Reports

Paleomagnetic Chronology of Pliocene–Early Pleistocene Climates and the Plio-Pleistocene Boundary in New Zealand

Abstract. *The paleomagnetic chronology established for a Pliocene–Early Pleistocene sequence of marine sediments in New Zealand reveals that marked climatic coolings based on Foraminifera and oxygen isotope ratios in the late Cenozoic preceded the Pliocene-Pleistocene boundary, which is taken to be at the base of the Gilsá geomagnetic polarity event (1.79 million years ago). Major temperature fluctuations occur from the upper Gauss (Middle Pliocene) to middle Matuyama (Early Pleistocene). The first major Pliocene cooling spans the Gauss-Matuyama boundary (2.43 million years ago). A uniform and rapid (40 centimeters per 1000 years) rate of deposition is shown for the moderately shallow marine environment.*

Geomagnetic polarity reversals for the last 5 million years (*1*) have been used to provide ages of and correlations between many deep-sea sedimentary cores (*2*) but have only rarely been applied to studies of Cenozoic marine sedimentary sequences exposed on land (*3*). We have extended the method to relatively shallow-water Pliocene to Early Pleistocene marine sediments exposed on New Zealand.

The remarkably complete Tertiary and Quaternary stratigraphic and paleontological record in New Zealand has enabled clear definition of relative paleotemperature oscillations resulting from periodic regional migrations of subantarctic water to the south and warmer subtropical water to the north (*4, 5*). These paleotemperature oscillations have been difficult to correlate in other parts of the world, however, because of the provincial character of New Zealand marine faunal assemblages and the local controls on paleooceanographic conditions.

The paleomagnetic stratigraphy was determined in the nearly continuous Pliocene to Early Pleistocene sequence at Mangaopari Stream–Makara River (Fig. 1), at the southern end of the North Island of New Zealand. Fresh sediments exposed in the stream beds and adjacent road cuts total 650 m of foraminifer-rich marine mudstone, sandstone, and limestone of upper bathyal to middle neritic depths. The section is of considerable importance because of prior biostratigraphic, paleoclimatic, and oxygen isotope studies (*6, 7*) (Fig. 2). Objectives of this study include determination of the stratigraphically defined Pliocene-Pleistocene boundary by correlation with the base of the marine Calabrian stage of southern Italy; the evaluation of relations between this stratigraphically defined boundary and marked climatic coolings, including that which defines the currently accepted Plio-Pleistocene boundary determined primarily by the appearance of cool-water Mollusca (*4, 6, 8*). Finer definition of the geomagnetic polarity history during the Matuyama epoch (0.69 to 2.43 million years ago) (*1*) may also result from detailed studies of such a section.

Three cores, 2.5 cm in diameter, were drilled with a gasoline-powered portable drill from each of 61 sites throughout the section (Figs. 1 and 2), as well as in two slightly younger (Marahauan) stratigraphic horizons in a nearby section (*9*). All cores were oriented in geographic coordinate, while still attached to outcrop, to an accuracy of $\pm 3°$. At each site vertical separation between the three cores was no greater than 30 cm, but horizontal separation was up to 3 m. In the laboratory each core was sliced into specimens 2.2 cm long for paleomagnetic analysis. The direction and intensity of the remanent magnetism in each specimen were measured with a spinner magnetometer, operating at 5 cycle/sec (*10*), before and after application of alternating magnetic fields (*11*) of 50 and 75 oersteds.

Intensities of magnetization are of the order of 10^{-7} electromagnetic unit per gram after the viscous components have been removed by the demagnetization treatments. In the log of the paleomagnetic polarities (Fig. 2) the latitude of the virtual geomagnetic pole (*12*) is used to indicate the polarity. Northern latitudes indicate normal polarity, and southern latitudes indicate reversed polarity. The few results with latitudes between 10°N and 10°S are not assigned to any polarity. These are clearly transitional and do not represent major polarity changes.

