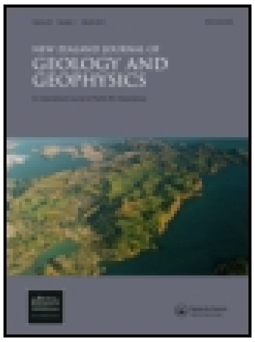


New Zealand Journal of Geology and Geophysics

ISSN: 0028-8306 (Print) 1175-8791 (Online) Journal homepage: http://www.tandfonline.com/loi/tnzg20

Geophysical study of the Taharoa ironsand deposit, west coast, North Island, New Zealand

Donald C. Lawton & Manfred P. Hochstein

To cite this article: Donald C. Lawton & Manfred P. Hochstein (1993) Geophysical study of the Taharoa ironsand deposit, west coast, North Island, New Zealand, New Zealand Journal of Geology and Geophysics, 36:2, 141-160, DOI: 10.1080/00288306.1993.9514564

To link to this article: http://dx.doi.org/10.1080/00288306.1993.9514564

New Zealand Journal of Geology and Geophysics, 1993, Vol. 36: 141–160

0028–8306/93/3602–0141 $2.50/0

Geophysical study of the Taharoa ironsand deposit, west coast, North Island, New Zealand

DONALD C. LAWTON
Department of Geology and Geophysics
The University of Calgary
2500 University Drive N.W.
Calgary, Alberta T2N 1N4, Canada

MANFRED P. HOCHSTEIN
Geothermal Institute and Geology Department
The University of Auckland
Private Bag
Auckland, New Zealand

Abstract The Taharoa prospect is one of the many beach and dune deposits of titanomagnetite sands ("ironsands") along the west coast of the North Island of New Zealand. Various geophysical methods were used to determine which of these is suitable for delineating titanomagnetite concentration patterns in the deposit, which covers an area of c. 15 km^2, and whether a reliable estimate of the total mass of titanomagnetite ore could be obtained.

Seismic refraction studies provided a detailed structural model of the deposit. Interpretation of these data, controlled in part by a few deep exploratory holes, defined an upper horizon of unconsolidated, titanomagnetite-rich sands (Nukumiti and Paparoa Sands Members) reaching a maximum thickness of 60 m. It is underlain by a weakly cemented, saturated sand layer (Te Akeake Sands Member) up to 100 m thick, with an average titanomagnetite concentration of about 18%. The two horizons are separated by a 42 ka old layer of tephras and paleosols up to 15 m thick. The compressional-wave seismic velocity of the upper, dry, enriched sands is very low, and increases linearly with depth from about 0.24 km/s to a maximum of 0.65 km/s, with a rate of increase between 18 and 32/s. The velocity of the lower horizon is almost constant at 1.7 ± 0.1 km/s. Mesozoic greywacke basement with a velocity of 4.1 ± 0.7 km/s underlies the deposit.

The concentration of titanomagnetite within the seismic model was determined by detailed interpretation of airborne magnetic surveys flown at altitudes of 185 m and 370 m above sea level. Residual anomalies were obtained after reducing the magnetic effect of the entire deposit, assuming a homogeneous induced magnetisation of 6.7 A/m (equivalent to that of sand with 18% by weight of titanomagnetite). The residuals were interpreted in terms of an array of vertical prisms representing the enriched Nukumiti and Paparoa sands. Magnetic susceptibilities of up to 0.75 were interpreted, corresponding to a titanomagnetite concentration of 54% by weight.

Although titanomagnetite concentrations in the sands can produce a gravitational effect of up to 10 $\mu m/s^2$, residual gravity anomalies could not be used to assess concentration patterns independently because the anomalies are disturbed by larger effects associated with the irregular greywacke basement. However, gravity interpretation models were used to define the depth to basement rocks in areas not covered by the seismic surveys. Tests showed that titanomagnetite sands at Taharoa are nonconductive; electrical resistivity, IP, and EM methods could not be used to define ore concentrations.

The total mass of titanomagnetite in the Taharoa deposit was obtained by combining the magnetic and seismic models. The Nukumiti and Paparoa Sands Members contain a total of 205 ± 30 million tonnes of titanomagnetite ore within sands with an average concentration of 38% (by weight). An additional 360 ± 75 million tonnes of titanomagnetite are contained in the Te Akeake Sands Member, but at a lower concentration of about 18% by weight.

Keywords Taharoa; titanomagnetite; magnetic; ironsands; geophysical exploration; gravity; seismic; density; modelling; ore

INTRODUCTION

Titanomagnetite sands (ironsands) form coastal dune, beach, and deltaic deposits along many parts of the circum-Pacific margin (Ohmachi 1960). The ironsands are derived from weathering of Cenozoic volcanic rocks associated with volcanic arcs. Some deposits of Tertiary age occur in Japan (Hattori 1960); other large deposits accumulated in the North Island of New Zealand during the Pleistocene (Williams 1974). A few deposits are of Holocene age and some are still aggrading. The most important constituent mineral in many ironsand deposits is titanomagnetite, $FeO(Fe,Ti)_2O_3$, which may comprise up to 80% by weight of some beach deposits (Kear 1979). Since pure titanomagnetite contains 60% Fe by weight, many ironsand deposits are important iron ore resources. This has long been recognised in Japan, where ironsand mining commenced in the Izumo region in A.D. 733 (Hattori 1960).

In New Zealand, titanomagnetite sands occur along much of the west coast of the North Island, from Wanganui in southern Taranaki, to Kaipara Harbour in Northland (Fig. 1). From 1940 to 1947, reconnaissance geological investigations of ironsand deposits south of New Plymouth were undertaken and quantities of titanomagnetite were estimated from stratigraphic data (Hutton 1940, 1945; Fleming 1946; Beck 1947). Nicholson & Fyfe (1958) made a survey of the coastline from New Plymouth to the Kaipara Harbour, and they noted significant ironsand deposits at Mokau, Marakopa, Taharoa, Kawhia, Aotea Harbour, Raglan, Waikato Heads, Manukau Heads, Piha, and Muriwai (Fig. 1). Most of these deposits were subsequently investigated with shallow (up to 7 m deep) drillholes.

G91027
Received 30 July 1991; accepted 26 January 1993

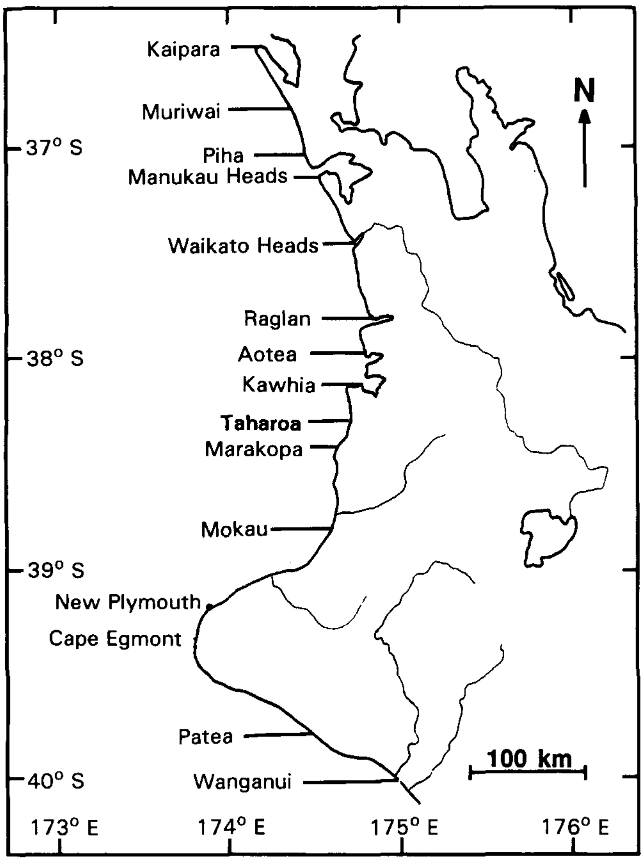


Fig. 1 Distribution of titanomagnetite sand deposits, North Island, New Zealand. The Taharoa deposit is highlighted.

Between 1957 and 1962, a comprehensive study was undertaken by the New Zealand Department of Scientific and Industrial Research (DSIR) for the New Zealand Steel Investigating Company (Kear 1979). As part of that project, extensive scout drilling programs tested many of the North Island west coast ironsand deposits. Kear (1979) calculated total reserves of 570×10^6 tonnes (t) of titanomagnetite, of which 190×10^6 t were proven by drilling, and the remainder were inferred reserves above sea level.

Ironsands offshore from the west coast were investigated by McDougall (1961) and Carter (1980). Generally, they found low concentrations (1–5%) in surficial seafloor sediments on the continental shelf, with local, richer concentrations near Patea, New Plymouth, and Waikato Heads (Fig. 1).

Before the present study, the exploration of coastal ironsand deposits had been based mainly on drilling and mapping to predict the volume and grade of the titanomagnetite sands. Whether a representative mean of the titanomagnetite concentration can be obtained by an irregular array of exploration drillholes is a fundamental problem of ironsand exploration. Drilling results reported by Kear (1979) and Waterhouse (1969) showed significant lateral and vertical variations in the concentration of titanomagnetite in the deposits tested.

The primary goal of this study was to assess the applicability of geophysical methods for delineating the vertical and lateral concentration patterns of titanomagnetite in New Zealand ironsand deposits. In addition, we attempted to determine whether the geophysical studies could provide reliable estimates of titanomagnetite ore reserves.

Geophysical exploration of ironsand deposits has in the past been limited to ground magnetic surveys, designed to assess the lateral extent of near-surface magnetic sands; the data were not used to obtain quantitative estimates of ore reserves. A survey by Coss (1959) in New South Wales, Australia, indicated that magnetic anomalies occur over heavy mineral beach concentrations containing zircon, rutile, ilmenite, and magnetite. Total force (ΔT) magnetic surveys were used to locate magnetite placer deposits offshore in Japan (Hattori 1960). In New Zealand, vertical magnetic intensity (ΔZ) surveys were made by the DSIR over ironsand deposits at Waikato Heads, Raglan, Kawhia, and New Plymouth (Kear 1979). However, no quantitative interpretation was made apart from some simple model calculations to explain anomalies caused by near-surface titanomagnetite enrichments. Untung & Hanna (1975) reported the results of a geophysical study of coastal titanomagnetite sands in East Java, where magnetic, gravity, resistivity, and seismic refraction surveys were made over 2.5 km^2 of coastal sands near Lumajang. They concluded that magnetic surveys, together with boreholes, can be used in delineating shallow ironsand deposits, and that gravity, resistivity, and seismic surveys can provide information about deeper structures. Integrated geophysical studies over heavy-mineral deposits in Australia were also reported by Robson & Sampath (1977) and Hone (1986).

Ironsand deposits at Taharoa, Waikato North Head, and Raglan (Fig. 1) were selected for our geophysical studies. The field surveys, undertaken between 1974 and 1977, were complemented by laboratory measurements which showed that the density and magnetic susceptibility of ironsand samples are closely related to the concentration (weight percent) of titanomagnetite (Lawton & Hochstein 1980). All studies have been described in detail by Lawton (1979). The present paper, as opposed to Lawton (1979), deals specifically with the geophysical surveys of the Taharoa deposit. A summary of some of the geophysical results was reported by Stokes et al. (1989)

GEOLOGY OF THE TAHAROA DEPOSIT

The geology of the Taharoa district is described by Henderson & Grange (1926) and Marwick (1946). The coastal cliffs north and south of Taharoa (Fig. 2) are formed by eastward-dipping greywacke of the western limb of the New Zealand Geosyncline. The northern boundary of the Taharoa ironsand deposit is made up by stocks of upper Miocene Orangiwhao Dacite (Martin 1967). In coastal areas, eolian, littoral, estuarine, and shallow-marine sediments of Quaternary age have infilled embayments and low-lying valleys, forming sandspits, bars, and active dune-fields. Tephras and associated paleosols are distinctive marker horizons within some of the Recent eolian deposits. The upbuilding and inland encroachment of eolian sand has caused ponding of streams which drain the hinterland, resulting in the formation of Lakes Taharoa, Nukumiti, and Rotoroa (Fig. 2) as well as swampy areas.

