A GEOPHYSICAL STUDY IN THE EASTERN CHALKIDIKI PENINSULA, N. GREECE. THE STRATONI GRANODIORITE AND ITS SIGNIFICANCE TO METALLOGENY.

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Abstract

Geophysical studies are carried out in Eastern Chalkidiki Peninsula. This area, geologicaly belongs to the Kerdylion and Vertiskos formations of the Serbomacedonian Massif.

Helicopter magnetic data are used to delineate the shape and areal extent of the Stratoni granodiorite which is intruded into the Kerdylion formation. Modelling is controlled by geological information and the study of the physical properties of the intrusive body and surrounding lithologies. This geophysical interpretation gives a new insight to the spatial association of the intrusion with the carbonate-hosted Pb-Zn (Au,Ag) mineralization in the area.

Gravity and magnetic anomalies in the area to the south of the Stratoni granodiorite (this area belongs to the Vertiskos formation and is separated from the area to the north by the E-W trending Stratoni-Varvara fault) are compatible with a common origin, a dismembered ophiolite overlying a non-magnetic basement.

Geological observations combined with the above interpretation are used to control the estimates of the regional gravity field in the area and deduce the continuation of the overall picture of the regional geology offshore.

1.0 Introduction

The area of study geologically belongs to the Vertiskos and Kerdylion formations of the Serbomacedonian Massif (Fig 1, Kockel et. al., 1977).

The Vertiskos formation consists of the tectonic juxtaposition of rock assemblages which have originated at different settings. These rock assemblages are represented primarily by Palaeozoic or older two-mica gneisses, amphibolites, Permotriasic metavolcanic and metasediments and dismembered metamorphosed ophiolites (Kockel et. al., 1977; Papanikolaou, 1984; Kalogeropoulos and Theodoroudis, 1988; Kalogeropoulos et. al., 1989). These rocks have been intruded along structural lineaments by Tertiary porphyry systems bearing Cu(Au) mineralization (Kockel et. al., 1977; Kalogeropoulos et. al., 1989).

The Kerdylion formation is a Cambrian or older heterogeneous assemblage of biotite - hornblende/biotite-gneisses (locally migmatitized) as well as leucocratic gneisses, amphibolites and marbles. These rocks, in places, have been intruded during Tertiary times by the exposed Stratoni granodiorite, calkalkaline lamprophyre dykes and a network of tonalitic-granitic pegmatites/aplites. The age of the Stratoni granodiorite is 29.6±1.4 Ma (Papadakis, 1971; Alther et. al., 1976; Frei, 1988 writ. comm.). This magmatic stock which is located approximately 0.5 km N-NW of the Stratoni village and has a

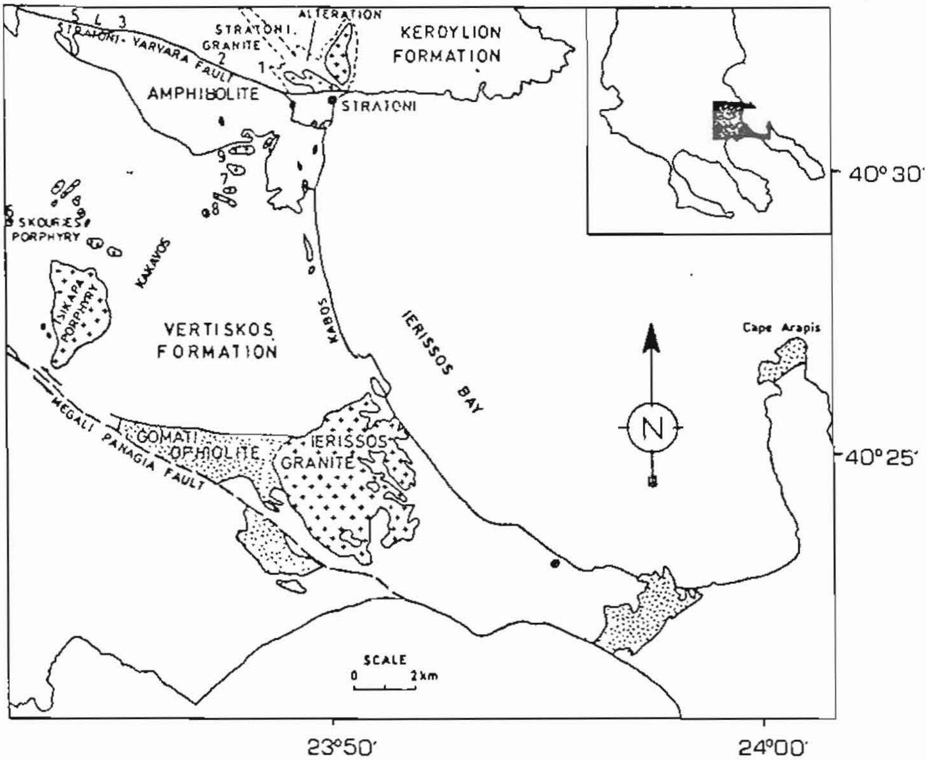

Fig.1 Simplified geological map of the study area (modified from Kockel et. al., 1977). Mineralizations are numbered as follows:
1,2,3 = Madem Lakos-Mavres Petres Pb-Zn (Au, Ag), Mn
4 = E. Piavitsa Pb-Zn-(Au, Ag), Mn
5 = Piavitsa Mn (Au)
6 = Skouries porphyry Cu(Au)
7 = Fisoka porphyry Cu(Au)
8 = Alatina porphyry Cu(Au)
9 = N.Fisoka porphyry Cu(Au)

surface outcrop of about 3 km^2 was intruded into the Kerdylion formation along with mineralized and hydrothermally altered pegmatite/aplite dykes. The chemistry of this granodiorite is compatible with an origin from a calk-alkaline magma of hybrid nature consisting of predominantly mantle and also crust derived components. It contains minor base metal sulfide veins and disseminations and is spatially associated with the Madem Lakos and Mavres Petres carbonate-hosted Pb-Zn (Au, Ag) massive sulfide orebodies (Kalogeropoulos et. al., 1989). Kalogeropoulos et. al. (1989) in a study of the Eastern Chalkidiki massive sulfide ores suggest that the Tertiary magmatism that also produced the Stratoni granodiorite is also responsible for the concentration of ore elements into ore deposits.

