AN AEROMAGNETIC STUDY OF THE STACCATO PEAKS AREA, ALEXANDER ISLAND, ANTARCTICA

I. A. CRAWFORD* *and* R. W. GIRDLER

School of Physics, The University, Newcastle upon Tyne, NE1 7RU, UK

and

R. G. B. RENNER

British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK

ABSTRACT. A total-field aeromagnetic anomaly map of the Staccato Peaks area of Alexander Island (71.3° S–72.3° S, 70.0° W–71.0° W) shows that Staccato Peaks are associated with small magnetic anomalies (< 200 nT). In contrast, there are two 500 nT anomalies associated with exposed gabbroic-dioritic intrusions over Astraea Nunatak and Ceres Nunataks, 15–25 km to the south. Three-dimensional modelling indicates (i) the Astraea and Ceres nunataks clearly belong to the same igneous body and (ii) the body is a near-surface intrusion with approximate dimensions 25 km (N–S) × 10 km (W–E) × 1 km (vertical) assuming a magnetization contrast of 4000 mA m^{-1} estimated from laboratory measurements on rock samples. The body is a shallow gabbroic intrusion, possibly a lopolith.

INTRODUCTION

Staccato Peaks (lat. 71° 47′ S, long. 70° 33′ W) are located in southern Alexander Island off the west coast of the Antarctic Peninsula (Fig. 1). They form a range trending north-west–south-east for nearly 30 km. There are five main peaks, the highest being The Obelisk, which reaches 984 m above sea level. Their jagged steep-sided form (Fig. 2) is probably due to glacial erosion along joints and cleavage planes (Bell, 1973).

Fifteen kilometres south of Staccato Peaks lies Astraea Nunatak (619 m) and a further 10 km south there is a small group of outcrops known as Ceres Nunataks (524 m). The surrounding area is ice-covered, the ice thickness being between 350 and 1000 m (Crabtree, 1983).

GEOLOGY

Since the late Palaeozoic, the geological history of the region has been dominated by the semi-continuous subduction of Pacific Ocean floor beneath the western margin of the Antarctic Peninsula. Subduction continued until sections of the Aluk ridge reached the trench, since when it has ceased progressively northwards. Barker (1982) estimated that the ages of the ridge-trench collisions range from 50 Ma in the south to 4 Ma in the north.

The country rocks in the Staccato Peaks area (Fig. 1) belong to the LeMay Group, a highly deformed metasedimentary formation known to crop out extensively in western and central Alexander Island. The succession at Staccato Peaks is similar to that found in Lully Foothills, approximately 100 km to the north, where marine fossils

* Present address: University of London Observatory, Mill Hill Park, London NW7 2QS.

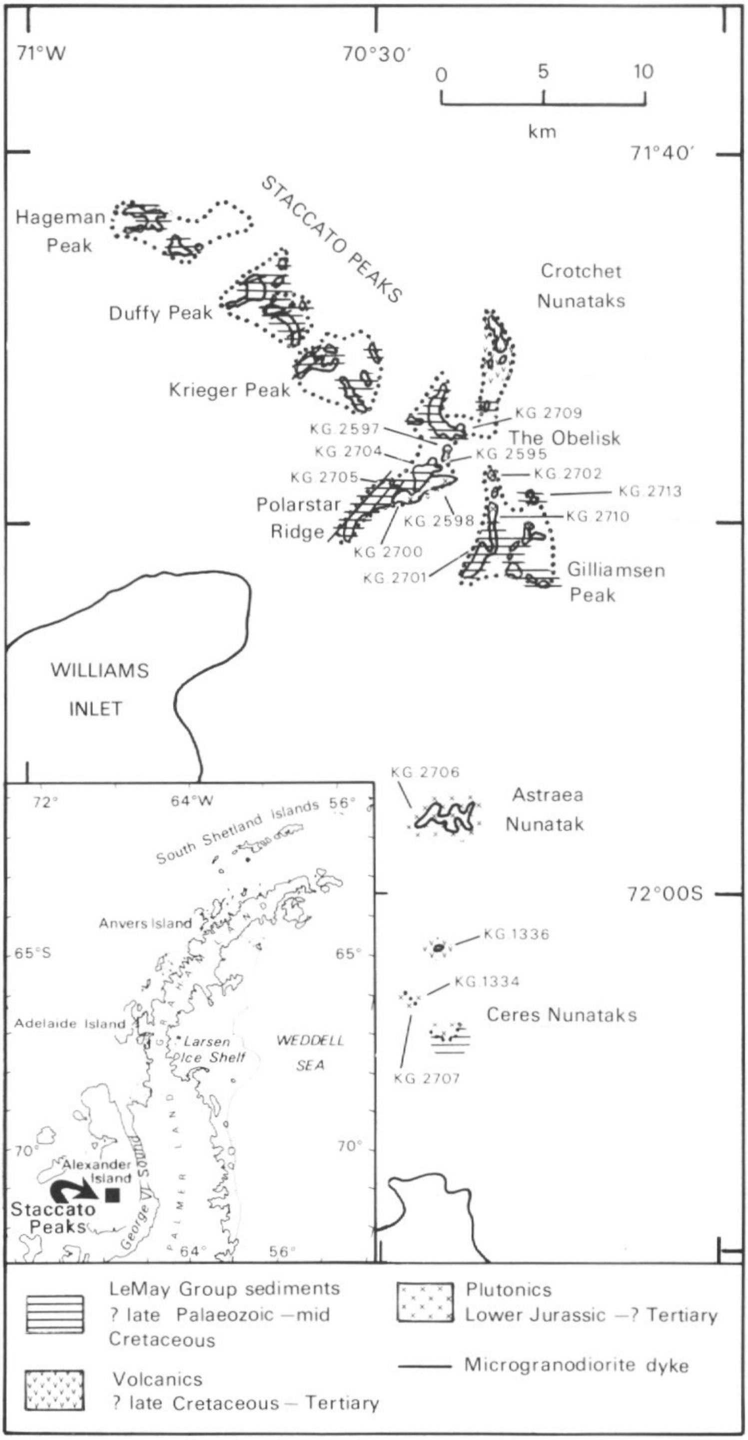

Fig. 1. Geological map of the Staccato Peaks area of Alexander Island. The numbers are the locations of rock samples used for magnetic measurements (Table I).

