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Gravity Constraints on the Crustal Structure of Central America

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ABSTRACT

Gravity data from Central America and the adjacent offshore regions were analyzed in conjunction with seismic reflection/refraction models, seismicity studies, geologic mapping, and well data to determine a gravity-based crustal structure for the region. Analysis of the gravity data included the construction of a Bouguer and three isostatic residual gravity-anomaly maps, and 2-D gravity models across Guatemala/Belize, Nicaragua/Honduras, and Panama, respectively. The isostatic residual-gravity anomaly map that emphasizes anomalies caused by crustal and upper mantle sources was used to correlate gravity anomalies with known geologic/tectonic features and to emphasize possible previously unknown geologic features in the upper crust. These include granitic rocks in central Guatemala that are related to the Chiapas Massif in southeastern Mexico, basement uplifts under the carbonate platform sediments in northern Guatemala, and thin or dense sediments in the El Salvador depression. In Nicaragua and Honduras, the Nicaragua depression thickens toward the Costa Rican border, and the Mosquitia Basin is seen to consist of a series of depositional centers, possibly pull-apart basins. In Panama, Quaternary volcanic rocks are shown to occur close to the Choco Block boundary in the Gulf of Mexico. However, based on isostatic residual-gravity maxima over mafic igneous material in northern Panama, the boundary between the Chorotega and Choco Blocks may extend 150 km west of its present position.

The 2-D gravity models indicate that the crustal thickness of the Maya and Chortis Blocks is approximately 36–38 km and approximately 22 km under Panama. However, the density of the upper mantle is higher under Panama than it is under Guatemala and Nicaragua. To model a large-amplitude gravity maximum along the Middle America subduction zone, a combination of an ophiolitic complex and a steeply dipping Cocos Plate was required. Isostatic residual-gravity anomalies indicate that the ophiolitic complex is not continuous along the Middle America trench but occurs in discontinuous steps. To explain a regional gravity maximum over the Nicaraguan volcanic belt, a deep (>5 km) mafic (?) body was required; however, its exact position cannot be determined from gravity modeling alone. Gravity modeling indicates that subduction does not occur between the Nazca and Caribbean Plates; however, this solution is not unique. If the boundary between the two plates is a transform boundary, this boundary must be dipping at a steep angle. To model a large amplitude gravity maximum and minimum along the northern coast of Panama, a subducting plate (Caribbean) was required, with the Caribbean upper mantle being denser than that beneath Panama.

INTRODUCTION

The tectonic development of Central America has been the subject of numerous investigations (e.g., Lonsdale and Klitgord, 1978; Anderson and Schmidt, 1983; Deaton and Burkart, 1984; Manton, 1987; Guzman-Speziale et al., 1989; Case et al., 1990; Donnelly et al., 1990; Pindell and Barrett, 1990; Silver et al., 1990; Kellogg and Vega, 1995; Kolarsky and Mann, 1995; Hinz et al., 1996; Weinberg, 1992). These investigations have shown that Central America is composed of several terranes consisting of continental blocks, volcanic arcs, and oceanic plateaus. The present study presents gravity evidence on the overall structure of Central America that will provide useful constraints on tectonic origin of the region.

The geologic framework of Central America ultimately is related to the present plate interactions and the tectonic history of the various plate boundaries (North American, Cocos, Caribbean, Nazca, South American [Figure 1]) that border parts of Central America. These plates have created two types of boundaries: transform (Motagua-Polochic fault system in Guatemala, Panama fracture zone) and convergent (Middle America trench, Columbia trench). The Middle America trench is particularly important to this study as it, along with the Central American volcanic belt (Carr et al., 1982; Carr and Stoiber, 1990), marks the location of the subduction of the Cocos Plate beneath the Caribbean Plate. The geological complexity of the subduction/trench system has been determined by numerous seismological studies (Protti et al., 1995; see this paper for seismic reflection/refraction studies) that have indicated that the subducting Cocos Plate varies in depth and dip angle from Guatemala to its terminus at the aseismic Cocos Ridge. However, there is evidence of subduction south of the Cocos Ridge (de Boer et al., 1991; Kolarsky and Mann, 1995), although the existence of subduction continuing to South America is controversial (Lonsdale and Klitgord, 1978; Pennington, 1981). Active subduction probably does not exist between the Nazca and Caribbean Plate boundary (Westbrook et al., 1995).

The Central American trench/forearc system has been extensively studied (Ibrahim et al., 1979; Shipley et al., 1992; Ye et al., 1996; Ranero et al., 2000) with the majority of the studies being conducted offshore of Costa Rica. These studies have concentrated on the velocity structure of the accretionary prism and the continental margin complex to determine along-strike structural variations. The main controversy has been determining the nature of the high and low velocities within a wedge-shaped unit on the upper plate of the subducting Cocos Plate. Ye et al. (1996) and Walther et al. (2000) speculate that the high velocities are due to an offshore extension of the ophiolites of the Nicoya Complex (Escalante, 1990), with low velocities representing subducted sediments. Although earlier studies (Seely et al., 1974) suggested that sediments were accumulating with a trench system, the above seismic investigations plus deep-sea drilling (von Huene et al., 1985) suggest that little accretion has occurred along the Middle America trench and that the basement slope consists of Mesozoic ophiolitic rocks.

The exposed land portion of Central America has been broken into four terranes or blocks (Maya, Chortis, Chorotega, and Choco, shown in Figure 1) based on rock types and ages, stratigraphic sequences, and structural patterns by numerous workers (Burkart, 1983; Burkart and Self, 1985; Dengo, 1985; Donnelly et al., 1990; Duque-Caro, 1990; Escalante, 1990). The Maya Block (Burkart and Self, 1985), which is separated from the Chortis Block by the Jocotan Fault, originated as a continental block in the Gulf of Mexico. It has rock ages ranging from Precambrian to Holocene. The most significant lithologies are the widespread Precambrian and Paleozoic metamorphic rocks exposed throughout Guatemala and encountered in wells in eastern Guatemala and Belize. Overlying the metamorphic rocks are thick sequences of Late Paleozoic marine sediments and Mesozoic continental sediments. In the early Tertiary, the block was emplaced (sutured) to its present position while ophiolite complexes were emplaced along the Motagua Fault (or zone).

The Chortis Block, which may have originated in southwestern Mexico as a continental block (Donnelly et al., 1990), extends to the Santa Elena Peninsula in Costa Rica. The Chortis Block, like the Maya Block, contains Precambrian through Holocene lithologies but differs from it in the type of metamorphic rocks and pre-Tertiary sediments. The pre-Tertiary sediments include Paleozoic mudstones, early Mesozoic marine and lacustrine sediments, and evidence of a possible marine transgression during the Cretaceous. Also of importance is the extensive cover of Cenozoic volcanic rocks in the western portion of the block.

The Chorotega and Choco Blocks of southern Central America (Duque-Caro, 1990; Escalante, 1990) are separated by a series of inverted faults reflected by a major change in the Bouguer gravity anomaly field.