The Kerdylion formation appears to be uplifted relative to the Vertiskos formation along a major E-W/NW-SE trending fault, the Stratoni-Varvara fault (Fig1.; Dixon and Dimitriadis, 1984; Kalogeropoulos and Theodoroudis, 1988). This fault, dipping at about 30-45 degrees S/SW, controls the distribution of manganese and base metal ores in the area (I.G.M.E. on-going studies).

The numerous mineral occurences of different ore deposit types in the study area and their association to pertinent geological and structural features as reffered to above can be delineated further by studying the geophysical characteristics of the latter. In the present study gravity and magnetic methods are employed for this purpose, together with some studies of the physical properties of the main lithologies. This approach might also contribute towards a more refined design of mineral exploration programmes in this area.

2. Geophysical Dataset

A terrain-corrected Bouguer gravity map (Lagios, pers. comm.) is shown in Fig. 2. The contour interval is 50 gu and Bouguer density 2.67 T/m^3.

Aeromagnetic maps for the area (flight height above ground 275$\pm$ 75 m, flight line spacing 800 m, corrected for diurnal variations and geomagnetic field gradient within Greece), were produced by ABEM Elektrisk Malmetning, Stockholm during 1966. Helicopter magnetic maps (at the mean altitude above ground of 50 m, flight line spacing 200 m, IGRF and time variation reduction (Sengpiel and Ostwald, 1983)) are also available. Both (aeromagnetic and helicopter-magnetic) datasets terminate along the coastline of the Chalkidiki Peninsula. Due to the different flying parameters and corrections applied to the above datasets not a simple relation exists between their amplitudes, even when the helicopter-magnetic data are continued upwards to the level of the aeromagnetic dataset. As an example, the helicopter magnetic anomaly of the Stratoni granodiorite (Fig. 3) when upward continued (Fig. 4) relates to the aeromagnetic anomaly in the same area (this anomaly has a peak to trough amplitude of 180 nT) (Anomaly A in Fig. 5) only in shape. In this study, the helicopter magnetic map in the area of the Stratoni granodiorite is used in the 3D magnetic modelling of this body whereas regional geophysical aspects are discussed with reference to the aeromagnetic map of the area.

3. Physical Properties of Principal Lithologies

Rock sampling of the main lithologies was carried out in the field. A

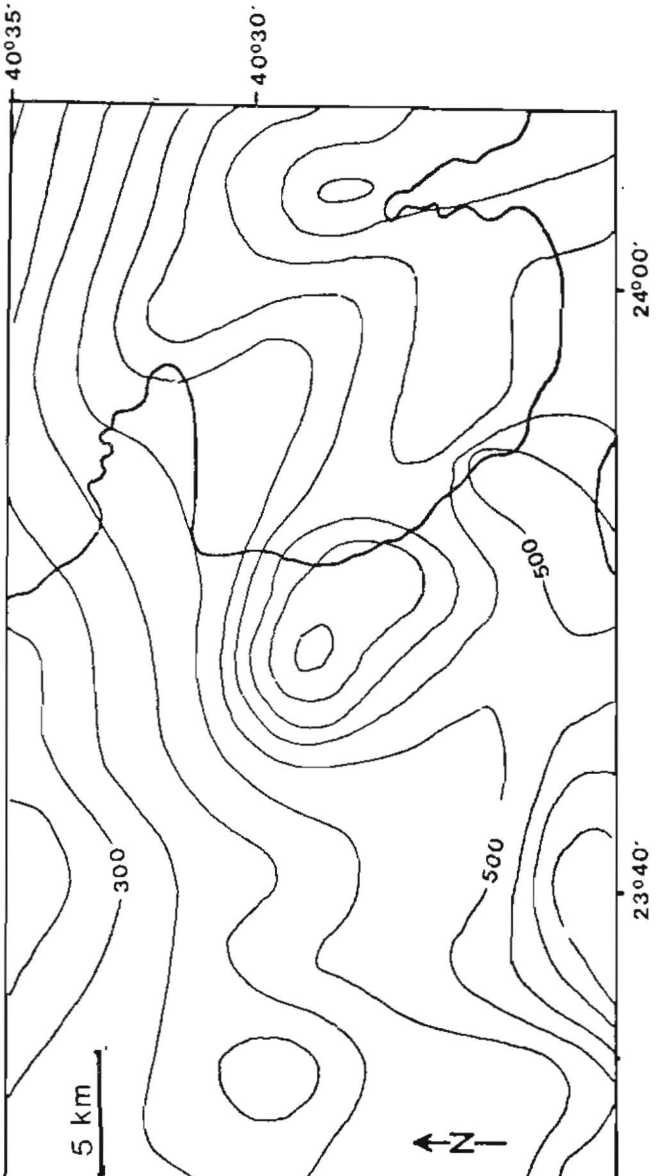

Fig.2 Bouguer anomaly gravity map. Contour interval 50 gu.