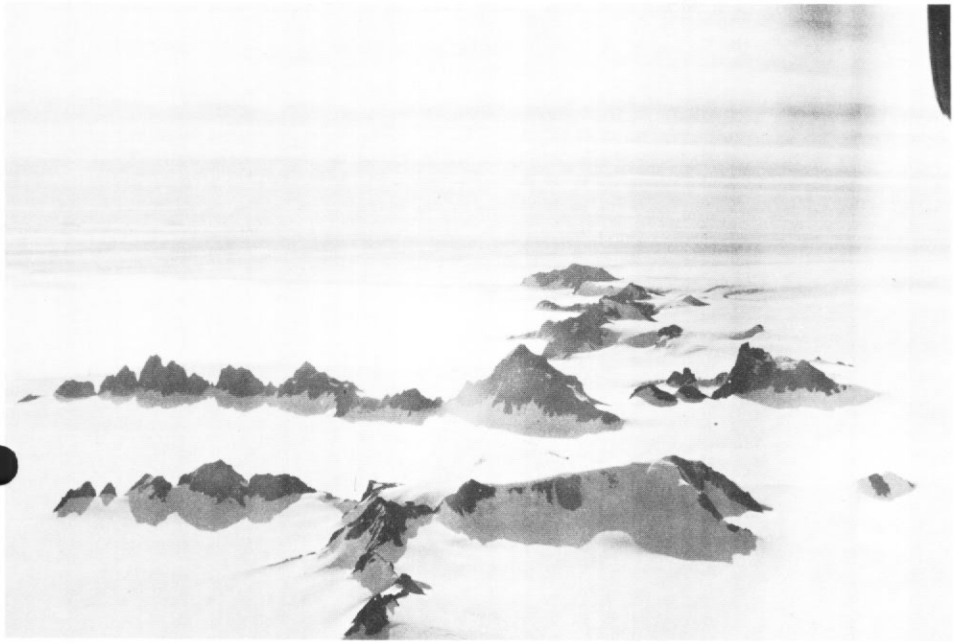

Fig. 2. Staccato Peaks looking north-west; The Obelisk, the highest peak (984 m) is visible in the middle distance with Polarstar Ridge adjacent and trending to the south-west.

were thought to indicate a middle–late Triassic age (Edwards, 1979). However, the discovery of an early Jurassic ammonite at this same locality renders a Triassic age untenable (personal communication 1984, Dr M. R. A. Thomson and T. H. Tranter). The stratigraphical age of the LeMay Group ranges from up into the mid-Cretaceous (Burn, 1984) to possibly older than early Jurassic. Together with other sequences discontinuously exposed along the Antarctic Peninsula, the group is considered to represent part of a fore-arc accretionary prism (Suárez, 1976; Smellie, 1981; Burn, 1984). Subduction-related processes are also responsible for the widespread plutonic activity found throughout the region, older plutons occurring along the eastern margin of the Antarctic Peninsula (Pankhurst, 1982). Radiometric dating has also demonstrated that the focus of magmatic activity migrated westwards with time (Smellie, 1981; Burn, 1984).

The plutons that intrude massive sheared arkoses and mylonites at Staccato Peaks (Bell, 1973; Care, 1976) are considered to be broadly contemporaneous with the Tertiary calc-alkaline volcanism of Alexander Island (Burn, 1981). The largest known intrusion at Staccato Peaks crops out along Polarstar Ridge south-west of The Obelisk. This intrusion, originally described as a porphyritic microgranodiorite (Bell, 1973), has been reclassified by A. B. Moyes (personal communication 1983, A. B. Moyes British Antarctic Survey) as a granodiorite according to Streckeisen (1976), although porphyritic microgranodiorite dykes do crop out elsewhere in Staccato Peaks. More basic, dioritic intrusions at Astraea Nunatak and Ceres Nunataks (Bell, 1973) also include gabbros, and Moyes suggested that modal variations were consistent with some type of layering although further field and laboratory studies will be necessary to confirm this. Modal analysis of an olivine gabbro (KB.1334.1) from Ceres Nunataks showed 6% to be magnetic ore minerals

