken is unknown. The scoria beds which were used to discriminate between the flows disappeared at a small headland between the two sample areas. A scoria bed reappeared near the Waihi Stream mouth (fig. 4) and gave the appearance that this flow (and therefore GA 2042) was possibly the end of a small valley flow and earlier than GA 2045.

Petrographically, GA 2044 is a fresh rock with only very rare areas of glass in the groundmass. Samples GA 2042 and GA 2045, however, show considerable alteration of the groundmass. This relative degree of freshness has been reflected in the percent air Ar^{40} contamination in table 2. The fact that both "less than ideal" samples, GA 2042 and GA 2045, gave dates very similar to GA 2044 is reassuring that very little (if any) argon loss has taken place. Overall, the 3 samples show reasonable agreement both internally and between one another. The total average indicated age is 2.54 ± 0.10 million years. As the basalts are stratigraphically slightly younger than the Pliocene-Pleistocene boundary, this age is a good minimum value for its age.

Marumaruaitu Stream discussion.—GA 2046 (2.28 m.y. avg) and GA 2047 (2.27 m.y. avg) were collected from the upper olivine basalt flows (p. 469) on the southwest side of Papanui Point located at the north end of the outcrop (fig. 5). The average ages indicated for these two samples agree closely; however, the uncertainty in the measured age for GA 2047 is larger than for GA 2046 because of the larger spread between runs. Run number 2 of GA 2047 appears too high, but no grounds have been found for rejecting it on a physical

TABLE 2

GA no.	Whole rock material	K%	$^*Ar^{40}/K^{40}$	Atm Ar^{40} (percent)	Calculated age (m.y.)
		Taranaki Point Ages			
2042	basalt	0.890 0.890 } 0.890	1.499	61.5	2.56
			1.544	63.9	2.63
2044	basalt	1.020 1.022 } 1.021	1.498	40.9	2.56
			1.429	40.9	2.44
			1.460	20.1	2.51
2045	basalt	0.855 0.850 } 0.853	1.405	49.1	2.40
			1.514	66.7	2.58
			1.535	69.4	2.62
		Marumaruaitu Stream Ages			
2046	basalt	0.746 0.759 } 0.752	1.336	70.7	2.28
			1.339	67.6	2.29
2047	basalt	0.753 0.749 } 0.751	1.230	81.3	2.13
			1.452	83.0	2.48
			1.289	70.0	2.20
2048	basalt	1.184 1.188 } 1.185	1.436	45.9	2.45
			1.390	76.3	2.37

$^*Ar^{40}$ — radiogenic argon, $\lambda_e = 0.585 \times 10^{-10}\ yr^{-1}$, $\lambda\beta = 4.72 \times 10^{-10}\ yr^{-1}$, $40_K = 1.19 \times 10^{-2}$ at %.

measurement basis. Petrographically, GA 2046 is quite fresh and holocrystalline, except for a small proportion of intersertal glass. GA 2047 is very similar, but the groundmass shows some alteration.

GA 2048 (2.41 m.y. avg) is from the lower basaltic andesite (fig. 5). Petrographically, the rock is holocrystalline and generally fresh. The older indicated age for this sample compared with the overlying lavas is consistent with the stratigraphy.

Probably the basaltic andesite was erupted during the marine regression that marked the beginning of the Pleistocene. Hence the age of 2.41 ± 0.10 million years also is minimum for the Pliocene-Pleistocene boundary. This age is essentially the same as or slightly younger than that found on the Taranaki Point basalts.

PALEOMAGNETISM AND THE PLIO-PLEISTOCENE BOUNDARY

General.—Cox, Doell, and Dalrymple, (1964) and McDougall and Tarling (1963) determined independently by K/Ar dating that the base of the Matuyama reversed paleomagnetic epoch occurred approximately 2.5 million years ago. Opdyke and others (1966) found from paleomagnetic studies of Pacific Antarctic sea cores that the first evidence of ice-rafted material (Connolly and Ewing, 1965) in those cores occurred just prior to the boundary between the Gauss normal and the Matuyama reversed epochs. The age of first cooling therefore appears to be at approximately 2.5 million years in the Southern Hemisphere.

