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Geology of the Composite Terranes of East and Central Mindanao

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The Philippine Archipelago represents an evolving microcontinent formed by the amalgamation of many recognizable geologic terranes. Many of these terranes are, in turn, composites of several distinctive geologic systems that also constitute terranes. Remnants of island arc systems (volcanic, plutonic, and clastic rocks) are predominant but there are large fragments of depleted mantle peridotite, ophiolite from backarc basins or deep-sea floor, continental blocks, and marine sediments. Metamorphosed terrigenous, oceanic, and mantle material is also widespread. This tectonic collage has been thickened and overprinted by younger arc plutonic-volcanic series and by successor sedimentary basins.

We recognize two composite terranes in eastern Mindanao that were sutured together by mid-Tertiary (late Oligocene ?) time. Each includes remnants of arc and backarc basin rocks, mantle fragments, metamorphic rocks that appear to be related to arc deformation, and, locally, melange units. The western terrane in Mindanao is an extension of the Sangihe arc; the eastern terrane extends from Samar southward through Mindanao to the Halmahera arc. A Miocene and younger sedimentary successor basin (Agusan-Davao Trough) covers the presumed suture zone on Mindanao. Postamalgamation arc-volcanism has added new crust to the western terrane; the active Philippine Fault has dismembered parts of the eastern terrane.

The complex geologic history of Mindanao appears to be typical of the Philippine "super terrane" that has yet to be accreted to a continental mass. The Philippines give insight to an intermediate stage in the evolution from immature intraoceanic island arcs to the tectonic collages accreted to cratons as in western North America.

INTRODUCTION

The Philippine Archipelago represents an evolving microcontinent formed by the tectonic amalgamation of a wide variety of rock types, by emplacement of volcanic and plutonic rocks that have thickened and welded together the tectonically coalesced fragments, and by accumulation of thick sedimentary successor basins that have formed in situ. Within the complex tectonic collage of allochthonous blocks and fragments, there are stratigraphic, disrupted, and composite terranes (Jones et al, 1983). These include recognizable fragments of island arcs, sea mounts, backarc or deep sea-floor crust, mantle-derived peridotites showing varied degrees of depletion, metamorphosed ultramafic (mantle), mafic (oceanic), and silicic (continental) rocks, and a wide range of sedimentary rocks representing clastic material derived from volcanic-plutonic arcs, pelagic and near-shore sediments, and reef deposits. In a very simplified view, the Philippine Islands comprise a composite terrane formed of displaced crustal fragments, some of which may be derived from the Asian mainland; allochthonous terranes comprising oceanic and island arc crust and upper mantle; autochthonous volcanic-plutonic arcs and their derivative clastic rocks; and autochthonous sedimentary basins. The allochthonous units have been juxtaposed on lateral slip faults or sutured together by thrust faults or along zones of melange (Hamilton, 1979); many show evidence for extensive internal disruption. The recognition of belts of ophiolite, melange zones, and "fossil" volcanic-plutonic arcs has been important in demonstrating the composite nature of the archipelago (e.g., Hamilton, 1979; Karig, 1982, 1983; Hawkins and Evans, 1983; McCabe, this volume) and has given insights to the temporal variation in convergence zone trends and subduction polarity. Radiometric dating (e.g., Wolfe, 1981) and paleomagnetic studies (e.g., Fuller et al, 1983) have shown that the islands were formed by the coalescence (amalgamation) of a number of discrete geologic units formed at different times and at different geographic locations. The present location and relation of the islands to oceanic trenches and great faults has no direct bearing on the geologic setting of many of the constituent units at the time they were formed. The present configuration is but one scene in a dynamic tectonic evolutionary process involving accretion of tectonostratigraphic terranes and their disruption by lateral-slip faulting.

Recognition of discrete geologic units or "terranes" has proved useful in interpreting the history of complex areas such as northwestern North America (Monger et al, 1972; Coney et al, 1980; Jones et al, 1982, 1983; Schermer et al, 1984). Application of the terrane concept to the Philippines has helped to draw attention to the diversity of rock series recognizable and has demonstrated the allochthonous nature of these units (e.g., Moore et al, 1981b; Hawkins et al, 1981, 1982, 1984; Wright et al, 1981; Karig, 1982, 1983; Hawkins and Evans, 1983; McCabe, this volume).

Our main objective in this paper is to describe the geology of a complex belt of rocks in central and eastern Mindanao that has been assembled by collision of several different crust-mantle units along a zone extending south from Samar towards the Sangihe-Halmahera arcs (Fig. 1). This belt was referred to by Hamilton (1979) as the "older volcanic rocks and melange of Philippine and Halmahera arcs." We prefer to describe the belt as a collision complex inasmuch as melange constitutes only a relatively minor part of the belt, ophiolite and arc-derived clastic rocks are equally as important as volcanic material, and because the scale of individual rock units is on the order of hundreds of meters to tens of kilometers rather than on the scale of meters (or less) as implied by the term melange.

We present here a discussion of the geology of five areas in central and eastern Mindanao (Figs. 1-3) that characterize some of the complexity of the region and show both the problems and advantages in applying the terrane concept to the evolution of collision belts. The composite terranes we recognize each comprise an assemblage of disrupted terrane fragments and stratigraphic terranes. The eastern Mindanao composite terrane includes: (1) Pujada Peninsula (a disrupted terrane comprising a heterogeneous assemblage of backarc ophiolite, arc-derived clastic rocks, metamorphic rocks, clastic rocks, and carbonates); (2) Dinagat–Nonoc–Hanigad Island area (a dismembered "stratigraphic terrane" largely formed of island arc ophiolite); (3) Surigao area (a disrupted terrane comprising depleted mantle peridotite, metamorphic rocks, oceanic crust, arc volcanic and plutonic rocks, and arc-derived clastic rocks). The central Mindanao composite terrane (4), in Bukidnon Province, is a composite terrane formed of backarc or deep sea-floor ophiolite, metamorphic rocks, melange, arc-derived clastic rocks, limestone, and a modern arc-volcanic belt. A successor basin (5), the Agusan-Davao trough, formed after the Neogene collision between 1 and 4.

REGIONAL GEOLOGIC SETTING

Eastern Mindanao, Philippines, is a composite terrane formed as the result of a collision between two island arc systems during the mid-Tertiary (Hamilton, 1979). The suture zone between the collided arcs in southeastern Mindanao is believed to be defined by an ophiolite belt exposed on the Pujada Peninsula (Fig. 1; Moore and Silver, 1983). The Pujada ophiolite is part of a discontinuous belt of ophiolite, interspersed with arc-derived clastic rocks and volcanic-plutonic rocks of island arc origin, which extends from Samar southward through East Mindanao to the Talaud Islands (Moore et al, 1981a; Evans et al, 1983).

The occurrence of an ophiolite belt in southeastern Mindanao has been known for some time (Melendres and Comsti, 1951; Santos-Ynigo et al, 1961; Santos-Ynigo, 1965), and its significance was recognized by Hamilton (1979), who suggested that the Pujada Peninsula is the northern extension of the Molucca Sea collision zone. The Talaud Islands mark the southernmost exposures of rock on this postulated collision zone. The collision complex, serpentinized peridotite, and ophiolite rocks are exposed near Surigao and on Dinagat, Nonoc, and Hanigad Islands to the north giving a total length of at least 750 km (466 mi). Samar includes rocks of similar type and may add another 250 km (155 mi) to the belt. Hamilton (1979) has proposed that this collision belt is part of a great collision belt (Pacific Cordilleran system) that may act as a double orocline transforming the motion between east-directed movement in the southern Philippines and west-directed movement in Luzon (cf. his Figure 109). The Mollucca Sea collision zone separates the Sangihe Arc (west) from Halmahera (east) and corresponds to the Agusan–Davao Trough (mid- to later Neogene sedimentary basin) that separates the Central Cordillera of Mindanao (west) from the collision complex and Pujada Peninsula (east).

The Sangihe Island arc system can be traced from northern Indonesia, where the arc is still active, northward through south-central Mindanao to the Central Cordillera of Mindanao (Figs. 1, 2), where the arc recently has become inactive (Hamilton, 1979). Andesitic tuff, agglomerate, and volcaniclastic sedimentary rocks of probable Cretaceous to Paleogene age are reported to underlie the young volcanic rocks in central Mindanao (Metal Mining Agency, 1972).

Much of eastern Mindanao (Fig. 2) is covered with Cretaceous to Oligocene arc volcanic rocks (Ranneft et al,

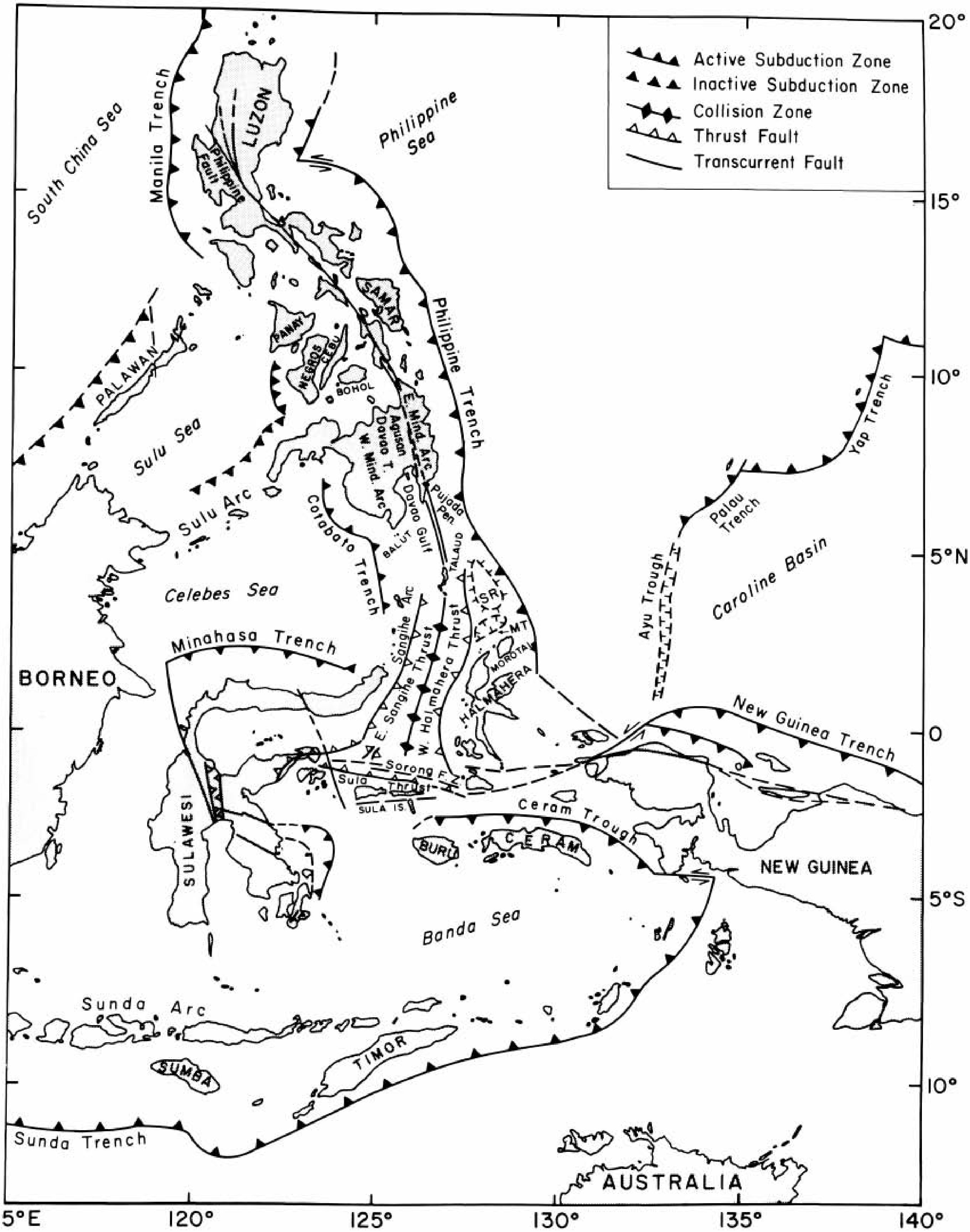

Figure 1—Tectonic map of Southeast Asia–Western Pacific basin showing Mindanao relative to major tectonic features. Modified from Hamilton (1979), Geologic Map of Philippines (1967), and Moore and Silver (1982).

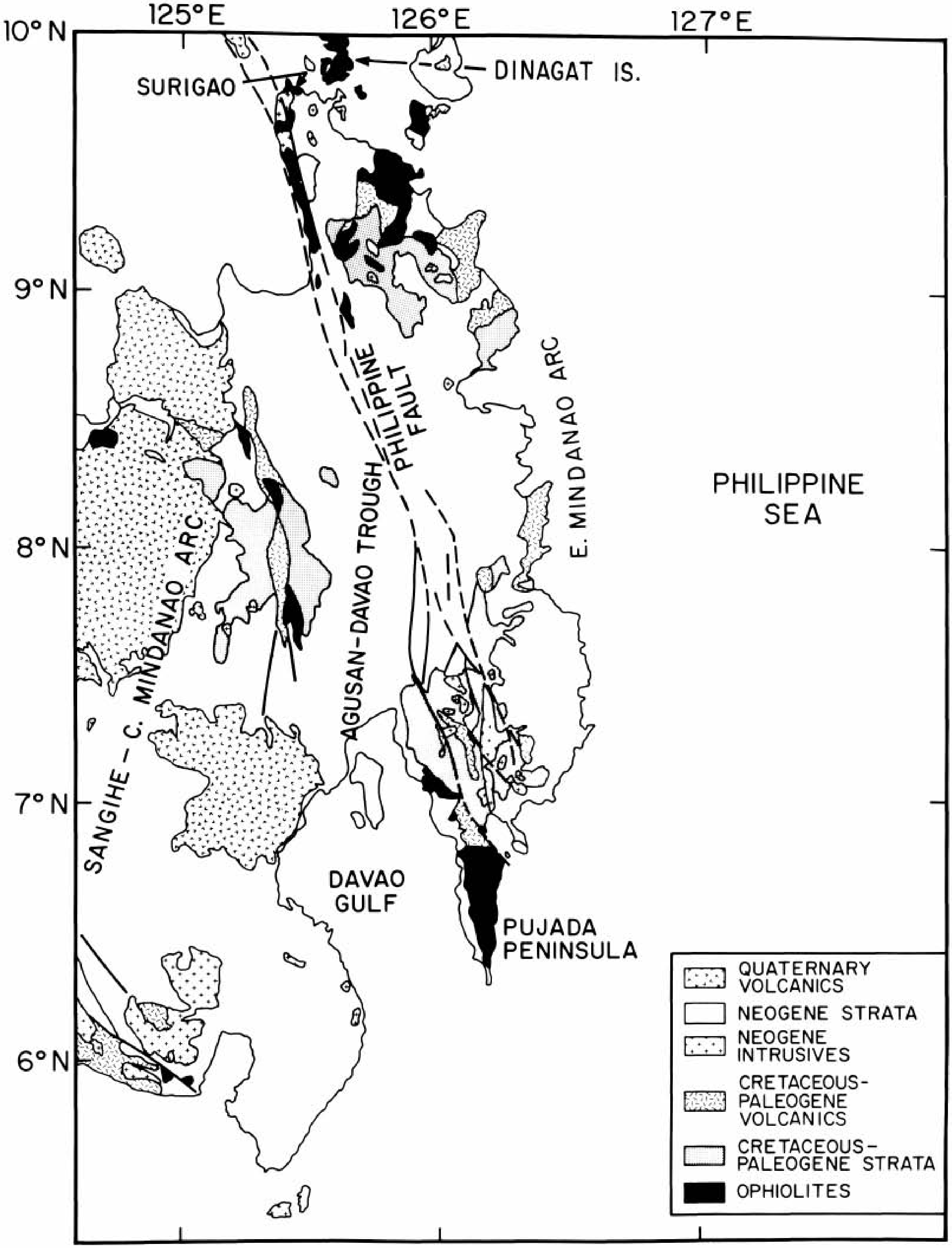

Figure 2—Central and eastern Mindanao showing major geographic and tectonic features. Agusan-Davao Trough successor basin separates central Mindanao composite terrane from eastern Mindanao composite terrane and covers the presumed suture zone. Philippine Trench, not shown, lies 100 km (62 mi) east of Mindanao.