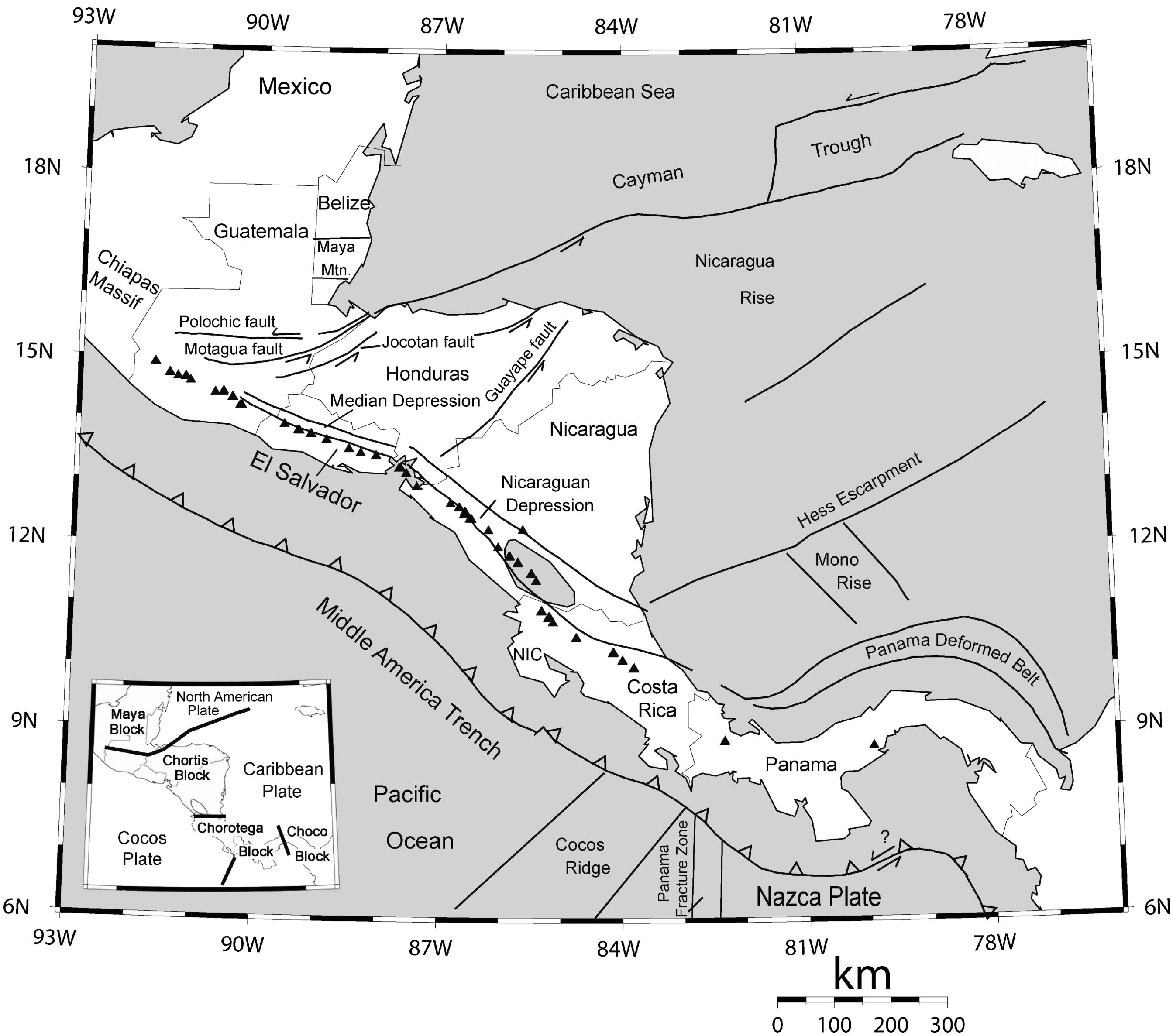

Figure 1. **Location of the study area and general tectonic features of Central America and surrounding areas. NIC = Nicoya Complex. Triangles represent volcanoes in the Central American volcanic belt. The inset shows the location of the four blocks that comprise Central America. Bolded lines represent faults. Strike-slip faults are represented with arrows showing displacement direction. The Middle America trench is represented by a solid line with triangles. Shaded regions represent water.**

The northern boundary of the Chorotega Block is a series of southwest-dipping thrust faults known as the Panama Deformed Belt (or North Panama Fault zone) (Figure 1) (Silver et al., 1995). The basement of both blocks consists of Mesozoic mafic igneous rocks of oceanic origin, and no Paleozoic or older lithologies have been found on either block. The Chorotega Block also contains Cretaceous marine sediments and Cenozoic volcanic and continental clastic sedimentary rocks.

The Choco Block, which also is bounded on the north by the Panama Deformed Belt, is bounded on the east by the Romeral Fault in the Andes Mountains of Columbia and on the south by an ill-defined region in the Gulf of Panama (Escalante, 1990). Even though its basement also consists of Mesozoic mafic igneous rocks, there is scant evidence that it is younger than the basement rocks of the Chorotega Block. The main differences between it and the Chorotega Block and the rocks in South America are that the Cenozoic pelagic and hemipelagic sequences do not have an affinity to South American sequences, and there are few, if any, Quaternary age volcanic rocks on the Choco Block.

Central America and the surrounding oceanic regions have been the site of numerous crustal seismic and gravity investigations; the most important have been seismic reflection and refraction studies along the coastal margins of Central America (Case et al., 1990). Case et al. (1990) provide the basic synthesis of available seismic and gravity crustal models that are concerned with Central America, while Bowin (1976) provides a basic overview of the gravity field of the entire Caribbean region, including portions of Central America. Since 1990, significant seismic investigations have been performed across the Middle America trench and Pacific margin off Costa Rica and Nicaragua (Protti et al., 1995; Ye et al., 1996; Pecher et al., 1998; Meschede et al., 1999; Ranero et al., 2000; Walther et al., 2000), the land bridge of Costa Rica (Colombo et al., 1997; Sallarès et al., 1999; Sallarès and Danobeitia, 2001), the Panama Deformed Belt (Silver et al., 1990; Reed and Silver, 1995; Silver et al., 1995), and western and southern Panama (de Boer et al., 1991; Moore and Sender, 1995).

While these geophysical studies have provided an enormous amount of information on the tectonic evolution of Central America, the majority of these studies have been seismic reflection and/or refraction investigations concentrated along plate boundaries. Some of the plate boundary studies (e.g., Victor, 1976; Westbrook et al., 1995; Sallarès and Danobeitia, 2001) have included gravity data in their investigations, but there have been only a few detailed gravity studies (Barday, 1974; Rafaels, 1977; Briceno-Guarupe, 1978; Couch and Woodcock, 1981; Anders et al., 1991; Kellogg and Vega, 1995; Elming and Rasmussen, 1997) of these regions. Even more scarce have been regional gravity studies of the Central American mainland, and these usually have included only selected portions of Central America, e.g., western Nicaragua (Elming and Rasmussen, 1997), Panama and Costa Rica (Case, 1974; Kellogg and Vega, 1995), Honduras (Anders et al., 1991), and western Guatemala (Machorro and Mickus, 1993).

In this investigation, previously available gravity data are analyzed in conjunction with seismic reflection and refraction models, well data, and geologic mapping to present a regional crustal structure model of Central America. Bouguer and isostatic residual anomaly maps were constructed, and in conjunction with three regional 2-D gravity models across Guatemala, Nicaragua, and Panama, respectively, a regional crustal structure for Central America will be determined.

GRAVITY DATA AND PROCESSING

Approximately 500,000 gravity stations obtained from the National Imaging and Mapping Agency, National Geophysical Data Center, and the University of Texas at Dallas were processed into simple Bouguer gravity anomaly values on land and free-air gravity anomalies over the ocean and merged into one coherent database. The merged data were gridded at a 6-km spacing using a minimum curvature algorithm (Briggs, 1974), and this grid was used to construct a gravity anomaly map (Figure 2).

There are numerous techniques to analyze gravity maps, including wavelength filtering, polynomial trend-surface fitting, and edge enhancements to determine the location and nature of crustal density variations. These techniques are useful in qualitatively interpreting regional and residual-gravity anomalies. However, they should not be quantitatively interpreted, because anomalies may be created that are not related to actual subsurface density contrasts (Ulrych, 1968). One technique — isostatic residual-gravity anomaly maps — is based on geologically estimated parameters (density of the topography, depth of compensation, and density between a crustal root and surrounding material) and thus is more likely to produce anomalies caused by crustal sources (Simpson et al., 1986). Regional seismic analyses (Matumoto et al., 1977; Kim et al., 1982; Case et al., 1990; Colombo et al., 1997) and regional gravity studies (Case et al., 1990; Anders et al., 1991; Kellogg and Vega, 1995) were used to determine a depth of compensation (30 km), density of the topography (2.67 gm/cc), and density contrast across the crustal root (0.35 gm/cc). These values, along with the 6-km topography grid, were used to determine isostatic regional gravity anomalies. This regional gravity anomaly grid then was subtracted from the Bouguer gravity anomaly grid (Figure 2) to create isostatic residual-gravity anomaly maps (Figures 3–5).