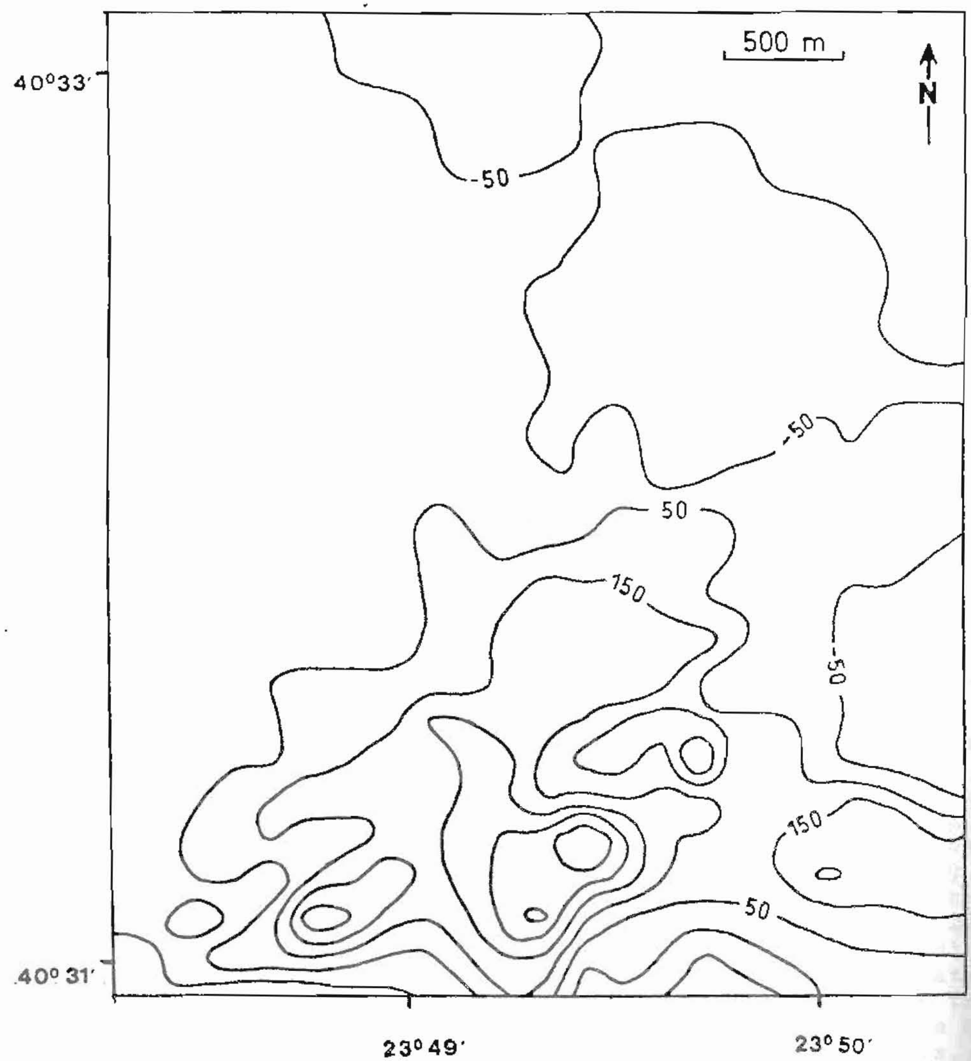

Fig.3 Helicopter magnetic anomaly in the area of the Stratoni granodiorite. Flight height 50m. Contour interval 100 nT.

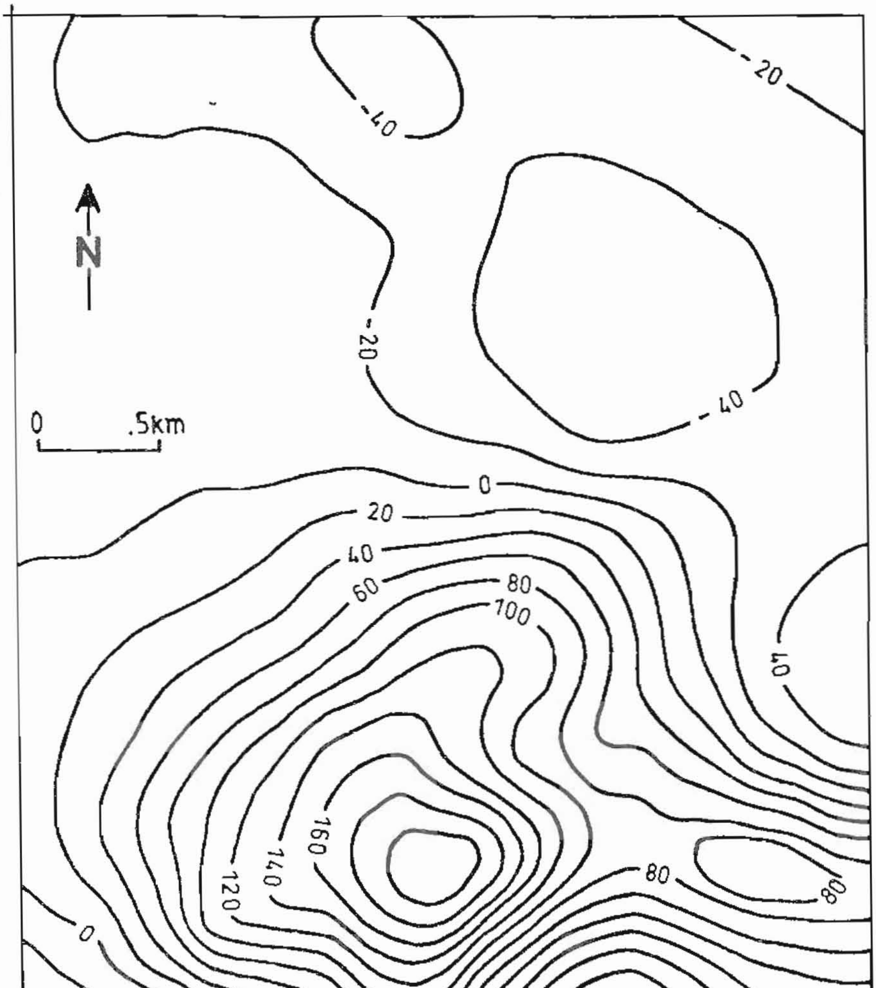

Fig.4 Helicopter-magnetic anomaly of the Stratoni granodiorite (Fig.3) continued upwards by 200 m. Contour interval 20 nT.

