The Geological Society of America
Special Paper 428
2007

Colon fold belt of Honduras: Evidence for Late Cretaceous collision between the continental Chortis block and intra-oceanic Caribbean arc

Robert D. Rogers*
Paul Mann
John A. and Katherine G. Jackson School of Geosciences, The University of Texas at Austin, 4412 Spicewood Springs Road, Building 600, Austin, Texas 78759-8500, USA

Peter A. Emmet
Cy-Fair College, Fairbanks Center, 14955 Northwest Freeway, Houston, Texas 77040, USA

Margaret E. Venable†
Consultant, Exploration Geology 3000 Brady Hoffman Road, Lincolnton, North Carolina 28092-8220, USA

ABSTRACT

We document a previously unrecognized, thin-skinned arc-continental collisional zone, termed here the Colon fold-thrust belt, which trends northeastward for 350 km near the Honduras-Nicaragua border region. The Colon belt occurs in three collinear segments: (1) a 200-km-long belt of remote but well-exposed Jurassic–Late Cretaceous rock outcrops described from original geologic mapping presented in this study; (2) a 75-km-long subsurface belt of Jurassic–Late Cretaceous rocks known from onland seismic reflection studies and exploration drilling for oil; and (3) an offshore 75-km-long subsurface belt of Late Cretaceous to Eocene rocks known from exploration studies. These three segments share a continuity of the deformation front and associated folds, as well as a similar timing of fold-thrust deformation (segment one: post-Campanian; segment two: post–Late Cretaceous; segment three: post-Cretaceous and possible to Eocene); and all segments display southeastward-dipping thrusts and related northeastward-verging folds that structurally elevate Cretaceous rocks.

The structural position of the Siuna belt of oceanic island arc affinity to the south of the Colon fold-thrust belt, its association with calc-alkaline volcanic rocks of the Caribbean arc, and its Campanian (75 Ma) emplacement age, suggest that the Siuna belt was overthrust to the north and northwest on the hanging wall of the Colon fold-thrust belt. The northwestward-transported Colon fold-thrust belt and adjacent Siuna belt document a Late Cretaceous collisional event between a south-facing open

*Present address: Department of Geology, California State University Stanislaus, 801 West Monte Vista Avenue, Turlock, CA 95382, USA; e-mail: rrogers@geology.csustan.edu.
†E-mail: mevenable@fastmail.fm.

Rogers, R.D., Mann, P., Emmet, P.A., and Venable, M.E., 2007, Colon fold belt of Honduras: Evidence for Late Cretaceous collision between the continental Chortis block and intra-oceanic Caribbean arc, *in* Mann, P., ed., Geologic and tectonic development of the Caribbean plate in northern Central America: Geological Society of America Special Paper 428, p. 129–149, doi: 10.1130/2007.2428(06). For permission to copy, contact editing@geosociety.org.

continental margin of the Chortis block of northern Central America and an eastward and northeastward-moving, Early to Late Cretaceous Caribbean arc system.

Keywords: collision, fold-thrust belt, Chortis, Caribbean.

INTRODUCTION

Rocks of the Cordillera region record the subduction arc systems of the western margin of the Americas throughout the late Mesozoic concurrent with the opening of first the North Atlantic Ocean and then the South Atlantic Ocean basins. Earlier opening in the north Atlantic produced the separation between the Americas that formed the Gulf of Mexico and the Caribbean region (e.g., Bullard et al., 1965; Pindell and Dewey, 1982; Pindell and Barrett, 1990). Ocean-ocean convergence had bridged the gap between the Cordilleras of North and South America by the Early Cretaceous, and the entry of the Caribbean arc (the modern Lesser Antilles arc) between the Americas is recorded by arc-continent collisional deformation and emplacement of ophiolites in Guatemala (Rosenfeld, 1981), as well as in Columbia and western Venezuela (c Kerr, 1998; Mann, 1999). The history of this diachronous collision along the southern North America margin is poorly constrained due in large part to the lack of detailed study of the regions of Central America, particularly the more remote regions. This study provides new constraints on the geologic evolution of the understudied regions of eastern Honduras and northern Nicaragua and the record of collision deformation along the southern margin of North America in the Late Cretaceous.

Tectonic and Geological Setting

Northern Central America straddles the North America and Caribbean plates and is divided into the Maya block and Chortis block (Dengo, 1973) (Fig. 1). The Chortis block is a Precambrian-Paleozoic continental block that presently occupies the northwestern corner of the Caribbean plate (Gordon, 1990). The Chortis block is bounded to the north by left-lateral strike-slip faults of the present-day North America–Caribbean plate boundary (Burkart and Self, 1985; Rogers and Mann, this volume) and to the southwest by the Middle America trench and volcanic arc of the present-day Cocos-Caribbean plate boundary. The southern and eastern edge of the Chortis continental block is not well defined because (1) it is located in remote areas of eastern Honduras and northern Nicaragua; (2) it is covered by lowlands of eastern Central America; or (3) it is blanketed by waters of the Caribbean Sea and the Cenozoic carbonate platform of the Nicaragua Rise (Fig. 1). South of the Chortis block is the Chorotega block with the oceanic island-arc affinity of Costa Rica and Panama (Dengo, 1973) developed on the western margin of the Caribbean large igneous province (Case et al., 1990; Sinton et al., 1997).

Most previous work on the Chortis block has focused on the northern edge of the block where it is juxtaposed with the Maya block of southern Guatemala across the Motagua and Polochic left-lateral strike-slip faults of the North America–Caribbean plate boundary (Fig. 1). Donnelly et al. (1990) and Burkart (1994) have documented a Late Cretaceous collisional orogeny that emplaced ophiolites along the northern edge of the Motagua fault valley and produced north-south shortening of pre-Cenozoic strata in eastern Guatemala and Belize. Reconstructing the two sides of the Late Cretaceous collision across the Motagua suture zone is complex because as much as 1100 km of late Eocene to Recent left-lateral motion accompanying the opening of the Cayman trough has been superimposed onto the suture zone (Rosencrantz et al., 1988; Leroy et al., 2000; Harlow et al., 2004) (Fig. 1). This large-scale eastward migration of the Chortis block along these strike-slip faults is supported by detailed fault kinematic and radiometric dating of igneous rocks in the zone of southernmost México affected by the lateral shear (Riller et al., 1992; Schaaf et al., 1995). Pre-Tertiary reconstructions of the Chortis block place it ~1100 km farther to the west along the southern margin of México (e.g., Azéma et al., 1985; Dengo, 1985; Pindell and Barrett, 1990; Tardy et al., 1994). Cretaceous-age piercing lines between the Chortis block and southwestern México are proposed by Rogers et al. (Chapter 5, this volume) and include the northwest-trending foldbelts of central Honduras with north trending foldbelts of Guerrero State of México, the Honduras Olancho arc with the Teloloapan arc, and a prominent magnetic boundary along the Pacific-facing margin of continental crust in both Honduras and México.

There have been few previous efforts to constrain in detail the location of the southern and eastern margins of the continental Chortis block and its tectonic relationships with oceanic and island arc terranes of southern Central America. Dengo (1985) placed the southern boundary of the Chortis block near the Honduras-Nicaragua political boundary and its offshore boundary along the Hess escarpment. Pindell and Barrett (1990) and Tardy et al. (1994) have shown reconstructions for a Chortis block suturing against arc and oceanic plateau terranes in southern Central America, but these reconstructions have remained largely conjectural since there are few published field observations from this area. Case et al. (1990) compiled crustal refraction lines that allowed the inference of a boundary between continental rocks of the Chortis terrane and arc rocks of the eastern Nicaragua Rise and southern Central America. Venable (1994) was the only field-based effort in northern Nicaragua to define a suture zone between the Chortis block and an oceanic terrane to the south, which she named the Siuna terrane (Fig. 1).

