GEOSEA '98 Proceedings, Geol. Soc. Malaysia Bull. 43, December 1999; pp. 537-543

Ninth Regional Congress on Geology, Mineral and
Energy Resources of Southeast Asia — GEOSEA '98
17 – 19 August 1998 • Shangri-La Hotel, Kuala Lumpur, Malaysia

GEOSEA '98
Kuala Lumpur

Magnetic and gravity fields in southern Zambales: implications on the evolution of the Zambales Ophiolite Complex, Luzon, Philippines

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Abstract: Ophiolites are rock associations representing crust–mantle sequences. Interest in these rock suites is reflected in the extensive geological, geochemical and petrological studies that have been carried out. It is only recently, however, that geophysical tools have found application in the study of these sequences. In the Philippines, the southern Zambales area was the subject of one of the few geophysical investigations applied on ophiolite complexes. The magnetic and gravity surveys conducted in the southern portion of the Zambales Ophiolite Complex defined a northwest-southeast linear feature which is believed to correspond to the Subic Bay Fault Zone. The fault zone was delineated on the basis of the steep gradients displayed by the magnetic anomalies and from inflections noted in the gravity contours. This structure is believed to be the tectonic contact between the central (Cabangan) and southern (San Antonio) massifs of this ophiolite complex. Recognition of the fault zone is consistent with a model which suggests that the San Antonio massif was a rifted unit from the Acoje block of the Masinloc Massif. The translation southward of this massif may have occurred along the Subic Bay Fault Zone.

INTRODUCTION

Ophiolites are suites of rocks that are believed to correspond to crust-upper mantle sequences. Initially, interest in these rock sequences was due to the presence of a variety of mineral deposits. Subsequently, however, the focus of various scientific investigations shifted to obtaining information on how these sequences evolved and how they were emplaced. Recent developments have seen the increasing use of geophysical investigations, specifically magnetic and gravity surveys, in the study of these ophiolite complexes (e.g. Manghnani and Coleman, 1981; Milsom, 1991; Milsom *et al.*, 1996; Ravaut *et al.*, 1997). In the Philippines, however, there have been limited applications of geophysical techniques in the study of ophiolites and ophiolitic complexes (e.g. Dimalanta, 1996, Dimalanta *et al.*, 1998; Barretto *et al.*, 1998).

The complete ophiolite suite in the Zambales area has been the subject of numerous geoscientific investigations. Extensive geological surveys (e.g. Hawkins and Evans, 1983; Bacuta, 1989; Rossman *et al.*, 1989) and geochemical studies (e.g. Geary *et al.*, 1989; Evans *et al.*, 1991; Hawkins and Florendo, 1992; Yumul, 1992, 1996) have been carried out. However, some questions remained unanswered regarding the evolution of this ophiolite complex.

The present-day scenario shows the ophiolite complex being divided into several units with different geochemical characteristics (i.e. the Acoje block and San Antonio massif manifest island arc signatures while the Coto block and the Cabangan massif show transitional mid-ocean ridge basalt — island arc characteristics). One question that needed to be addressed was how can an island arc terrane (San Antonio massif) be juxtaposed to a mid-ocean ridge crust (Cabangan massif)?

Recent geological and geochemical data suggests the presence of a major structural feature (e.g. Yumul *et al.*, 1990; Yumul and Dimalanta, 1997a) which helps elucidate the observed arc terrane accretion. Given the possibility that a major structural feature may be present in the southern part of the Zambales region warranted the conduct of geophysical surveys in the area. The role of this structural feature in the evolution of the Zambales Ophiolite Complex has been discussed extensively elsewhere (e.g. Yumul and Dimalanta, 1997a) but will be reiterated in the subsequent discussion.

