



## **Subic Bay fault zone: its role in the geologic history of the Zambales Ophiolite Complex, Philippines**

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**Abstract:** Several models have been forwarded to explain the distribution of the three massifs, Masinloc, Cabangan and San Antonio, of the Zambales Ophiolite Complex. Available information support a model that calls for the separation and southward translation of the San Antonio massif from the Acoje block of the Masinloc massif. Translation occurred along the left-lateral West Luzon Shear/Subic Bay Fault Zone. This would explain the presence of clinopyroxenite-gabbro-norite allochthonous hills scattered along the western edge of the ophiolite complex where the fault zone is thought to have passed. The recognition of the existence of the Subic Bay Fault Zone helps elucidate our understanding on how this crust-mantle sequence had evolved.

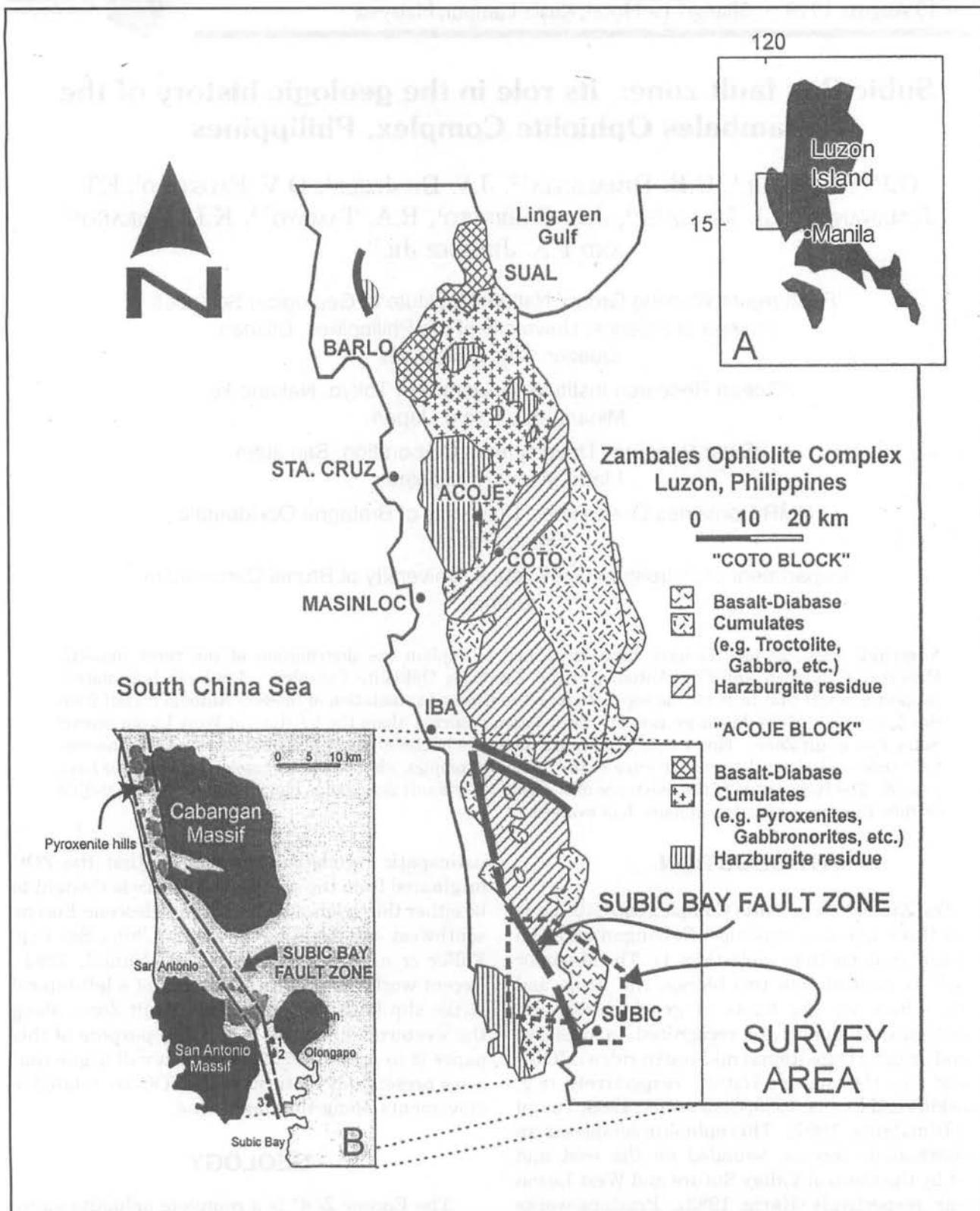
### **INTRODUCTION**

The Zambales Ophiolite Complex (ZOC) is made up of three massifs, Masinloc, Cabangan and San Antonio, from north to south (Fig. 1). The Masinloc massif is divided into two blocks, the Acoje and Coto, which on the basis of geochemical and petrological evidence are recognized to preserve island arc and transitional mid-ocean ridge (MOR)-island arc (IA) characteristics, respectively (e.g. Hawkins and Evans, 1983; Geary *et al.*, 1989; Yumul and Dimalanta, 1997). This ophiolite complex is an allochthonous terrane bounded on the east and west by the Central Valley Suture and West Luzon Shear, respectively (Karig, 1983). Previous works showed that the Masinloc, Cabangan and San Antonio massifs are cut by very young faults resulting into the formation of grabens in between these massifs. Available paleomagnetic data and

palinspatic reconstruction suggest that the ZOC originated from the south. The source is thought to be either the Celebes Basin or the Paleocene-Eocene southwest sub-basin of the South China Sea (e.g. Fuller *et al.*, 1983; Honza, 1991; Yumul, 1994). Recent works showed the presence of a left-lateral strike slip fault, the Subic Bay Fault Zone, along the western side of the ZOC. The purpose of this paper is to present evidence which will argue that some present day features of the ZOC are related to movements along this fault zone.

### **GEOLOGY**

The Eocene ZOC is a complete ophiolite suite. Geological and geochemical data confirmed the differences between the Acoje and the Coto blocks of the Masinloc massif. The Acoje block contains a well-developed layered ultramafic cumulate