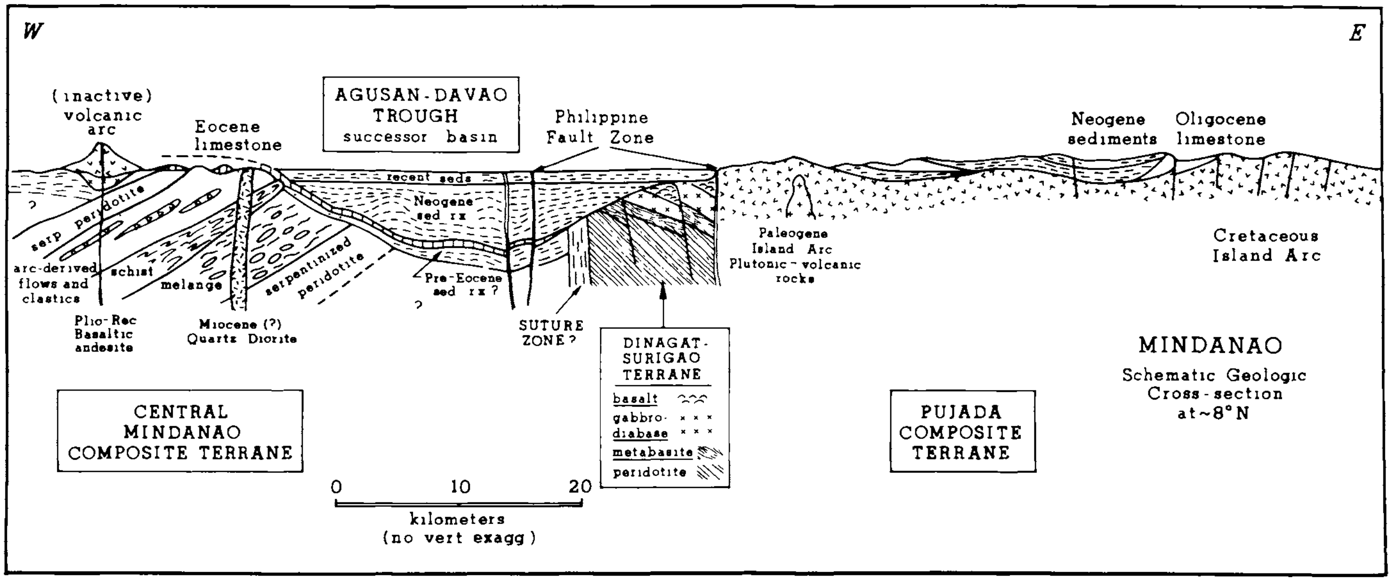

Figure 3—Schematic geologic cross section, at about 8° N, showing Agusan–Davao successor basin, probable location of suture zone between the terranes, and locus of Pliocene–Recent volcanoes. Details of structure and lithology in subsurface rocks based on inferences from exposures at surface and projected to depth. Subsurface details in Agusan–Davao Trough are based on seismic data (Murphy, 1981, written communication). Cross section is modified from a drawing by J. Murphy, AMOCO International.

1960; Metal Mining Agency, 1973; Matsumaru, 1974; Hashimoto, 1981; Wright et al, 1981). Similar Cretaceous and younger volcanic rocks have been found on Samar and Luzon Islands north of Mindanao (Reyes and Ordonez, 1970; Hashimoto et al, 1975; Hashimoto, 1981). These rocks have been interpreted as remnants of a Cretaceous to mid-Oligocene volcanic arc that extended from north of Samar through eastern Mindanao (Hamilton, 1979; Cardwell et al, 1980). The volcanic rocks are overlain by upper Oligocene limestones and Miocene coals and shales indicating cessation of volcanism by late Oligocene (Vergara and Spencer, 1957; Matsumaru, 1974).

The two arcs appear to have collided during the Neogene. The collision is still active south of Mindanao in the area of the Molucca Sea (Silver and Moore, 1978; Hamilton, 1979; McCaffrey et al, 1980). On Mindanao, the collision zone between the two arcs is occupied by the Agusan-Davao Trough (Figs. 1-3). The eastern margin of the Agusan-Davao Trough is composed of a complex of highly faulted and folded basement rocks that is exposed from Surigao southward to the Pujada Peninsula (Ranneft et al, 1960). The Philippine Fault Zone, which disrupts the eastern margin of the trough, presents a major tectonic complication in this region. Little is presently known about magnitude or age of offset along this fault, but it can be traced as a continuous feature in Mindanao from the Surigao region southward to the Pujada Peninsula (Ranneft et al, 1960; Allen, 1962; Fig. 1). The Philippine Fault Zone in Mindanao, and the area to the south, is still active as evidenced by the high concentration of seismicity in this region (Cardwell et al, 1980). Hamilton (1979) believes that the fault, although a major regional fault, does not exhibit strike-slip motion. During our field studies, we found evidence of en echelon folds and faults northeast of Pujada Peninsula that are consistent with left-lateral strike-slip along the fault. We were unable to define any strike-slip faults cutting Pujada Peninsula, but we suspect that some of the structural complexity in this region may be caused by strands of the Philippine Fault system that cut the Peninsula.

The tectonic grain of the Pujada Peninsula is north-northwest. This trend extends south to the Talaud Islands (Fig. 1), a Tertiary forearc terrane that also has a north-northwest structure (Moore et al, 1981a). The Philippine Fault Zone can be traced from Pujada Bay south-southeast along a bathymetric ridge to Talaud (Moore and Silver, 1983). The ridge is a horst block with fault strands on each side. These faults can be seen in two seismic profiles south of Mindanao and one profile just north of Talaud (Moore and Silver, 1983). The Philippine Fault Zone undoubtedly continues into the Talaud Islands area, but because of the complex geology on Talaud, the fault has not been recognized in the field. The volcanic rocks exposed on the Nanusa Islands east of Talaud may have been moved northward from the vicinity of Halmahera by motion along one of these strike-slip fault traces.

The structure of the Molucca Sea region changes drastically at Talaud. Bathymetry changes from a north-northwest trend to a north-northeast trend south of Talaud. The seismicity also changes: The active east-dipping subduction zone under Halmahera does not continue northward to the latitude of Talaud (Cardwell et al, 1980). Deformation in the collision zone south of Talaud is still active (Silver and Moore, 1978), whereas north of Talaud, deformation has slowed dramatically as indicated by the thick sediments of Davao Gulf region that are only moderately deformed (Cardwell et al, 1980). South of Talaud, the deformed collision complex is being thrust outward onto the flanks of the Sangihe and Halmahera arcs (Silver and Moore, 1978). These thrust faults can be traced northward only as far as the Talaud Islands. At the present time, the nature of the change in tectonic style at the Talaud Islands is unclear.

GEOLOGY OF THE PUJADA COMPOSITE TERRANE

The igneous and metamorphic rocks of the Pujada Peninsula and southeastern Mindanao constitute a distinctive terrane that may itself be a composite of two or more distinctive but dismembered microterranes (Fig. 4). For this discussion we will call it the Pujada composite terrane. The overall petrologic characteristics indicate an assemblage of rocks representing ophiolite, volcanic arc material, and their metamorphic equivalents (Tables 1, 2, 3).

Greenschist-facies metamorphosed mafic rocks are the lowest structural unit exposed on the Pujada Peninsula. Chlorite-actinolite schists forming the basement of the northern Pujada Peninsula are best exposed at Batobato Point (Fig. 4) and on the southern part of the peninsula. These schists (Magpapangi greenschist) underlie the amphibolite which in turn is overlain by peridotite (Villamor et al, 1984). Fault zones, presumed to be thrust faults, separate these rock units (Villamor et al, 1984). The degree of metamorphism of the schists exposed in the northern Pujada Peninsula appears to decrease to the east, and our impression is that these rocks grade into essentially unmetamorphosed rocks to the east in the area of Dawan where they are interbedded with basaltic volcanic rocks and thin-bedded red siliceous argillites (Melendres and Comsti, 1951). In the area northwest of Dawan it is clear that a fault juxtaposes the volcanic rocks and red sediments. In this area, the volcanic and sedimentary rocks are intersheared on a very small scale. Some of this intercalation may be a primary feature, the original material having been interlayered volcanic and sedimentary rocks. South of Dawan, along the coast of Pujada Bay, these sedimentary and volcanic rocks are strongly sheared and resemble melange. Pillow structures are preserved in the volcanic rocks at several localities.

The core of the Pujada Peninsula has thin discontinuous lenses of calcite and calc-silicate marble and metamorphosed mafic and ultramafic rocks (amphibolite and metaperidotite that comprise the lithologic types considered to be diagnostic of an ophiolite. Unmetamorphosed peridotite, gabbro, diabase, and basalt are also present and structurally overlie the metabasites.

The peridotite (Table 4) includes olivine and orthopyroxene cumulates and olivine-orthopyroxene-plagioclase cumulates. Serpentinization of the peridotite ranges from mild to nearly complete. Some peridotite samples show effects of extensive high-temperature shearing and recrystallization with thin streamers formed of a mosaic of tiny olivine crystals. Chromite forms individual grains and grain aggregates. The mafic rocks have the chemistry typical of midocean ridge or backarc basin basalts (Table 1). There are no distinctive chemical signatures to differentiate between these two origins in altered or weakly metamorphosed basalts. We can, however, distinguish between these rock types and basalts from sea mounts, island arcs, or continental settings.

Basalts from southeastern Mindanao (Fig. 2) and from the northwest side of Pujada Bay, near the Philippine Fault Zone (Fig. 4), have phenocrysts of plagioclase, hornblende, and clinopyroxene. The groundmass consists of plagioclase laths, pyroxene, and opaque minerals. At least some of these basalts have arc-tholeiitic chemistry (Wright et al, 1981, and Table 1). Thus, we have evidence in the Pujada terrane for crustal rocks from both an island arc terrane and a backarc or midocean ridge. We favor a backarc origin because of the nature of the associated rocks that indicate a large component of arc material.

Amphibolites from the northern Pujada Peninsula appear to have undergone retrograde metamorphism from amphibolite to greenschist facies. The amphibole is actinolite to calcic-Al-hornblende (see Table 4). The amphibole ranges from anhedral to euhedral and generally shows a preferred orientation of its long axis, which gives the rocks a lineated fabric. Epidote is common, forming clusters of small crystals. Garnets (almandine-grossularite-pyrope mixtures, Table 4) are also present in several of the amphibolites. Some of the garnets are euhedral, although some are poikiloblastic, and filled or rimmed with chlorite. Chlorite is also common as a replacement mineral on amphibole. Amphibolites from the central Pujada Peninsula are composed mostly of green hornblende in parallel blades, and plagioclase. Microprobe analyses indicate that they are all calcic amphiboles. No sodic amphiboles have been found. This is critical in establishing the P–T relations of metamorphism.

Petrology and Chemistry

The crystalline rocks of the Pujada composite terrane consist of a variety of types, which points to an affinity with oceanic lithosphere, volcanic arcs, and their metamorphic equivalents (Melendres and Comsti, 1951; Ranneft et al, 1960). Hamilton (1979) called attention to the significance of the ophiolite assemblage as an indication of former oceanic lithosphere. Ophiolite assemblages may form in several different tectonic settings (e.g., Hawkins, 1980; Hawkins and Evans, 1983) so we must look for distinctive characteristics to identify the type of ocean crust/mantle they represent. The Pujada terrane comprises rock types derived both from an island arc environment and from a backarc basin. These may have been part of a single convergent plate system, but now they have been juxtaposed by faults and thus they constitute different petrologic domains (stratigraphic terranes) within the larger terrane. For simplicity, we will refer to these as the backarc ophiolite and the island arc series. The backarc ophiolite forms much of the Pujada Peninsula; the arc series rocks are exposed, with arc-derived clastic rocks, along the eastern cordillera between 7° N and 10° N.