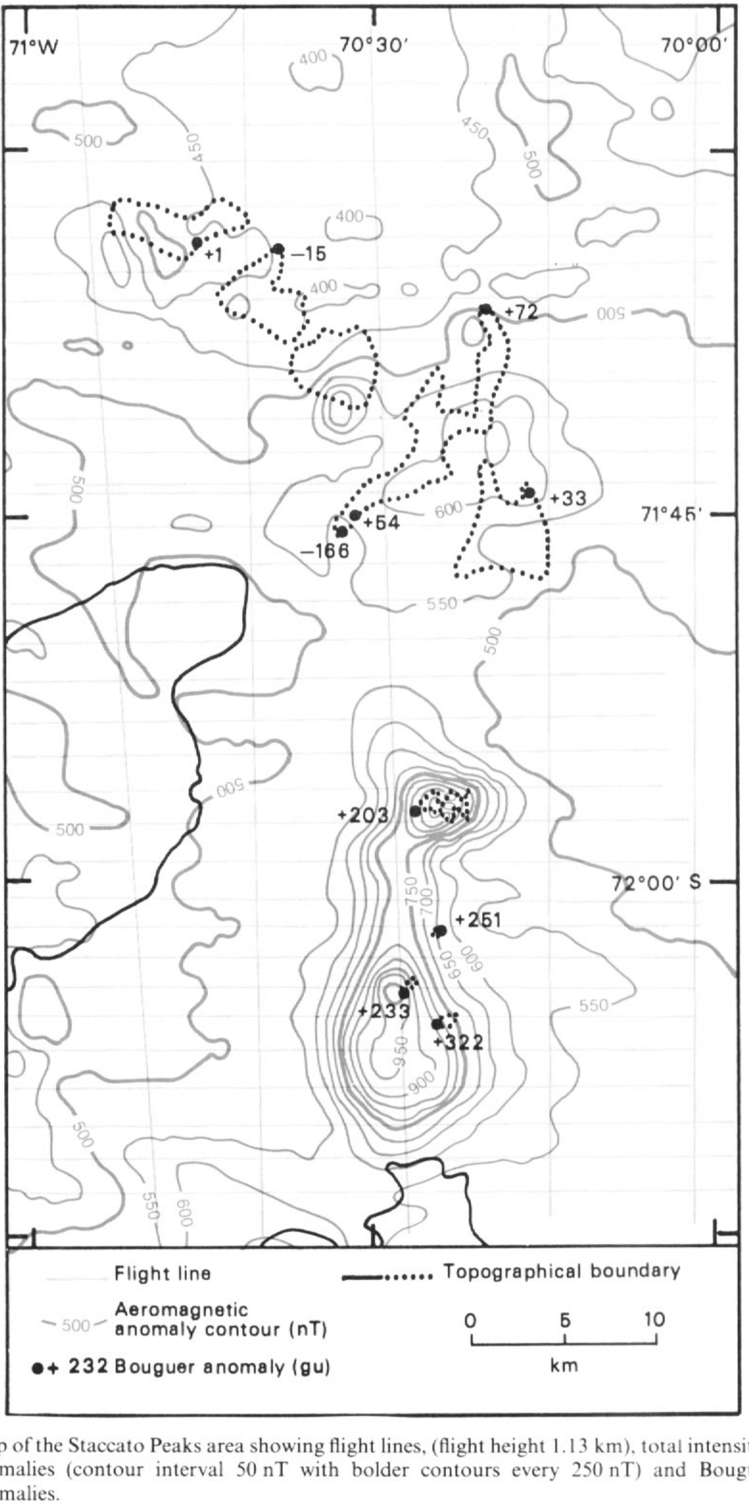

Fig. 3. Map of the Staccato Peaks area showing flight lines, (flight height 1.13 km), total intensity magnetic anomalies (contour interval 50 nT with bolder contours every 250 nT) and Bouguer gravity anomalies.

(personal communication 1983, A. B. Moyes), which conforms with the revised classification of the rocks.

The only other rock outcrops in the survey area are Crotchet Nunataks, a group of four isolated nunataks lying 5 km north of The Obelisk. These consist of thin-bedded tuffs, agglomerates and andesitic lavas and are probably of Tertiary age (Care, 1976; Burn, 1981).

Aeromagnetic Survey

The Staccato Peaks survey covers a small part of Alexander Island to the west of the Antarctic Peninsula (inset Fig. 1).

Palmer Land and Graham Land are associated with large magnetic anomalies, which may be related to plutons arising from the Jurassic island arc or to back-arc spreading centres. A linear anomaly follows the west coast for about 900 km and may be related to a continuous batholith intruded into the continental basement similar to the Patagonian batholith in the southern Andes (Renner and others, 1982).

In contrast, the magnetic field over Alexander Island is relatively quiet, reflecting the thick sequences of the LeMay and Fossil Bluff formations (Renner and others, 1982). The magnetic anomalies associated with Astraea and Ceres nunataks are amongst the largest over the island.

The Survey

The Staccato Peaks survey (track chart Fig. 3) was flown during December 1975 and January 1976 at a constant barometric altitude of 1130 m, with an east–west flightline separation of 1.6 km and a north–south tie grid separation of about 7.5 km. Data were sampled at one-second intervals, which, at a ground speed of 120–140 knots (220–260 km h^{-1}), equates to 15 data points per kilometre. The total track coverage was 2200 km. The equipment included a Geometrics G-803 proton precession magnetometer with both analogue and digital recording, a Bendix DRA-12 Doppler navigation system and Sperry C-12 gyro-magnetic compass, and a Bonzer radio altimeter.

A wing-tip sensor unit was employed and the largest source of error in the magnetic measurements is the aircraft heading error, which was found, from 'clover-leaf' tests to be less than ± 10 nT.

The navigation equipment computed the position of the aircraft relative to a fixed starting point; this was usually an identifiable topographic feature such as The Obelisk. The positional accuracy of the west–east lines is estimated to be within ± 0.5 km. During the north–south network, technical problems with the aircraft navigation system introduced larger closure errors. As lack of time prevented repetition of the lines they have not been included in the computer contouring.

Throughout the survey, the transient variations of the Earth's magnetic field were monitored at Adelaide station (67° 46′ S, 68° 55′ W) and at the Geomagnetic Observatory at Faraday (65° 15′ S, 64° 16′ W). Whilst these stations lie several hundreds of kilometres to the north, previous BAS experience has shown the results are applicable.

Data reduction

The track chart is shown in Fig. 3. Over 10000 data points were corrected for transient variations, the maximum recorded amplitude at Faraday station for the daily variation being 56 nT.