**Figure 1.** Geologic map of the Zambales Ophiolite Complex showing the different massifs and the location of the Subic Bay Fault Zone.

sequence and a transition zone dunite which cannot be said for the Coto block. The Acoje block is also characterized by metallurgical chromitites (spinel Cr#  $[Cr/(Cr+Al)] > 0.60$ ), the presence of platinum group minerals and pyroxene crystallizing ahead of plagioclase in the crystallization order. Mineral chemistry analyses of chromites and clinopyroxenes show the distinct geochemical difference between the Acoje and Coto blocks (e.g. Yumul, 1993) (Figs. 2a–2d). Whole rock together with mineral chemistry analyses for the Acoje block show island arc affinity.

On the other hand, the Coto block is known for its refractory chromitites (spinel Cr#  $< 0.60$ ), plagioclase crystallizing ahead of pyroxene in the crystallization order and the presence of troctolite in its mafic cumulate sequence. The Coto chromitites have lower spinel  $Cr_2O_3$  and FeO but higher NiO and  $Al_2O_3$  with respect to the Acoje chromitites (Figs. 2a–2b). At the same XMg ( $Mg/(Mg+Fe_{total})$ ) number, the Coto volcanic rock clinopyroxenes contain higher  $TiO_2$  and  $Na_2O$  compared to their Acoje counterparts (Figs. 2c–2d). Although there is an overlap in the rare earth element contents of the Acoje and Coto mafic cumulate rocks, the Coto block gabbros are characterized by higher olivine forsterite and lower anorthite contents as compared to the Acoje block mafic cumulate rocks (Yumul *et al.*, 1998) (Figs. 3a–3c). Whole rock and mineral chemistry analyses exhibit a transitional MOR-IA characteristics for the Coto block.

Interestingly, the geology of the ZOC show that there are similarities between the Acoje block and the San Antonio massif; the Coto block and the Cabangan massif display the same lithological assemblage (e.g. Yumul *et al.*, 1990). It is believed that the Coto block of the Masinloc massif and the Cabangan massif are just one contiguous body. This has also led to the model that the San Antonio massif originated from the Acoje block. It then separated and was translated southward to its present position through the Subic Bay Fault Zone. This fault zone passes through the western edge of the Zambales Range and swings southeastward towards the Subic Bay area (Fig. 1).

The presence of the tectonized, layered clinopyroxenite and gabbronorite hills along the western boundary of the Cabangan massif lends credence to this model (Figs. 4a–4d). These hills, which expose rocks geochemically and lithologically similar to the Acoje block and San Antonio massif, are allochthonous units with respect to the Cabangan massif (Yumul *et al.*, 1996) (Fig. 1). This is for the simple reason that the *in situ* cumulate sequence of the Cabangan massif does not include a well-developed layered ultramafic cumulate rock suite. Gabbronorites are also not part of the Coto

block and Cabangan massif mafic cumulate sequence. The hills were left behind during the southward translation of the San Antonio massif to its present position. For that matter, the location of the clinopyroxenite-gabbronorite hills mark the translation path of the San Antonio massif and gives a good idea where the Subic Bay Fault Zone passes through.