The basalts and diabases from the backarc ophiolite (Table 1) have TiO_2 concentrations in the range 1.16 to 1.63 wt%, Ni contents between 55 and 100 ppm, and FeO^*/MgO ratios between 1.00 and 1.60, where FeO^* indicates all iron represented as ferrous iron (see Fig. 5). These data are typical of fractionated midocean ridge basalts (MORB) or backarc basin basalts (BABB). In view of their close association with island arc volcanic rocks, we

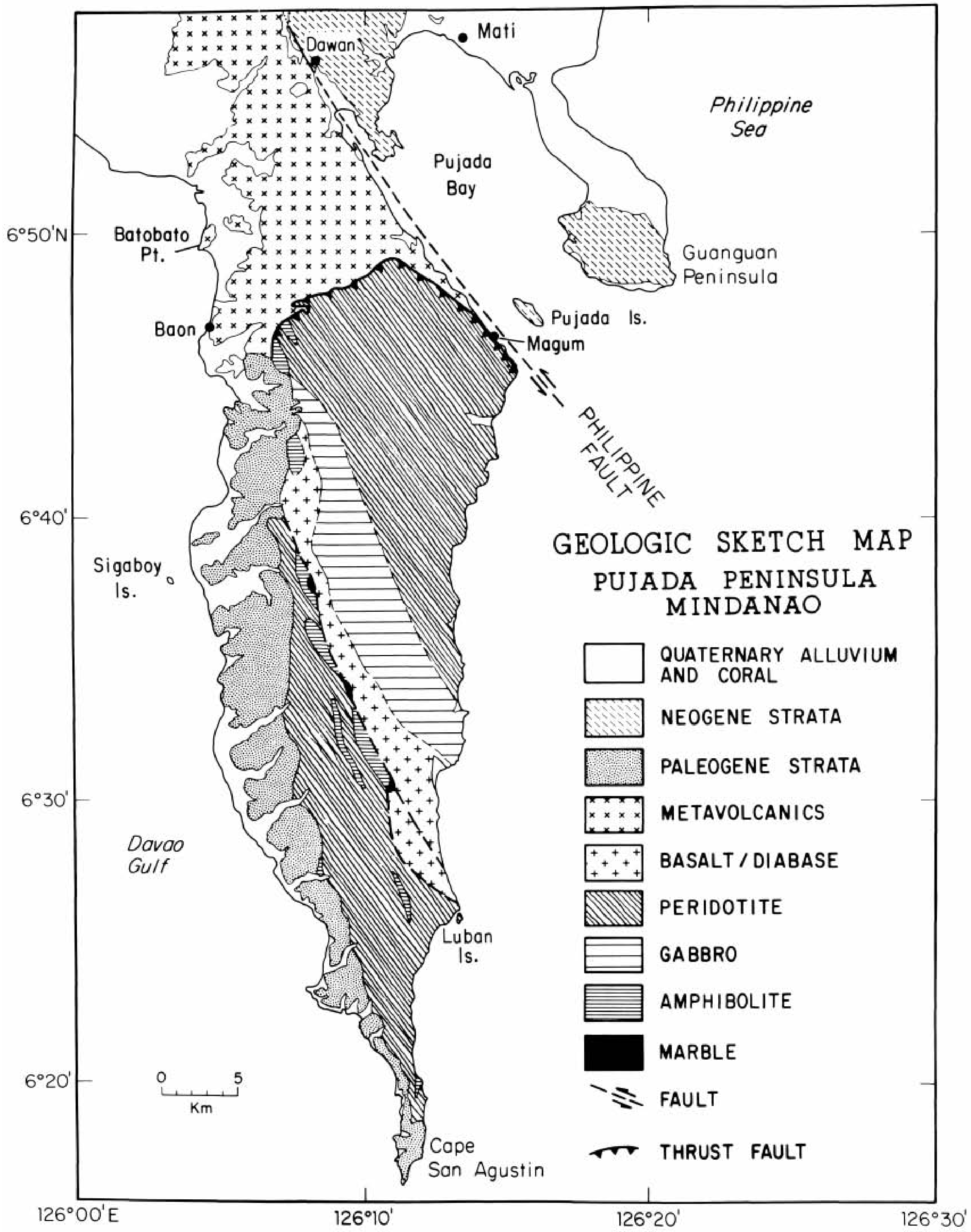

Figure 4—Geologic map of Pujada Peninsula. Based on Philippine Bureau of Mines (1967), Santos-Ynigo et al (1961), Melendres and Comsti (1951), and our field mapping.

Table 1

Sample	MIN 316	MIN 161	MIN 162	MIN 203	MIN 191	MIN 321	MIN 164	MIN 180	MIN 130
Type	B	D	D	D	D	D	G	G	G
Mg#	.646	.626	.607	.563	.575	.523	.623	.641	.802
					Weight Percent				
SiO_2	49.14	53.24	50.63	49.47	51.02	50.09	49.02	49.48	49.45
TiO_2	0.70	1.46	1.28	1.63	1.52	1.62	1.15	0.56	0.52
Al_2O_3	16.01	15.41	15.29	13.38	14.88	13.50	15.30	20.79	18.76
FeO^*	8.90	9.00	9.71	11.32	10.18	11.62	9.49	4.98	3.93
MnO	0.18	0.17	0.17	0.24	0.21	0.19	0.18	0.10	0.07
MgO	9.12	8.46	8.40	8.18	7.72	7.16	8.78	6.41	8.94
CaO	12.67	9.27	11.60	11.80	11.76	11.35	14.11	14.02	17.32
Na_2O	2.72	3.42	2.73	2.78	2.13	3.18	1.80	2.65	1.05
K_2O	0.11	0.03	0.20	0.10	0.08	0.08	0.04	0.18	0.02
P_2O_5	0.08	0.01	0.11	0.13	0.07	0.21	0.05	0.19	0.02
Sum	99.74	100.47	100.19	99.07	99.61	99.04	99.92	99.36	100.15
					Trace Elements (ppm)				
Cr	384	262	—	234	—	117	195	—	—
Ni	141	100	85	71	56	63	90	78	161
V	251	253	275	287	284	349	284	189	236
Rb	1	1	1	1	2	1	1	1	1
Sr	145	99	121	131	106	152	124	185	213
Ba	31	2	7	11	11	8	12	27	25
Zr	56	97	88	111	110	146	72	49	21
Y	24	35	32	36	33	44	28	18	17
Nb	1	1	1	2	4	2	2	1	1

Abbreviations: B = basalt; D = diabase; G = gabbro, Mg# = Mg/(Mg + Fe).

Table 1—Backarc basin crustal rocks, Pujada Peninsula, eastern Mindanao; chemical composition.

interpret these as BABB. The element abundances and ratios clearly distinguish the backarc ophiolite basalts from the arc series.

Basalts and basaltic andesites of the island arc volcanic series (Table 2) contain 0.60 to 0.90 wt% TiO_2, Ni contents less than 27 ppm, usually in the 6 to 17 ppm range, and FeO^*/MgO ratios between 1.75 and 3.30. These samples plot in the field for island arc basalts on element discriminant diagrams (Figs. 5–7). On some of these plots there is an overlap between arc and ocean-floor samples, but when all of the discriminants are considered, an arc origin is seen. The low Cr, Ni, Ti, Zr content and high Ba, Sr (Table 2) are distinctive characteristics of island arc basalts and basaltic andesites (e.g., Jakes and Gill, 1970).

As the FeO^*/MgO ratios indicate, the island arc volcanic samples as a group are more differentiated than the BABB samples, and they show generally higher K_2O and SiO_2 contents. Sr values are high (> 300 ppm) in the arc samples as well. The BABB samples have 8% normative hypersthene and 8% normative olivine in contrast to the arc samples, which lack normative olivine and have about 16% normative hypersthene. The Y concentrations for the two groups are comparable (most fell in the 25–45 ppm range), which implies, once the effect of differentiation is subtracted, that the arc source was depleted in Y relative to the BABB source. The low concentration of Y, as well as Zr and Ti, is a characteristic of island arc tholeiites and helps to distinguish them from MORB or BABB.

In a plot of TiO_2 vs. Zr (Fig. 6), which utilizes the fields defined by Pearce and Cann (1973) for ocean-floor basalts (OFB), calc-alkaline basalts, and low-K tholeiites, the BABB samples plot as OFB, while the arc samples are in the calc-alkaline field. Similar distinctions are found in ternary plots of Ti-Zr-Y (Fig. 7) again using the fields of Pearce and Cann (1973). In general, arc tholeiites lie in the fields for calc-alkaline rocks in plots of this type, whereas BABB will plot in the ocean-floor basalt field.

Petrologic Discussion

The intensity of metamorphism in the rocks from the core of the peninsula is highly varied; it ranges from tectonized peridotite with granulite-facies mineral assemblages to serpentinites formed at low P and T. Some mafic rocks have amphibolite to greenschist-facies assemblages with well-developed lineation and schistosity while others have mineral assemblages and textures

Table 2

Sample	MIN 280	MIN 260	MIN 283	MIN 272	MIN 271	MIN 270	MIN 331-A
Type	B	B	BA	BA	BA	A	D
Mg#	.509	.406	.482	.478	.473	.421	.131
				Weight Percent			
SiO_2	50.85	48.04	55.16	53.87	54.45	59.71	70.34
TiO_2	0.82	1.05	1.11	0.80	0.80	0.65	0.16
Al_2O_3	14.97	20.88	15.14	18.04	20.41	18.99	15.59
FeO*	11.84	10.89	10.19	8.29	7.12	5.20	3.67
MnO	0.3	0.43	0.21	0.34	0.15	0.17	0.06
MgO	6.89	4.18	5.32	4.25	3.59	2.12	0.31
CaO	9.82	10.62	7.64	8.98	8.92	6.49	0.33
Na_2O	2.13	2.59	4.06	3.38	3.26	3.93	1.63
K_2O	1.03	0.26	0.06	1.14	0.20	2.45	5.86
P_2O_5	0.22	0.28	0.22	0.22	0.13	0.29	0.03
Sum	98.87	99.20	99.11	99.31	99.03	100.00	98.01
				Trace Elements (ppm)			
Cr	19	19	21	15	13	21	—
Ni	11	16	17	6	6	8	11
V	272	319	387	232	226	101	5
Rb	10	5	1	18	2	57	232
Sr	524	300	435	300	249	838	29
Ba	181	89	164	194	54	401	79
Zr	105	60	98	150	172	123	1177
Y	32	24	35	33	43	20	122
Nb	1	2	1	6	2	9	—

Abbreviations: B = basalt; BA = basaltic andesite, A = andesite; D = dacite, Mg# = Mg/(Mg + Fe).

Table 2—Island arc crustal rocks, Pujada Peninsula, and eastern Mindanao; chemical composition.

indicative of only low T hydrous static recrystallization. The diversity of textures and metamorphic facies strongly suggests that the core of the Peninsula is formed of an accumulation of slabs or blocks that have been derived from different levels of an oceanic lithosphere section and that have experienced different styles and intensities of metamorphism. At this time we have no basis to differentiate between different metamorphic cycles or a single event followed by tectonic disruption of a zoned metamorphic belt.

There is always a problem in determining the protolith of metamorphic rocks, but the chemical and mineralogic data for the Pujada samples appear to be distinctive enough to permit us to make a fairly reliable estimate. The serpentinites and metamorphosed ultramafic rocks were derived from depleted peridotite. The relict mineralogy of some samples clearly indicates that they were derived from harzburgite (OL + OPX) with chromite. This mineralogy is typical of depleted mantle peridotite; i.e., mantle that has been through a melting episode and represents the unmelted refractory residue beneath a spreading center, arc edifice, sea mount or some other magma generation site. Neither the textures nor the mineral composition [OL = Fo_{91}, OPX = $En_{90}Fs_9Wo_1$, CHR = Cr/(Cr + Al) = 0.43] are diagnostic of crystal accumulations found in stratified, fractionated mafic magma chambers, but this cannot be totally ruled out because the lowest (first to form) cumulate levels of some of these stratiform complexes resemble residual mantle material in composition.

The metamorphosed basaltic and gabbroic rocks exhibit a range in mineral and textural types (Table 4). Amphibolite-facies rocks include garnet-amphibole, garnet-amphibole-plagioclase, amphibole-zoisite (plagioclase), amphibole, calcite-amphibole, and amphibole-plagioclase assemblages. Sphene, chlorite, epidote, rutile, Fe-Ti oxides, and sodic plagioclase are present as accessory minerals or retrograde assemblages. Calcite marble forms discontinuous layers or lenses in the amphibolite terrane and clearly was derived from sedimentary material. The amphibole-bearing assemblages must have been derived from Ca, Al, Mg-rich rocks. The trace element (e.g., Ni, Cr, Sr) and minor element (e.g., Ti, Mn, Na, K) abundances of these samples argue for a basalt-gabbro source. The most likely parental rock would have been a (cumulate?) gabbro from the base of an oceanic or arc crustal section. Some of the mafic schists have chlorite-rich

Table 3

Sample	MIN 151	MIN 51	MIN 210	MDO 10b	MIN 50
Type	A	GA	A	A	GA
			Weight Percent		
SiO_2	44.52	43.75	52.05	49.70	47.95
TiO_2	1.44	1.58	1.01	0.99	2.58
Al_2O_3	17.32	18.30	14.33	14.44	14.47
FeO^*	11.00	9.57	10.44	9.02	12.63
MnO	0.26	0.15	0.18	0.28	0.18
MgO	9.95	9.71	8.86	7.79	7.33
CaO	12.52	14.23	10.44	13.42	11.78
Na_2O	2.78	1.76	3.02	3.08	2.31
K_2O	0.24	0.08	0.15	0.34	0.10
P_2O_5	0.05	0.07	0.09	0.17	0.07
Sum	100.16	99.20	99.85	99.23	99.40
			Trace Elements (ppm)		
Ni	178	161	123	91	70
V	211	288	257	241	466
Rb	1	1	<1	6	3
Sr	348	597	145	118	155
Ba	17	48	21	—	0
Zr	273	99	38	66	146
Y	50	41	25	30	54
Nb	7	1	1	1	1

Abbreviations A = amphibolite, hornblende, clinozoisite, sphene, GA = garnet amphibolite, hornblende, almandine, clinozoisite, oligoclase, sphene

Table 3—Metamorphic rocks, Pujada Peninsula, eastern Mindanao; chemical composition.

assemblages and represent greenschist-facies rocks. These samples typically have strongly schistose textures. They probably represent the same rock types as the amphibolites, but they experienced lower T metamorphism. It is likely that they are the result of retrograde metamorphism of the amphibolite rather than a regional gradient in metamorphic intensity. This inference is based mainly on their distribution and the abundant evidence for tectonic transport and dislocation of all of the units. Low temperature-low pressure static metamorphism resulting from hydrothermal circulation formed vein-filling assemblages in some samples.

At this stage, it is not clear when or where the metamorphism took place. We have an assemblage of rocks representing depleted upper mantle and a crustal series of gabbro-basalt that could have come from the deep sea-floor (MORB-type crust) or backarc basin, and a young island arc (arc tholeiite-type crust). The metamorphic assemblages indicate that the rocks were sheared and recrystallized at high T and moderate P. The ultramafic rocks must have been close to their solidus temperature. If we assume that the ultramafic rocks are genetically related to the mafic schists, the simplest explanation is that the rocks were metamorphosed before parts of the crustal series had cooled below about 500°C and while the subjacent mantle was still at about 900 to 1000°C. This implies either that the metamorphism occurred close to the site of crustal generation and within 5 to 10 m.y. of the time of formation or that they have been brought up from great depths (e.g., 30 to 50 km [19–31 mi]) in the mantle. There is no indication of any high P mineral assemblages. Blueschist and eclogite minerals *have not* been identified in any of the microprobe analyses. If we postulate that the metamorphism formed while the crust/mantle series was still hot (and young), and if we consider the abundance of arc-derived clastic and igneous rocks, a possible explanation for the metamorphism may be constructed. Collision of arcs and backarcs, or arcs and "obducted" ocean crust, has been proposed to explain occurrences of similar rock series in other orogenic belts. The dynamo-thermal metamorphism of the Pujada series may have resulted from the thrusting of a slab of oceanic lithosphere into, or onto, an arc complex. The high temperature of this metamorphism suggests that young oceanic lithosphere was involved and an origin in a backarc basin would be consistent with these observations.