The International Geomagnetic Reference Field (IGRF) 1965 (Fabiano and Peddie, 1969) for 1975–76 was subtracted. As can be seen from Fig. 3, there is still a residual background field of about 500 nT, suggesting that the IGRF is not strictly applicable to this area. This is confirmed by Peddie (1983), who compared the predicted and definitive main field models and showed that differences exceeding 300 nT can be expected over Alexander Island.

Mean values were calculated for every ten observations giving total-field magnetic anomaly data points at approximately every 0.6 km along the flight lines. The values along the west–east lines were contoured and the resulting map is shown in Fig. 3.

Description of the anomalies

Inspection of Fig. 3 shows that the largest anomalies are associated with Ceres and Astraea nunataks, where values of 500 nT are observed above the background field. The two maxima are coincident with the nunataks but both are considered components of a single more extensive anomaly trending north–south for 25 km and with a width of 10 km. Maximum east–west gradients approach 150 nT km^{-1}. The anomaly contrasts with the magnetic relief over Staccato Peaks, which is quieter despite the high altitude of some of the peaks; for example, The Obelisk reaches 984 m, almost twice the height of the southern nunataks. Furthermore, comparison with the geology shows that neither of the two small (< 200 nT) magnetic highs in the area of the Staccato Peaks are directly associated with igneous outcrops. Similarly, the igneous intrusions to the north have no significant magnetic relief.

Interpretation of the Magnetic Anomalies

To assist the interpretation of the magnetic anomalies, laboratory measurements were made to ascertain the magnetic properties of all the available rock samples. These included 15 from Staccato Peaks but, unfortunately, only two from Astraea Nunatak and three from Ceres Nunataks, which have the strongest magnetic anomalies. The samples were collected for geological studies several years before the survey and were not orientated.

Rock Magnetic Properties

Two cores were taken from each sample and their remanent and induced magnetizations were measured (Crawford, 1983), the former with a Digico spinner magnetometer and the latter with a susceptibility meter (Collinson and others, 1963). The results are given in Table I. The Königsberger ratio, which is the ratio of the remanent to the induced magnetization, is also given. It is seen that this is less than unity for 14 out of 20 of the samples, indicating that the induced component is the more dominant.

It is apparent from Table I that there is a wide variation in the magnetic intensities although samples from Ceres and Astraea nunataks generally possess larger magnetizations than those from Staccato Peaks. The sample KG.2701.2 from Staccato Peaks is regarded as atypical since it comes from a mafic-rich enclave. The intrusion at Astraea Nunatak appears to be less strongly magnetized than that at Ceres Nunataks. If both outcrops belong to the same body, as is indicated by the geometry of the anomaly, this difference might be explained by layering in the intrusion (personal communication, A. B. Moyes).

If it is assumed that the direction of the remanent magnetization is parallel to the

Table I. Induced and remanent magnetization values of selected rock specimens.

Locality	*Specimen number*	*Field classification*	*Magnetization* ($mA\ m^{-1}$) *remanent* (Mn)	*induced* (Mi)	*Königsberger ratio* $Qn = Mn/Mi$
Staccato Peaks	KG.2595.6	Porphyritic diorite	29.1 ± 0.9	25.2 ± 0.7	1.16 ± 0.05
Staccato Peaks	KG.2595.11	Diorite	129 ± 14	35.7 ± 2.6	3.62 ± 0.48
Staccato Peaks	KG.2597.4	Diorite	78.4 ± 2.5	68.8 ± 1.2	1.14 ± 0.04
Staccato Peaks	KG.2598.1	Granodiorite[1]	146 ± 2	230 ± 16	0.64 ± 0.04
Staccato Peaks	KG.2700.1	Diorite	12.5 ± 4.8	35.7 ± 4.0	0.35 ± 0.14
Staccato Peaks	KG.2701.2	Granodiorite[1]	218 ± 76	6760 ± 120	0.03 ± 0.01
Staccato Peaks	KG.2702.1	Diorite	132 ± 2	1210 ± 52	0.11 ± 0.01
Staccato Peaks	KG.2704.1	Metasedimentary	1.0 ± 0.6	25.3 ± 1.3	0.04 ± 0.02
Staccato Peaks	KG.2705.1	Porphyritic microdiorite	2.4 ± 0.3	8.5 ± 0.3	0.28 ± 0.04
Staccato Peaks	KG.2705.10	Metasedimentary	1.5 ± 0.2	9.7 ± 1.1	0.15 ± 0.03
Staccato Peaks	KG.2705.11	Xenolithic dyke material	59.8 ± 2.9	230 ± 74	0.27 ± 0.09
Staccato Peaks	KG.2705.12	Xenolithic dyke material	9.4 ± 0.3	21.4 ± 0.6	0.44 ± 0.02
Staccato Peaks	KG.2709.1	Metasedimentary	0.8 ± 0.2	7.2 ± 1.3	0.11 ± 0.03
Staccato Peaks	KG.2710.1	Granodiorite[1]	48.0 ± 2.7	736 ± 12	0.07 ± 0.01
Staccato Peaks	KG.2713.1	Metasedimentary	65.7 ± 5.6	16.2 ± 5.4	4.06 ± 1.40
Astraea Nunatak	KG.2706.7	Diorite[1]	225 ± 40	335 ± 11	0.67 ± 0.12
Astraea Nunatak	KG.2706.8	Tonalite	617 ± 34	1710 ± 250	0.36 ± 0.06
Ceres Nunataks	KG.1334.1	Gabbro[1]	5290 ± 450	2750 ± 90	1.92 ± 0.18
Ceres Nunataks	KG.1336.1	Andesite	106 ± 4	29.1 ± 0.4	3.64 ± 0.20
Ceres Nunataks	KG.2707.3	Diorite	1030 ± 84	3340 ± 200	0.31 ± 0.03

[1] Specimens examined and classified from thin Section (A. B. Moyes, personal communication).

induced, the mean total intensity for the Staccato Peaks igneous rocks is 947 mA m^{-1} ($N = 11$). This falls to 344 mA m^{-1} ($N = 10$) if sample KG.2701.2 is omitted. The mean intensity (bearing in mind the small number of samples) for Astraea Nunatak is 1440 mA m^{-1} ($N = 2$) and for Ceres Nunataks (omitting the andesite KG.1336.1) is 6200 mA m^{-1}, ($N = 2$).