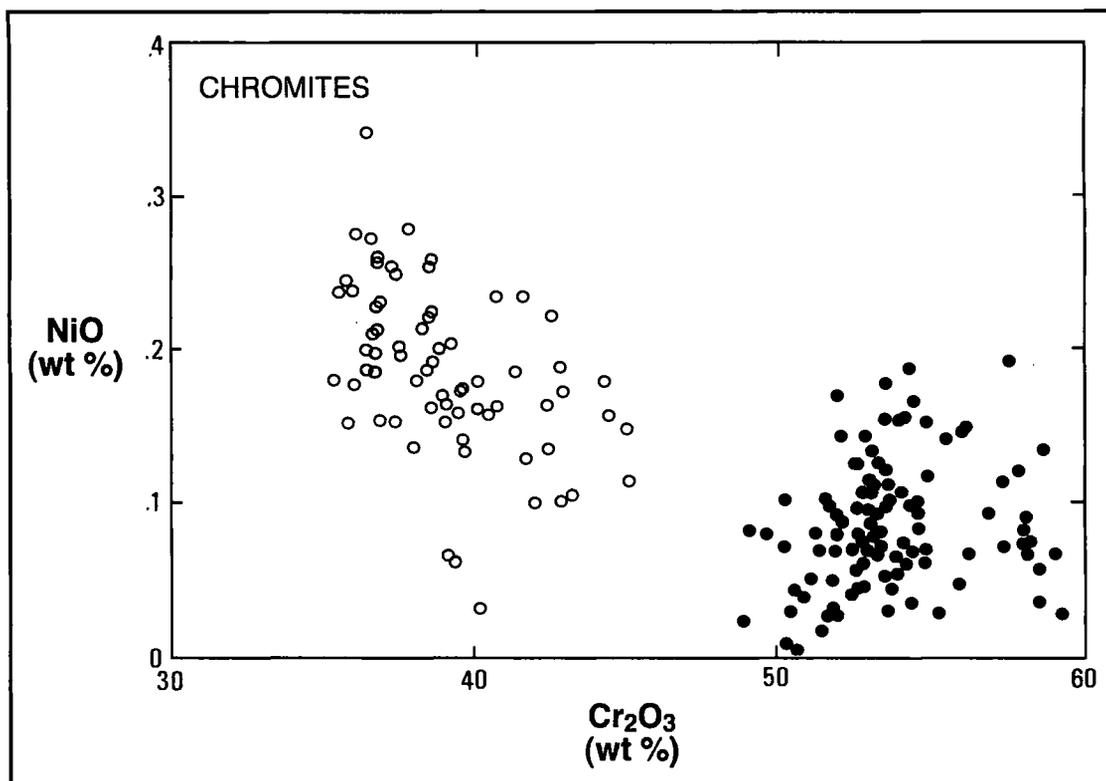
## SUBIC BAY FAULT ZONE AND THE ZAMBALES OPHIOLITE COMPLEX

The Subic Bay Fault Zone is a strike-slip fault believed to be responsible for the transport and accretion of the San Antonio Massif southward. From the Acoje block of the Masinloc massif all the way to the Cabangan Massif, the fault zone trends N-S which then swings to a NNW-SSE direction towards the Subic Bay area (Fig. 1) (Yumul and Dimalanta, 1997). Two possibilities can be thought of with regards to the origin and configuration of the fault zone. The Subic Bay Fault Zone can be a splay of the West Luzon Shear Zone of Karig and others (1986) or it may be related to the San Antonio Fracture Zone (Yumul *et al.*, 1990). Recent magnetics and gravity data do not support the presence of the San Antonio Fracture Zone (Dimalanta, 1996). It is more viable to model the fault zone as the southeastern extension of the West Luzon Shear as supported by available geophysical evidence (Dimalanta *et al.*, this issue).