New Zealand.—Three oriented samples were taken of a flow between flow samples GA 2044 and GA 2045 from Taranaki Point, Manuaitu Basalt (fig. 4). All three determinations plotted very closely and were of normal polarity. This indicates that the first climatic cooling based on stratigraphic evidence occurred shortly before the geomagnetic field changed from the Gauss Normal to the Matuyama Reversed paleomagnetic epoch.

Therefore, from the preliminary results at Taranaki Point there appears to be good agreement between this and the work of Opdyke and others for the age of the climatically defined Pliocene-Pleistocene boundary in the Southern Hemisphere.

Oriented sampling at Marumaruaitu Stream was, unfortunately, inadequate. The slightly younger ages here than at Taranaki Point make this area quite important from the paleomagnetic point of view, to further pinpoint the time of magnetic reversal. Additional sampling by drill is planned.

The fact that the Gauss-Matuyama paleomagnetic boundary appears to be close to the Plio-Pleistocene boundary suggests that paleomagnetic measurements could be very useful in locating the Pliocene-Pleistocene boundary elsewhere.

CONCLUSION

The long period of climatic stability which continued throughout the Later Tertiary in New Zealand was terminated by rapid climatic cooling and generation of glaciers in the south, accompanied by fall of sealevel. After a short interval of unknown length and before sealevel and climates had re-achieved their late Pliocene condition, in the return swing of the first of a number of such cycles, basalts were erupted from centers along the west coast of the Auckland Province. Potassium-argon dates of 2.4 to 2.6 million years were found for samples from lava flows that were erupted during the marine regression which occurred at the base of the Pleistocene. Hence the age of the Pliocene-Pleistocene boundary in New Zealand is at about 2.5 million years.

ACKNOWLEDGMENTS

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APPENDIX

Taranaki Point

GA 2042.—Olivine basalt flow at mouth of Waihi Stream on Tasman coast (N64/316233). From core of spheroidally weathered boulder at foot of cliff consisting of similar material. Massive with large olivines and slightly vesicular. Petrography: abundant large olivine phenocrysts and common augite set in a matrix of flow aligned fresh but ill-defined plagioclase laths. Common titaniferous pyroxene. Considerable areas of interstitial alteration.

GA 2044.—Olivine basalt flow at extreme north end of coast outcrop (N64/313238). Dense with horizontal jointing. Sample taken in-situ. Petrography: common augite and very abundant partly iddingsitized olivine phenocrysts. Rock is holocrystalline with groundmass consisting of randomly oriented plagioclase and pyroxene. Appears to be very fresh and near-ideal for dating.

GA 2045.—Olivine basalt flow approximately 100 meters south and at least one flow above GA 2044 (N64/314234). Petrographically similar to GA 2042, however, groundmass is more altered.

Marumaruaitu Stream

GA 2046.—Olivine basalt flow on south coastal side of Papanui Point (N64/287349). Strong subhorizontal jointing and dense. Sample in-situ. Petrography: abundant marginally iddingsitized olivine and common titaniferous pyroxene. These are set in groundmass of plagioclase and pyroxene with very small amout of interstitial glass. Appears quite fresh and acceptable for dating.

GA 2047.—Olivine basalt in-situ 30 meters west of GA 2046 in same flow. Petrography: very similar to GA 2046 but appears to have somewhat more interstitial glass which shows some incipient devitrification. In general fresh and reasonable for dating.

GA 2048.—Basaltic andesite at top of waterfall along Marumaruaitu Stream. Fresh angular block from the lava flow. Petrography: very abundant plagioclase and less common augite and olivine as phenocrysts with interstitial poorly crystallized groundmass in which plagioclase and pyroxene occur as small crystals. Some development of chlorite in the groundmass. In general fresh and suitable for dating.

ADDENDUM

Since the writing of this paper Mathews and Curtis (1966) have published an article containing two K/Ar dates on formations thought to lie near the New Zealand Pliocene-Pleistocene boundary. One of the ages quoted apparently agrees with the 2.5 million year age as indicated by our work; however, it should be noted that a large uncertainty is assigned to their ages because of the very high (95 percent) air corrections in the argon runs. Duplicate runs would make it easier to evaluate whether the uncertainties quoted are realistic.

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