The stratigraphy of the Quaternary sands is summarised in Table 1 and the geology of the deposit is shown in Fig. 2. Brothers (1954) included the sands of the Taharoa deposit in the Kaihu Group. This group was enlarged and subdivided by

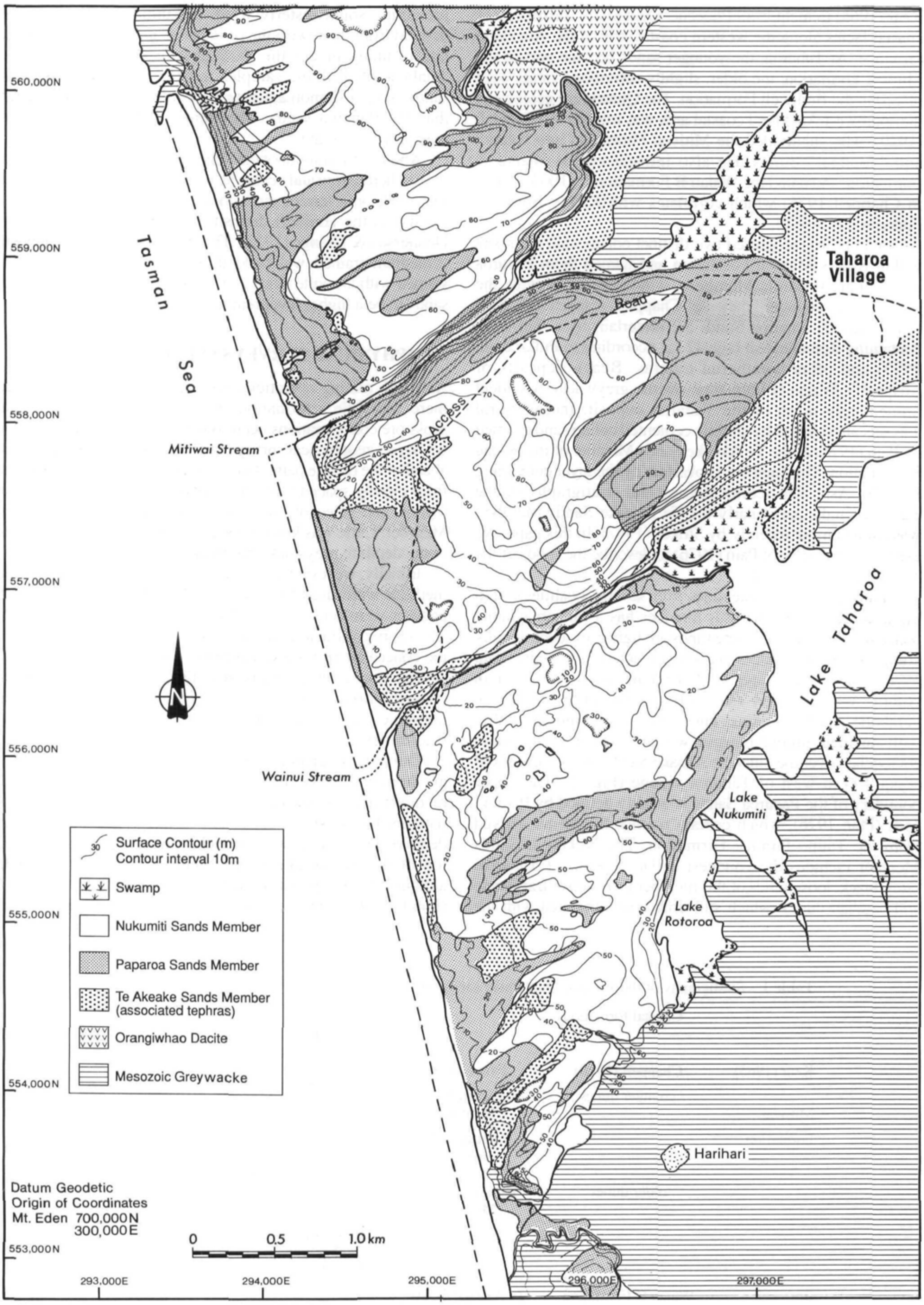


Fig. 2 Geological map and surface topography of the Taharoa titanomagnetite sand deposit.

Kear (1965) to include all Pliocene–Quaternary formations of coastal facies along the western coastal strip of the Auckland Province. At Taharoa, the younger sands became part of the Mitiwai Formation; the older, slightly compacted sands were placed in the Bothwell Formation. The Quaternary geology of the southwest Auckland coastal area was revised by Chappell (1970), who subdivided the Mitiwai Formation into "older" and "younger" dunes. He also introduced the Waiau A Formation, and dated the Waiau B Formation (c. 100 ka; cited in Chappell 1975) which correlates with Kear's Bothwell Formation (Table 1).

Pain (1976) recognised two distinct eolian sand members within Kear's Mitiwai Formation and named them Paparoa and Nukumiti Sands Members, which correlate with the "older" and "younger" dunes of Chappell, respectively. Pain found that the Paparoa Sands are underlain by a thin layer containing Rotoehu Ash (age 42 ka, according to Pullar et al. 1973) and other weathered tephras. Beach deposits of Chappell's Waiau B Formation overlie greywacke basement immediately north of the Taharoa deposit; these littoral deposits are covered by slightly cemented eolian sands named by Pain (1976) as the Te Akeake Sands Member of the Waiau B Formation. This member is overlain by the layer containing Rotoehu Ash. The sedimentology and stratigraphy of the Taharoa sands, particularly the Te Akeake Sands Member, was studied more recently by Stokes (1987). In this paper we use the stratigraphy of Pain (1976) to describe the sands of the Taharoa deposit (Fig. 2).

Analysis of Te Akeake sands from several localities within the deposit indicate that this member has a titanomagnetite concentration of c. 18%. The sands are light grey, occasionally compacted, and, in places, weakly cemented by limonite (Pain 1976). Sands of the Paparoa Member are loose, grey-black in colour, and relatively rich in titanomagnetite (25–50%). Parabolic and longitudinal dune forms are common, with a well-defined inland margin which formed as the sand encroached over the older Te Akeake Sands and became fixed about 400 m west of Taharoa village (Fig. 2). The upper boundary of the Paparoa Sands is weakly defined by Parangi soils (Pain 1976), which contain pumice fragments derived from the Taupo Pumice Formation. The Nukumiti Sands Member includes the youngest eolian deposits at Taharoa. Grey-black, loose sands of this member form active transverse and barchan dunes, which still drift across the area with the prevailing southwesterly wind. Nukumiti sands are partly derived from the reworking of Paparoa and Te Akeake sands, and in many places the Parangi soils have been eroded. Analysis of drillhole samples indicates that the Nukumiti sands have a titanomagnetite concentration slightly higher than the Paparoa sands, with values of up to 55% titanomagnetite by weight.

About 0.5 km south of the Taharoa deposit, a small outcrop of weathered ironsand occurs at an elevation of c. 150 m above sea level, on a terrace cut into the greywacke (Fig. 2). It is known as the Harihari deposit and was first described by Henderson & Grange (1922). The sand in the Harihari deposit is medium grained, well bedded, and is strongly cemented and stained with limonite. Kear (1979) considered these cemented sands to be a higher level remnant of the Awhitu Formation.

GEOPHYSICAL SURVEYS SELECTED

Although mining operations had started at Taharoa in 1972, there was little information available that indicated where gross ore concentrations occur outside the central area. When we began geophysical surveys in 1974, concentration patterns ahead of the dredge path of the mining activities were assessed from closely spaced (100 m) drillholes that all terminated in tephras and paleosols near the top of the Te Akeake Sands Member. Little was known about the thickness of these sands or the depth to greywacke basement.

Initially, we tested several geophysical methods. Electrical methods were used to check whether known concentration patterns were detectable by electrical conductance anomalies. The seismic refraction method was used to determine whether the concealed greywacke basement could be mapped. Other, similar tests at Waikato Heads (Fig. 1) showed that gross concentration patterns could be recognised from airborne magnetic surveys and sometimes by detailed gravity surveys (Lawton 1979).

Out tests at Taharoa showed that the titanomagnetite sands are nonconductive and that DC resistivity, IP, and EM methods are not suitable for delineating ore concentration patterns. DC resistivity soundings, however, indicated that the depth to the conductive, clay-rich, saturated paleosols at the top of the Te Akeake Sands Member could be assessed, although the interpretation suffers from equivalence problems (Lawton 1979). The seismic tests were encouraging because

Table 1 Stratigraphy of the Taharoa Quaternary sands (after Pain 1976).

Coastal formations			Tephra formations	Age (yr B.P.)
Kear (1965)	Chappell (1970)	Pain (1976)		
Mitiwai Formation	'younger dunes'	Nukumiti Sands Member		post-Maori occupation
		Parangi soils -erosion	Taupo Pumice Formation	c. 1850
	'older dunes'	Paparoa Sands Member		
			Late Quaternary tephra with Rotoehu Ash	41 700 ± 3500
Bothwell Formation	Waiau B Formation	Te Akeake Sands Member		< 83 000– c. 107 000

refracted arrivals from the greywacke basement were recorded.

After evaluating the results of the test surveys at Taharoa and Waikato North Head, we decided to investigate the Taharoa ironsand prospect by using detailed seismic, magnetic, and gravity surveys. The results of these surveys are described in this paper.

REFRACTION SEISMIC SURVEY

The refraction seismic survey was undertaken to determine the geometry of sand bodies within the deposit, and to obtain depth constraints for the interpretation of magnetic and gravity data. Profiles were selected to cross scout boreholes throughout the deposit; additional control was available from closely spaced (100 m) drillholes in the active mining area south of Wainui Stream. The seismic lines and drillhole control are shown in Fig. 3. A total of 12.5 line-kilometres of data were acquired using a 24-channel Texas Instruments DFS II recording system. Each spread was 575 m long with a geophone interval of 25 m. Single, 30 Hz geophones were used, buried c. 0.5 m below the ground surface to improve energy coupling.

Seven shots were fired into each spread, comprising five shots spaced equally along the spread and two shots offset 600 m from each end. Most shot holes were 1.5–2.0 m deep, and the near-surface P-wave velocity was obtained by placing an uphole geophone adjacent to the shot hole. The energy source was *AN Polar 60* gelignite with charges of 0.3–0.5 kg used for in-spread shots, and up to 2.0 kg for the offset shots. Generally, the first arrivals observed were sharp, but severe energy attenuation was noticeable over the higher sand dunes. Seismic data were recorded on photographic paper and stored on digital magnetic tape.

Velocity structure of Nukumiti and Paparoa sands

Analysis of the uphole times of most shots yielded an average velocity of 240 ± 40 m/s for the unconsolidated surface sands. However, first-arrival traveltime data on the near traces of seismic records showed a nonlinear behaviour, indicating that the compressional-wave velocity in the unconsolidated sands increases with depth. This velocity-depth relationship was investigated in two borehole velocity surveys.

The first borehole was located on a high dune in the central area of the deposit, 100 m southwest of shot point A13 (labelled "Q Line Uphole" in Fig. 3). It was drilled to a depth of 38 m, ending at the water table in Paparoa sands. For the experiment, charges of 0.2 kg were fired successively at 3 m intervals in the hole. Recorded uphole times are plotted versus depth in Fig. 4. The scatter in the traveltimes for shallow charges is caused by the disruption of uncompacted sand around the borehole during drilling. Projected traveltimes from geophones offset 10 m from the borehole collar show significantly less scatter. At shallow (<20 m) depths, the traveltime data in Fig. 4 can be fitted by assuming a linear velocity increase with depth, given by:

$$V_z = V_0 + kz \qquad (1)$$

where V_0 is the surface velocity, z is the depth, and k is the rate of velocity increase with depth (k-factor). It can be shown (Lawton 1979) that the one-way time, T_z, to a depth z is given by:

$$T_z = \left(\frac{1}{k}\right) \ln \left[\frac{V_0 + kz}{V_0}\right] \qquad (2)$$

Using a surface velocity V_0 = 240 m/s, the data in Fig. 4 fit a theoretical curve generated using a k-factor of 18.5/s in equation (2). At depths >21 m, the observed traveltimes indicate a constant velocity (V_{max} = 650 m/s).

A similar analysis was undertaken for the velocity test in a second borehole, which was located near shot point R14 (designated "R Line Uphole" in Fig. 3). A k-factor of 28.5/s was obtained for the unconsolidated sands, and again a constant velocity of 650 m/s was observed, in this case, below a depth of 16 m.

Analysis

Ewing & Leet (1932) showed that the raypaths of waves obeying a linear velocity-depth function are circular, and that the traveltime, T_x, along a ray emerging at a distance x from the shotpoint is given by:

$$T_x = \left(\frac{2}{k}\right) \sinh^{-1} \left[\frac{kx}{2V_0}\right] \qquad (3)$$

Using equation (3), theoretical traveltime-distance curves were calculated for a range of k-factors. These curves were matched with observed traveltime data and showed that the k-factor varies from 18–32/s between different areas of the deposit. The lowest values were observed over the highest sand dunes, which implies that the k-factor is related to compaction of the sand.

As examples of the data analysis, observed first-arrival data and interpreted sections along profiles A and R are shown in Fig. 5 and 6, respectively. Clearly, the traveltime data (Fig. 5A, 6A) are distorted by the effects of topography and the low near-surface velocities. To assist the analysis, the effects of topography were removed by reducing the observed traveltimes to values which would have been observed if the shot points and geophones were placed on a datum plane that was chosen to coincide with the water table. For the reductions, the k-factor in the upper layer was determined at each shotpoint using curves generated from equation (3). An average value of 24.2/s was obtained along profiles A and R and ranged from 18.5/s over the highest dunes, to 28.5/s in lower lying areas where the sand is more compacted. The k-factors at geophone stations between shot points were obtained by interpolation. Analysis of the reduced data proceeded using standard delay time (Gardner 1939) and plus-minus (Hagedoorn 1959) methods.