A section from lowermost Gauss to middle Matuyama geomagnetic polarity epochs is recorded (Fig. 2). This is closely similar to the established geomagnetic polarity scale of Cox (*1*) (Fig. 2). Age assignments, made by simple comparison with the established scale (Fig. 2), are corroborated by the sedimentation rate diagram, which indicates a linear relation between age and sediment thickness (Fig. 3). The sedimentation rate was nearly constant at 40 cm per 1000 years. A uniform rate might be expected for such a sedimentary section, which consists for the most part of rather uniform blue-gray massive mudstone deposited mainly in upper bathyal depths. It is unlikely that such a linear relationship (Fig. 3) would result fortuitously from a combination of a variable sedimentation rate and misidentification of magnetic boundaries. Such rapid rates of sedimentation fall within ranges more typical for flysch and molasse troughs (*13, 14*), although similar rates have been suggested for some nonturbidite terrigenous sediments (*14*).

The variation of the virtual geomagnetic latitude within periods of constant polarity (Fig. 2) may reflect the lack of cancellation of geomagnetic secular variation, which might be expected in sediments accumulating at a rate that is one to two orders of magnitude faster than in deep-sea sediments (*15*), or it may be in part the result of imperfections in recording of the ambient geomagnetic field resulting from burrowing activities of benthonic faunas (*16*).

The geomagnetic stratigraphy, when compared with previous oxygen isotope and foraminiferal paleotemperature curves determined on the same sequences (Fig. 2) by Devereux *et al.* (*6*), indicates pronounced cold phases in the New Zealand Middle Pliocene (Waipipian stage), the Late Pliocene (upper Mangapanian), and at the beginning of the currently accepted

Pleistocene [lower Hautawan (*6*)]. Additional cold intervals indicated by cold-water megafaunas (*7*) coincide with the two Hautawan limestone members of the Pukenui Limestone (Fig. 2).

In terms of magnetic stratigraphy and chronology the first major Pliocene cooling (2.50 to 2.30 million years ago; Middle Pliocene) spans the Gauss-Matuyama boundary; the late Pliocene cooling (2.13 to 2.10 million years ago) coincides approximately with the lower part of the Olduvai event; and the Early Pleistocene cooling (1.98 to 1.88 million years ago) approximates the upper part of the Olduvai event (Fig. 2). At least one and possibly two cool intervals (1.77 to about 1.61 million years ago) shown by Vella and Nicol (*7*) coincide with the Gilsá event. According to the data (Fig. 2), sea temperatures during the intermediate warmer oscillations were not significantly warmer than at present-day similar latitudes (*6*). Uniform warm-water conditions existed during most of Gauss time, except for a slight cooling coinciding approximately with the end of the Kaena (?) event (2.80 million years ago).

The position and age of the climatically defined Plio-Pleistocene boundary (based on the first severe cooling) and the stratigraphically defined boundary (based on correlation with the Calabrian stage in southern Italy) have been examined by many workers (*17–20*). Our data are relevant to the interpretation of both definitions, and we first discuss the position of the climatically determined boundary.

The currently accepted Plio-Pleistocene boundary in New Zealand is climatically determined (*4*) and is at the boundary between the Waitotaran (Mangapanian) and Hautawan stages (*18*). A duration of 2 to 5 million years for the Pleistocene, suggested by a panel of five New Zealand scientists, was based on relative rates of evolutionary change and on sedimentation within the Cenozoic (*19*). Isotopic age determinations made by two independent groups (*21, 22*) show that the first recognized cooling is at 2.5 million years ago, in good agreement with our paleomagnetically dated first cooling in the Mangaopari Stream section (2.50 million years ago). The magnetic stratigraphy shows, however, that this cooling took place in the middle of the Pliocene, and not at the Plio-Pleistocene boundary.