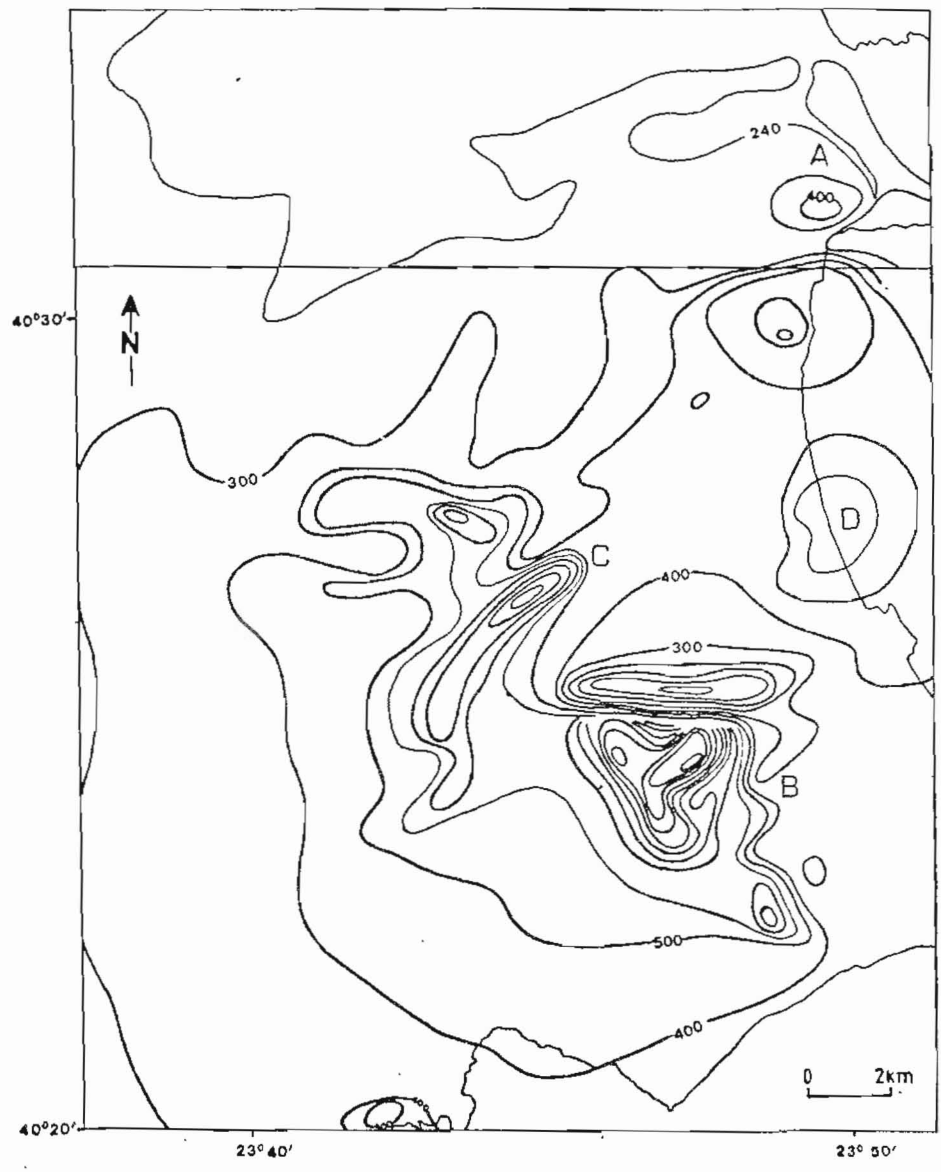

Fig.5 Aeromagnetic map.
The square area has been selected for pseudogravity transformations. Contour interval 100 nT. To its north the map is extended to include the aeromagnetic anomaly of the Stratoni granodiorite (anomaly A). The 240 nT contour is also included in this part.

number of oriented cylindrical samples were collected by using a portable drill and a core orientation table (Tarling, 1983). Standard palaeomagnetic specimens of approximate height of 2.5 cm, were subsequently prepared from the collected field cores. A number of unoriented samples was also collected from the surface outcrops. A location map with all sampling sites is shown in Fig.6.

The density of the collected set of samples was obtained by laboratory measurements.

Magnetic properties (susceptibility, NRM intensity) were measured for each sample, using a susceptibility bridge and the Digico Fluxgate magnetometer, at the Palaeomagnetic laboratory of the University of Southampton. The direction of the remanent component of magnetization has also been obtained for the set of oriented samples. Table 1 lists the values of the measured physical properties and the Koeningsberger ratio (Q) which is the ratio of the amplitudes of the remanent to the induced component of magnetization for each sample.

The susceptibility and NRM values of the gneisses in the vicinity of the granodiorite are highly variable, even between samples from the same borehole. This is due to the variable degree of hydrothermal alteration and the associated mineralization. Due to the presence of paramagnetic minerals these values cannot be used to characterize the body and surrounding formations in terms of expected magnetic properties. Therefore some very high susceptibility and NRM values measured for some of the gneisses are considered to be of local significance only distributed in the immediate vicinity of the granodiorite.

The measured magnetic properties of the Stratoni granodiorite are grouped in (a) those with high susceptibility and NRM values (sites 1, 4, 5, 6 and 10) and (b) a second group with lower susceptibility and NRM values (sites 2 and 3). For subsequent calculations the average values of the magnetic properties calculated for the majority of the sites (group a) are used.

When the average Q value for the samples from the first group is calculated this is found to be 0.34 and if we except one anomalously high value the average Q value becomes 0.16. These low Q values suggest the dominance of the induced component of magnetization.

For the same group of samples the average susceptibility value is found to be $21056X10^{-6}$ SI ($=1676X10^{-6}$ CGS). This value is of the same order of magnitude with the susceptibility values measured for Tertiary granites in the Rhodope area, such as the Xanthi granite ($42500X10^{-6}$ SI and the Leptokarya granite ($38500X10^{-6}$ SI) (Spais, 1987; Maltezou and Brooks, 1988).

Mean density for the Stratoni granodiorite is only by 3% less than the density of the gneisses. Only detailed gravity sampling might reveal a low-amplitude negative anomaly which is otherwise overprinted by the regional gravity values resulting from the coursely sampled gravity field within the Kerdylion formation.