Interpretation

For the interpretations shown in Fig. 5B and 6B, the surface layer of sand with a linearly increasing velocity with depth is designated layer 1, and the dry, compacted sands with a constant velocity V_2 = 650 m/s are combined into layer 2. Underlying the dry sands is a refractor (layer 3) which has a lithology and velocity that varies considerably over the deposit. At the western end of profile A (Fig. 5B), layer 3 is actually exposed at the surface, where it is comprised of a clay-bound, damp Te Akeake paleosol with a velocity V_3 = 800 m/s. To the east along profile A, the velocity of this layer increases, due probably to increasing compaction and water saturation, reaching 1120 m/s near shotpoint A17 (Fig. 5B). In contrast, along profile R (Fig. 6B), layer 3 has a constant velocity V_3 = 1500 m/s, and its lithology is interpreted to be saturated, unconsolidated Paparoa sands. The refracting interface in this area is the top of the water table which is at an elevation close to that of Lake Taharoa (11 m above sea level).

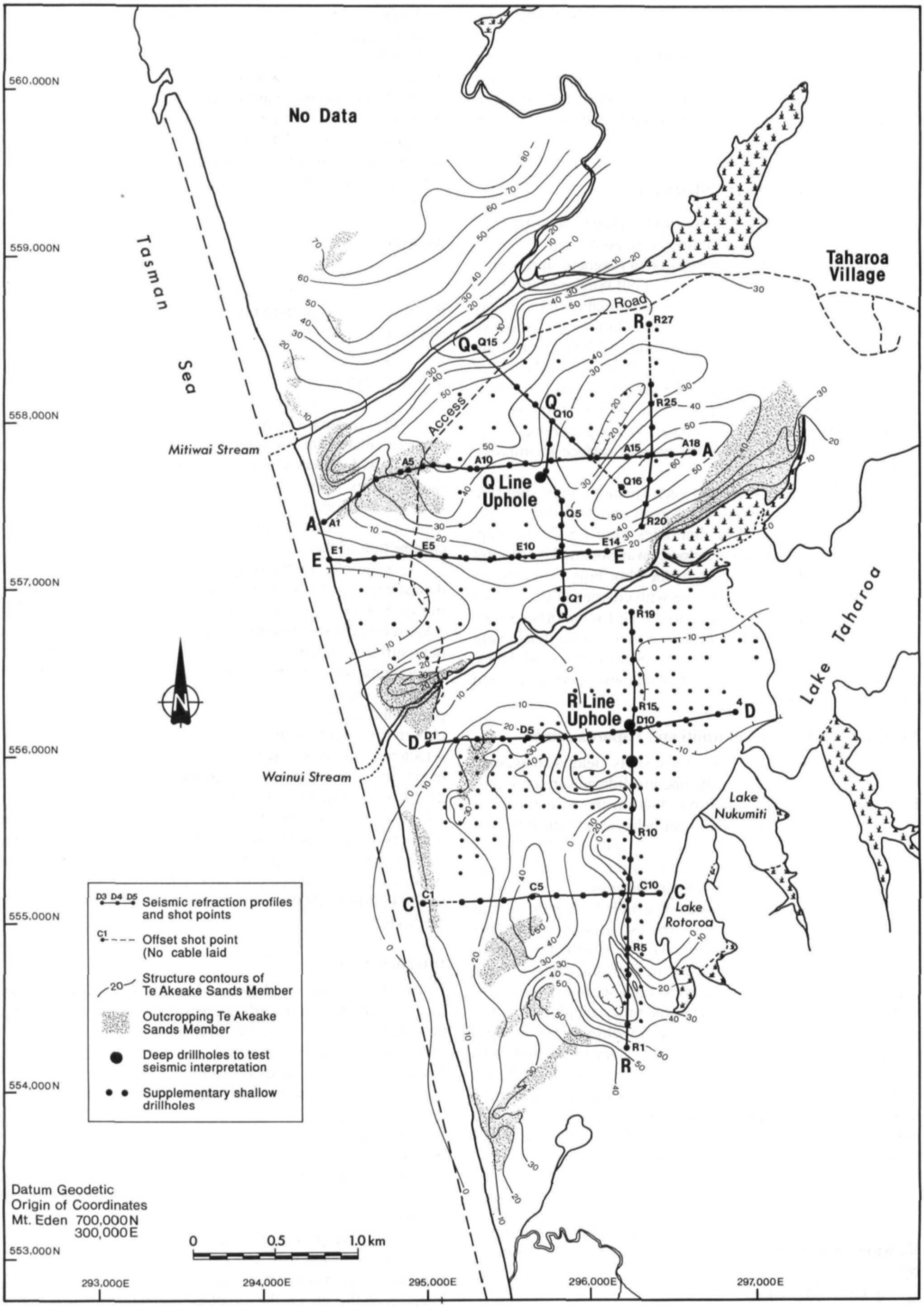


Fig. 3 Refraction seismic profiles, drillhole control, and the topography of the top of the Te Akeake Sands Member.

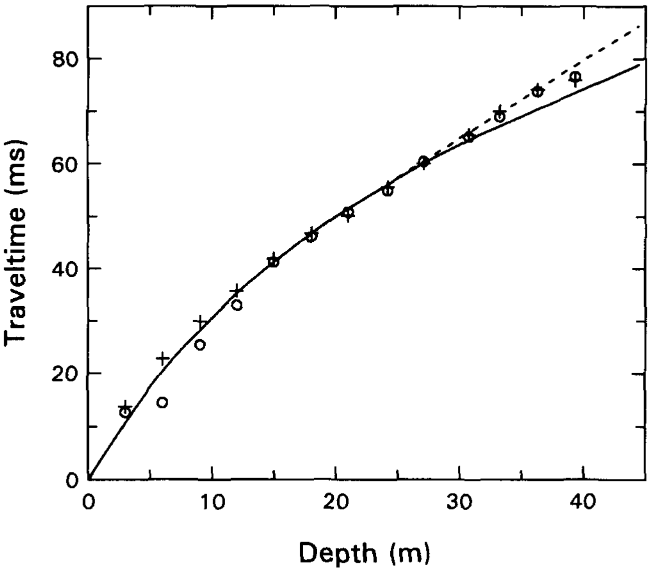


Fig. 4 Results of the Q-line borehole velocity survey. Open circles are observed uphole traveltimes; crosses are uphole traveltimes projected from 10 m offset; the solid line represents the relationship $V_z = 240 + 18.5\,z$ (m/s); the dashed line represents a constant velocity of 650 m/s.

Although the saturated, unconsolidated sand and weathered clay-bound sand components of layer 3 are stratigraphically different, they cannot be distinguished by the seismic analysis. Layer 3 is underlain by layer 4 which has a velocity (V_4) of 1600–1800 m/s. It is composed of massive, weakly cemented Te Akeake sand. Greywacke basement, with a velocity (V_5) of 3400–4800 m/s, underlies layer 4.

A contour map of the top of Te Akeake sand is shown in Fig. 3. In areas between the seismic profiles, some drillhole data were available, and outcrop control (Fig. 2) was also used to assist in construction of this map. To the south of Wainui Stream, the top of the Te Akeake Sands Member forms a north–south-trending ridge along the western side of the deposit, where it attains elevations of up to 50 m above sea level. East of this ridge, near Lake Taharoa, the top of Te Akeake sand drops to 10 m below sea level. Between Wainui and Mitiwai Streams, this interface rises from the coast to a general elevation of about 40 m. Ancient dunes with a northeasterly trend are apparent in this region (Fig. 3) and are still visible in the present topography (Fig. 2) where the younger sands thin. A depression in the top of the Te Akeake Sands Member immediately south of profile E is interpreted to be an ancient stream channel.

The morphology of the greywacke/Te Akeake sand interface was defined using a combination of gravity and refraction seismic data and is discussed later, following the gravity analysis.

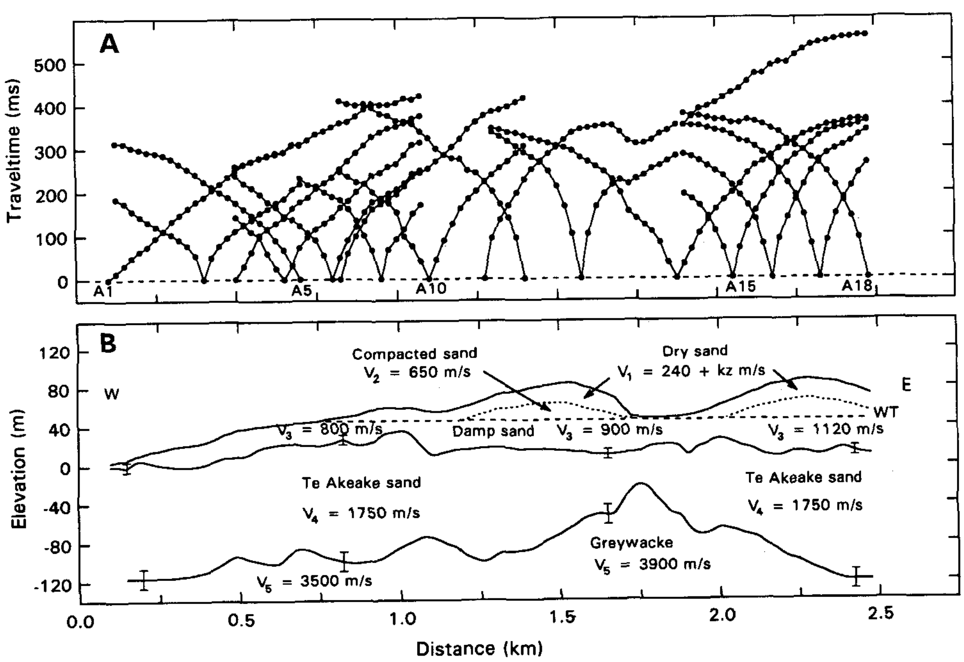
Errors

Observed first-arrival traveltimes in the seismic records could be picked to within ±1 ms. Errors in both V_0 and the k-factor tend to cancel because an erroneously high surface velocity is compensated by a low k-factor. However, because the velocities of layers 1 and 2 are so low, errors in the computed thicknesses of these layers will have an effect on the interpretation of deeper structures. For example, given a nominal thickness of 20 m for layers 1 and 2, an error of ±20 m/s in V_0 and ±2/s in the k-factor results in an error of about ±4 ms in traveltimes reduced to the datum level. For average velocities V_4 = 1750 m/s and V_5 = 3500 m/s, this results in an error of c. ±6 m in the level of the V_3/V_4 interface and ±12 m in that of the V_4/V_5 interface. These errors may be slightly greater between shot points where the k-factors were obtained by interpolation.

AIRBORNE MAGNETIC SURVEYS

Airborne magnetic surveys were conducted over the Taharoa deposit at elevations of 185 ± 20 m and 370 ± 20 m above sea level. The two flight levels were surveyed to obtain additional

Fig. 5 Refraction seismic survey, seismic profile A. **A**, First arrival traveltimes versus distance. **B**, Interpreted cross-section. For location of profile, see Fig. 3.