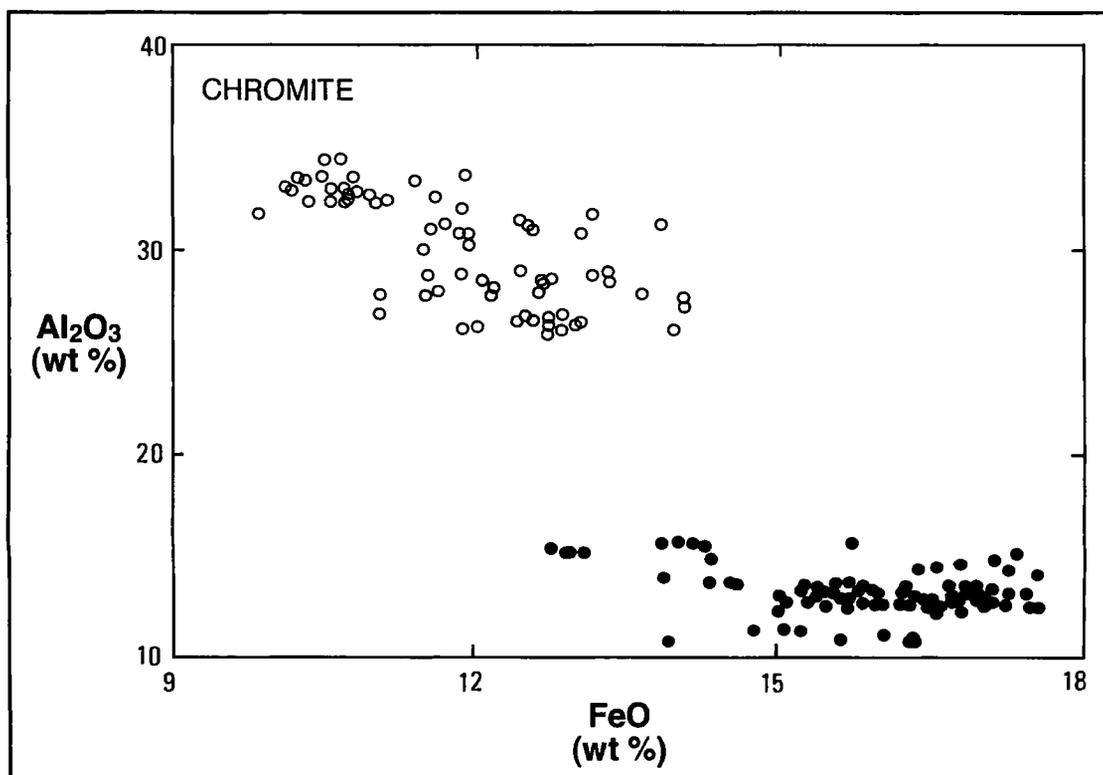
Preliminary structural measurements showed different paleostress fields that include both left lateral and right lateral sense of motions. No cross-cutting relationship was observed in the field, thus, making it difficult to establish the chronology of faulting. Whether the measured stresses were generated before, during or after the movement along the SBFZ must be looked into in future works. The possibility also exists that the measured stresses may not even be caused by movements along the fault zone. Furthermore, future works must also attempt to determine the continuation (onshore and offshore) and subsurface configuration of the fault if we are to fully grasp its role in the evolution of the Zambales Ophiolite Complex. Whether it is active or not will also be important to know.

## CONCLUSIONS

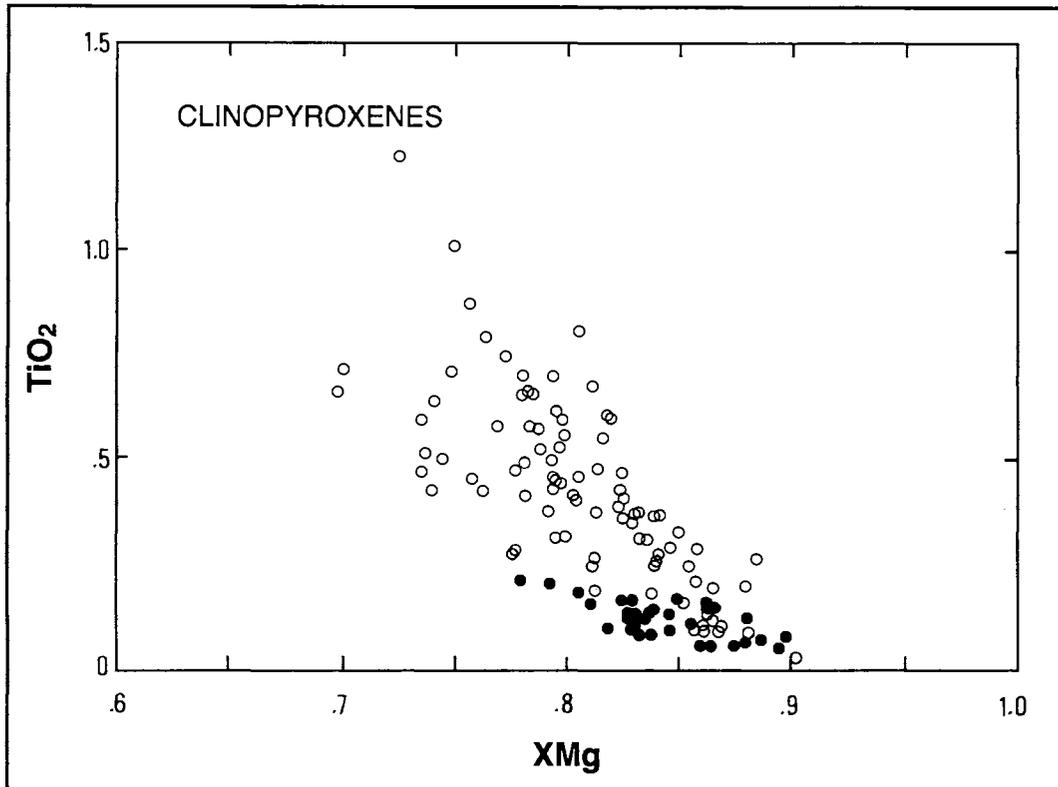
The present day configuration of the Zambales Ophiolite Complex can be explained with the recognition of the role played by the Subic Bay Fault Zone in the evolution of this crust-mantle sequence. The Coto block and the Cabangan massif are believed to be a contiguous body. On the other