Sedimentary Rocks

North of the Pujada Peninsula, along the east coast of the Davao Gulf, there is an extensive terrane of weakly metamorphosed graywacke (Figs. 2–4). This graywacke belt trends to the southeast toward the Pujada Peninsula, and it extends nearly to the east coast of Mindanao east of Mati. The predominant exposures are thin-bedded volcaniclastic graywacke sandstones and shales. In the Hijo River area, calcarenite beds containing large foraminifera are interbedded with the graywackes. Ages of the fossils are Late Cretaceous, Paleocene, and Eocene. Planktonic forams from deep-water shales near the east coast also yield Eocene ages.

The Cretaceous to Miocene graywacke sandstones are composed of angular basaltic and andesitic volcanic rock fragments, ortho- and clino-pyroxene, plagioclase, amphibole, opaque minerals, minor quartz, and carbonate clasts. The volcanic rock fragments appear to have come from a hypersthene-clinopyroxene-bearing calc-alkaline (island arc) volcanic terrane. Microprobe data show that the clinopyroxene and hypersthene are typical of arc volcanic rocks. These graywackes are extremely hard and well indurated, and many are slightly metamorphosed. Epidote and chlorite are common, and several samples contain zeolites (laumontite identified by x-ray diffraction). The presence of laumontite indicates temperatures in excess of 200°C.

The Miocene–Pliocene sandstones exposed along the west coast of Pujada Peninsula (Fig. 4) are composed of angular fragments of andesitic volcanic rocks, hornblende, detrital chlorite and biotite, plagioclase, epidote, pyroxene, and ultramafic rocks. The source terranes for these rocks were an andesitic volcanic chain (Apo volcanics exposed across Davao Gulf?) and the Pujada ophiolite terrane. X-ray diffraction analyses of several samples yielded no low-grade metamorphic minerals.

Table 4

		Origin
A. Ultramafic Rocks		
1. Serpentinized harzburgite		Partly depleted mantle
olivine	Fo_{90-91}	
orthopyroxene	$En_{90}Fs_9Wo_1$ Al_2O_3 1.85%	
clinopyroxene	$En_{49\ 5}Fs_{3\ 4}Wo_{47\ 1}$ Al_2O_3 1.74%	
chromian spinel	Cr# = 0.365 – 0.430 Mg# = 0.622 – 0.625	
2. Serpentinite		
B. Metamorphic Rocks		
1. Metaperidotite		Metamorphosed peridotite (possibly from ultramafic cumulate rocks)
olivine	Fo_{90-91}	
orthopyroxene	$En_{90}Fs_{9-10}Wo_{0\ 5}$	
tremolitic-hornblende	Mg# = 0.90 – 0.94	
Mg-spinel	Mg# = 0.765 – 0.793	
2. Garnet amphibolite		
calcic amphibole		Metamorphosed mafic cumulate rocks
Mg-hastingsitic hornblende	Mg# = 0.68 – 0.73	
actinolitic-hornblende	Mg# = 0.56 – 0.70	
pargasitic-hornblende	Mg# = 0.71	
almandine garnet		
almandine	46–57 grossularite 19–27	
pyrope	13–27 andradite 1–4	
spessartine	1–5	
sphene		
ilmenite		
epidote		
plagioclase	$Ab_{29}An_{71}Or_{<1}$	
3. Amphibolite (several varieties)		
calcic amphibole		Metamorphosed (backarc basin) basalt
tschermakitic-hornblende	Mg# = 0.85 – 0.93	
tremolite	Mg# = 0.94	
tremolitic-hornblende	Mg# = 0.87 – 0.90	
actinolitic-hornblende	Mg# = 0.59	
clinozoisite		
zoisite		
plagioclase	$Ab_{55}An_{39}Or_6$	
Ti-magnetite		
sphene		
4. Marble		
calcite		Metamorphosed limestone
quartz		
5. Metagabbro		
plagioclase	$Ab_{3\ 3-4\ 1}An_{95\ 9-96\ 7}Or_{0-0\ 1}$	Metamorphosed mafic cumulate rocks (e.g., gabbroic-anorthosite)
magnesio-hornblende	Mg# = 0.84 – 0.86	

Mg# = Mg/(Mg + Fe)
Cr# = Cr/(Cr + Al)
Mineralogy based on electron probe micro-analyzer data.

Table 4—Mineralogic data, Pujada Peninsula ophiolite.

Similar volcaniclastic sediments are also observed on Pujada Island and the Guanguan Peninsula (Fig. 4). Along the eastern side of the Guanguan Peninsula, we also observed a thick volcanic conglomerate and beds (~ 2 m [7 ft] thick) of massive upper Oligocene to lower Miocene limestone. Based on the apparent interbedding with the limestones, the graywackes are also tentatively assigned an Oligocene/Miocene age.

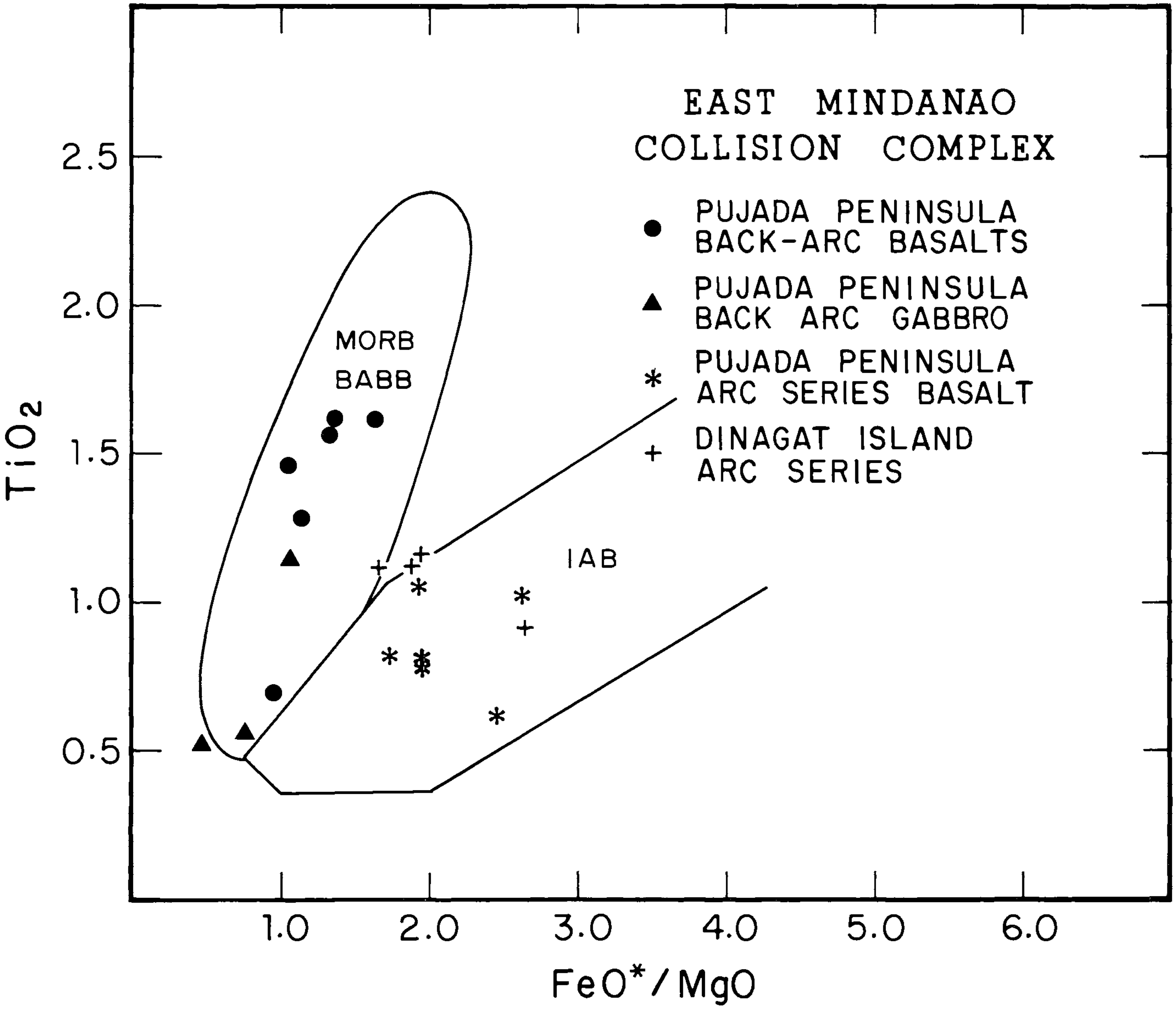

Figure 5—Plot of TiO_2 vs. FeO*/MgO (FeO* = all iron expressed as FeO). Fields for midocean ridge basalts (MORB), backarc basin basalts (BABB), and island arc tholeiites (IAB) serve as discriminants to determine origin of basaltic rocks of ophiolites.

The youngest rocks on the Pujada Peninsula are tuffaceous sandstones, shales, and conglomerates that are exposed along the west coast. The conglomerates clearly are in depositional contact with the underlying crystalline rocks and contain angular fragments up to 1 m (3 ft) in diameter of the underlying ultramafic, mafic, and amphibolitic rocks. The conglomerate units are highly resistant to weathering and produce high peaks and other elevated areas. The conglomerates are apparently lenses that represent large channel fillings. Stratigraphic sections were not measured, but the total thickness of the Neogene strata appears to be approximately 500 m (1,640 ft) based on measurements from our geologic maps. A mid-Miocene to Pliocene age is assigned to these strata, based on the identification of a few poorly preserved foraminifera (Billman, personal communication), their stratigraphic occurrence, and similarity to Mio-Pliocene strata exposed to the north. A schematic stratigraphic column for the Pujada Peninsula is presented in Figure 8.

Structural Geology

The regional structure in central and southern Pujada Peninsula is best interpreted as an imbricated sequence of northwest-trending ophiolite slabs. The internal structure of the ophiolite slabs is complex. Contacts between the slabs are high-angle faults. We interpret these as original thrust faults that have been modified by later normal faulting and/or strike-slip movement along the Philippine Fault.

In the central Pujada Peninsula, ultramafic rocks on the west structurally overlie chlorite schists on the east. The foliation in the schists strikes northwest and dips southwest, parallel to the fault contact. The orientation of the foliation adjacent to the fault contact indicates a west-

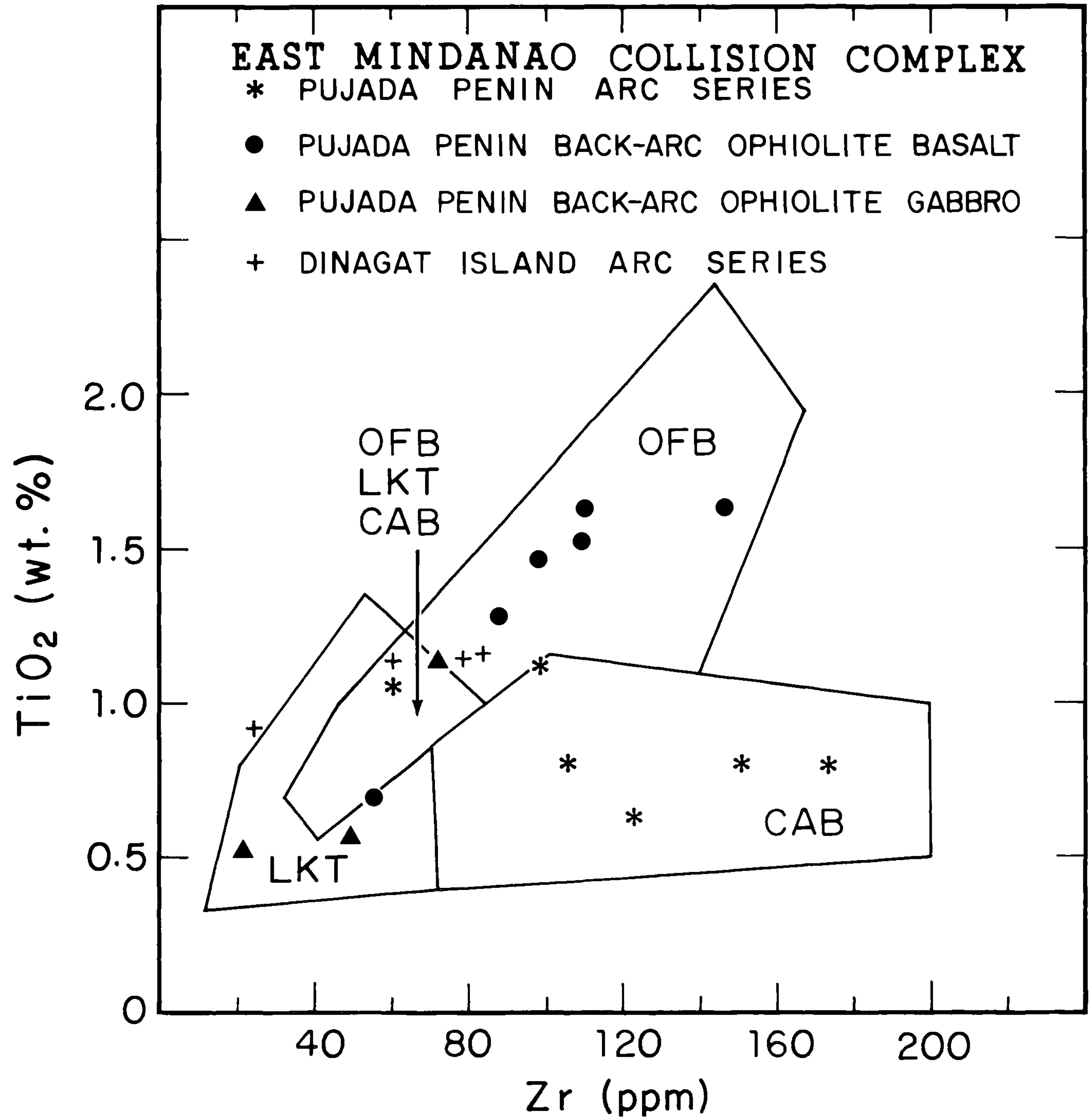

Figure 6—Plot of TiO_2 vs. Zr, after Pearce and Cann (1973), showing fields for ocean floor, calc-alkaline, and low-K basalts. The Pujada ophiolite lies in the ocean-floor field, as do backarc basin basalts. The east Mindanao arc volcanic series, Dinagat Island dikes, and most island arc series plot in the field of overlap or the calc-alkaline field, even though they are not truly calc-alkaline series rocks. This diagram does not discriminate between arc-tholeiitic and calc-alkaline basalts but separates most arc basalts from sea-floor or backarc material.

dipping fault that is most easily interpreted as a thrust.