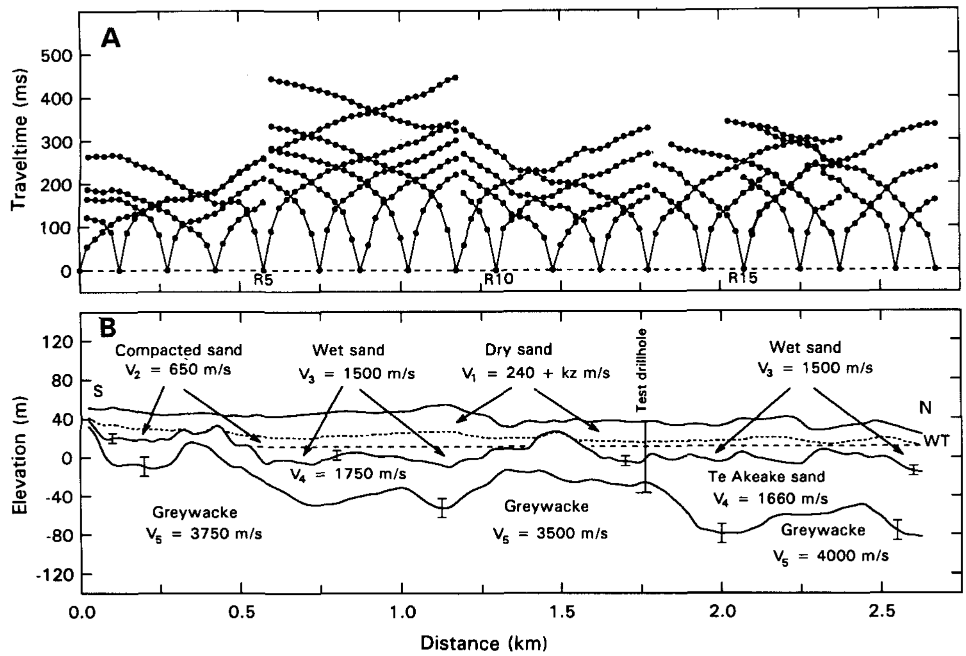


Fig. 6 Refraction seismic survey, seismic profile R. **A**, First arrival traveltimes versus distance. **B**, Interpreted cross-section. The test drillhole confirmed the seismic interpretation and is the location of regional gravity station G6. For location of profile, see Fig. 3.

depth control of the magnetic masses. An ELSEC proton precession magnetometer mounted in a fixed-wing Beechcraft aeroplane was used for the surveys; to eliminate the interfering magnetic effect of the aeroplane, the sensor was slung on a cable and tracked about 20 m below and 30 m behind the aircraft. Sensitivity of the instrument was ±1 nT, and the total magnetic field intensity was sampled at intervals of 2 s, corresponding to a ground separation of about 80 m between readings. Data were recorded on punch tape and on analogue records. Navigation was visual, along profiles about 0.5 km apart, which had been selected on the basis of scout drilling programs over the deposit. Flight paths were recovered from vertical photographs which were taken at 4 s intervals for the low-level flights and at 8 s intervals for the high-level flights. For both surveys, readings at tie-line intersections were within 20 nT. A base station was operated at Bridge Pa, Hastings, to record diurnal variations which were later removed from the field data.

Regional magnetic field

The mean undisturbed regional field intensity observed over nonmagnetic sediments during the Taharoa survey was 56 030 nT, a value similar to that reported by Hunt et al. (1975). In view of the rather short flightlines (<10 km) and the large magnetic anomalies caused by the ironsand deposit, the small effect of any horizontal gradient in the regional field could be neglected. First-order residual magnetic anomalies were obtained by subtracting a constant value of 56 030 nT from the data after diurnal corrections had been made. These residual anomalies have zero values over the outcropping nonmagnetic sediments to the south and east of the deposit.

Interpretation

First-order residual anomalies range in value from –600 nT to +1600 nT in the low-level survey, and decrease to about one-half of this amplitude range in the high-level survey. Flightpaths and contoured total-force residual anomalies at 370 m and 185 m elevations are shown in Fig. 7 and 8, respectively. Both maps show similar trends, with large, positive anomalies occurring along the eastern side of the deposit, where the Nukumiti and Paparoa sands reach maximum thickness. The high spatial frequency of anomalies in Fig. 8 results from the magnetic effects of individual dunes and local titanomagnetite enrichments; the contouring of these anomalies between the relatively widely spaced profiles is rather subjective. A small, negative anomaly (–500 nT) on line B (Fig. 8), south of the Wainui Stream, indicates the location of the dredge-pond of the ironsand mine at the time of the survey (June 1974).

Measurements of the remanent magnetisation of ironsands were reported by Lawton & Hochstein (1980). The Koenigsberger ratio was found to be <0.1, and it was concluded that the remanent magnetisation vectors of grains in the deposit are randomly oriented. Hence, the magnetic anomalies were interpreted in terms of induced magnetisation. Forward modelling was preferred to inversion methods for interpreting the data because the geometry of the magnetic masses had been established by the seismic interpretation and was controlled by drilling data. Two-dimensional magnetic modelling was found to be unsatisfactory because of the lateral variability in the concentration of titanomagnetite in the sands of the deposit.

Three-dimensional modelling was undertaken in three steps. Firstly, a topographic model of the entire deposit was constructed from digitised surface contours (10 m interval), with the base of the model placed at sea level. Theoretical total magnetic force anomalies ("topographic anomalies") of this model were computed by assuming a constant magnetic susceptibility (κ) of 0.15 (induced magnetisation = 6.7 A/m), equivalent to that of the Te Akeake sand with a known titanomagnetite concentration of 18% (Lawton & Hochstein 1980). This average concentration was determined from analysis of outcrop and drillhole samples of the Te Akeake Sands Member. The polygonal lamina method of Talwani (1965) was used for the computations. Examples of first-order residual and calculated topographic anomalies are shown in Fig. 9A and 9B for profile A and in Fig. 10A and 10B for profile R, at the high and low survey elevations, respectively.

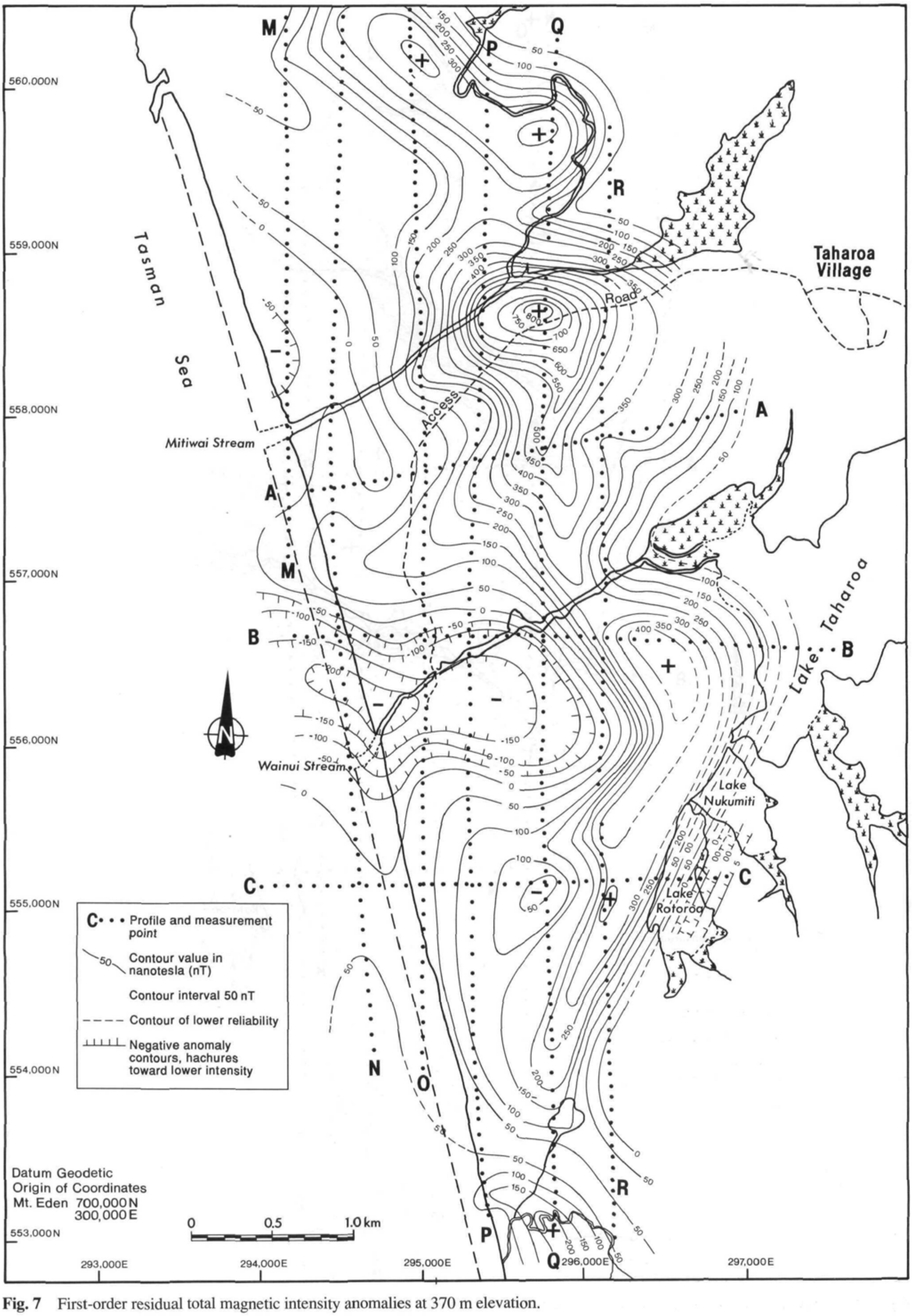


Fig. 7 First-order residual total magnetic intensity anomalies at 370 m elevation.

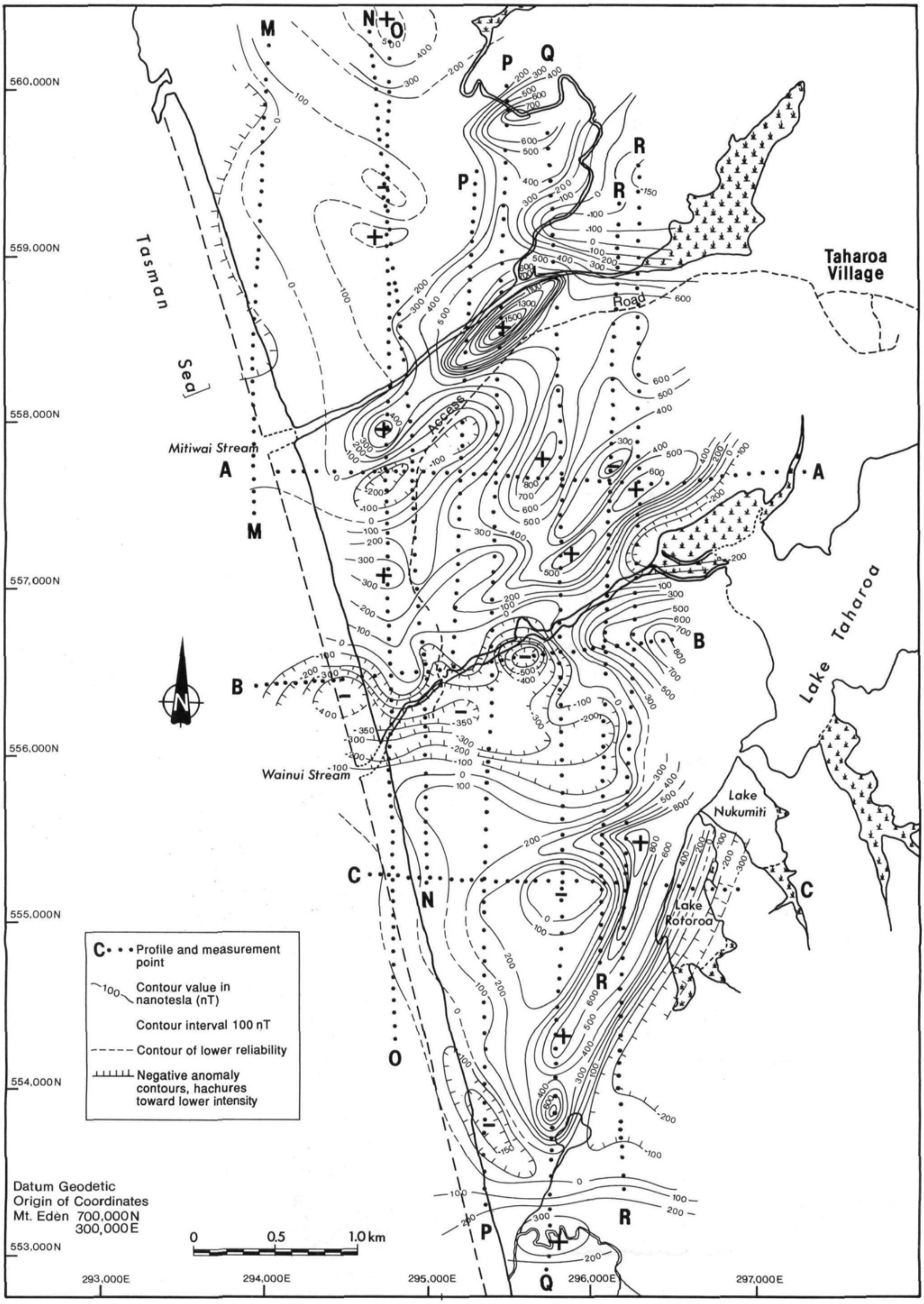


Fig. 8 First-order residual total magnetic intensity anomalies at 185 m elevation.