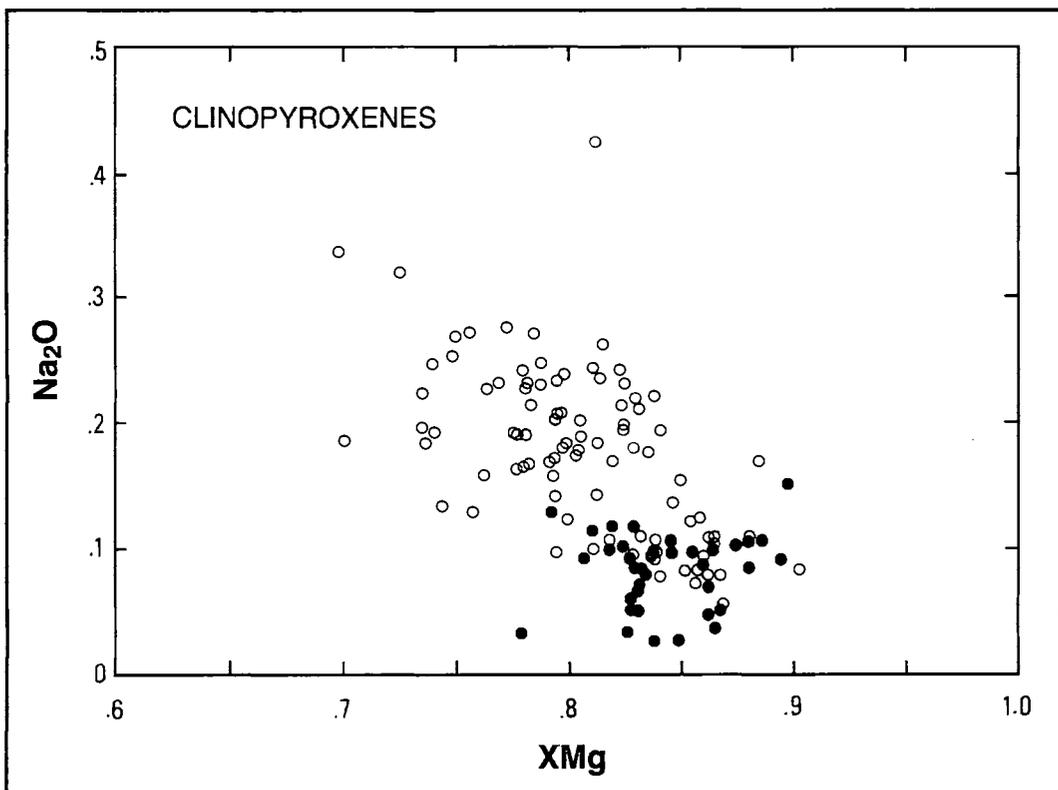
**Figure 2a.** Chromite  $\text{Cr}_2\text{O}_3$  (wt %) versus NiO (wt %) shows that the Acoje block chromitites are higher in chromium and lower in nickel compared to the Coto block chromitites. Aside from being a function of melt composition, the difference is a reflection of the degree of partial melting the source region/s of each block had undergone. See text for discussion. Legend: Filled circles — Acoje chromitites; Open circles — Coto chromitites.



