CRUSTAL SETTING OF MAFIC AND ULTRAMAFIC ROCKS AND ASSOCIATED ORE DEPOSITS OF THE CARIBBEAN REGION

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Contents

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Introduction

With the advent of modern concepts of plate tectonics during the 1960's and 1970's, the geological community became increasingly aware that in many parts of the world huge blocks of exposed rocks probably represent segments of oceanic crust and upper mantle that have reached the surface as a result of tectonic processes. The distribution of such rocks, their associated ore deposits, and geophysical expression in the circum-Caribbean region are reviewed here. These rocks are thought to have formed primarily at mid-ocean ridges, sites of crustal divergence, and to have been tectonically emplaced and uplifted at sites of crustal convergence (Dewey and Bird, 1971, Coleman and Irwin, 1974, Coleman 1977). Some of these rocks, however, may have formed over plumes (Morgan, 1971), "leaky" transform faults (Thompson and Melson, 1972, Fox and others, 1976)), back-arc spreading centers (Karig, 1971), or other sites of oceanic mafic volcanism (Donnelly, 1974, 1975). These "oceanic" rocks tend to contain relatively high contents of magnesium and iron (mafic and ultramafic rocks) as compared with rocks comprising average "continental" crust, which are relatively high in silicon and aluminum (sialic rocks). Some such assemblages of oceanic rocks have been termed ophiolites (fig. 1) and, quoting Coleman and Irwin, (1974) and Geotimes (1972):

> "Ophiolite, as used by those at the GSA Penrose Conference on ophiolites, refers to a distinctive assemblage of mafic to ultramafic rocks. It should not be used as a rock name or as a lithologic unit in mapping. In a completely developed ophiolite, the rock types occur in the following sequence, starting from the bottom and working up:
>
> "Ultramafic complex, consisting of variable proportions of harzburgite, lherzolite [varieties of peridotite (fig. 2)] and dunite, usually with a metamorphic tectonic [tectonite] fabric (more or less serpentinized);
>
> "Gabbroic complex, ordinarily with cumulus textures commonly containing peridotites and pyroxenites and usually less deformed than the ultramafic complex;
>
> "Mafic sheeted dike complex;
>
> "Mafic volcanic complex, commonly pillowed.
>
> "Associated rock types include (1) an overlying sedimentary section typically including ribbon cherts, thin shale interbeds, and minor limestones; (2) podiform bodies

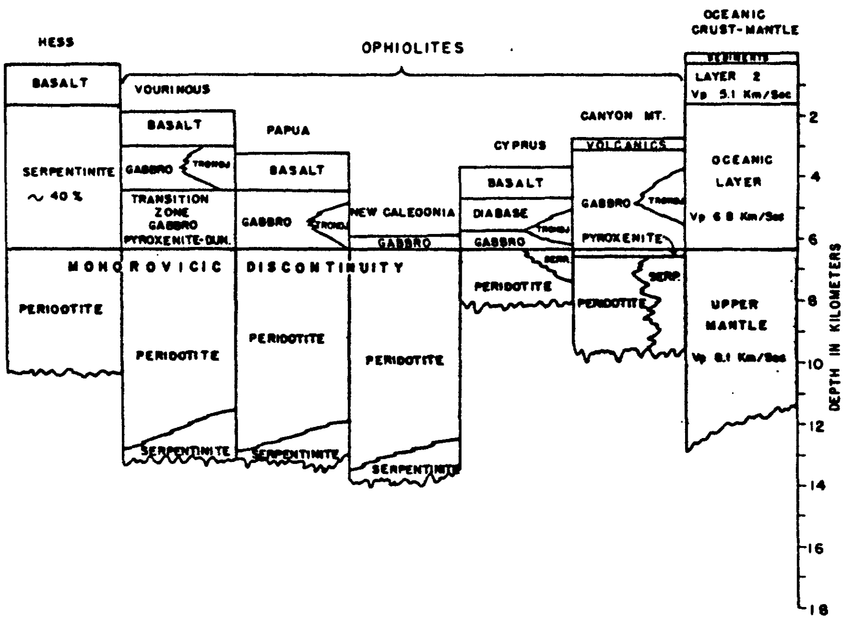


Figure 1. Comparison of the stratigraphic thickness of igneous units from various ophiolitic masses with the geophysical estimate of the oceanic crustal layers (from Coleman, 1977). The rock name "Trondj" (trondhjemite) should be replaced by plagiogranite (oral communication, R. G. Coleman, March 15, 1979).

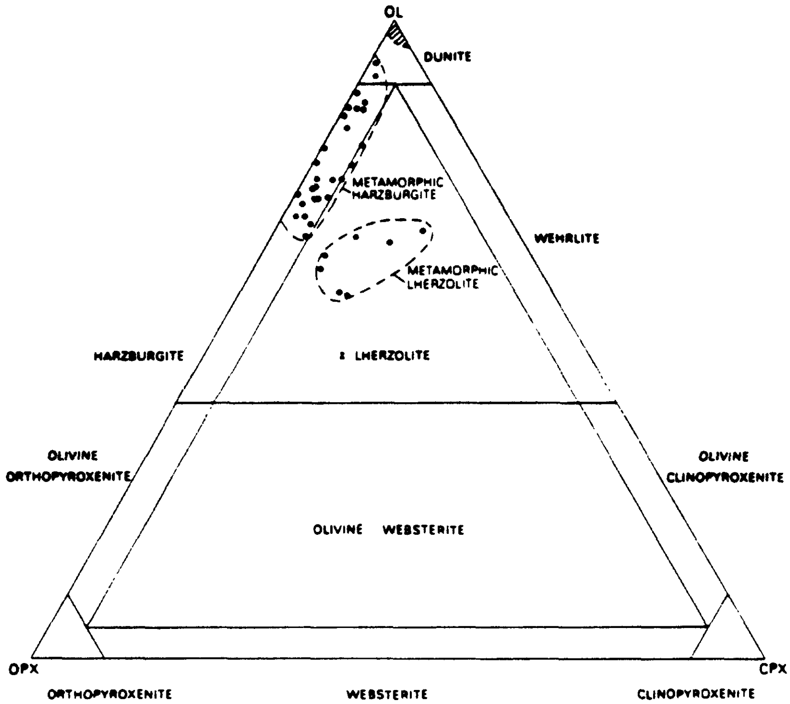


Figure 2. Modal proportions of olivine, orthopyroxene, and clinopyroxene in harzburgite and dunite from ophiolite metamorphic peridotites compared to the lherzolite subtype (after Coleman, 1977, p. 26).

of chromite generally associated with dunite; (3) sodic felsic intrusive and extrusive rocks [plagiogranites and keratophyres]. [To this might be added the common occurrence of nickel, copper, and platinum deposits.]

Unserpentinized ophiolites tend to be of high mean density (ρ = 2.9 - 3.3 g/cm^3) and of high seismic velocity (V_p = 5.0 to 8.4 km/sec) (Fox and others, 1973, Salisbury and Christensen, 1978, and others). Serpentinization of ultramafic rocks can lower densities to as low as 2.3 g/cm^3 (Bromery and Griscom, 1964). Magnetization of ophiolites is variable, but large magnetic anomalies are not uncommon, depending on the metamorphic grade and degree of serpentinization (Griscom, 1964; Cox and others, 1964; Soloviev and others, 1964b). Magnetization of ultramafic rocks commonly increases with serpentinization. But magnetization of basalts commonly decreases with regional metamorphism to greenschist facies. (Andrew Griscom, oral communication, 1975-1979, Stern and others, 1976).

Many ophiolite complexes contain significant deposits of ore minerals that have a genesis related to the formation of oceanic crust and mantle. Around the world, economic or potentially economic deposits of nickel, chromite, platinum, copper, and gold(?) are variably associated with these fragments of oceanic crust and mantle. Nickel, chromite, and platinum deposits tend to be associated with the ultramafic parts of the complexes, and copper and gold(?) with the higher mafic parts. Perhaps of lesser current economic significance are deposits of iron, cobalt, talc, asbestos, magnesite, manganese, and possibly mercury, which are found in many ophiolite belts. Several groups of major porphyry coppers occur in intermediate to silicic (granitoid) plutonic rocks that rest on foundations of oceanic crust, and these deposits probably are genetically related, albeit indirectly, to the underlying ophiolites.

It should be pointed out that another clan of mafic and ultramafic rocks is host to major deposits of some of the same metals. This clan comprises the great stratiform complexes such as Bushveld, Stillwater, and Sudbury, most of Precambrian age, which contain much of the world's reserves of copper, nickel, and chromium. The stratiform complexes may have had a different origin from those formed at oceanic spreading ridges and will not be further discussed here because none have been recognized in the immediate circum-Caribbean region

Several concentric or zoned "Alaska-Ural" ultramafic complexes (Jackson and Thayer, 1972; Irvine, 1974) have been recognized in recent years in Venezuela and Colombia (Murray, 1972, Martín Bellizzia and de Arozena, 1972, and Barrero, 1977, 1979). According to Jackson and Thayer (1972), these complexes:

> ".... have the following features in common: (1) intrusive contacts with strong thermal aureoles; (2) they tend to be cylindrically zoned, with ultramafic rocks in the central parts grading out toward two-pyroxene gabbros and tonalites; (3) the principal mineral associations in the ultramafic

parts are olivine - clinopyroxene - magnetite; and (4) they typically contain magnetite-rich pyroxenite dikes, amphibolitized border rocks, and, in some places, platinum deposits."

They further noted that deposits of titaniferous magnetite, native platinum, platinum sulfides, and high-iron chromite may occur. Genetic relations of such zoned complexes to oceanic rocks have not yet been defined.

An additional group of rocks has many chemical similarities to the upper parts of the ophiolite sequence: these are mafic rocks that form primitive island arcs, and they tend to be tholeiitic (and sodic), as are the upper parts of ophiolite complexes, but are formed by igneous processes near sites of tectonic convergence and subduction, probably by partial melting of upper mantle and lower crust. Although differences in abundances of rare-earths and trace elements, and other geochemical and isotopic data, have been used to distinguish primitive island-arc basalts from those formed at spreading ridges (Pearce and Cann, 1973; Pearce, 1975; Cann, 1970), the requisite analytical work to make such distinctions has progressed rather slowly, particularly in the circum-Caribbean region (Pushkar, 1968), although much recent work is in progress (for example, see Donnelly and Rogers, 1978a, 1978b; Sayeed and others, 1978; Sigurdsson and others, 1978; Stipp and Nagle, 1978; Waggoner, 1978; Thompson and others, 1978, etc.)

One of the world's largest, but most poorly known belts of mafic and ultramafic rocks is exposed in the circum-Caribbean region and adjacent parts of northern South America and Central America (fig. 3,in pocket). This review describes the general occurrence of known and inferred ophiolites, belts of mafic volcanic rocks and ultramafic rocks which may be either ophiolites or parts of primitive island arcs (or both), and the general distribution of known ore deposits associated with these belts. Summaries of ore deposits and their genesis by Kesler (1978), Guild (1974), Guild and Cox (1977), and by Dayton and White in a special issue of Engineering and Mining Journal (1977) are key elements of this review. Gravity and magnetic anomalies (or lack thereof) associated with these belts are briefly su marized, and some suggestions of regional crustal setting, geophysical ore guides, and prospecting techniques are formulated.

The most comprehensive summaries of the age, tectonic setting, and distribution of serpentinites and peridotites of the region have been presented in several papers by G. Dengo (1969a, b, 1972). Gravity anomalies of the Caribbean region have been reviewed by Bowin (1976), and magnetic anomalies of the region (published coverage is somewhat sparse over the mafic and ultramafic belts) have been presented by Matthews (1976). A general review of geophysical studies in the region (now considerably out-of-date) was prepared by Case (1975). General geologic occurrences of these rocks are shown on regional map compilations by Case and Holcombe (1975, 1977, in press).

As Dengo (1972) has pointed out, most of the ultramafic belts lie close to boundaries of the Caribbean plate. Some lie close to currently active boundaries and others lie in or adjacent to older quiescent boundaries. Most of the mafic and ultramafic belts are thought to be Late Mesozoic in age, although some bodies in Guatemala, Colombia, and Venezuela may be older. Furthermore, many of the belts have a close spatial association with metamorphic belts, including some blueschists, most of which are believed to have been formed prior to middle Eocene time.

Crustal definitions: For convenience, some definitions of terms are provided for this report: Continental crust is of low average density, 2.7-2.9 g/cm^3, intermediate to silicic bulk composition in its upper part, and contains a high proportion of pre-Mesozoic metamorphic and igneous rocks. The crust is relatively thick 20 to 45 km, based on refraction data. Normal oceanic crust tends to be mafic or ultramafic, of high density, 2.85-3.0 g/cm^3, typically 6-10 km thick, based on refraction data. Transitional crust has properties that are intermediate between those of oceanic and continental crust. Multiple crust, in this report, refers to crust causing large positive gravity anomalies and which appears to be not only dense but substantially thicker than normal oceanic crust (thicknesses of 20-30 km). Such thickened crust may have originated by imbricate stacking of slabs of oceanic crust, by volcanic loading, or by downfolding in a "tectogene". Crust under the deep basins of the Caribbean Sea, identified from seismic refraction, ranges between 10-20 km in thickness, which is thicker than typical oceanic crust. Basement here refers to the crystalline layer of variable composition below the oldest dated sequence of sedimentary, volcanic, or metamorphic rocks.

Mafic and ultramafic belts of the Caribbean region, their associated geophysical anomalies, and ore deposits, will be described in a clockwise fashion, starting with Guatemala and Honduras.

Guatemala and Honduras

Serpentinite, serpentinized periodotite, and peridotite are exposed in a broadly arcuate band across south-central Guatemala, from near the Mexican border to the Caribbean margin (G. Dengo, 1972; fig. 4). These bodies are in or adjacent to the Polochic, Motagua, and Chamelecón fault zones, which together constitute the left-lateral transform boundary between the Caribbean plate and the North American plate (G. Dengo, 1972, Molnar and Sykes, 1969, Plafker, 1976). The ultramafic rocks are in fault contact with a variety of rocks including Precambrian(?) and Early Paleozoic metamorphic-igneous complexes, with Late Paleozoic unmetamorphosed strata, with Late Mesozoic ophiolites (pillow basalts, radiolarian chert, marble, and greenschists of the El Tambor sequence), and with unmetamorphosed Mesozoic and Cenozoic strata. These belts, including petrographic descriptions, have been discussed by McBirney (1963), McBirney and Bass (1969), G. Dengo (1972), C. Dengo (1976, 1977), Bertrand and Vuagnat (1975, 1976) Donnelly (1977), Roper (1978), and others. Although Meyerhoff (1966) has argued for a Paleozoic age for the serpentinites, Bonis (1967) reported that the first recognized serpentinite detritus occurs in sedimentary rocks of Maestrichtian Age, so that the age may be younger than Paleozoic. Some of these bodies had been emplaced and exposed to erosion prior to the Cenozoic. Dengo and Bohnenberger (1969) considered that emplacement of serpentinites may have started as early as Paleozoic and culminated in Late Cretaceous time. Bertrand and others (1979) recently determined an Ar^{40}/K^{36} isochron age of 58.5 m.y. from the complex, but analyzed samples were from widely separated localities.

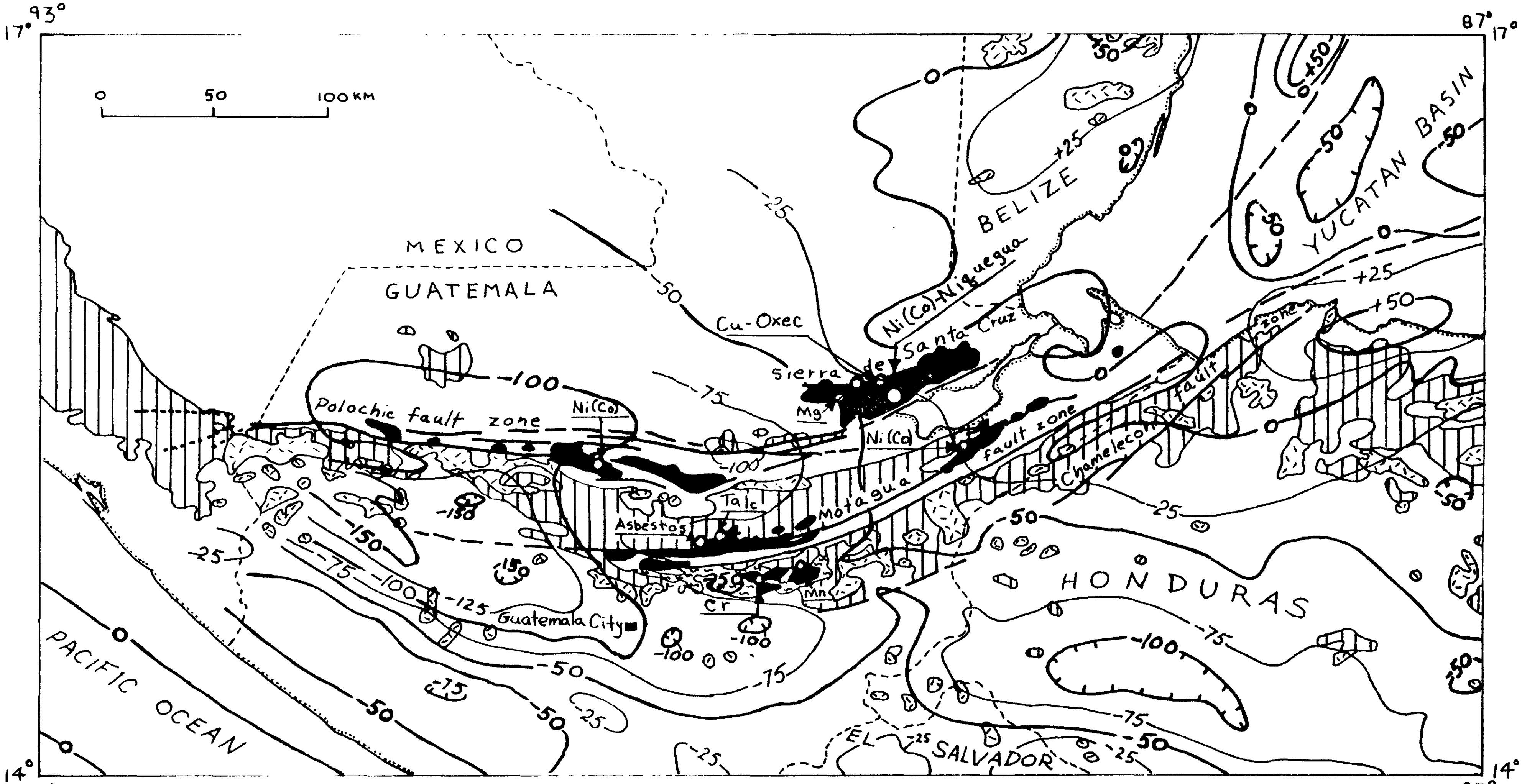


Figure 4. Simplified geologic map and simple Bouguer anomaly map of ultramafic and mafic complexes in Guatemala. Ultramafic complexes in dark pattern, Mesozoic metamorphic rocks (including some ophiolites(?)) in lazy-S pattern, Paleozoic and Precambrian(?) metamorphic-igneous complex in vertical pattern, silicic plutons with dash pattern. Major mineral deposits indicated by open circles. Contour interval for Bouguer anomalies 25 mgal onland and nearshore; contour interval for free-air anomalies 50 mgal offshore. Gravity data modified from Bowin (1976), Instituto Geográfico Nacional de Guatemala (1965), U.S. Department of Defense gravity library (written commun. 1972-1976), T. W. Donnelly (written commun. 1974-1975), J. Monges-Caldera and R. Jachens (written commun. 1974-1975) and other sources.

Two controversies exist about this belt of ultramafic rocks: (1) Are they part of an ophiolite assemblage? (2) Are they detached or are they unattached "diapiric" protrusions from the upper mantle? In 1972, G. Dengo specifically commented that "they are not typically associated with the ophiolite suite of rocks" because the only associated mafic volcanic rocks were found in the El Tambor Formation (McBirney, 1963; McBirney and Bass, 1969) in a restricted segment of the ultramafic belt." C. Dengo (1976, 1977) and Bertrand and Vuagnat (1975, 1976), however, later postulated that the serpentinites may be one of several units which comprise a dismembered ophiolite suite, and Kesler (1978) and Petersen (1979) mentioned a massive sulfide deposit in the Sierra de Santa Cruz in diabase and basalt associated with serpentinite that may be in an ophiolite sequence. Roper (1978) likewise postulated that serpentinites and associated amphibolites represent the lower portion of an ophiolite sequence. Wilson (1974, p. 1389) has pointed out that ophiolites may occur in the Río Chamelecón and extend northeast to the Bay Islands, Honduras, and has further (p. 1392) reported jadeite from the serpentinites. McBirney and others (1967) and T. W. Donnelly (1977) and his students have reported jadeite and eclogites, and melange associated with the southern part of the ultramafic belt, near the Motagua and Chamelecón faults. The present consensus appears to be that these rocks <u>are</u> part of an ophiolite assemblage, although insufficient detailed geologic mapping has been done to establish presence or absence of ophiolites throughout the Guatemalan belt. Presence of high-pressure minerals, such as jadeite, implies that some of these rocks have undergone a subduction event.

Origin of the exposed mafic and ultramafic rocks in Guatemala is problematic. They may have originated at igneous sites far-removed from their present site. But they may have originated from a relatively close precursor to the mid-Cayman Rise spreading center (fig. 5).

Parts of the area bounded by the Motagua-Polochic-Chamelecón fault zone, now part of the left-lateral transform boundary between the Caribbean and North American plates, were probably sites of tectonic convergence during the Late Mesozoic-Early Tertiary (Lawrence, 1976, Schwartz and Newcombe, 1973, Roper, 1973, 1976, 1978, Donnelly, 1977). Belts of seismicity (Molnar and Sykes, 1969), offshore geomorphology (Holcombe and others, 1973), and suites of recent dredge hauls (Eggler and others, 1973; Perfit, 1977, Perfit and Heezen, 1978, White and Stroup, 1979) strongly suggest that the Cayman Trough, the currently active boundary between the Caribbean and North American plates, thought to have formed since Eocene time, extends into the Motagua-Polochic fault zones. The mid-Cayman Rise, probably an active mini-spreading center (Holcombe and others, 1973, Ballard, 1976, Perfit, 1977, Thompson and others, 1978), is the site of occurrences of serpentinite, serpentinized peridotite, cumulate mafic rocks, gabbro, and pillow basalt. Hence, it seems possible that the ophiolites become younger eastward from Guatemala-Honduras toward the mid-Cayman Rise.

The second controversy concerns the depth extent of the ultramafic masses in Guatemala. Van den Boom and others (1971) evidently regarded some of the ultramafic masses in the Motagua-Polochic (Chixoy) fault zone as diapiric or mushroom-shaped bodies. Wilson (1974) and Williams (1975) considered that some of the larger masses have been emplaced by northward gravity-sliding. Williams cited private-company aeromagnetic data that suggest that the

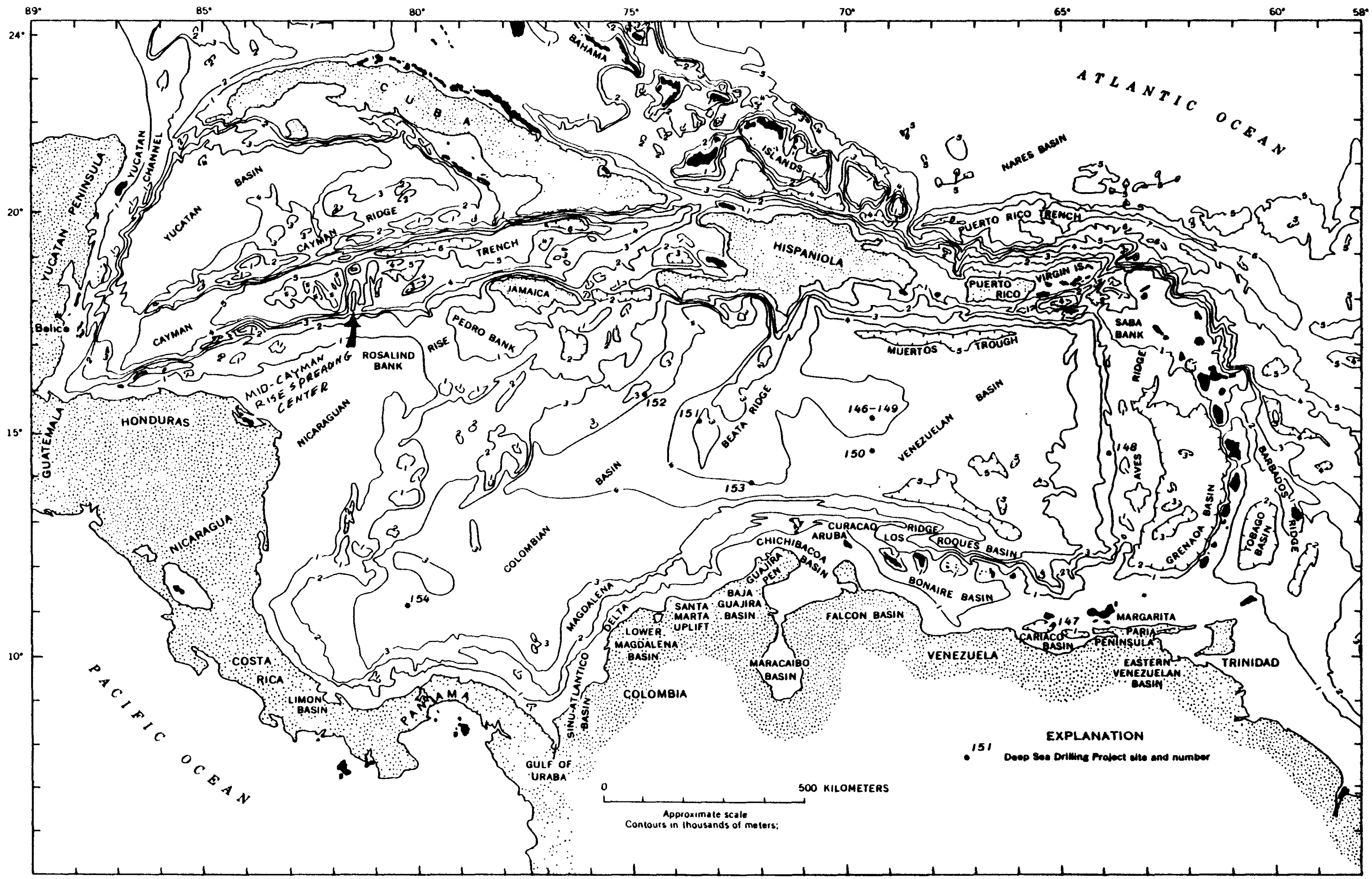


Figure 5. Simplified bathymetric map of the Caribbean region.

ultramafic body at the Sierra de Santa Cruz (fig. 4) is detached at relatively shallow depth. McBirney (1963) conducted a gravity traverse across some ultramafic masses in central Guatemala but drew no conclusions from the data regarding depth extent of the ultramafic masses. Roper (1978) has shown that ultramafic masses north of the Motagua fault zone are bordered by thrust faults, and he postulated northward thrusting of the masses. The problem of the depth extent of the masses is certainly not resolved at present.

Ore deposits associated with Guatemalan ultramafic bodies have been described by Dengo and others (1969), Dengo and Levy (1970), Levy (1970, 1977), White (1977), Kesler (1978), and Petersen (1979). Lateritic nickel-cobalt deposits, especially in the Sierra de Santa Cruz, are the most important economically, and were being commercially developed in 1978. Guild and Cox (1977) estimated 1,500,000 short tons of nickel reserves in Guatemala. Cornwall (1973) estimated 100,000,000 tons of "nickel-laterite" resources. Minor deposits of chromite, asbestos, talc, magnesite (some of which are being developed, Northern Miner, 1977), and manganese in Guatemala and Honduras are shown on the metallogenic map of Central America (Dengo and others, 1969). According to Kesler (1978):

> "Among the most primitive massive sulfide deposits in the Caribbean region are the strongly deformed pyrite-chalcopyrite lenses of the Oxec belt in Guatemala. These deposits appear to occupy a relatively thin zone of diabase and basalt associated with a large block of serpentinite that occupies the fault system that extends westward from the Cayman trench."

Petersen (1979) recently provided additional details on the deposit:

> "In the mine vicinity the .... assemblage consists of serpentinized peridotite, sheeted dike complex, a hydrothermally altered lower pillow lava sequence (ore horizon), and an upper pillow lava sequence".