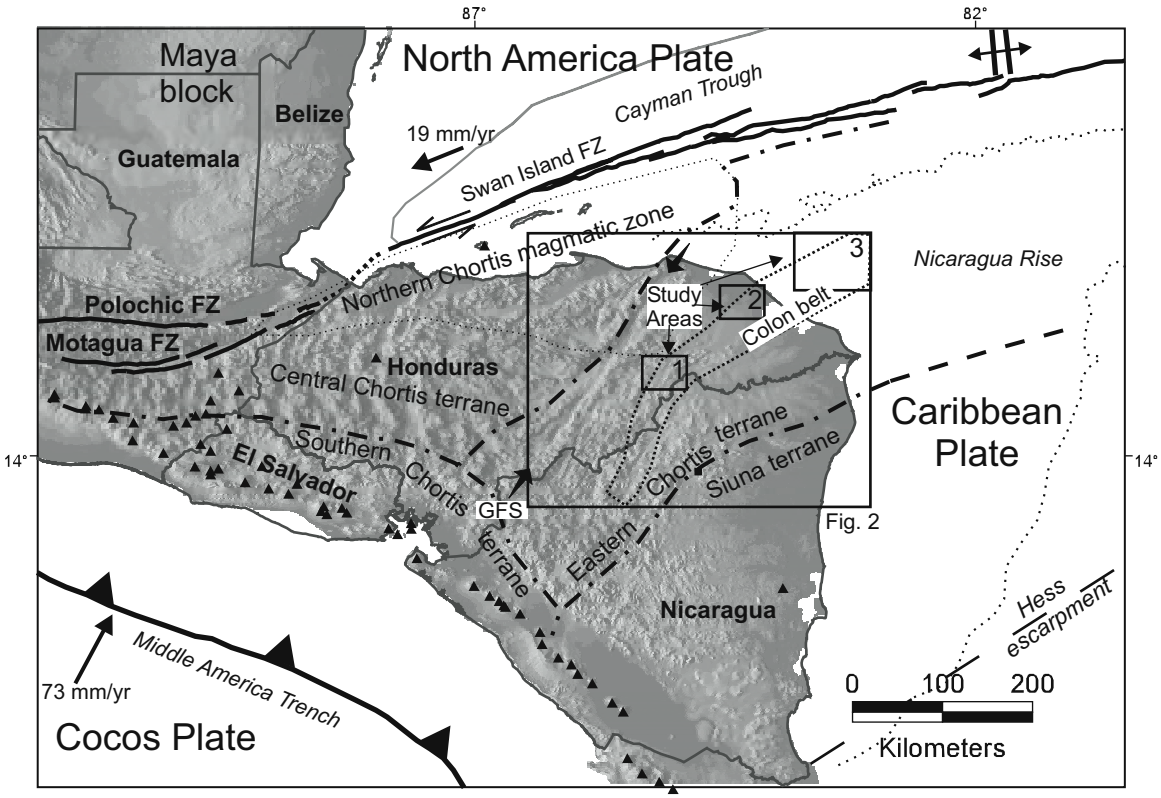

Figure 1. Topographic and tectonic setting of the Late Cretaceous Colon fold-thrust belt. Individual study areas are (1) the Colon Mountains, (2) the Mosquito plains, and (3) the offshore region of the Nicaragua Rise. Box displays geologic map location of the area shown in Figure 2. The Maya block on the North America plate and the Chortis block on the Caribbean plate are the two main continental blocks of northern Central America. The two blocks are separated by the Motagua, Polochic, and Swan Islands left-lateral strike-slip faults. Black triangles are active volcanoes of the Middle America arc. Note the orthogonal relationship between northeast-trending topography of the East Chortis terrane and Colon fold-thrust belt to the active Middle America arc. Plate velocities are relative to a fixed Caribbean Plate (DeMets et al., 2000). GFS—Guayape fault system; FZ—fault zone.

The specific objectives of this study include the following:

1. Presentation of new geologic field observations from the northeast-trending Colon Mountains of the eastern Chortis block. We have also incorporated the paleontological results of Scott and Finch (1999), which are based on Cretaceous sedimentary rock samples collected in the Colon study area. The only previous work in eastern Honduras was reconnaissance in nature and was restricted to outcrops along major rivers (Mills and Hugh, 1974).
2. Integration of unpublished geologic field mapping, isotopic, and radiometric results from Venable (1994) from the Siuna terrane of Nicaragua into a regional tectonic framework. These results are the only modern geologic data and isotopic dating results from northeastern Nicaragua. Previous studies relied only on reconnaissance traverses along major rivers (Zoppis Bracci and del Giudice, 1958; Paz-Rivera, 1963).
3. Integration of published onland seismic reflection and well data from the along-strike continuation of the Colon Mountains beneath the Mosquitia coastal plain of easternmost Honduras. We have correlated the stratigraphy encountered in these wells and tied to seismic reflection lines with the stratigraphy mapped in the Colon Mountains 70 km to the southwest.
4. Integration of subsurface seismic reflection and well data from an unpublished industry report by Rockwell (1985) from the along-strike continuation of the Colon Mountains beneath the submarine area of the eastern Nicaragua Rise. These geophysical data are inferred to correlate both to the Mosquitia plains subsurface study of Mills and Barton (1996) and to the geologic study of the Colon Mountains.

Together, these objectives address the significance of the Colon belt as a useful marker for late Mesozoic reconstructions of the region and its usefulness in determining when the Siuna terrane to the south of the Colon Belt accreted to the Chortis block.

Geology of Eastern Honduras and Northern Nicaragua

A geologic map summarizing the geologic setting of the Colon Mountains study area is shown in Figure 2. This map,