GEOLOGICAL BACKGROUND

The Zambales Ophiolite Complex (ZOC) in Luzon, Philippines is a supra-subduction zone ophiolite formed in a marginal basin (e.g. Geary *et al.*, 1989; Yumul and Dimalanta, 1997a). It underlies the Zambales area in the western part of Luzon Island, Philippines. This north-south trending, east-dipping ophiolite suite consists of residual harzburgites and lherzolites, transition zone dunites, layered ultramafic and mafic cumulates, dike-sill complexes and volcanic rocks (Fig. 1).

Three massifs — Masinloc, Cabangan and San Antonio — comprise the ZOC (Fig. 1). Due to the observed petrological and geochemical differences, the Masinloc massif is further divided into two units — the Acoje and Coto blocks. Moreover, available data show that the Cabangan massif and the Coto block are geochemically similar (transitional mid ocean ridge-island arc) while the San Antonio massif exhibits the same island arc (IA) characteristics as the Acoje block. The present-day configuration of this ophiolite complex proved to be intriguing to those who were studying the area.

In addition, there was the question of the juxtaposition of an island arc terrane (San Antonio massif) to a mid-ocean ridge/marginal basin-like crust (Cabangan massif), as seen from an east-west section in the southernmost portion of the ZOC (Yumul *et al.*, 1990). Another enigma is presented by the small hills noted along the western edge of the Cabangan massif (Yumul and Dimalanta, 1997a) (Fig. 1). Closer investigation of these small hills reveal that they consist of layered clinopyroxenites and gabbronorites. Available geologic information clearly shows that the Cabangan massif does not have a well-developed layered clinopyroxenite-gabbronorite member within its ultramafic-mafic sequence. But such layered clinopyroxenites and gabbronorites are reported to be extensive in the Acoje block and San Antonio massif. If these small hills are not part of Cabangan massif, then how can their presence along the western edge of Cabangan massif be explained? Yumul *et al.* (1998a; 1998b) suggest that these small hills were left behind as the San Antonio massif was translated southward after being rifted from the Acoje block of the Masinloc massif. The presence of a major tectonic feature was involved along which this translation took place.

In order to establish the presence of this structural feature which is deemed to have played a significant role in the evolution of this ophiolite complex, combined ground and magnetic surveys were conducted in the southern part of ZOC. The area covered by the magnetic and gravity surveys is located between 14°50' and 15°10'N and 120°00' and 120°20'E (Fig. 1).

MAGNETICS

The gravity and magnetic methods of geophysical prospecting are effective in delineating faults and similar structural features (e.g. Wright, 1981; Irvine and Smith, 1990; Zeng *et al.*, 1997). Combining the magnetic investigation with a gravity survey would, hence, serve to confirm or verify the presence of any structural feature.

The total magnetic intensity anomaly map for the study area was generated using measurements obtained from three hundred and thirty stations. Details of data acquisition and reduction are presented elsewhere (Yumul *et al.*, 1998b).

Total magnetic field intensities in the southern portion of ZOC range from 40800 to 41300 nT. Relatively low magnetic anomalies are noted in areas underlain by sediments such as the Castillejos area and southeast of the Sindol Hill area. On the other hand, magnetic highs are observed in the Subic and Sindol Hill areas. Pillow basalts (magnetic susceptibility 25 SI units) intruded by sheeted diabase dikes (magnetic susceptibility 0.18–0.46 SI units) are encountered in the Subic-Olongapo area. These rock units display a large magnetic susceptibility contrast which produced the high anomaly. The magnetic high in the Sindol Hill area is attributed to the presence of highly serpentinized clinopyroxenites. Magnetic susceptibility measurement of a sample from Sindol Hill gave a value of 13.08 SI units. This is consistent with observations noted elsewhere regarding the high magnetic susceptibilities of fully serpentinized ultramafic rocks (Clark *et al.*, 1992).