Petersen postulated that the ore deposit is similar to that of Troodhos on Cyprus. The Oxec belt is evidently along the northern flank of the Sierra de Santa Cruz, about 35 km north of the Buena Vista nickel deposit, which is west of the main Exmibal nickel deposit (Northern Miner, 1977).

As G. Dengo (1972) has pointed out, the Guatemalan ultramafic rocks are now in or surrounded by mainly continental crust, as defined by metamorphic-igneous complexes of Precambrian(?) and Early Paleozoic age. This concept is supported by values of the regional Bouguer gravity anomalies which range from about zero to -100 mgals over most of the ultramafic belt (fig. 4). Case and Donnelly (1976) estimated a crustal thickness of about 45 km, north of Guatemala City, based on gravity models (fig. 6). Kim and others (1979) derived a crustal thickness of 35 km in the vicinity of Guatemala-Honduras from analysis of shallow earthquake data. However, local blocks of oceanic crust caught up in fault zones, the El Tambor complex, expressed by relative gravity highs of up to 50 mgals, occur in relatively restricted areas south of the Motagua fault (Lawrence, 1976; Case and Donnelly, 1976, Donnelly, 1977).

Although gravity coverage is scanty for most of the ultramafic belt, except for the area surveyed by T. W. Donnelly and students, it appears that several of the larger bodies in the northern part of the belt do not have much

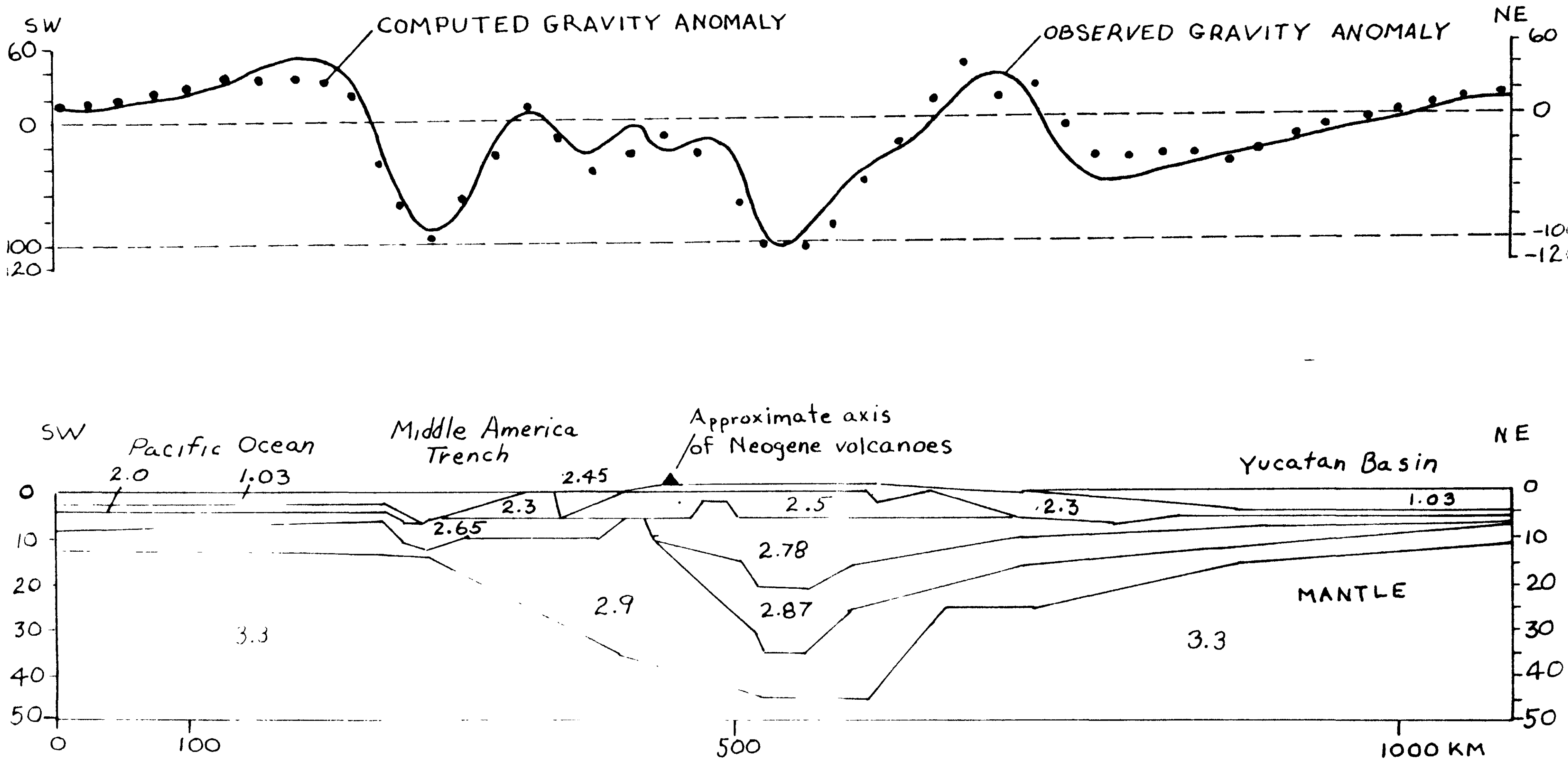


Figure 6. Generalized crustal model across Guatemala, near Guatemala City. Numbers are assumed densities in g/cm^3. Free-air anomalies offshore; simple Bouguer anomalies onland. No attempt has been made to obtain an exact fit between observed and computed gravity profiles because much additional modern gravity data are in process of being obtained. Approximate line of profile shown on figure 39.

gravitational expression. This suggests that these bodies are extensively serpentinized or that their depth extent is not great. Systematic density determinations and closely spaced gravity profiles should resolve these questions.

Cuba

One of the largest mafic and ultramafic belts in the Caribbean region--and one of the most enigmatic and controversial--occurs in Cuba (fig. 7, in pocket). The origin, age, and geological significance of these rocks has received much attention in recent years (Kozary, 1968, Khudoley and Meyerhoff, 1971, Pardo, 1975, etc.), not only with respect to their setting in schemes involving plate-tectonics but even to such questions as to the extent and direction of thrust-faulting that involves them (Mattson, 1972, 1973a,b; Malfait and Dinkleman, 1972, 1973; Meyerhoff and Meyerhoff, 1972, 1973; Walper, 1973, Knipper and Cabrera, 1974; Pardo, 1975, etc.). For this review, no attempt will be made to elaborate on the controversy. Most authors seem to agree that these rocks were originally oceanic (Khudoley and Meyerhoff, 1971, p. 86-87, Pardo, 1975, p. 590), that they were emplaced during the Late Mesozoic, as igneous masses or as cold intrusions, perhaps diapiric, or both, and that most of them have been intimately involved in Late Cretaceous-Eocene convergent deformation, either by gravity sliding, subduction, or obduction. Some of the serpentinite masses, however, appear to be pluglike, domical, or diapiric bodies (Kozary, 1968, Khudoley and Meyerhoff, 1971, Pardo, 1975).

The belt of ultramafic bodies is bordered on the north (generally in fault contact) by thick carbonate and evaporite sequences of Late Mesozoic Age, similar to those of the Bahamas platform. In a general way, ultramafic rocks appear to be overlain by mafic volcanic rocks and these, in turn, by andesitic volcanic and volcaniclastic rocks. Most of the ultramafic and mafic rocks are thought to be pre-Cenomanian, and the more silicic volcanic assemblages range in age from Late Cretaceous into Eocene in eastern Cuba. The more silicic volcanic assemblages, presumably products of island-arc volcanism, generally occur south of the mafic assemblages (Pardo, 1975). Although the dating is speculative, Pardo (1975, p. 608) believed that the inception of ultramafic and mafic igneous activity was during early to middle Cretaceous. Final tectonic emplacement of the ultramafic and some of the mafic belts was accomplished during the interval Paleocene-middle Eocene.

Field relations, petrography, and petrology of the mafic and ultramafic complexes have been described by many authors. Most pre-1968 sources are summarized by Khudoley and Meyerhoff (1971). Kozary (1968) recognized several types of ultramafic and mafic occurrences in Cuba: (1) crystalline ultramafic rocks (peridotite), including harzburgite, that are serpentinized in varying degrees. (2) He noted that associated banded gabbros are common, and inferred that they are the top of the ultramafic-gabbro complexes. (3) Some masses of submarine ultramafic lava flows [komatiites?] have been recognized near Habana and in the Gibara District. (4) Cold intrusive and extrusive serpentinites occur in the Holgüin-Gibara area and, finally (5) sedimentary serpentinites have been recognized.

Ultramafic and mafic bodies in eastern Cuba are adjacent to two groups of metamorphic rocks: a high-temperature assemblage and a high-pressure, low-temperature (blueschist) assemblage. The blueschist terrane is extensive in the Oriente Province, south of the main belt of ultramafic rocks, and smaller areas occur in the Sierra de Trinidad (Boiteau, Michard, and Saliot, 1972, 1977; Boiteau and Michard, 1974, 1976). Boiteau and Michard (1974) stated that the schists were derived from spilitic to keratophyric pillow flows and pillow breccias. Occurrence of the high-pressure mineral assemblages suggests formation as part of a subduction episode.

Chromite deposits are widely associated with the ultramafic belts of northern Cuba (Thayer, 1942; Flint and others, 1948; Judoley and others, 1963). In eastern Cuba Thayer (1942) observed that:

> "Gabbro, troctolite, and anorthosite are associated with the peridotite, and form large masses in the Camagüey district."

He noted that most of the chromite deposits occur in belts of serpentinized peridotite along the length of Cuba, but chromite production has been limited to the eastern half of the island. In the Camagüey district: "The chromite is closely associated with dunite, and to a lesser degree with troctolite and more or less pegmatitic gabbro" (Thayer, 1941). According to Guild and Cox (1977, p. 78-79):

> "The deposits are tabular to irregular, are of the podiform type, and range in size from very small to perhaps half a million tons. They occur in ultramafic rocks of uncertain age and origin, which can be interpreted as either very early island arc or obducted ocean floor. The chromite itself is early magmatic, undoubtedly cumulus, and must have been concentrated in the mantle prior to the emplacement of its peridotite host into the upper crust (Guild, 1974)."

Thayer (1973) estimated up to 1,000,000 long tons of conditional chromite resources.

In eastern Cuba, laterization of the peridotites and serpentinites has formed major nickel deposits. Guild and Cox (1977, p. 89-90) reported:

> "The Cuban deposits cover large areas and are as thick as several tens of feet. The genetic processes that produced these deposits, although simple in broad terms, are complex in detail. Regardless of the intermediate steps, which include incorporation of nickel originally present in the olivine lattice into magnesian serpentine minerals and ferrous nontronite, the end products are ferruginous laterites containing 1 to more than 2 percent nickel, minor amounts of cobalt, several percent chromic oxide, and as much as about 50 percent iron (Kudelasek, et al., 1967); Vletter, 1955) Nickel increases downward; most is near the bottom of the laterite profile or in the uppermost foot or two of the underlying serpentine."

Although production of gold in Cuba has never been large, it appears that most of the gold deposits have a close spatial association with the ophiolite belts. In the region near Santa Clara, three types of deposits have been recognized (Cabrera and Tolkunov, 1973): (1) gold in late pyrite in quartz veins along contacts between ultramafic bodies and gabbro, especially where contacts are tectonic; (2) fine-grained native gold, disseminated in serpentinized ultramafic rocks and altered mafic rocks adjacent to fault zones; and (3) gold in pyrite associated with chalcopyrite in stock works in tuffaceous rocks and porphyritic basaltic andesite.

In eastern Cuba, near Holgüin, gold occurs as small lode deposits associated with small silicic plutons, according to Phillip Guild (oral communication, July 27, 1977), but A. A. Meyerhoff (written communication, June 1977) has stated that they:

> "....are very small placer deposits, derived presumably from one of the small, nearby granodioritic stocks. They are uneconomical and have been mined only by the local citizenry. I doubt that any serious mining has gone on for at least 35 to 40 years."

Most of the known copper-bearing massive sulfide deposits of Cuba occur either in sedimentary rock sequences in western Cuba or in association with the andesitic to dacitic volcanic sequences of eastern Cuba (Kesler, 1978, Bogdanov and others, 1966) rather than with the mafic-ultramafic complexes. The sedimentary deposits (in rocks of Jurassic age) are poorly understood. Some of them are shown on figure 7 as it is possible that their original sources are in underlying ophiolites (either older ophiolites or tectonically-overridden ophiolites). Recent summary discussions of these deposits have been prepared by Tolkunov and others (1974) and by Guild and Cox (1977).

Manganese deposits associated with Late Cretaceous-Paleocene volcanic rocks (island arc?) of eastern Cuba have been summarized by Park (1942), Park and Cox (1944), Simons and Straczek (1958), and Sokolova and others (1974). Other deposits occur in the Jurassic sedimentary terrane of western Cuba.

<u>Geophysical studies</u>- Several detailed gravity surveys have been made in the Camagüey Province, Cuba, to determine if chromite deposits could be found directly by the gravity method (Hammer and others, 1945, Davis and others, 1957, 1960). According to Davis and others (1957):

> "A large number of anomalies were found and evaluated according to geology, areal extent, and gravity relief. Depths to disturbing hypothetical bodies were computed to guide drilling. Test drilling of 106 positive anomalies revealed that ten features overlie deposits of chromite and 89 occur over bodies of other dense materials. The other seven anomalies were not explained by material found in drilling. Core drilling on five of the chromite deposits revealed about 236,000 tons of chromite. An additional 12,000 tons are contained in three deposits which were not blocked out. No estimate was made of tonnage in two small deposits."

Several different regional gravity anomaly maps of Cuba have been compiled (Soloviev and others, 1964a, Ipatenko and Sashina, 1971; Pardo, 1975; and Bowin, 1976). The map shown in figure 7 is taken largely from data of Bowin with modifications from Pardo and Soloviev and others. In comparing this compilation, which used a reduction density of 2.67 g/cm^3, with that of Soloviev and others, reduction density 2.3 g/cm^3, most of the larger gravity anomalies are essentially the same with minor differences in position or shape. Bouguer anomalies range from -25 mgals in central Cuba to an enormous positive anomaly, greater than +150 mgals, in the Oriente Province of eastern Cuba. Most of the exposed ultramafic rocks are in terranes of relative negative to slightly positive Bouguer anomalies in northern Cuba, with the exception of the bodies in the Oriente Province. Much of southern Cuba is characterized by ovoid positive anomalies of +50 mgals, or more, except where Tertiary sedimentary basins are known.

From the huge positive anomaly in the Oriente Province, one may infer that easternmost Cuba is underlain by oceanic crust (Woollard and Strange, 1962, Demenitskaya and Belyaevsky, 1969). The area is clearly not in isostatic equilibrium and is the site of Neogene-Recent vertical uplift (Horsfield, 1975). Bouguer anomalies in the rest of Cuba have values that can be interpreted as either oceanic or continental. If one made corrections for the low-density Tertiary sedimentary rocks, however, most of the Cuban anomalies would be positive, on the order of +25 to +75 mgals, and it seems that multiple oceanic or transitional crust is suggested rather than continental. Because of the occurrence of lead deposits (Cumming and Kesler, 1976) and tungsten deposits, however, which may characterize continental crust, this interpretation should be left open. It should be pointed out that the metamorphic "basement" areas at the Isla de Pinos and the Sierra de Trinidad have Bouguer anomalies of +25 to +50 mgals, or more. Bouguer anomalies over metamorphic areas of the Oriente range from +100 to +150 mgals. In a gravity model across Cuba, Soloviev and others (1964a) assumed a crustal thickness (dense) of 20-25 km (fig. 8,in pocket).

A summary residual aeromagnetic map of Cuba has been prepared and discussed by Soloviev and others (1964b). The regional map was prepared by compositing data from numerous surveys made during the 1950's and early 1960's which were flown at different elevations and compiled using various magnetic datums. A somewhat simplified version was prepared by Matthews (1976) as part of the Caribbean-wide compilation, and an even more simplified version is shown here on figure 9 (in pocket).

Because of lack of information on relationship between flight elevation and ground topography, it is difficult to make a realistic geologic interpretation of the magnetic anomalies of figure 9. A few general comments can be made about magnetic patterns over some of the rock units: Ultramafic bodies are associated with both positive and negative anomalies, but relative negative anomalies appear to be most prominent in central and eastern Cuba. Positive magnetic anomalies dominate over the mafic volcanic rocks, although some very prominent negative anomalies, A and B, for example, are present in central Cuba. Most of the granitic plutons appear to cause positive anomalies, although details are obscured by anomalies caused by adjacent mafic volcanic rocks. The main metamorphic masses on the Isla de Pinos and in the Sierra de Trinidad do not produce conspicuous closed anomalies and thus are essentially nonmagnetic. Late Cretaceous and Early Tertiary volcanic rocks are variably magnetic. Because most of the Mesozoic and Cenozoic sedimentary sequences are believed to be virtually nonmagnetic, anomalies over those terranes are probably caused by concealed ultramafic, volcanic, or granitic rocks. According to Khudoley and Meyerhoff (1971, p. 86):

> "Much additional serpentinite underlies late Eocene and younger strata in Cuba, as shown by its presence at total depth in numerous wildcat petroleum tests drilled in Habana,

Matanzas, and Las Villas Provinces. Kozary (1968) estimated that at least 15,000 sq km of serpentinite would be exposed in Cuba if all late Eocene and younger strata were removed."

Patterns of positive and negative anomalies over the ultramafic and mafic rocks may be caused in several ways, as discussed by Soloviev and others (1964b). For many anomalies, the component of remanent magnetization may exceed the induced component. If the remanent component is reversed, negative anomalies may result. Second, some of the apparent negative anomalies may be caused by edge effects of relatively thin dipping sheets, especially at this low magnetic latitude. Third, the magnetic lows may simply be associated with rocks having less magnetite than adjacent rocks. For example, the lows may represent relatively unserpentinized ultramafic bodies. Clearly, satisfactory quantitative analysis of the magnetic field in Cuba requires an anomaly-by-anomaly approach using information on survey parameters, measured magnetic properties of the rocks, and structural data.

Jamaica

Mafic and ultramafic rocks are of very limited exposure in Jamaica (fig. 10). Serpentinites, in part serpentinized lherzolite, occur in eastern Jamaica in the Blue Mountains and are areally associated with metamorphic rocks of greenschist, amphibolite, and blueschist facies near fault zones (Draper and others, 1976, Wright and others, 1974; Robinson and others, 1971). Wadge and Draper (1978) have recognized a sequence of volcaniclastic sedimentary rocks of Campanian-Maestrichtian age overlying spilitic lavas in the southeastern Blue Mountains. Small exposures of volcanic and volcaniclastic rocks of Cretaceous age include some mafic flows in central Jamaica, but andesitic volcanic rocks predominate there and elsewhere. Volcanism had largely ceased by Maestrichtian time, but local andesitic to dacitic volcanic activity resumed and then ceased during the Eocene (Robinson and others, 1971; Roobol, 1972). Minor andesitic volcanic activity resumed briefly during the Miocene. From Roobol's descriptions (1972), it appears that the younger Jamaican volcanic and volcaniclastic rocks are largely of the island-arc type and that exposed ophiolites, if present, are minor.

Bouguer anomalies in Jamaica are all strongly positive, ranging from about +40 mgal on the south coast to more than +125 mgals on the west coast and +100 mgal on the east coast (Bowin, 1976). Although "edge" effects across the margin of the north coast probably contribute to the relative Bouguer anomaly high, the south coast borders shallow areas of the Nicaraguan Rise, hence edge effects are not great. From isostatic-anomaly maps (Andrew, 1969), Bowin (1976) concluded that the entire island is undercompensated. In different terms, the gravity field indicates that Jamaica is underlain by dense crust and (or) upper mantle, probably oceanic.

Aeromagnetic surveys were flown at three levels (fig. 10): 1,000 feet above water and at 4,000 and 8,000 feet above land areas (Bowin, 1976). Prominent magnetic highs in central Jamaica suggested to Robinson and others (1971) that a general concentration of volcanic centers occurs in the subsurface of this region. Bowin (1976) has noted that magnetic anomalies of south-central Jamaica have regional trends that differ from those of the

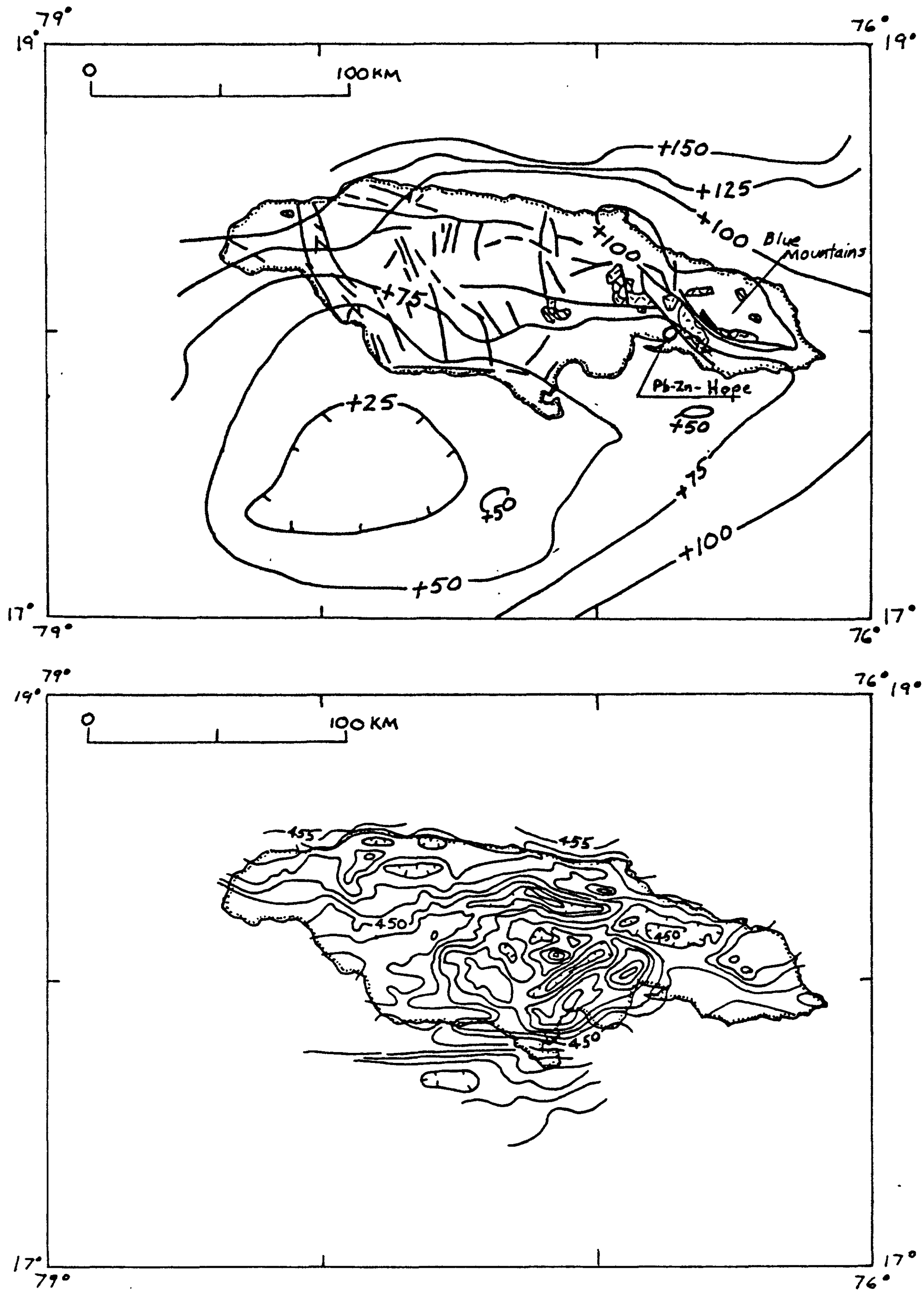


Figure 10. Upper diagram - Simplified geologic and Bouguer anomaly map of Jamaica. Ultramafic mass in dark pattern; blueschist in cross hatch; other metamorphic rocks in lazy-s pattern; granitic plutons with dash pattern, volcanic rocks in diagonal rule. Contour interval for Bouguer anomaly map, 25 mgal. Data modified from Bowin (1976). Lower diagram - Simplified magnetic anomaly map of Jamaica, contour interval 100 gammas. Data modified from Bowin (1976) and Matthews (1976).

dominant faults and suggested that the basement rocks of south-central Jamaica are structurally part of the Nicaraguan Rise. Extremely prominent magnetic lows, as well as highs, suggest that the magnetic basement, whatever its composition, includes reversely magnetized rocks.

From the association of blueschists, a possible "paired" metamorphic belt, and ultramafic rocks, Draper and others (1976) postulated that a southwest-dipping subduction zone might have existed in eastern Jamaica in Cretaceous time, but Krijnen and Lee Chin (1978) proposed that a subduction zone dipped northeast in Cretaceous and changed to southwest dip during Early Tertiary time after a collision event in Late Maestrichtian-Early Tertiary.

Apart from the huge bauxite deposits, which are lateritic deposits formed on various carbonate units of the Tertiary sedimentary sequence, ore deposits of Jamaica are rather small and sparse (Hughes, 1973). Minor deposits of copper, lead, and zinc are associated mainly with silicic plutons and volcanic or volcaniclastic rocks. Minor nickel anomalies have been reported from one of the serpentinite bodies. A few enigmatic reports of platinum occurrences exist (Hughes, 1973).

Hispaniola

A most comprehensive summary of the geology and geophysics of Hispaniola has been presented by Bowin (1975), but geologic details for many parts of the island are still poorly-known. Serpentinites and peridotites occur in two main belts (fig. 11): a larger belt that trends northwest in east-central Hispaniola and a smaller belt that occurs along the north coast. The larger "central" belt is bordered on the south and west by a large zone of metamorphosed mafic volcanic rocks, mainly amphibolites, and on the north and east by metamorphosed felsic volcanic rocks. Many of the ultramafic bodies are associated with shear zones. Several varieties of metamorphic rocks, including blueschists, occur along both belts, and eclogites have been reported have been reported (Nagle, 1971) from the north coast belt. Kesler and others (1977) have summarized the isotopic age data from the metamorphosed mafic belt in central Hispaniola, and the ages are in the range 123-127 m.y. (Early Cretaceous). Numerous intermediate to silicic plutons, tonalitic to granodioritic, trend northwest in or parallel to the ultramafic-metamorphic belts of central Hispaniola. The plutons range in age from about 90 to 35 m.y., according to Bowin.

Mafic volcanic rocks of Cretaceous age are widely exposed in southwestern Hispaniola, but smaller exposures occur throughout the island. Andesitic to dacitic volcanic and volcaniclastic rocks of Cretaceous age appear to be concentrated in a west-northwest trending belt across the island, parallel to the ultramafic and metamorphic belts. Spilites, keratophyres, andesite flows, and tuffs occur in the north coastal area.

Mafic volcanic and silicic volcanic rocks are as old as Aptian-Albian (Bowin, 1975, p. 512-513) and range up into Campanian-Maestrichtian. Local volcanic and volcaniclastic rocks are as young as Eocene. Minor alkaline mafic volcanic activity occurred during the Pleistocene(?) in south-central Hispaniola.

Gravity anomalies of the island have been discussed by Bowin (1975, 1976) and Reblin (1973); simple Bouguer anomaly contours on figure 11 are modified from Bowin's data. Bouguer anomalies range from less than -25 mgals to more than +125 mgals across the island, but most of the island is characterized by positive Bouguer anomalies. Two main highs occur: one along the southwest peninsula, where exposures of mafic volcanic rocks are abundant, probably an ophiolite complex of Late Campanian and older age (Maurasse and others, 1977, 1979), and a second high that extends from eastern Hispaniola, north of west across the island to the northwest peninsula. The western part of this high generally coincides with the mafic metamorphic belt, and a splay high extends southeast over the main ultramafic belt. Bouguer anomaly values are considerably lower, zero to +50 mgals, over the north coast ultramafic belt. Gravity lows in south-central Hispaniola and in the northern valley of Hispaniola are generally correlated with thick sequences of low-density sedimentary rocks (Bowin, 1975, 1976). As in Cuba and Jamaica, if corrections were made for the low-density sedimentary rocks in the basins, most of the anomalies of Hispaniola would be strongly positive. Bowin has noted that parts of the island are undercompensated. Again, the gravity data strongly suggest that Hispaniola has a crust of oceanic character. Reblin (1973) calculated crustal models from gravity data that show thickness of 15 to 35 km, averaging about 25 km (fig. 12, in pocket).