The Astraea–Ceres Magnetic Anomaly

The magnetic anomalies are shown in isometric form in Fig. 4. Fig. 4(a) shows how the anomalies associated with the Astraea–Ceres Nunataks dominate the survey area and Fig. 4(b) shows a close up of the Astraea–Ceres anomalies.

The anomaly has been interpreted with the aid of a three dimensional magnetic interpretation programme (Coles, 1974; Crawford, 1983) based on the method of Bhattacharyya (1964). This computes the magnetic field due to a series of prism shaped bodies with a given intensity and direction of magnetization. In the models, the top surface is constrained by (i) the size, shape and positions of the outcrops of the Astraea and Ceres nunataks and (ii) ice thickness data from an airborne radio-echo survey. The nunataks reach an altitude of approximately 500 m, making their summits about 630 m below the survey altitude. The land surface between Astraea and Ceres nunataks is at about sea level with undulations of up to ± 80 m. It is assumed that the direction of magnetization is parallel to the Earth's magnetic field, i.e. with declination, $D = 24°$ E and inclination, $I = -63.6°$. From Table I it is seen that the total intensity of magnetization (remanence plus induced) ranges from about 2000–6000 mA m^{-1} for the strongly magnetized rocks from Astraea and Ceres nunataks. This leads to an assumed total intensity of 4000 mA m^{-1} for the intrusion although this is poorly constrained because of few samples.

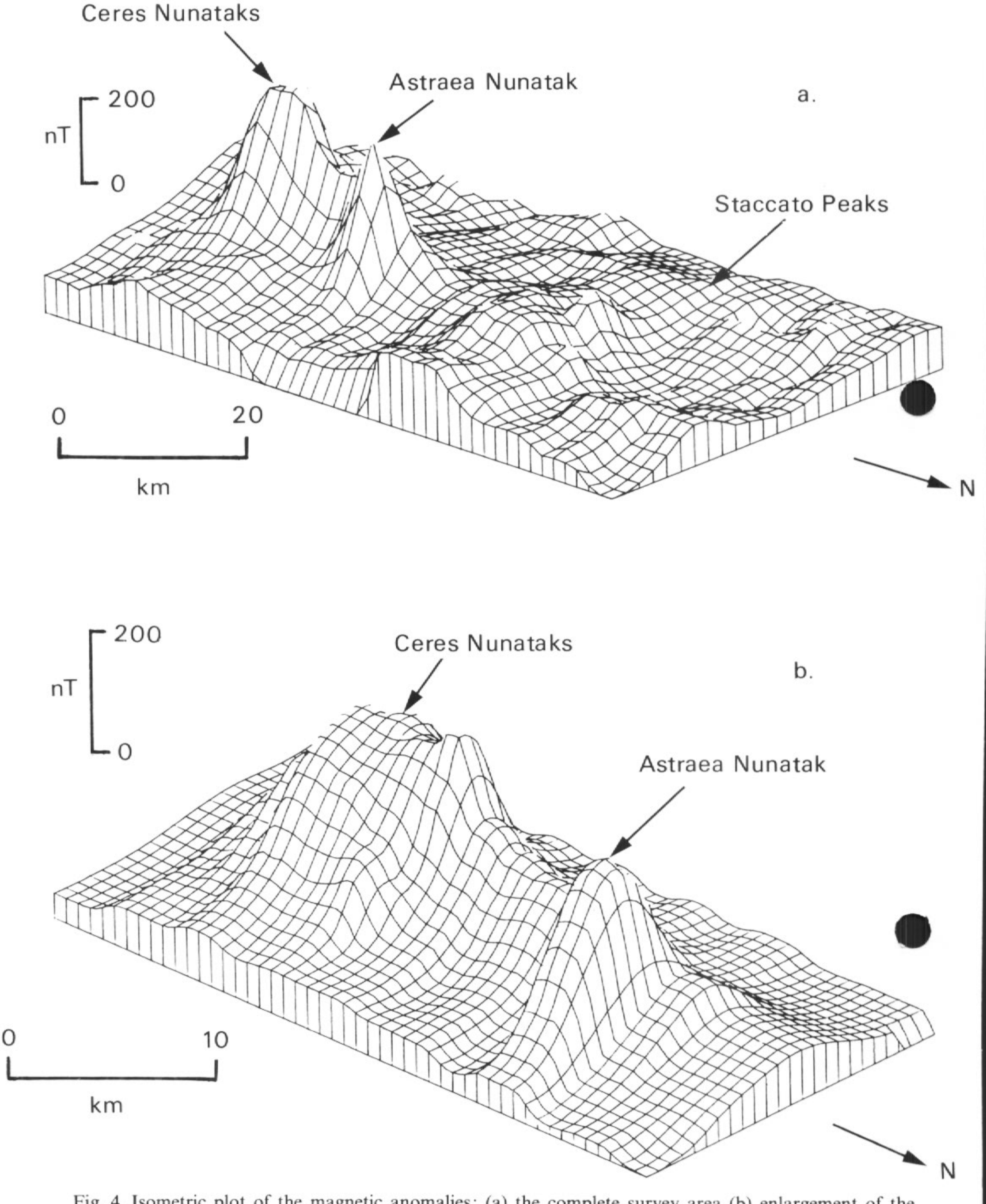

Fig. 4. Isometric plot of the magnetic anomalies; (a) the complete survey area (b) enlargement of the Astraea Nunatak–Ceres Nuntak's anomaly.