The magnetic intensities gradually decrease from Subic to Cawag. The Cawag section is underlain by gabbronorites (27.45 SI units) on the east. These are in fault contact with intensely sheared, highly weathered clinopyroxenites (0.10 SI units) on the west (Yumul and Dimalanta, 1997b). A relatively pronounced closed contour high can be noted northwest of the Castillejos area. This anomaly high might conceivably owe its presence to the dacite plugs in that vicinity. Magnetic susceptibility measurements of dacite samples gave values of 2.39 and 3.94 SI units.

Another significant feature of the magnetic anomaly map is the steep gradient that separates the western side from the eastern side. Relatively steep, closely spaced contours characterize the eastern side while broadly spaced contours can be noted on the west (Yumul *et al.*, 1998b) (Figs. 2 and 3).

GRAVITY

In order to verify the results obtained from the magnetic survey, a follow-up ground gravity survey was conducted. The gravity anomaly map was produced utilizing one hundred and ninety one measurements taken with a LaCoste and Romberg gravity meter. Details on data acquisition and reduction are presented elsewhere (Yumul *et al.*, 1998b).

The gravity anomaly map is characterized by the gradual increase of anomalies (from 220 to 270 mgals) from the central to the northwestern part of the study area (Figs. 2 and 3). The main geological factors causing the gravity anomalies are the different units of the ophiolite complex. The central portion of the area is characterized by low gravity anomalies. This corresponds to the low density