The only published aeromagnetic coverage in Hispaniola of which I am aware is a detailed survey discussed by Bowin (1976). It is a map of a small area over the main serpentinized peridotite belt in the central part of the island (fig. 13). According to Bowin (1976):

> "Magnetic anomalies are associated with the serpentinized peridotite mass and clearly outline its extent."

The survey was flown at about 500 feet above the ground, and it can be seen that positive anomalies of several hundred to more than 1000 gammas occur over the belt.

Although only a few disseminated copper deposits associated with porphyry bodies have been identified in Haiti and the Dominican Republic, several base metal massive sulfide deposits occur along the "central" belt of Hispaniola (Kesler, 1978). Contact base metal-limestone replacement deposits occur in the Memé area, Haiti, which is a chalcopyrite-bearing skarn associated with a granodiorite having an age of 66 m.y. (Kesler, 1968, 1978). A few syn-volcanic manganese deposits also occur along the "central" belt in both Haiti and the Dominican Republic and on the southern Peninsula of Haiti. A base-precious metal vein-breccia pipe occurs at Mata Grande in the "central" belt. Genetic relationships, if any, of these deposits, to the mafic and ultramafic rocks are obscure.

A major lateritic nickel-iron deposit over serpentinized peridotite is being exploited in the Bonao region of the Dominican Republic in the "central" belt (Bowin, 1966; Kesler, 1978; and Guild, 1974). Guild (1974) estimated 1,000,000 short tons of nickel reserves in the Dominican Republic; Cornwall (1973) estimated 70,000,000 tons of "nickel-laterite resources."

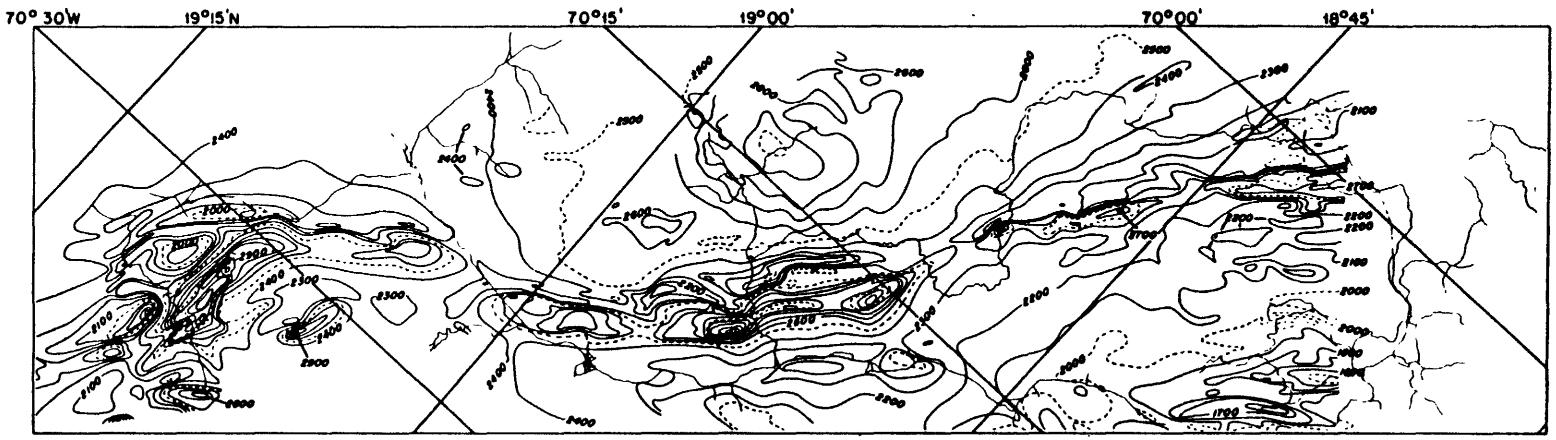


Figure 13. Magnetic field of the central Dominican Republic (from Bowin, 1976). Contour interval is 100 gammas. Data are from an aeromagnetic survey conducted in 1956 for Falconbridge Nickel Mines Limited by Aeromagnetic Surveys Limited. Mean terrain clearance was 500 ft.

A major new gold deposit has been discovered in the Dominican Republic at Pueblo Viejo. According to Guild and Cox (1977, p. 88):

> "A new mine at Pueblo Viejo in the Dominican Republic will produce about 350,000 oz. of gold and 1,500,000 oz. of silver per year when it reaches planned capacity; it will be the second largest gold producer of the Western Hemisphere (Eng. Mining Jour., October 1975, p. 71-78). The deposit consists of disseminations and veinlets of gold, auriferous pyrite, several copper sulfides, and sphalerite in a highly altered Cretaceous(?) volcanic-sedimentary series that was intruded by a quartz keratophyre. The oxidized surficial zone will be mined by open cut; it is estimated to have 30 million tons of ore containing 0.126 oz. of gold and 0.76 oz. of silver. The unoxidized material beneath it may be valuable for copper and zinc also."

Kesler (1978, p. 434), considered this deposit to be a type of massive sulfide mineralization and wrote:

> "Pueblo Viejo, the newly developed oxide gold deposit in the Dominican Republic, could underlie the probable feeder system for such a massive sulfide system [Kuroko or Noranda type] although it exhibits some peculiarities such as abundant pyrophyllite alteration. Mineralization at Pueblo Viejo occupies the uppermost part of a volcanic pile that grades from basalt to dacite and fragmental dacite (Bowin, 1966)."

Again, the geometry and timing of underthrusting (if it occurred) in Hispaniola has been the subject of an extensive controversy, as in Cuba and Jamaica (see, for example, Molnar and Sykes, 1969, Khudoley and Meyerhoff, 1971, Mattson, 1973, 1977, Bracey and Vogt, 1970, etc.). According to Bowin (1975, p. 542-543):

> "From the evidence available, I infer that from at least late Early Cretaceous time to early Maestrichtian time, lithospheric underthrusting was taking place beneath Hispaniola, and presumably from the north towards the south. The former island-arc trench edge may now be exposed in the Puerto Plata region of northern Dominican Republic. The main volcanic arc may now be exposed as the Cretaceous volcanic belt across the length of the island...."
>
> "Another fundamental question concerns the relationship of tonalite intrusions to underthrusting. Do the intrusions occur at the same time as underthrusting, only after cessation of underthrusting, or both during and after? If the range in radiometric ages for the tonalites of Hispaniola are accepted, then it is highly likely that tonalite intrusions are emplaced while underthrusting is active. If the 35 m.y. radiometric age for some tonalite bodies is verified, then some intrusions probably continued after cessation of underthrusting, which in central Hispaniola is herein inferred to have happened in late Eocene, about 40 m.y. ago. If the 35 m.y. age is not verified, then it would be likely that the acidic intrusions

require active underthrustng for their formation and emplacement."

Puerto Rico and Virgin Islands

The geologic literature on Puerto Rico and the Virgin Islands is voluminous; significant recent summaries, some of which include extensive bibliographies, have been prepared by Cox and Briggs (1973); Khudoley and Meyerhoff (1971), etc. Mafic to intermediate volcanic and volcaniclastic rocks form the backbone of Puerto Rico and the Virgin Islands (fig. 14). The volcanic rocks range from Early Cretaceous to middle Eocene in age. The older rocks tend to be spilitic, keratophyric, and marine. The younger rocks tend to be calc-alkaline, and shallow marine to subaerial. Limestones are found throughout the sequence. Numerous batholiths and smaller plutons of granodiorite, diorite, quartz diorite, gabbro, and quartz monzonite trend easterly through Puerto Rico and the Virgin Islands. Plutons in Puerto Rico tend to fall in three main age groups: 109 m.y., 88 to 65 m.y., and 46 to 38 m.y. (Cox and others, 1977).

Serpentinites and serpentinized peridotites, cherts, and a variety of metamorphic rocks, including gneissic amphibolite and metavolcanic rocks, occur in the Bermeja complex of southwestern Puerto Rico (Mattson, 1960). The oldest faunally dated rocks in Puerto Rico are the cherts in thrust zones of the Bermeja complex which contain Radiolaria of early Tithonian to late Valanginian-Hauterivian (Late Jurassic-Early Cretaceous) age (Mattson and Pessagno, 1974, 1979).

Nickel-iron-cobalt laterites occur over the serpentinites of southwest Puerto Rico. The larger ones at Las Mesas and Guanajibo contain more than 200,000 metric tons of nickel deposits (Cox and Briggs, 1973). Guild (1974) has estimated that nickel reserves in Puerto Rico are about 900,000 short tons.

Porphyry coppers are scattered through the length of central Puerto Rico (Cox and Briggs, 1973). Although not directly related to the ophiolites, the numerous copper deposits are associated with early Tertiary porphyry stocks. Because the foundation of Puerto Rico appears to be multiple oceanic crust, as discussed below, these copper deposits may have had an origin in underlying ophiolites. Deposits at Tánama and Río Viví are large enough to warrant exploitation, but environmental and other considerations have delayed development. According to Kesler (1978), the Río Viví-Tánama system was emplaced at 41 m.y. just before the cessation of volcanism in the Greater Antilles. According to Guild (1974), the copper deposits "....in Puerto Rico are of medium size, totaling about 250 million tons of 0.7% Cu." Syn-volcanic manganese deposits occur in south-central Puerto Rico, and small base metal and iron limestone replacement deposits occur in eastern Puerto Rico (Kesler, 1978; Cox and Briggs, 1973). A few small porphyry copper occurrences have been reported from the Virgin Islands, according to Kesler (1978).

Bouguer anomalies of Puerto Rico (Bowin, 1976; Shurbet and Ewing, 1956; Talwani and others, 1959, Andrew Griscom, personal communication, 1977) are all strongly positive, and range from about +95 to more than +165 mgals. Relative lows occur over the Tertiary sedimentary basins along the northwest and south-central coasts of the island. Although the positive anomalies over

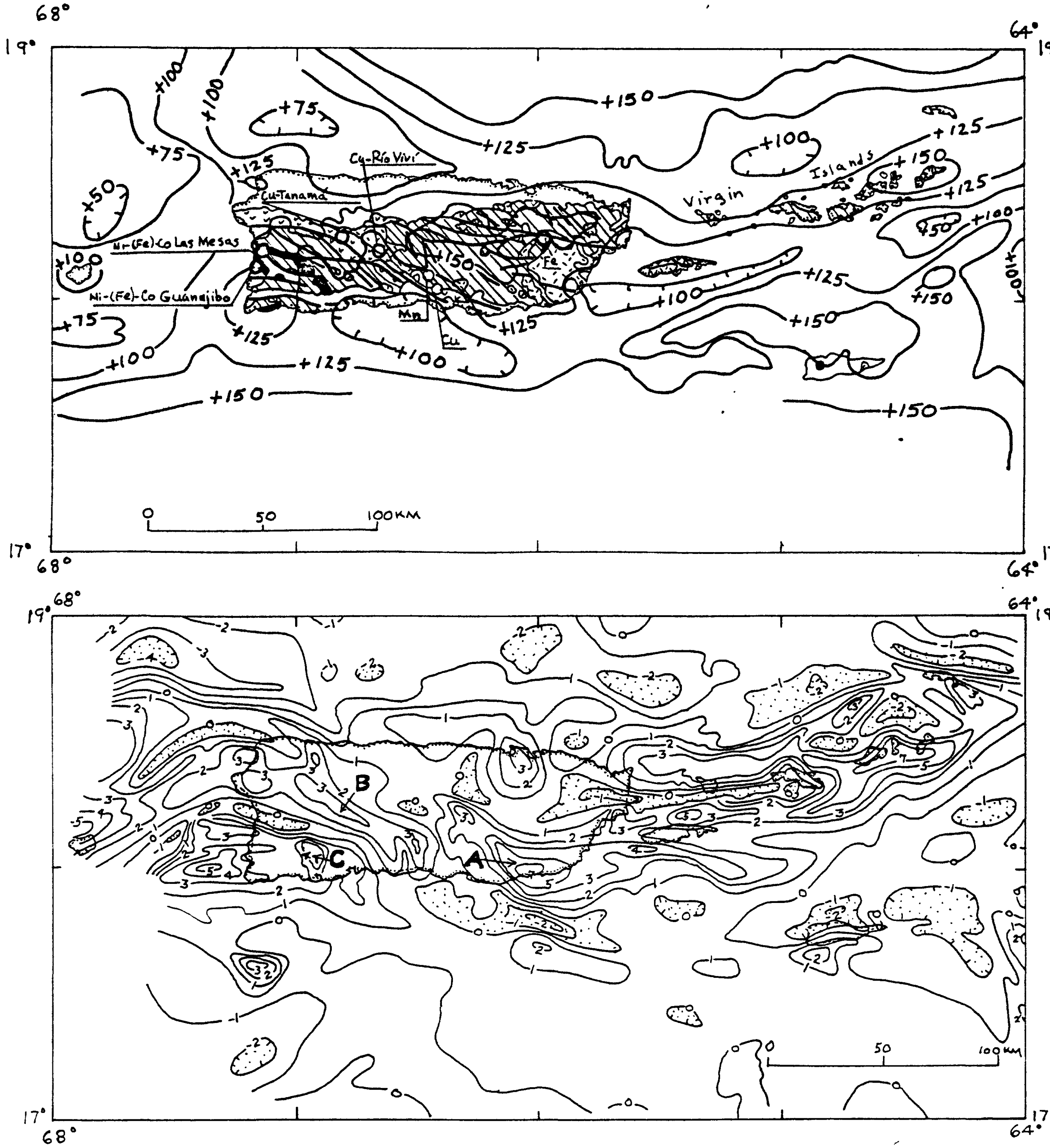


Figure 14. Upper diagram - Simplified Bouguer anomaly and geologic maps of Puerto Rico and the Virgin Islands. Dark shaded areas indicate ultramafic masses and associated ophiolitic complexes; diagonal rule indicates Cretaceous volcanic rocks, spilitic and keratophyric to andesitic; vee-pattern indicates Mesozoic-Tertiary volcanic and sedimentary rocks; dashes indicate intermediate to silicic plutons. Contour interval for Bouguer anomaly map, 25 mgals. Lower diagram - Simplified aeromagnetic map of Puerto Rico and vicinity. Contour interval 100 and 200 gammas. Stipple indicates relative magnetic low. Modified after Griscom and Geddes (1966), and Garrison and others (1972).

the island are partly edge-effects related to the proximity of the island to the Puerto Rico Trench on the north and the Muertos Trough on the south, an excess mass seems to be present. According to Bowin (1976):

> "A Bouguer anomaly high over the mountains of central Puerto Rico is shown both on the map of simple Bouguer anomalies and on maps of modified Bouguer anomalies (topographic correction through zone 0) presented by Shurbet and Ewing (1956). This high suggests that the mountains are undercompensated, and the mass anomalies across Puerto Rico shown by Talwani (1964, fig. 10) supports this view. The Bouguer anomaly high thus indicates that the large positive free-air anomaly high over the island is not entirely due to topographic effect."

As elsewhere in the Greater Antilles, the gravity anomalies suggest dense crust and upper mantle, and multiple oceanic rather than continental crust is probable. Talwani and others (1959) derived a crust thickness of 30 km from gravity data (fig. 15).

Density and magnetic properties of serpentinites in southwestern Puerto Rico have been described by Griscom (1964), Bromery and Griscom (1964), and Cox and others (1964). Bromery and Grisom (1964) found relative gravity lows of as much as 10 mgals over serpentinite bodies in the Mayagüez area of southwestern Puerto Rico (fig. 16). They assumed a density of 2.55 g/cm^3 for the serpentinite and 2.7 g/cm^3 for the Cretaceous rocks (largely volcanic) and concluded that the serpentinite body in the Guanajibo anticline extends to a depth of at least 2,800 m and that the south flank of the anticline dips more steeply than the north flank (fig. 17). They further stated:

> "Contoured gravity data along the coast between Mayagüez and Laguna Joyuda suggest that the serpentinite of the Guanajibo and Las Mesas-Fraile anticlines is connected in the form of an arcuate belt around the west end of the Hormigueros syncline."

Implicit from their interpretation is that nickel-laterites could be associated with the body, if it does continue under alluvium or the shelf deposits of the area near Mayaguez. According to Dennis and Gunn (1964), the serpentinite produces a negative magnetic anomaly with respect to the surrounding rock as revealed on a series of aeromagnetic profiles flown northeast across the northwestern end of serpentinite belts near Mayagüez. Griscom (1964), however, found that the serpentinite southwest of Mayagüez, exposed in the Guanajibo anticline, causes mixed anomalies. According to Griscom (1964): ".... line 25 is difficult to interpret, but lines 27 and 28 clearly indicate a magnetic high associated with the serpentinite." Measured values of magnetic properties, discussed by Griscom (1964) and Cox and others (1964), indicate that positive magnetic anomalies are more expectable than negative magnetic anomalies over the serpentinites.

East of Puerto Rico, a major gravity high extends along the main trend of the Virgin Islands and another over St. Croix. A major gravity low extends from the large batholith in eastern Puerto Rico, across Vieques Sound and Isla de Vieques, thus suggesting continuity of the batholith at depth.

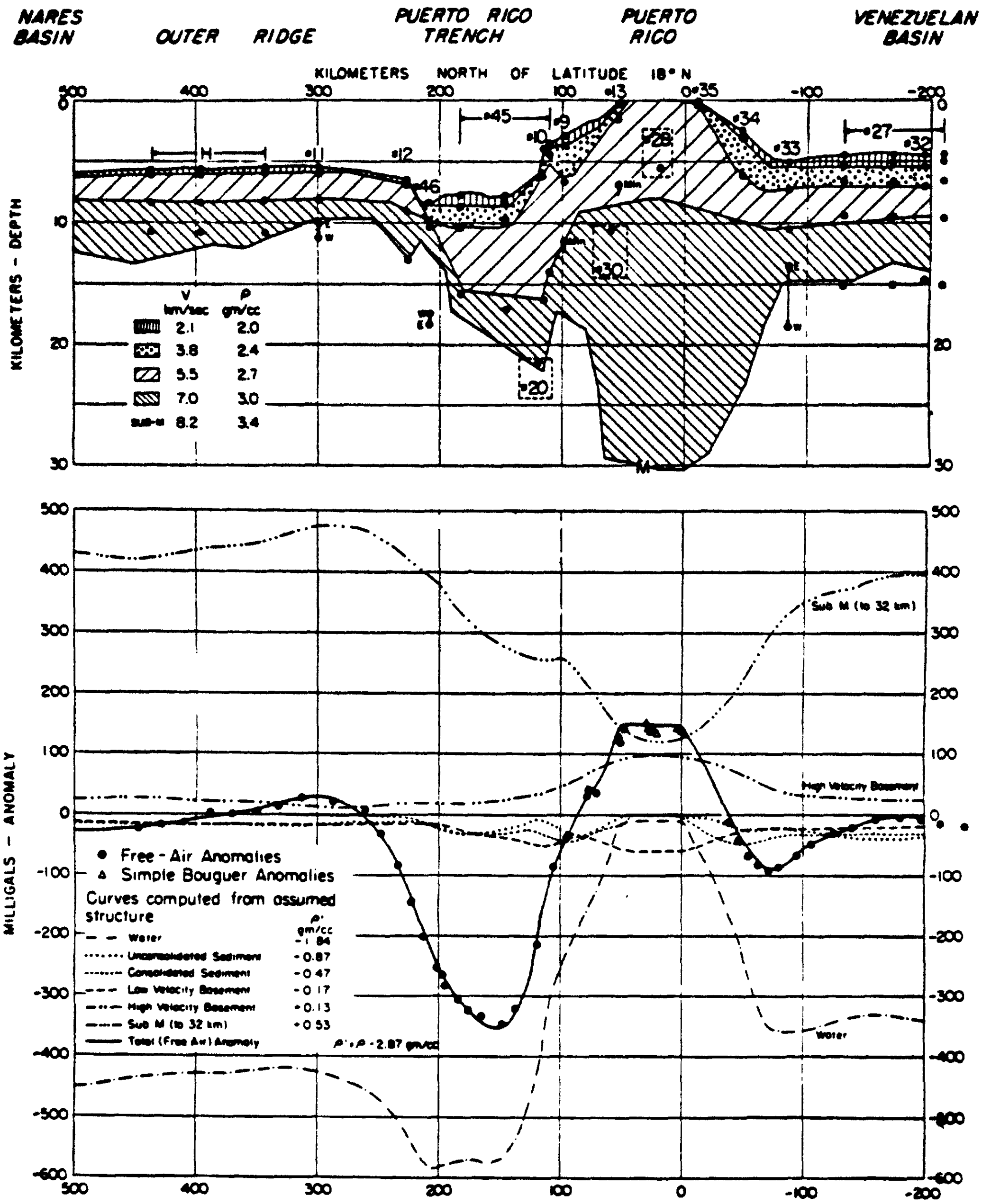


Figure 15. Crustal model across Puerto Rico (From Talwani and others (1959). Upper diagram - Computed crustal section. Crustal layering is from seismic data; M is from gravity data; points are seismic interfaces. Lower diagram - Computed attraction of layers to 32-km depth using reduced densities ρ'. Solid curve is total attraction (computed free-air anomaly) which is compared with observed anomalies.

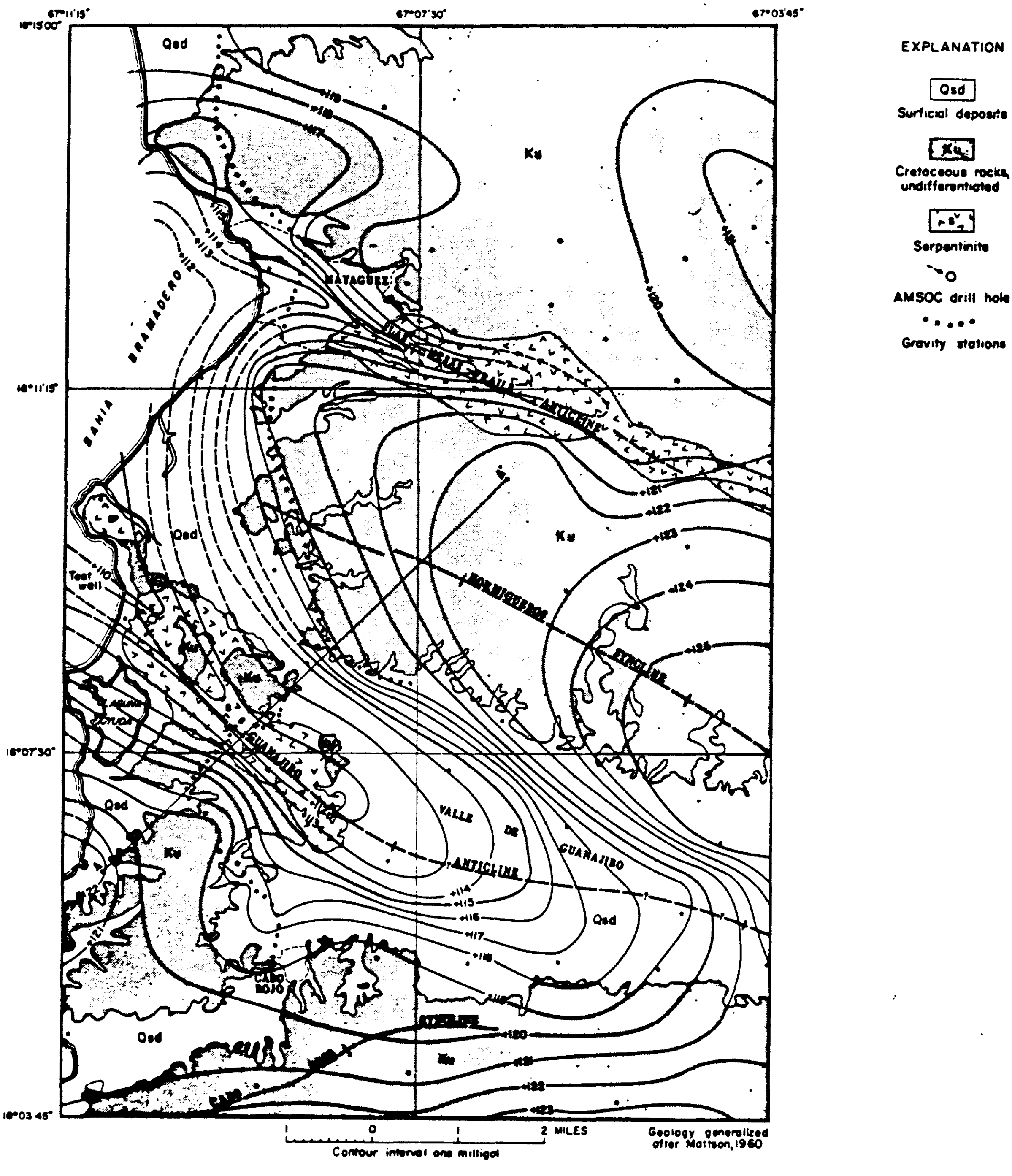


Figure 16. Simple Bouguer gravity map of southwest Puerto Rico (from Bromery and Griscom (1964). Contour interval 1 mgal.

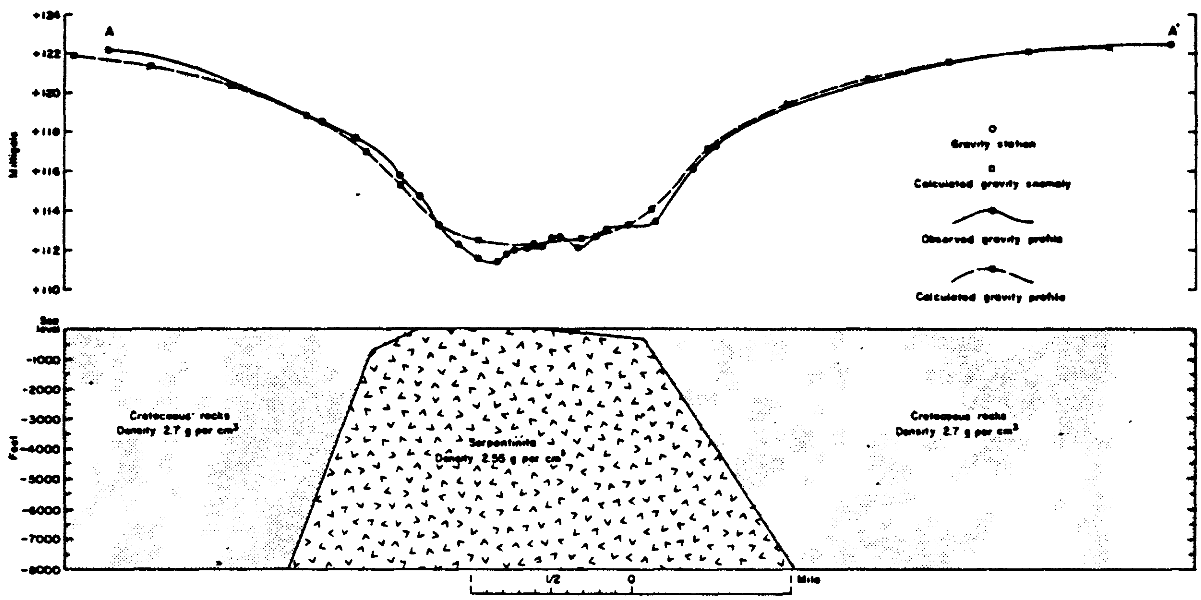


Figure 17. Calculated section A-A' across the Guanajibo anticline (from Bromery and Griscom, 1964)

The regional aeromagnetic map (fig. 14) has been interpreted by Griscom and Geddes (1968). They stated that:

> ".... the Puerto Rico-Virgin Island Platform is characterized by typical high-amplitude, closely spaced anomalies expectable over volcanic and plutonic rocks which are at or near the surface."