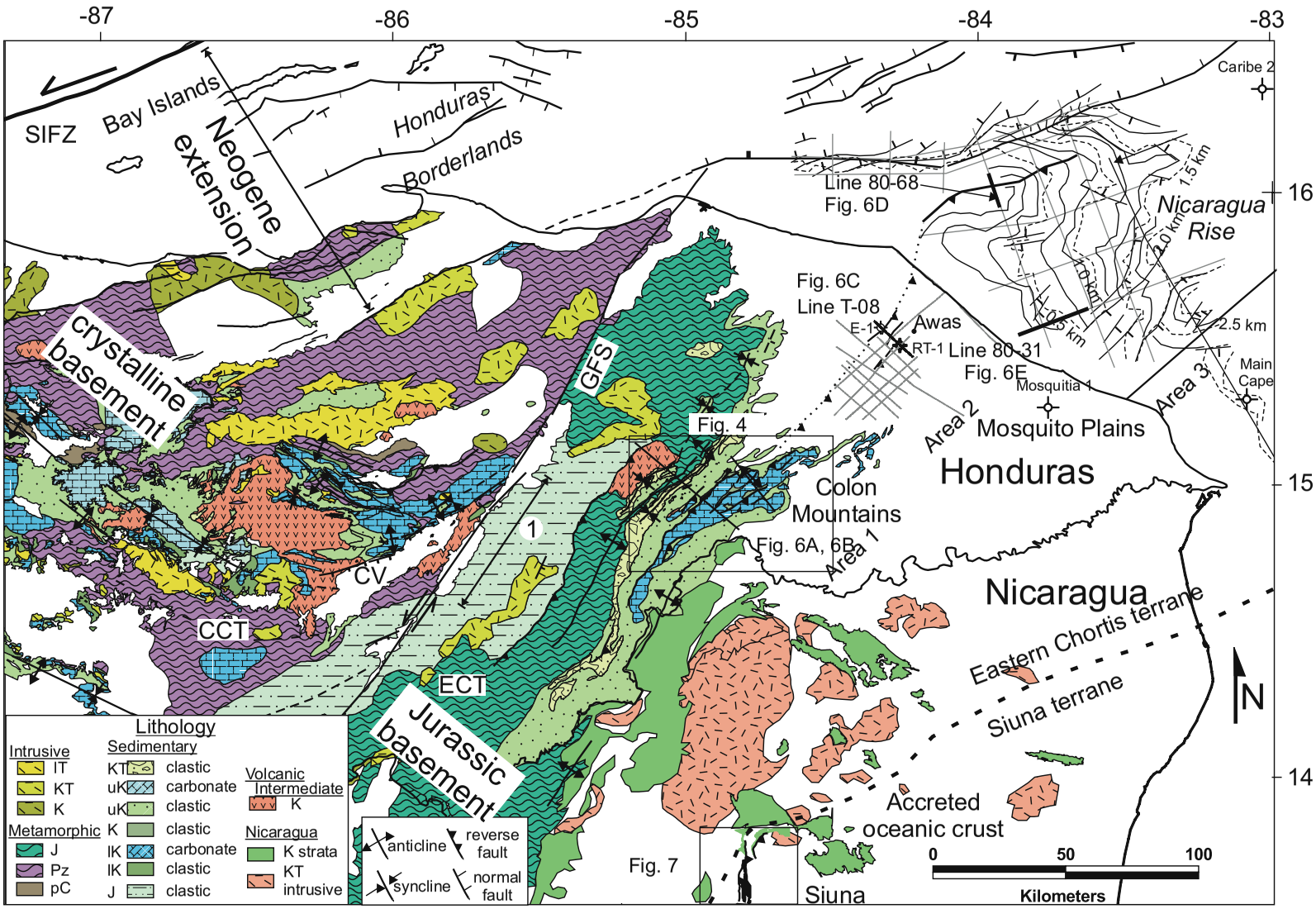

Figure 2. Pre-Tertiary geology of the continental Chortis block (Eastern Chortis terrane and Siuna terrane) of eastern Honduras and northeastern Nicaragua compiled from Kozuch (1991), Rockwell (1985), Mills and Barton (1996), INETER (1995), and this study. The Colon fold-thrust belt is described in this study in three along-strike segments: Area 1—the Colon Mountains of eastern Honduras; Area 2—the Mosquitia Plains of eastern Honduras; and Area 3—the Nicaragua Rise (Caribbean Sea). The Siuna terrane of northeastern Nicaragua is inferred to represent the leading edge of the collided Caribbean arc system. The Guayape fault system (GFS) forms a major terrane boundary between the Eastern Chortis terrane (ECT—basement of Jurassic metasedimentary rocks) and the Central Chortis terrane (CCT—basement of Precambrian and Paleozoic crystalline rocks). Contour lines (dashed at 0.5 km interval) on the Nicaragua Rise show depth in kilometers to top of the Cretaceous (Rockwell, 1985), indicating a structurally elevated block along the trend of the Colon belt. RT-1—Raite Tara 1 well; E-1—Embarcadero 1 well. CV—Catacamas valley; line 1 (noted in the blank circle) denotes the amount of left-lateral displacement on the GFS. The white parts of map are post-Cretaceous in age. SIFZ—Swan Island fault zone.

showing all pre-Tertiary geologic units of eastern Honduras and northeastern Nicaragua, was compiled from Kozuch (1991) and INETER (1995), supplemented with surface and subsurface information from Rockwell (1985), Mills and Barton (1996), and this study. Eastern Honduras is an ideal area to examine pre-Tertiary tectonic history of the Chortis block because the area has remained tectonically stable in the Cenozoic and therefore has not been overprinted by tectonic events affecting either the North American–Caribbean strike-slip boundary in the Honduran borderlands (Rogers and Mann, this volume) or by tectonic events associated with the subduction of the oceanic Cocos plate beneath the Caribbean plate (Rogers et al., 2002; Jordan et al., this volume). One disadvantage of geologic studies in eastern Honduras is that there are few units of Tertiary age. For this reason, correlations must be made into the subsurface of the Mosquitia plain or of the Nicaragua Rise in order to establish the age of the Cretaceous deformation seen in the Colon Mountains.

The Colon belt of fold-thrust deformation is described in this study in three along-strike segments shown on Figure 2: the Colon Mountains of eastern Honduras; the Mosquitia Plains of eastern Honduras near Awas; and offshore along the Nicaragua Rise (Caribbean Sea). The Siuna belt of northeastern Nicaragua is also described using data from Venable (1994) and is inferred to represent the leading edge of the collided Caribbean arc system.

Geologic mapping and radiometric studies have shown that the Northern Chortis Magmatic Zone and Central Chortis terrane (areas north of the Guayape fault system in Fig. 2) have a Grenville- to Paleozoic-age basement composed of gneiss and schist (Case et al., 1990; Donnelly et al., 1990; Manton 1996; Manton and Manton, 1999; Nelson, et al., 1997; Rogers, 2003; Rogers et al., this volume, Chapters 4 and 5) (Fig. 1). Seismic refraction studies compiled by Case et al. (1990) show that these regions are underlain by a continental crust ~45 km in thickness.

Thinner, 30–35-km-thick continental to transitional crust consisting of Jurassic sedimentary and metasedimentary rocks make up the basement of the Eastern Chortis terrane southeast of the Guayape fault system (Case et al., 1990; Gordon, 1993a, 1993b; Rogers, 1995; Viland et al., 1996). The continental to transitional affinity of the crust is based on refraction data and gravity models summarized in Case et al. (1990). Mapping in the Valle de Jamastran at the SW termination of the Guayape fault, Rogers (1995) observed a gradational vertical contact between the Bathonian-age sandstone and shale of the Agua Fria Formation (Gordon and Young, 1993) and greenschist-facies phyllite and quartzite. A major nonconformity between the Agua Fria Formation and underlying Paleozoic metamorphic basement is inferred from the much lower degree of deformation in the Agua Fria than observed in surrounding basement outcrops. These metasedimentary rocks, with metamorphic grade increasing to the east, were followed east of the Guayape fault along the Río Patuca into the metamorphic rocks previously assumed by Kozuch (1991) to be the Paleozoic Cacaguapa Group (Fig. 2).

The Siuna terrane is an oceanic terrane defined and named for the open-pit mining Siuna mining district of northeastern Nicaragua by Venable (1994) (Figs. 1 and 2). Case et al. (1990) compiled seismic refraction data from the area of the Siuna terrane and proposed a 20–25-km island-arc crust built on oceanic crust. A fundamental observation from the map shown in Figure 1 is that the overall structural strike and related topography of the Eastern Chortis continental terrane and the Siuna oceanic terrane is at right angles to the trend of the Middle America trench and volcanic arc. Moreover, trends of the Eastern Chortis and Siuna terranes are at a high angle to the Central Chortis terrane.

The linear and topographically prominent Guayape fault system (Finch and Ritchie, 1991; Gordon and Muehlberger, 1994) forms a major terrane boundary between the northeasterly striking rocks in the Eastern Chortis terrane (basement composed of Jurassic metasedimentary rocks) and more eastward-striking rocks in the Central Chortis terrane underlain by basement composed of Precambrian and Paleozoic crystalline rocks (Rogers, 2003; Rogers et al., this volume, Chapter 4). Gordon and Muehlberger (1994) documented several kilometers of right-lateral strike-slip motion along the fault during Neogene time. Finch and Ritchie (1991) proposed ~50 km of left-lateral motion based in part on the apparent lateral offset of the Agua Fria Formation on either side of the fault. The map compilation shown in Figure 2 indicates that the apparent left-lateral offset is closer to 60 km (length of line indicated by "1" in Fig. 2). The sense of oroclinal bending of the parallel ranges northwest of the fault in the Central Honduras terrane also supports the left-lateral sense of slip.

Mesozoic Stratigraphy of the Central and Eastern Chortis Terranes

Despite the lack of crystalline basement east of the Guayape fault and evidence of an apparent 60 km of left-lateral offset, a very similar Mesozoic stratigraphy occurs on both the Central and Eastern Chortis terranes on both sides of the fault. Figure 3 compares the names, thicknesses, and ages of the main Mesozoic formations found on both sides of the fault; these are shown in map view on Figure 2.