4.0 Modelling of magnetic and gravity anomalies.

The helicopter-magnetic anomaly in the area of the Stratoni granodiorite was isolated for subsequent modelling. The anomaly, when smoothed by upward continuation (Fig. 4) was found to have a shape similar to that of the aeromagnetic anomaly in the same area. (Fig. 5). 3D forward magnetic modelling was carried out by using the method of Talwani (1965). As a starting point during modelling, the surface periphery of the granite was adjusted to the dimensions of the actual

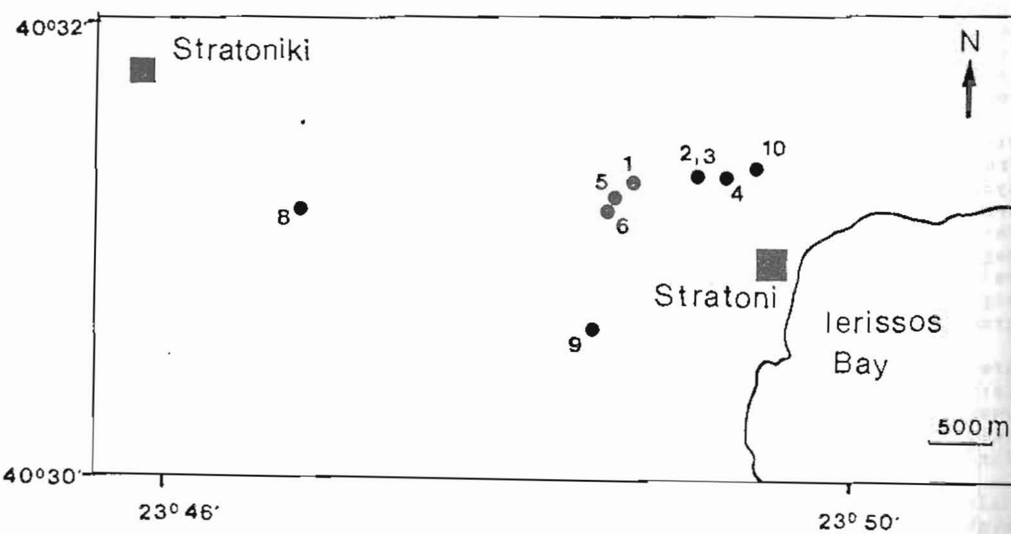

Fig.6 Location map showing sampling sites in the area of the Stratoni granodiorite.

TABLE I

Sample code	K (x10^{-6}) SI	J_{NRM} (10^{-3}) SI	D°	I°	Q	ρ (t/m³)
STRGR 1.1	15582	118.33	108.9	41.9	0.19	2.78
STRGR 1.2	1664	4.23	107.0	66.3	0.06	2.74
STRGR 1.3.1	5328	85.71	209.4	18.0	0.00	2.63
STRGR 1.3.2	3393	20.80	195.8	45.4	0.15	2.61
STRGR 4.1	55116	65.08	117.5	23.6	0.03	2.73
STRGR 5.0.1	19314	88.53	-	-	0.12	2.64
STRGR 5.0.2	6663	103.83	-	-	0.39	2.67
STRGR 6.1.1	995	101.03	-	-	2.56	2.69
STRGR 6.1.2	2982	83.56	-	-	0.70	2.28
STRGR 10.1.1	29062	77.22	132.8	28.8	0.07	2.71
STRGR 10.1.2	29895	79.35	140.7	6.8	0.07	2.74
STRGR 10.2.1	43869	147.40	204.0	66.1	0.08	2.62
STRGR 10.2.2	39803	84.68	213.4	53.1	0.05	2.65
STRGR 2.1.1	925	14.93	339.2	-44.1	0.41	2.70
STRGR 2.1.2	940	22.49	12.7	-25.9	0.60	2.67
STRGR 2.2	1100	3.90	298.2	-51.6	0.09	2.73
STRGR 3.1.1	7	0.36	352.5	-86.2	1.22	2.54
STRGR 3.1.2	14	0.46	279.5	-66.5	0.86	2.57
STRGR 3.2.1	9	0.44	246.4	-73.8	1.29	2.63
STRGR 3.2.2	4	0.55	298.2	-76.9	3.14	2.54
STRGN 6.2.1	49474	1704.76			0.87	2.90
STRGN 6.2.3	30775	926.78			0.76	2.83
STRGN 6.3.1	7726	131.32			0.43	2.82
STRGN 6.3.2	11835	553.10			1.17	2.88
STRGN 6.4.1	212	16.81			1.98	2.78
STRGN 6.4.2	78	10.27			3.31	2.66
STRGN 6.5.1	2732	41.75			0.39	2.89
STRGN 6.5.2	86	52.93			1.19	2.79
STRGN 11.1.1	240	6.74			0.07	2.71
STRGN 11.1.2	368	10.34			0.69	2.61
STRGN 11.2	172	5.21			0.77	2.65
STRGN 11.3	3632	102.03			0.71	2.73
STRAM 8.1	855	1.38			0.04	3.18
STRAM 8.2	150708	603.27			0.10	3.24
STRAM 8.3.1	1920	9.80			0.13	2.95
STRAM 6.3.2	3614	17.10			0.12	2.83
STRAM 8.4.1	10820	36.33			0.08	2.87
STRAM 8.4.2	10113	123.37			0.31	3.05
STRAM 8.5.1	32660	233.93			0.18	3.00
STRAM 6.5.2	32886	688.91			0.53	2.79
STRAM 8.6.1	1382	11.64			0.21	2.77
STRAM 6.6.2	1363	10.66			0.20	2.62
STRAM 8.7.1	1035	10.34			0.26	2.74
STRAM 8.7.2	2136	25.53			0.30	2.56
STRAM 9.1.1	6157	33.56			0.14	2.94
STRAM 9.1.2	2269	33.37			0.38	2.95
STRAM 9.2.1	21809	44.30			0.05	2.92
STRAM 9.2.2	7825	57.43			0.18	2.96

STRGR: GRANODIORITE
STRGN: GNEISS
STRAM: AMPHIBOLITE

granite outcrop as shown on the geological map of the area. Induced magnetization was assumed, as suggested by the low Q values and the susceptibility value was fixed to the average measured susceptibility value (see section 3).