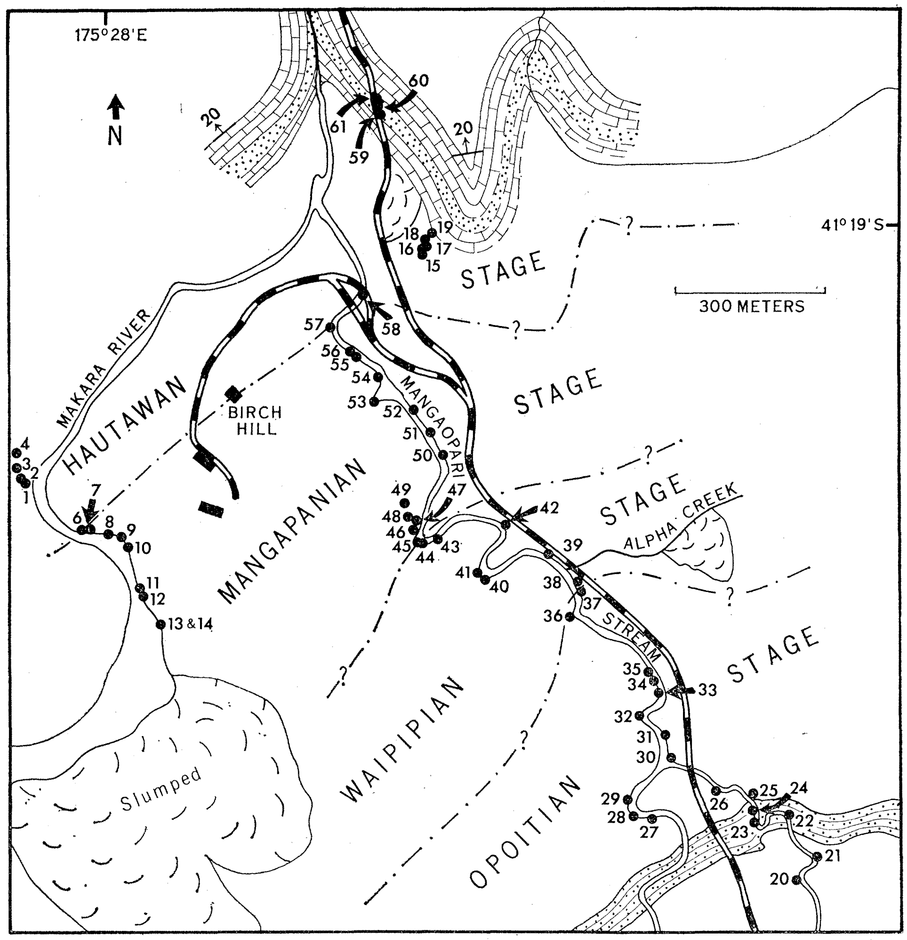

Fig. 1. Map of the Mangaopari Stream–Makara River section showing the location of paleomagnetic sample sites. Opoitian (Lower Pliocene) sandstone and Hautawan (Lower Pleistocene) limestones and sandstones are shown.

At Timaru (South Island of New Zealand), a basalt sheet with reversed polarity (*20*) overlying sedimentary rocks of earliest Pleistocene and Pliocene age (*23*) was dated at 2.5 ± 0.4 million years (*21*). This cooling is almost certainly that which spans the Gauss-Matuyama boundary. In the Wanganui Basin, the base of the Hautawan shell bed, which represents the currently accepted Plio-Pleistocene boundary, has been dated by extrapolation to be a maximum of 2.15 million years old. Beu (*24*) correlated this shell bed with the base of the Pukenui Limestone in southern Wairarapa, which we date as 1.72 million years (Fig. 2), coinciding with the Gilsá event. Either these stratigraphic units are diachronous or the radiometric age is too old by about 0.5 million years. The cooling events dated in Timaru and Wanganui are unlikely to be synchronous. Basalts thought to be at the Plio-Pleistocene boundary on the west coast of New Zealand (*22*) provided maximum ages ranging from 2.55 ± 0.1 million years to 2.3 ± 0.2 million years for the beginning of the "Pleistocene." It was concluded that the age data and limited paleomagnetic results indicated a first climatic cooling before the geomagnetic field changed from normal (Gauss) to reversed (Matuyama). Our data confirm this interpretation but indicate that the cooling is not basal Pleistocene (Hautawan) in age, as suggested from previous floral analyses (*25*), but rather is the Middle Pliocene Waipipian cooling.

Evidence for possible contemporaneous Pliocene cooling elsewhere includes pronounced faunal change in antarctic cores at about 2.5 to 3 million years (*26*), glaciations recorded in the Sierra Nevada of the United States at 2.7 million years (*27*), tillites in Iceland at 3 million years (*28, 29*), and calcium carbonate peaks reflecting cool temperatures in the upper Gauss of equatorial Pacific cores (*30*). The climatic cooling we report in the lower and middle Matuyama (Fig. 2) therefore clearly occurred elsewhere (*29, 30*).