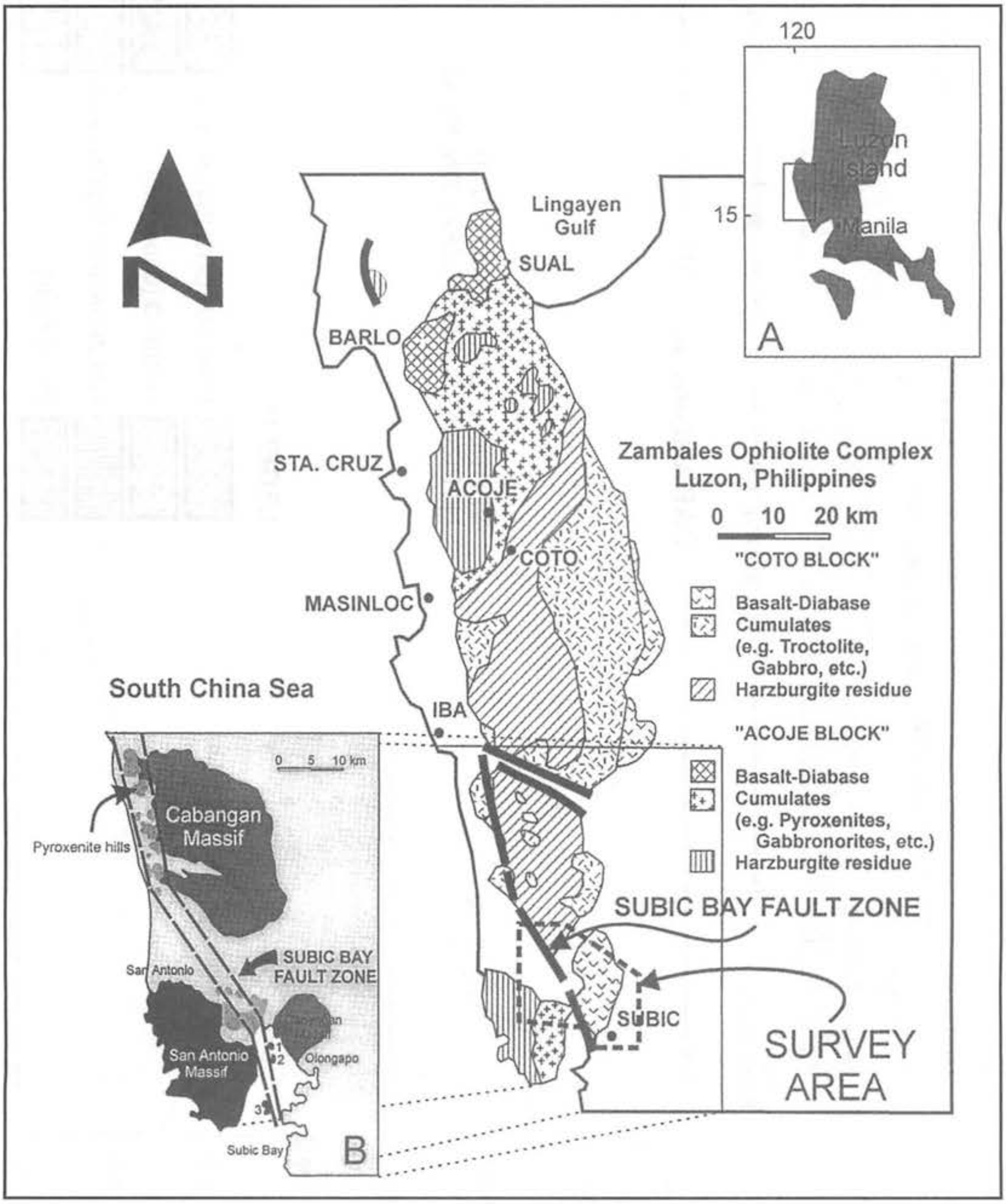

Figure 1. Geologic map of the Zambales Ophiolite Complex. Inset B shows the location of the allochthonous clinopyroxenite-gabbronorite hills that are lithologically and geochemically similar to the rocks of the Acoje block and the San Antonio Massif. The Masinloc Massif corresponds to the area where the Acoje and Coto blocks are formed. See text for discussion.