MODELING AND DISCUSSION

In order to quantify the interpretations of the Bouguer and isostatic residual-gravity anomalies discussed below, three crustal-scale gravity models (Figures 6–8) were constructed that cross the major tectonic provinces in Central America (Figures 3–5). The models were derived using a forward-modeling algorithm (Schmidt and Götze, 1999) where the predicted gravity anomalies were determined using the gravity station elevations. Since simple Bouguer gravity

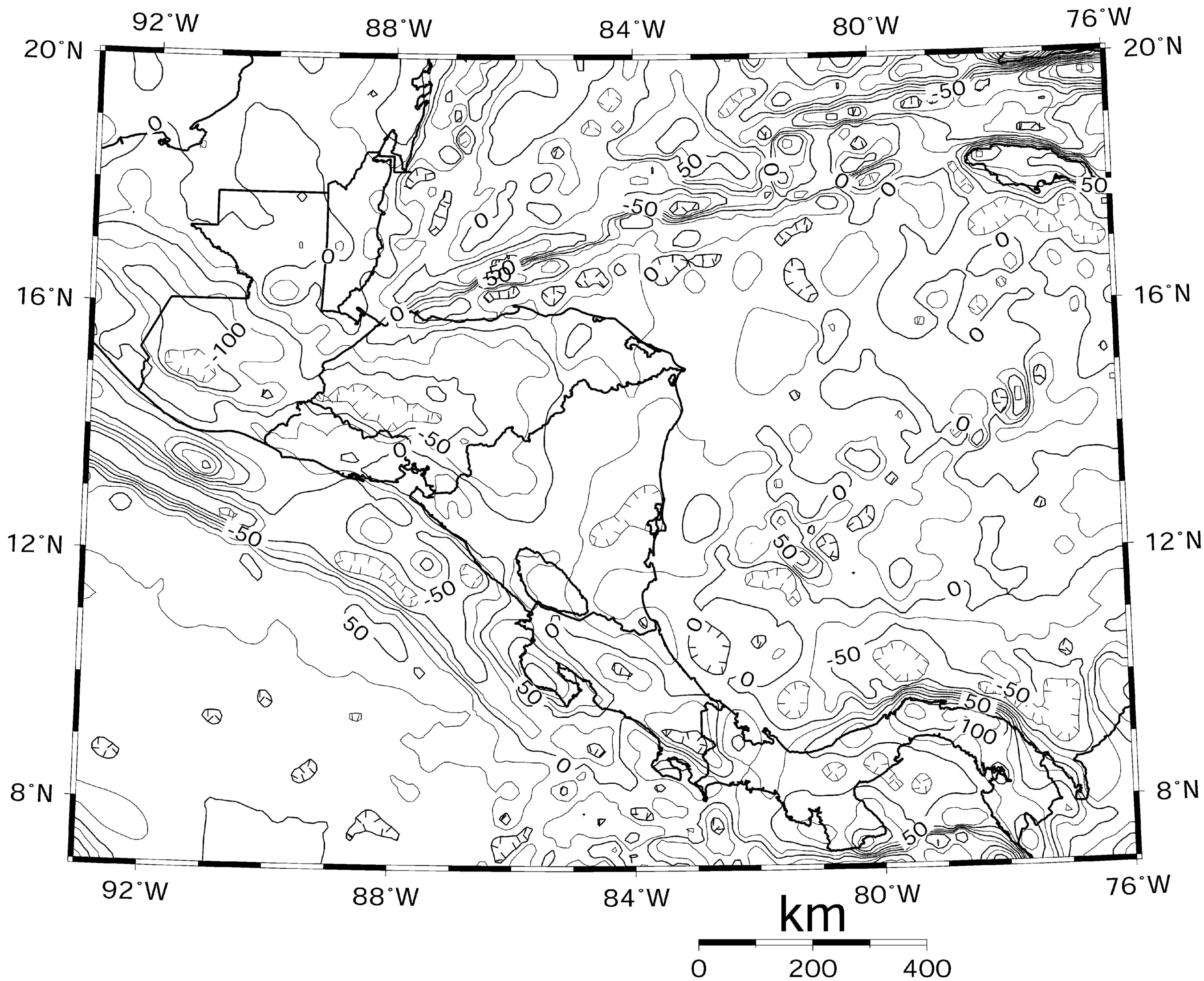

Figure 2. **Bouguer gravity anomaly map of the study area. Contour interval is 25 mGal. Relative gravity minima are shown by hachured contour lines.**

anomalies are being used, the topography was included in the models. Because gravity models are nonunique, constraints (e.g., rock densities, depth to, thickness, and lateral variation of rock units) must be used to constrain geologically meaningful models. Rock densities and subsurface depths/geometries of rock units are not available readily in Central America. However, crustal thickness variations were available from regional seismic studies (see references in the introduction), and average crustal and upper-mantle densities were estimated from these studies using P-wave velocities and experimental density/velocity relationships (Nafe and Drake, 1957). These densities were varied by as much as 5% during the modeling process in order to match the observed gravity anomalies.

The final models (Figures 6–8) were obtained through a trial-and-error process until the predicted gravity values matched the observed Bouguer gravity anomalies using the above constraints. The final models are not unique, but they represent what I feel are reasonable geological cross sections given the constraints that were available. These models mainly were created to help determine the general crustal structure of Central America. The main points in each model and the relationship of the model to nearby isostatic residual-gravity anomalies are discussed below.

Model 1

Model 1 (Figures 3 and 6) crosses the Middle America trench, the Guatemalan volcanic belt, the

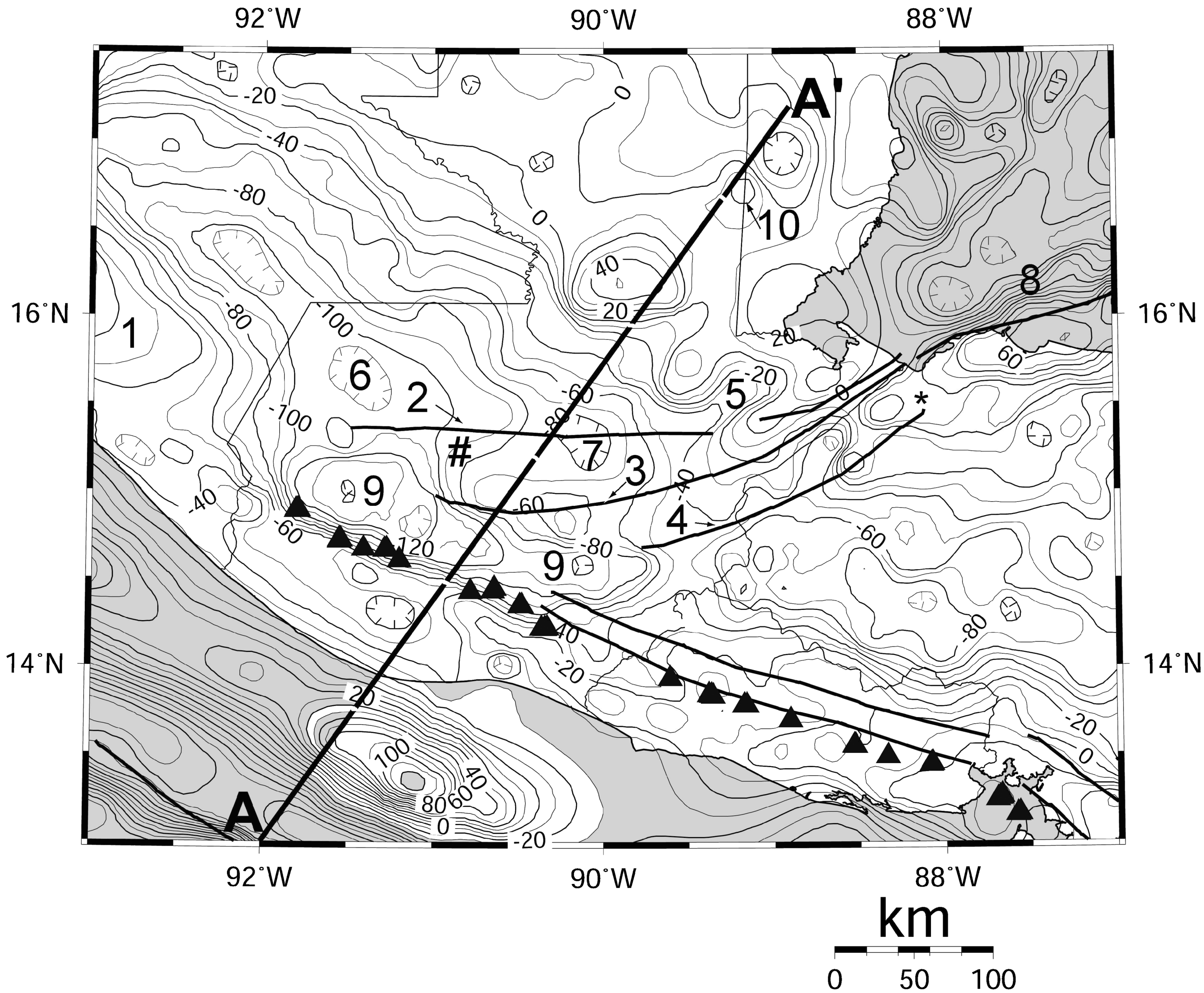

Figure 3. **Isostatic residual-gravity anomaly map of the northern section of the study area including southern Mexico, Belize, Guatemala, western El Salvador, and western Honduras. Contour interval is 10 mGal. Relative gravity minima are shown by hachured contour lines. Major tectonic features shown in Figure 1 are also shown. To illustrate left-lateral offset along the Polochic Fault, the following numbers were used: (1) Chiapas Massif, (2) Polochic Fault, (3) Motagua Fault, (4) Jocotan Fault, (5) Izabal half graben, and (6) the Cuchumatanes Mountains. The symbols #, *, 7, and 8 are used in the text to illustrate a palinspastic reconstruction along the Polochic Fault. Numbers 9 and 10 refer to gravity anomalies mentioned in the text. Profile A-A′ represents the location of gravity model 1. Gaps in the model profile represent 100-km distance increments with the start being on the southwestern edge of the profile line. Shaded regions represent water.**