Middle Pliocene cooling is not the

earliest major Late Cenozoic cooling reported in New Zealand. Cold-water faunas and evidence of a fall in sea level occur in the uppermost Miocene Kapitean stage (*31, 5*). The age of the Kapitean stage and supposed Miocene-Pliocene boundary in New Zealand could not be determined in our study because of a disconformity at the base of the Opoitian stage in the section (*32*).

There may be a relationship between paleoclimatic and geomagnetic polarity changes (Fig. 2). Cooling trends commonly began at, or shortly after, geomagnetic polarity changes [for example, at the top of Kaena (2.80 million years); base of Olduvai (2.13 million years); upper part of Olduvai (1.98 million years); and base of Gilsá (1.79 million years)] or cooling maxima coincided with geomagnetic reversals [for example, at the Gauss-Matuyama boundary (2.43 million years)]. Exceptions are the Mammoth (?) event and base of Kaena (?) event, which do not coincide with any climatic changes, and the top of the lower part of the Olduvai event (2.11 million years), which occurred immediately before a warming trend. Therefore, six of eight definite polarity changes are close to, or at, climatic changes. This may be interpreted to be either coincidence of two unrelated variables or to be support for an indirect connection between

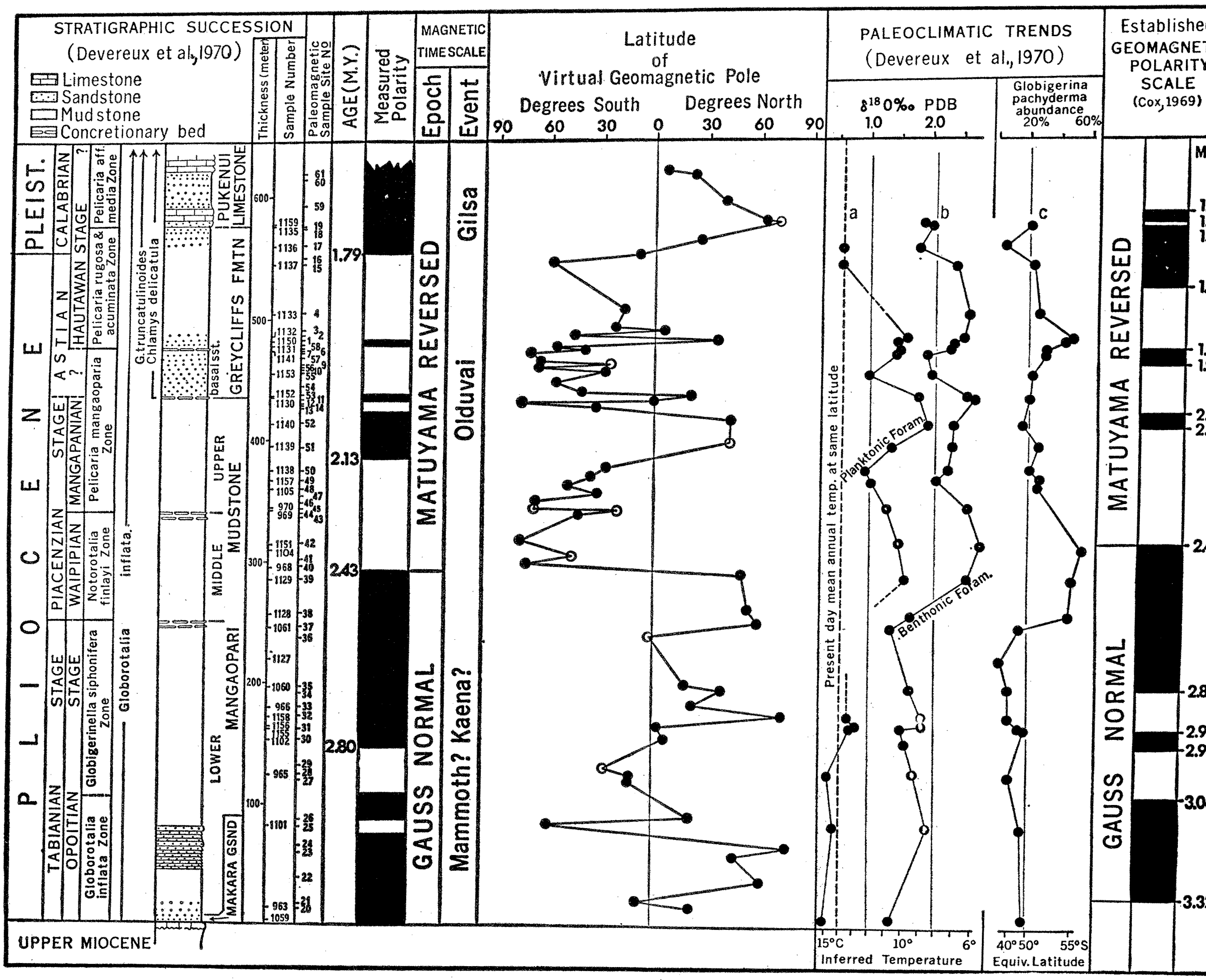

Fig. 2. Paleomagnetic stratigraphy, stratigraphic succession, and paleoclimatic trends (*6, 7*) at Mangaopari Stream–Makara River, New Zealand. Sample positions, ranges of some key fossils, local stratigraphic units, and possible European correlations are shown (*M.Y.*, million years). Magnetic polarity in the section (left polarity column) is interpreted from the latitude of the virtual magnetic pole (*12*); black is normal polarity and clear is reversed polarity, which corresponds to the latitude of the virtual geomagnetic pole being higher than 10°N and 10°S, respectively. Latitudes between 10°N and 10°S are not assigned to polarity changes for reasons including the inherent uncertainty of the position of the spin axis and axial dipole in terms of present geographic coordinates. The established geomagnetic polarity scale (*1*) is given at the far right for comparison. The ages of the polarity column are substantiated by Fig. 3. Note that the data points at each site result from the mean remanent magnetism from three separate cores after demagnetization: solid circles have a resultant vector, corresponding