Agua Fria Formation

The middle Jurassic Agua Fria Formation forms the basal clastic unit on both terranes to the northwest and southeast of the Guayape fault system. The formation is at least 1700 m thick and consists of coastal plain fluvial deposits, minor shallow-marine carbonate rocks, and rhythmically-bedded siliciclastic sedimentary rocks that have been interpreted as marine turbidites by Ritchie and Finch (1985), Gordon (1990), and Rogers (1995). The basal contact of this formation on older rocks has never been observed. Gordon (1993b) inferred an underlying metamorphic basement in the Catacamas Valley of the Central Chortis terrane based on the presence of recycled, metamorphic clasts in conglomerate of the Agua Fria Formation. Viland et al. (1996) document regional deformation in the Late Jurassic that metamorphosed parts of the Agua Fria Formation prior to deposition of Cretaceous strata.

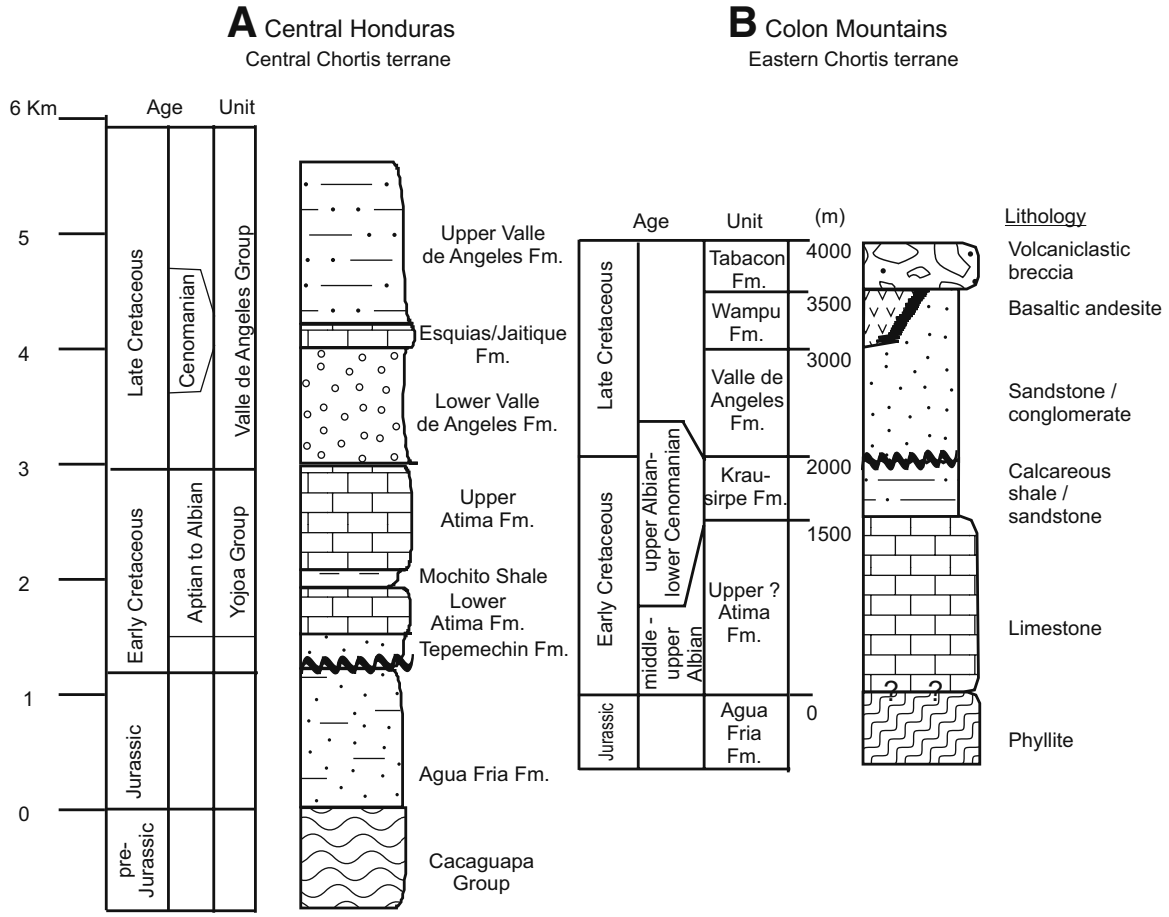

Figure 3. Comparison of Mesozoic stratigraphic units, nomenclature, and thicknesses in meters northwest and southeast of the terrane boundary (Guayape fault system) separating Central and Eastern terranes (A) compiled from previous workers (Finch, 1981; Donnelly et al., 1990; Gordon, 1993a; Scott and Finch, 1999) and Rogers (2003) and (B) the Eastern Chortis terrane exposed in the Colon Mountains. Ages in the Colon Mountains are based on paleontological dating by Scott and Finch (1999) and radiometric dating of the Wampu volcanics by Weiland et al. (1992).

Tepemechin Formation

The Tepemechin Formation is a thin conglomerate that unconformably overlies the Agua Fria Formation and forms the base of the overlying Cretaceous carbonate stratigraphy of the Yojoa Group on the Central Chortis terrane (Gordon, 1993a). This unit includes the unnamed siliciclastics of Simonson (1977) and the Todos Santos Formation of Mills et al. (1967).

Yojoa Group

Early Cretaceous-Cenomanian shallow-marine limestone of the Yojoa Group overlies the basal clastic rocks of the Agua Fria Formation on both sides of the Guayape fault (Mills et al., 1967; Scott and Finch, 1999; Rogers et al., this volume, Chapter 5) (Fig. 3). The Yojoa Group is divided into the upper and lower Atima Formations, and the intervening Mochito water–shelf limestone of the Atima Formation is locally up to 1400 m thick. Volcanic rocks, including andesite and dacite flows and pyroclastic rocks, occur within the Atima Formation on the Central and Eastern Chortis terranes (Carpenter, 1954; Simonson, 1977; Gordon, 1990; Rogers, 2003; Rogers et al., this volume, Chapter 5).

Valle de Angeles Formation

Overlying the Yojoa Group is a thick sequence of coarse-grained, terrigenous redbeds of the Valle de Angeles Formation (Mills et al., 1967; Finch, 1981) (Fig. 3). Clastic rocks of the formation include clay-rich, lithic conglomerate (both matrix- and clast-supported) and sandstone and shale deposited as submarine and subaerial debris flows (Rogers and O'Conner, 1993). The conglomerate contains clasts of all underlying lithologies including the Yojoa Group and redbed clasts derived from syndepositional reworking (Mills et al., 1967; Finch, 1981; Rogers, 1996). Thickness of the lower redbeds of the Valle de Angeles

Formation can range from several hundred up to 1000 m. Where exposed, the contact between the Valle de Angeles redbeds and the limestone of the underlying Yojoa Group is unconformable, with paleo-epikarst developed at the contact in one location in the Colon Mountains.

Discontinuous shallow marine carbonate strata of Campanian age (Esquias-Jaitique Formation) is recognized in central Honduras and was used as a datum to subdivide the Valle de Angeles Formation into a lower and upper sequence (Finch, 1981; Scott and Finch, 1999) (Fig. 3). Limestone associated with minor gypsum deposits occurs locally in this unit and suggests an isolated marine depositional basin (Horne et al., 1974; Finch, 1981). Limestone of this unit varies in thickness from a few tens of meters to several hundred meters.

The upper redbeds of the Valle de Angeles Formation are generally finer-grained than the lower redbeds. Upper redbeds are interbedded with minor mafic volcanic rocks that thicken to >300 m in eastern Honduras (Weiland et al., 1992; Rogers, 1996). Scott and Finch (1999) proposed that the upper Valle de Angeles redbeds rapidly blanketed the carbonate rocks of the Valle de Angeles Formation without producing an erosional unconformity. The grain size transition from lower, coarse-grained to upper, fine-grained redbeds of the Valle de Angeles Formation is gradational, and diminishing grain size and bedding thickness are noted over several hundred meters of section (Rogers and O'Conner, 1993). Like the lower redbeds, the upper redbeds have been interpreted as debris flows in the Tegucigalpa region (Rogers and O'Conner, 1993).