Motagua and Polochic faults, the Peten Basin, and the Maya Mountains in Belize. This model shows the Cocos Plate subducting beneath Central America, with the exact dip of the plate relatively unconstrained by gravity data. However, changing the dip by more than 10° will require that the near-surface geology be altered so that it would not agree with published models in the region (Rafaels, 1977; Couch and Woodcock, 1981; Ye et al., 1996). There are no detailed seismic reflection/refraction profiles in the region, so seismic profiles of offshore Nicaragua and Costa Rica (Ye et al., 1996; Ranero et al., 2000) were used as starting models for the trench and coastal-plain units. The main aspect of these units is the dense mafic unit (ophiolite?) that extends to 10 km in depth. The ophiolite and the subducting plate are responsible for the large negative free-air gravity anomaly offshore of Guatemala. This high-amplitude gravity anomaly and sparse seismic data have been interpreted to be a continuation of the Cretaceous Nicoya

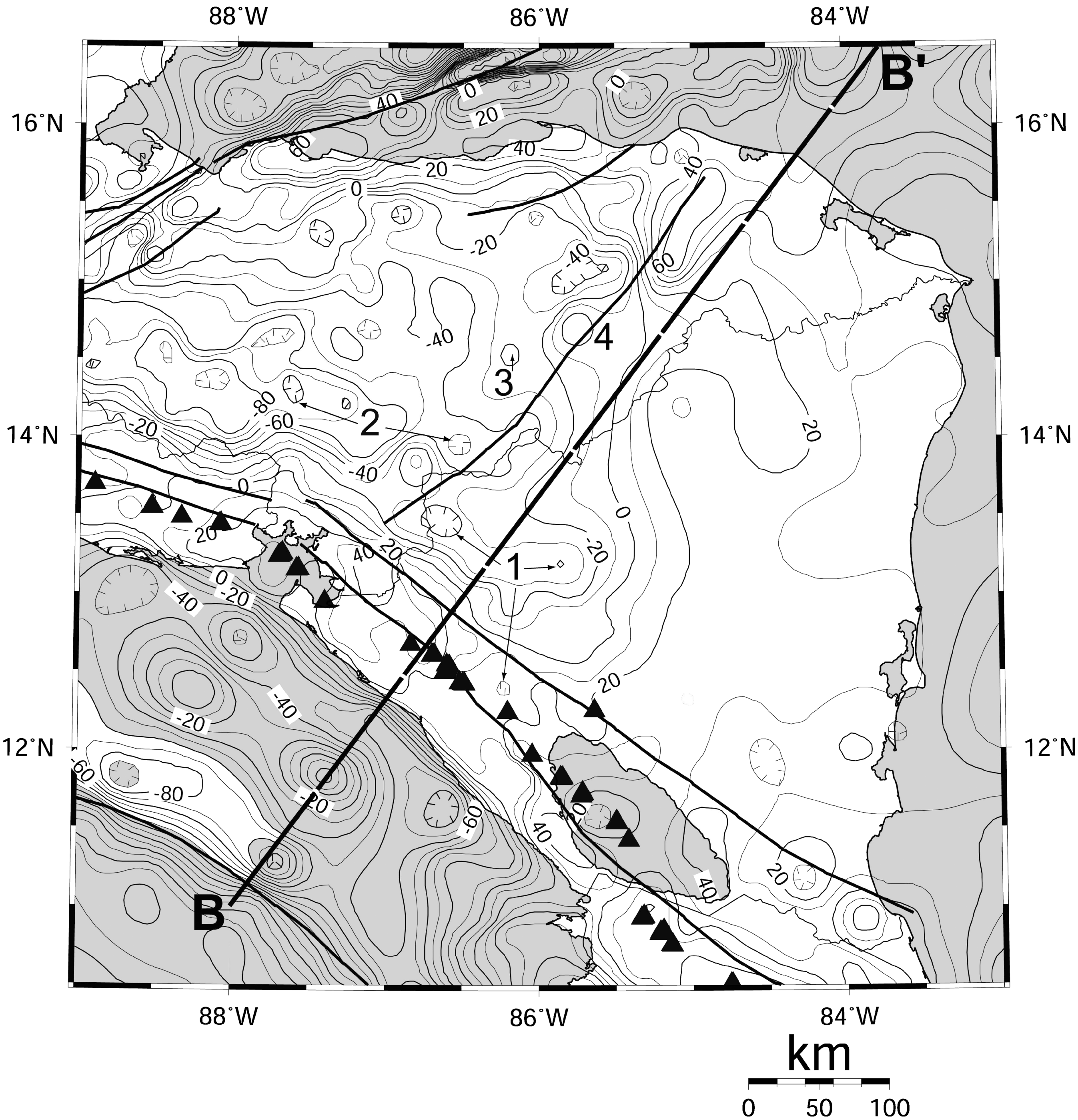

Figure 4. Isostatic residual-gravity anomaly map of the northern section of the study area including eastern Honduras, Nicaragua, eastern El Salvador, and northern Costa Rica. Contour interval is 10 mGal. Relative gravity minima are shown by hachured contour lines. Major tectonic features shown in Figure 1 also are shown. Numbers 1–4 refer to gravity anomalies mentioned in the text. B-B′ represents the location of gravity model 2. Gaps in the model profile represent 100-km distance increments with the start being on the southwestern edge of the profile line. Shaded regions represent water.

Complex in Costa Rica (Seely et al., 1974; Ibrahim et al., 1979; Couch and Woodcock, 1981). Based on a series of discontinuous isostatic residual-gravity anomalies (Figures 3 and 4), I suggest that this complex does continue northwest of Costa Rica but consists of either a discontinuous or thickening and thinning ophiolite complex from Costa Rica to Guatemala.

The coastal-plain sediments (forearc region) are broken into two units: a near-surface layer that is less dense, and a denser unit extending to approximately