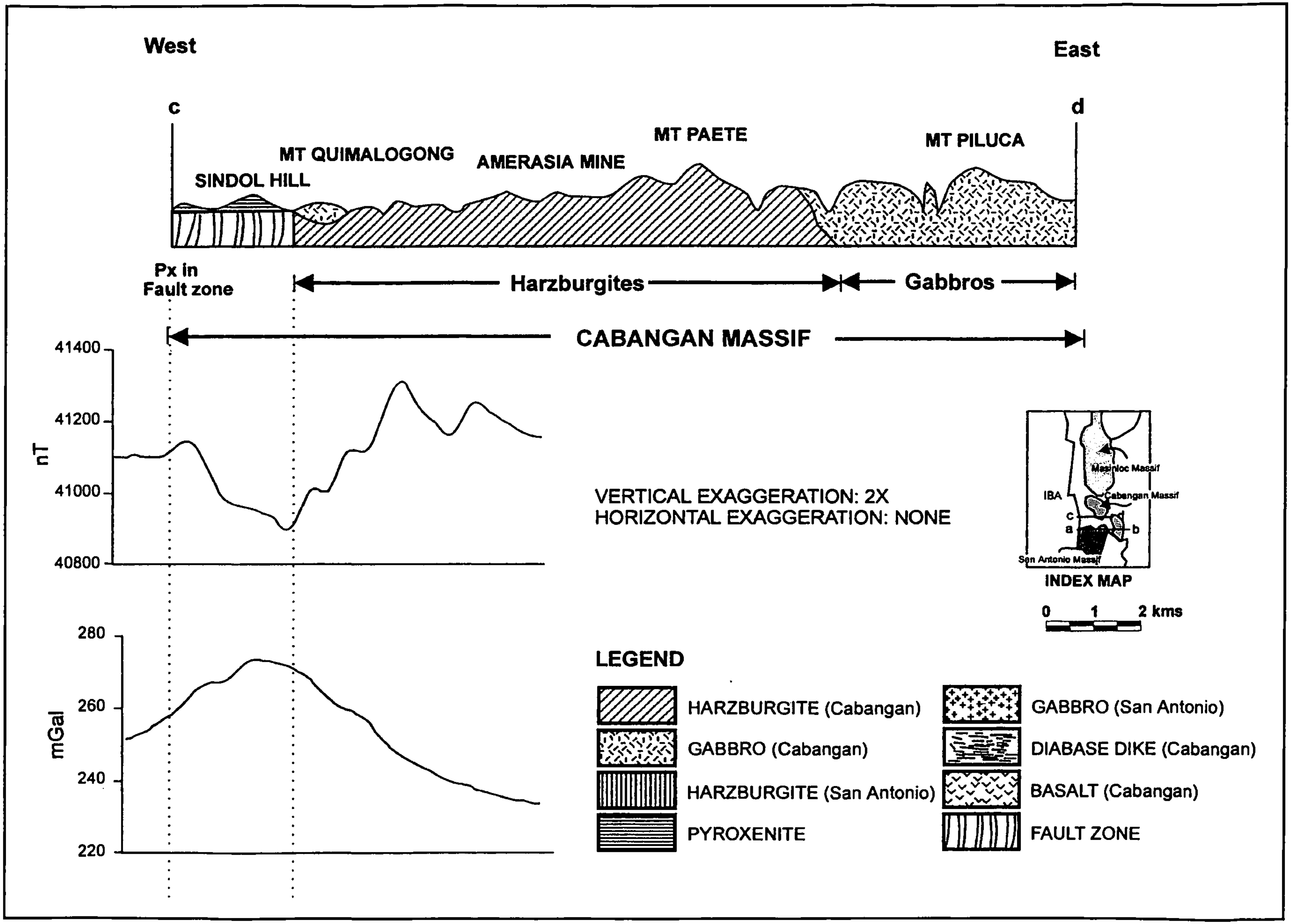

Figure 2. Intensely tectonized clinopyroxenites are found in the Sindol hill area as is shown by section c-d. A relatively steep gradient in both magnetic (top) and gravity (bottom) profiles coincide with the shear zone depicted by wavy lines.