Intrusive Rocks

Felsic plutons ranging in age from Cretaceous to early Tertiary intrude the stratigraphic units described above and are shown on the compilation map in Figure 2 (Southernwood, 1986; Kozuch, 1991; INETER, 1995). Ages of the plutons are known mainly from field relations and from radiometric dating (cf. Rogers et al., Chapter 4, this volume, Table 1 therein) for a compilation of radiometric ages from Honduras).

THE COLON FOLD-THRUST BELT IN EASTERN HONDURAS

The Colon fold-thrust belt is expressed as folded, massive limestone beds of the Cretaceous Atima Formation (Fig. 3B) in the Colon Mountains between the Río Coco and Río Patuca (Fig. 4). Maximum elevation of the range is 880 m above sea level (masl); average elevation of the area of the surrounding range the varies from 100 m in the lowlands along the Patuca and Coco Rivers to an average of 300–400 masl in the Patuca Mountains northwest of the Colon Mountains. A broad zone of open folds affecting all Cretaceous units shown on the column in Figure 3B parallels the Colon belt and extends at least 20 km to the northwest of the belt into the Patuca Mountains (Fig. 4).

As seen on the LANDSAT image in Figure 4, the Río Patuca closely follows the structural grain of the Colon fold-thrust belt defined by a reverse fault bounding the northeast side of the Colon Mountains (Fig. 5). Both the Río Patuca and Río Coco south of the Colon Mountains are entrenched bedrock rivers showing no signs of deflection or offset by Quaternary faults. Moreover, the regional geomorphology of eastern Honduras supports the interpretation that the area is a tectonically stable part of the Caribbean plate (Rogers et al., 2002; Rogers and Mann, this volume). The northeast flow directions of the Río Patuca and Río Coco reflect their origins as northeast-flowing alluvial rivers prior to the late Neogene epeirogenic uplift that incised their channels into bedrock canyons (Rogers et al., 2002).

The Colon Mountains were originally described as block faulted by Mills and Hugh (1974). However, parallelism between the northeast-trending Guayape strike-slip fault system and the northeast-trending Colon Mountains (Fig. 2) has previously led workers to interpret the deformation of the Colon Mountains as a large, topographically-elevated, "flower structure" produced by lateral shearing and transpression on vertical strike-slip fault planes (Gordon and Muehlberger, 1994; Mills and Barton, 1996). This interpretation was mainly supported by interpretation of satellite imagery (Fig. 4) and aerial photographs and not by detailed structural observations in the field.

Riverbank and stream exposures in the area of the confluence of the Río Wampu and Río Patuca provide excellent cross sectional exposures of the structural and stratigraphic units of the Colon Mountains (Fig. 5). Mapping and paleontological dates from sedimentary units sampled in the Colon Mountains (Scott and Finch, 1999) reveal a pre-Cenomanian, south-facing, continental margin setting. Shallow-water Cretaceous carbonate rocks and clastic strata totaling 4 km in thickness were deformed by thin-skinned, northwestward-directed thrusting following Campanian time.

Stratigraphy of the Colon Fold-Thrust Belts

Basement and Overlying Yojoa Group

Low-grade metasedimentary basement of the area is composed of phyllite and quartzite of presumed Jurassic age (metamorphosed Agua Fria Formation) (Fig. 3). This metasedimentary unit crops out in the north-central part of the study area (Fig. 5) and extends to the northeast to the Guayape fault (Gordon, 1993a) (Fig. 2). Agua Fria Formation metasedimentary rocks are moderately resistant and, coupled with their diverse bedding plane foliations, produce a rugged upland topography with a dendritic drainage (Fig. 4).

An estimated 1500 m of massive shallow water limestone of the Atima Formation of the Yojoa Group overlies the Agua Fria Formation, although this contact has not been observed in the field. The resistant limestone of the Atima Formation is a prominent ridge-former, and extensive karst topography is developed on landscapes underlain by the Atima Formation. The limestone contains upper Albian foraminifera as well as Albian to lower Cenomanian foraminifera, indicating a stratigraphic position equivalent to the Upper Atima Formation (Scott and Finch, 1999).

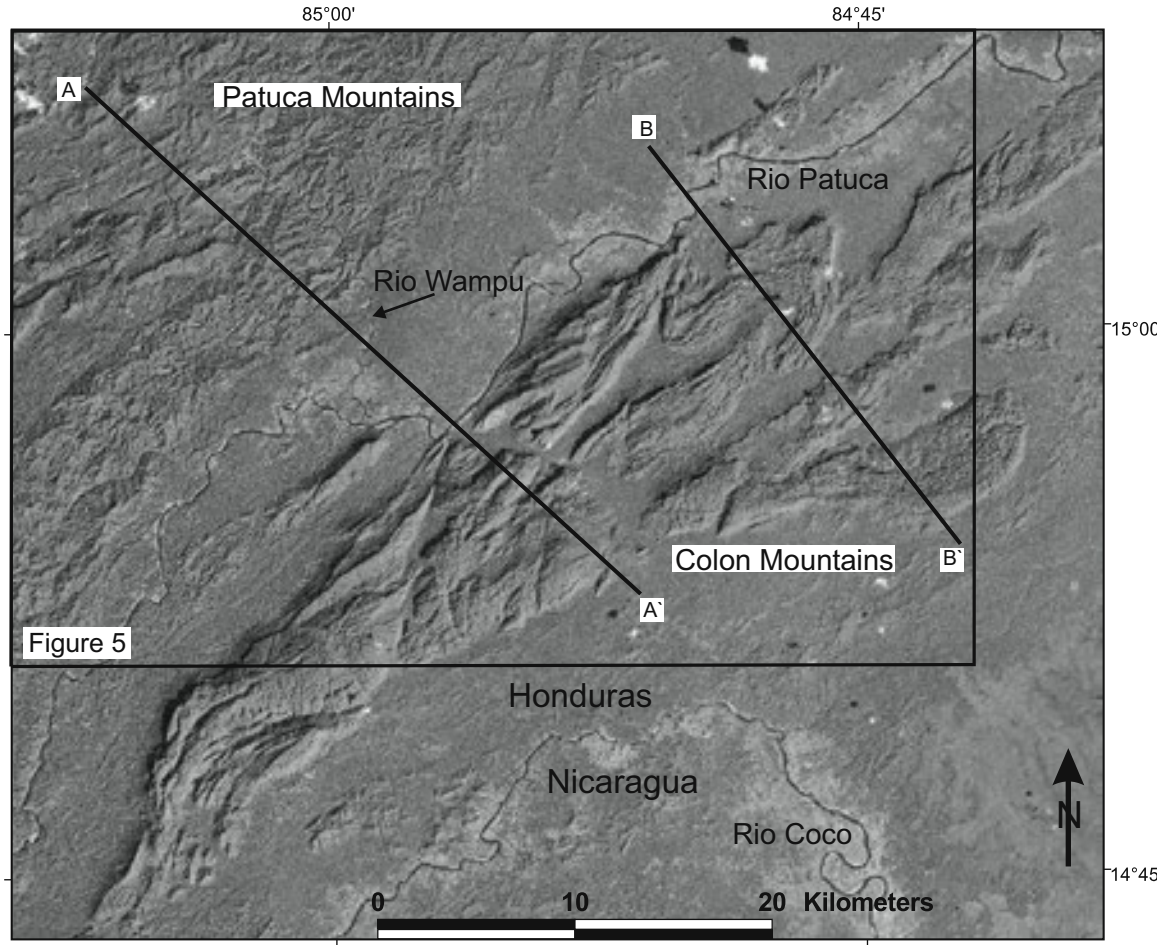

Figure 4. Landsat image of the Colon Mountains of eastern Honduras showing large-scale, northwest-verging folds in Mesozoic sedimentary units (shown on Figure 3B), major rivers, and the location of the geologic map in Figure 5. The inner box shows the extent of field-based mapping. Lines A–A′ and B–B′ show the locations of cross sections in Figure 6. The Río Coco forms the political boundary between Nicaragua and Honduras.