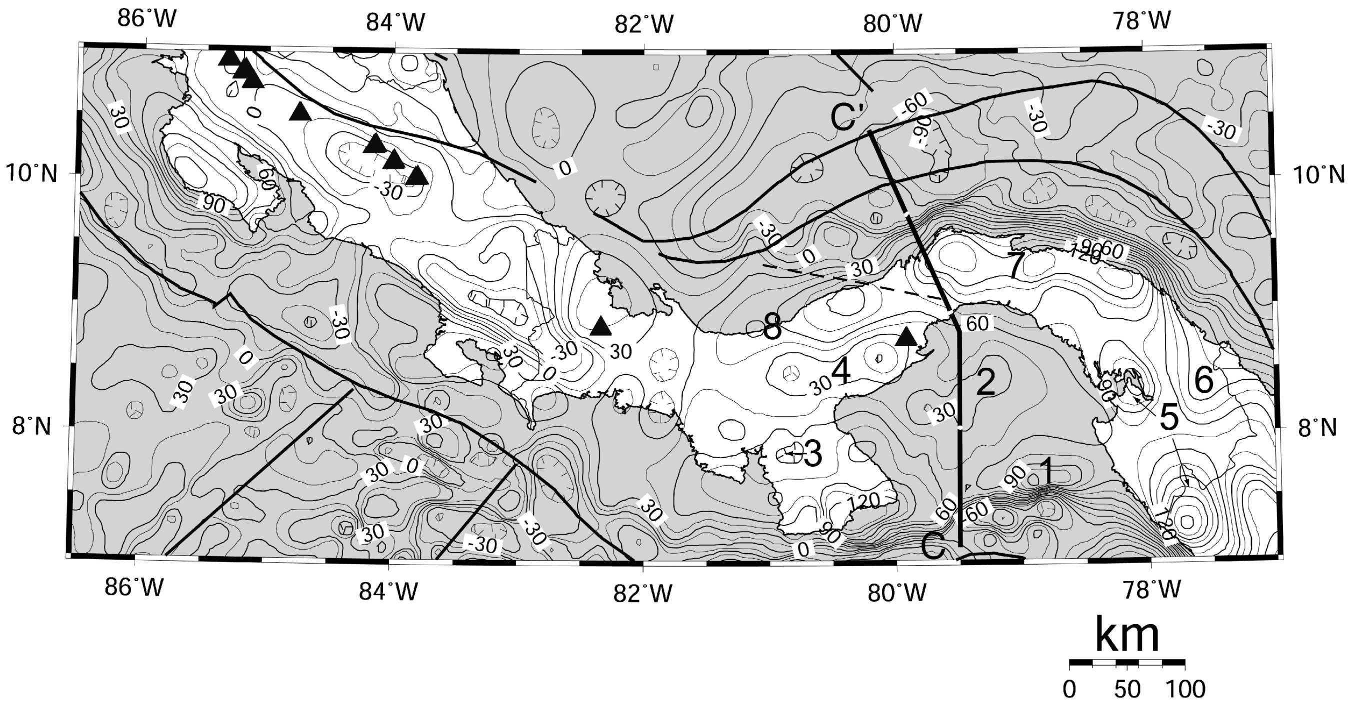

Figure 5. Isostatic residual-gravity anomaly map of the southern section of the study area including southern Costa Rica and Panama. Contour interval is 15 mGal. Relative gravity minima are shown by hachured contour lines. Major tectonic features shown in Figure 1 also are shown. The dashed line represents a proposed boundary between the Choco and Chorotega Blocks. Numbers 1–8 refer to gravity anomalies mentioned in the text. C-C′ represents the location of gravity model 3. Gaps in the model profile represent 100-km distance increments with the start being on the southern edge of the profile line. Shaded regions represent water.

7 km in depth. The forearc basin is associated with gravity minima, with its largest amplitude northwest of the gravity profile (Figure 3). As with the ophiolite unit, the gravity minima associated with the forearc basin is discontinuous along the entire length of the Middle America subduction zone.

The volcanic belt was modeled as a thick (as much as 6 km), low-density unit. However, because of the lack of constraints, one could also model the Bouguer gravity minimum with a thinner layer of volcanic rocks and a low-density granitic unit at depth. The isostatic residual-gravity anomaly caused by the volcanic belt (anomaly 9, Figure 3) extends southeast to the El Salvador/Honduras border and into southwestern Mexico to the north. The active volcanoes end at Volcán Tacaná on the Mexican border, and gravity minima occur over the Permian-Triassic Chiapas Massif in western Guatemala and southwestern Mexico (Guzman-Speziale et al., 1989). A batholith extending to at least 10 km would explain the observed gravity anomaly; the observed gravity data cannot determine if the batholith extends south to intersect this gravity model.

The most complicated and unconstrained region of this model is the Motagua and Polochic Fault zones. This region represents the boundary between the North American and Caribbean Plates (Burkart, 1983) and consists of metamorphic lithologies, continental sedimentary units, and ophiolite sequences (Donnelly et al., 1990). Burkart (1983) first noticed that Bouguer gravity maxima parallel these fault systems, and Machorro and Mickus (1993) extended this observation into southwestern Mexico. The Bouguer gravity anomalies along the model consist of a narrow gravity maximum along the Motagua Fault zone with a gravity minimum to the north that has a small wavelength maximum superimposed on the minimum. The gravity maximum is modeled as Paleozoic or older metamorphic rocks (these units are less dense than the underlying basement units) that extend to 7 km in depth. These metamorphic units also cause part of the gravity minimum; the gravity maximum is caused by the juxtaposition of the metamorphic rocks next to the low-density volcanic units. The small wavelength gravity maximum is modeled as a thin ophiolite unit, and the gravity minimum is caused partly by the metamorphic units and two low-density units containing volcanic rocks and/or sediments on the south and low-density sediments to the northeast. The exact thickness of these modeled low-density

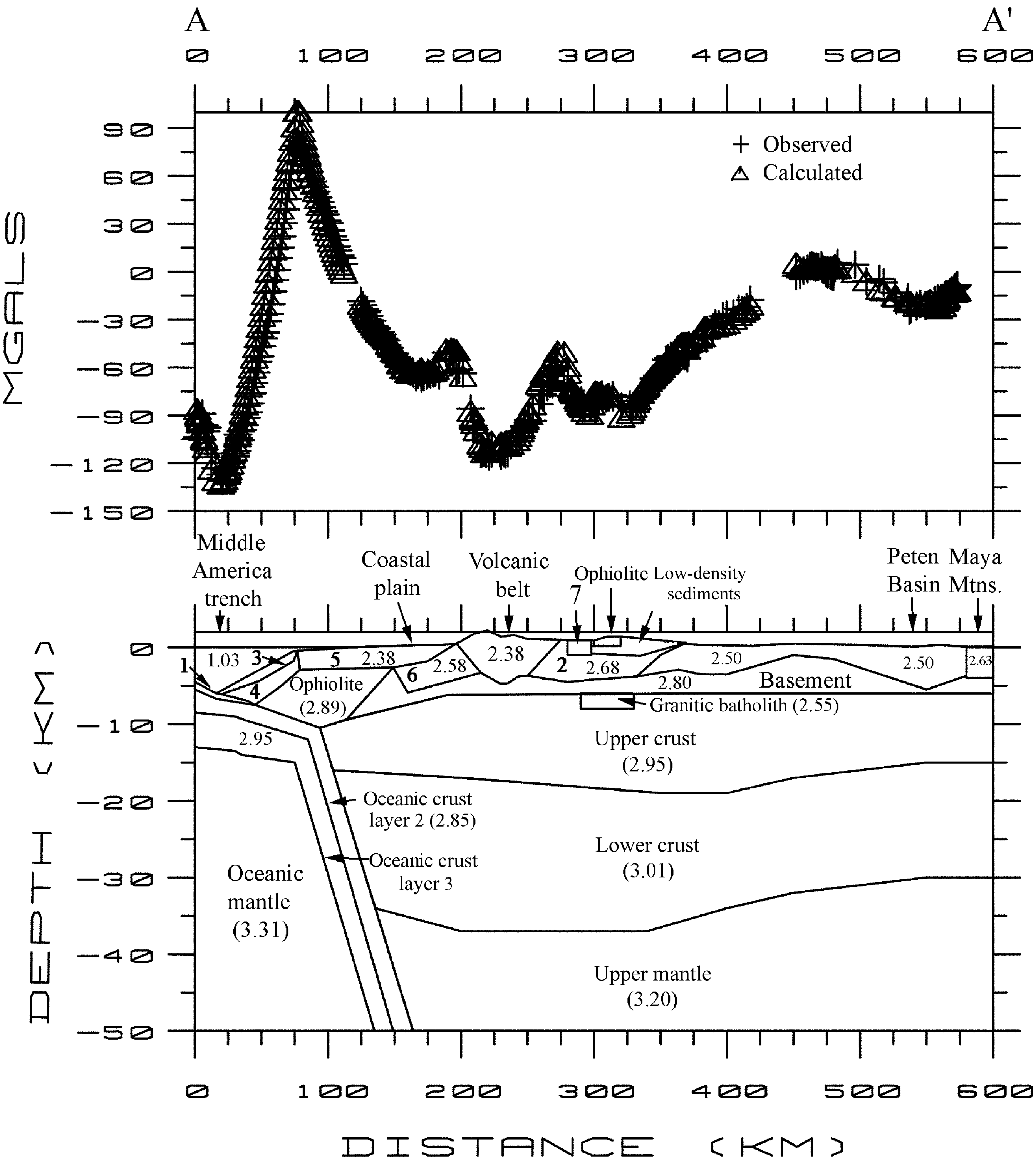

Figure 6. Two-dimensional gravity model along profile 1 (Figure 3). This model crosses Guatemala and Belize. The numbers represent a body's average density in gm/cc. 1 = oceanic sediments (1.90 gm/cc), 2 = metamorphic units near the Motagua and Polochic faults (2.68 gm/cc), 3 = trench slope sediments (1.75 gm/cc), 4 = accretionary prism sediments (2.72 gm/cc), 5 = coastal plain sediments (2.38 gm/cc), 6 = older coastal plain/oceanic sediments, and 7 = low-density lithologies (volcanic rocks or sediments) (2.63 gm/cc). Density of the low-density sediments is 2.63 gm/cc, and the ophiolite near the Polochic fault is 2.90 gm/cc.