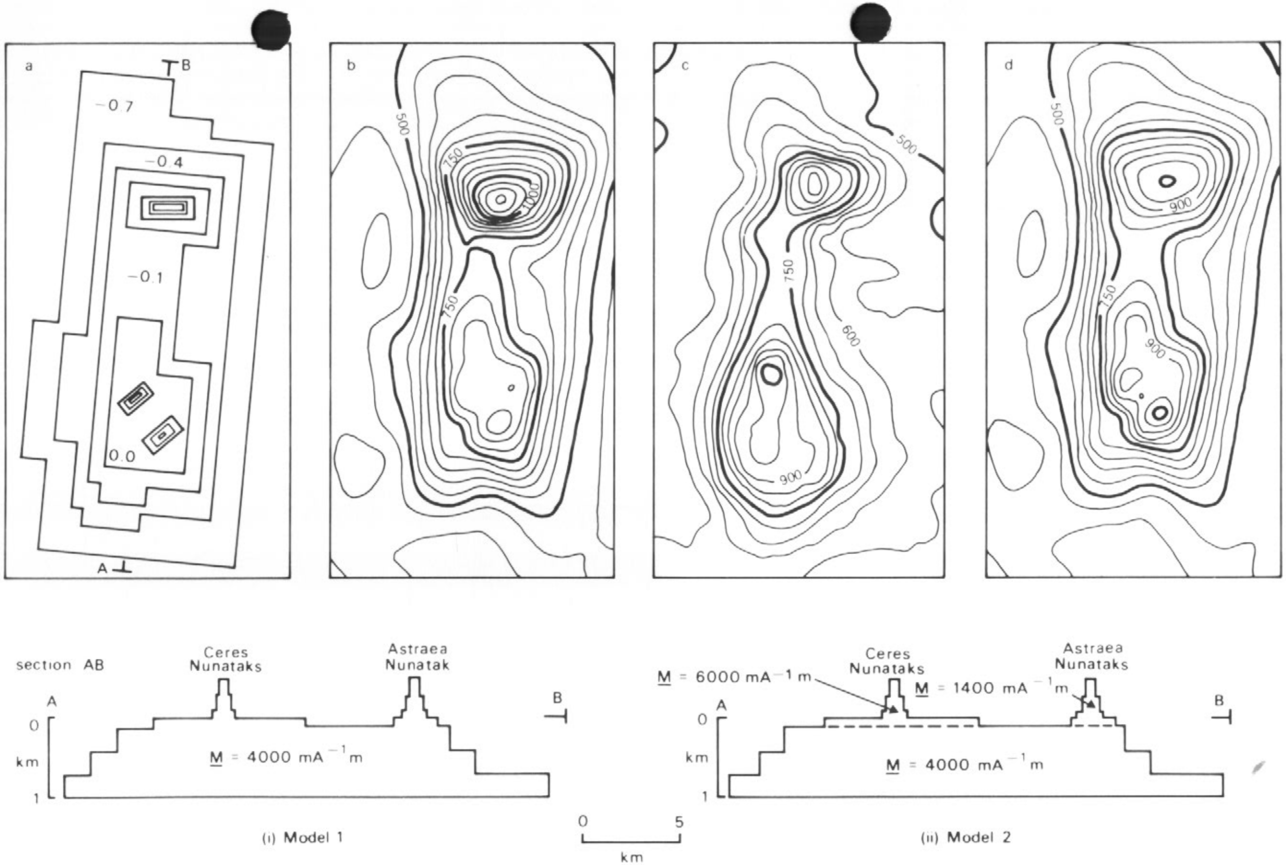

Fig. 5. Three-dimensional interpretation of the Astraea Nunatak–Ceres Nunataks magnetic anomaly. (a) Plan view of model; values represent elevation of upper surface (km) relative to sea level; (b) Computed anomaly for Model 1; (c) The observed total field anomaly; (d) Computed anomaly for Model 2.