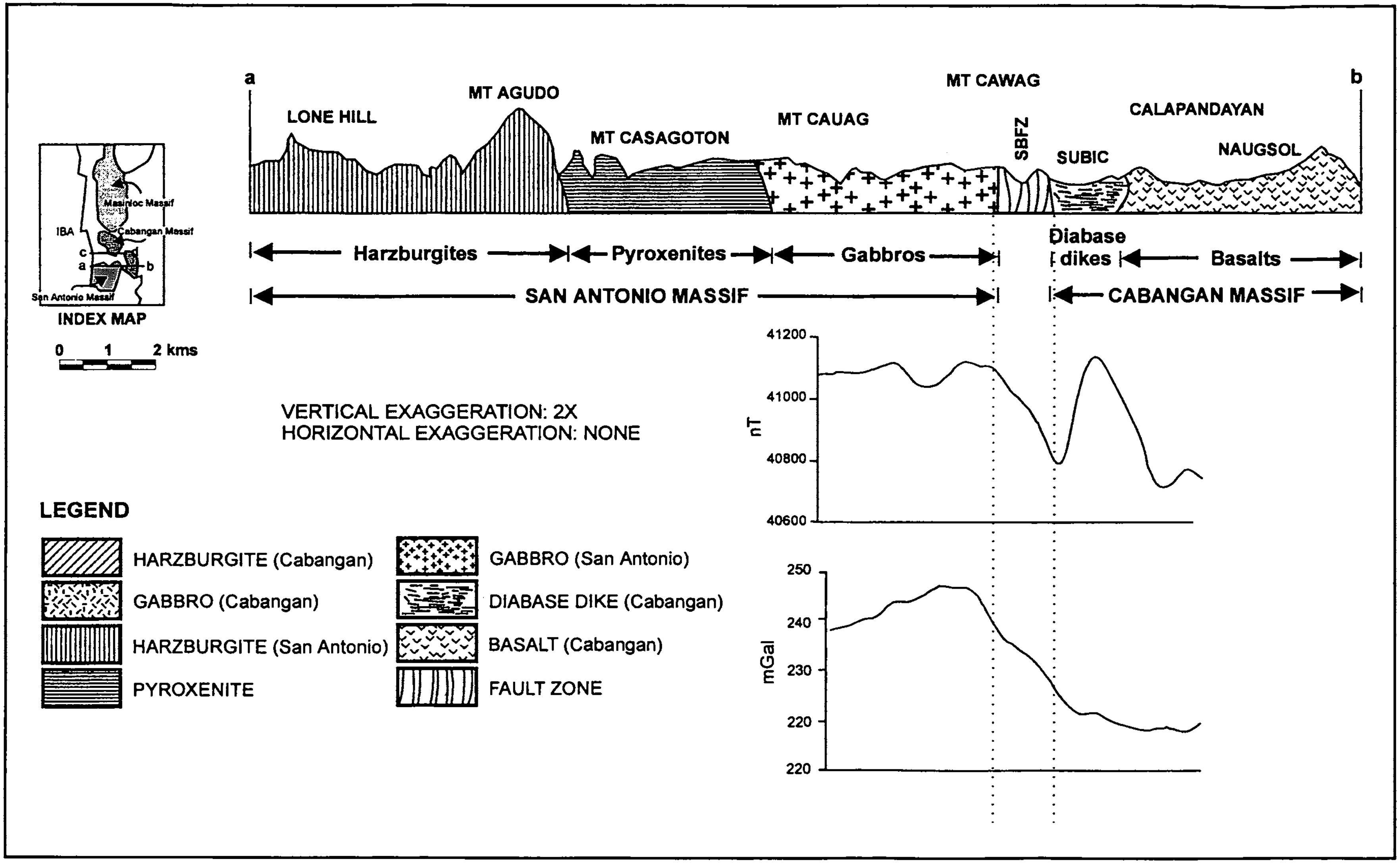

Figure 3. East-west profile taken along Cawag Road as is shown in section a-b. The vicinity of Cawag Road coming from the Philseco Shipyard consists of intensely sericitized gabbronorites. These are in fault contact with clinopyroxenites. Total magnetic intensity (top) and Bouguer anomaly (bottom) profiles show the steep gradient which coincides with the shear zone depicted by wavy lines.

volcanic and sedimentary deposits that comprise the low-lying areas (e.g. Arita *et al.*, 1998). The high gravity anomalies, on the other hand, generally correspond to the different ultramafic and mafic units of the ophiolite complex (e.g. Milsom *et al.*, 1996; Ravaut *et al.*, 1997; Arita *et al.*, 1998). The Sindol Hill area, underlain by clinopyroxenites, coincides with high gravity values. This is consistent with density measurements of clinopyroxenite samples which yielded values ranging from 3.18 to 3.76 g/cm^3.

Low gravity anomalies mark the Subic area where pillow basalts are intruded by diabase dikes. Laboratory measurements give density values from 2.46 to 2.90 g/cm^3 for the diabase dikes. No density values are available for the basalt samples. The gravity anomalies increase gradually from the Subic area towards the Cawag area. In the Cawag section, gravity stations were established only up to the gabbronorite outcrop. Density measurements of gabbronorite samples reveal values ranging from 2.67 to 2.99 g/cm^3.

DELINEATION OF THE SUBIC BAY FAULT ZONE

The magnetic and gravity methods were utilized in this study with the objective of delineating structural features. A qualitative interpretation of the magnetic anomalies clearly reveals a difference in the character of the contour lines. The magnetic anomaly map can be divided into two parts based on the configuration of the magnetic anomalies (e.g. Zeng *et al.*, 1997). Relatively steep, closely spaced magnetic anomalies characterize the eastern part of the investigated area, while gentle, broadly spaced contours are noted in the western part (Figs. 2 and 3). The gradient zone defined by the boundary between these two parts extends from the Maloma area in the northwesternmost corner to Subic in the southeast (Fig. 1).