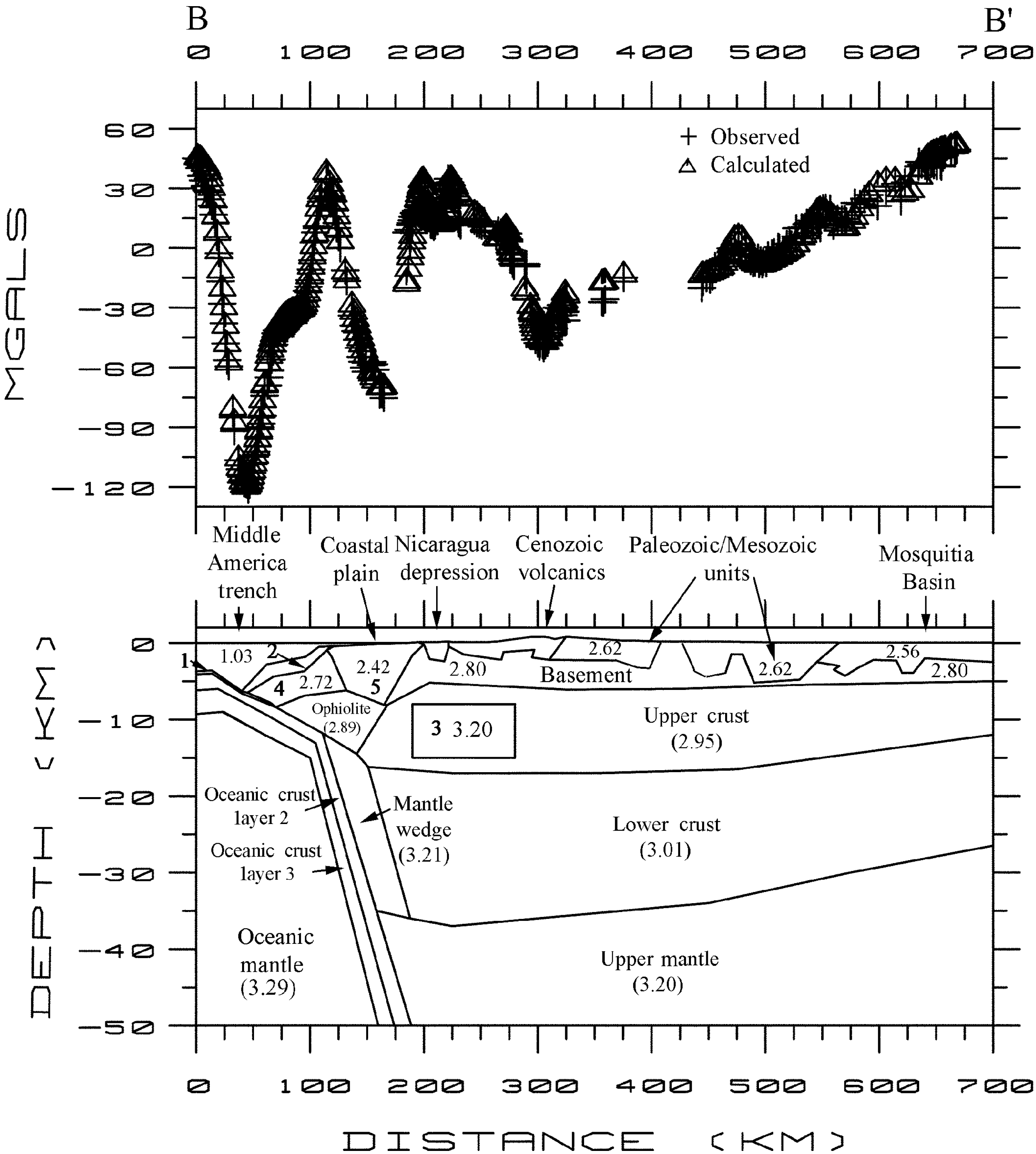

Figure 7. Two-dimensional gravity model along profile 2 (Figure 4). This model crosses Nicaragua and Honduras. The numbers represent a body's average density in gm/cc. 1 = oceanic sediments (1.90 gm/cc), 2 = trench slope sediments (1.75 gm/cc), 3 = dense (mafic?) upper crustal body, 4 = accretionary prism, and 5 = coastal plain sediments. The density of the Nicaragua depression fill is 2.38 gm/cc, the Cenozoic volcanic rocks is 2.36 gm/cc, oceanic crust layer 2 is 2.85 gm/cc, and oceanic crust layer 3 is 2.95 gm/cc.

units is unknown. However, the low-density rocks to the northeast of the ophiolitic sequences are partially part of a fold and thrust belt in which commonly thick layers of thrusted sediments can accumulate as the crust is flexed downward. Additionally, granitic rocks crop out in the region (Donnelly et al., 1990),

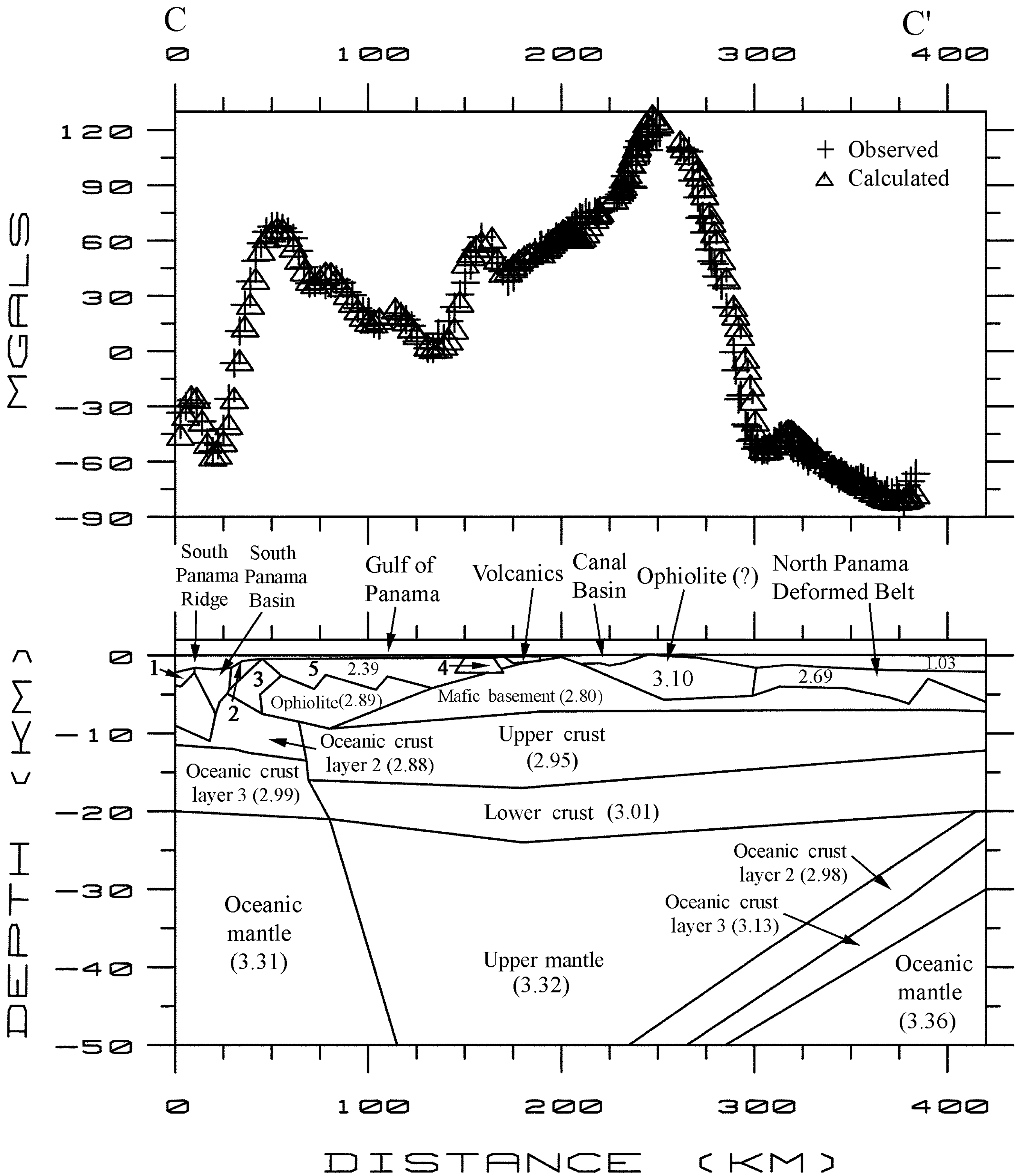

Figure 8. Two-dimensional gravity model along profile 3 (Figure 5). This model crosses Panama. The numbers represent a body's average density in gm/cc. 1 = oceanic sediments (2.20 gm/cc), 2 = slope sediments (2.20 gm/cc), 3 = accretionary prism sediments (2.55 gm/cc), 4 = dense (mafic uplift?) body within the Gulf of Panama (2.98 gm/cc), and 5 = coastal plain sediments (2.39 gm/cc). The density of the South Panama Ridge is 2.80 gm/cc, the South Panama Basin fill is 2.25 gm/cc, the volcanic rocks is 2.54 gm/cc, and the Canal Basin fill is 2.58 gm/cc.

and to help explain the observed anomaly, a deep granitic batholith was included in the model. This unit is totally unconstrained with respect to geometry and depth and could be located at any depth in the upper crust. An explanation follows for the possible existence of a deeper igneous body.