Based on carbonate petrography, Scott and Finch (1999) infer an upward-shoaling carbonate succession. Biofacies indicate that this succession occurred as the result of marine transgression from middle to inner shelf paleodepths that gave rise to a "keep-up" carbonate platform that aggraded during a relative sea-level rise. Atima Formation strata are entirely missing north of the Río Patuca (Figs. 4 and 5).

Krausirpe Formation

Calcareous marine shale containing organic detritus of the Krausirpe Formation conformably overlie the carbonate rocks of the Upper Atima Formation (Rogers, 1996) (Fig. 3B). Rocks of the Krausirpe Formation are not resistant and form the strike valleys of the Colon Mountains (Fig. 4). The Krausirpe Formation is estimated to be 500 m thick, and its floral and faunal components include late Albian to early Cenomanian palynomorphs as well as late Albian to early Cenomanian foraminifera (Scott and Finch, 1999). Biofacies indicate that these beds represent a transition from carbonate shelf (Atima lithology) to terrigenous shelf (Krausirpe lithology) with paleowater depths of up to 50 m as indicated by the presence of planktic foraminifers and dinoflagellates.

Late Cretaceous Valle de Angeles Formation

The Valle de Angeles Formation overlies marine strata of the Yojoa Group and contains medium to coarse-grained immature sandstone and conglomerate with subrounded clasts of metamorphic, volcanic, carbonate, and redbed lithologies. Rocks of the Valle de Angeles Formation are not resistant and form the non-alluvial lowlands of the region. Total thickness of the Valle de Angeles redbeds is estimated to be 1500 m in the eastern part of the study area and decreases to several hundred meters in the western part of the study area below the volcanic flows of the Wampu Formation (Fig. 5). Carbonate clasts were derived from limestone of the Atima Formation and contain late Aptian to late Albian foraminifera Cenomanian calcareous Dasyclad alga and the late Albian rudist *Mexicaprina* sp. (Scott and Finch, 1999).

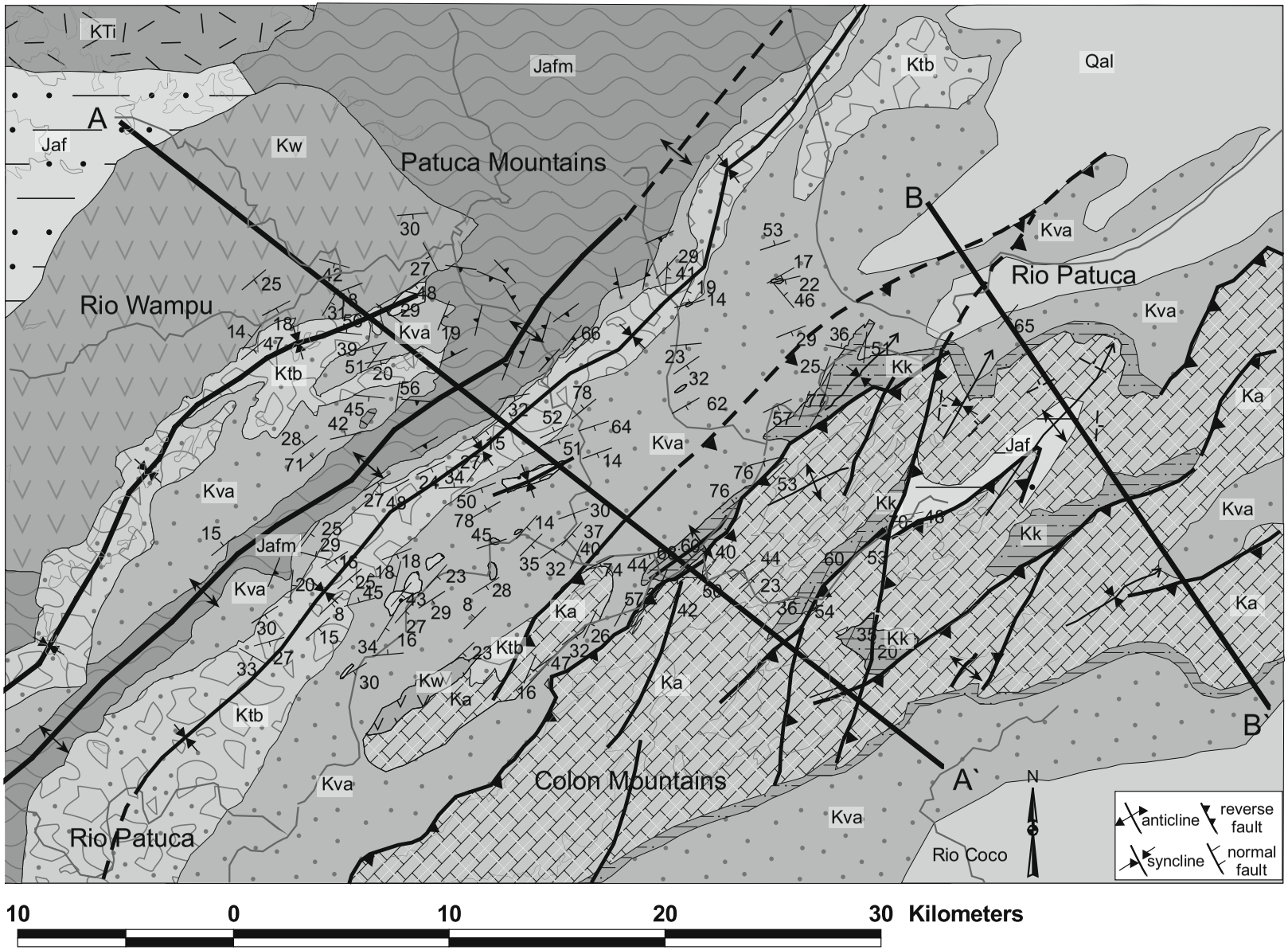

Figure 5. Geologic map of Colon Mountains study area near the confluence of the Río Wampu and Río Patuca (see Figure 4 for map location area relative to the entire Colon fold-thrust belt). Southeastward-dipping thrust faults transport early Cretaceous massive limestone of Atima Formation to the northwest over Late Cretaceous Valle de Angeles redbeds. A–A′ and B–B′ show the locations of the geologic cross sections in Figure 6. Jaf—Jurassic Agua Fria Formation; Jafm—Jurassic metamorphosed Agua Fria Formation; Ka—Cretaceous Atima Formation; Kk—Cretaceous Krausirpe Formation; Ktb—Cretaceous Tabacon Formation; KTi—Cretaceous-Tertiary intrusive rocks; Kva—Cretaceous Valle de Angeles Formation; Kw—Cretaceous Wampu volcanics.

Limestone-clast conglomerate in the lower part of the Valle de Angeles Formation is abundant proximal to the limestone massif of the Colon Mountains (Fig. 3B). In areas to the northwest of the Colon Mountains, metamorphic clasts predominate and limestone clasts are absent to rare. The Atima Formation (source of the limestone clasts) is not present northwest of the Río Patuca (Figs. 4 and 5). Subangular pebble clasts of red sandstone appear throughout the section becoming more prevalent toward the top of the redbeds.

Wampu Volcanic Unit

Flows of basaltic andesite within clastic strata of the Valle de Angeles Formation are exposed along the Río Patuca upstream of its confluence with the Río Wampu (Fig. 5). Wampu volcanic flows are somewhat less resistant than the Agua Fria metasedimentary rocks and develop a rectangular drainage (Fig. 4). These volcanic exposures define a northeast-trending outcrop belt that is an outlier of the basaltic andesite flows of the main Wampu volcanic field to the northwest that was studied by Weiland et al. (1992) (Fig. 5). Weiland et al. (1992) reported K/Ar ages of 70.4 (±3.4) Ma and 80.7 (±4.3) Ma from volcanic flows in this northern area. In the upper 500 m of the Valle de Angeles Formation, Wampu volcanic flows are interbedded with the clastic strata (Fig. 3B).