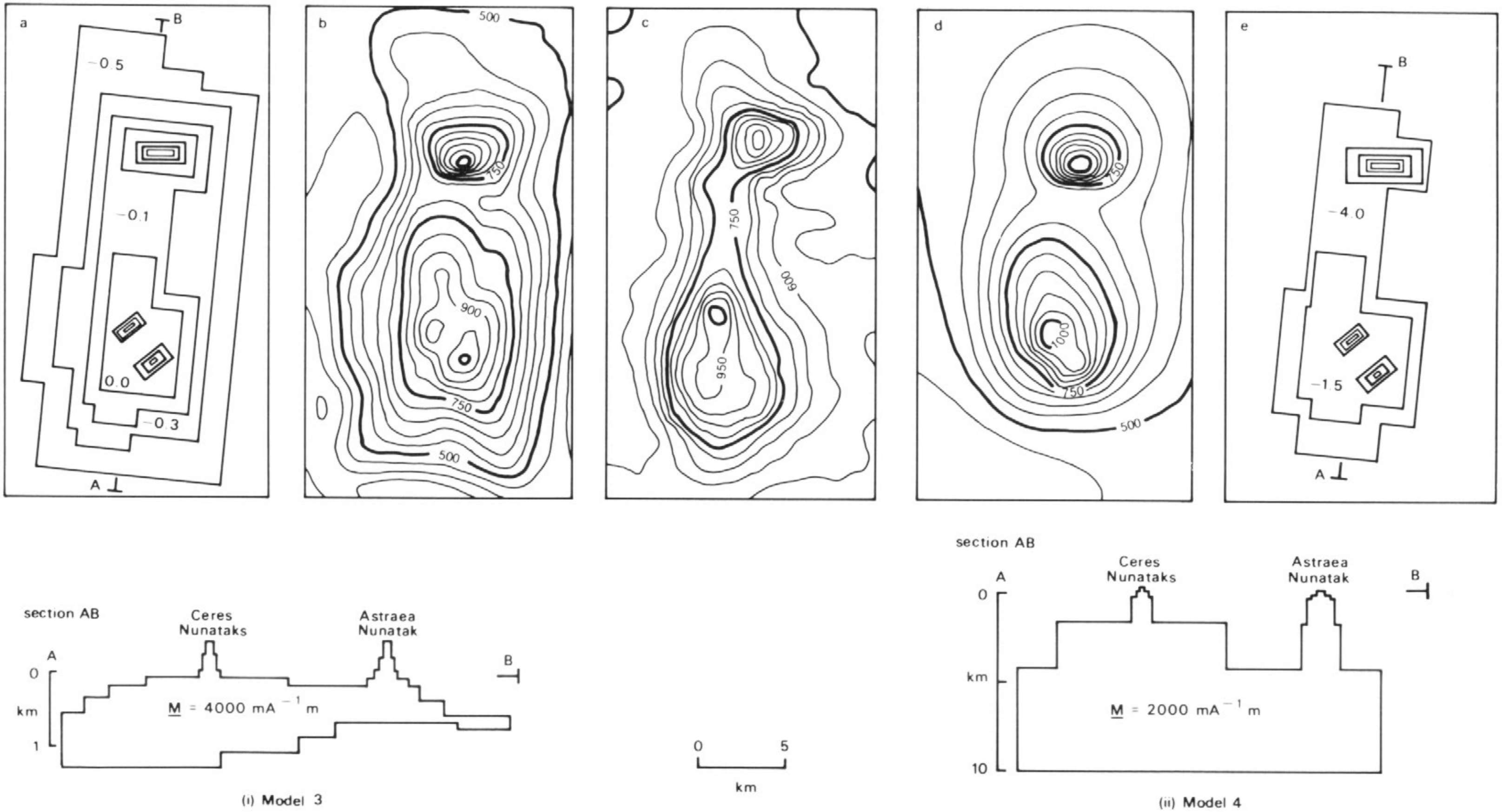

Fig. 6. Three-dimensional interpretation of the Astraea Nunatak–Ceres Nunataks magnetic anomaly. (a) Plan view of Model 3 (cf. Fig. 5); (b) Computed anomaly for Model 3; (c) The observed total field anomaly; (d) Computed anomaly for Model 4; (e) Plan view of Model 4.

Four models are presented to illustrate the range of possibilities.

Model 1, Fig. 5. This assumes a uniform total intensity of magnetization of 4000 mA m^{-1}. In order to reproduce the observed anomaly we find (a) the body is unlikely to extend to depths much greater than 1 km below sea level, i.e. 1.5 km below the height of the outcrops and (b) the source body has to be continuous beneath the Astraea and Ceres nunataks. Comparison of the computed and observed anomalies shows the general agreement with differences in detail i.e. the overall shape is good but the computed anomaly over Astraea Nunatak is 200 nT too high and that over Ceres Nunataks 100 nT too low.

Model 2, Fig. 5. A uniform magnetization of 4000 mA m^{-1} is retained for the main part of the body but, in order to improve the relative amplitudes of the anomalies associated with the nunataks, the magnetization of Astraea Nunatak is decreased and that of Ceres Nunataks increased, bringing the magnetizations closer to the measured values (Table I). This improves the amplitudes, especially for Astraea Nunatak, but not the shape of the anomaly over Ceres Nunataks.

Model 3, Fig. 6(i). A uniform magnetization of 4000 mA m^{-1} is assumed with the same top surface geometry but the depth of the base is varied so as to give the observed anomaly strength over Astraea Nunatak.

Model 4, *Fig. 6(ii).* A uniform magnetization of 2000 mA m^{-1} (near to the lower limit) is assumed. This requires the body to extend to a depth of 10 km but the computed anomaly shows poor agreement with that observed. Similarly, if the magnetization is increased to 6000 mA m^{-1} (near to the upper limit) the computed anomalies (not shown) are far too large and the gradients too steep.

Throughout, it has been assumed that the remanent magnetization is parallel to the Earth's present field. If the intrusion is of Tertiary age, it is possible that it may be reversely magnetized. Consideration of the Königsberger ratios (Table I) suggests that, if the remanent magnetization is reversed, the total magnetization would be insufficient to account for the observed amplitudes of the magnetic anomalies and therefore this seems unlikely.

In the absence of other geophysical and geological data, no single potential field interpretation uniquely resolves the shape of a causative body. Here we have used the few data available and from geological constraints coupled with the 'best-fit' geophysical interpretation it is likely that Models 1 and 3 give a fair indication of the geometry and magnetization of the body responsible for the Astraea–Ceres magnetic anomaly with Model 3 being preferred. Reconnaissance gravity measurements (Renner and others, 1985) show positive Bouguer gravity anomalies (Fig. 3) over the Astraea–Ceres nunataks. These are consistent with the presence of a basic intrusive body and do not contradict the possible thinning beneath Astraea Nunatak shown in Model 3, Fig. 6(i).