The isostatic residual-gravity map indicates that the gravity minimum is confined to a small region (anomaly 7, Figure 3). However, a bending of the gravity contours to the northwest suggests that this anomaly may be connected to the larger gravity minimum associated with the Chiapas Massif. This is not a new explanation; several authors (e.g., Burkart, 1983; Deaton and Burkart, 1984) have performed palinspastic reconstructions along the Polochic Fault to link the granitic rocks in the Chiapas Massif with those mentioned above. This palinspastic reconstruction assumes 130 km of left-lateral offset along the east-west-striking Polochic Fault and matches several geologic features that have been offset. These include, in addition to the granitic rocks, the fold and thrust belt southwest of the Cuchumatanes Mountains (Figure 3), which is connected to the thrust faults in central Guatemala. The domal structure in the Cuchumatanes Mountains now are continuous with similar structures to the east, and the Izabal half graben (Figure 3) now is connected to the Cayman Trough to the east. This reconstruction can be seen easily on the isostatic residual-gravity map, as the northwest bending would be continuous with the Chiapas Massif if the number 1 was connected with the symbol # on Figure 3. Additionally, the gravity minima associated with the Cuchumatanes Mountains would be associated with the gravity minimum at number 6, while the gravity minimum associated with the Isabal half graben (anomaly 5) would be placed at the symbol *. By placing the Isabal half graben to the east, the Jocotan Fault would line up with the steep gravity gradients (anomaly 8) that mark the edge of the Cayman Trough. This reconstruction would adequately explain the existence of a granite batholith and the thick folded and thrusted sediments at 290–320 km on Model 1 (Figure 6).

The northern quarter of Model 1 overlies the carbonate platform consisting of the Peten Basin, which extends to the Yucatán Peninsula and consists of mainly Cretaceous and younger strata (Weidle et al., 1979; Donnelly et al., 1990). However, Mesozoic and Paleozoic units (e.g., Santa Rosa Group) do exist and are encountered in the numerous wells in the region (Banks and Carballo, 1987a, b). Based on well data (Weidle et al., 1979; Banks and Carballo, 1987a, b; Morrice, 1993), the Peten Basin was modeled with a maximum thickness of 7 km next to the Silurian plutons (Steiner and Walker, 1996) in the Maya Mountains. Of interest is that the Peten Basin is separated into two distinct basins by a basement high at 450 km along Model 1. This basement high is relatively isolated (anomaly 10, Figure 3). However, the addition of gravity data to the northwest may extend this feature farther north.

The general upper and lower crustal thicknesses were obtained from a sparsely spaced teleseismic study by Kim et al. (1982). The crust is thickest (37 km) under central Guatemala and thins toward the northeast. The most striking feature is the relatively dense (2.95 gm/cc) upper crust. This density agrees with the seismic models, and a less dense upper crust would require it to be abnormally thick. The same pattern of crustal and mantle densities are seen also in Model 2 (Figure 7), with the crustal thickness being slightly less in Nicaragua and eastern Honduras.

Model 2

Model 2 (Figures 4 and 7) crosses the Middle America trench, Nicaragua Depression, Nicaraguan volcanic belt, a Paleozoic basement complex along the Nicaragua/Honduras border, and the Mosquitia Basin. Just as for Model 1, the model shows the Cocos Plate subducting beneath Central America. This subduction zone is constrained by seismic models (Colombo et al., 1997) and seismicity data (Protti et al., 1995). Protti et al. found that the Cocos Plate subducted from steep to shallow dip angles from Nicaragua to western Panama. However, the gravity models could be fit with basically the same degree of dip for both the Guatemalan and Nicaraguan models. However, there are several differences between the Guatemalan and Nicaraguan subduction zone complexes. The most obvious difference is the mantle wedge that was imaged on the seismic wide-angle reflection data (Walther et al., 2000). This narrow wedge, or sliver, is approximately 20-km thick and is thought to have formed during the Eocene-Oligocene during the development of a new subduction zone offshore of Nicaragua (Walther et al., 2000). A mantle wedge was not required in the modeling of Model 1 as it was for Model 2.

An ophiolite was also modeled because it was required in order to match the observed gravity maximum at 120 km (Figure 7). This feature has been imaged on numerous seismic profiles (e.g., Ranero et al., 2000; Walther et al., 2000). The difference between this body and the ophiolite on Model 1 is that it is thinner and deeper, probably related to the formation of the deep mantle wedge under Nicaragua. The gravity minimum at 175 km is modeled by a thick (8-km) sequence of sediments that forms the forearc basin. A separation of the forearc sequence into two units was not required to match the observed minimum; however, seismic reflection profiles (Hinz et al., 1996) do indicate that such a separation may exist. The observed gravity minimum cannot be matched solely by a thick forearc basin, as the thickness would exceed 15 km, which is not imaged by any seismic data. The combination of a forearc basin and the dense mantle wedge juxtaposed against the less dense lower crust accounts for the observed gravity minimum.

The most unconstrained region of Model 2 includes the Nicaragua depression and Cenozoic/Tertiary volcanic cover between 200 and 320 km along Model 2. This region is characterized by a regional gravity maximum with several small-wavelength maxima and minima superimposed on it (anomaly 1, Figure 4). One gravity minimum is associated with the Nicaragua depression that is defined as a half graben (Weinberg, 1992) related to the change in direction of subduction when the Farallon Plate split into the Cocos and Nazca Plates approximately 26 m.y. ago (Elming and Rasmussen, 1997). The depression is modeled with 3 km of Cenozoic volcanic rocks and sediments. The gravity minimum associated with the Nicaragua depression increases in amplitude southeast of Model 2. This suggests that the depression thickens and/or the depression fill decreases in density. Additionally, the gravity minimum decreases in amplitude toward the northwest, and when it enters the El Salvador depression, there is only a bending of gravity contours, implying the existence of a thin layer of sediments/volcanic rocks in El Salvador.

The gravity maximum over the Nicaraguan volcanic belt is explained by a dense (mafic?) body located somewhere in the crust (Figure 7). This interpretation is not new; Elming and Rasmussen (1997) used a thinning of the crust and a midcrustal mafic body to explain a similar anomaly southeast of Model 2. Without seismic constraints, a unique solution using gravity data is not obtainable. However, given the gravity maximum's amplitude and width, a dense near-surface body (<5 km in depth) cannot be a viable source, and the source must be deep. The volcanic layer on Model 2 is thinner (2.5 km) at this location than it is northwest of the model. This observation is based on larger-amplitude gravity minima (anomaly 2, Figure 4) that occur over the volcanic layers in Honduras (Figure 4).

Paleozoic and Mesozoic units, including Paleozoic metamorphic units, Mesozoic plutons, and Mesozoic red beds (Donnelly et al., 1990; Weinberg, 1992; Viland and Henry, 1996) are located northeast of the volcanic layers. The region contains little gravity data (Figure 7) making any interpretations questionable. The most unique features include a thickening the Paleozoic/Mesozoic units at 450 km. However, this gravity minimum also may be caused by the northeastward extension of the Dipilto batholith intruding the metamorphic rocks (Donnelly et al., 1990). A definite gravity minimum occurs west of this location (anomaly 3, Figure 4) and is probably related to the batholith. The gravity maximum at 475 km, which is at the southeastern edge of a more extensive gravity maximum (anomaly 4, Figure 4), is probably caused by a basement uplift. However, the emplacement of ultramafic material along the Guayape or Patuca fault system (Finch and Ritchie, 1991) cannot be ruled out in this region because of the lack of detailed geological investigations (Donnelly et al., 1990).