As a result of the modelling detemination of the shape and thickness of the body have been obtained: The granite, to the south terminates abruptly against the Stratoni-Varvara fault, which also marks the contact between the Kerdylion and Vertiskos formations of the Serbomacedonian Massif. Towards N-NW, and for about 3.5 km, the body extends under the gneisses with outward sloping contacts (Fig.7). This is consistent with the extent of the metamorphic aurole as shown on the 1:50000 scale geological map of the region (Kockel et. al., 1977) (Fig.1).

Localised aeromagnetic anomalies are present throughout the area to the south of the Stratoni-Varvara fault, appearing to be the components of a regional aeromagnetic anomaly in this area of high magnetic relief.

Over the same area, a regional gravity high is observed in the Bouguer anomaly map. Pseudogravity transformations of the aeromagnetic field (interpolated on a 1 km grid) closely match the gravity anomaly over the same area when a constant(regional)value of 500 gu is removed from the observed gravity values (Figs.8 and 2). The assumption made is that amphibolites are lying over a non-magnetic basement consisting of gneisses with a density contrast of +0.3 T/m^3. The susceptibility value used is $32500X10^{-6}$ SI which is compatible with the values measured for amphibolites south of the Stratoni-Varvara fault and also within the range of values used for other ophiolite complexes (Telford et. al., 1976).

In the southern part of this area, a mass of variably serpentinized peridotites and dunites, occupy an area of about 14 km^2. This mass, known as the Gomati ultrabasic body, together with two other basic-ultrabasic complexes (the Volvi and Therma complexes) within the Vertiskos formation and close to the boundary with the Kerdylion formation, constitute the Therma - Volvi - Gomati complex, tentatively interpreted as a dismembered ophiolite (Dimitriadis, 1980 as cited in Dixon and Dimitriadis, 1984).

A more detailed assessment of the aeromagnetic field in this area reveals that an aeromagnetic anomaly with a peak to trough amplitude of 1500 nT (anomaly B in Fig.5) appears to be associated with the Gomati ultramafic body. Magnetic anomaly C in the area Kakavos corresponds to a sub-outcroping ultramafic body known from field observations whereas magnetic anomaly D is present in the area Kabos, where the outcroping lithologies consist mainly of Tertiary sediments. Although lack of aeromagnetic data to the east of this area, due to termination of the aeromagnetic survey along the coastline of the Chalkidiki peninsula, does not allow for similar observations in the Ierissos Bay, some information can be obtained from the gravity field in this area. A negative gravity anomaly in the Ierissos bay is flanked by the two regional highs of 700 gu and 690 gu to the west and east, respectively (Fig.2). An analytical regional, residual is calculated by 1st degree polynomials for the gravity map of Fig.2. The analytical regional gives a general idea about gravity trends but its values have been influenced by the presence of the Tertiary sediments in the Ierissos Bay (Fig 9). A constant gravity level of approximately 700 gu is taken to represent the level of the regional gravity field in this area controlled by geological observations. The observed gravity anomaly with an amplitude of approximately -130 gu is compatible with the anomaly calculated by a sedimentary pile of about

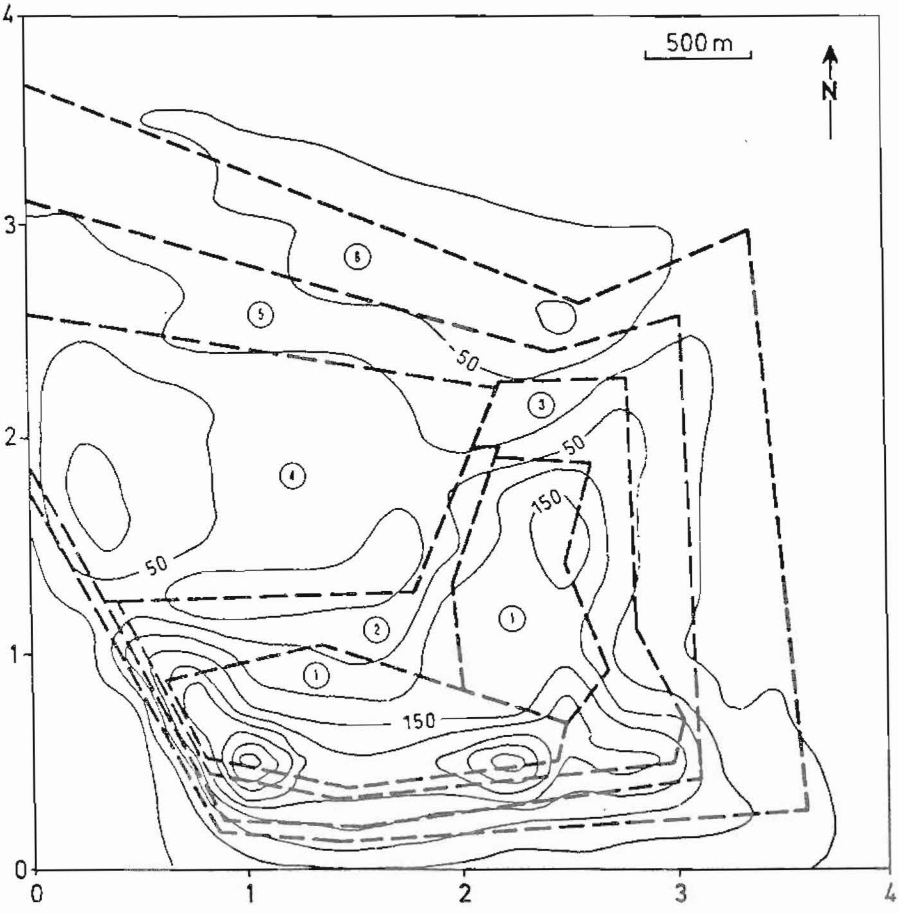

Fig.7 Interpretation model for the Stratoni granodiorite. Calculated anomaly is also shown. Contour interval 50 nT. The depths to the top of its component polygons and their thickness are as follows:

for polygons	depth to body top	thickness
(1)	0 m	200 m
(2)	50 m	150 m
(3)	200 m	250 m
(4)	300 m	150 m
(5)	450 m	300 m
(6)	750 m	400 m