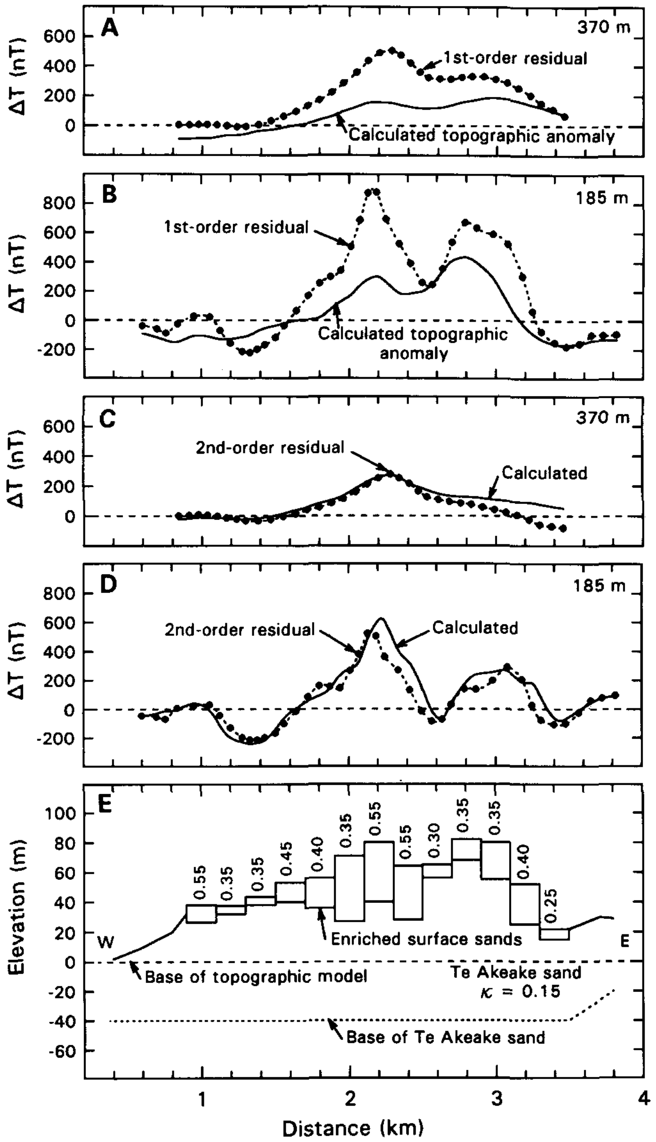


Fig. 9 Magnetic interpretation, profile A. **A**, 1st-order residual anomalies and calculated topographic anomalies at 370 m elevation. **B**, 1st-order residual anomalies and calculated topographic anomalies at 185 m elevation. **C**, 2nd-order residual and calculated anomalies of the prism array at 370 m elevation. **D**, 2nd-order residual and calculated anomalies of the prism array at 185 m elevation. **E**, Interpreted cross-section. For location of profile, see Fig. 7 and 8.

Generally, the amplitudes of the topographic anomalies are about half of the first-order residual anomalies.

In the second step of the interpretation, the magnetic effect of Te Akeake sand below sea level, to a depth of –40 m, was computed, again assuming $\kappa = 0.15$. Results from the refraction seismic interpretation, as well as test drilling, showed that the Te Akeake Sands Member extends at least to this depth throughout the deposit. It was found that the position of the lower boundary had little effect on the calculated anomalies; that is, there is little contribution from Te Akeake sands which might occur below –40 m. The model was extended 2 km offshore to avoid spurious edge effects. Anomalies calculated for the topographic and basal Te Akeake sand models were then subtracted from the first-order residual anomalies to yield second-order residual anomalies which were interpreted to be caused by the magnetic effects of enriched sands at the surface of the deposit.

In the last step of the magnetic interpretation, the enriched upper sands were modelled as an array of vertical, rectangular prisms with horizontal tops and bases. The array, shown in Fig. 11, is given by a 33×13 matrix of square prisms, each with a side-length of 200 m. This was considered to be a suitable dimension without causing spatial aliasing, given the flight line spacing of the survey. The elevation of the top of each prism was taken from surface contours, and the base level corresponded to the top of the Te Akeake Sands Member (Fig. 3). The grid did not cover the northern part of the deposit because the topographic anomalies indicated that no enriched sand exists in this area.

The magnetic effect of the prism array was computed using the method of Plouff (1976). In an iterative process, the magnetisation of each prism was varied until an acceptable fit was obtained between the calculated and second-order residual anomalies along all profiles at both survey elevations. Examples of the second-order residual anomalies and calculated magnetic effect of the prism array are shown in Fig. 9C and 9D (profile A), and Fig. 10C and 10D (profile R) at elevations of 370 m and 185 m, respectively. The interpreted cross-sections for profiles A and R are presented in Fig. 9E and 10E, respectively. In each example, the prisms which occur directly below the flightline are shown in the cross-section, along with the best-fit magnetic susceptibility of each prism. During the interpretation, it was found that the negative residual anomaly south of Wainui Stream (Fig. 7, 8) could be modelled only by reducing slightly the magnetic susceptibility of the basal Te Akeake sand to a value of $\kappa = 0.05$ over a 500 m wide strip across this region.

Figure 11 summarises the final data of the prism array which provided the best-fit solution to modelling. Ore reserve calculations (bottom figure of each prism) are discussed later.

Errors

Errors in the topographic model are small due to the high quality of contour maps available. Small errors were introduced by the assumption of $\kappa = 0.15$ for the Te Akeake Sands Member over most of the deposit and because of the uncertainty in the extent and thickness of the basal Te Akeake model. However, these are estimated to be $< \pm 30$ nT. Other, small errors in the prism model were introduced by the use of stepped surfaces, but tests showed that these were $< \pm 20$ nT. Some short-wavelength anomalies were difficult to match because of the assumption of homogeneous magnetisation in each prism. With reference to selected drillholes, it was estimated that the actual concentration of titanomagnetite may vary locally by up to 10% from that deduced in the magnetic interpretation.

GROUND MAGNETIC SURVEY

Magnetic measurements at ground level are strongly affected by surface and near-surface sources. The high variability in the titanomagnetite content of Taharoa dune sands causes irregular, short-wavelength magnetic anomalies at ground level, which obscure the effects of deeper magnetic sources. For this reason, extensive ground magnetic surveys were not undertaken. Instead, such measurements were made to examine the concentration pattern of titanomagnetite along the beach.

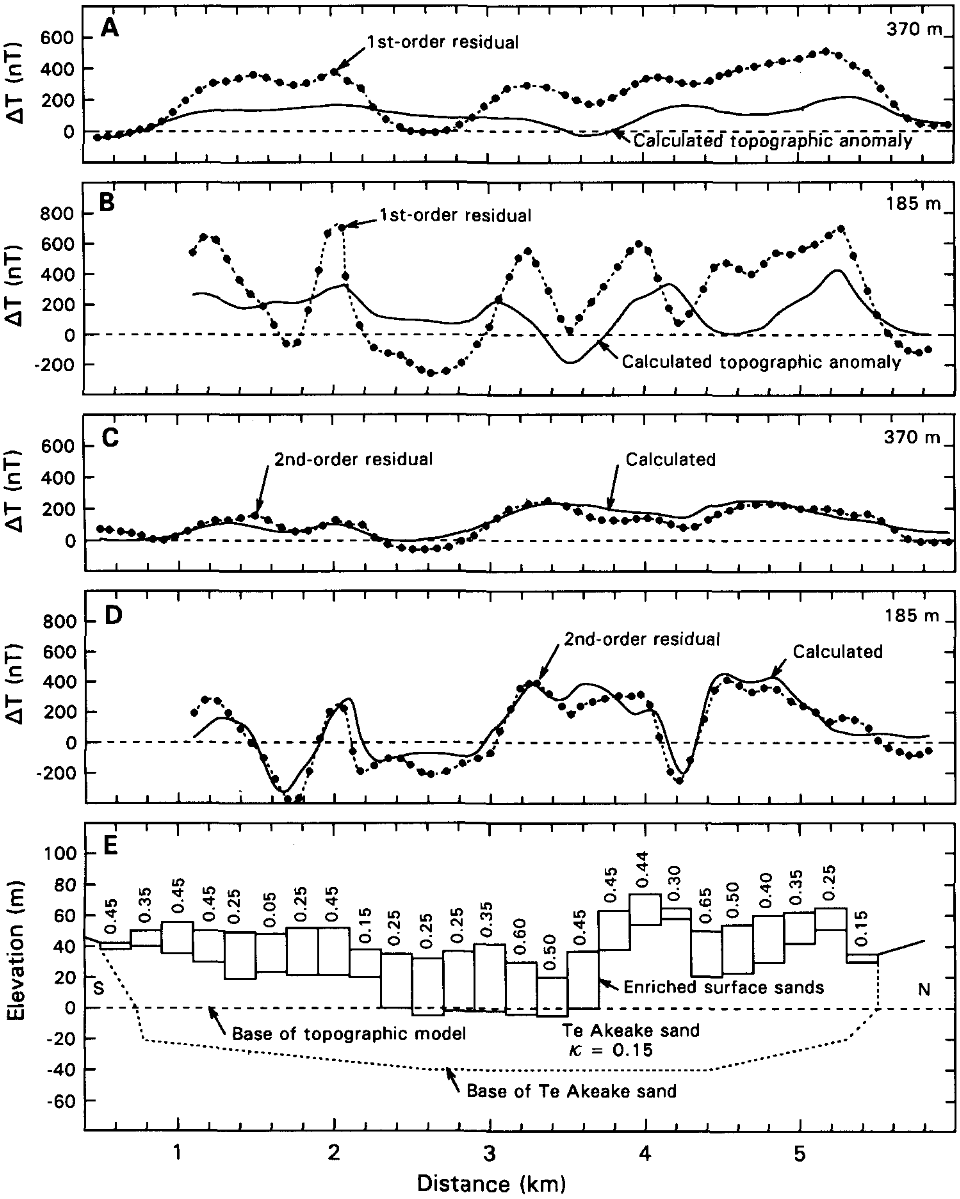


Fig. 10 Magnetic interpretation, profile R. **A**, 1st-order residual anomalies and calculated topographic anomalies at 370 m elevation. **B**, 1st-order residual anomalies and calculated topographic anomalies at 185 m elevation. **C**, 2nd-order residual and calculated anomalies of the prism array at 370 m elevation. **D**, 2nd-order residual and calculated anomalies of the prism array at 185 m elevation. **E**, Interpreted cross-section. For location of profile, see Fig. 7 and 8.

The profile crossed the beach at the western end of profile A (Fig. 3). Relative vertical force (ΔZ) measurements were made with an Askania GFZ torsion magnetometer at intervals of 15 m. An arbitrary zero level was defined with reference to a base station located on Te Akeake sand outcropping nearby; the anomalies therefore indicate titanomagnetite enrichment relative to the Te Akeake sand. The vertical force magnetometer records a negative anomaly over enriched sands, whereas the total force magnetometer, used for the airborne surveys, records a dipolar anomaly at this latitude. Results of the ground magnetic survey are presented in Fig. 12 and show large negative ΔZ anomalies above the high-water mark and also at the low-water mark. The qualitative interpretation of the ΔZ data (Fig. 12B) is that the greatest concentrations of titanomagnetite occur at the high and low water regions of the beach, and the intertidal area is less enriched in titanomagnetite. A similar distribution was found by Ross (1963) who studied the magnetic permeability of ironsands along the Taranaki coast. The back beach enrichment of titanomagnetite indicates a primary depositional process since no reworking of older deposits is necessarily involved. Unfortunately, the rate of accumulation of fresh titanomagnetite sands on the Taharoa beach is not yet known. The sands deposited at high water dry out as the tide recedes, and are then picked up by prevailing onshore winds and deposited in small dunes up to 20 m inland from the beach. During storms, wind velocities often exceed 30 m/s (New Zealand Steel Mining meteorological data), and the sands are blown further inland, forming parabolic and transverse dunes of the Paparoa and Nukumiti Sands Members. This inferred local source for the enriched surface dunes is supported by studies of Christie (1975) who found little difference between the beach and dune sands in several ironsand deposits between New Plymouth and Taharoa. Concentrations of c. 60% titanomagnetite were measured in samples from dunes near the beach, but reduced to 45% in surface dunes on the eastern side of the Taharoa deposit. The apparent dilution is the result of erosion of older, low-grade Te Akeake sands exposed within the deposit.