Tabacon Formation

The Tabacon Formation is a 500 m-thick, massive bedded, subangular cobble breccia, composed of volcanic clasts derived from the flows of the Wampu Formation and reworked clasts from the redbed strata (Rogers, 1996) (Fig. 2 and 5). Its age is taken as Late Cretaceous (<70 Ma) based on its stratigraphic position above the radiometrically dated Wampu volcanic rocks (70–80 Ma) (Weiland et al., 1992). It is the youngest stratigraphic unit present in the study area and is involved in the folding and thrusting. The volcanic breccia of the Tabacon Formation is a prominent ridge former that is distinguishable from the ridge-forming Atima Formation by the lack of karst development (Fig. 4).

Mills and Hugh (1974) mapped the Late Jurassic Todos Santos Formation and Atima Formations along the Río Wampu and west of the Río Patuca in an area where Rogers (1996) mapped Late Cretaceous breccia of the Tabacon Formation (Fig. 5). We suggest that the resistant beds of the Tabacon breccia were incorrectly identified by Mills and Hugh (1974) because the Tabacon unit forms strike ridges remarkably similar in appearance to the ridge-forming Atima limestone when viewed from a distance or on aerial photographs. Because Tabacon breccia overlies the metasedimentary Agua Fria Formation along the Río Wampu, Mills and Hugh (1974) may have simply assumed that the first clastic unit would be the Todos Santos Formation.

An angular unconformity with 10–15 degrees of discordance separates the Krausirpe Formation from the overlying clastic strata of the Valle de Angles Formation. A zone of paleo-epikarst is developed where the Valle de Angeles Formation unconformably blankets the massive limestone of the Atima Formation. Paleo-epikarst at the contact and the complete erosion of the underlying Krausirpe strata record a period of subaerial exposure of the limestone prior to the beginning of the Late Cretaceous Valle de Angeles deposition. North of the Río Patuca, limestone of the Atima Formation is absent, and the Valle de Angeles redbeds were observed in direct unconformable contact with the metasedimentary strata of the Agua Fria Formation. Patchy deposition of Atima Formation limestone has been reported across the Chortis block (cf. Finch, 1981; Donnelly et al., 1990; Rogers, 2003), and its complete absence north of the Río Patuca (Fig. 5) could signify its nondeposition rather than its deposition and subsequent erosion. However, the angular unconformity between the Krausirpe and Valle de Angeles Formation, the Atima clasts within the Valle de Angeles redbeds, and the karstified erosion surface at the Valle de Angeles–Atima contact are evidence for a peripheral bulge developed in front of the advancing Colon thrust belt. The antiformal basement exposure northwest of the Río Patuca marks the trace of the bulge (Figs. 2 and 5).

Because no obvious angular unconformity is observed in the Late Cretaceous section, we infer that the main shortening event that formed the Colon fold-thrust belt occurred after the deposition of the Tabacon Formation ca. 70 Ma (Fig. 3B). Because the contact between the Valle de Angeles redbeds and the Tabacon breccia is gradational with upward coarsening, progressive increase in clast angularity, and increasing volcanic clast content, it is possible that the Tabacon Formation is an early syntectonic deposit related to the early phase of the shortening event. To the northeast and southwest, away from the Wampu volcanic field, the breccia clasts in the Tabacon Formation contain a greater abundance of metamorphic rock fragments, suggesting a regional uplift and source from the northwest in latest Campanian to Maastrichtian time. Because the Tabacon breccia blanketed the latest Cretaceous landscape and rests unconformably on the Agua Fria phyllite and schist, we interpret the Tabacon Formation as a synorogenic clastic wedge shed southeastward from subaerially exposed highlands formed during Late Cretaceous–early Tertiary shortening as the peripheral bulge formed in front of the advancing Colon thrust sheet.

Structural Geology of the Colon Fold-Thrust Belt

The Colon belt is a fold-thrust belt of imbricate, southeast-dipping reverse faults that place Cretaceous carbonate strata of the Atima Formation over post-Cenomanian Valle de Angeles Formation (Fig. 6A and 6B). Broad, open folds are found 20 km northwest of the thrust front, indicating a broad foreland zone of convergent deformation (Figs. 4 and 5). The northeast-striking frontal thrust parallels the Río Patuca on the west flank of the Colon Mountains (Fig. 4). Reverse faults and northeastward-plunging folds of the Colon Mountains coincide with the outcrop area of shale of the Krausirpe Formation, which forms an incompetent horizon on which northwest directed shortening is facilitated (Figs. 4 and 5). West of the Río Patuca where the Krausirpe Formation is absent, large folds with northeastward-trending axial

surfaces deform Jurassic metasedimentary rocks and overlying Cretaceous strata.

At least four thrust sheets comprise the Colon Mountains as displayed in the structure profile (Figs. 6A and 6B). The location of the faults is revealed by the repetition of the distinctive Atima-Krausirpe stratigraphy visible in the strike valleys of the Colon Mountains (Fig. 4). In the Patuca Mountains west of the Río Patuca, the ridges composed of volcanic breccia of the Tabacon Formation form two open synclines separated by a metamorphic-cored anticline flanked by Valle de Angeles strata dipping off the anticline (Fig. 6A). This represent the peripheral bulge in front of the main thrust sheets (Fig. 5).

THE SIUNA TERRANE OF NICARAGUA

Seventy kilometers southeast of the Colon fold-thrust belt of Honduras is the Siuna mining district (Figs. 2 and 7) (Venable, 1994). Here serpentinite bodies containing high nickel and chromium, ultramafic cumulates, and podiform chromite are thrust to the north and west and are imbricated with Cretaceous sedimentary strata and calc-alkaline volcanic rocks. Wehrlite is associated with the serpentinite. X-ray diffraction analysis shows the serpentinite bodies to be composed of lizardite and chrysotile with minor magnetite and chromite (Venable, 1994). Undeformed diorite and granodiorite plutons intrude strata and volcanic rocks and postdate the shortening deformation. Venable (1994) reports an $^{40}Ar/^{39}Ar$ age of 59.89 (±0.47) Ma for a biotite separate from a diorite pluton. Whole rock analysis of the diorite yielded a $^{147}Sm/^{144}Nd$ ratio of 0.135624 and a present day $^{143}Nd/^{144}Nd$ of 0.512985, with a present day epsilon Nd value of +6.8, corresponding to an initial epsilon Nd value of +7.2 at 60 Ma, indicating lack of contamination from continental crust. Small, undeformed hornblende andesite dikes intrude the faulted contacts between the serpentinites and sedimentary strata. $^{40}Ar/^{39}Ar$ dating of a hornblende separate from the andesite dikes yielded an age of 75.62 (±1.33) Ma.

Venable (1994) defined the Siuna terrane as an oceanic island arc developed on an oceanic basement that was active from the Early to middle Late Cretaceous and subsequently deformed in the Late Cretaceous as the Siuna arc accreted to the southern margin of the continental Chortis block. We propose that the Siuna terrane formed the leading edge of the Guerrero-Caribbean island arc that accreted to the margin of southern México and to the Chortis block in Late Cretaceous times. This arc system formed the leading edge of the Caribbean oceanic plateau province, which formed in Late Cretaceous time (95–88 Ma) (Tardy et al., 1994; Hoernle et al., 2002).

THE COLON FOLD-THRUST BELT BENEATH THE MOSQUITIA COASTAL PLAIN OF EASTERN HONDURAS

The location of the subsurface seismic reflection grid and well study of Mills and Barton (1996) is shown on Figure 2 and covers a large area of the Mosquitia alluvial plain of Honduras centered on the village of Awas. The area is underlain by a large Quaternary alluvial plain related to fluvial deposition from the combined outflow of the Río Patuca and Cocos (Fig. 2). The overall elevation of the plain is a few tens of meters above sea level with the highest points confined to bedrock hills (Mills and Hugh, 1974). A small part of the Mosquitia alluvial plain is apparent on the southeast corner of the LANDSAT image shown in Figure 4.