The most conspicuous magnetic high, A, figure 14, up to 700 gammas in amplitude, occurs over Cretaceous volcanic rocks, but locally over gabbroic rocks in southeastern Puerto Rico. A second major high, B, having anomalies up to 300 gammas in amplitude, occurs over a belt of early Tertiary volcanic rocks that trends northwest across western Puerto Rico. A large high, having values up to 400 gammas, occurs over Cretaceous volcanic rocks and serpentinite in southwestern Puerto Rico. Most of the granitic plutons, at this scale, do not appear to cause positive anomalies. Because many of them have experienced strong hydrothermal alteration (Cox and Briggs, 1973), original magnetite, if present, may have been converted to nonmagnetic alteration products

Lesser Antilles-La Désirade

The Lesser Antilles are a volcanic arc comprised mainly of calc-alkaline rocks of Eocene-Recent age (fig. 18, in pocket). According to modern schemes of plate-tectonics, the volcanic arc is caused by melting associated with under-thrusting of the Caribbean plate by the Americas plate. No ophiolites are known from the Lesser Antilles except at the small island of La Désirade, east of Guadeloupe, where Fink (1970) discovered spilitic pillow basalts, chert, quartz keratophyre, and trondhjemite. The trondhjemite was reported to have a Late Jurassic isotopic age (Fink and others, 1972), but Dinkelman and Brown (1977) suggested that the age of the quartz-keratophyres (87 $\pm$ 3 m.y., early Late Cretaceous) should be used as an upper limit to the age of the ophiolite suite in any model of Caribbean tectonic evolution. Fox and Heezen (1975) reported on dredge hauls of basalts--metamorphosed to greenschist facies-- gabbros, and intermediate plutonic rocks on scarps near La Désirade:

> "The mineralogy and mafic textures are similar to greenschist metabasalts and metagabbros recovered from fracture-zone escarpments of the Mid-Ocean Ridge system."

Nagle and others (1973) have reported that native copper occurs in hematite-rich spilitic amygdaloidal pillow basalts on the east coast of La Désirade. The copper-bearing flows contain 0.5-1.5% Cu, but not all flows carry copper.

Free-air, Bouguer, and isostatic anomalies are all strongly positive over the main Lesser Antilles arc (fig. 18; Andrew and others, 1970) and a second prominent Bouguer anomaly high lies to the east, generally about 50-80 km from the islands (Peter and Westbrook, 1976; fig. 18). This high is present near La Désirade and it is possible that a belt of these older mafic rocks causes the high that extends southward to the latitude of St. Lucia. Magnetic coverage is poor near La Désirade (Matthews, 1976, Peter and Westbrook, 1976).

The positive gravity anomalies over the Lesser Antilles and vicinity indicate dense crust and(or) upper mantle (Case, 1975, Bowin, 1976). The zone of positive gravity anomalies extends southwest to at least the island of Margarita. Limited refraction data, summarized by Case (1975), Westbrook and others (1973), and Westbrook (1975), indicate that the crust is thickened to as much as 30-35 km beneath the Lesser Antilles (fig. 39). Two modern crustal models across the arc are shown on figures 19 and 20 and some older models on figure 21.

Fink (1971) originally speculated that the La Désirade suite of volcanic rocks was an ancestor of the Lesser Antilles formed in place by submarine extrusions. Later, Nagle and others (1973) suggested three possible origins:

> "The igneous basement may represent autochthonous oceanic crust on which the basalt part of a volcanic ridge was constructed early in the development of the Lesser Antilles, then uplifted by post early Miocene faulting into its present position.... A second possibility is allochthonous oceanic crust obducted into its present position by sea floor spreading. The third alternative is that the basement rocks of La Désirade represent the continuation of the Greater Antilles (Fink, 1970; Fink and others, 1972; Meyerhoff and Meyerhoff, 1972)."

Fox and Heezen (1975) speculated that these rocks represent pieces of ridge-formed oceanic crust that were tectonically emplaced along the subducting margin of the Lesser Antilles.

Trinidad and Tobago

Small ultramafic masses on Tobago (fig. 22), areally associated with schists and diorite, have been described by Maxwell (1948). These rocks consist of augite peridotite, serpentinite, and rare pyroxenite. Maxwell (1948) regarded these masses as intrusive. The metamorphic basement contains metavolcanic rocks--greenschists, greenstones, and amphibolites of presumed Mesozoic age. No significant mineral deposits were reported for these rocks by Maxwell.

In a more recent reconnaissance study, MacGillavry (1977) found that the ultramafic rocks are typical cumulates: cumulate phases include olivine + chromite, and olivine + chromite + ortho- and clinopyroxene. Intercumulate phases are orthopyroxene, ortho- and clinopyroxene, or clinopyroxene. A main conclusion was:

> ".... that the entire succession of pre-Tertiary rocks on Tobago belongs to the oceanic realm....
> The succession consists of:
> 1. An older island arc or inter-arc sequence of cherts and albitic volcanics plus intrusive amphibole albitites;
> 2. A series of cumulates with amphibolite locally at its base;
> 3. A series of volcanics including pillow lavas and breccias and the more acid rocks of Hawk's Bill and Rocky Point, all intruded by dikes of dioritic composition.
>
> These rocks have been subjected to a complex succession of movement and metamorphism."

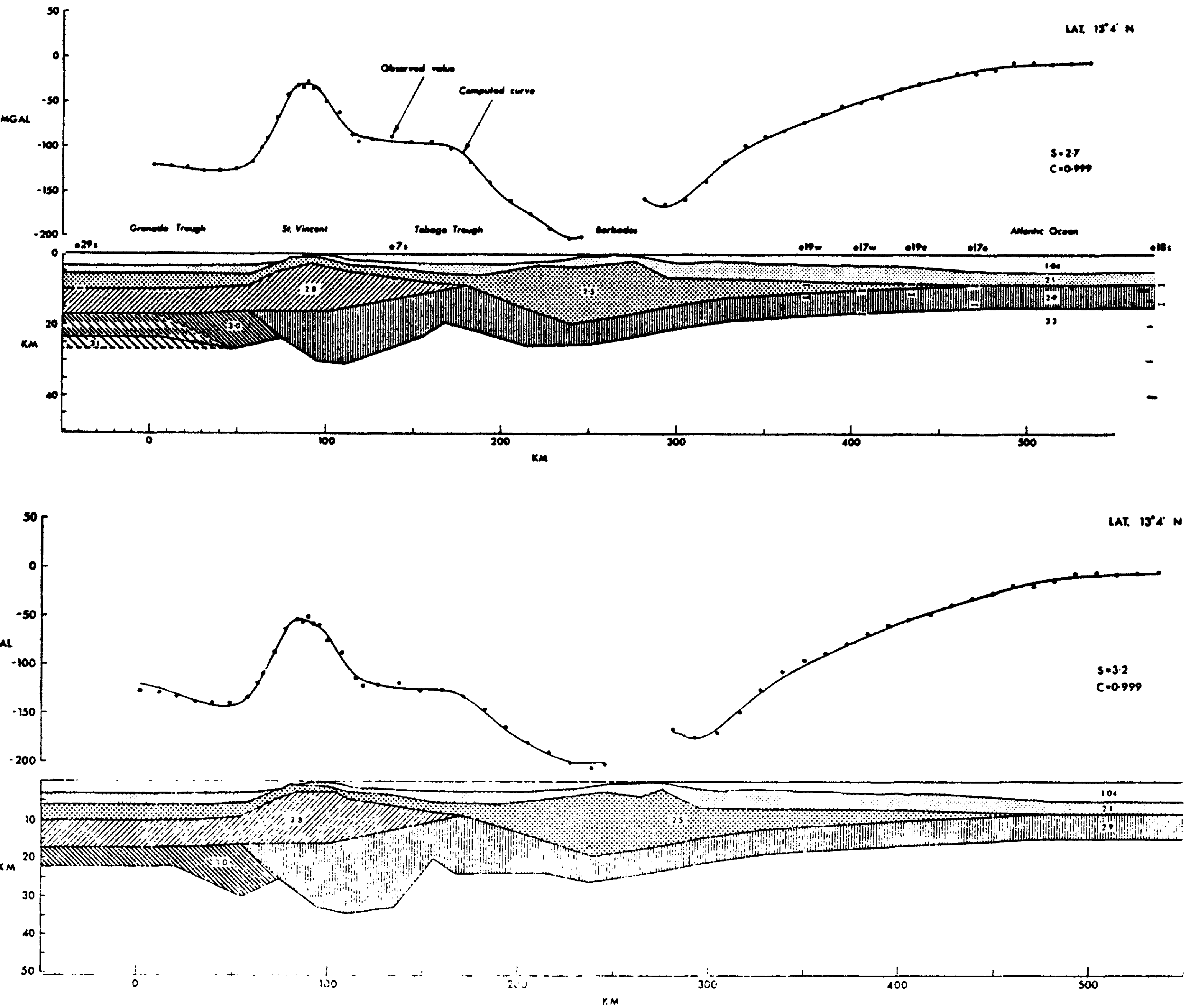
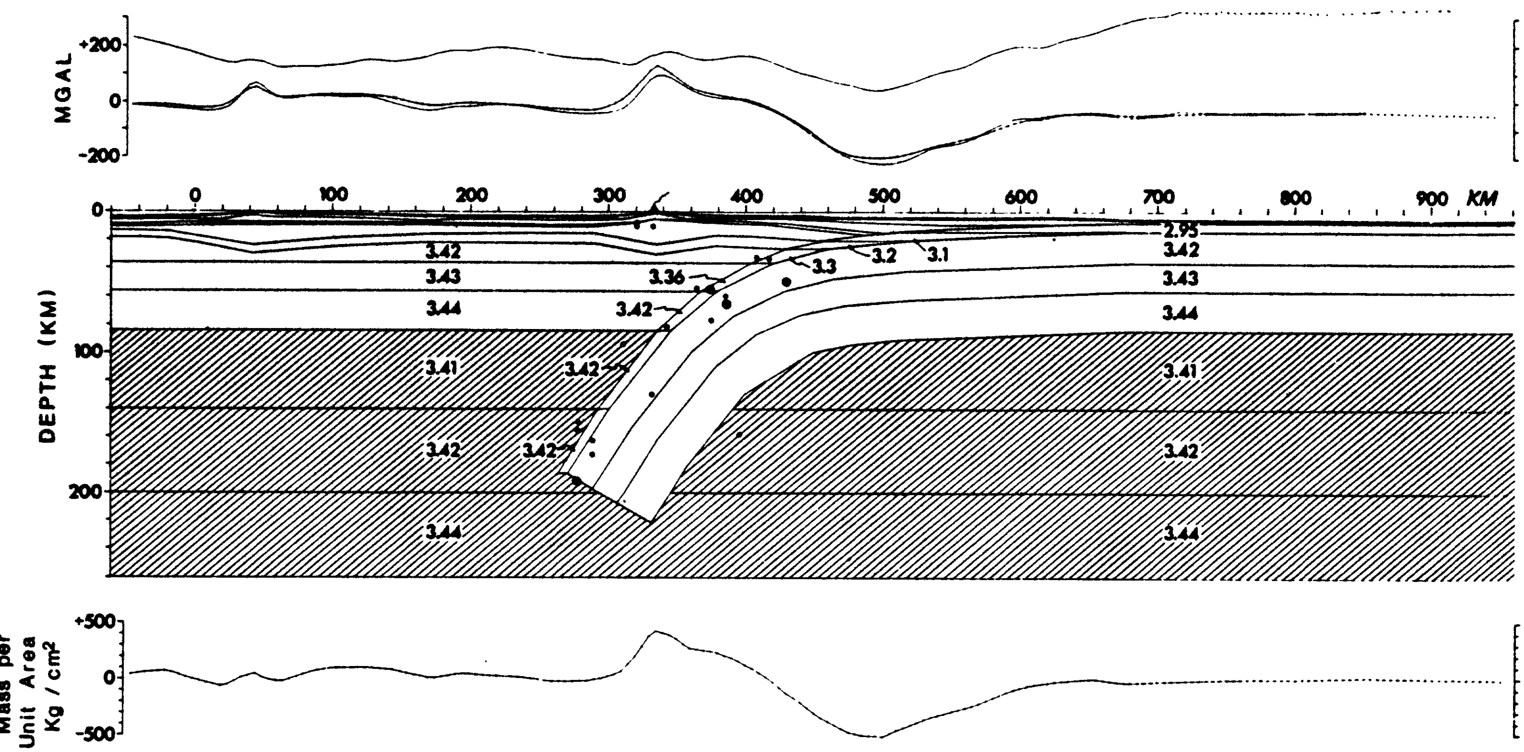


Figure 19. Two models of crustal structure across the Lesser Antillean arc at $13^{\circ}4'N$ (from Westbrook, 1975). Upper diagram - Model derived from gravity and seismic data. Dots are observed values of the Bouguer gravity anomaly (correction density = 2.1 g/cm^3). The continuous curve is the anomaly calculated from the model. Bodies of different density are shown with different ornament, with the values indicated. The short bars below letters and figures such as e17w indicate the depths of layers determined by the seismic refraction lines of Ewing and others (1957). C is the correlation coefficient between the observed and computed gravity anomaies. S is the standard error. Horizontal scale is kilometers east of long. $62^{\circ}W$. Vertical exaggeration 2:1. Lower diagram-Crustal model of the arc at lat. $13^{\circ}4'N$, derived using a Bouguer anomaly (correction density = 2.1 g/cm^3) from which the gravity anomaly caused by lithosphere subducted to 200 km has been removed.

Figure 20. Upper diagram - Model of crustal structure across Lesser Antillean island arc along lat. 14°14'N (from Bowin, 1976). No vertical exaggeration. Density gradient in mantle of lithosphere is simulated by three layers with increasing density with depth. Low-density zone (asthenosphere) indicated by inclined ruling. Above model, upper profile is complete Bouguer gravity anomaly, calculated assuming two-dimensionality of the bathymetry; lower solid line is free-air gravity anomaly; solid line with dots is free-air anomaly calculated from model. Profile of mass per unit area (below model) is calculated from model; value referenced to zero is typical and occurs at both ends of model. Dots in model indicate location of earthquake hypocenters from January 1, 1961, through September 17, 1968. Volcano symbol indicates location of active volcanism on island arc. Only data within 100 km of lat. 14°14'N have been projected into model.

Lower diagram - The same model as in the upper diagram is plotted with 5x vertical exaggeration to show details in upper 40 km. Large-sized numbers give density values in grams per cubic centimetre. Small-sized numbers are seismic-refraction velocities in kilometres per second. Velocities less than 4.0 km/sec are not indicated. Vertical lines indicate location of seismic-refraction profiles. Heavy line in model is Mohorovičić discontinuity; heavy dots and volcano symbol as in figure above.


MGAL
+200
0
-200
DEPTH (KM)
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600
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800
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KM
2.95
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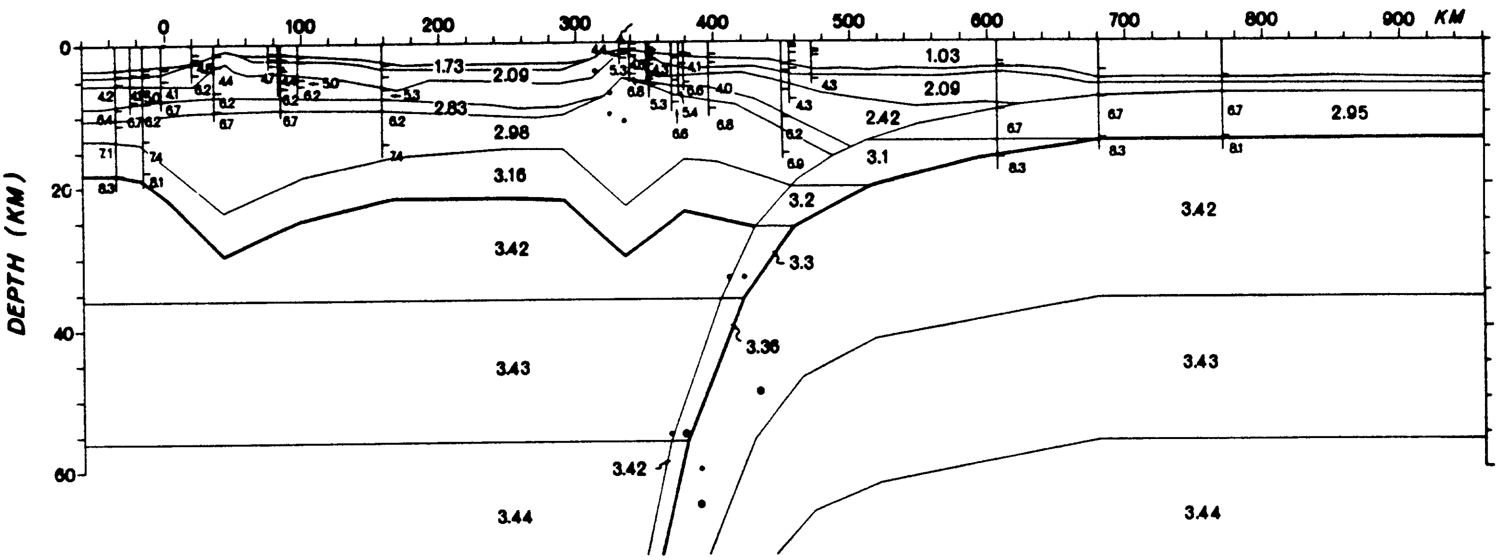
3.3
Mass per Unit Area Kg / cm²
+500
-500


DEPTH (KM)
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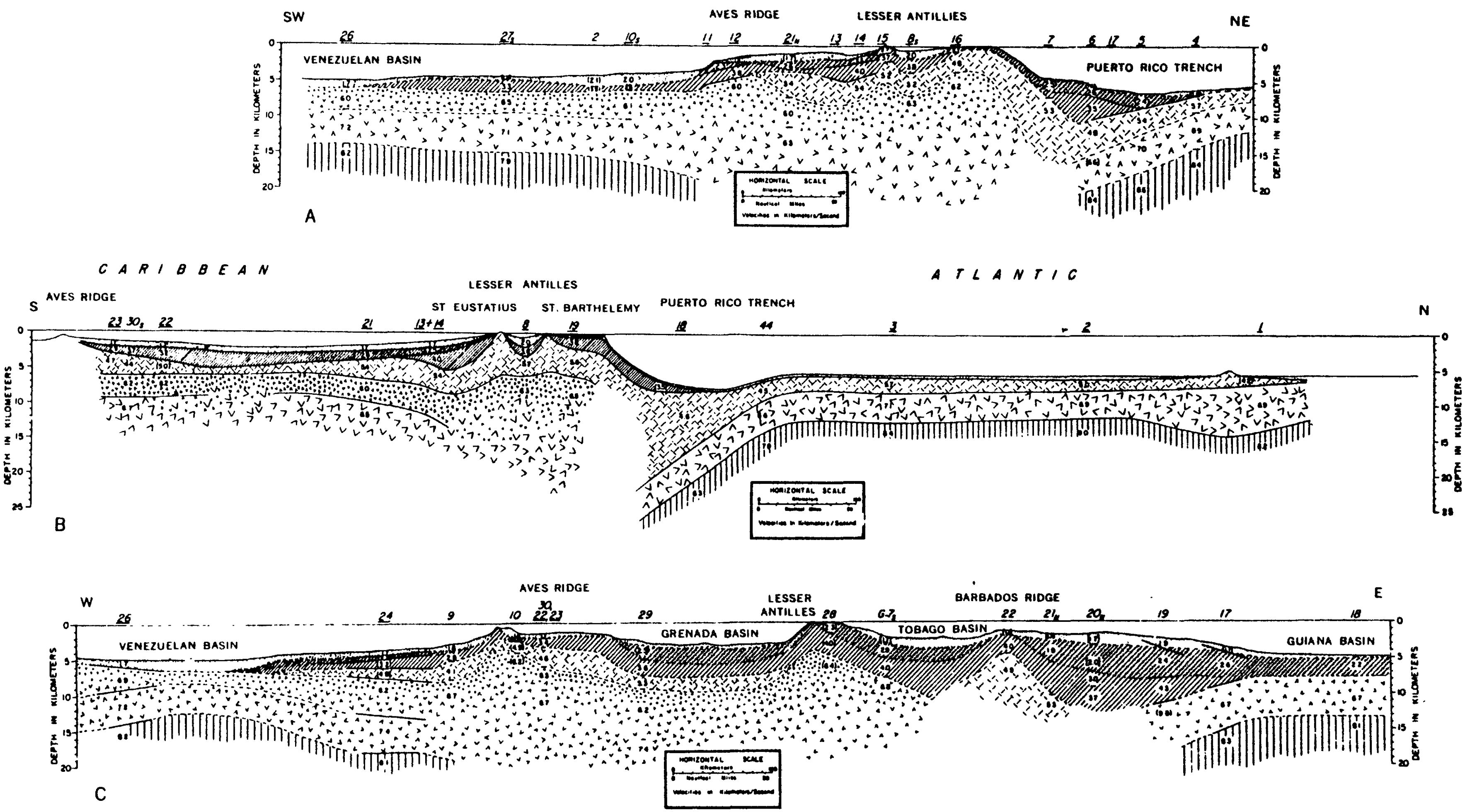


Figure 21. Representative crustal models across the Lesser Antilles. Lines of profiles shown on figure 39. From Officer and others (1959).

These rocks have been subjected to a complex succession of movement and metamorphism."

No ultramafic rocks have been reported from the northern range of Trinidad, although the range is comprised of a wide variety of Mesozoic metamorphic rocks of variable grade, similar to those of the Venezuelan coastal ranges.

Unfortunately, magnetic surveys flown by the United Nations (fig. 22) appear to have stopped just short of the ultramafic bodies in Tobago. Most of the central and southern parts of the island are associated with a negative magnetic anomaly of several hundred gammas, and it might be postulated that the Mesozoic granitic pluton there is reversely magnetized. Most of the north range of Trinidad is magnetically flat, but an elongate magnetic high of up to three hundred gammas trends northeast off the north coast of the island, and this anomaly could well be caused by concealed ultramafic masses.

No special gravity anomalies appear to be associated with Tobago or with the north range of Trinidad (fig. 22). Although Bowin (1976) contoured a free-air high of +75 mgals over Tobago, his compilation showed only one station, having a value of +12 mgals, on the island, and offshore surveys near the island are weakly positive or negative. The compilation of Bonini and others (1977) shows a gravity high of +50 mgals off the east coast of Tobago. From gravity data, Folinsbee (1972) derived a crustal thickness of 20-25 km across Trinidad.

Venezuela and Netherlands Antilles

Phanerozoic mafic and ultramafic belts of Venezuela occur mainly along the Caribbean coastal ranges, on the Netherlands and Venezuelan Antilles, and on the island of Margarita (fig. 23, in pocket). A few isolated masses occur on the Paraguaná Peninsula, in the Falcón Basin, and south of the Cordillera de Mérida. Virtually all of the ultramafic bodies are associated with metasedimentary and metavolcanic rocks, largely of Mesozoic and Mesozoic(?) age, which range from zeolite to amphibolite facies. Some ultramafic masses occur south of the coastal range in and adjacent to the Villa de Cura belt, a mafic metavolcanic sequence that includes rocks of blueschist facies (Shagam, 1960).

Rather extensive studies of many of these bodies have been conducted by geologists from various universities, especially Princeton University. A summary review of the overall regional geologic setting, geochemical aspects of serpentinization and laterization, and the associated mineral deposits was prepared by Bellizzia (1967). The literature on these rocks is extensive and growing rapidly. Many of the papers cited in this review include rather complete bibliographies. A preliminary metallogenic map of Venezuela has been prepared by Martín (1975).

González de Juana and Muñoz (1971) have reported seven ultramafic masses on the Paria Peninsula of northeastern Venezuela. Quoting from their abstract:

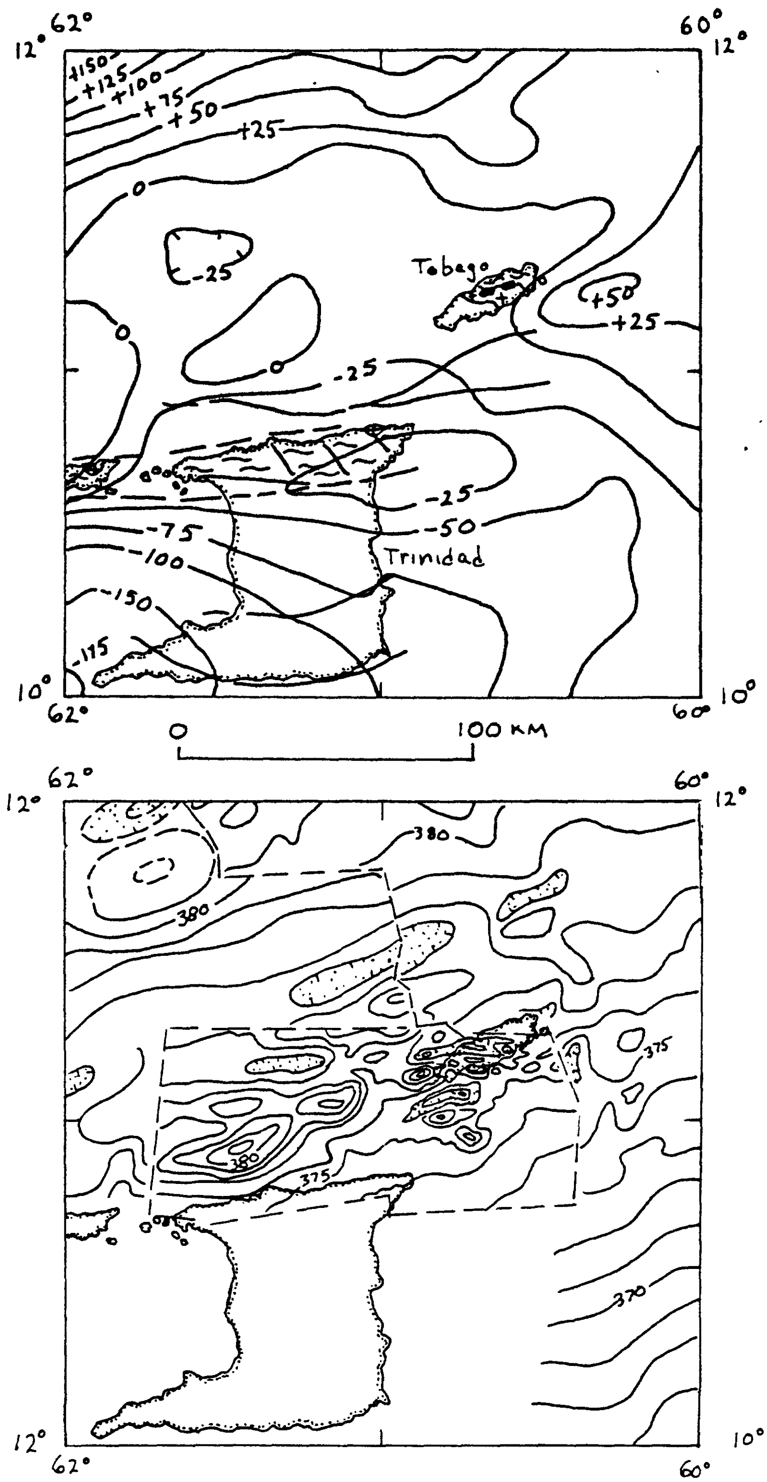


Figure 22. Upper diagram. Simplified geologic and Bouguer anomaly map of Trinidad and Tobago and vicinity. Pluses indicate granitic bodies, lazy-s pattern indicates metamorphic rocks, and dark shade in upper diagram indicates ultramafic masses on Tobago. Gravity data modified from Bowin (1976) and Bonini and others (1977); contour interval 25 mgals. Lower diagram. Magnetic anomaly map in vicinity of Trinidad and Tobago. Modified after Matthews (1976). Relative negative magnetic anomalies in stipple pattern. Contour interval 100 gammas. Survey near land area is an aeromagnetic survey.

"The rocks are almost exclusively pyroxenic peridotites, serpentinized to a high degree and mostly composed of antigorite, chrysotile, and bastite, showing relic structures of olivine and pyroxene. The pyroxenite found at Cabo Tres Puntas.... is not serpentinized and is essentially composed of diopsidic augite and actinolitic tremolite, resulting from altered pyroxene.

"The serpentinized bodies intrude quartzites and quartz-chloritic or quartz-graphitic schists. No true contact aureole has been observed, but some of the contact meta-sediments have been altered by the ultramafics. The intruding rocks are considered synorogenic, associated with other plutonic peridotites known in the Venezuelan Coast Ranges."

They concluded that the age of intrusion was post-Albian and probably pre-Paleocene.

Seijas (1972) has described amphibolitized pyroxenite and numerous small serpentinite bodies in the region between the Paria and Araya Peninsulas.

Farther west, on the Araya Peninsula, Schubert (1972, p. 1855-1857) has described numerous small bodies of serpentinite and serpentinized peridotite that trend ENE, south of a fault that separates chloritic phyllites from calcareous quartz-mica schists. The serpentinites include mainly antigorite, chrysotile, and chlorite with some sphene, magnetite, and local iron oxides; some chromite occurs, and relict subhedral pyroxene crystals are common. Schubert did not report any significant mineral deposits for these bodies. He regarded the serpentinites as being of alpine type, and many are associated with fault zones.