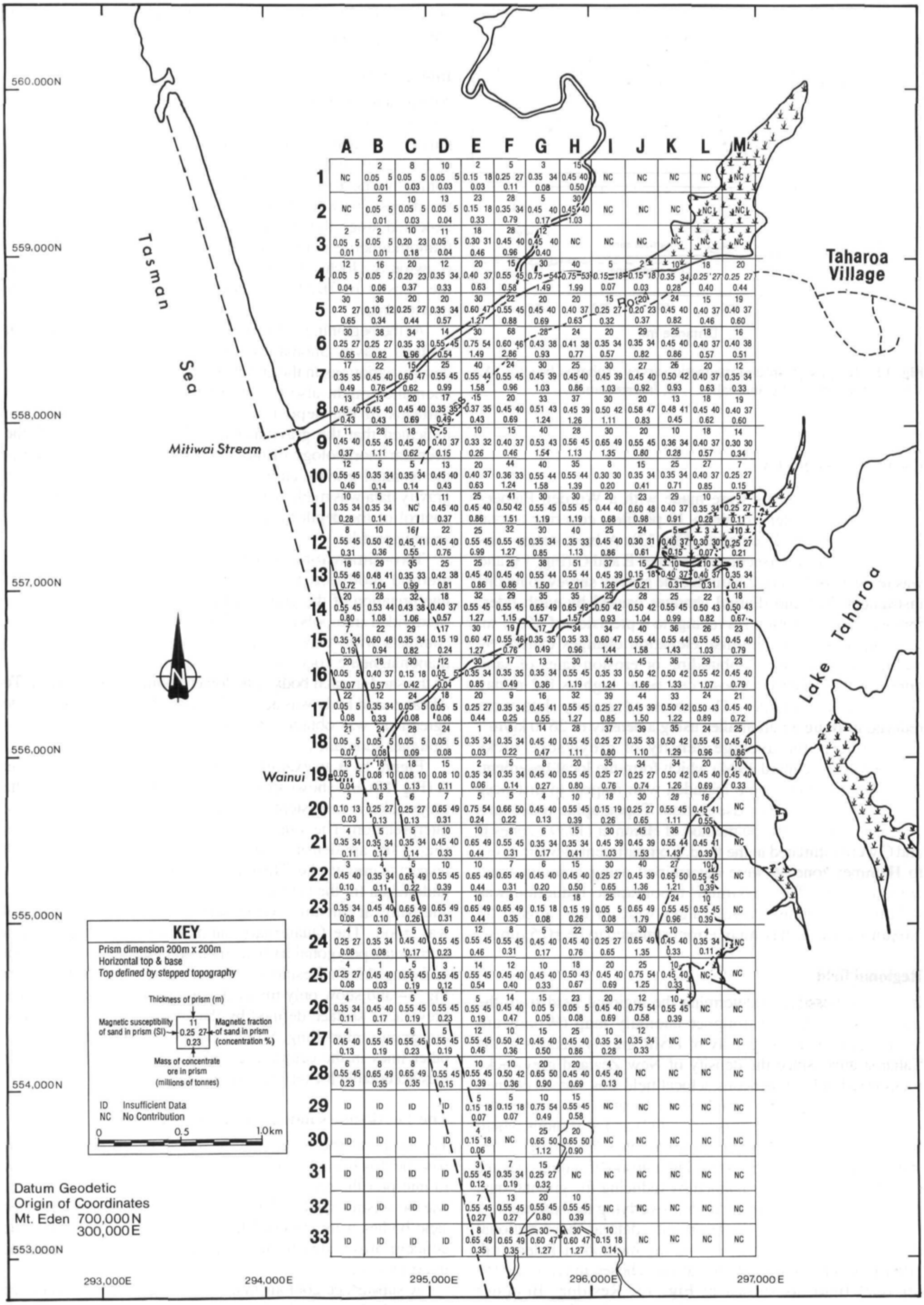


Fig. 11 Summary of the magnetic interpretation and distribution of titanomagnetite ore reserves in the Nukumiti and Paparoa Sands Members of the Taharoa deposit.

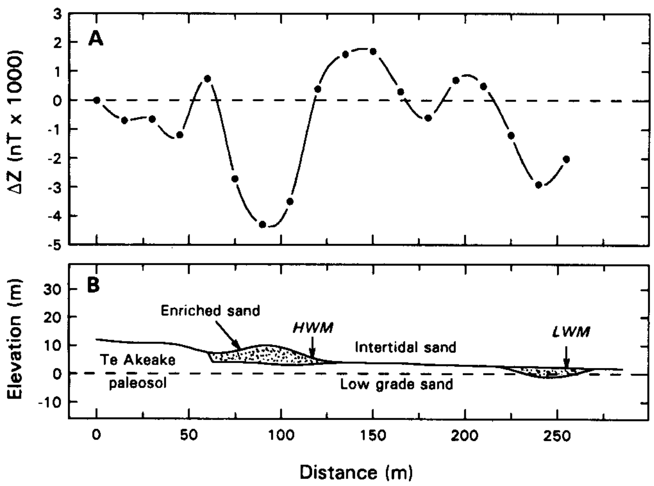


Fig. 12 Results of ground magnetic survey, Taharoa beach. **A**, Vertical force magnetic anomalies. **B**, Interpretation.

GRAVITY SURVEY

Gravity measurements were made with a Worden Pioneer meter at 100 m intervals along 13 profiles, covering a total distance of 30 line-kilometres (Fig. 13). A base station was esablished at the intersection of profiles E and O (Fig. 13) and was re-occupied every 2 h during the gravity survey to record instrument drift and diurnal changes caused by earth tides. Simultaneous elevation surveying, to a precision of ±0.05 m, was undertaken to minimise elevation changes caused by mobile, drifting sand. Upbuilding or erosion rates of sand dunes in the Taharoa deposit can be as high as 0.2 m/day during stormy weather. The observed gravity data were reduced to Bouguer anomalies using a density of 2670 kg/m^3. This value is the average density of greywacke rocks (Hatherton & Leopard 1964) which form the local basement. Latitude corrections were included with respect to distances north and south of the base station. Topographic reductions were calculated using the method of Hammer (1939); zones B and C were estimated in the field. Compartment elevations out to Hammer zone M were determined using graticules and contour maps. The maximum topographic reduction was 4.7 μm/s^2, whereas typical values were in the range 1.5–2.0 μm/s^2, with a maximum error estimated to be ±0.5 μm/s^2.

Regional field

It was not possible to determine the regional field from the published 1:250 000 Bouguer anomaly map (Woodward 1971) because of the sparsity of DSIR gravity stations in the Taharoa area. Since the density of New Zealand greywacke rocks is rather homogeneous, a local field was instead defined from gravity stations which were located on greywacke outcrops (Fig. 13, stations G1, G3, G7) and at stations where the depth to unweathered greywacke was known (Fig. 13, stations G2, G4, G5, G6). At the latter group of stations, values of the local field were obtained by reducing the gravitational effect of the low-density sediments overlying the basement. A trend surface analysis of the gravity data at these regional defining stations was made using the method of Esler et al. (1968). A third-order polynomial was chosen to represent the regional field, as shown in Fig. 13. Residual Bouguer anomalies were calculated by subtracting this field from the observed Bouguer anomalies; a residual Bouguer anomaly map is shown in Fig. 13.

Interpretation

All residual Bouguer anomalies (Fig. 13) over the deposit are negative, indicating that the average density of the Recent and Quaternary sands is less than that of greywacke. Amplitudes of anomalies range from zero to about −30 μm/s^2, with minima commonly occurring over high dunes in the central region of the deposit between Wainui and Mitiwai Streams. This is expected since the density of dry, compacted sand with a titanomagnetite concentration of 50% is only 2300 kg/m^3 (Lawton & Hochstein 1980), which is significantly less than the density of 2670 kg/m^3 used for the reductions of the gravity data.

At the beginning of the project, it had been anticipated that residual gravity anomalies could be interpreted in terms of density variations in the enriched surface sands, and that these anomalies might also outline titanomagnetite concentration patterns in the deposit. However, initial interpretation indicated that the gravitational effects associated with the irregular morphology of the greywacke basement dominates the residual gravity anomalies. Hence, interpretation of the gravity data was made with the revised aim of obtaining better control of the depth to greywacke basement away from the seismic profiles.

Two-dimensional modelling was undertaken using a method modified from Talwani et al. (1959). For the interpretation of the gravity data, the Quaternary sands were subdivided into polygonal bodies and were assigned density contrasts with respect to greywacke, based on the average titanomagnetite concentration and degree of water saturation of the sand in each body. The lower boundary of the basal Te Akeake sand body was adjusted iteratively until an acceptable agreement was obtained between the computed and residual Bouguer anomalies.

Figure 14 is an example of the interpretation along profile A (Fig. 13) and shows that the gravity model of the top of the greywacke is consistent with that obtained from the seismic interpretation. The values shown in each body of the model (Fig. 14B) are density contrasts (in units of 10^3 kg/m^3) with respect to greywacke. Three-dimensional (3-d) modelling was undertaken for the central area of the deposit between Wainui and Mitiwai Streams, where surface and subsurface control was good. The Quaternary sands were modelled using a horizontal, polygonal laminae method modified from Talwani & Ewing (1960). Results of 3-d modelling are also included in Fig. 14 and show only minor deviations in comparison to the greywacke surface defined by the seismic interpretation and 2-d gravity modelling. Similar consistency was found along other lines in the central area, indicating that 2-d modelling was acceptable for the interpretation.

The Te Akeake sands/greywacke interface

To complete the investigation of the depth to greywacke basement beneath the deposit, 2-d modelling was undertaken to interpret the remaining gravity profiles along which there was no seismic control. The density contrasts for the enriched sand bodies were obtained from the average titanomagnetite concentrations determined previously from the magnetic interpretation.

A subsurface contour map of the top of the unweathered greywacke basement is shown in Fig. 15, based on the gravity

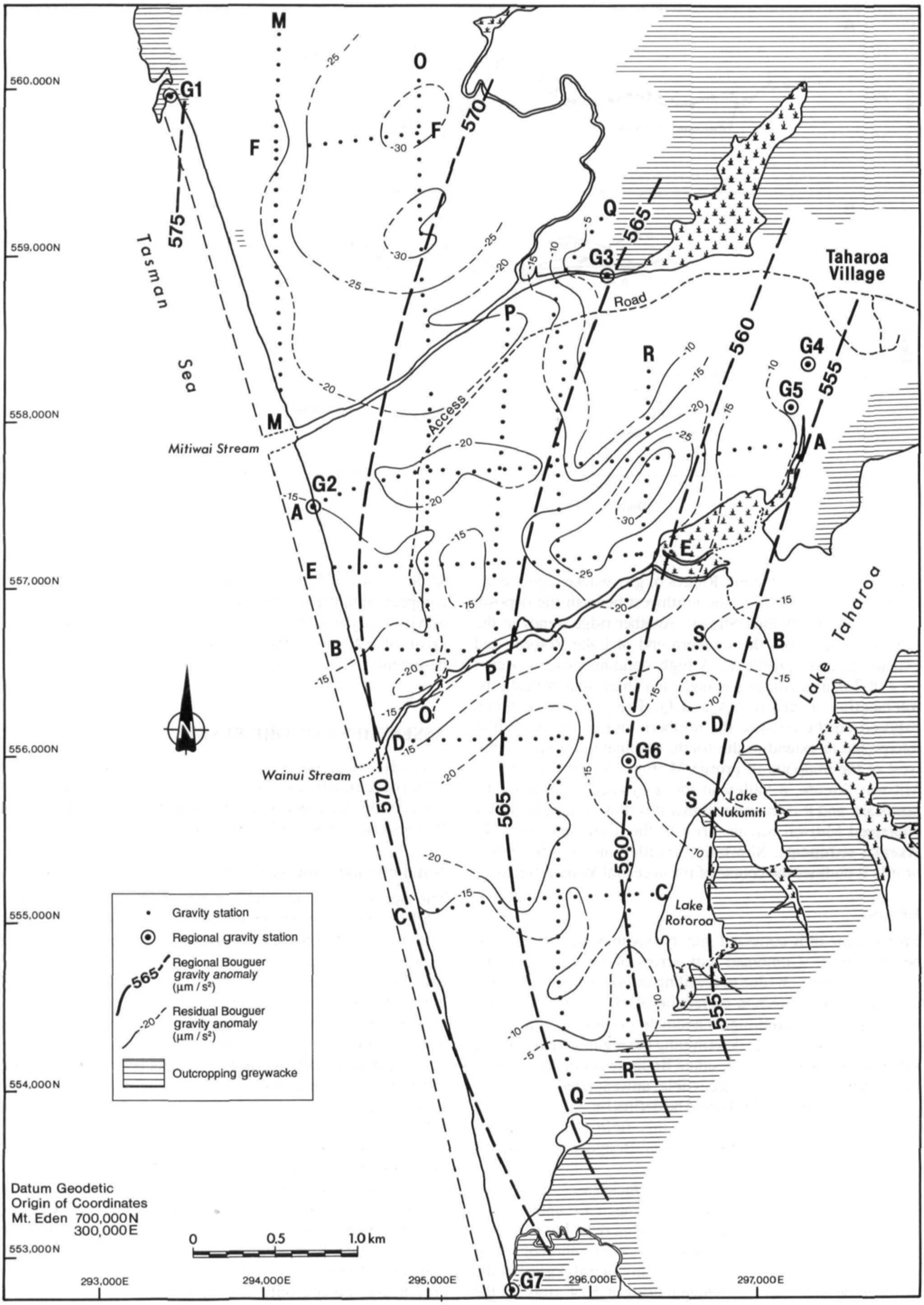


Fig. 13 Gravity profiles, the regional gravity field, and contoured residual Bouguer anomalies at Taharoa.