The isolation of the outcrops at Astraea and Ceres nunataks and Staccato Peaks means that attempts at geological correlation can only be tenuous. However, similar isolated plutons occur to the north in western Alexander Island and it is likely that these belong to the Mesozoic–Tertiary subduction-related Andean Intrusive Suite. Furthermore, they are probably contemporaneous with the batholith of the Rouen Mountains in northernmost Alexander Island (Care, 1983), which has yielded an age of 46 ± 3 Ma (Pankhurst, 1982).

Conclusions

The area includes a granodioritic intrusion at Staccato Peaks and a more basic gabbroic-dioritic body at Astraea and Ceres nunataks. Both bodies could be representatives of the more extensive calc-alkaline suite known collectively as the Andean Intrusive Suite. Astraea and Ceres Nunataks have a 500-nT amplitude anomaly reflecting the higher concentration of magnetic minerals in the more basic rocks. Interpretation suggests the presence of a hypabyssal gabbroic intrusion about $25 \times 10 \times 1$ km with a maximum depth 1.5 km below the top of the surface outcrops and which may shallow northwards beneath Astraea Nunatak. A uniform total intensity of magnetization of 4000 mA m^{-1} from rock magnetic measurements gives approximately the correct amplitude of the anomalies. For weaker or strong magnetizations, the body could extend to deeper or shallower depths and still give an anomaly consistent with that observed but these parameters cannot be changed very much since reducing the magnetization by a factor of two (Model 4) gives a very poor fit. It is concluded that the body is possibly a laccolith or lopolith. Bouguer gravity anomalies are not in conflict with this interpretation.

Acknowledgements

The authors are grateful to the BAS personnel at Adelaide Island and Fossil Bluff for help with the flying operations and especially to G. Harvey, the pilot and B. J. Dikstra and J. L. Martin, fellow geophysicists. They also express their gratitude to P. D. Clarkson and A. B. Moyes for their help with geological aspects, and to W. Rutherford for coring the rock samples for magnetic measurements. I. A. Crawford is grateful to the Natural Environment Research Council for an Advanced Course Studentship.

Received 20 August 1985; accepted 21 October 1985

References

Barker, P. F. 1982. The Cenozoic subduction history of the Pacific margin of the Antarctic Peninsula: ridge crest-trench interactions. *Journal of the Geological Society, London*, **139**, 787–801.

Bell, C. M. 1973. The geology of southern Alexander Island. *British Antarctic Survey Bulletin*, Nos. 33 and 34, 1–16.

Bhattacharyya, B. K. 1964. Magnetic anomalies due to prism-shaped bodies with arbitrary polarization. *Geophysics*, **29**, 517–31.

Burn, R. W. 1981. Early Tertiary calc-alkaline volcanism on Alexander Island. *British Antarctic Survey Bulletin*, No. 53, 175–93.

Burn, R. W. 1984. The geology of the LeMay Group, Alexander Island. *British Antarctic Survey Scientific Reports*, No. 109, 65 pp.

Care, B. W. 1977. Areas in Alexander Island (Rothschild Island, Havre Mountains and Staccato Peaks). Interim geological report (BAS Archives No. AD6/2R/G1/1976), 10 pp. (Unpublished.)

Care, B.W. 1983. The petrology of the Rouen Mountains, northern Alexander Island. *British Antarctic Survey Bulletin*, No. 52, 63–86.

Coles, R. W. 1974. Two magnetic interpretation methods using rectangular prisms. Department of Energy, Mines and Resources, Ottawa, Ontario. Report No. 74–3.

Collinson, D. W. & Molyneux, L. *and* Stone, D. B. 1963. A total field and anisotropic susceptibility meter. *Journal of Scientific Instruments*, **40**, 310–12.

Crabtree, R. D. 1983. British Antarctic Territory Ice Thickness Map, Scale 1:500,000, Alexander Island, Series BAS 500R, Sheet 1, Edition 1.

Crawford, I. 1983. *An analysis of aeromagnetic data over the Staccato Peaks region of Alexander Island, Antarctica.* MSc Thesis, University of Newcastle upon Tyne, 63 pp. (Unpublished.)

Edwards, C. W. 1979. Early Mesozoic marine fossils from central Alexander Island. *British Antarctic Survey Bulletin*, No. 49, 33–58.

Fabiano, E. B. *and* Peddie, N. W. 1969. Grid values of total magnetic intensity IGRF-1965. *ESSA Technical Report*, No. 38, 55 pp.

Pankhurst, R. J. 1982. Rb–Sr geochronology of Graham Land, Antarctica. *Journal of the Geological Society, London*, **139**, 701–11.

PEDDIE, N. W. 1983. International geomagnetic reference field – its evolution and the difference in total field intensity between new and old models for 1965–1980. *Geophysics*, **48**, No. 12, 1691–6.

RENNER, R. G. B., DIKSTRA, B. J. *and* MARTIN, J. L. 1982. Aeromagnetic surveys over the Antarctic Peninsula. (*In* CRADDOCK, C. *ed. Antarctic geoscience*, Madison, University of Wisconsin Press, 363–7.)

RENNER, R. G. B., STURGEON, L. J. S. *and* GARRETT, S. W. 1985. Reconnaisance gravity and magnetic surveys of the Antarctic Peninsula. *British Antarctic Survey Scientific Reports*, No. 110, 54 pp.

SMELLIE, J. L. 1981. A complete arc-trench system recognised in Gondwana sequences of the Antarctic Peninsula region. *Geological Magazine*, **118**, 139–59.

STRECKEISEN, A. 1976. To each plutonic body its proper name. *Earth Science Review*, **12**, 1–33.

SUÁREZ, M. 1976. Plate-tectonic model for southern Antarctic Peninsula and its relation to southern Andes. *Geology*, **4**, No. 4, 211–14.