To the north, on the island of Margarita, Hess and Maxwell (1949), Taylor (1960), González de Juana (1972), Maresch (1972a,b), and Iturralde de Arozena (1972) have described various aspects of the ultramafic bodies that comprise much of the western part of the island. Most of the ultramafic bodies appear to intrude metamorphic sequences which range from greenschist to garnet-bearing amphibolite facies. Maresch (1972b) recognized eclogitic amphibolites on the island. The metamorphic rocks, described rather completely by Taylor (1960), have an extremely varied lithology, which suggested to Taylor that Margarita was the scene of complex sedimentary deposition and volcanic activity during the Mesozoic (eugeosynclinal).

Taylor (1960) recognized pyroxenite, dunite, and peridotite, having variable degrees of serpentinization, and serpentinite. These bodies appear to intrude the basal metamorphic complex. Localization along faults is less common than in other areas of Venezuela. Taylor regarded the time of emplacement as probably middle to Late Cretaceous, and he regarded most of the bodies as alpine peridotites of high temperature origin. Various granitic to dioritic plutons cut the ultramafic complexes, and Santamaría and Schubert (1974) reported ages of 70-72 m.y. for a sodic granite and trondhjemite from the island. A pegmatite yielded an age of 32 m.y.

Bellizzia (1967) reported that deposits of magnesite on Margarita are associated with several of the ultramafic bodies, and they occur as veins and irregular masses in the serpentinized rocks. Until 1953, about 36,000 metric tons of ore having an average of 45 percent MgO, had been exploited. Only minor mining activity was occurring in 1967, but as much as 5,000,000 metric tons of magnesite may occur in Loma de Guerra. Minor occurrences of nickel-cobalt-chromite were reported by Taylor (1960), but commercial deposits have not been found. A few very small occurrences of talc and asbestos were reported by Taylor.

Excellent recent discussions of the western Caribbean mountain belt of Venezuela have been presented by Bellizzia (1972) and Bell (1972). The Caribbean coastal ranges include several great orogenic belts, most of which contain ultramafic masses. The most northerly belt is a complex of Mesozoic metasedimentary and metavolcanic rocks of greenschist to amphibolite facies. A belt of Paleozoic gneissic rocks occurs south of Lago de Valencia. Farther south is a belt of Mesozoic metamorphic rocks (amphibolite facies), and still farther south is the great Villa de Cura belt, a complex of metavolcanic rocks of blueschist to prehnite-pumpellyite metagraywacke facies (Bell, 1972, p. 372). Along the south edge of the range is the folded and thrust foothills belt, and most of the thrusts dip northerly. Much evidence exists that the Villa de Cura belt has been transported from north to south (Bell, 1971, 1972), and Bellizzia (1972) has postulated that the entire Caribbean Mountain Belt is allochthonous. Much of the thrusting occurred during Paleocene-Eocene time, because thrust blocks are embedded in flysch of those ages.

Numerous granitic plutons cut the metamorphic rocks and their ages range from about 30 to 79 m.y. according to Santamaría and Schubert (1974).

Only a few of the many ultramafic masses of the central ranges will be discussed in this review. As Dengo (1972) has pointed out:

> "In this area the serpentinites are found as sills within metasedimentary rocks (Dengo, 1953), as lenticular tectonic intrusions along faults and foliation planes (Smith, 1953, Shagham, 1960; Bellizzia, 1967), as high-temperature intrusives such as those at Tinaquillo (MacKenzie, 1960) and as exotic masses associated with large allochthonous blocks of metavolcanic rocks (Menéndez, 1966; Bell, 1972)."

One of the most intensively studied bodies is that at Loma de Hierro, about 50 km southwest of Caracas (Lavie, 1967). This body is one of a string of ultramafic bodies which are elongate ENE, along one or more large faults. Loma de Hierro is the site of the major nickel-laterite deposit of Venezuela. The body proper is about 21 km long, strikes N70°E, and has a breadth of 1 to 5 km. The rock is serpentinized harzburgite (M. de Graterol, 1967) and of relatively uniform mineralogical composition. It is composed chiefly of crysotile, antigorite, and serpophite, vestiges of olivine and enstatite, with accessory chromite and magnetite. The serpentinites have been cut by dikes of pyroxenite and gabbro related to younger igneous activity.

The nickel-bearing lateritic mantle covers about 600 hectares and has a mean thickness of 6.36 meters (Lavie, 1967). It has been estimated that the district contains about 55 million tons of ore, averaging about 1.53 percent nickel. Guild and Cox (1977) have estimated that Venezuela has reserves of about 1,000,000 short tons of nickel. Cornwall (1973) estimated 60,000,000 tons of 1.6 percent ore at Loma de Hierro. As far as is known, no substantial quantities of ore have been actually produced from Loma de Hierro.

Tinaquillo, southwest of Lago de Valencia, is an unserpentinized to partly serpentinized peridotite body that occurs as a sill that has intruded hornblende gneisses (probably of Paleozoic age). It is cut off on the north by a major south-dipping thrust. Most of the mass is dunite, but about 10 percent is serpentinized dunite and thin layers of pyroxenite and amphibolite. The dunite contains about 10 percent of lamellar enstatite. The peridotite contains inclusions of gneissic hypersthene gabbro. From study of contact effects, MacKenzie (1960) concluded that the body was emplaced as a high-temperature (1000°C) alpine-type body; this interpretation is disputed by some geologists, however.

Asbestos deposits were exploited from Tinaquillo for many years, but they were not being exploited in 1967 while further exploration was being conducted. Pasquali (1967) has studied the lateritic nickel deposits associated with Tinaquillo and concluded that in situ lateritic materials with good drainage might offer possibilities for the economic extraction of nickel.

Farther west, a small ultramafic mass near La Bimba intrudes a metamorphic complex of green schists, quartz-mica schists, graphitic schists, and crystalline limestones. Talc deposits are associated with the serpentinized ultramafic mass and occur as discontinuous lenses of about 5 meters thickness (Martín Bellizzia and Bellizzia, 1967). The talc occurs as steatite or saponite. From the occurrence of skeletal crystals of olivine and enstatite, the authors concluded that the original rock was a peridotite and that formation of the talc occurred after the main mass was serpentinized. More recent detailed descriptions of the talc deposits have been presented by Rodriguez (1976b).

Several enigmatic ophiolite bodies occur in the Falcón Basin. These have been briefly described by Bellizzia and others (1972). They are embedded in Paleocene-Eocene turbidites, essentially in a melange or olistostrome that contains blocks from several different geologic provinces. The melanges include mainly three types of rocks: (a) spilitic pillow basalt, tuff, gabbro, anorthositic gabbro, serpentinized olivine gabbro, and serpentinized peridotites which represent fragments of oceanic crust; (b) chert, limestone, siltstone, and phyllites from the formations La Luna and Barquisimeto (Late Cretaceous) and (c) turbidites of the Matatere Formation [Paleocene-Eocene]. Bellizzia and others regarded these occurrences as allochthonous and derived from a ".... trace or suture of an ancient Benioff zone of Late Mesozoic age, developed north of the present coast of Venezuela"[a free translation]. Some of the cherts are radiolarian, and preliminary indications are that some are of late Paleozoic age and others are of late Mesozoic age (D. L. Jones, personal communication, 1979).

Several zoned ultramafic complexes of Alaskan or Uralian type have been identified in Venezuela. Murray (1972, p. 314-315) has described the complexes of El Chacao and Cerro Pelón of the Serranía del Interior:

> "The [El Chacao] complex is an irregularly shaped body 8 km long and 6 km wide which intrudes the volcanic Villa de Cura Group of probable Lower Cretaceous age. It is divided into two parts by a narrow belt of contact metamorphosed rocks. In both parts of the intrusion, central cores of olivine pyroxenite consisting of about 75 percent clinopyroxene and 25 percent olivine with minor hornblende and opaque minerals are surrounded by hornblendite. The transition between these rock types is gradational through intermediate types such as pyroxenite, hornblende pyroxenite, and pyroxene hornblendite.... The appearance of abundant hornblende is accompanied by .... substantial quantities of magnetite, which forms a nearly constant proportion (about 15 percent) of all the hornblende-rich ultramafic rocks.
>
> "Wherever the contact with the enclosing Villa de Cura Group is exposed, either hornblendite or hornblende gabbro is the marginal rock type of the intrusion. Dikes of hornblende gabbro cut the other rock types of the igneous complex and the surrounding metamorphic rocks...."

Nearby masses of hornblende gabbro and hornblende-pyroxene diorite, intrusive into keratophyric-spilitic sequences of the Villa de Cura Group, have been described by Rodriguez (1976a). Some magmatic segregation of titanium-rich magnetite has occurred and some pyrite-pyrrhotite-chalcopyrite mineralization is present.

The other mass at Cerro Pelón (Murray, 1972, p. 325):

> "....is an elliptical body 2 km long and 1.5 km wide consisting of a dunite core (which makes up about half the area of the mass) surrounded by successive zones of pyroxenite and hornblende gabbro.... The dunite is cut by veins and dikes of pyroxenite and by dikes of coarse grained hornblende gabbro. Gabbro dikes also cut pyroxenite. In contrast to the El Chacao intrusion, where hornblende-bearing rocks make up the bulk of the body, the hornblende gabbro at Cerro Pelón forms only a narrow outer rim to the complex.
>
> "Contact metamorphic rocks were found at the margins of the Cerro Pelon intrusion at a few localities. It intrudes low-grade regional metamorphic rocks characteristic of the Los Cristales Group of Lower Cretaceous age (Bellizzia and Rodriguez, 1968)."

Murray postulated that zoned complexes represent feeder pipes of andesitic volcanoes.

Two distinct petrogenetic associations of mafic-ultramafic complexes occur on the Paraguaná Peninsula: (a) the zoned ultramafic complex of Tausabana-El Rodeo, associated with the zoned olivine-anorthosite gabbro of

Sibara-Capuana and (b) the stratified subvolcanic complex of gabbroic basalt of Santa Ana, according to Martín Bellizzia and de Arozena (1972).

The main ultramafic mass has the form of an irregular ellipse about 8 km long and 2.5 km wide, and includes, from the center to the periphery, dunite with boudins or truncated lenses of chromite, harzburgite-lherzolite, olivine pyroxenite, hornblende pyroxenite and a marginal intrusion of pegmatitic pyroxene-hornblende gabbro or gabbroic pegmatite on the southern border. In addition to the chromite (evidently not economic at present), minor asbestos deposits have been found.

Metamorphosed mafic volcanic rocks are exposed on many of the Venezuelan islands: from west to east they have been reported from Los Monjes, Los Roques, and La Orchila (where small ultramafic bodies also occur). Most of these are thought to be Mesozoic in age.

In the Netherlands Antilles (Beets, 1972), metamorphosed mafic volcanic rocks have been described from Aruba where schists contain Turonian(?) ammonites and are intruded by a diorite batholith with an age of about 73 m.y. (MacDonald and others, 1971). Tholeiitic pillow basalt and diabase are widely exposed on Curaçao, and ammonites from thin pelagic intercalations in the Curaçao Lava Formation are of Middle Albian age (Wiedmann, 1978). Similar rocks are exposed on Bonaire. Middle(?) to Late Cretaceous fossils (Beets and others, 1977) have been found in sedimentary rocks associated with these mafic rocks on Bonaire (Beets and MacGillavry, 1976, 1977).

Gravity studies in Venezuela and vicinity

During the interval 1968-1978 an enormous quantity of modern gravity data was obtained in Venezuela and vicinity--both onland and offshore. Bonini and others (1977) have presented a Bouguer anomaly map of northern Venezuela and vicinity which includes much of the data, although some revisions may be required in offshore areas (fig. 23). Bowin (1976) presented both free-air and Bouguer anomaly maps. Because only two onland crustal refraction studies have been made in northern Venezuela as of 1977 (Gettrust and others, 1978), the gravity data, combined with inferences from known geology, provides the main basis for estimates of crustal thickness and composition. A subjective discussion of inferred crustal setting of various mafic-ultramafic belts will start in the north, over the Netherlands and Venezuelan Antilles, and progress southward.

Most gravitational crustal models across the area have been tied to crustal structure in the Venezuelan Basin to the north (fig. 39) determined by refraction surveys (Edgar and others, 1971, Ludwig and others, 1975). The crust there averages about 14 km (depth to the M-discontinuity is 15-20 km).

The major gravity high along the Netherlands and Venezuelan Antilles (figs. 23-26) suggests that the crust is dense (oceanic) and is perhaps as much as 30 km thick (Worzel, 1965; Silver and others, 1975; Bonini and others, 1977, Folinsbee, 1972). The crust thins to about 20 km under Bonaire Basin (whether it is oceanic or continental is not defined). Beneath the Venezuelan

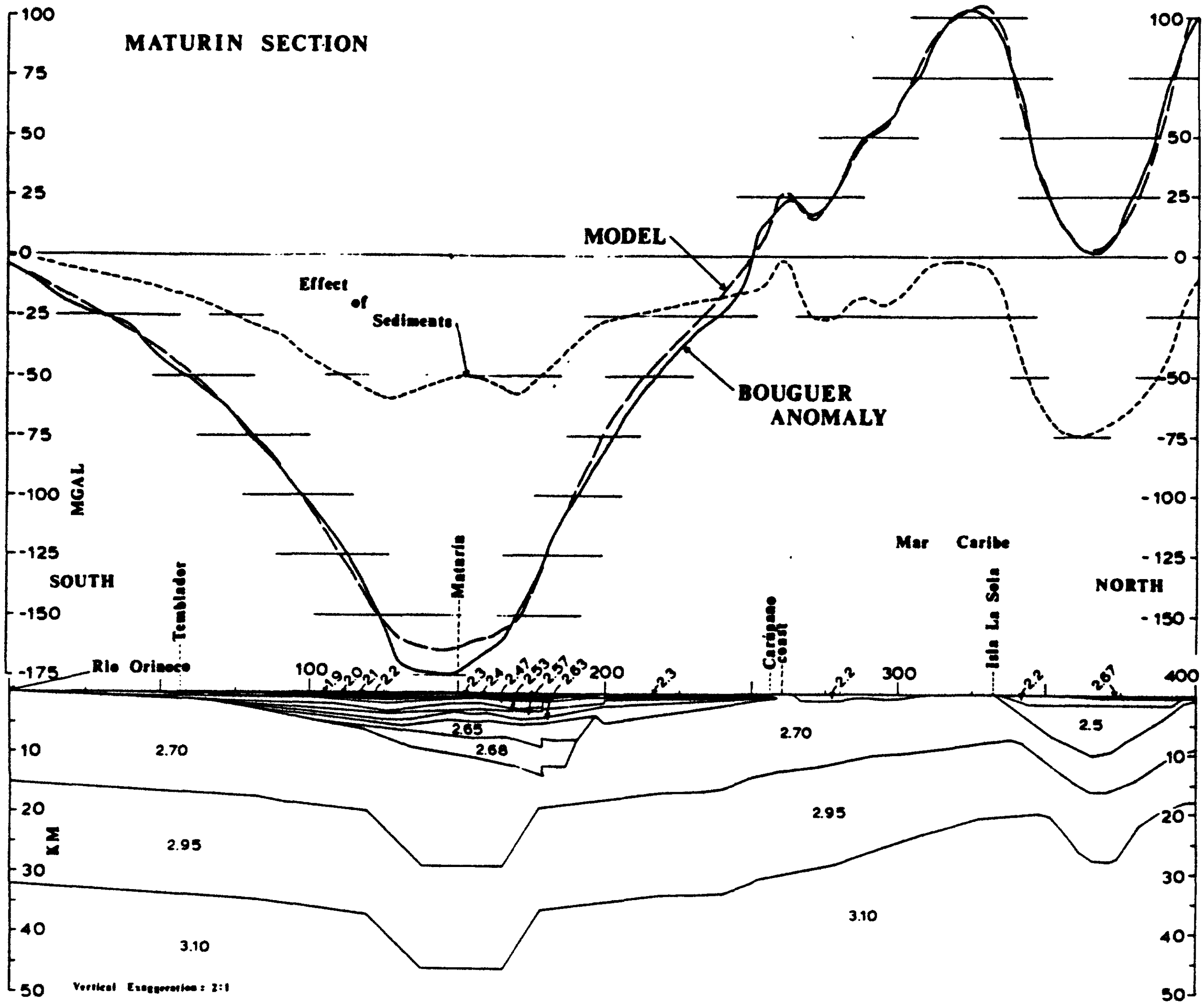


Figure 24. Section through Maturín on a bearing of N.12°W. from the Orinoco River to the Grenada Trough. Densities are in grams per cubic centimeter. The 2.67 g/cm^3 layer in the Grenada Trough is the water-layer correction used in the Bouguer reduction. In the model the 2.95-3.10 g/cm^3 interface is the Mohorovičić discontinuity. The effect of sediments plot is the contribution of those layers with densities of 2.68 g/c^3 and less. From Bonini (1978).

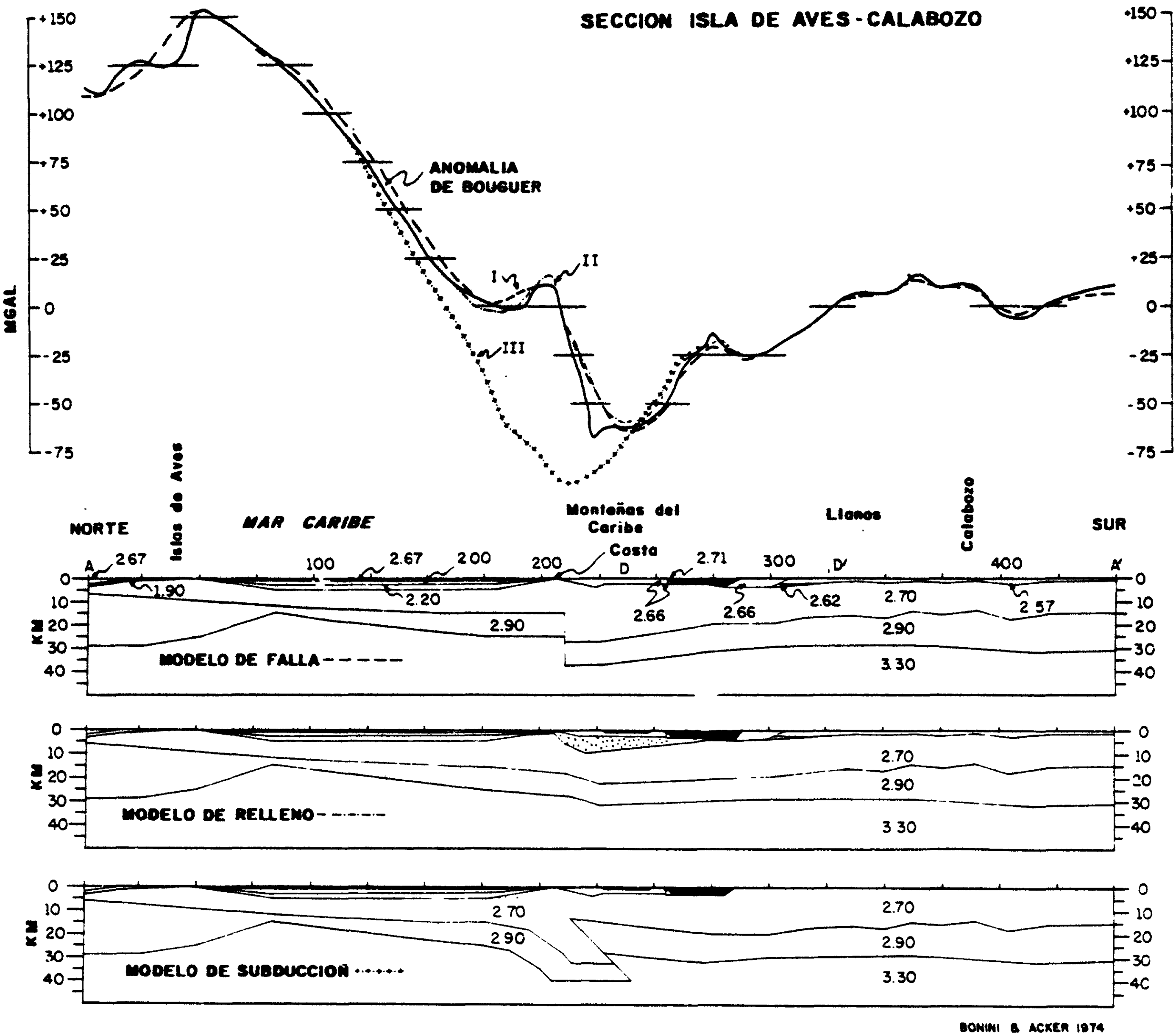
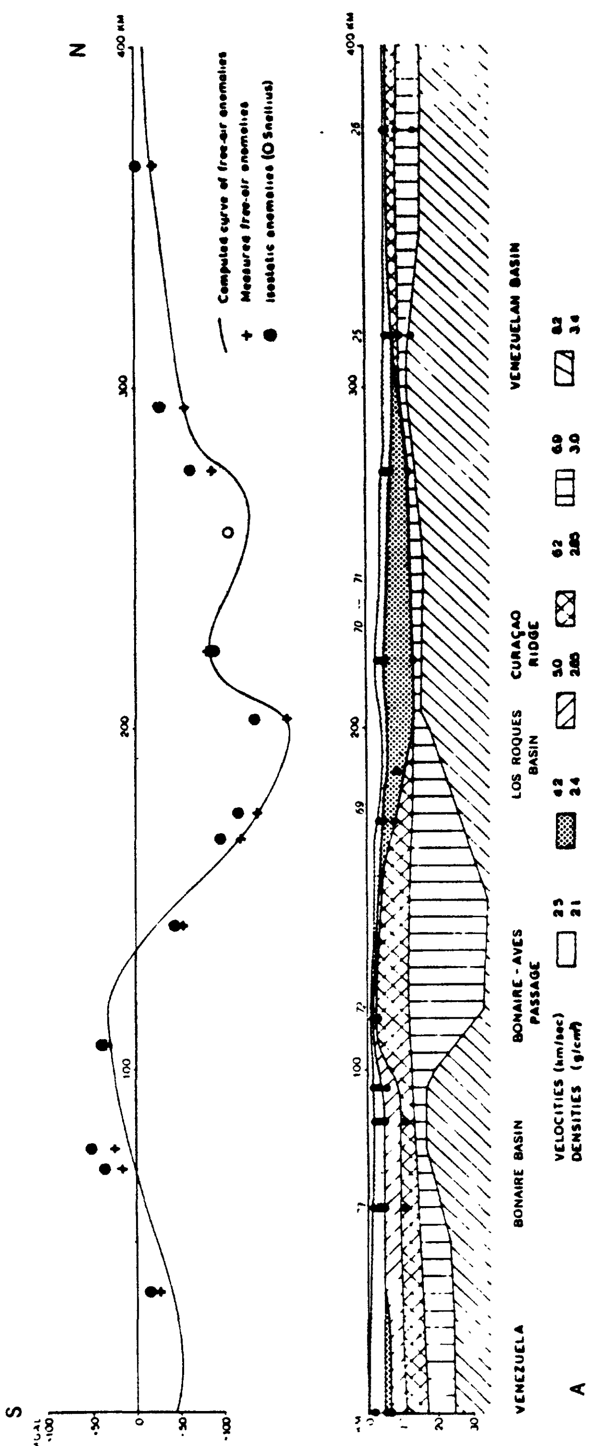


Figure 25. Gravity models of section AA' from Isla de Aves on the north to Calabozo on the south showing observed Bouguer anomalies and calculated anomalies for three models. Section is drawn at true scale. Rocks of the Villa de Cura are shown in black; assumed density of Villa de Cura block is 2.81 g/cm^3. Modified after Bonini and others (1977).

Figure 26. Crustal models across Venezuelan margin. (A) Section at 68°W, constructed by Hambleton (Worzel, 1965) from free-air anomalies and seismic information. The black dots in the crustal model indicate the position of the observed seismic discontinuities (from fig. 21, Lagaay, 1969). (B) Crustal section across Venezuelan borderland near Curaçao (from Folinsbee, 1972). Numbers refer to type of material and assumed densities: (1) water, 1.03 gm/cm^3; (2) sediments, 2.2 gm/cm^3; (3) sediments on land and probably mixed basalts and sediments beneath ocean, 2.4 gm/cm^3; (4) oceanic basement, 2.8 gm/cm^3; (5) continental basement, 2.7 gm/cm^3; (6) Cretaceous sediments, 2.5 gm/cm^3; (7) sediments, 2.3 gm/cm^3; (8) Cretaceous sediments, 2.6 gm/cm^3; (9) sediments, 2.4 gm/cm^3; (10) mantle, 3.3 gm/cm^3.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Computed curve of free-air anomalies
Measured free-air anomalies
Isostatic anomalies (O Snellius)
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BONAIRE BASIN
BONAIRE - AVES PASSAGE
LOS ROQUES BASIN
CURAÇAO RIDGE
VENEZUELAN BASIN
VELOCITIES (km/sec)
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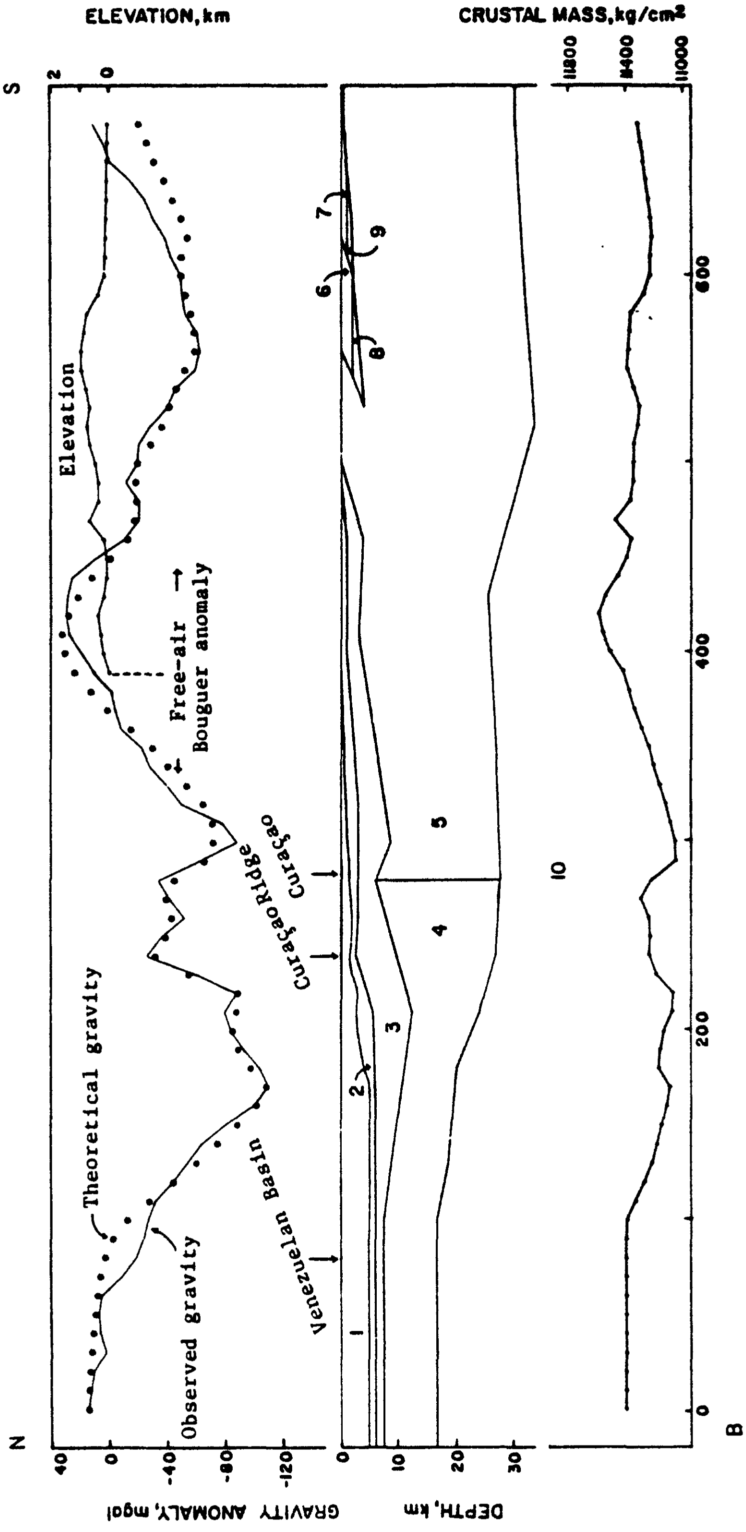
ELEVATION, km
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Curaçao Ridge
Curaçao
GRAVITY ANOMALY, mgal
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coastal range the crust is 30-40 km thick and is probably continental (Bonini and others, 1974, 1977; Bonini, 1978; Folinsbee, 1972; Bowin, 1976). Bowin (1976, p. 32) concluded that the North Range of Trinidad and the Coast Range of Venezuela are nearly in isostatic equilibrium.