The ultramafic rocks adjacent to the thrust fault are strongly sheared and serpentinized. Within the schist body is a 4 to 6 m (13-20 ft) thick marble lens similar to that observed to the north. In this area, the schists appear to be sheared and metamorphosed basalts. To the west of the thrust fault, the ultramafic rocks are approximately 50 to 100 m (164-328 ft) thick and are succeeded to the west by a 1 km (.6 mi) wide zone of gneissic amphibolite which has a foliation that strikes northwest and dips southwest. This amphibolite is succeeded to the west by 1 to 2 km (.6-1.2 mi) of ultramafic rocks and then another 500 m (1,640 ft) wide amphibolite zone. In the eastern Pujada Peninsula (Fig. 4), a well-defined shear zone at least 20 m (66 ft) thick

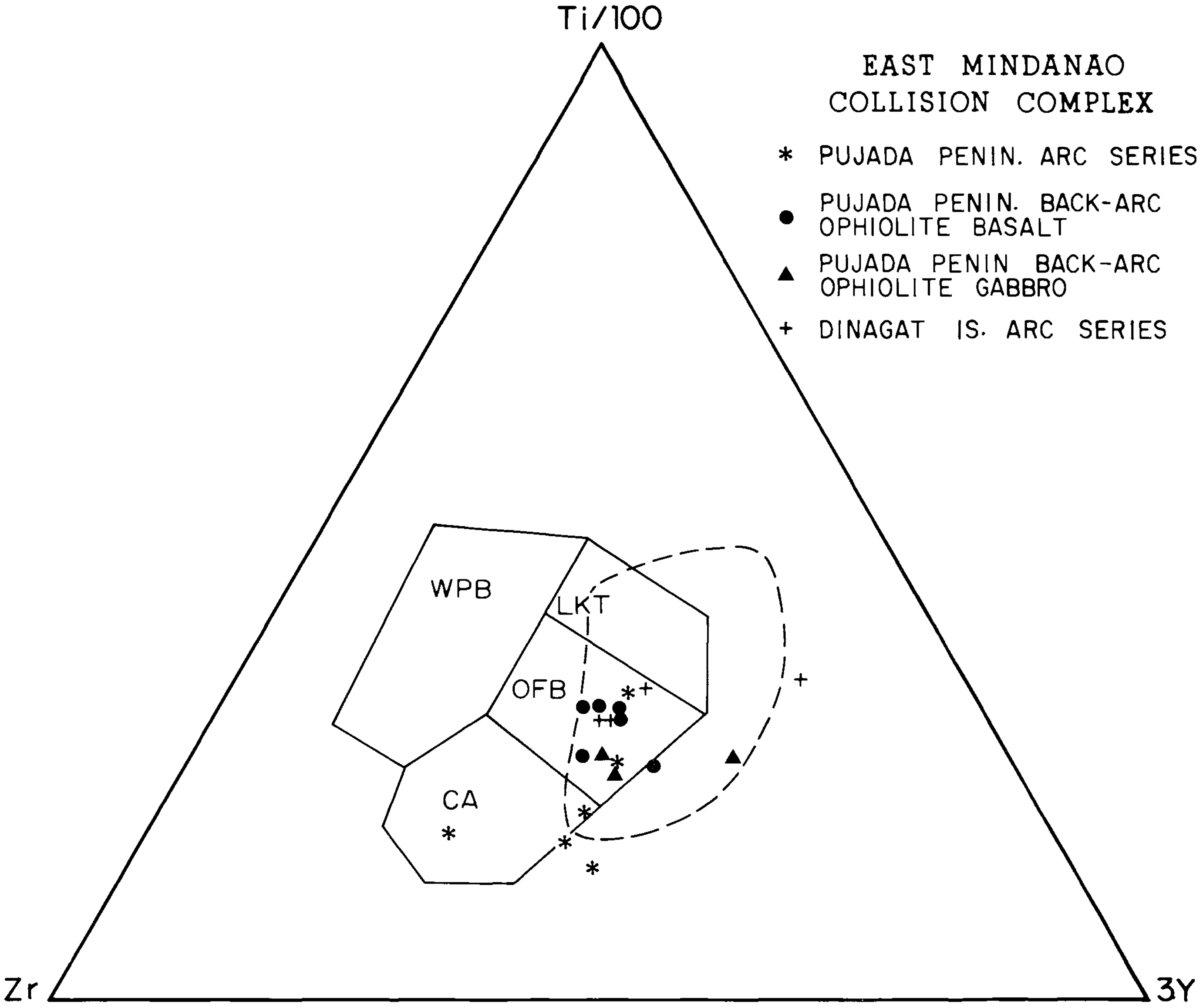

Figure 7—Discrimination diagram using Ti-Zr-Y, after Pearce and Cann (1973). The large field outlined by a dashed line is for island arc series rocks; it includes most of the eastern Mindanao arc series. The Pujada ophiolite samples lie largely in the ocean floor (= backarc) field. Dinagat Island dikes also lie in the island arc field.

is exposed along the beach. This shear zone trends northwest and dips 10 to 30° to the southwest. In this zone, various kinds of ultramafic rocks are intensely sheared into phacoids 1 to 2 m (3-7 ft) long. To the northwest of Magum, the ultramafic rocks are thrust over the red sedimentary and volcanic rocks. The fault can be easily located by the contrast between the steep topography formed by the ultramafic rocks and the low reddish topography formed by the sedimentary rocks.

The amphibole prisms in the greenschists exposed along the coast of the northwest Pujada Peninsula define a lineation approximately N 60° W at 35°. The strike of the foliation varies from approximately N 10° to 50° E with a dip of 40 to 70° NW. At Baon, the metamorphic rocks are phyllites with a lineation of approximately N 30° W at 55° that is produced by cleavage-bedding intersections.

The graywackes exposed north of Pujada Peninsula strike generally northwest and dip southwest, but there are structural complications in several areas, where folds of very short wavelengths were observed. Beds are often overturned to the northwest. To the east across the top of the coastal mountain range, the beds dip northeast, defining a major anticline.

In the northern Pujada Peninsula, near the contact with the ultramafic rocks, the Neogene strata are folded into a series of anticlines and synclines, with wavelengths of approximately 400 to 500 m (1,312-1,640 ft) and fold axes that trend northwest. Along the west coast the structure in these younger sediments is less clear, owing to poor exposures. The age of folding must be Pliocene or younger, because the entire Miocene to Pliocene sedimentary section appears to be deformed to the same degree.

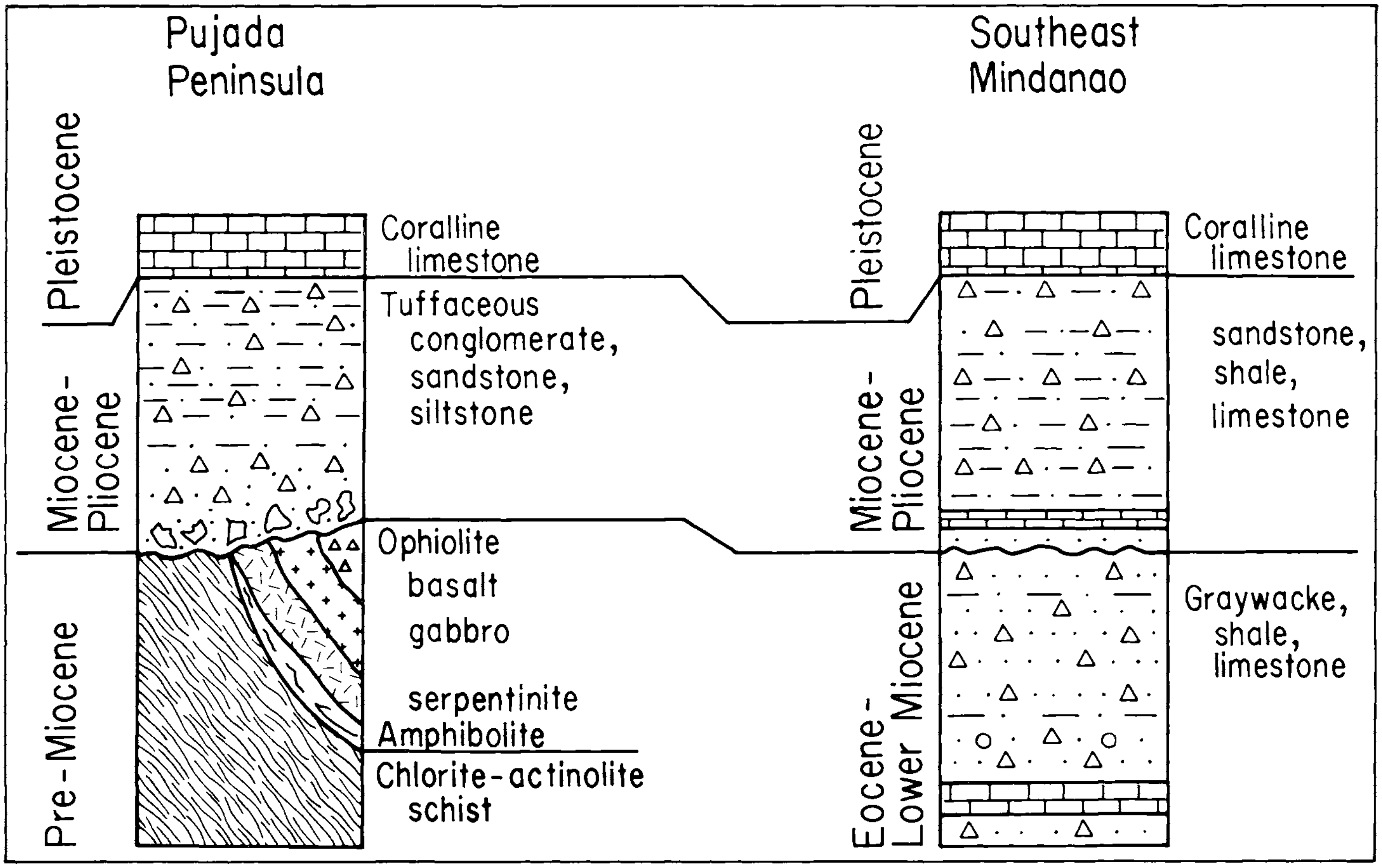

Figure 8—Schematic stratigraphic column for Pujada Peninsula.

GEOLOGY OF DINAGAT ISLAND TERRANE

Introduction

The Eastern Mindanao collision complex may be traced north toward Samar through Dinagat, Nonoc, Doot, and Hanigad Islands (Figs. 1, 2, 9). The northern end of Dinagat Island has exposures of upper mantle and lower crustal rocks (gabbro-diabase) that constitute part of a classic ophiolite assemblage. The southern part of Dinagat Island has garnet amphibolite and other metabasites which, by analogy with Pujada Peninsula rocks, probably were derived largely from cumulate mafic and ultramafic rocks from the basal crustal section of oceanic crust. Dunite, harzburgite, and clinopyroxene bearing harzburgite are present on Nonoc and Hanigad; the clinopyroxene-rich rocks have cumulate textures. Amphibolite (amphibole-oligoclase-epidote-sphene) is found on Hanigad Island. The Doot Island pillow basalts have abundant phenocrysts of olivine and clinopyroxene; they have heavy alteration by calcite but some aspects of their chemistry suggest an alkaline affinity, and they could be fragments of a sea mount. The sedimentary rocks on these islands are mainly fine-grained calcareous rocks that represent pelagic sediments deposited on the basaltic crust. A complete "stratigraphic section" from peridotite to basalt is not preserved, and we cannot be certain that all of the rocks are genetically related. However, the chemical and mineralogic characteristics of both the peridotite and the gabbro-diabase series indicate an arc tholeiitic assemblage, and we conclude that much of this ophiolite represents disrupted fragments of an island arc terrane. We give the informal name "Dinagat Island terrane" to the island group north of Surigao.

Northern Dinagat Island

The northern part of the island is formed largely of ultramafic rock and includes dunite, harzburgite, chromite-rich peridotite, and minor amounts of wehrlite, websterite, and clinopyroxenite. The peridotites show varied extent of serpentinization, and some samples are completely serpentinized. The peridotite mass has well-developed planar structures owing to preferred orientation of orthopyroxene and layers of chromite. The regional trend of the layering is northwesterly to nearly east-west; dip directions are variable with inclinations from 30° to vertical. Tightly folded chromite layers indicate intense ductile deformation. Some of the ultramafic rocks, especially those on the ridge crest of the island, have cumulate textures and planar structures that are the result of mineral stratification. We lack data to describe the orientation of this layering on a broad scale, but it appears to trend north-south and dips east at 50°. This suggests regional tilting down to the east, but we recognize that the igneous layering may not have been horizontal when formed.