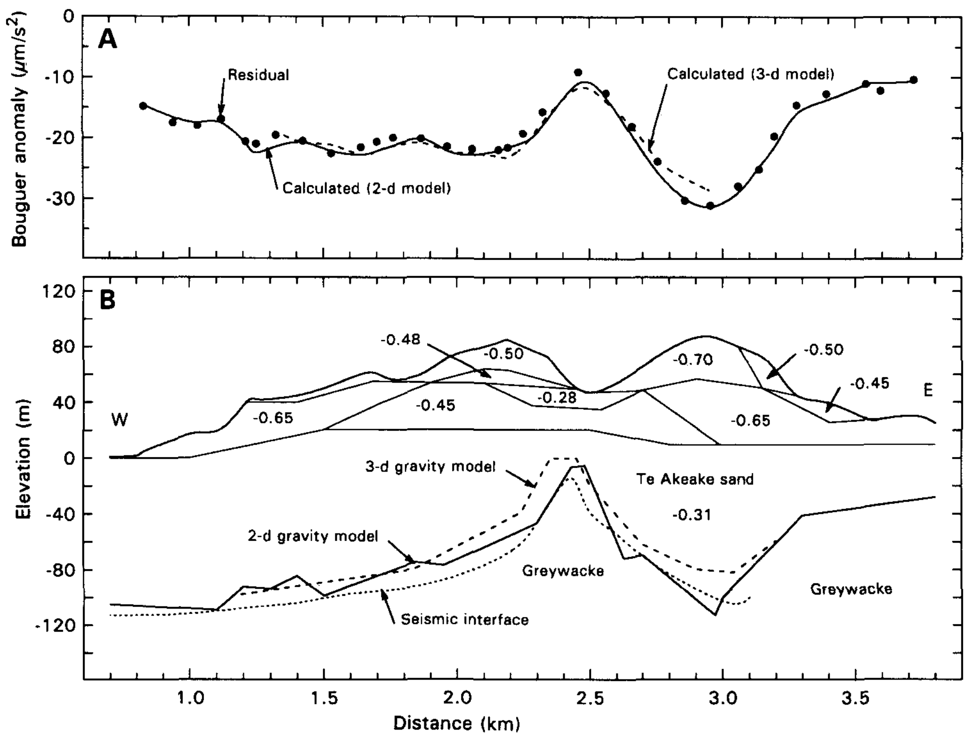


Fig. 14 Gravity interpretation, profile A. **A**, Residual and calculated Bouguer anomalies. **B**, Cross-section of interpreted density model. Numbers within the bodies are density contrasts (in units of 10^3 kg/m^3) with respect to greywacke.

and seismic interpretations. Ridges of greywacke separate the three lakes and extend to the northwest beneath the deposit, almost reaching Wainui Stream. Another ridge trends in the same direction from the southern end of Lake Rotoroa and extends beneath profile C. A high-standing plateau occurs west of Taharoa village and ends in a sharp spur beneath the intersection of profiles A and Q. The greywacke block exposed on the coast at the northern end of the deposit is interpreted to extend to the south, terminating in an outcrop west of the midpoint of profile M (Fig. 15). To the north of Mitiwai Stream, a valley in the greywacke trends to the northeast, and it is interpreted that this now-concealed valley contained Mitiwai Stream prior to the accumulation of Te Akeake sediments. Similarly, a valley and saddle below profile E outlines the course of the ancestral Wainui Stream.

Errors

Errors in the drift-corrected gravity readings are estimated to be ± 0.1 μm/s^2. Combined with errors of ± 0.1 μm/s^2 in the elevation correction (due to levelling errors), and an estimated uncertainty in the terrain correction of ± 0.5 μm/s^2, the total error in the observed Bouguer anomalies is thus ± 0.7 μm/s^2. A greater error occurred in determining the regional field and the subsequent calculation of residual Bouguer anomalies. Due to the scarcity of stations on accessible, unweathered greywacke outcrops, the regional field could be defined at only seven field points. The maximum error of this field is ± 1.5 μm/s^2, resulting in a total error in the residual Bouguer anomalies of ± 2.2 μm/s^2.

Errors in the density contrasts and thicknesses of the near-surface sand bodies, taken from the magnetic and seismic models, also propagate into the gravity models. For example, an error of $\pm 5\%$ in the titanomagnetite concentration of a sand body 20 m thick results in an uncertainty of ± 50 kg/m^3 in the assumed density, and a subsequent error of ± 0.4 μm/s^2 in the computed gravity anomaly. Further possible errors, estimated to be up to ± 0.5 μm/s^2, may arise by neglecting partial compaction in the uppermost sand layer. The total error in the gravity analysis is thus c. ± 3.1 μm/s^2, which translates to an error of ± 20 m in the interpreted depth to greywacke basement.

ASSESSMENT OF ORE RESERVES

The total ore reserves of titanomagnetite calculated for the Taharoa deposit are summarised in Table 2. Previous estimates by Nicholson & Fyfe (1958), Kear (1965, 1979), and Waterhouse (1969) are included for comparison.

Nukumiti and Paparoa Sands Members

The average titanomagnetite concentration of these sands (38%), which we designate as the upper ore body, was obtained from the best-fit magnetic model, summarised in the prism array of Fig. 11. In each prism, the mass of titanomagnetite was determined from the volume and inferred concentration using the relationships between density, magnetisation, and titanomagnetite concentration for dry Taharoa sands derived by Lawton & Hochstein (1980). Some allowance was made for partial compaction of near-surface sands by assuming that the bulk density of sand in the uppermost 15 m is an average value lying between those of fully compacted and uncompacted sands. The error in the mass of titanomagnetite calculated from the geophysical data was estimated to be $\pm 15\%$.

The total mass of 205×10^6 t of concentrate in the enriched sands is an increase of c. 20% over the estimates of Nicholson & Fyfe (1958) and is about five times greater than that given by Kear (1965). Kear's figures were based on shallow drilling, and the volume of ore was estimated by assuming that the enriched sands are only c. 6 m thick. Waterhouse (1969) reassessed reserves of the Nukumiti and Paparoa sands after

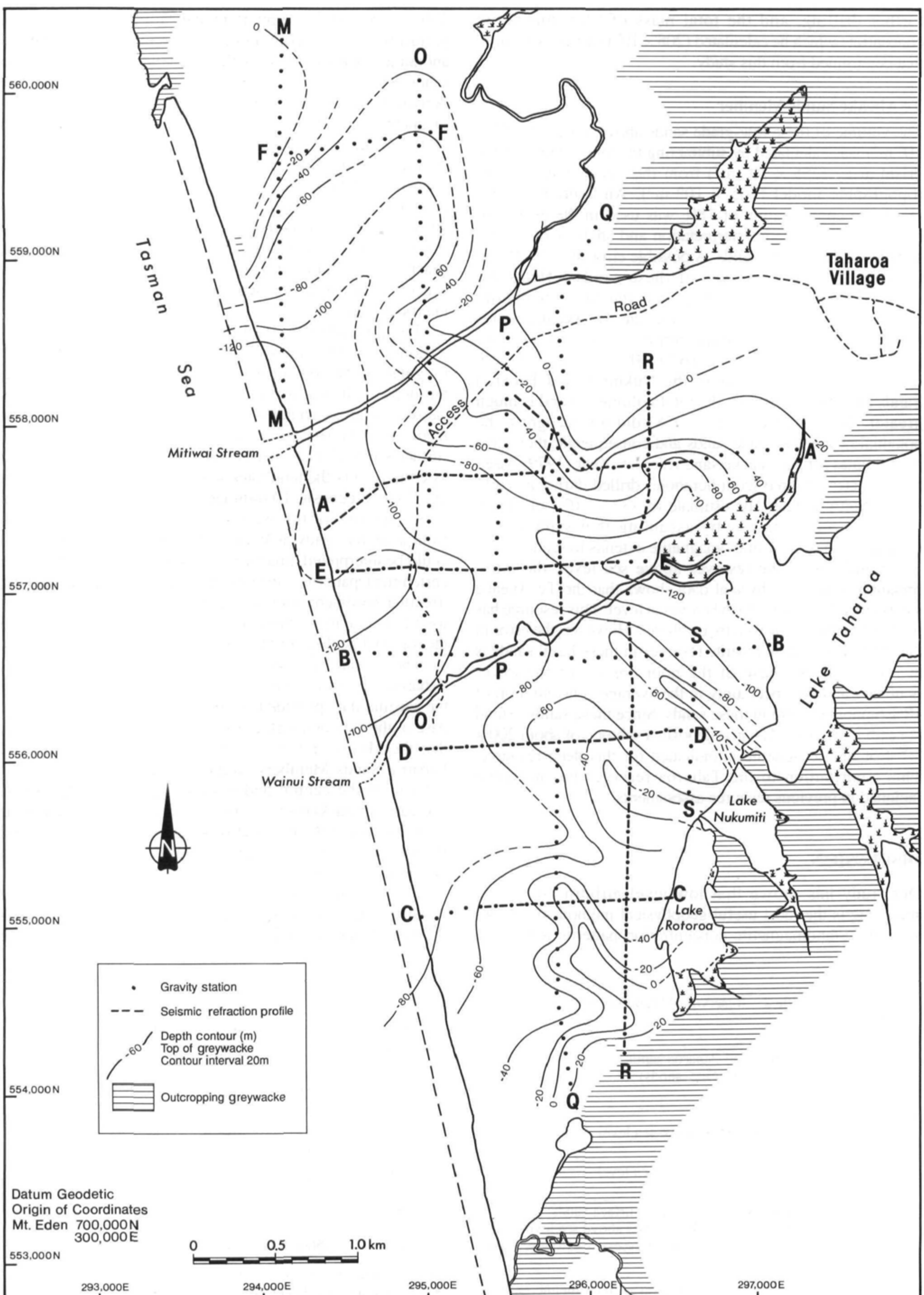


Fig. 15 The subsurface topography of the top of unweathered greywacke basement at Taharoa, based on the seismic and gravity interpretations.

further drilling, and the total mass of titanomagnetite concentrate which he calculated (208×10^6 t) is very similar to that determined from this study.

Te Akeake Sands Member

The volume of these low-grade sands above sea level (450×10^6 m^3) was calculated by subtracting the total volume of the prism array (255×10^6 m^3) from the total volume of the topographic model (705×10^6 m^3). An average titanomagnetite concentration of 18% was used in the estimates, based on the magnetic interpretation and analysis of several samples of Te Akeake sands. A possible error of ±15–20% in the calculated ore reserves of these sands reflects the uncertainty in the assumption that the titanomagnetite concentration is uniform throughout the Te Akeake Sands Member. The total titanomagnetite reserves in the low-grade sands above sea level (160×10^6 t) are only slightly less than the ore reserves in the Nukumiti and Paparoa Sands Members, although the total volume of sand is much greater. Nicholson & Fyfe (1958) did not recognise the potential of the low-grade sands and consequently they gave no estimates for Te Akeake sand reserves. Kear (1979) based his estimates on three scout boreholes drilled during an early exploration program. His estimate of 137×10^6 t of titanomagnetite was obtained by assuming that sand with a concentration of 27% titanomagnetite extends to sea level.

In addition to the reserves above sea level, the interpretation of the geophysical data shows that the Te Akeake sands extend to at least 40 m below sea level. This resource has now been partially proven by drillholes. However, the error in the estimated titanomagnetite reserves in these basal sands is at least ±20% because of the poor control of the lower boundary and the uncertainty in the average concentration of 18% titanomagnetite in these sands. Since these sands extend beneath most of the Taharoa deposit, a subtotal of about 200×10^6 t of titanomagnetite is indicated for this deep resource. This contribution to the Taharoa reserves has not been included in previous resource assessments.

DISCUSSION

Our study has shown that low-level airborne magnetic surveying is the most useful geophysical method for delineating the titanomagnetite concentration patterns within the Taharoa deposit. An important step in our magnetic interpretation was the computation of magnetic topographic anomalies. Allowing also for the magnetic effect of low-grade sands below sea level, second-order residual anomalies were derived which were interpreted to be caused by the titanomagnetite concentration patterns in the enriched, surface sands of the Nukumiti and Paparoa Sands Members. Gravity, seismic, and drillhole data provided the necessary structural control to enable a quantitative interpretation of the second-order residual magnetic anomalies to be made in terms of an array of vertical, rectangular prisms, with variable magnetic susceptibility. Ground magnetic measurements showed that beach concentrations of titanomagnetite occur above the high water mark and at the low water mark, with lower grades in the intertidal zone.

The gravitational effect of the titanomagnetite concentrations is small and is overwhelmed by the effect of the irregular morphology of the greywacke basement underlying the deposit. It was difficult to separate density variations caused by gross changes in titanomagnetite concentration from those caused by compaction and saturation of near-surface sands. Hence, interpretation of gravity anomalies gave essentially only the total thickness of the Quaternary sands in the Taharoa deposit. Two-dimensional modelling was found to be adequate for this purpose. In contrast, the gravity data from a similar study at Waikato North Head (Lawton 1979) could be interpreted directly in terms of gross titanomagnetite enrichment patterns, since the problem created by shallow, irregular basement does not occur there. Thus, the effective use of the gravity method in ironsand exploration depends on the regional geology of the particular area.