The northerly belt of positive free-air and Bouguer anomalies that overlies the Netherlands and Venezuelan Antilles from Los Monjes and Aruba to Los Hermanos partly coincides with mafic volcanic rocks. Late Cretaceous pillow basalts and diabase on the islands may represent part of the "great flood basalt" event of Donnelly (1973, 1975) in the Caribbean region, but oceanic crustal materials, probably Albian or older, are inferred to occur beneath the Late Cretaceous mafic rocks (Houtz and Ludwig, 1977; Ludwig and others, 1975). The young Late Cretaceous pillow basalts and diabases on Curaçao and Bonaire (Beets and MacGillavry, 1976) are regarded as effective outcrops of seismic horizon B" recognized under the Venezuelan Basin. Older mafic rocks on Curaçao (Albian) and Aruba (Turonian) may represent true oceanic crust.

A continuous gravity high extends southwest from the volcanic Lesser Antilles to Margarita. A high density mass is present to cause this anomaly, and it must be pre-Eocene, because younger volcanic and sedimentary rocks are too low in density to cause the positive anomaly. Edge effects, although causing part of the anomaly, can be ruled out between Grenada and Margarita because water depths there are shallow. According to seismic refraction data and gravity models, the crust is thickened (20-30 km), and dense, beneath the volcanic Lesser Antilles (see summary by Bowin, 1976, Westerbrook, 1975), and this belt of thickened and dense crust extends to Margarita, the site of Mesozoic metamorphic rocks and extensive ultramafic masses, and beyond. The Margarita ultramafic masses could well be "rooted" in oceanic crust or upper mantle.

Ultramafic masses on the Paria and Araya Peninsulas occur close to a zero Bouguer anomaly contour, and Bonini (1978) and Bonini and others (1977) have modeled a gradual increase of crustal thickness from about 20 km at Isla de La Sola (northeast of Margarita) to more than 45 km beneath the Maturin Basin south of the peninsulas (fig. 24). Similarly, ultramafic masses along the coastal ranges near Caracas tend to occur near the zero Bouguer anomaly contour, although many masses occur at a local gravity high of 10-30 mgals. Models of Folinsbee (1972) and Bonini and others (1974, 1977) indicate crustal thickening from about 20 km beneath the Bonaire Basin to 30 or 40 km beneath the coastal ranges (figs. 25 and 26). Thus the northern belt of ultramafic rocks appears to lie along a zone of major southward increase in crustal thickness.

Ultramafic belts in the southern part of the coastal ranges, including the zoned Alaskan-type complexes, occur in gravity fields that are weakly positive to strongly negative. Analysis of detailed profiles across the Villa de Cura belt by Bonini and others (1974, 1977) clearly indicated that this block of relatively dense mafic rocks and accompanying ultramafic bodies is not very thick; it has a depth extent of less than 5 km for an assumed mean density of 2.81 g/cm^3 (fig. 25). If the mean density is greater, say 2.9 g/cm^3, the block is correspondingly thinner.

Ultramafic masses in and adjacent to the Falcón Basin occur in both weakly positive and negative Bouguer anomaly fields, and no conclusions are drawn about the thickness or nature of the crust.

Major positive Bouguer anomalies over the Paraguaná Peninsula, including a local high of as much as 70 mgals over the El Rodeo ultramafic complex (W. Bonini, 1971, personal communication, Martín-Bellizzia and de Arozena, 1972), suggest that the Peninsula is underlain by oceanic crust or that continental crust is relatively thin. The positive gravity anomaly appears to extend northwest over the metamorphosed mafic rocks of Los Monjes.

Few magnetic data have been published for the region. Lagaay (1969), Silver and others (1975), and Peter (1972) have discussed the offshore magnetic anomalies, but few conclusions have been drawn from the data, except that most of the anomalies can be readily generated by the mafic and granitic rocks of the Netherlands-Venezuelan Antilles.

Colombia

Mafic and ultramafic rocks are present along the Caribbean and Pacific coastal regions and in the Cordilleras Central and Occidental of Colombia (fig. 27, in pocket), and detailed information is gradually becoming available for many of the bodies.

Extensive serpentinite exposures occur at Cabo de la Vela on the Guajira Peninsula (Alvarez, 1967, Lockwood, 1971), and serpentinite detritus occurs in sedimentary rocks of the Serranía de Jarara (Lockwood, 1971). Small bodies of ultramafic rocks, including serpentinite and harzburgite peridotite, have been reported from the northern part of the massif of the Sierra Nevada de Santa Marta near the Sevilla lineament (Tschanz and others, 1969, 1974). MacDonald and others (1971) have reported an amphibolite belt having metamorphic ages of 110-128 m.y. and 63-91 m.y. near Santa Marta. These rocks are probably metamorphosed mafic volcanic and volcaniclastic assemblages. Tschanz and others (1974) speculated that the arrangement and pattern of the Mesozoic plutons and metamorphic belts relative to the Sevilla lineament may be the outcrop of a fossil subduction zone.

Farther southwest, many mafic and ultramafic bodies are present in or near the Romeral-Cauca-Patía fault zone in the western part of the Cordillera Central and eastern Cordillera Occidental. The Romeral fault zone (Barrero and others, 1969) is thought to be a major zone of Late Mesozoic-Early Tertiary tectonic activity where continental crust of the Cordillera Central has converged with oceanic crust of the Cordillera Occidental (Case and others, 1971, Gansser, 1973, Shagam, 1975, Barrero and others, 1969, etc.). Many geologic details along the zone remain to be worked out, and controversy exists over whether these ophiolite bodies were emplaced mainly along a subduction or obduction zone or both (Case and others, 1971, 1973; Touissant and Restrepo, 1974a, 1974b, 1976, Restrepo and Touissant, 1974, 1975, Estrada, 1972, 1974, Barrero, 1977, 1979, etc.). The zone involves Paleozoic metamorphic and igneous rocks, Mesozoic sedimentary and volcanic rocks, and local Tertiary plutonic, volcanic, and sedimentary rocks which are in fault or depositional contact with mafic volcanic and associated sedimentary rocks of

Mesozoic, mainly Cretaceous age. Barrero (1976) has recognized local patches of melange, which he believed to be of Cretaceous age, along segments of the Romeral fault zone.

Only a few of the mineralized ultramafic masses will be discussed in this review.

Cerro Matoso-Uré - Very little published information was available until late 1978 on the petrology of the Cerro Matoso-Uré area, the site of a major nickel-laterite deposit north of the Cordillera Central and on the trend of the Romeral fault zone. According to Hall and others (1970), the rocks of the Uré region are serpentinized ultramafic rocks associated with metagabbro and metabasalt. Additional details on the Uré deposits are provided in a report by Castro and Martínez (1978). The nickel-laterite deposit at Cerro Matoso contains about 2.5 percent nickel ore, with a potential production rate of 50 million lbs. per year (Dayton, 1977). According to Cornwall (1973), the deposit contains 40,000,000 tons of 2.5 percent ore. Guild and Cox (1977) have estimated that the deposit contains 1,000,000 short tons of nickel reserves,but various economic and other factors have delayed exploitation of the deposit.

An excellent recent summary of the geology of the deposit has been prepared by Castro and Martínez (1978). Because so little geological information on the deposit has been published in English, I have prepared a free translation of the geological part of their report (Castro and Martínez, 1978, p. 389-391):

> "Geology
>
> The nickeliferous laterites of Cerromatoso are the product of alteration of ultramafic rocks of Cretaceous age. The deposit appears as an elongate body whose orientation is north-south.
>
> Within the ultrabasic complex of the area of Cerromatoso, harzburgites, serpentinized dunites, and outcrops of gabbros and basalts have been reported. Petrographically, the mother rock of Cerromatoso is a harzburgite, in some parts slightly serpentinized, and whose principal minerals are olivine and enstatite, for which it is believed that the nickel and cobalt [may] occupy spaces in the crystalline lattice.
>
> In Cerromatoso the grade of serpentinization is relatively low; only a small area of serpentinites is encountered in the west, representing approximately 5% of the ultramafic rocks, which seems curious in contrast to observations of the analyses where apparently the enrichment in nickel is inversely proportional to the degree of serpentinization of the peridotite.

> The contacts between the ultramafic rocks, gabbros, and basalts have an intimate relation with the great Romeral fault [zone]. Cretaceous sediments [deposits] studied to the north, and which are composed of sandstones, shales, calcarenites, cherts and volcanic rocks, comprising a possible eugeosynclinal sequence, serve as wall [enclosing] rocks for the ultramafic body. In the region of Cerromatoso the Cretaceous sediments do not crop out; instead Tertiary arenaceous rocks with argillaceous zones of light color are found. These sediments demark the nickeliferous laterites with very well-defined contacts at the surface, and [the contacts] are apparently nearly vertical at depth, because the holes drilled to determine the shape of the ultrabasic body at depth penetrated 300 feet of sediments [presumably holes drilled on the side of the body]."

Mineralization occurs in four zones, including: an upper laterite cap about 7 m thick, 0.74 percent Ni; a saprolite zone about 3 m thick, 4.9 percent Ni; a serpentinite zone 1.8 m thick, 2.5 percent Ni; and a serpentinite zone 4.9 m thick, 1.76 percent Ni.

Castro and Martínez described other small nickel-laterite deposits at Planeta Rica, near Montería, and Ituango, whose geologic setting is similar to those at Cerro Matoso and Uré.

<u>Yarumal - Morro Pelón - Alto Nechí</u> - A large ophiolite complex occurs east of the town of Yarumal, north of the Antioquian batholith, about 100 km NNE of the city of Medellín. The most extensive studies of this complex have been made by Estrada (1967), and geology of the region has been briefly summarized by Estrada (1974), and Restrepo and Toussaint (1974). The complex is about 65 km long and 8 km wide. It is in fault contact with metamorphic rocks of probable Paleozoic Age that range from greenschist to amphibolite facies and that are intruded by the Antioquian batholith of Late Cretaceous age. The complex includes serpentinite, serpentinized peridotite, anorthositic gabbro, trondhjemite, and spilites. Restrepo and Toussaint (1974) postulated that the contacts of the complex are subhorizontal faults, and believed that the complex is a klippe.

Morro Pelón, seven km northeast of the village of Campamento, has deposits of iron-nickel laterite, according to Hall and others (1970), and the ore reserves are probably as much as 4 million metric tons in an area of about 60 hectares, with a mean thickness of about 3 m. From 74 analyses, the deposit runs 25 to 56 percent iron and 0.23 to 1.2 percent nickel, with averages of 27.6 percent iron and 0.69 percent nickel. As far as is known, the deposit is not being exploited. Other details are provided in the report by Castro and Martínez (1978).

Small deposits of talc north of the town of Yarumal were exploited on a small scale from 1952 until 1970 (Hall and others, 1970). The talc occurs in lenses of steatized serpentinite in a band 400 m wide and 15 km long in (fault?) contact with augen gneiss (presumably of Paleozoic age). Six million tons of reserves to a depth of 200 m have been identified from drilling, and an additional 14 million tons may be present. About 4,500 tons were produced annually for use in paints, plastics, and gum products. Other uses include cosmetics, pharmaceutical products, and for cleaning ink rollers used for printing textiles.

Small asbestos deposits, 10 km north of Campamento were being explored in 1969, according to Hall and others (1970). Dayton (1977) reported that companies are developing an asbestos ore body 150 km north of Medellin, presumably in the same area. The ore is reported to contain both long and short fiber grades. Production is expected in 1979, according to Dayton.

Medellín area - Several bodies (possibly continuous) of serpentinite, serpentinized dunite, local harzburgite, and actinolite-tremolite serpentinite occur east of the city of Medellín in a belt 35 km long (Botero, 1963, Jaramillo and others, 1971, and Posada and Serna, 1974). They are in fault contact with Paleozoic(?) amphibolites and metasedimentary rocks (Echeverría, 1973, 1974), and the faults are regarded as thrusts.

Minor deposits of chromite occur about 5 km southeast of Medellín (Santa Helena) and extensive exploration for chromite has been conducted in a few areas. Detailed geophysical studies, including gravity and ground magnetic surveys, have been used to guide exploratory drilling on some of the deposits. The deposits are podiform or lenticular. Minor and sporadic production of chromite has occurred since the 1940's. Posada and Serna (1974) estimated that as much as 100,000 tons of chromite might be present.

Some iron-nickel-laterites have formed on these ultramafic masses, but the deposits do not appear to be commercially significant as of 1978. Further details are provided in the report by Castro and Martínez (1978).

Hall and others (1970) described a small manganese deposit near Santa Bárbera, about 50 km south of Medellín. This deposit evidently is near a major trace of the Romeral fault zone and may occur in melange from inspection of the maps of Arango and others (1976) and Barrero (1976). The deposits are associated with thin red, green, and black cherts, tuffs, greenstones, phyllites, quartzites and marls[?]. Hall and others (1970, p. 53) suggested that the manganese deposit formed as part of a process of submarine volcanism at great oceanic depths, but other interpretations were made by Botero (1945).

Major gold deposits are associated with the Mesozoic batholiths of the Cordillera Central (Hall and others, 1970), and porphyry copper deposits have been found, south of the area of this report, in silicic plutons in or near the Romeral fault zone (Barrero, 1976; White, 1977).

Near the south edge of the area covered by this report, near Salamina, deposits of native mercury, cinnabar, and other mercury-bearing minerals, together with geochemical anomalies of mercury, occur in what appears to be a melange zone along the Aranzazu-San Jerónimo fault which is probably a strand of the great Romeral fault system (Lozano, 1978). Other mercury deposits of California occur in a similar tectonic setting: Bailey and others (1973, p. 411) have noted that

> ".... virtually all of the productive deposits of mercury [in California] lie close to, and generally just below, the

Coast Range thrust which is a major late Mesozoic subduction zone...."

Another point of similarity between the Romeral zone and other regions of tectonic convergence is the occurrence of blueschists near the Romeral zone, near Pijao, northeast of Popayán (Nuñez and Murillo, 1978).

South of 5°N, the southern boundary of the main area covered by this report, more than 10 other ultramafic complexes in the Romeral-Cauca-Patía fault zone have been discovered by geologists of INGEOMINAS (fig. 28), and descriptions of several of them have been presented by París and Cepeda (1978) and Espinosa (1978). Although no significant mineral deposits have yet been reported for these rocks, with the exception of a small magnesite deposit in serpentinite near Bolívar (Mariño, 1978), and detailed studies are barely underway, these bodies merit thorough exploration for mineral deposits.

Cordillera Occidental - Serranía de Baudó - The poorly mapped Cordillera Occidental includes a great thickness of complexly deformed mafic volcanic rocks, including pillow basalt and diabase dikes and sills (DeBoorder, 1978), deep-sea sedimentary rocks, and flysch deposits, many of which have been metamorphosed to zeolite or greenschist facies (Nelson, 1957, Barrero, 1976). These rocks, regarded by some as an ophiolite sequence and by others as a primitive island arc, are of Late Cretaceous Age (Duque-Caro, 1972a, 1972b) and may range back to Jurassic (Goosens and Rose, 1973). Local ultramafic bodies have been reported by Nelson (1957,1962) and others, and numerous ultramafic masses are shown on the new geologic map of Colombia (Arango and others, 1976), but few petrographic descriptions are available. The whole complex is thought to represent oceanic crust or to have formed on oceanic crust, as discussed in a subsequent section. Numerous granitic plutons of about middle Tertiary age cut the ophiolite sequence of the Cordillera Occidental, and porphyry copper deposits are associated with some of these plutons. Presumably, these plutons are associated with subduction of the "Pacific" [Nazca] plate beneath the South American plate.

Barrero (1977, 1979) has described the Bolívar zoned mafic-ultramafic complex, which is exposed immediately west of the Cauca Valley near latitude 4°15'N., longitude 76°15'W: "The complex is an elliptical body some 12 km long by 3.5 km wide, extending from the hamlet of Robledo in the south as far as the town of Bolívar in the northern end of the complex." According to Barrero:

"The complex is distinctive structurally in showing a good concentric zoning, which consists of a dunite core surrounded by successive shells of olivine clinopyroxenite, clinopyroxenite, and peridotite. This ultramafic sequence is enveloped by normal gabbro which in turn is surrounded by amphibolite."

According to Barrero: "In several ways the complex can be compared with those from Southern Alaska described by Irvine (1974) and with those from the central Ural Mountains, Soviet Union, briefly described by Taylor (1967)."

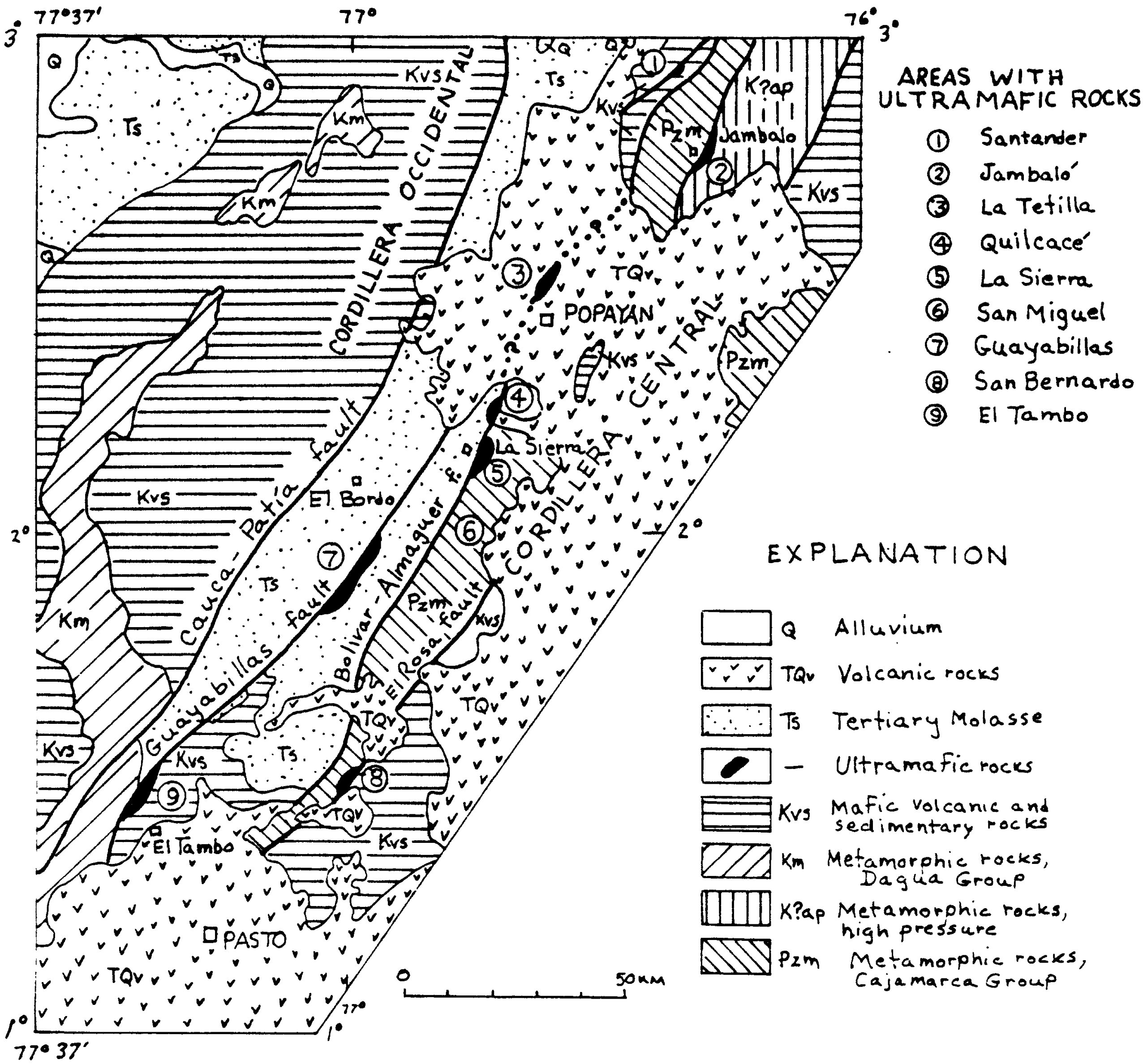


Figure 28. Schematic regional geologic map of part of southern Colombia, showing distribution of ultramafic bodies. Modified after unpublished map of Gabriel París Q., and Héctor Cepeda V. (1978)

A major sedimentary basin, the Atrato-San Juan Basin or Bolívar Trough, separates the Cordillera Occidental from the Serranía dé Baudo, the Pacific coastal range of Colombia. The trough contains at least 4 km of Tertiary sedimentary rocks, as determined by drilling, and may contain as much as 10 km based on the associated negative gravity anomalies (Case and others, 1971). The Serranía de Baudó has an extensive basement terrane of pillow basalt, mafic volcanic conglomerate, mafic dikes and sills, and pelagic sedimentary rocks that range in age from Late Cretaceous to mid-Eocene (Case and others, 1971, Bandy, 1970, Bandy and Casey, 1973, Duque-Caro, 1972). Some serpentinized gabbros have been found along the Pacific coast, and ultramafic bodies are almost certainly present in the coastal terrane.

Pichler, Stibane, and Weyl (1974), and Barrero (1977, 1979) have reported on the chemical composition of the mafic rocks from the Cordillera Occidental, and Goossens, Rose, and Flores (1977) on the chemical composition of rocks from the Serranía de Baudó. Although the samples are rather scanty, most of the basalts are tholeiitic and have many chemical similarities to ridge-formed basalts, based on the major element composition. Some of the samples, however, including ones from the Cordillera Occidental, the Serranía de Baudó, and adjacent areas of eastern Panamá, are basaltic andesites and may represent early island-arc volcanic activity rather than spreading ridge activity. Of special interest is that many samples of basalt along the Pacific coast of Colombia and eastern Panamá contain 200-300 ppm Cu (average ridge basalts contain about 70-100 ppm Cu according to Engel and others, 1965).

Platinum placer deposits in western Colombia have been described by Monroy (1978), and gold placers by Rosas and Monroy (1978). One of the most intriguing metallogenic problems of the region occurs along the drainages of the Río San Juan and Río Atrato (fig. 27) where placer deposits of platinum and gold, in both modern gravels and older terrace gravels, have been mined for many years. The platinum and gold occur in roughly equal amounts in these deposits. The gravels include pebbles and cobbles of diorite, gabbro, basalt, andesite, andesite porphyries, shales, cherts, milky quartz, and pyroxenites in minor quantity. The scarcity of ultramafic rocks is attributed to serpentinization, which lowered resistance to transportation. The platinum (Naldrett and Cabri, 1976, Razin, 1976) is almost surely derived from ultramafic sources in the Cordillera Occidental and possibly from the Serranía de Baudó, but the origin of the gold is problematical. The obvious sources are the silicic plutons in the Cordillera Occidental, but is it possible that the gold might have been derived from the oceanic rocks of the basement complex or from concentric ultramafic complexes such as that found by Barrero? Some evidence is accumulating that gold mineralization may accompany hydrothermal activity along active ocean ridges (Keays and Scott, 1976); gold is associated with the massive sulfide deposits in the ophiolites of Cyprus (Bear, 1963); and gold-platinum placers appear to be associated with zoned ultramafic complexes in the Urals (Duparc and Tikonowitch, 1920). Bear (1963: Table 3, and p. 185-189) reported that gold and silver have been produced from gossan cappings in the Upper and Lower Pillow Lavas of Cyprus:

> "The deposits carrying the gold [very fine] are generally of small extent and occur in the weathered portions of gossans overlying disseminated or massive cupreous pyrite. Gold has

been reported from the Skouriotissa and Agrokipia ore-bodies, as well as others, and the total production during the interval 1934-1944 exceeded 160,000 oz. The total production of silver exceeded 900,000 oz."

Geophysical Surveys--Some of the mafic-ultramafic complexes of Colombia are associated with gravity highs that indicate oceanic crust, and others occur in areas of relative negative anomalies and metamorphosed Paleozoic and Precambrian rocks that suggest continental crust. Enormous highs of more than +100 mgal occur over the Cabo de la Vela and Sierra Nevada de Santa Marta areas of northern Colombia, suggestive of oceanic crust or very thin continental crust (Case and MacDonald, 1973). Farther southwest, the ophiolite complexes of the Romeral fault zone are located in a region of gravity transition from positive anomalies to the west to strongly negative anomalies to the east, which has been interpreted as reflecting a transition from oceanic crust under the Serranía de Baudó and Cordillera Occidental to continental crust under the Cordillera Central (Case and others, 1971). In western Colombia, gravity anomalies are strongly positive except over the Atrato-San Juan Basin or Bolívar Trough. If corrections were made for the low-density Tertiary sediments in the basin, the whole Bouguer anomaly field of western Colombia would be strongly positive, +50 to +125 mgals, so multiple oceanic crust rather than continental crust is suspected (Case and others, 1971, 1973). These inferred crustal relations (fig. 29) were partly confirmed by results of refraction surveys of project Nariño in western Colombia (Ocola and others, 1975, Meyer and others, 1976, Meissner and others, 1976 and Mooney and others, 1979), where high velocities (V_p = 5.5 - 6.8 km/sec) were found at shallow depth beneath the Cordillera Occidental. Interpretations of the seismic data by various groups have been drastically different (figs. 30 and 31), but all groups agree that "oceanic" velocities occur at shallow depth beneath the Cordillera Occidental and that the crust is substantially thicker than normal.

Published magnetic surveys in Colombia are rather scanty. A magnetic high (ground survey) of several hundred gammas occurs over the serpentinite mass of Cabo de la Vela on the Guajira Peninsula (unpublished data of J. E. Case). Reconnaissance ground magnetic surveys indicate high amplitude, variable magnetic anomalies over the Serranía de Baudó, and a general magnetic high appears to occur over the Cordillera Occidental (Case and others, 1971). Oil company data (ground surveys) in the Caribbean coastal basins (Matthews, 1975) show high-amplitude anomalies of several hundred gammas on trend with the Romeral fault zone and Cordillera Central that could be caused by virtually any type of crystalline basement.

Panamá

Some geologic data (fig. 32) for eastern Panamá are provided in reports by the Interoceanic Canal Study Commission (1968) for the geology along Canal Route 17, by Wing and MacDonald (1973), Bandy (1970), Bandy and Casey (1973), Case (1974), Terry (1956), and by the Panamá Direccion de Recursos Minerales (1976). Although geologic details are poorly known, the basement of eastern Panamá includes mafic pillow basalts, sills, dikes, and volcanic conglomerates

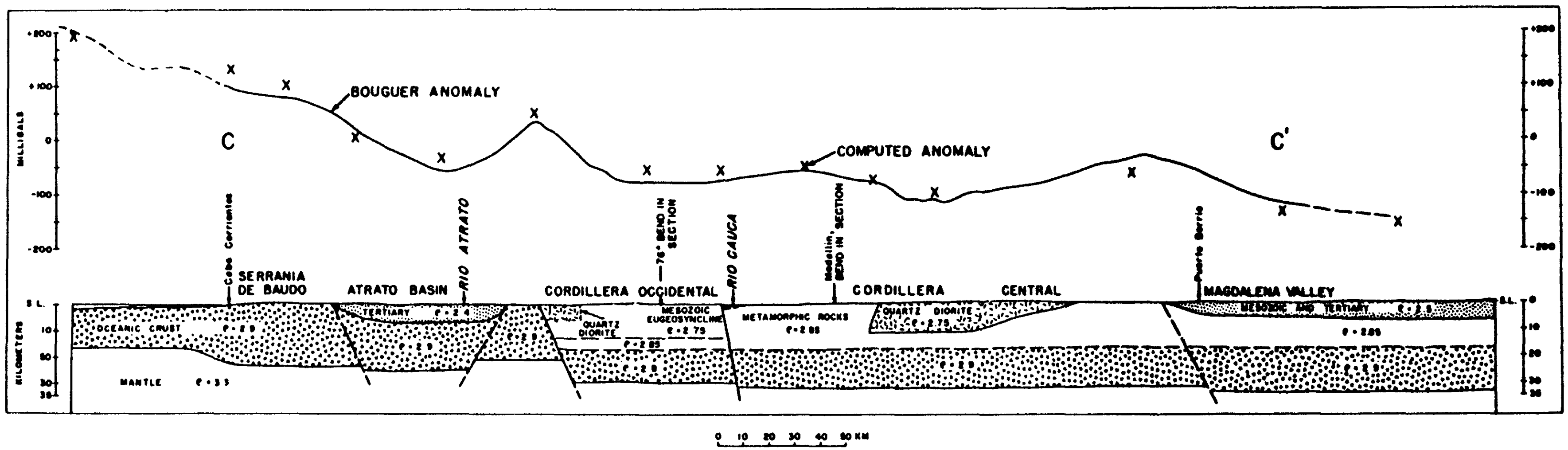


Figure 29. Crustal model, Cabo Corrientes-Magdalena Valley, Colombia. Location of profile shown on Figure 39. Dashed offshore Bouguer anomaly profile is schematic; approximate values were estimated from Hayes (1966), using free-air anomalies and water depths. Modified after Case and others (1971).