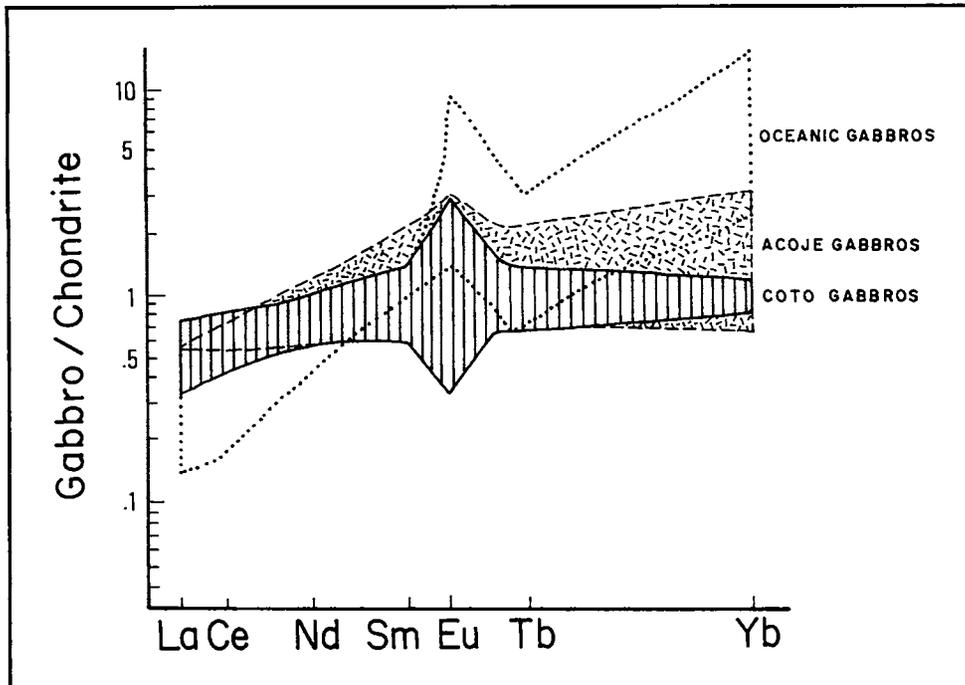
**Figure 2b.** Chromite FeO (wt %) versus  $\text{Al}_2\text{O}_3$  (wt %) shows the high alumina content of the Coto refractory chromitites as compared to the Acoje metallurgical chromitites. See text for discussion. Symbols as in Figure 2a.



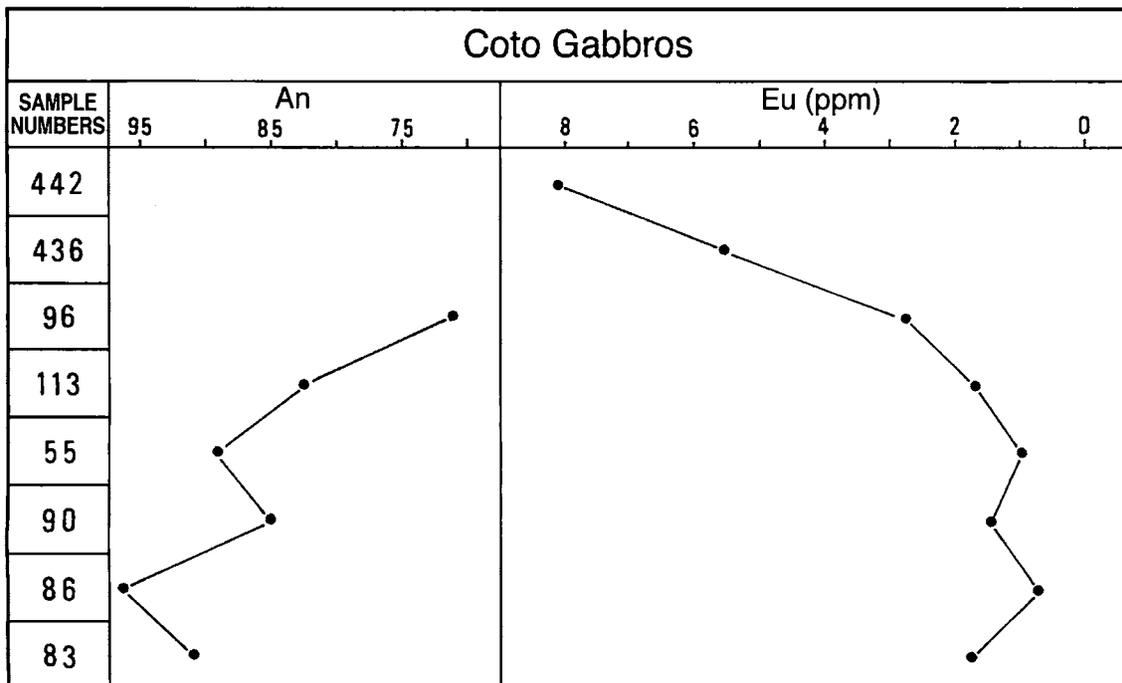
**Figure 2c.** Clinopyroxene XMg versus TiO<sub>2</sub> shows that at the same XMg number, the Coto volcanic clinopyroxenes have higher TiO<sub>2</sub> compared to the Acoje volcanic rocks. This is consistent with reported whole rock geochemistry. See text for discussion. Symbols as in Figure 2a.