The Mosquitia Basin (Mills and Barton, 1996) along the northeastern edge of Model 2 contains extensive sequences of Jurassic, Cretaceous, and Tertiary sediments. Drill holes and seismic reflection data have shown that the basin is at least 4.6-km thick and possibly as much as 12-km thick. The gravity model crosses the northwestern edge of the basin and is modeled with a maximum thickness of 4.5 km. The basin contains at least two separate deposition centers that may be pull-apart basins that have been recognized in the region (Manton, 1987; Mills and Barton, 1996).

Model 3

Model 3 (Figures 5 and 8) crosses the Gulf of Panama, the Panama mainland, the Canal basin, and the Panama Deformed Belt in the Caribbean Sea. The oceanic portion of this model differs from Models 1 and 2, as the Nazca Plate does not subduct beneath Central America. This model has been controversial; several authors (e.g., Silver et al., 1990) have argued for a subduction zone in this region. There is no seismic evidence for a subduction zone, and the seismicity evidence for a well-developed transform fault or subduction is inconclusive (Westbrook et al., 1995). The boundary between the two plates was modeled as a discontinuity that can be interpreted as a transform fault that dips toward the east. This model differs from that of Briceno-Guarupe (1978), who constructed a gravity model northwest of Model 3 that suggested subduction. As with most of Central America, deep seismic refraction/reflection data are needed to resolve this issue.

The other main issues of the deep crustal structure of the Panama region is the existence of the Caribbean Plate subducting beneath Central America and the greater upper-mantle density of the Chorotega/ Choco Blocks as compared to the Maya/Chortis Blocks. Based on scant seismicity and earthquake focal mechanisms (Wolters, 1986; Munez, 1988), the Caribbean Plate appears to be subducting along portions of northern Panama. In addition, a subducting plate (or some type of dense body to the east) is required in order to match the gravity maximum at 255 km along Model 3, and the upper mantle of the Caribbean plate has to be denser. Seismicity studies (Wolters, 1986) suggest that Model 3 is located at the edge of the subduction zone with a transform fault extending to the west. The isostatic residual-gravity anomaly patterns also change in this region (Figure 5). Along the proposed subduction zone, the anomaly patterns contain the characteristic large-amplitude gravity maxima and minima; to the west, the gravity field becomes more subdued, which is characteristic of transform-faulted regions.

The structure in the Gulf of Panama was taken from seismic studies (Mann and Kolarsky, 1995; Westbrook et al., 1995). Of significance on Model 3 is a basement ridge (South Panama Ridge) that extends to 10.5 km in depth. Based on isostatic residual-gravity anomalies, this basement ridge is a relatively isolated feature and extends east of the model (anomaly 1, Figure 5). The South Panama Basin, which contains up to 9 km of sediments (Westbrook et al., 1995), is modeled with 6 km of sediments. Model 3 crosses the western edge of the basin and is associated with a small-amplitude gravity minimum that extends east of the profile.

Seismic reflection data also imaged an accretionary wedge north of the South Panama Basin. Based on gravity data, this prism is smaller and thinner than those associated with the Middle America Trench (Figures 6 and 7). As with Models 1 and 2, an ophiolite sequence is imaged next to and beneath the accretionary prism. The Bouguer gravity anomaly caused by the prism is smaller in amplitude than those along the Costa Rica to Guatemala region. The relatively smooth isostatic residual-gravity anomalies (Figure 5) do not indicate the small-wavelength Bouguer gravity maxima seen on the Bouguer gravity profile that is associated with the ophiolite offshore of Panama. The Bouguer gravity-anomaly data along the profile indicate at least two uplifts (at 80 and 110 km) in the ophiolite. These may be thrust fault that formed during the emplacement of the ophiolite.

The most unconstrained feature on Model 3 is the dense, near-surface body at 150 km. This body occurs in the Gulf of Panama and produces a relatively large-amplitude isostatic residual-gravity anomaly (anomaly 2, Figure 5). It may be an extension of the early Tertiary rhyolites, andesites, and basalts (Maury et al., 1995) that occur on the Panama mainland (Cerro Alto Higo) west of the model. A small amplitude isostatic residual-gravity anomaly is associated with these volcanic rocks (anomaly 3, Figure 5).

A thin layer of Quaternary volcanic rocks is postulated to exist south of the Panama coastline (Figure 8). These volcanic rocks are an extension of the calc-alkaline volcanic rocks that exist to the west of the model (de Boer et al., 1989) and extend to Costa Rica. Small-amplitude gravity minima (anomaly 4, Figure 5) are associated with these volcanic rocks, with the amplitude and thickness increasing toward Costa Rica. The gravity anomalies caused by these volcanic rocks end approximately at Model 3, which is also the proposed boundary between the Chorotega and Choco Blocks. Escalante (1990) has shown that the Choco Block does not contain recent volcanic deposits and the gravity evidence suggests that the Quaternary volcanic rocks do not extend to the Choco Block.

The Panama mainland is modeled with a Mesozoic mafic basement, thin (2 km) Tertiary and Quaternary sediments in the Canal Basin, and a pre-Eocene ophiolitic or basaltic body (Figure 8). The numerous thin sedimentary basins in northern and eastern Panama (Escalante, 1990) do not have significant isostatic residual-gravity anomalies. For example, the Sambu Basin in southeast Panama is located between two relatively large-amplitude gravity maxima (>30 mGal) (anomaly 5, Figure 5). The origin of these two gravity maxima is unknown, as this region of southeast Panama consists of Cretaceous, Eocene, and Tertiary sediments that have been folded and strike-slip faulted (Mann and Kolarsky, 1995). Since this region once underwent subduction, the existence of ophiolitic bodies beneath the sediments may explain the gravity maximum. The only anomaly associated with a sedimentary basin is anomaly 6, which marks the southern extent of the Chucanaque Basin. The anomalies caused by the other sedimentary basins are obscured by the large-amplitude gravity maximum (anomaly 7, Figure 5), which occurs over thick (modeled to be at least 7-km thick) mafic igneous rocks.

Case (1974, 1980) used the edge of these gravity maxima as the boundary between the Choco and Chorotega Blocks. The anomaly caused by these igneous rocks actually extends west of the proposed boundary and may extend as much as 180 km west of Model 3 (anomaly 8, Figure 5). However, a portion of the region west of Model 3 contains Quaternary volcanic rocks that do not occur on the Choco Block (Escalante, 1990). So, based on isostatic residual-gravity anomalies, a proposed boundary would not be a straight line drawn down the Canal Zone but would be drawn to extend north of the exposed Quaternary volcanic rocks to the western edge of the isostatic residual-gravity maximum 150 km west of Model 3 (Figure 5).

CONCLUSIONS

The isostatic residual-gravity field of Central America and the surrounding offshore region is interpreted to be caused mainly by Mesozoic and younger tectonic events. However, Precambrian and Paleozoic tectonic events are important in interpreting several gravity anomalies in Guatemala, Honduras, and Nicaragua. The isostatic residual-gravity anomalies can be correlated with several known and possibly new tectonic/geologic features throughout Central America. These include possibly more extensive Paleozoic/Mesozoic granitic rocks in western and central Guatemala, basement uplifts in northern Guatemala and western Belize, and Paleozoic granitic material intruding into Paleozoic metamorphic rocks along the Nicaragua/Honduras border. Analysis of gravity maxima in northern Panama suggests that the boundary between the Chorotega and Choco Blocks may extend as much as 150 km west of its present location.

Three 2-D gravity models that cross Guatemala/Belize, Nicaragua/Honduras, and Panama, respectively, aided in determining the geometry of crustal bodies in Central America. These models, constrained by seismic data, well data, and geologic mapping, indicate that the continental crustal thickness in Guatemala and Nicaragua/Honduras was between 36–38 km, while under Panama it was approximately 22 km. Major features of these models include the Middle America subduction zone with varying thicknesses of the accretionary prism and ophiolites. Based on isostatic residual-gravity anomalies, the ophiolitic bodies are not continuous along the subduction zone but occur as discontinuous lenses from Costa Rica to Guatemala. Gravity models across Panama indicate that the boundary between the Chorotega/Choco Block and the Nazca Plate may be a transform fault that dips steeply to the east. A large-amplitude gravity maximum occurs along the northern Panama coast and is modeled as a combination of the Caribbean Plate subducting beneath the Chorotega/Choco Block and a 7-km-thick mafic igneous body occurring under thin Cenozoic oceanic sediments.

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