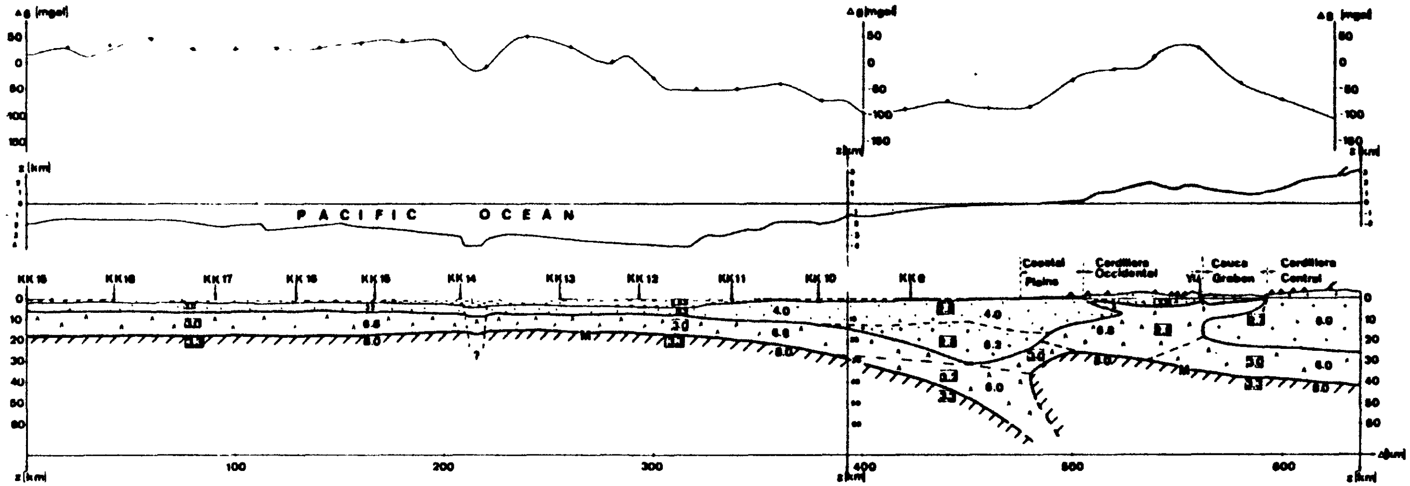
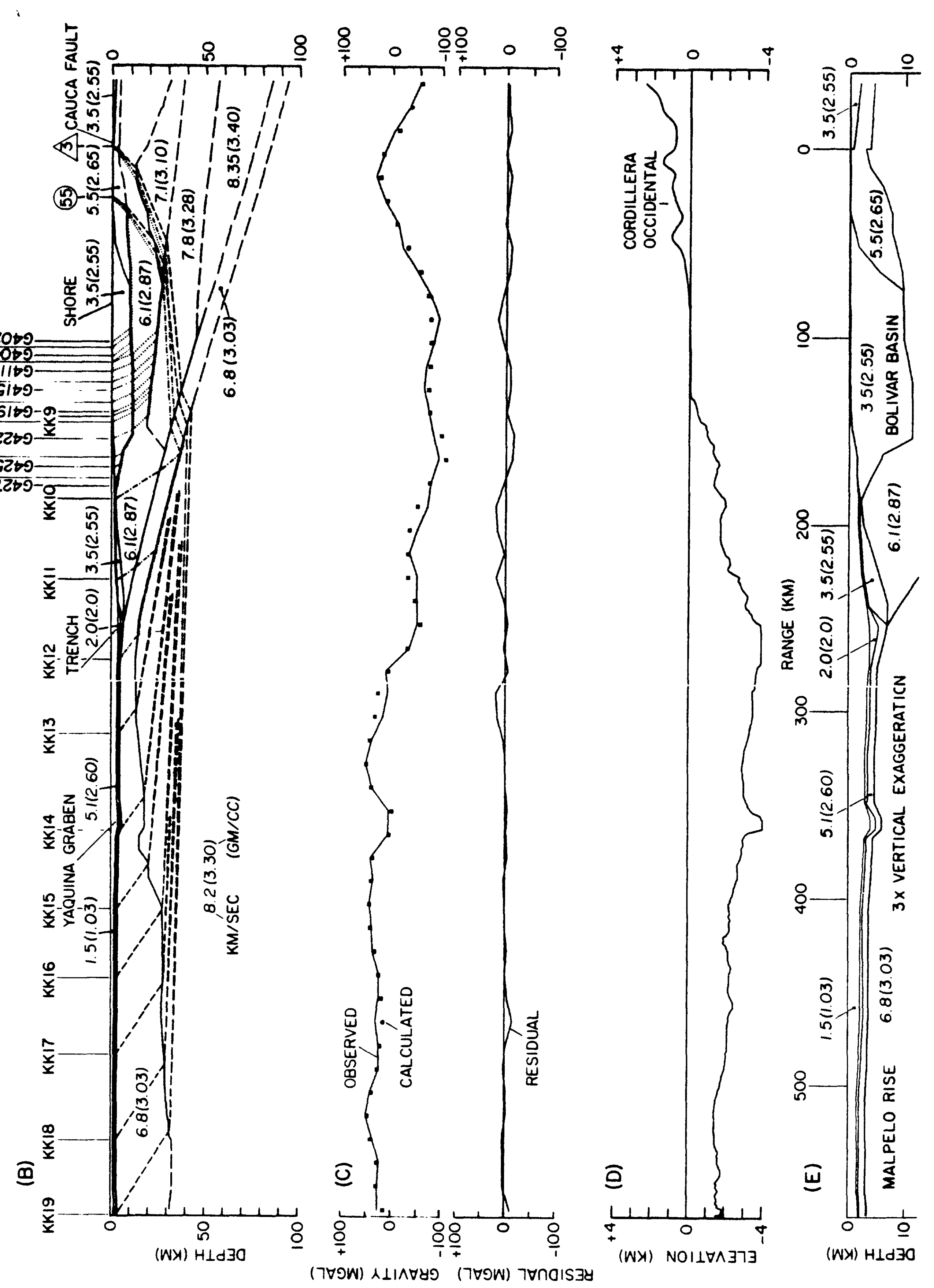


Figure 30. Refraction profile in western Colombia. Crustal cross-section of profile I: Malpelo-Buenanentura-Yumbo. Upper part shows gravity values, (-) and calculated (+). Middle part shows topography, five times exaggerated. Lower part shows crustal model with velocity (6.8) in km/sec and density values [3.2] in g/cm^3; ↓ = shot point; ▲ = recording station, M = Mohorovičić discontinuity, distance from Malpelo Island. (After Meissner and others, 1976). Compare with figure 31.

Figure 31. Crustal model western Colombia (modified after Meyer and others, 1976). B) The true scale model derived from the seismic and gravity data. Shot points, ray paths and stations 55 and 3 are indicated. The dotted paths are those critically refracted solely within the continental structure, the dash-dot ray paths are those critically refracted along the oceanic mantle, and the dashed show the rays used to simulate diving waves. All paths from the shots shown were individually calculated; only representative paths through the continental structure are shown for the diving waves. The stippled area represents schematically the location of a hypothetical region of lowered mantle velocity suggested to reduce the consistent travel time residuals associated with Shots KK14 through KK19 as observed at Stations 55 and 3. C) The observed, calculated and residual gravity for the profile. The free-air anomaly displayed at sea is from data taken during the project along the shot profile by the R/V Kana Keoki, and the Bouguer anomaly shown on land is taken from the map of Case et al (1971). The model gravity is calculated using a two-dimensional algorithm. Values, which were computed at 49 points along the model, when subtracted from the observed values give the residual gravity curve. The maximum residual is 22 mGal.


(B)
(C)
(D)
(E)
DEPTH (KM)
GRAVITY (MGAL)
RESIDUAL (MGAL)
ELEVATION (KM)
RANGE (KM)
CAUCA FAULT
SHORE
TRENCH
YAQUINA GRABEN
CORDILLERA OCCIDENTAL
BOLIVAR BASIN
MALPELO RISE
3x VERTICAL EXAGGERATION
OBSERVED
CALCULATED
RESIDUAL
8.2(3.30)
KM/SEC
(GM/CC)
3.5(2.55)
5.5(2.65)
7.1(3.10)
7.8(3.28)
8.35(3.40)
6.1(2.87)
6.8(3.03)
2.0(2.0)
5.1(2.60)
1.5(1.03)
KK9
KK10
KK11
KK12
KK13
KK14
KK15
KK16
KK17
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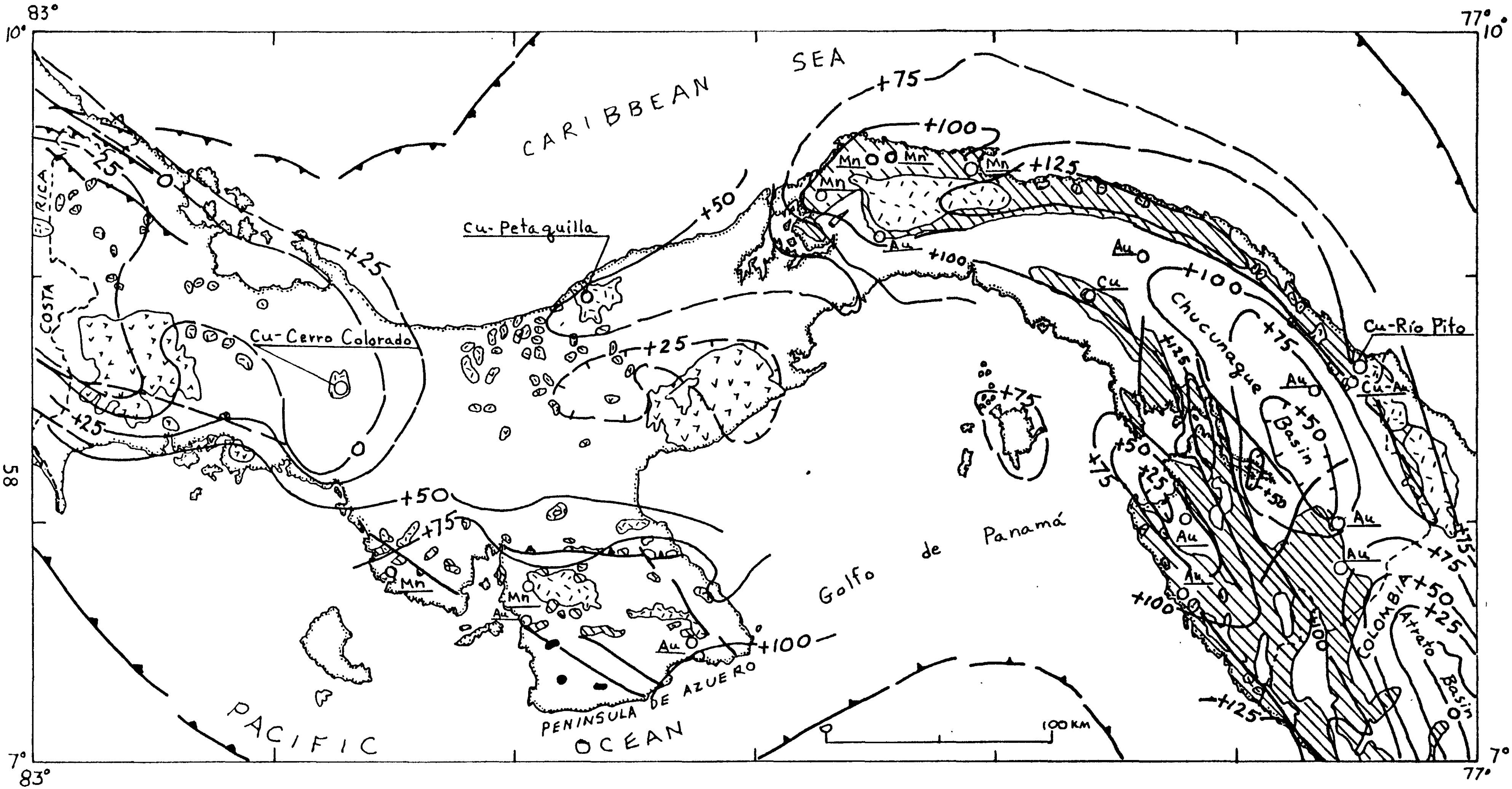


Figure 32. Simplified geologic and gravity anomaly map of Panamá. Dark shade indicates small ultramafic masses on the Azuero Peninsula; diagonal rule indicates mafic volcanic rocks, including pillow basalts, and associated volcaniclastic and pelagic rocks of Late Mesozoic-Early Cenozoic Age; dash pattern indicates granitic plutons; vee-pattern indicates Late Tertiary-Quaternary volcanic rocks. Contour interval 25 mgal. Gravity data modified from Case (1974), Case and others (1971), and Bowin (1976).

overlain by or intercalated with deep-water Campanian radiolarian cherts indicating probable oceanic crust (Case, 1974, Bandy and Casey, 1973), but some mafic to andesitic volcanism persisted into the Eocene. The mafic basement has been intruded by intermediate to silicic plutons. As in adjacent parts of Colombia, the basalts are mainly tholeiitic, having chemical similarities to ridge-formed basalts, but some are basaltic andesites, more like those from primitive island arcs, according to Goossens, Rose, and Flores (1977). Several porphyry copper deposits, especially at Río Pito, near the Colombian border in the Serranía del Darién, are associated with intermediate to silicic plutons and have been extensively prospected. The porphyry coppers of eastern Panamá occur in quartz diorite plutons that range in age from about 48 to 65 m.y

Recchi (1977) has reported on a program for gold prospecting in eastern Panamá. Some placer prospecting was reported by Levy (1977). No large massive sulfides have been reported from the basement rocks, but the basalts of eastern Panamá contain 200-250 ppm Cu (Goosens and others, 1977), anomalously high values. No platinum exploration has been conducted as far as is known. Simons (1957) has described manganese deposits in Panamá, most of which occur in the Serranía del San Blas (or Darién), along the north side of eastern Panamá, and on the Pacific side of western Panamá near Bahía Montijo and Bahía Hondo. Most of the deposits appear to occur in or near the basement complex of Cretaceous (or older) volcanic, volcaniclastic, and sedimentary rocks and most of them are intimately associated with red and yellow jasper which may have been derived from silicic pelagic sedimentary rocks.

Patches of mafic and ultramafic rocks, and minor greenschist metamorphic rocks, mostly near shear zones, locally overlain by intermediate to silicic volcanic rocks, occur on the Azuero Peninsula of southern Panamá. Geology of the area has been described by del Giudice and Recchi (1969) and Ferenčić and others (1971). A large positive gravity high over the peninsula suggests that the basement terrane is probably one of oceanic crust like that of the Nicoya and Osa Peninsulas of Costa Rica and eastern Panamá (Dengo, 1967, Henningsen and Weyl, 1967).

Most of the central part of western Panamá is a Tertiary-Recent volcanic sequence (calc-alkaline) intruded by granitoid plutons that are as old as 26 m.y. at Petaquilla and 3.3 m.y. at Cerro Colorado, (Kesler and others, 1977). A Tertiary sedimentary sequence crops out intermittently along the Caribbean margin of western Panama.

The gravity field (fig. 32) of the northern and southern sides of the eastern isthmus is strongly positive, having Bouguer anomalies in excess of 100 mgals (Case, 1974). A relative gravity low occurs over the Chucunaque Basin of axial eastern Panama and is caused by at least 4 km of Tertiary low-density sedimentary rocks. If the gravitational effect of the sedimentary basin were removed, the whole gravity field of eastern Panamá would be positive, suggestive of oceanic crust.

Some offshore seismic evidence suggests that the isthmus is now or has recently been underthrust both by the Caribbean plate and by the Nazca plate (Case, 1974, Bally, 1979, Jordan, 1975, McMillen, 1979).

An aeromagnetic survey of eastern Panamá has been briefly described by Baron and Lorentzen (1965) and Case and others (1971). Matthews (1976) has recontoured the original data and a further simplified version is shown here (fig. 33). The main features are a magnetic low of several hundred gammas near the Serranía de Darién that crosses the Colombia-Panamá border in the vicinity of the copper-bearing plutons. Small discontinuous highs and lows of several hundred gammas occur over the southern part of the isthmus but no special correlation with geology has been found as yet. The low in the Darién region may be a composite low caused by topographic effects, some Tertiary sedimentary deposits, and altered granitoid plutons.

Another aeromagnetic survey has been conducted from the Azuero Peninsula and vicinity to the north coast of Panamá by a United Nations group, and a simplified version is shown on Matthews' compilation. The main features are a large low that trends west-northwest across the peninsula, and several small highs that are superimposed on the regional low. The low crosses various geologic units, including Tertiary sedimentary and volcanic rocks and granitoid plutons. It is suspected that the low represents relatively great depth to the magnetic basement beneath the sedimentary sequence. A magnetic high appears to occur over the pluton at Petaquillo, on the north coast of Panamá, which is a porphyry copper deposit. Other small, high-amplitude anomalies along the strip north of the Azuero Peninsula are characteristic of volcanic rocks.

A very large porphyry copper is being exploited at Cerro Colorado in the mountainous part of west-central Panamá. It is a young porphyry, about 3.3 m.y., presumably related to magmatism related to underthrusting (Kesler and others, 1977). The gravity field in western Panamá is about zero to negative, based on rather scanty published data, and the data could be consistent with either continental or oceanic crust. A large sedimentary basin may extend west from the Canal Zone, both onshore and offshore, to the Limon Basin of eastern Panamá. If a sedimentary basin occurs beneath the volcanic rocks of the north part of western Panamá, part of the negative gravity anomaly could be accounted for.

Costa Rica

Tertiary to Recent volcanic complexes (calc-alkalic--Pichler and Weyl, 1973, 1974) form most of the central axial region of Costa Rica (fig. 34). Tertiary sedimentary rocks are exposed in the Limón Basin in the southeastern part of the country and intermittently along the coastal region of the southwestern part.

Mafic and ultramafic rocks that are parts of ophiolite complexes are exposed on the Pacific margin of Costa Rica at the Osa and Nicoya Peninsulas (Dengo, 1962). Pillow basalts, mafic breccias, dikes and sills are most common, but a large peridotite body occurs on the Santa Elena Peninsula. The peridotite is locally serpentinized and is composed of harzburgite and local dunite; in places it exhibits a "pseudo-stratification" or banding, especially bands where enstatite and possibly chrome diopside are concentrated (Dengo, 1962). Pichler and Weyl (1975) and Weyl (1969) have reported lherzolite from the complex. De Boer (1979) has reported isolated peridotite masses with

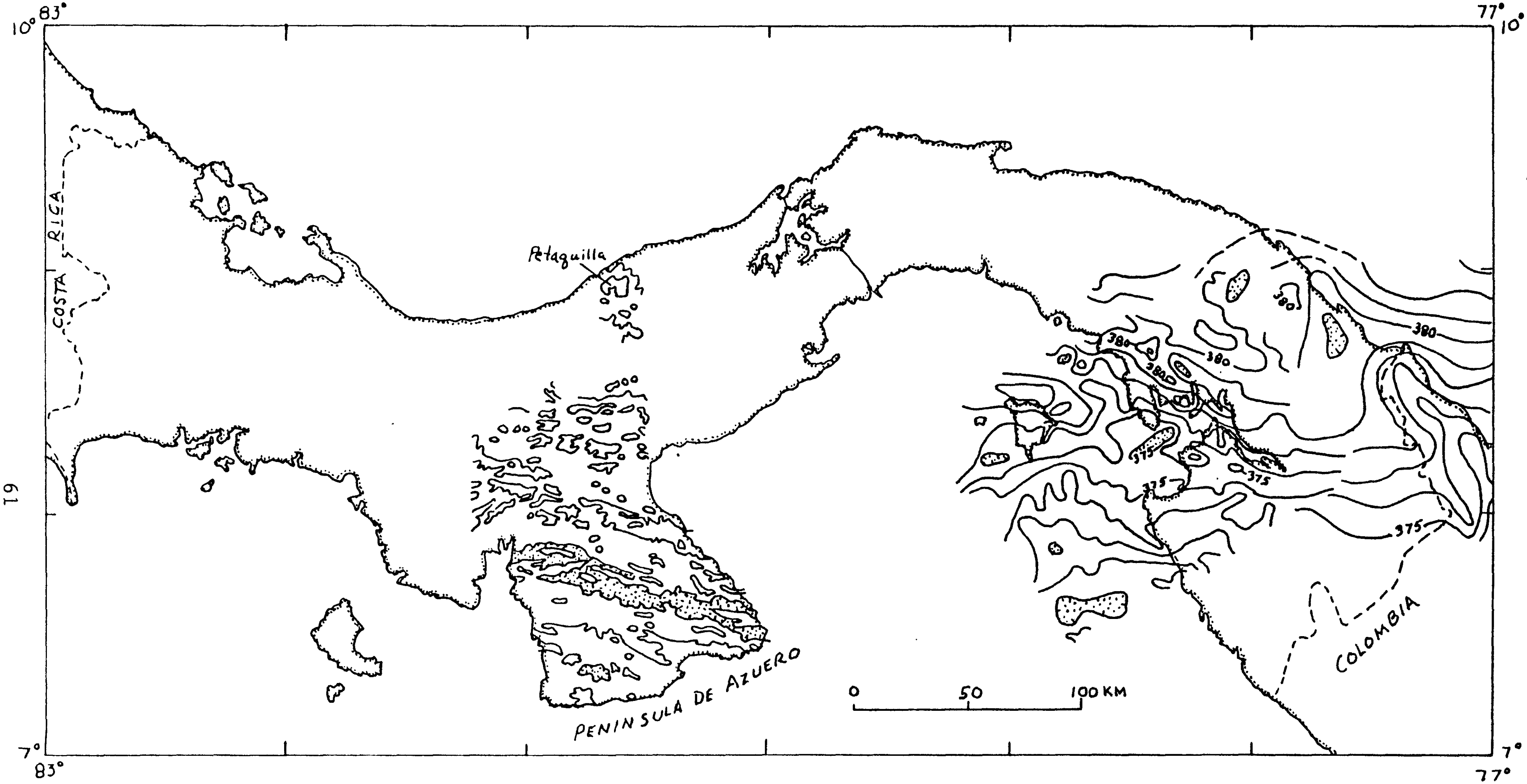


Figure 33. Magnetic map of parts of Panamá (modified after Matthews, 1976). Contour interval in eastern Panamá, 100 gammas. Contour interval in western Panamá, 500 gammas. Stipple pattern represents relative negative anomalies. Flight elevation in eastern Panamá was about 3000 meters.

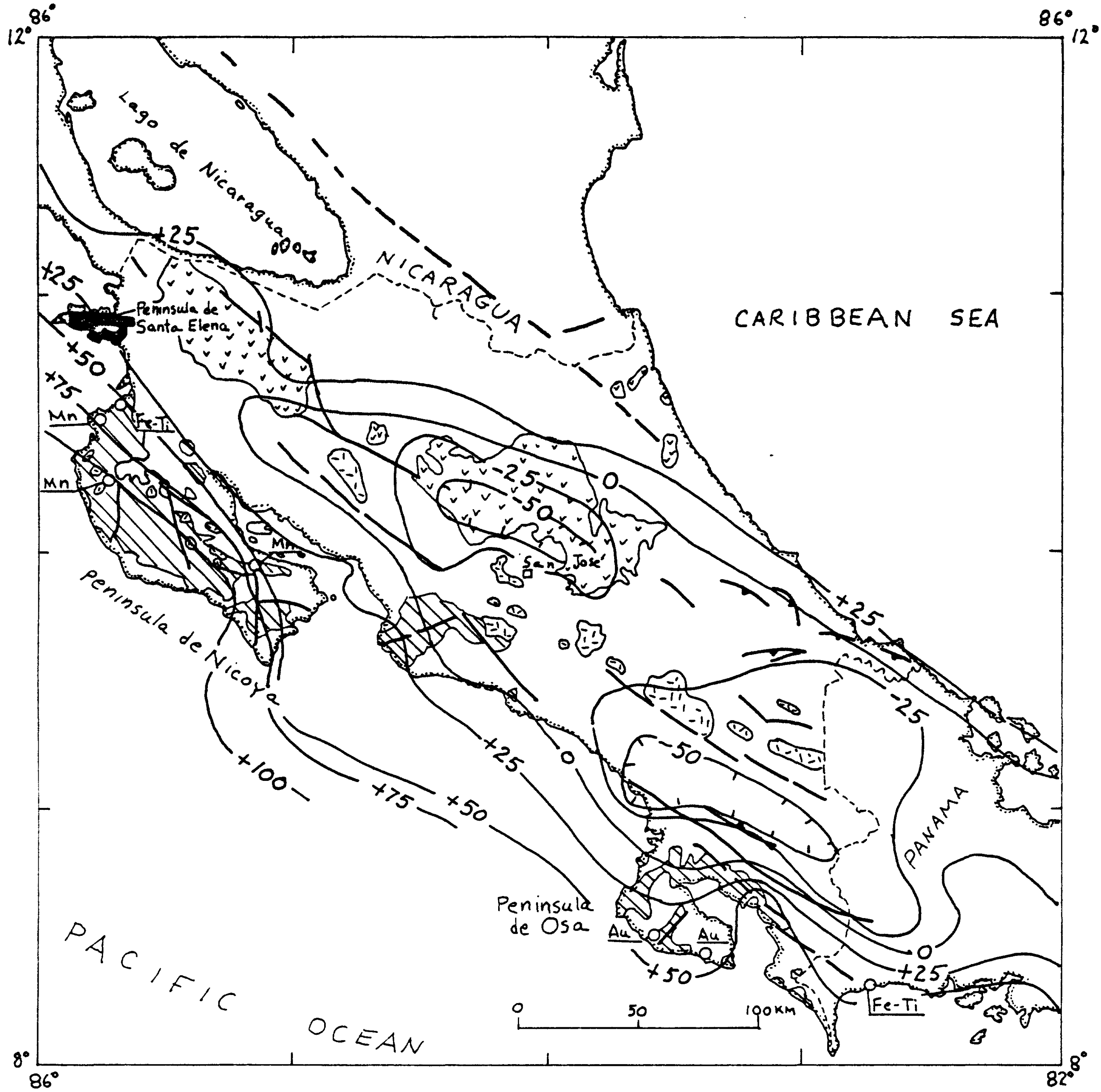


Figure 34. Simple Bouguer anomaly map and simplified geologic map of Costa Rica. Ultramafic bodies in shaded pattern. Diagonal rule indicates mafic volcanic complexes and associated sedimentary rocks of Late Mesozoic-Early Cenozoic age. Stipple pattern indicates Cretaceous sedimentary rocks. Dash pattern indicates granitic plutons. Vee-pattern indicates main Quaternary volcanic edifices. Gravity data modified from de Boer (1974) and Bowin (1976). Contour interval 25 mgal.

distinct tectonite fabric. The peridotite was intruded by swarms of mafic amphibolitized dikes ("metabasite", Dengo, 1962). Dengo (1962) also reported bodies of gabbro and diorite. The pillow basalt complex appears to overlie the ultramafic complex with angular unconformity, according to de Boer (1979).

Mafic volcanic rocks are interlayered with a variety of sedimentary rocks, including pelagic sequences with abundant chert, turbidite sequences, and carbonate sequences, some of which are pelagic and some of which are shallow water. According to Schmidt-Effing (1979), the submarine relief during Campanian time may have been more than 4 km.

De Boer (1979) has recognized several different groups of pillow flows, sills, dikes, and associated volcanogenic sedimentary rocks [Junquillal-Coyote and Montezuma types] and gabbroic and dioritic intrusives [Bahía Culebra type]. Schmidt-Effing (1979) has identified as many as six "packages" of mafic volcanic rocks and associated sedimentary rocks in different parts of the area which suggest a wide range in ages for the whole complex.