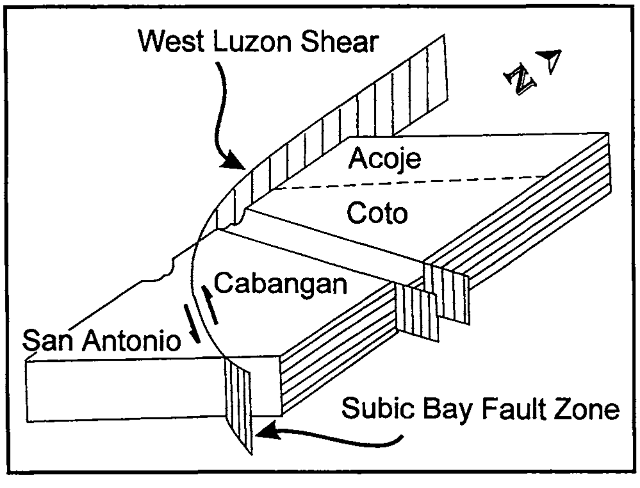

Figure 4. Block diagram showing the different major geologic structures in the Zambales Ophiolite Complex (after Yumul and Dimalanta, 1997a). See text for discussion.

The same feature defined by the magnetic anomalies can be delineated on the gravity anomaly map. This feature is identified on the basis of inflections in the gravity contours (Figs. 2 and 3). However, this feature is not as pronounced on the gravity anomaly map. This may be due to the lack of a significant density contrast between the adjacent rock units (e.g. Mickus and Durrani, 1997).

Ground checking of this geophysically delineated linear feature reveals the presence of highly sheared outcrops in places where this geologic structure is believed to have passed through (Yumul and Dimalanta, 1997a). The magnetic and gravity anomalies have defined a northwest-southeast trending linear feature. Upon synthesis of the geophysical results with available geological and geochemical data, the delineated structure is interpreted to correspond to the Subic Bay Fault Zone (Fig. 4).

From the synthesis of available data, a model suggesting that the San Antonio massif is a displaced terrane seems to be the most tenable. This model proposes that the San Antonio massif was derived originally from the Acoje block of the Masinloc massif. It was subsequently rifted and translated southward to its present position along a major strike-slip fault (Yumul and Dimalanta, 1997a). This scenario is consistent with the different geological constraints that have been recognized. Moreover, it provides an answer to some of the puzzles posed by the present configuration of this ophiolite complex.

CONCLUSIONS

Ground magnetic and gravity surveys conducted in the southern portion of the Zambales Ophiolite Complex have led to the recognition of a major structural feature. Upon synthesis with available geological and geochemical data, this structural feature is interpreted to correspond to the Subic Bay Fault Zone.

Delineating the Subic Bay Fault Zone is significant in that it corroborates the proposed model regarding the evolution of the Zambales Ophiolite Complex. The southward translation of the San Antonio massif from the Acoje block of the Masinloc massif and its subsequent emplacement to its present position may have taken place along the SBFZ. This model provides the answers to some of the enigmas posed by the present-day configuration of the Zambales Ophiolite Complex.

ACKNOWLEDGEMENTS

Financial support for this work came from the Philippine Department of Science and Technology — Grants-in-Aid Program (Project No. 92-02-0170), National Research Council of the Philippines (Project No. L-33) and the University of the Philippines-National Institute of Geological Sciences. Logistic support extended by the Philippine Geothermal, Inc., Philippine Institute of Volcanology and Seismology, TVI Pacific Inc. and the Zambales Lahar Scientific Monitoring Group are appreciated. Field support by the ZLSMG volunteers, E. Marquez, F. Jumawan, M. Beroya and R. Reyes are also acknowledged.

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Manuscript received 30 October 1998