to a mean direction, which, for three specimens, is nonrandom at the 95 percent confidence level, whereas the few open circles represent a 5 percent possibility of randomness. For nonrandomness at the 95 percent level when there are three cores per site, the resultant vector must be 2.62, when a unit vector is assigned to each core (*39*). Two sites from a nearby section (*9*), which is stratigraphically slightly younger than the highest sample in this section, are both of reversed polarity (*40*). The paleoclimatic curves are, from left to right: (*a* and *b*) oxygen isotope ratios of planktonic and benthonic foraminiferal tests; (*c*) abundance of *Globigerina pachyderma* as a percentage of all planktonic foraminiferal tests. Note that the position of the Plio-Pleistocene boundary and the base of the Calabrian have been modified from that previously determined by Devereux *et al.* (*6*).

polarity changes, climatic variations, and faunal changes (*33*).

We now examine the evidence for the position of the stratigraphically defined Plio-Pleistocene boundary. In the first attempt at determining this boundary in New Zealand, Fleming (*34*) correlated the base of the Hautawan with that of the Calabrian on paleoclimatic evidence. A further attempt was based on the biostratigraphic succession at Mangaopari Stream (*6*), where the boundary was placed at the first appearance of *Globorotalia truncatulinoides* (at the base of the Hautawan stage) corresponding to the upper Olduvai event as shown in Fig. 2. The first definite appearance of *G. truncatulinoides* (*6*), however, is at a level coinciding with the base of the Gilsá event and near the middle of the Hautawan stage. Rare, atypical specimens, previously reported below this level as *G. truncatulinoides*, have been reexamined and are referrable to the *G. crassaformis* complex. The first appearance of *G. truncatulinoides* in tropical deep-sea cores occurs within the major normal event in the Matuyama epoch (*35*), which has often been called the Olduvai but is now regarded as the Gilsá (*1*, *36*), the base of which is dated at 1.79 million years (*1*). The first appearance of *G. truncatulinoides* gives correlation with the type Calabrian (*37*), at the base of the type Italian Pleistocene. The age of the base of the Gilsá (1.79 million years) is close to the age of 1.8 million years for the Plio-Pleistocene boundary in the Calabrian type section based on extrapolation of sedimentation rates (*38*).