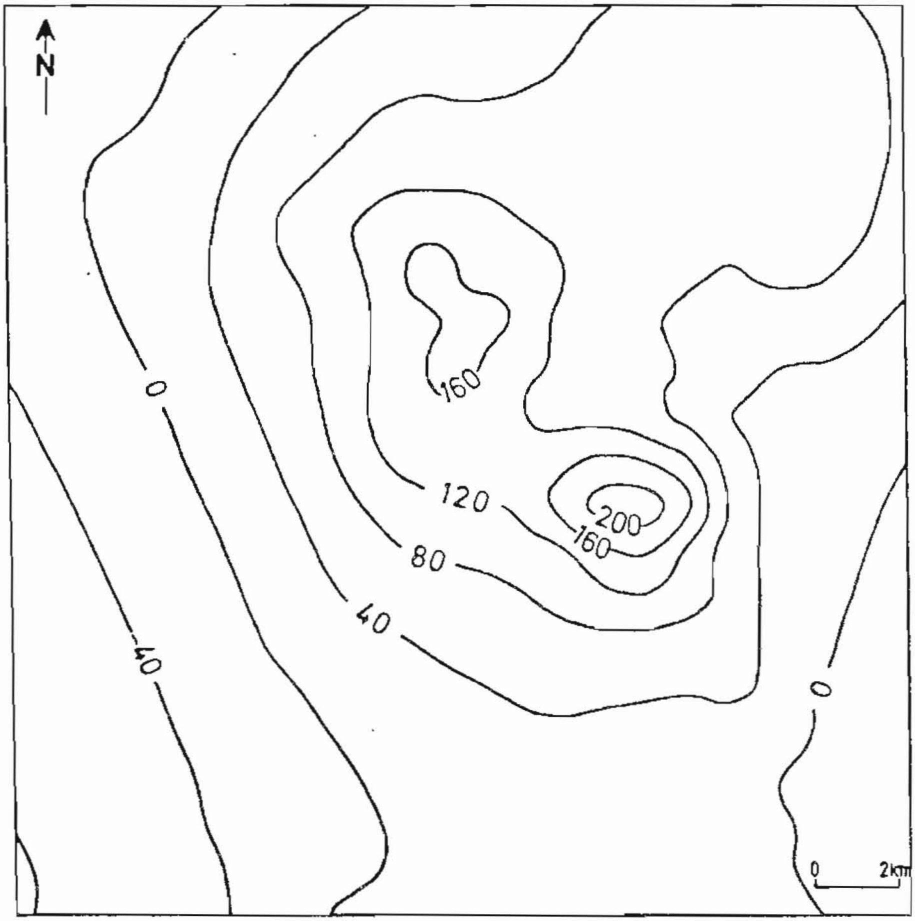

Fig.8 Pseudogravity anomaly of the aeromagnetic map of the square area of Fig.5. Contour interval 40 gu.

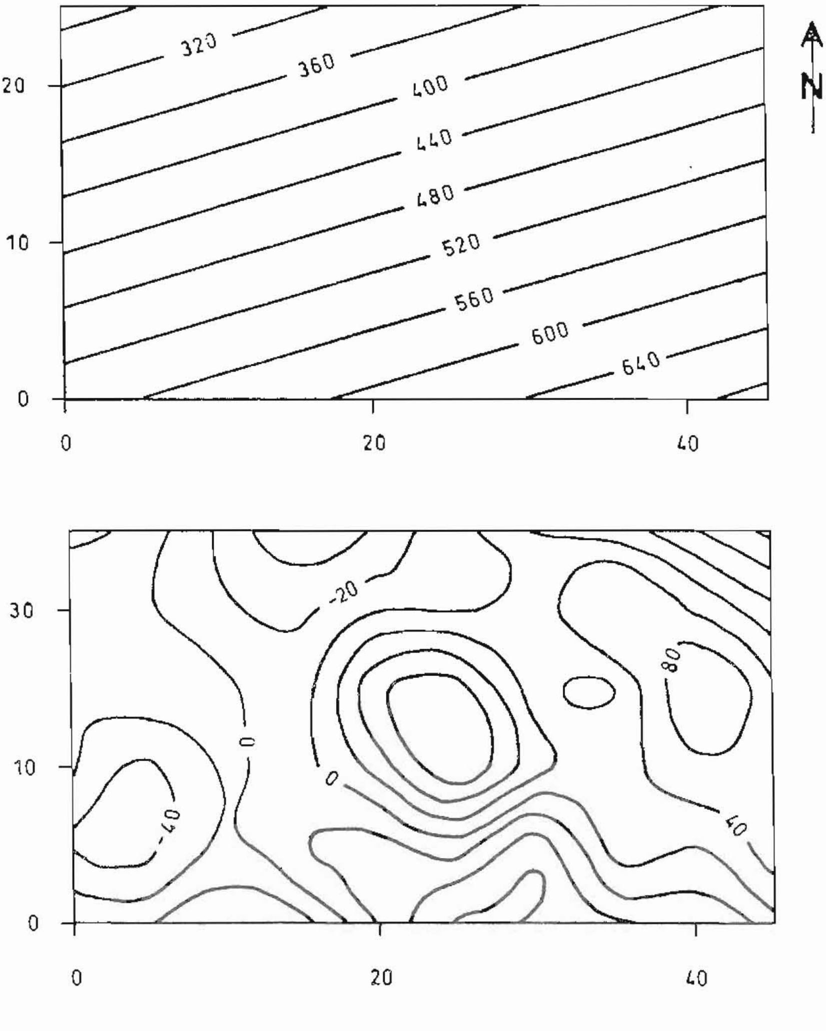

Fig.9 First degree gravity a. Regional. C.I. 40 gu.
b. Residual. C.I. 20 gu.