**Figure 2d.** Clinopyroxene XMg versus Na<sub>2</sub>O shows that as the same XMg number, the Coto volcanic clinopyroxenes have higher sodium compared to the Acoje volcanic rocks which is believed to be a function of melt composition. See text for discussion. Symbols as in Figure 2a.



**Figure 3a.** Gabbro samples normalized to chondrite (after Masuda *et al.*, 1973) show a clear overlap between the Coto and Acoje mafic cumulate rocks in terms of rare earth element contents.



**Figure 3b.** The Coto mafic cumulate rocks (gabbros, troctolites, olivine gabbros), in general, have lower plagioclase anorthite rocks compared to the Acoje mafic cumulate rocks (norites, gabbro-norites, gabbros). Coto gabbros: 83 — troctolite; 86 — gabbro; 90 — troctolite; 55 — troctolite; 113 — gabbro; 96 — gabbro; 436 — gabbro; 442 — gabbro.

hand, the San Antonio massif, which originated from the Acoje block, was separated and translated southward to its present position. Translation resulted into clinopyroxenite and gabbronorite hills being left behind along the pathway of the Subic Bay Fault Zone. These allochthonous clinopyroxenite and gabbronorite hills found along the western side of the Cabangan massif are lithologically and geochemically similar to the Acoje block and the San Antonio massif.

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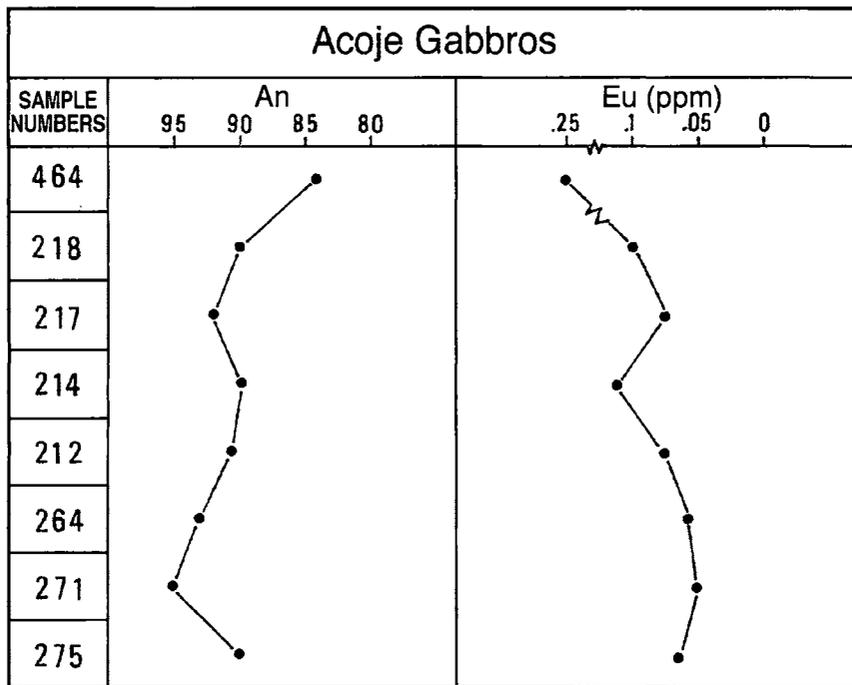
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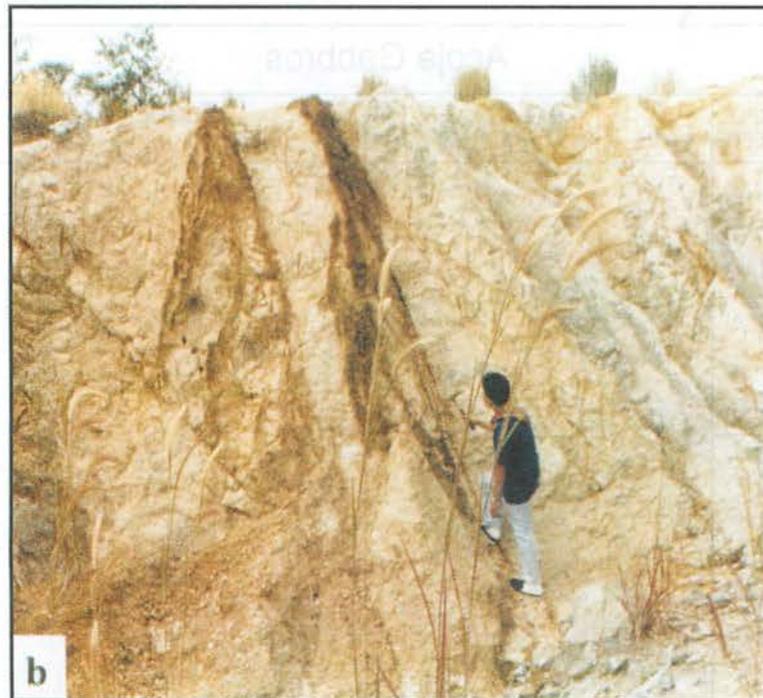
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**Figure 3c.** The Coto mafic cumulate rocks (gabbros, troctolites, olivine gabbros), in general, have lower plagioclase anorthite rocks compared to the Acoje mafic cumulate rocks (norites, gabbronorites, gabbros). Acoje gabbros: 275 — olivine gabbronorite; 271 — olivine gabbronorite; 264 — olivine gabbronorite; 212 — gabbronorite; 214 — melagabbronorite; 217 — gabbronorite; 218 — olivine gabbronorite; 464 — gabbronorite.