We therefore place the stratigraphically defined Plio-Pleistocene boundary at the base of the Gilsá and first definite appearance of *G. truncatulinoides*. This level occurs near the middle of the Hautawan stage, the base of which is the generally accepted position for the Plio-Pleistocene boundary in New Zealand. The coincidence of the first appearance of *G. truncatulinoides* with the base of the Gilsá in our section strongly supports the coincidence of the Gilsá event with at least part of the Calabrian stage. As both Italy and New Zealand are in temperate latitudes, it is likely that there was little or no lag between the two areas in the first appearance of *G. truncatulinoides*.

We conclude that marked cooling occurred much earlier than the stratigraphically defined beginning of the Pleistocene, which is at the base of the Gilsá geomagnetic polarity event.

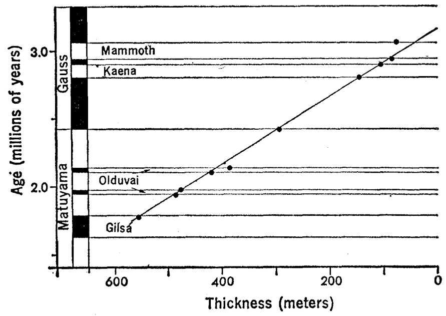

Fig. 3. Sedimentation rate diagram. The paleomagnetic polarity boundaries (Fig. 2) in the Mangaopari Stream–Makara River section are plotted against the assigned ages resulting from the known geomagnetic polarity history (*1*). In the ordinate, polarity epochs are in vertical print; polarity events are in smaller horizontal print; normal polarity is in black; and reversed polarity is clear. The slope of the line indicates a linear sedimentation rate of 40 cm per 1000 years for the section.

Correlations of a climatically defined Plio-Pleistocene boundary, when the first marked climatic cooling is used, are unlikely to be valid. The Pliocene epoch would be eliminated if the first marked late Cenozoic climatic cooling is taken as the beginning of the Pleistocene, because the first known major cooling took place in Late Miocene time (*5*, *31*). We have shown that paleomagnetic dating of marine sediments now exposed on land can assist in correlation of Plio-Pleistocene strata and climatic changes. The extension of this method to marine sediments exposed on land will hopefully contribute significantly to definition of the geomagnetic polarity history.