The peridotite is cut by tabular intrusive bodies of

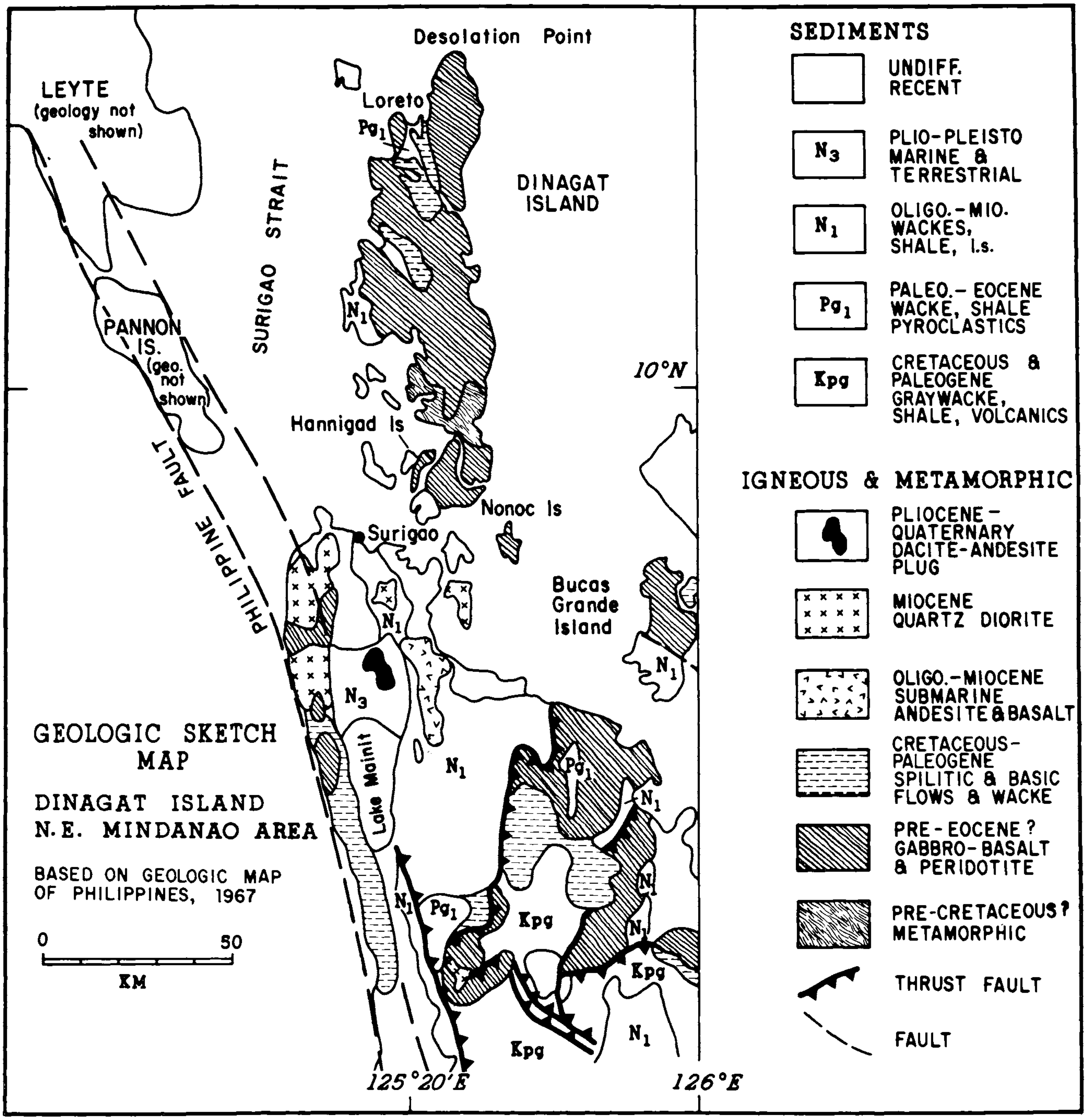

Figure 9—Geologic map of Dinagat Island–Surigao region showing major rock types and geologic structures. Based on Geologic Map of Philippines. (Copyright © 1967 The Philippine Bureau of Mines and Geosciences. Used with permission.)

diabase and microgabbo that are presumed to be feeder dikes to surface flows, although there are no known exposures of layered gabbro or basalt flows on the northern part of the island. Chromite is abundant in the peridotite, especially in the highly deformed dunite and harzburgite, and occurs as disseminated grains, in layers, pods, nodules, and orbicular structures.

Petrologic Summary

The peridotites are typical of ultramafic rocks found in other ophiolites (e.g., Hawkins and Evans, 1983). Harzburgite (olivine plus orthopyroxene) is the dominant rock type. Zones of dunite form layers nearly concordant with mineralogic layering in the harzburgite or form irregular discordant masses. The harzburgite has Mg-rich olivine ($Fo_{90-91.5}$) and enstatite (En_{89-90}); the dunite is even more Mg-rich (Fo_{93}). Chromite compositions in the harzburgite ($Cr/[Cr + Al] = .50$) are less enriched in Cr and Mg (less refractory) than in the dunite ($Cr/[Cr + Al] = .75 - .80$) and suggest that the dunite masses are the residue of more extensive melting than the harzburgite. The chromite compositions (Fig. 10) lie in the field

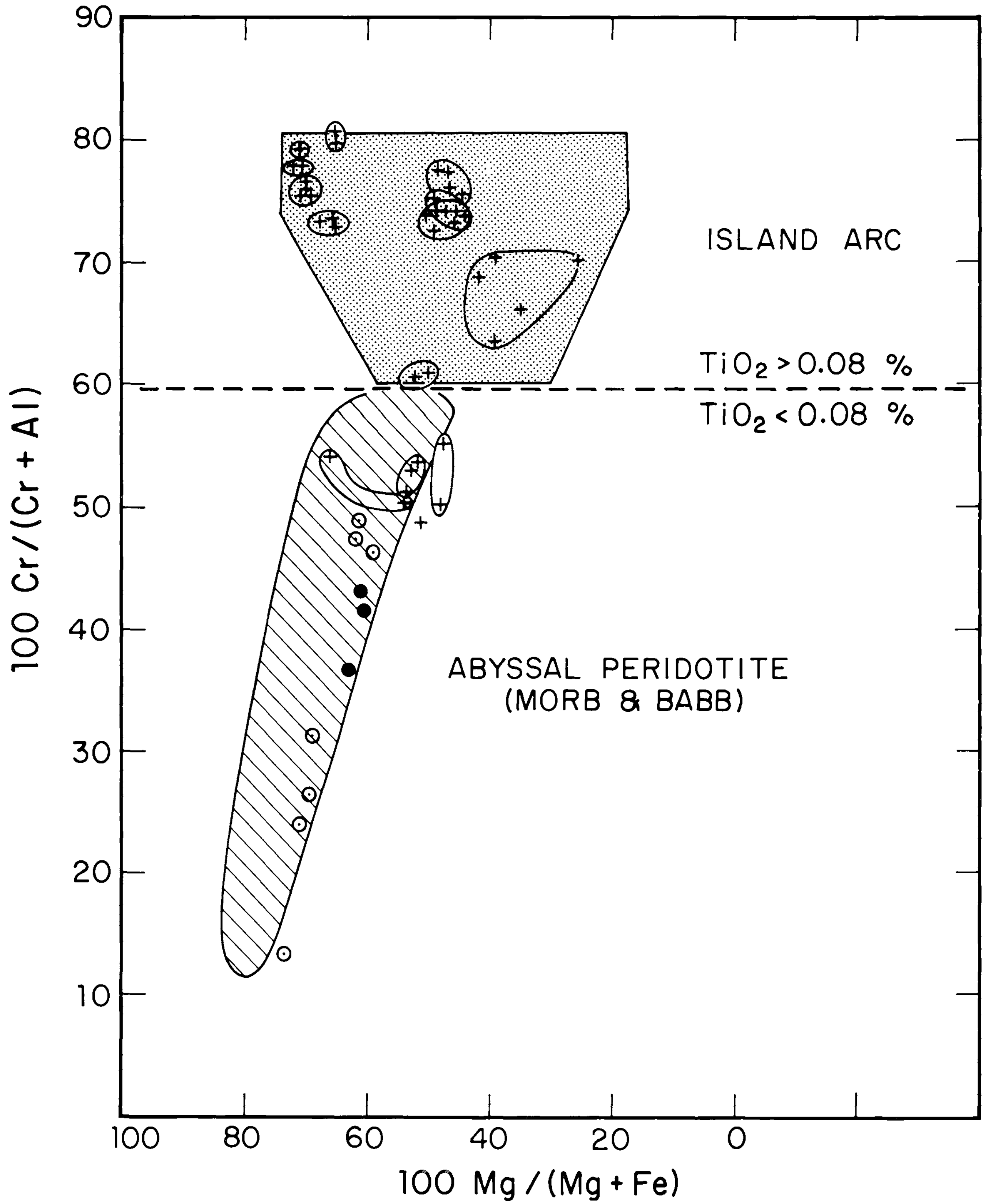

Figure 10—Chromite data for Mindanao peridotites (ratios are in atomic proportions). Fields are from Dick and Bullen (1984) and Hawkins and Evans (1983). Some Dinagat Island chromite plots close to the MORB-BABB field; these may be in pods of mantle less extensively melted than the main peridotite mass that has chromite typical of island arcs. Circled points are from Bukidnon Region, solid circles are from Pujada backarc ophiolite, and crosses are from Dinagat Island ophiolite. Data enclosed in circles are from the same sample.

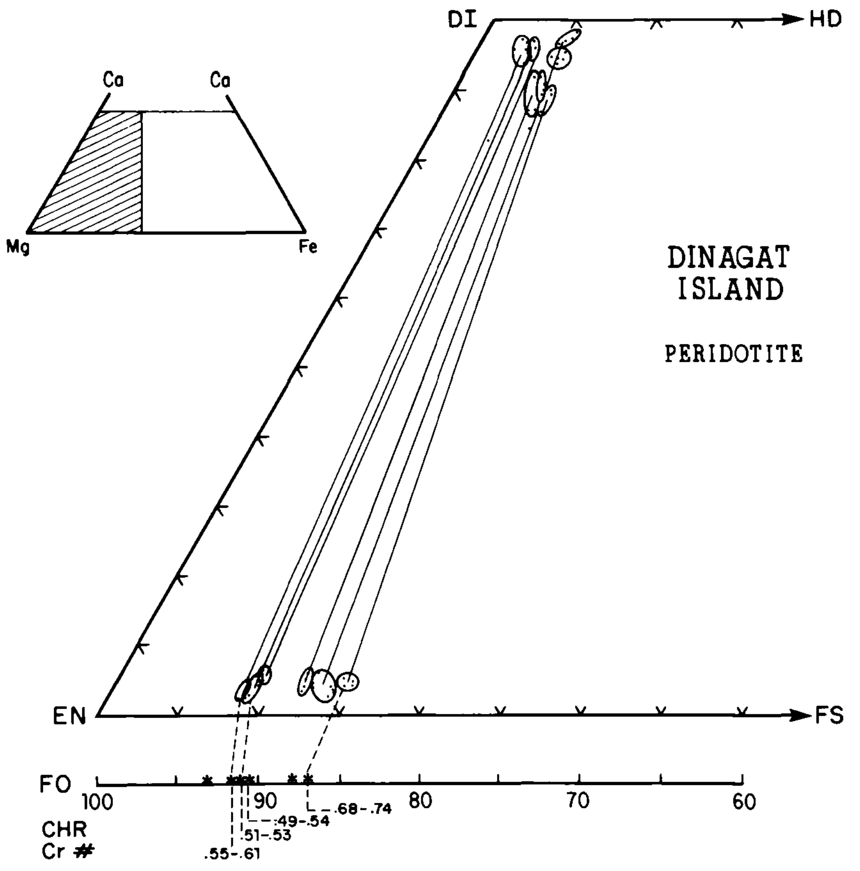

Figure 11—Microprobe data for olivine, chromite, and pyroxene from Dinagat Island peridotite. The lines link coexisting minerals. The high Mg# of silicates and high Cr# of spinels point to a depleted mantle composition and is consistent with an island arc setting. The samples with Fs 13–15 are from the cumulate textured section and represent lower crustal rocks. Inset shows location of this sketch relative to the pyroxene quadrilateral.

proposed for island arc settings (Hawkins and Evans, 1983; Evans, 1983; Dick and Bullen, 1984; Evans and Hawkins, in preparation). Some of the chromite data overlap the field proposed for ocean-floor rocks; these may be from pods of peridotite that were less extensively melted than the rocks with arc-like chromite data.

The internal structure of the peridotite is complex and resembles that of tectonized peridotite from other areas (e.g., Nicolas et al, 1971, 1980; Hawkins and Evans, 1983) The tight folding of mineralogic layering suggests high-temperature ductile deformation or "aesthenospheric flow" (Nicolas et al, 1971, 1980). The small-scale structures are typical of the transition we have studied in the Zambales Range, Luzon, at the boundary between depleted upper mantle peridotite and cumulate ultramafic rocks of the lower crustal section.

The cumulate-textured rocks of Dinagat include interlayered dunite, wehrlite (olivine plus clinopyroxene), and websterite (clinopyroxene plus orthopyroxene). In general, the cumulate-textured rocks have less Mg-rich minerals than the tectonized peridotite, e.g. Fo_{87} and En_{85} (Fig. 11). The sequence of crystallization appears to have been olivine and chromite-clinopyroxene-orthopyroxene. Plagioclase is not present but presumably formed last, and its absence may be due to crystal flotation. This crystallization sequence is typical of island arc magma series; it resembles the mineral sequence of the arc-series crust of the Zambales Range (Hawkins and Evans, 1983) and further supports the inference about tectonic setting based on the chromite data.

Mafic intrusive "dikes" cutting the peridotite give the best evidence for the nature of the tectonic setting in which the ophiolite formed. The diabase and microgabbro have island arc chemical characteristics (Table 5). For example, they have high silica, low Ti, Zr, Cr, and Ni for a given Mg content, normative hypersthene and quartz and distinctive element ratios. The presence of quartz and biotite in the micro-gabbro is also an important indicator of the similarity to arc material. We compare these to samples from island arc and other settings in Figures 5 through 7, using discriminant diagrams. They are similar to arc-tholeiitic series rocks from regions such as the Mariana arc and to samples from the Pujada Peninsula described in a separate section. The chemical data for these dikes are shown in Figure 12 where they are compared to "normal mid-ocean ridge basalt" and to island arc volcanic rocks. The Dinagat samples closely resemble basalts and basaltic andesites from the Mariana arc and are definitely different from N-MORB. This gives further support to the inferences made from mineralogy, bulk chemistry, and the

Table 5

Sample	DIN 5	DIN 3C	DIN 3B	DIN 10A	MIN 110	MIN 120
Type	D	D	G	D	B	BA
Mg#	.531	.488	.483	.405	.616	.490
			Weight Percent			
SiO_2	56.62	55.61	56.34	55.00	47.61	53.68
TiO_2	1.13	1.13	1.15	0.91	0.83	1.07
Al_2O_3	15.37	15.05	15.01	15.27	12.05	15.60
FeO*	8.93	10.39	10.32	12.15	10.44	10.20
MnO	0.21	0.21	0.21	0.21	0.22	0.24
MgO	5.67	5.55	5.40	4.63	9.39	5.50
CaO	7.60	5.84	7.14	8.68	16.73	7.77
Na_2O	3.17	4.92	3.52	2.60	1.34	4.84
K_2O	1.01	0.98	0.59	0.32	1.69	.20
P_2O_5	0.29	0.32	0.32	0.16	0.39	.17
Sum	100.00	100.00	100.00	99.93	100.69	99.27
			Trace Elements (ppm)			
Ni	58	67	81	288	129	221
V	383	370	354	411	337	279
Rb	16	13	8	2	1	26
Sr	381	281	236	290	96	673
Ba	421	309	197	79	11	450
Zr	60	79	83	24	67	49
Y	26	28	28	28	27	16
Nb	4	6	5	7	1	1

Dinagat Island samples DIN-5, 3C, 3B, 10A
Nonoc Island MIN-110
Doot Island MIN-120, pillow basalt
Abbreviations: D = diabasic textured andesite, G = micro-gabbro; B = basalt; BA = basaltic andesite, Mg# = Mg/(Mg + Fe).

Table 5—Dinagat, Nonoc, and Doot Islands, dikes and flows, chemical composition.

data for chromite in the peridotite intruded by the dikes.

Our data for crustal rocks on the southern end of the island are limited to the pillow basalts of Doot and Nonoc Islands, which are not distinctive enough to permit making a distinction between backarc basin crust or a deep sea-floor origin. We favor a backarc basin origin because of the close proximity to the Dinagat Island arc-series rocks.