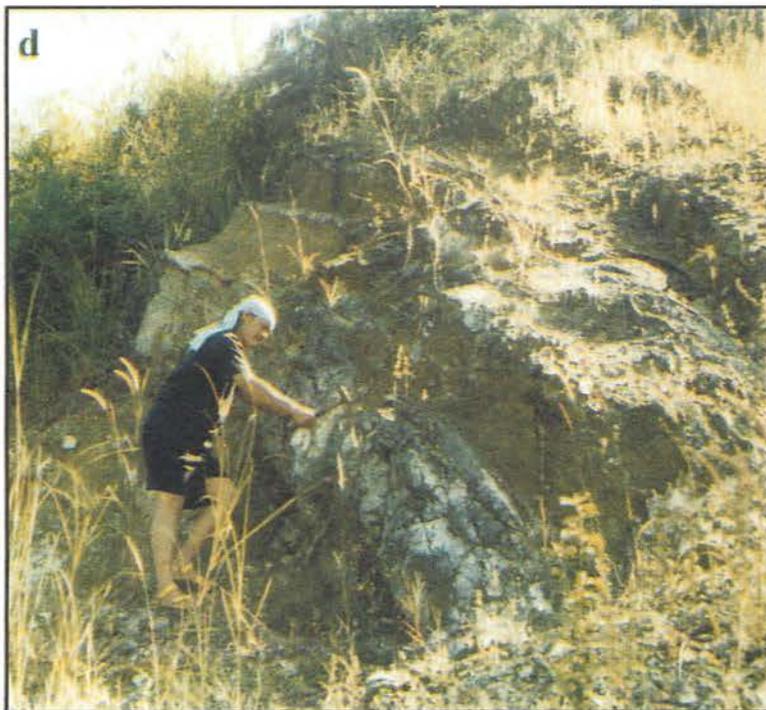
**Figure 4a.** A typical small, allochthonous gabbronorite hill found along the western boundary of the Cabangán massif. See text for discussion.



**Figure 4b.** A gabbronorite hill that has been extremely altered. The oxide stains define a series of N-S trending faults consistent with the trend of the Subic Bay Fault Zone.



**Figure 4c.** A sheared outcrop within the Subic Bay Fault Zone. The uppermost rocks are clinopyroxenites thrust on top of the lower gabbronorites.



**Figure 4d.** Tectonized layered clinopyroxenite hill found in Sindol which is lithologically and geochemically similar to the clinopyroxenites of the Acoje block and San Antonio massif. See text for discussion.

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