Stratigraphic and structural problems have not yet been resolved as can be seen in figure 35. Apparently, mafic volcanism extended intermittently from Late Jurassic into Paleocene or early Eocene time (Galli-Olivier, 1977, 1979; Schmidt-Effing, 1978, 1979; Galli-Olivier and Schmidt-Effing, 1977, Stibane and others, 1977).

It appears that true oceanic crust (ridge-formed??) is of Late Jurassic-Cretaceous age, and that Late Cretaceous-Paleocene mafic rocks may represent tholeiites of a primitive island arc (de Boer, 1979), similar to the two-phase pattern suggested for western Ecuador, western Colombia, and eastern Panamá by Goossens and others (1977), and Barrero (1977, 1979), but the Late Cretaceous-Early Tertiary (especially Campanian-Maestrichtian) mafic occurrences may represent activity related to the great "flood basalt" event of the southern Caribbean basins identified by Donnelly (1975). Other possibilities include magmatism related to plumes, leaky transform faults, or back-arc spreading centers.

Although no modern commercial mineral deposits have been reported for these rocks, extensive prospecting programs in Costa Rica were recently in progress. These tended to focus on possible porphyry coppers and bauxite deposits along the main Cenozoic volcanic belt, but nickel-chromite (and possibly other base metals) exploration concessions have been let for the Santa Elena peridotite area. Pichler and others (1974) found Ni and Cr anomalies at two localities in the region. Because of the locally high background copper values (>100 ppm) in the pillow basalt sequence, it appears that a search for massive sulfide deposits in the Osa and Nicoya Peninsulas might be warranted. According to de Boer (1979 and personal communication):

> "Massive sulfides (51% Fe, 36% S, 1 to 2% Cu) are interlayered in the pillow-lava sequence [in the Junquillal-Coyote sequence] near Punta Gorda. The approximately 50-cm-thick mineralization here consists of two layers in an anticlinal structure. Lateral extent is unknown."

On the Nicoya Peninsula, according to Roberts (1944), manganese deposits, including hypogene, supergene and residual, occur

> ".... in bedrock associated with masses of red and yellow jasper, which replace both sedimentary and igneous rocks. In sedimentary rocks the jasper follows bedding planes, commonly along contacts with igneous rock. In igneous rock [basalt, diorite, and diabase] it follows fracture zones. The manganese minerals replace jasper and the adjacent wall rocks."

About 32,000 long tons of ore containing about 50 percent manganese was produced during the interval 1915-1938. One wonders if the jasper could represent abyssal pelagic silicic sediments, perhaps remobilized near hot springs on the sea floor.

Magnetite sands and local magnetite-rich beachrock occurs near the Golfo de Papagayo; some samples contain as much as 25 percent TiO_2 (Weyl, 1969). Gold placer deposits occur on the Osa Peninsula (Dengo and Levy, 1970).

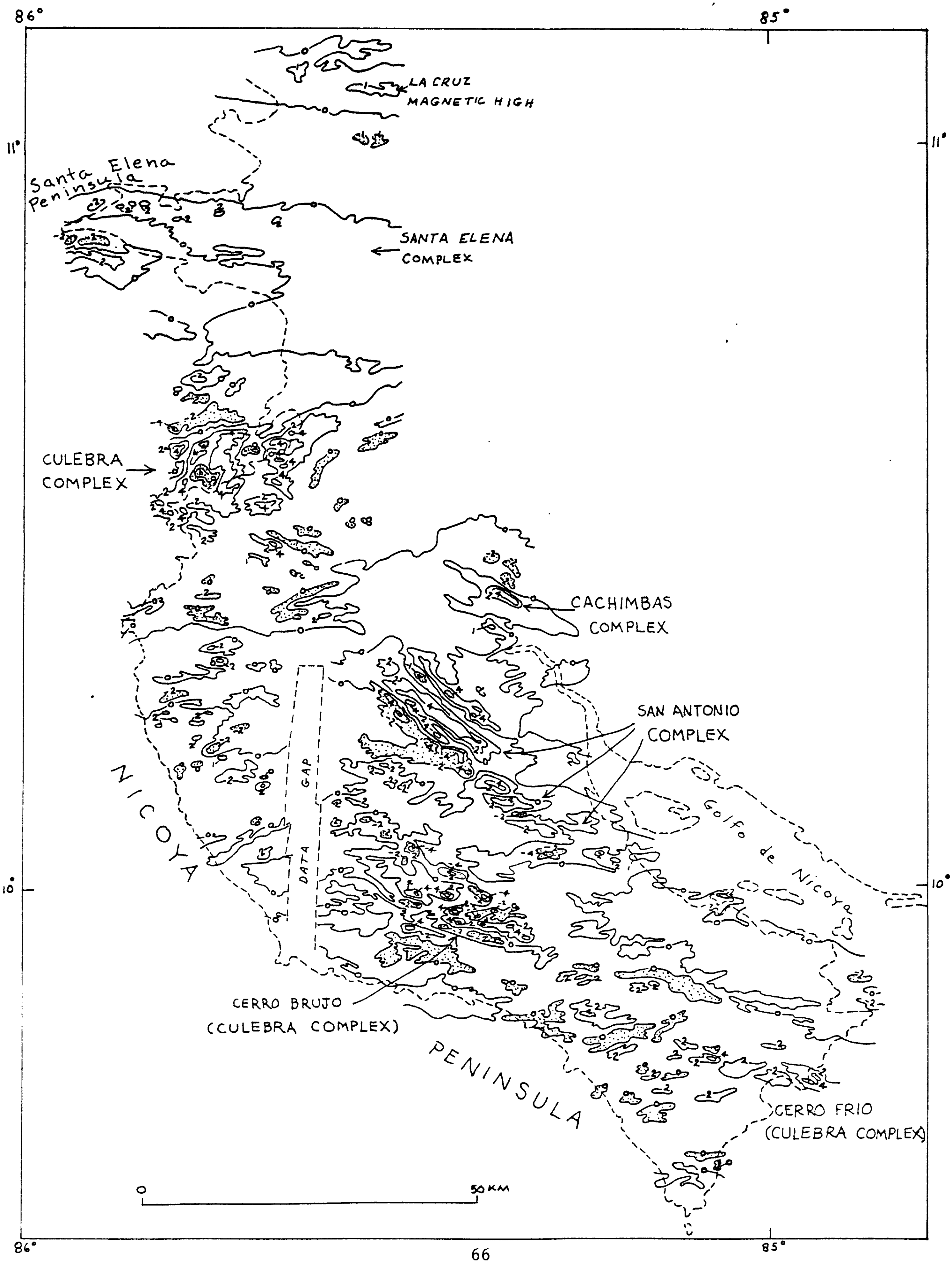
Gravity anomaly and aeromagnetic maps of Costa Rica have been published by de Boer (1974, 1979, figs. 34 and 36). The gravity map was computer-contoured, and I have recontoured the map, using presumably the same data from the U.S. Department of Defense gravity library and data from Bowin's (1976) compilation. Large positive anomalies, in excess of +100 mgals, occur over the Nicoya complex and more than +40 mgal over the Osa peninsula, and the values suggest that the crust is oceanic in composition. The aeromagnetic data over the Nicoya Peninsula, flown as part of a United Nations mineral survey, has been interpreted by de Boer (1979). Most of the mafic masses cause conspicuous anomalies of both normal and reversed polarity. Patterns of magnetic anomalies associated with the mafic-ultramafic complexes are distinctly different than those over the Cenozoic volcanic terranes and can be used to trace the lateral extent of the ophiolite masses beneath cover of younger rocks. De Boer (1979) has obtained extensive data on susceptibilities and remanent magnetization of these rocks (Table 1) and has provided interpretations of the data which will not be summarized here.

From refraction data offshore between the Nicoya and Osa Peninsulas, Matumoto and Latham (1977) reported a crustal thickness of 30 km and an upper mantle velocity of 7.9 km/sec. In northern Costa Rica [evidently in the vicinity of San José], Matumoto and others (1976) derived a crustal thickness of 43 km from analysis of travel times from local earthquakes. A large negative gravity anomaly, having values more negative than -50 mgals, occurs near San José, so that "continental" crust may be suspected in north-central Costa Rica. Cumming and Kesler (1976) have suggested that cratonic [continental] crust is the site of Ag - (Pb-Zn-Au) and Pb-Zn-(Ag) mineralization, whereas some other kind of crust [presumably oceanic or transitional] is associated with Cu-Au-Ag and Cu-Au mineralization. The only major Pb-Zn occurrences in Costa Rica occur just west of San José in the area of the negative gravity anomaly. Might a small block of pre-Mesozoic continental crust, 43 km thick, cause the negative gravity anomaly?

Offshore Middle America

From analysis of multichannel seismic data off western Guatemala, Seely, Vail, and Walton (1974) identified a "basement high" at the outer edge of the continental shelf, just east of the Middle America trench. They postulated

Figure 36. Generalized residual aeromagnetic map of parts of Costa Rica, contour interval 200 gammas with local contours at 100 gamma interval (modified after de Boer (1974). Relative negative anomalies shown by stipple. Flight lines were flown north-south at 1-km spacing and control lines flown east-west at 40 km intervals. Terrain clearance was 150 m. De Boer (1974, 1979) has prepared residual anomalies from the original data. Some groups of magnetic anomalies discussed by de Boer (1979) are shown. Stratigraphic-geographic nomenclature is shown on figure 35 and some magnetic properties of various rock groups are shown on table 1.



86°
85°
11°
10°
LA CRUZ
MAGNETIC HIGH
Santa Elena
Peninsula
SANTA ELENA
COMPLEX
CULEBRA
COMPLEX
CACHIMBAS
COMPLEX
SAN ANTONIO
COMPLEX
DATA GAP
Golfo de Nicoya
NICOYA
PENINSULA
CERRO BRUJO
(CULEBRA COMPLEX)
CERRO FRIO
(CULEBRA COMPLEX)
0
50 KM

Table 1 - Some magnetic properties of rocks from the Nicoya region, Costa Rica. Modified after de Boer (1979).

Rock Unit	Number of samples	Mean K	Mean Q	Characteristic anomalies
Santa Elena peridotite-Unit A	32	0.0007 emu/cc	0.07	Low gradient Low amplitude
Bahía Culebra complex-Unit D	18	.0092		High gradient High amplitude 300-1100 gammas
Culebra complex intrusives- Unit D; associated volcanic rocks(?)	64 18	.0042 .0056	0.8 -	 800-1800? gammas
Junquillal-Coyote complex- Unit B	77	.0025	2.31	Positive and negative anomalies Locally reversed -125 to +350 gammas
Diorite intrusives (Culebra complex?)	-	-	-	Normal and reversed polarities
San Antonio intrusives	-	-	-	Anomalies up to 2700 gammas
Volcanic rocks of San Antonio complex	28	.0136	-	- - - -

that the high is an extension of the Nicoya complex. From more recent seismic work, Ladd and others (1978) reached the same conclusion. Ibrahim and others (1979) inferred the presence of at least two separate landward-dipping slabs of oceanic crust within the upper slope from seismic reflection, refraction, and magnetic data. Gravity data compiled by Victor (1976) and Woodcock (1975) indicate that a major gravity high occurs along the east margin of the trench, and further detailed work by Couch (1976), and Couch and Woodcock (in press) suggests that the high is nearly continuous from the Nicoya Peninsula to the Isthmus of Tehauntepec (fig. 37). If, indeed, the "basement high" and gravity anomaly are caused by an ophiolite complex of late Mesozoic to Eocene age, the strike extent of the Pacific margin belt of these ophiolite-like rocks may be 18-20 degrees, from south of the equator in Ecuador (Feininger, 1977) to southern Mexico, and it constitutes a major geologic feature of the Earth.

The relatively low metamorphic grade of most of the exposed rocks in the belt, especially absence of blueschists, and the near-absence of penetrative deformation of the pillow flows, suggests that the belt was emplaced by an obduction or a shallow accretionary process rather than by a subduction process. The pillow flows have not descended into a Benioff zone for any great depth and then been subsequently uplifted.

If the gravity high is, indeed, continuous and if it is caused by rocks equivalent in age and lithology to those in the Nicoya Complex, a major tectonic problem is presented. Figure 38 shows that a triple junction between the Cocos, Caribbean and North American plates should exist where the Motagua left-slip transform system intersects the underthrust zone of the Middle America Trench. If left-lateral displacement of 132 kilometers or more has occurred along the Motagua system during the Cenozoic (Burkhart, 1978), and if the triple point is at the trench, the gravity high (fig. 37) should be offset. As it is not appreciably offset, the rocks causing the gravity high must be very young or the left slip displacement along the Motagua system must be very small between the coast and the Middle America Trench. Another possibility is that the Motagua system curves drastically northward and intersects the trench north of the Isthmus of Tehauntepec (see model by Bowin, 1976, fig. 16, p. 59). Still another possibility is that the apparent decrease of displacement westward along the fault zone is caused by progressive eastward tensional opening of associated graben (Plafker, 1976, fig. 38).

Summary and conclusions

Ophiolites of central Guatemala and Honduras are in or surrounded by continental crust that may be as thick as 30 km near the coast and 45 km near Guatemala City (fig. 39). At least some of these ophiolites were emplaced and available for erosion prior to latest Cretaceous The age of formation of the ophiolites and relations to those along the upper slope of the Pacific margin, described in the previous section, are unknown. Although the area is now dominated by a sinistral transform fault system, convergent deformation occurred in Late Cretaceous to Early Tertiary(?), presumably in a subduction mode, as judged from the occurrence of rocks of blueschist facies and local melange. Many ultramafic blocks appear to be detached, but local blocks of

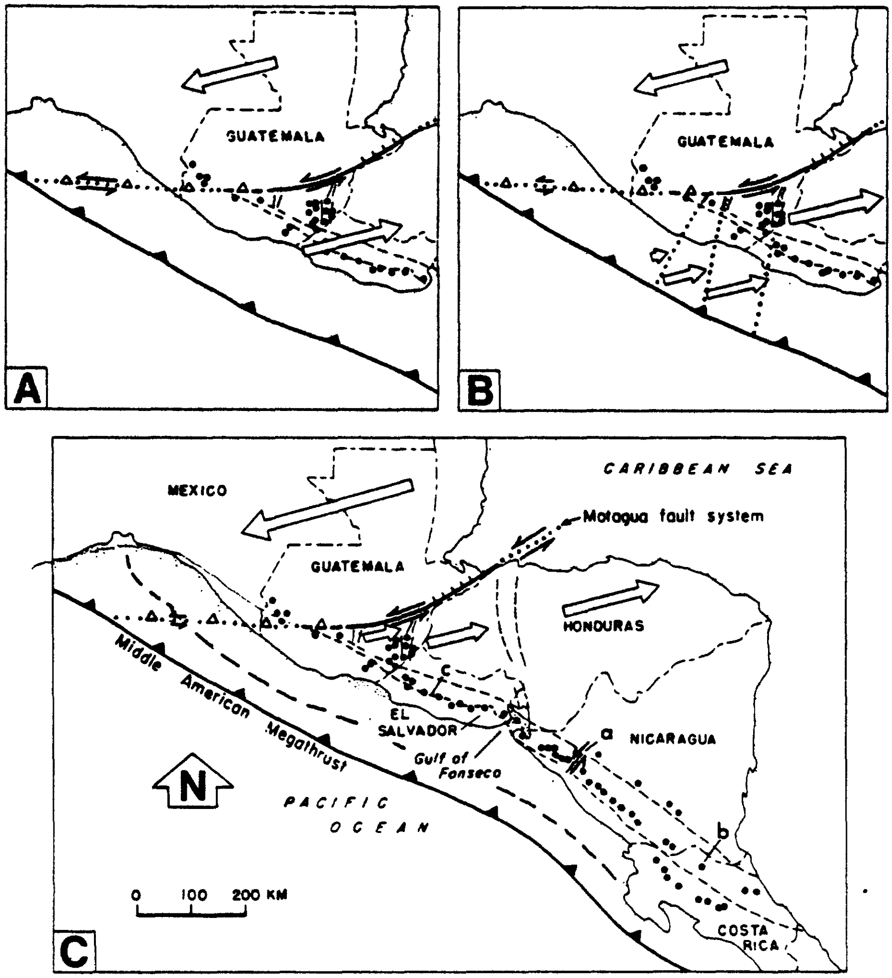


Figure 38. Plate-tectonic setting of Middle America (modified after Plafker, 1976). Heavy dashed line represents axis of the shelf gravity high. Schematic diagrams showing three alternative models for the present tectonics of part of Middle America. Inferred plate motion directions and relative velocities are indicated by the open arrows; relative fault displacements are indicated by conventional symbols; black dots indicate major volcanoes; the shaded pattern outlines major zones of extension faults. The locations of the 1972 Managua, Nicaragua (a), 1973 Costa Rica (b), and 1965 San Salvador (c) earthquakes are shown in (C).

Mesozoic oceanic rocks, possibly having considerable depth extent, occur in the Motagua fault zone. Major deposits of nickel-cobalt laterites, probably formed after final emplacement, and massive Cu-sulfides, probably formed before final emplacement, occur in the ophiolite belt. Minor deposits of chromite, asbestos, talc, magnesite, and manganese are associated with these rocks.

Cuban ophiolites were emplaced during Late Cretaceous-Early Tertiary convergence events. Many masses are detached along thrusts of variable inclination. Metavolcanic rocks of blueschist facies suggest a subduction event during the Late(?) Mesozoic. From gravitational evidence, the crust in eastern Cuba is multiple oceanic; anomalies are less pronounced in central and western Cuba, but oceanic rather than continental crust is most likely. Gravitationally derived crustal thickness is about 20-25 km. Whether convergence in Cuba was oceanic-oceanic, oceanic-continental, or a combination is not resolved by available evidence. Major deposits of post-emplacement nickel-cobalt-iron laterites, and pre-emplacement podiform chromite occur in the ophiolites, as well as minor deposits of talc, magnesite, and gold(?). Island-arc volcanic rocks of eastern Cuba are the hosts for copper and manganese deposits, and sedimentary rocks of western Cuba are hosts for copper and manganese deposits.

Small ophiolite masses of pre-Late Cretaceous age on Jamaica are geographically associated with zones of blueschist metamorphic rocks, partly of volcanic origin, indicating a subduction event, presumably in Late Mesozoic time. Oceanic or multiple oceanic crust probably underlies Jamaica, judged from positive isostatic anomalies. Ore deposits are negligible except that nickel anomalies have been reported.

In Hispaniola, at least parts of the ophiolite or early island-arc belts are as old as Aptian-Albian and range up to Late Cretaceous. Some amphibolites, possibly metamorphosed ophiolites, are as old as 127 m.y. The crust is thought to be oceanic, and crustal thickness averages about 25 km according to gravity models. Major post-emplacement nickel-laterite deposits are found in ultramafic masses of the Dominican Republic, and minor syn-volcanic manganese deposits occur in the southern Peninsula of Haiti. Although evidently not related directly to the ophiolites, copper (Memé) and gold (Pueblo Viejo) deposits occur near the ophiolite belts and probably rest on a foundation of oceanic crust.

The only probable "ophiolites" exposed in Puerto Rico are in the Bermeja complex of Late Jurassic-Early Cretaceous age. Post-emplacement nickel-iron-cobalt laterite deposits have formed on ultramafic masses. According to gravity models, the crust of Puerto Rico is multiple oceanic and may be as thick as 30 km. Porphyry coppers, syn-volcanic manganese deposits, and base metal iron replacement deposits are associated with rocks other than ophiolites but, again, as in Hispaniola, an oceanic crust at depth is suspected.

Although the only ostensible ophiolites exposed in the Lesser Antilles are pillow basalts, dikes, and trondhjemite--including native copper-bearing basalts--on La Désirade, refraction and gravity data suggest that the crust beneath the Lesser Antilles is abnormally thick--20-30 km--and oceanic.

Ultramafic rocks on Tobago do not contain significant mineral deposits, and crustal thickness and composition has not been defined because of lack of gravity and refraction data.

Ultramafic rocks on Margarita are presumably of Late Mesozoic age and they are associated with the belt of thickened, dense crust that extends southwest from the Lesser Antilles. Ore deposits include magnesite, talc, and asbestos, and minor occurrences of nickel-cobalt-chromite have been reported.

Many ultramafic bodies occur in the Araya and Paria Peninsulas and the Caribbean Coastal Ranges of Venezuela. These are thought to be of Mesozoic age, and they are associated with a variety of metamorphic rocks of greenschist and amphibolite facies. Ophiolites of the Villa de Cura belt, a great allochthonous block, are of blueschist facies. Some of the ophiolites were tectonically emplaced in Paleocene-Eocene time. Presence of metavolcanic rocks of blueschist facies indicates a subduction event prior to Early Tertiary convergence (see Maresch, 1974, for example). Ore deposits include nickel laterites, asbestos, and talc. Several concentrically zoned ultramafic bodies have been described, and minor prospects of chromite, copper sulfides, titaniferous magnetite, and asbestos have been reported. With the exception of the zoned masses on the Paraguaná Peninsula, most of the ophiolites of the Venezuelan coastal ranges occur in or on continental crust or along the transition zone between oceanic crust to the north and continental crust to the south. Crustal thickness under the coastal ranges is about 30-40 km, according to models from gravity data.

Ophiolites of the Netherlands and Venezuelan Antilles, except on Margarita, appear to lack significant known ore deposits, perhaps because of limited outcrops. Some of the ophiolites (largely basalts and associated sedimentary rocks) are of middle to Late Cretaceous age but some could be older. From gravity models, the crust is dense, probably oceanic, and as thick as 30 km.

In Colombia, ophiolites(?) on the Guajira Peninsula probably rest on oceanic crust, and the small serpentinite bodies in the Sierra Nevada de Santa Marta occur near the boundary between oceanic and continental crust. Ophiolites along the great Romeral-Cauca-Patía system of faults are also near the boundary of oceanic crust to the west and continental crust to the east. Local blueschists and melanges along the zone suggest a Late Mesozoic subduction event but local coherent ophiolite masses, relatively unmetamorphosed, may indicate an obduction event. Continental crust is estimated at about 30-45 km from combined refraction and gravity data. The ophiolites are pre- middle Eocene; some are known to be of mid-to Late Cretaceous age, but some are probably older. One concentrically zoned ultramafic-mafic complex has been found.

Associated ore deposits in Colombia include major deposits of nickel-iron laterites, small talc and asbestos deposits, local small manganese deposits, small chromite deposits, and possible mercury deposits. Platinum placers in western Colombia were probably derived from the ophiolite complexes, and it is possible that some of the associated placer gold was derived, directly or indirectly, from ophiolite terranes. Although numerous porphyry copper deposits occur near the Romeral fault zone, and in the Cordillera Occidental, no major massive sulfide deposits have been found as yet. But many basaltic rocks of the Pacific coastal ranges have anomalously high values of copper (± 200 ppm), so that exploration for massive sulfides in this terrane seems warranted.

In Panamá, basalts and associated rocks having ophiolitic or early island arc affinities are exposed in the eastern part of the isthmus and on the Azuero Peninsula. A crustal thickness of about 25 km has been estimated for central Panamá, and strongly positive gravity anomalies in eastern Panamá and on the Azuero Peninsula, plus the abundance of tholeiitic pillow basalts and pelagic sedimentary rocks of Late Cretaceous age, suggest that the crust is essentially oceanic. Available evidence suggests that the isthmus has been or is being underthrust by both the Nazca and Caribbean plates. Ore deposits include manganese and gold whose relationships to the ophiolites are obscure. Copper anomalies (± 200 ppm) occur in basalts of eastern Panamá. Porphyry coppers in eastern Panamá appear to have a foundation of oceanic crust, but the crustal thickness and composition, in western Panamá, where very large porphyry copper deposits exist, is still unknown.

In Costa Rica ophiolites occur on the Osa, Nicoya, and Santa Elena Peninsulas along the Pacific margin. Mafic volcanic rocks and associated sedimentary rocks evidently have a wide range of ages--from Late Jurassic into Early Tertiary, and several episodes of mafic volcanism have occurred. Known ore deposits associated with these rocks are not very large. Various small manganese deposits, occurrences of small massive sulfides, and local geochemical anomalies of chromite and nickel have been reported. From positive gravity anomalies, the crust beneath the peninsulas is probably oceanic, but a block of continental crust may be present farther east near San José. From refraction data, crustal thickness may be as great as 30 km offshore and 43 km in northern Costa Rica.

Presence of positive gravity anomalies and data from multichannel reflection surveys indicate that the block of dense rocks may extend offshore northwest from the Nicoya and Santa Elena Peninsulas, near the shelf edge, to the latitude of the Isthmus of Tehauntepec, where the gravity anomaly turns abruptly inshore.

<u>Some geophysical ore guides and prospecting techniques</u>.--Far more gravity data are needed in the entire region to provide ore guides at three levels: on a crustal level, the gravity anomalies can be used to make preliminary estimates of whether specific areas are underlain by oceanic, continental, or transitional crust; to trace crustal units offshore; and to determine whether crustal blocks have been tectonically transported. On a more local scale, gravity anomalies constitute a powerful tool in determining the depth extent of mafic and ultramafic masses, specifically related to the problem of whether the masses are "rooted" or are detached along thrust faults. On a detailed scale, gravity anomalies have been successfully used to prospect for specific chromite deposits, and could be used to prospect for any dense mineral accumulations.

Magnetic data over the ophiolite belts of the region are sparse, except in Cuba, Puerto Rico, parts of Panamá, and parts of Costa Rica. Aeromagnetic data are probably most useful in extrapolation of the belts under cover of various types. Depth estimates can be made for uniformly magnetized masses, and both aeromagnetic and ground magnetic surveys have been useful in location of deposits associated with magnetite-rich rocks. Modeling can aid in determination of the shape and structural orientations of mafic and ultramafic bodies. Complete modern aeromagnetic coverage of the region would unquestionably provide major advances in regional geologic analysis and very likely would provide specific exploration targets.

The whole array of electrical and electromagnetic techniques, of course, has application to prospecting for specific targets.

Refraction surveys are urgently needed in the whole Caribbean region for determination of crustal thickness, velocity structure, and, in combination with gravity data, the density distribution. On a prospecting scale, refraction surveys probably would be useful in prospecting for a variety of commodities: for example, it should be possible to determine thickness of laterite zones with shallow refraction techniques.

Radiometric surveys may or may not have applications to prospecting over ophiolite terranes, but such data would almost certainly aid in regional geologic mapping programs.

Major regional problems.--In addition to the usual questions regarding origin, age, and emplacement mechanisms for the ophiolite complexes, perhaps the most perplexing geological problem in the circum-Caribbean region is that of thick crust (20-35 km) which appears to be of oceanic density beneath eastern Cuba, Jamaica, Hispaniola, Puerto Rico, the Lesser Antilles, Margarita, the Venezuelan and Netherlands Antilles, the Cordillera Occidental and Serranía de Baudó of Colombia, possibly eastern Panamá and the Azuero Peninsula, and probably on the Pacific margin of Costa Rica at the Osa, Nicoya and Santa Elena Peninsulas. If these areas were once formed at typical spreading ridges, having a thickness of 8-15 km, the crust is two or three times as thick as normal.

Various tectonic-igneous processes may be envisioned to account for abnormal thicknesses of oceanic crust (fig. 40). Some constraints may be obtained from the presence or absence of associated high pressure-low temperature (blueschist facies) or low pressure-high temperature (greenschist to amphibolite facies) metamorphic rocks. Presence of blueschist facies metamorphic rocks is considered to be strong evidence for a subduction event.

1. Oceanic crust may be thickened by imbricate stacking related to unidirectional convergence, either in a subduction or obduction mode. The basic convergence zone may occupy the same position through time or step or jump laterally from the initial position. (Possible examples: Greater Antilles, Lesser Antilles, Venezuelan Borderland, western Colombia.)

2. The crust may be thickened where undirectional convergence changes to the opposite direction ("flipping"). (Possible examples: Greater Antilles, Lesser Antilles, Venezuelan coastal ranges, Panamá(?).)

3. Simultaneous bidirectional convergence may thicken crust. (Possible examples: Panamá, Puerto Rico, Hispaniola.)

4. Mafic volcanism, such as in a primitive island arc or associated with plumes or leaky transform faults, may load the crust causing depression. (Possible examples: Greater Antilles, Venezuelan Borderland, western Colombia, Panamá, Costa Rica.)

5. Combinations of the above.

Where some of the ophiolite masses of the region were emplaced by an obduction process, as may be the situation in western Colombia, Panamá, and Costa Rica, we are confronted by the problems of an energy source and mechanism for emplacement, a subject elegantly addressed by Coleman (1971, 1977).

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