400 m on the assumption that this is overlying predominantly amphibolitic rocks. This information together with the observation that near the area Cape Arapis (Fig.1) outcroping ultramafic rocks appear to be the cause of the high regional gravity level (690 gu) and the aeromagnetic anomaly over the same area (ABEM, 1966), are interpreted to suggest the continuation of rocks belonging to the Vertiskos amphibolitic-ophiolitic suite towards east.

Discussion

Geophysical data in the area of the Stratoni granodiorite reveal a shape of this body compatible with its surface outcrop but occupying a much larger volume at depth extending further towards N-NW. To the south, it terminates abruptly against the Stratoni-Varvara fault. The abudant distribution of sulfide and/ or manganese mineralizations along this fault and the nearby marbles, in the vicinity of the Stratoni granodiorite, together with the presence of similar mineralization within the intrusive body itself underline the significance of the concomitant presence of these features to mineral exploration in the area.

The presence of outcroping NW-SE trending marble occurences which are located 3-5 km N 315 degrees from the SE corner of the intrusive body coincides in space with the in depth (750 m) extension of the Stratoni granodiorite (Fig.10). NW/SE and NE/SW intensive fault systems (Tsompos and Karmis, 1988) are also present in this area which is rated to be of prime importance to exploration for Pb-Zn (Au,Ag) sulfide ores.

Exploration priority for manganese, base metal and gold is in the area along the Stratoni-Varvara fault and the area where the latter meets the Stratoni granodiorite and the group of Fisoka-Alatina porphyries.

Gravity and magnetic data in the area to the south of the Stratoni-Varvara fault appear to be compatible with a common origin that is an ophiolite from which the amphibolites and the ultramafic rocks in this area appear to be some of its dissmembered components overlying a non-magnetic basement consisting of gneisses. This regional picture is further refined by field observations revealing the presence of most likely imbricate thrusts into which two-mica gneisses occur alternating with amphibolites. The Gomati body in this area possibly represents a thicker piece of old oceanic thrust. The tectonic emplacement into its present position possibly involved more than one stages of thrusting evidenced by its contact zones with country rocks (Christodoulou and Hirst, 1985). Geophysical interpretation suggests a similar regional geological picture for the area under the sediments of the Ierissos bay. This is also supported by the rock assemblage outcroping in the area of cape Arapis in the easternmost part of the bay.

The above interpretation is compatible with a geological model suggested for the Vertiskos formation (model C of Dixon and Dimitriadis (1984); Sengor et. al., (1984)) which implies tectonic and metamorphic discontinuities between an ophiolitic complex and the "basement" part of the envelope.

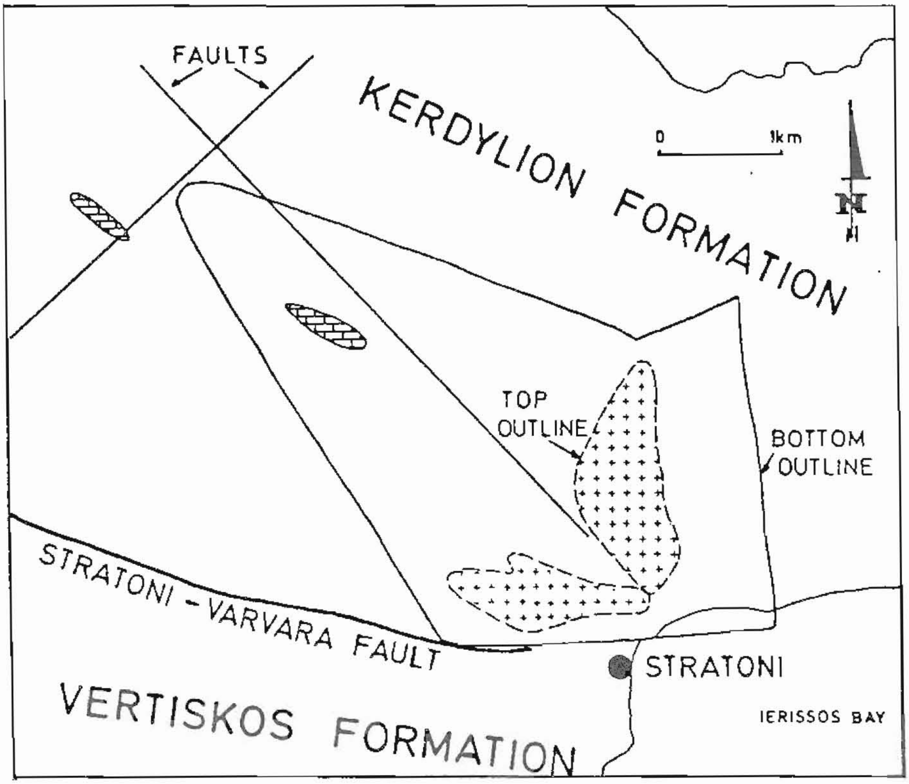

Fig. 10 Modelling of the Stratoni granodiorite on the basis of aeromagnetic and field data. Upper and bottom outlines of the body are given. The bottom outline occurs at an estimated depth of 750 m. The NW-SE and NE-SW faults shown on map are from Heliborne EM (HEM) and remote sensing data (Karmis, 1987; Tsompos and Karmis, 1988). Marbles are from the 1:50000 scale map of Kockel et.al. (1977). The concomitant presence of the Tertiary granodiorite, marbles and faulting give high priority for exploration to the area at and near to the northwest end of the Stratoni granodiorite. The area to the south of this body where the Stratoni-Varvara fault, the Alatina-Fisoka porphyries and the Madem-Lakos marble converge is another area of exploration significance.

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