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References and Notes

1. A. Cox, *Science* **163**, 237 (1969). Unless otherwise stated, all age assignments of the known geomagnetic history are after this most recent compilation.
2. N. D. Opdyke, B. Glass, J. D. Hays, J. Foster, *Science* **154**, 349 (19[illegible] N. D. Watkins and H. G. Goodell, *Earth Planet. Sci. Lett.* **2**, 123 (1967).
3. H. Nakagawa, N. Niitsuma, I. Hayasaka, *J. Geol. Soc. Japan* **75**, 267 (1969).
4. C. A. Fleming, *Trans. Roy. Soc. N.Z.* **74**, 207 (1944).
5. J. P. Kennett, *Int. Union Geol. Sci. Comm. Mediter. Neogene Stratigr. G. Geol. Annoli Mus. Geol. Bologna* **35**, 143 (1969).
6. I. Devereux, C. H. Hendy, P. Vella, *Earth Planet. Sci. Lett.* **8**, 163 (1970).
7. P. Vella and W. H. Briggs, Jr., *N.Z. J. Geol. Geophys.*, in press; P. Vella and E. R. Nicol, *ibid.*, in press.
8. A. U. E. Boreham, *ibid.* **6**, 3 (1963).
9. Two additional sites were drilled in slightly younger (Marahauan) sediments 2 km north of the Mangaopari Stream section in the Huangaroa River, 0.5 km downstream from Hautotara Bridge. The stratigraphic thickness between this location and the highest sample (sample 61) in the Mangaopari Stream section is still unknown. Sample 62 is from marine fossiliferous mudstone in the east side of the river and the other (sample 63) is from slightly younger conformable lignitic mudstone on the west side of the river.
10. J. H. Foster, *Earth Planet. Sci. Lett.* **1**, 463 (1966).
11. M. W. McElhinny, *Geophys. J. Roy. Astron. Soc.* **10**, 369 (1966).
12. The virtual geomagnetic pole is that pole resulting from a geocentric axial dipole that causes the observed declination and inclination of remanent magnetism at the sample site.
13. D. C. Krause, *N.Z. Dep. Sci. Ind. Res. Bull.*, No. 183 (1967).
14. A. G. Fisher, *Geol. Soc. Amer. Bull.* **80**, 549 (1969).
15. For example, see N. D. Watkins and H. G. Goodell, *Science* **156**, 1083 (1967).
16. N. D. Watkins, *Earth Planet. Sci. Lett.* **4**, 341 (1968).
17. For summary, see I. McDougall and J. J. Stipp, *Nature* **219**, 51 (1968) and (*18–20*).
18. I. McDougall and J. J. Stipp, *Nature* **219**, 51 (1968).
19. D. F. Squires, *N.Z. J. Geol. Geophys.* **3**, 137 (1960).
20. D. S. Coombs and T. Hatherton, *Nature* **184**, 883 (1959).
21. W. H. Mathews and G. H. Curtis, *ibid.* **212**, 979 (1966).
22. J. J. Stipp, J. M. A. Chappell and I. McDougall, *Amer. J. Sci.* **265**, 462 (1967).
23. H. S. Gair, *N.Z. J. Geol. Geophys.* **4**, 89 (1961).
24. A. G. Beu, *ibid.* **12**, 643 (1969).
25. R. A. Couper and D. R. McQueen, *N.Z. J. Sci. Technol. Sect. B* **35**, 398 (1954).
26. J. D. Hays and N. D. Opdyke, *Science* **158**, 1001 (1967).

R. R. Curry, *ibid.* **154**, 770 (1966).

28. M. G. Rutten and H. Wensink, *Int. Geol. Congr. Rep. Session, Norden 21st, Part 4*, **1960**, 62 (1960).
29. I. McDougall and H. Wensink, *Earth Planet. Sci. Lett.* **1**, 232 (1966).
30. J. D. Hays, T. Saito, N. D. Opdyke, L. H. Burckle, *Geol. Soc. Amer. Bull.* **80**, 1481 (1969).
31. J. P. Kennett, *N.Z. J. Geol. Geophys.* **10**, 1051 (1967).
32. In addition to lithological evidence for disconformity, well-developed *Globorotalia inflata* occurring immediately above the disconformity suggest that much of the lower Opoitian is missing. Typical *G. inflata* has not been observed in the lower Opoitian of several other New Zealand sections examined by one of us (J.P.K.) but seems to first appear higher in the Opoitian.
33. J. P. Kennett and N. D. Watkins, *Nature* **227**, 930 (1970); J. R. Heirtzler, *J. Geomagn. Geoelec.* **22**, 197 (1970).
34. C. A. Fleming, *N.Z. Geol. Surv. Bull.*, No. 52 (1953).
35. W. A. Berggren, J. D. Phillips, A. Bertels, D. Wall, *Nature* **216**, 253 (1967); J. D. Phillips, W. A. Berggren, A. Bertels, D. Wall, *Earth Planet. Sci. Lett.* **4**, 118 (1968); B. Glass, D. B. Ericson, B. C. Heezen, N. D. Opdyke, J. A. Glass, *Nature* **216**, 437 (1967).
36. N. D. Watkins and A. Abdel-Monem, *Geol. Soc. Amer. Bull.*, in press.
37. D. D. Bayliss, *Lethaia* **2**, 133 (1969).
38. R. Selli, *Progr. Oceanogr.* **4**, 67 (1967).
39. S. A. Vincenz and J. M. Bruckshaw, *Proc. Cambridge Phil. Soc.* **56**, 21 (1960).
40. These two sites are important because they show that the normal polarity at the top of the Mangaopari section, identified as the Gilsá event (1.79 to 1.61 million years ago), is not the Brunhes geomagnetic polarity epoch.
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