GEOLOGY OF THE SURIGAO AREA

The northeastern tip of Mindanao, near Surigao, is cut by the northwesterly trending Philippine fault that has dismembered and laterally translated large blocks and slivers of the eastern Mindanao collision complex. Rock types in this area (Fig. 9) include metamorphosed mafic rocks, peridotite, and gabbro similar to those exposed on the Pujada Peninsula and on the small islands off the north shore of Mindanao. This apparent continuity of distinctive rock types helps to link parts of the eastern Mindanao collision complex and gives support to the contention that it is a geologic terrane. The ultramafic rocks include dunite, pyroxene-rich peridotite (harzburgite), and serpentinite. Extensive Fe- and Ni-rich laterite covers much of the area (Esguerra, 1960, 1967). Gabbro dikes (probable arc-related magmas) cut the peridotite, and the peridotite is overlain by Eocene basalt and limestone (Esguerra, 1967). These in turn are overlain by Miocene clastic rocks that include conglomerate, coarse sandstone, and carbonaceous shale.

Metamorphic rocks are various metamorphosed mafic and ultramafic rocks including garnet amphibolite. The descriptions of these rocks, plus amphibolite samples we have studied, lead us to infer that they are equivalent to the metamorphic mafic rocks of Pujada Peninsula and Hanigad Island. That is, they probably represent metamorphosed cumulate rocks, formed at the base of ocean crust, and metamorphosed while the crust was still near solidus temperatures (young crust). We see no reason to consider these to be part of a distinct metamorphic terrane.

Our samples do not include any examples of melange, but Hamilton (1979) speculates that the "chaotic conglomerates" of the area may be post-Eocene melange comprising ultramafic rocks, fossiliferous Eocene limestone, and fragments of metamorphic rock. This interpretation seems consistent with our observations, and we speculate that the melange development may be related to the (mid-Tertiary?) collision between the eastern and central belts. We also recognize the possibility that the chaotic disruption of rock units could be a consequence of lateral slip along major faults and not necessarily related to plate convergence.

GEOLOGY OF THE BUKIDNON COMPOSITE TERRANE

The northward extension of the Sangihe volcanic arc marks the western boundary of the Agusan-Davao Trough; it forms part of Mindanao's Central Cordillera (Ranneft et al, 1960) comprising volcanic rocks, deformed clastic rocks, and crystalline "basement" (Figs. 2, 3). Mapping in Bukidnon Province by the Philippine Bureau of Mines (Villamor and Marcos, 1981) has delineated areas of metamorphosed igneous and sedimentary rocks; serpentinized peridotite; and mappable units of highly diverse rock types such as graywacke, siltstone, shale, volcanic rocks, pyroclastic rocks, and marble (probable melange) and deformed nearly monolithologic belts of sedimentary and volcanic rock (Fig. 13). The key to the original tectonic setting of these rocks is in their mineralogy and chemistry (Table 6) and is summarized in Table 7. We conclude that they were derived from an island arc setting and represent imbricated slabs and fragments of depleted mantle peridotite, island arc volcanic-plutonic rocks and clastic rocks derived from them, and rocks metamorphosed under low-temperature-moderately high-pressure conditions. The latter include derivatives of terrigenous clastic rocks and arc or sea-floor rocks; metamorphic conditions were transitional between lower greenschist and blueschist facies. These rocks represent several subterranes that have an earlier history of tectonic assembly. Plio-Pleistocene and Holocene basaltic-andesite from the modern volcanic arc caps the collision complex.

The internal structure of the rocks of this belt of deformed rocks (here informally called the Bukidnon collision complex) is not well known. The map pattern and attitudes of rock types suggest that the belt is formed of several imbricated layers or thrust slices that have been folded along northwesterly trending fold axes. Erosion has breached the folded thrust planes, exposing deeper layers in erosional windows. An alternative explanation may be that several large (tens of kilometers) elongated blocks of strongly folded rocks have been juxtaposed on northwesterly trending lateral-slip faults. We favor the first explanation in view of the collision history of the region of the Sangihe arc, but more mapping is needed before this can be proved.

Metamorphic Rocks

The rocks considered to be the oldest unit in the Bukidnon collision complex are schists, phyllites, and slates (Villamor and Marcos, 1981), but neither the age of metamorphism nor the age of the protolith are known. The metamorphic rocks include slate, phyllite, sericite schist, chlorite schist, and muscovite schist (Villamor and Marcos, 1981). In this report we give mineral data for a quartz-two mica schist collected by Villamor that has characteristics of metamorphic conditions transitional from lower greenschist to blueschist facies. The schist has a well-developed foliation formed by planar alignment of the mica and flattened lenticles of polycrystalline, mosaic-textured quartz grains. A second schistosity has developed along axial planes of flattened folds. The main minerals are quartz, colorless and green mica, and chlorite. Other minerals include porphyroblasts of albite, spessartine garnet, clinozoisite, Ti-magnetite, and graphite (?) (<3 modal percent of each). Apatite, tourmaline, and zircon are trace constituents (<1 modal percent of each). There are two micas (colorless and light green) that are phengite or solid solution series mixtures of muscovite and celadonite.

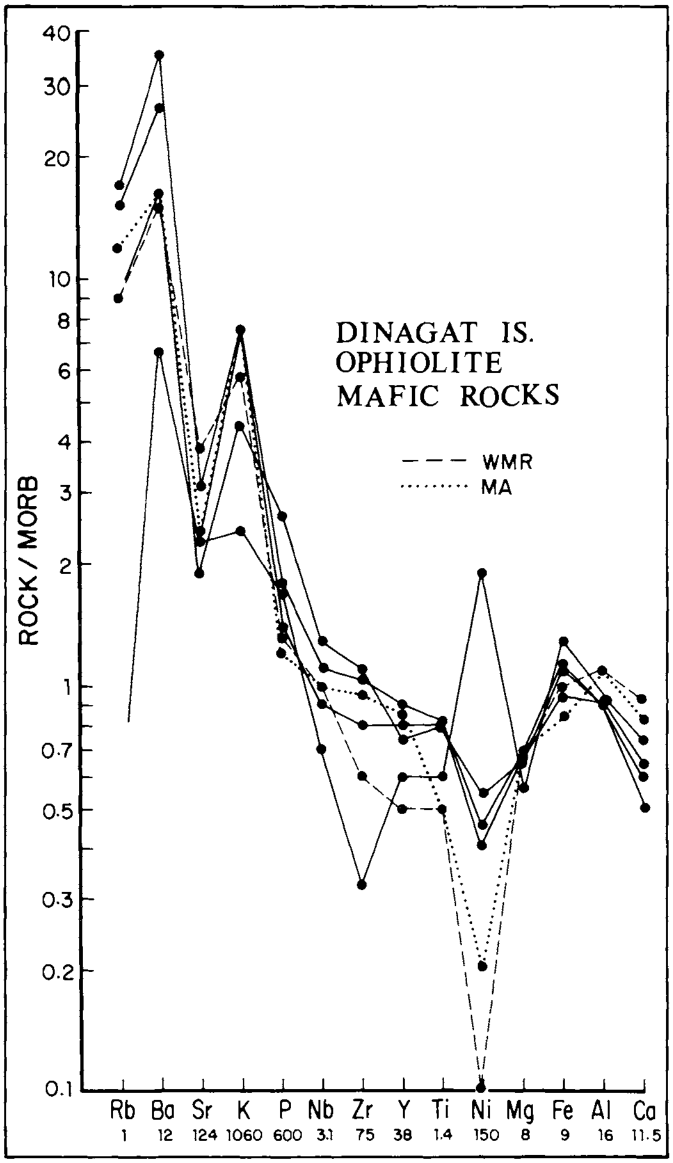

Figure 12—Element abundances in Dinagat Island basaltic andesite and micro-gabbro dikes normalized to element abundances in N-MORB (shown on abscissa). MORB-like samples should plot as straight line at 1 on ordinate. Data for Mariana Arc and West Mariana Ridge basaltic andesites closely parallel the Dinagat Island pattern and argue for an island arc origin of the Dinagat ophiolite.

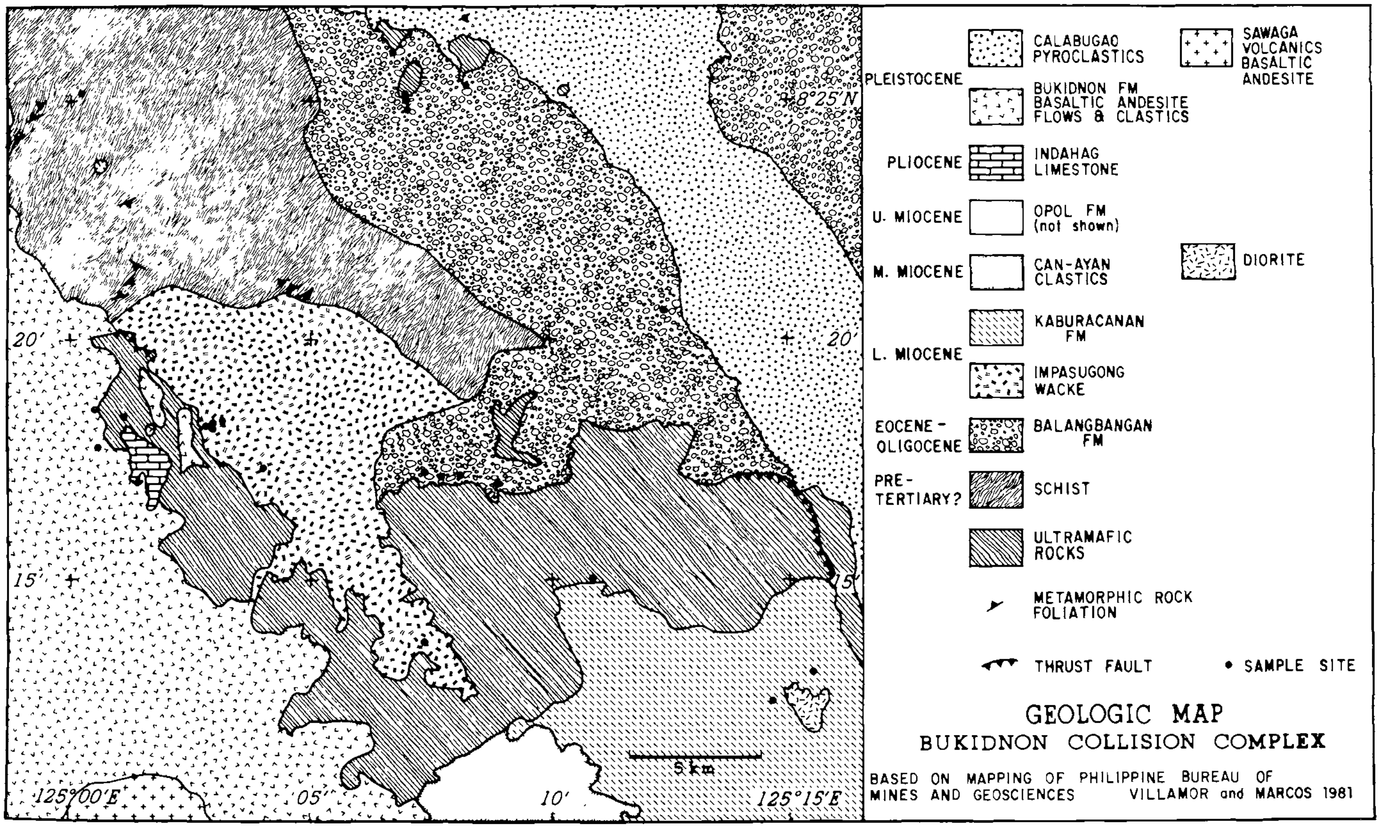

Figure 13—Geologic map of part of Bukidnon Province showing rocks of the central Mindanao collision complex. Ages shown are tentative and are based on comparisons with rocks from nearby areas. (After Villamor and Marcos, 1981. Copyright © 1981 The Philippine Bureau of Mines and Geosciences. Used with permission.)

Table 6

	1	2	3	4	5	6	7
SiO_2	48.59	24.99	36.14	36.51	45.20	55.87	—
TiO_2	0	0.08	0.24	0.05	0.44	0.07	0.05
Al_2O_3	27.34	21.49	20.57	20.63	10.57	2.13	46.38
FeO*	4.47	22.68	9.52	3.95	14.49	6.12	13.69
MnO	0.04	1.09	27.92	12.15	0.47	0.17	0.17
MgO	2.74	16.86	0.53	0.32	12.70	34.26	17.65
CaO	0.01	0	5.55	21.38	12.13	0.51	0.02
Na_2O	0.66	0	0	0	1.30	0	0
K_2O	9.91	0.02	0	0	0.36	0	0
Cr_2O_3	0	0	0.02	0	0.04	0.28	21.66
Sum	93.98	87.20	100.48	95.00	97.68	99.39	99.62

1. Phengite, quartz mica schist, basal spacing $d_{(001)}$ 9 9611 Å, optic angle, 2vα 0-5°
2. Chlorite; quartz mica schist
3. Garnet; quartz mica schist; spessartine 63.3, pyrope 2 1, almandine 18 7, andradite 4 0, grossularite 11 9
4. Piedmontite; quartzite clast in melange unit
5. Actinolitic-hornblende; greenschist clast in melange unit
   (amphibole, oligoclase, epidote, sphene, magnetite)
6. Orthopyroxene, En_{90}, with Fo_{90-91} in serpentinized harzburgite, "backarc" mantle
7. Chromian spinel, serpentinized harzburgite, "backarc" mantle with opx #6 and Fo_{90-91}

Table 6—Microprobe analyses, key minerals in Bukidnon terrane collision complex.