The seismic velocity structure of the Quaternary sands at Taharoa is complex, but careful analysis and interpretation of the seismic data provided an important depth control for the base of the enriched surface sands. It was found, for example, that the Mitiwai Formation (made up of the Nukumiti and Paparoa Sands Members) attains a maximum thickness of c. 60 m in the central and eastern parts of the deposit. It decreases in thickness to c. 10–15 m in the western area, near the coast. Since the physical properties of the Nukumiti and Paparoa sands are similar, these sands cannot be separated in the seismic interpretation models.

The seismic refraction survey confirmed that the Te Akeake sands are separated from the overlying, unconsolidated Nukumiti and Paparoa sands by a sequence of late

Table 2 Reserves of titanomagnetite in the Taharoa deposit.

I	II	III	IV	V	VI
Nukumiti and Paparoa sands	38	255	545	205	±15
(enriched surface sands)	42*	209*	418*	175*	–
	41†	45†	102†	42†	–
	35‡	297‡	593‡	208‡	–
Te Akeake sands above sea level	18	450	900	160	±15–20
	27†	244†	509†	137†	–
Te Akeake sands below sea level	18	560	1115	200	±20
Subtotal of enriched, near-surface sands:		255	545	205	±15
Subtotal of possible reserves above sea level:	705	1445	365	±15	
Total resources, including reserves below sea level:		1265	2560	565	±20

I Stratigraphic member
II Average concentration of titanomagnetite (%)
III Total volume of sand ($\times 10^6$ m^3)
IV Total mass of sand ($\times 10^6$ tonnes)
V Total mass of concentrate ($\times 10^6$ tonnes)
VI Estimated error in mass of concentrate (%)
*Nicholson & Fyfe (1958) †Kear (1965, 1979) ‡Waterhouse (1969)

Quaternary tephras and associated paleosols, interbedded with titanomagnetite sands. The base of this sequence is a well-developed, coherent paleosol which formed beneath the Rotoehu Ash (Pain 1976). This sequence is locally rather thick (up to 15 m), and we propose that this horizon at the top of the Te Akeake Sands Member should become a new, additional member of the Waiau B Formation. The largest thickness (>100 m) of the Te Akeake Sands is one of the important findings of our geophysical surveys. This layer was found to be a large, low-grade subdeposit of titanomagnetite, and its potential as an ore resource had not previously been recognised.

Integrating all existing, deep drillhole data and the seismic, magnetic, and gravity interpretation models, we found that the Taharoa ironsand deposit consists of a rich, upper ore body made up of the Nukumiti and Paparoa Sands Members. These sands have an average titanomagnetite concentration of 38% (by weight) and contain about $205 \pm 30 \times 10^6$ t of titanomagnetite. They accumulated during the last 40 ka from beach deposits at high tide level, and significant deposition of titanomagnetite at this level of the beach still occurs today. The upper sand ore body is separated by an up to 15 m thick tephra/paleosol layer from deeper, low-grade, slightly cemented sands (thickness >100 m), of the Te Akeake Sands Member. The titanomagnetite concentration in this layer is low, c. 18% (by weight), this figure being based on analyses of numerous samples from surface outcrops and from deep drillholes, as well as from our best-fit magnetic model. The Te Akeake sands were deposited c. 100 ka ago and can be correlated stratigraphically with the Waiau B Formation of Chappell (1975). The total reserves of titanomagnetite in this lower grade sand body are $360 \pm 65 \times 10^6$ t of titanomagnetite, although it is doubtful that this concentrate is economically recoverable (Stokes et al. 1989).

The total reserves of the Taharoa deposit are therefore 565 $\pm 120 \times 10^6$ t of titanomagnetite. The magnetic interpretation model presented here can be used for management not only of the Nukumiti and Paparora Sands Members, but also of the Te Akeake Sands Member, whose full potential was only recognised by this study.

ACKNOWLEDGMENTS

The airborne magnetic survey was undertaken using equipment from Geophysics Division of DSIR (observer, L. Carrington); the survey was funded by Grant 136 SCI 22 from the New Zealand Scientific Research Distribution Committee. We thank D. Buist and N. MacArthur of New Zealand Steel Mining Ltd. for logistic and financial support. Technical support throughout the field studies was provided by M. Bertram of the Geology Department, University of Auckland. The studies were part of a Ph.D. research project at the University of Auckland. Derek Woodward and two anonymous reviewers made constructive criticisms of the manuscript. Funds for figure preparation were provided by the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

Beck, A. C. 1947: Ironsands at Waitara, New Plymouth. *New Zealand journal of science and technology B28 (6)*: 307–313.

Brothers, R. N. 1954: The relative Pleistocene chronology of the South Kaipara District, New Zealand. *Transactions of the Royal Society of New Zealand 82*: 677–694.

Carter, L. R. 1980: Ironsand in continental shelf sediments off western New Zealand—a synopsis. *New Zealand journal of geology and geophysics 23*: 455–468.

Chappell, J. M. A. 1970: Quaternary geology of the southwest Auckland coastal region. *Transactions of the Royal Society of New Zealand 8*: 133–153.

Chappell, J. M. A. 1975: Upper Quaternary warping and uplift rates in the Bay of Plenty and west coast, North Island, New Zealand. *New Zealand journal of geology and geophysics 18*: 129–155.

Christie, J. 1975: Sedimentology of Pleistocene and Recent ironsands, west coast, North Island. Unpublished M.Sc. thesis, lodged in the Library, Victoria University of Wellington, Wellington, New Zealand.

Coss, P. 1959: Geophysical survey of heavy beach sand mineral concentrates at Terrigal Haven Beach. Unpublished report, Geological Survey of New South Wales, Department of Mines, Australia. 4 p.

Esler, J. E.; Smith, P. F.; Davis, J. C. 1968: KWIKR8, a Fortran IV program for multiple regression and geological trend analysis. *Computer contribution 28*. State Geological Survey, University of Kansas.

Ewing, M.; Leet, L. D. 1932: Comparison of two methods for interpretation of seismic time-distance graphs which are smooth curves. *Transactions of the American Institute of Mining and Metallurgical Engineers 32*: 263–270.

Fleming, C. A. 1946: Magnetic ironsands west of Wanganui. *New Zealand journal of science and technology B27 (5)*: 347–365.

Gardner, L. W. 1939: An areal plan of mapping subsurface structure by refraction shooting. *Geophysics 4*: 247–259.

Hagedoorn, J. G. 1959: The plus-minus method of intepreting seismic refraction sections. *Geophysical prospecting 7*: 158–182.

Hammer, S. 1939: Terrain corrections for gravimeter stations. *Geophysics 4*: 184–194.

Hatherton, T.; Leopard, A. E. 1964: The densities of New Zealand rocks. *New Zealand journal of geology and geophysics 7*: 605–625.

Hattori, T. 1960: Titaniferous ironsand resources in Japan. *In*: Titaniferous ironsand and pyrrhotite resources in Japan. *Geological Survey of Japan special report (E)*: 1–38.

Henderson, J.; Grange, L. I. 1922: Notes to accompany a geological sketch map of the Marakopa district. *New Zealand journal of science and technology 5*: 177–183.

Henderson, J.; Grange, L. I. 1926: The geology of the Huntly–Kawhia Subdivision, Pirongia and Hauraki Divisions. *New Zealand Geological Survey bulletin 28.*

Hone, D. 1986: Application of geophysics to explore for heavy-mineral sand deposits. *Bureau of Mineral Resources Australia report 249.*

Hunt, C. P.; Syms, M. C.; Carrington, L.; Williams, R. B. 1975: Aeromagnetic survey of the west coast of the North Island, New Zealand, 1973–1974. *Dèpartment of Scientific and Industrial Research Geophysics Division technical note 74*: 43 p.

Hutton, C. P. 1940: The titaniferous ironsands of Patea, with an account of the heavy residues in the underlying sedimentary rocks. *New Zealand journal of science and technology B21 (4)*: 190B–205B.

Hutton, C. P. 1945: The ironsands of Fitzroy, New Plymouth. *New Zealand journal of science and technology B26 (6)*: 291–302.

Kear, D. 1965: Geology of New Zealand's ironsand resources. Paper 219, Eighth Commonwealth Mining and Metallurgical Congress, Australia and New Zealand. 10 p.

Kear, D. 1979: Geology of ironsand resources of New Zealand (with notes on limestone, silica and bentonite). Report for the New Steel Investigating Company, Wellington, New Zealand. Department of Scientific and Industrial Research. 154 p.

Lawton, D. C. 1979: Geophysical exploration of Quaternary ironsand deposits at Taharoa, Waikato North Head and Raglan, west coast, North Island, New Zealand. Unpublished Ph.D. thesis, lodged in the Library, University of Auckland, Auckland, New Zealand.

Lawton, D. C.; Hochstein, M. P. 1980: Physical properties of titanomagnetite sands. *Geophysics 45*: 394–402.

McDougall, J. C. 1961: Ironsand deposits offshore from the west coast, North Island, New Zealand. *New Zealand journal of geology and geophysics 3*: 283–300.

Martin, K. R. 1967: Mesozoic sequence at southwest Kawhia, New Zealand. Unpublished M.Sc. thesis, lodged in the Library, University of Auckland, Auckland, New Zealand.

Marwick, J. 1946: The geology of the Te Kuiti Subdivision. *New Zealand Geological Survey bulletin 41.*

Nicholson, D. S.; Fyfe, H. E. 1958: Borehole survey of North Island ironsands from New Plymouth to Kaipara Harbour. *New Zealand journal of geology and geophysics 1*: 617–634.

Ohmachi, H. 1960: Summarised data of titaniferous ironsand in Japan. *In*: Titaniferous ironsand and pyrrhotite resources in Japan. *Geological Survey of Japan special report (E)*: 67–72.

Pain, C. F. 1976: Late Quaternary dune sands and associated deposits near Aotea and Kawhia Harbours, North Island, New Zealand. *New Zealand journal of geology and geophysics 19*: 153–177.

Plouff, D. 1976: Gravity and magnetic fields of polygonal prisms and application to magnetic terrain corrections. *Geophysics 41*: 727–741.

Pullar, W. A.; Birrell, K. S.; Heine, J. C. 1973: Named tephra and tephra formations occurring in the central North Island, with notes on derived soils and buried paleosols. *New Zealand journal of geology and geophysics 16*: 497–518.

Robson, D. F.; Sampath, N. 1977: Geophysical response of heavy-mineral sand deposits at Jerusalem Creek, New South Wales. *BMR journal of Australian geology and geophysics 2*: 149–154.

Ross, D. I. 1963: Surface magnetic permeability measurements on some Taranaki ironsand deposits. *New Zealand journal of geology and geophysics 6*: 197–208.

Stokes, S. 1987: Stratigraphy and sedimentology of late Neogene coastal deposits at Taharoa, southwest Auckland. Unpublished M.Sc. thesis, lodged in the Library, University of Waikato, Hamilton, New Zealand.

Stokes, S.; Nelson, C. S.; Healy, T. R.; MacArthur, N. A. 1989: The Taharoa ironsand deposit. *In*: Kear, D. *ed.* Mineral deposits of New Zealand. The Australasian Institute of Mining and Metallurgy monograph 13. Melbourne. Pp 105–109.

Talwani, M. 1965: Computation with the help of a digital computer of magnetic anomalies caused by bodies of arbitrary shape. *Geophysics 30*: 797–817.

Talwani, M.; Ewing, M. 1960: Rapid computation of gravitational attraction of three-dimensional bodies of arbitrary shape. *Geophysics 25*: 203–225.

Talwani, M.; Worzel, J. L.; Landisman, M. 1959: Rapid gravity computations for two-dimensional bodies with application to the Mendicino submarine fracture zone. *Journal of geophysical research 64 (1)*: 40–59.

Untung, M.; Hanna, W. R. 1975: Geophysical investigation of coastal magnetite sands at Meleman, Lumajang, East Java. *Geological Survey of Indonesia Publikasi Teknik-Seri Geofisika 5*: 39 p.

Waterhouse, B. C. 1969: N.Z. Steel Ltd: Taharoa ironsand deposits. Unpublished report, New Zealand Geological Survey, Otara. 4 p.

Williams, G. J. 1974: Iron and titanium-bearing minerals. *In*: Williams, G. J. *ed.* Economic geology of New Zealand. The Australasian Institute of Mining and Metallurgy monograph 4. Melbourne. Pp 127–142.

Woodward, D. J. 1971: Sheet 4—Hamilton. Gravity map of New Zealand 1:250 000. Bouguer anomalies. Wellington, New Zealand. Department of Scientific and Industrial Research.