Table 7

		Origin
A. Metamorphic Rocks		
1. Quartz-mica schist		Terrigenous quartzofeldspathic sediment
quartz	epidote	moderately high P fluid, low T
phengite	Ti-magnetite	(greenschist to blueschist)
Mg-chlorite	spessartine garnet	
Na-plagioclase	tourmaline	
2. Amphibole schist		
actinolitic-hornblende	chlorite	Intermediate composition
Na-plagioclase	sphene	volcanic or volcaniclastic rock
epidote		moderate P, low T
phengite		(greenschist)
1 and 2 in schist unit		
3. Piedmontite-rich laminated siliceous marble		Manganiferous pelagic sediment
quartz calcite piedmontite		moderate P, low T
4. Calc-silicate marble		
calcite	epidote	Marly limestone
grossularite garnet	quartz	moderate P, moderate T
amphibole		(lower amphibolite)
5. Amphibolite		
actinolitic hornblende	Fe-Ti oxide	Basalt
plagioclase	$An_{25-27}Ab_{71-74}Or_1$	moderate P, moderate T
epidote		(higher greenschist)
sphene		
3, 4, and 5 in "melange" unit (Balangbangan Fm.)		
B. Ultramafic Rocks		
1. Serpentinized harzburgite		
olivine	Fo_{90-91}	Depleted upper mantle
orthopyroxene	$En_{90}Fs_9Wo_1 - En_{89}Fs_{10}Wo_1$	
clinopyroxene	$En_{50}Fs_3Wo_{47} - En_{47}Fs_5Wo_{48}$	
chromite	$Cr/(Cr + Al)$ 0.13 − 0.31	
	Fe''/Mg 0.36 − 0.45	
2. Serpentinite		
C. Volcanic Rocks		
1. Basaltic andesite (Impasugang Fm.)		Immature island arc
plagioclase	$(An_{49}Ab_{50}Or_1)$	
clinopyroxene	$En_{42-46}Fs_{7-15}Wo_{41-47}$	
2. Andesite (Balangbangan Fm.)		
plagioclase	$An_{1-2}Ab_{98-99}Or_{0.5}$	
clinopyroxene	$En_{43-45}Fs_{12-14}Wo_{42-44}$	
amphibole, magnesio-hastingsite		
epidote		
Fe-Ti oxide		
3. Basaltic andesite (Calabagao Pyroclastics)		
plagioclase	$An_{61-73}Ab_{37-27}Or_1$	
clinopyroxene	$En_{43-45}Fs_{13-14}Wo_{42}$	
Fe-Ti oxide		
D. Graywacke (Balangbangan and Impasugang Fms.)		
plagioclase	amphibole	Clastic rocks from immature island arc
clinopyroxene	orthopyroxene	
chlorite	Fe-Ti oxides	
quartz	andesite clasts	

Table 7—Mineral assemblages and origin of rock types, Bukidnon collision complex, Mindanao.

This is confirmed by microprobe, x-ray, and optical data (Table 6). Al-rich Mg-chlorite is also present interspersed in the mica layers (Table 6). Pumpellyite has been tentatively identified by optical and x-ray diffraction techniques as a trace mineral. The presence of spessartine garnet and phengite plus chlorite are important indicators of the metamorphic environment. Phengite is characterized by low Al^{IV}, high Si, and contains several wt% Mg and Fe oxides (Ernst, 1963). Phengite could form as the result of "retrograde" metamorphism of a pelitic assemblage (e.g., quartz + muscovite + biotite + K-feldspar + H_2O) under conditions of high fluid pressure at low temperature (Ernst, 1963; Velde, 1965). Pumpellyite would be compatible with this assemblage if mafic material were metamorphosed under similar conditions. The protolith of the schists must have been an Fe-Mg enriched pelitic sediment with a minor amount of Mn. Although the spessartine garnet is distinctive, the amount of Mn in the rock is low (<1%); the abundance of Al and K (in the phengite) and the moderate amount of SiO_2 (about 70%) make it unlikely that the parent was a Mn chert, and a (mature) terrigenous sediment seems probable.

In addition to the quartz mica schist, there are areas formed of actinolitic-hornblende, epidote, oligoclase, sphene, and chlorite schist that represent greenschist-facies metamorphism of a basaltic protolith. We do not consider this metamorphic unit to be a distinctive "metamorphic terrane" because it is compatible with the type of rock series that would have formed at moderate depth in a forearc accretionary complex and thus is genetically related to the melange unit and associated clastic and ultramafic rocks.

The lack of blue amphibole or other diagnostic blueschist-facies minerals provides an upper limit for pressure of about 4 Kb and the albite-epidote-phengite assemblage provides a temperature limit. We estimate that the physical conditions were about 250 to 300°C with P fluid = P Total = 0.3 GPa (3 Kb). The forearc of a subduction zone environment seems a likely setting for these conditions.

Ultramafic Rocks

The map pattern suggests that there are at least two slabs of ultramafic rock interleaved with the schist and "melange" units. The ultramafic rock is heavily serpentinized (70% or more), but relict grains of olivine, orthopyroxene, clinopyroxene, and chromite help to establish the composition of the parent rock (Tables 6, 7). The high Mg content of the olivine (Fo_{90-91}) and enstatite ($En_{90}Fs_9Wo_1$) indicate that the original peridotite had been partly depleted of basaltic components by previous melting episodes. The ratio Cr/(Cr + Al) of the chromite (Fig. 10) appears to be useful in estimating the extent of melting and in identifying the tectonic environment of the melting (e.g., Hawkins and Evans, 1983; Evans, 1983; Dick and Bullen, 1984). The data for chromite from the Bukidnon region suggest either a backarc basin or deep sea-floor (midocean ridge) origin. In view of the associated rock types, we favor the idea of a backarc basin origin and propose that in the collision process backarc lithosphere was imbricated with arc forearc material.

Melange Unit

A heterogeneous unit comprising phyllite, slate, mylonite, metagraywacke, metavolcanic rocks, metasediments, quartzite, and ferruginous cherts (Balangbangan Formation, Villamor and Marcos, 1981) may represent a melange. The beds strike northwesterly and dip moderately to steeply; in some cases dips are to the southwest and in other areas to the northeast. As discussed below, this unit must represent a pre-Eocene subduction event if it is indeed a melange in the classical sense.

Sedimentary Rocks

An Eocene limestone overlies the highly deformed rocks of the melange unit to the south of the Bukidnon area (Philippines Bureau of Mines, 1967). This puts an important age constraint on the timing of amalgamation of basement subterranes of the Central Mindanao belt (Fig. 8).

There are several mapped units reported to range in age from Oligocene to early Miocene (Villamor and Marcos, 1981) that are deformed but retain a coherence of rock types. The Impasugong Wacke (Oligocene–early Miocene) is graywacke interbedded with pyroclastic and volcanic layers. Microprobe analyses of clinopyroxene in pebbles in these volcanic clastic rocks indicate that they were derived from an island arc source. The Kaburacanan Formation (early Miocene) comprises red sediments (weathered ultramafic debris?), graywacke, chert, siltstone, and silty shale that have been weakly metamorphosed. The graywacke contains pebbles of basaltic andesite; the clinopyroxene indicates an island arc source like that for the Impasugong Wacke. The structural relations between these graywacke-volcanic units and the Eocene limestone are not known but is an important problem in unraveling the collision history.

Middle to upper (?) Miocene conglomerate, sandstone agglomerate, tuffaceous sandstone, and tuff (Opol Formation) show only moderate deformation and probably postdate the main tectonism that accompanied the collision of the central and east Mindanao arcs. The presence of tuffaceous beds suggests that volcanism was still active during deposition, but some of this may be reworked older deposits.

Coralline limestone (Indahag limestone, considered to be Pliocene age) caps the ultramafic rocks and is exposed in erosional windows in the Pliocene and younger volcanic rocks.

Intrusive Rocks

The Kaburacanan Formation is intruded by a dioritic stock (quartz, plagioclase, hornblende) that has caused some local contact metamorphism and pyrite mineralization. Although the timing of the intrusion is not known, this pluton is further support for the island arc setting for accumulation of the graywacke series.

Discussion

The timing of the collision that caused imbrication of the basement subterranes in central Mindanao is not accurately known, but it must predate the Eocene coralline limestone exposed to the south. West-directed subduction under the newly amalgamated arc probably began in the

Eocene and continued at least until the late Oligocene (?) collision with the east Mindanao arc. Clastic rocks of the mid-Miocene Canayan Formation and mid-to-upper Miocene Opol Formation (overlap assemblage) show only minor deformation (Villamor and Marcos, 1981), indicating that minor crustal shortening probably continued for some time after the two arcs had been joined.

Basaltic andesitic volcanism of the modern Mindanao volcanic arc began in the late Pliocene and blanketed the coralline limestone and older rocks. The location of volcanic centers with respect to the Philippine Trench and the deep-level seismicity suggests that they are not a response to Philippine Trench subduction but, if they are related directly to subduction, may reflect either the remnants of west-directed subduction under the central Mindanao arc or young east-directed subduction at the Cotobato Trench.

AGUSAN-DAVAO TROUGH

The Agusan-Davao Trough (Figs. 2, 3) occupies the area between the central and eastern Mindanao arcs. Although its early history probably began as the forearc basin of the central Mindanao arc (Moore and Silver, 1983), it has been a "successor" or "overlap" basin since the collision between the two arcs.

The Agusan-Davao Trough contains approximately 6 km (4 mi) of Cretaceous to Recent sedimentary rocks (Ranneft et al, 1960). A thick sequence of massive limestones interbedded with coarse graywacke sandstones is exposed along the southeast flank of the basin. Samples of the limestone have yielded Upper Cretaceous to Eocene larger foraminifera (Adams, 1982, personal communication). The graywackes contain abundant volcanic detritus.

A massive reefal limestone of Eocene age overlies the deformed basement complex along the east flank of the central Mindanao arc (Ranneft et al, 1960). This limestone is approximately 650 m (2,133 ft) thick and is overlain by interbedded upper Oligocene calcarenites and volcaniclastic sandstones and siltstones.

In the interior of the Agusan-Davao Trough, lower Miocene to Recent clastic sedimentary rocks are exposed. They consist of interbedded coarse conglomerates, arkosic sandstones, tuffaceous siltstones, coal beds, and shales. Fossil mollusks, ostracods, and benthic foraminifera are common in the section and indicate a shallow marine environment of deposition. The conglomerates contain abundant clasts of ultramafic rocks, diorite, chert, and volcanic rocks, all of which were probably derived from exposures of the basement complex along the flanks of the basement.

The Eocene limestone exposed along the west flank of the basin can be traced into the subsurface on proprietary seismic reflection lines acquired for AMOCO International Oil Company as a high-amplitude reflector that dips to the east (Fig. 3). It can be followed to the eastern edge of the basin where it attains a depth of 3 seconds (approximately 4 km [2.5 mi]). Younger strata onlap the high-amplitude reflector toward the west. The younger strata are not strongly deformed except along the east flank of the basin where they are truncated by the Philippine Fault Zone. Structural mapping in the Agusan-Davao Trough also indicates that the Miocene to Recent strata are only broadly folded, except along the Philippine Fault Zone (Teves et al, 1951; Casasola, 1956; Philippines Bureau of Mines, 1977; Castillo, 1980).

Discussion

The tectonic history of the Mindanao collision belt can be inferred from the sedimentary rocks of the Agusan-Davao Trough. The strata exposed on the east flank of the basin record a different history than those exposed on the west flank of the basin. The strata overlying the east Mindanao arc terrane show that volcanism was active from at least the Late Cretaceous through the late Oligocene, at which time volcanism apparently ceased. Strata along the western margin of the basin overlie a pre-Eocene volcanic terrane and indicate a period of volcanic quiescence during the Eocene and early Oligocene. Volcanism began again along the central Mindanao arc in the late Oligocene and continued into the Recent.

The lower Miocene and younger strata exposed in the Trough and along its flanks are sedimentologically very similar throughout the region, indicating that the east and central Mindanao arc terranes were welded together by the end of the Oligocene. Following the collision, the Agusan-Davao Trough became a successor, or overlap, basin. Deposition took place in shallow water and was dominated by the influx of coarse terrigenous detritus from the basin's flanks. The uplift and erosion of the arc basement complexes is indicated by the coarse conglomerates that contain clasts of basement rocks.

SUMMARY

The Philippine Archipelago represents an evolving microcontinent formed by the amalgamation of many recognizable geologic terranes that include fragments of continental crust; island arc systems; oceanic crust from backarc basins, and, possibly, deep sea floor; and large tracts of depleted mantle peridotite. This tectonic collage has been overprinted by volcanic-plutonic arcs and by successor sedimentary basins. The recognition that the Philippine Islands comprise diverse rock assemblages or terranes, formed at different geographic locations, which have undergone rotation as well as great lateral transport, is important to understanding the geologic history of the Philippines and gives insights to the evolution of other geologically complex regions such as western North America.

The geologic complexity of the Philippines has long been recognized, and early workers (e.g., Gervasio, 1971) applied the geosynclinal concept in synthesizing the geologic history. The importance of "peridotite arcs" and plutonic-volcanic arcs was emphasized by Santos-Ynigo (1966), who also drew attention to the importance of the large transcurrent faults cutting the archipelago. Hamilton (1979) interpreted the islands as "a jumble of the subduction complexes, magmatic rocks and volcaniclastic sediments of different island-arc systems." These observations, plus the application of detailed studies on geochemistry, geochronology, and paleomagnetism, make it possible to fingerprint crystalline rock terranes and to interpret their tectonic setting at the time of their origin.

Our objective in this report has been to focus on a part of the complex region in central and eastern Mindanao where we recognize the accretion of two composite terranes comprising ophiolite, subduction complexes, and island arc material. Each of these terranes is a composite of mantle and crustal rocks; the crustal rocks include forearc, arc, and backarc basin material. We use the general term collision complex for each belt because of the evidence for extreme internal deformation that has juxtaposed a variety of rock types. Each collision complex may comprise more than one terrane or may be a single disrupted terrane that has been extensively deformed before or during the accretion event. We see evidence, in the central Mindanao belt, for a pre-Eocene collision that was followed by subsidence and deposition of limestone and then by generation of an island arc–backarc system prior to its amalgamation with the eastern Mindanao belt. Amalgamation of the two collision complexes probably was completed by the end of Oligocene time, and the Agusan–Davao Trough (successor basin) covers the suture zone. The collision between the Sulawesi and Halmahera arcs represents a southward extension of the tectonic accretion event we recognize on Mindanao.

In addition to the deposition of sediments in the Agusan–Davao successor basin, the central Mindanao part of the accretionary belt has been overprinted by a modern volcanic-plutonic arc. This volcanism may reflect east-directed subduction in the Cotabato Trench or be a remnant of west-directed subduction under the central Mindanao arc that formed in mid-Tertiary time. The Philippine Trench, which lies east of Mindanao, represents a major change in subduction polarity and probably postdates the mid-Tertiary collision between the east and central Mindanao belts. It seems doubtful that volcanism directly related to the Philippine Trench subduction can yet be identified, but areas of hydrothermal activity in the eastern cordillera may be precursors of a new volcanic arc. Some of these are centered on volcanic cones and intrusive plugs of presumed Miocene age.

The accretionary belt is being disrupted by faulting while at the same time it is being overprinted and thickened by the volcanic-plutonic arc. Sinistral strike-slip motion on the Philippine Fault system is nearly parallel to the east Mindanao belt and, in time, may displace and rotate segments of it along the margin of the West Philippine Sea.

The complex geologic history that we recognize in the two terranes of central and east Mindanao gives a microcosmic view of the evolution of the Philippine Archipelago, which itself constitutes a tectonic collage of terranes potentially available for accretion to the Asian continent. In a sense, the Philippines are an intermediate evolutionary stage between immature intraoceanic island arcs, such as the Mariana arc, and the end result of terrane amalgamation and accretion that forms the complex tectonic collages such as western North America.

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