Seismic interpretations tied to the two wells drilled along multichannel seismic line T-08 of Mills and Barton (1996) (Fig. 6C) identified several of the same lithologic formations described herein from outcrops in the Colon Mountains. These relationships are summarized on the stratigraphic column in Figure 3B.

Our interpretation of the units encountered in the two wells differs significantly from the stratigraphic interpretation by Mills and Barton (1996). Their approach was to adopt new formation names for units that we consider to be correlatable to the stratigraphic section of the Colon Mountains (Rogers, 1996). Part of the correlation problem with both wells was related to the fact that no paleontological age determinations were made, so none of the units described by Mills and Barton (1996) were dated. Our correlations rely solely on lithostratigraphic correlation. The first author visited the well sites in February 1992 and examined cuttings from the wells. The stratigraphic units described in the two wells included the units summarized in Table 1, which are shown in detail on Figure 13 *in* Mills and Barton (1996) and schematically on Figure 6C herein.

Adopting these stratigraphic correlations, the Embarcadero well and multichannel seismic line T-108 document duplex thrusting of Jurassic Agua Fria Formation over a fault sliver of Late Cretaceous Valle de Angeles Formation, which in turn is thrust over Jurassic Agua Fria Formation (Fig. 6C). The northern part of the seismic line shows repetitions in the unit we interpret as the Late Cretaceous (post-80 Ma) Tabacon Formation. These observations constrain the age of thrusting in eastern Honduras as post-dating the deposition of the Tabacon Formation, or Late Cretaceous–Tertiary (post-80 Ma).

The structural style displayed on the seismic line consists of duplexed, south-dipping reverse faults. The hanging wall of these faults produce a structural high centered near the Embarcadero well seen in Figure 6C. This elevated hanging wall in the subsurface is directly along-strike from the topographically-elevated hanging wall of the Colon Mountains (Fig. 2).

Aeromagnetic data provided to us by the Dirección General de Energia (Honduras) was used to trace the frontal thrust along-strike in the subsurface from the Colon Mountains, across the Mosquitia Plains and the coast of Honduras, to the Nicaraguan Rise offshore (Fig. 8). The magnetic character of the autochthonous hanging wall of the Colon fold-thrust belt is dominated by low amplitude (<100 gamma) short-to-medium wavelength (5–10 km peak to trough distance) anomalies that range in color from orange to dark green in the area to the south and southeast of the

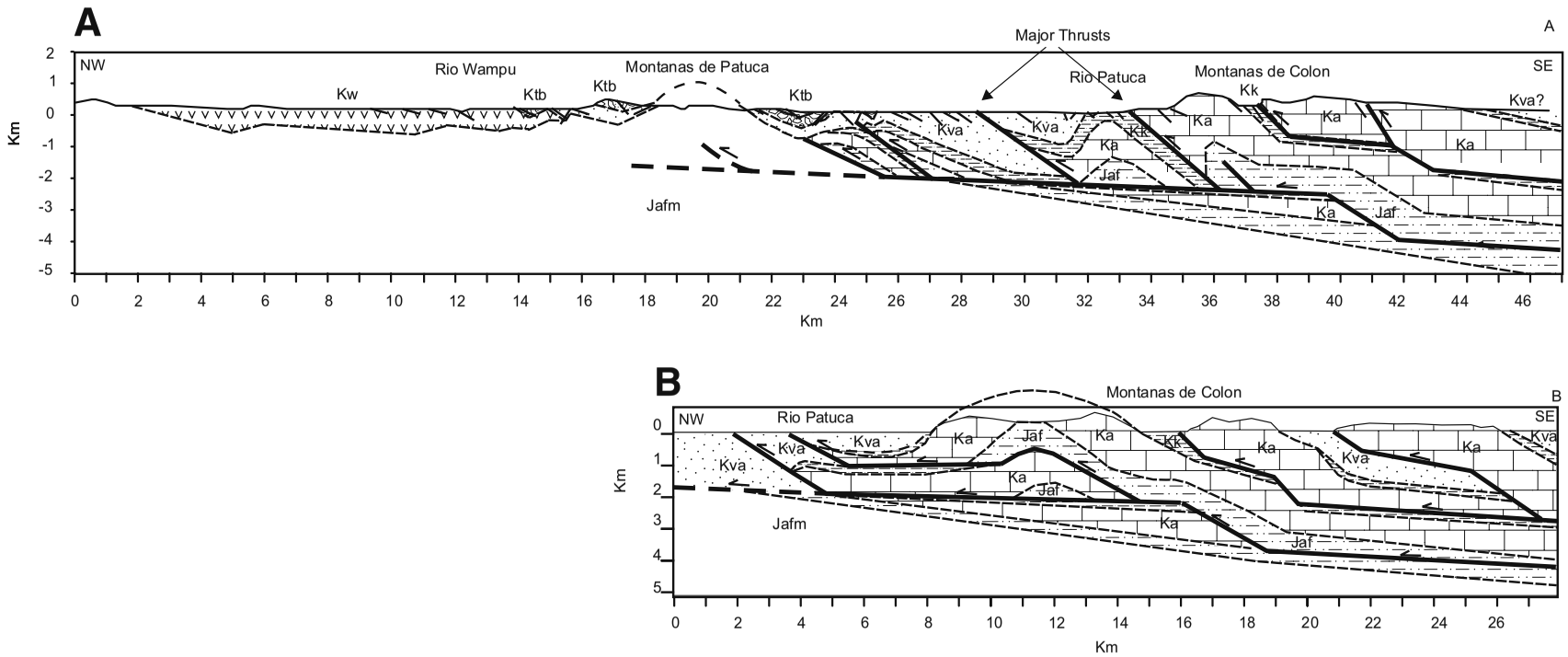

Figure 6 (*on this and following page*). Structural cross sections and multi-channel seismic profiles across all three segments of the Colon fold-thrust displayed at the same horizontal scale (except for C, which is at 2×) to facilitate structural comparisons between segments. (A and B) Geologic cross sections through the Colon Mountains segment, eastern Honduras, based on 1:50,000 scale geologic mapping shown in Figure 5. Scale is in kilometers, and there is no vertical exaggeration. Jaf—Jurassic Agua Fria Formation; Jafm—Jurassic metamorphosed Agua Fria Formation; Ka—Cretaceous Atima Formation; Kk—Cretaceous Krausirpe Formation; Ktb—Cretaceous Tabacon Formation; KTi—Cretaceous-Tertiary intrusive rocks; Kva—Cretaceous Valle de Angeles Formation; Kw—Cretaceous Wampu volcanics. Measured dips are plotted along ground surface. (C) Onland multi-channel seismic reflection section across the Mosquitia Plains near the village of Awas modified from seismic line T-08 in Figure 7 *in* Mills and Barton (1996) (see Fig. 2 for location of line, position of frontal thrust, and associated grid of seismic data). Vertical scale is in two-way travel time. Age control and position of some of the higher level, southeast-dipping thrusts are constrained by well logs from Raiti-Tara-1 and Embarcadero-1. Main thrust in Raiti-Tara-1 well places lithologic equivalent of Tabacon Formation rocks over Cretaceous Valle de Angeles Formation; upper thrust in Embarcardero-1 places Jurassic Agua Fria Formation over Cretaceous Valle de Angeles Formation. (D) Offshore multi-channel seismic reflection section across the leading edge of the Colon fold-thrust belt beneath the Nicaragua Rise from Rockwell (1985) (see Fig. 2 for location of line, position of frontal thrust, and associated grid of seismic data). (E) offshore multi-channel seismic reflection section displays Cretaceous strata (G-horizon) elevated to near seafloor beneath the Nicaragua Rise and the unconformity at the base of the Tertiary from Rockwell (1985) (see Fig. 2 for location of line and associated grid of seismic data). P—top of Eocene; B—top of Atima Formation; dashed line is a Miocene marker. Inset map shows location of seismic lines and wells.

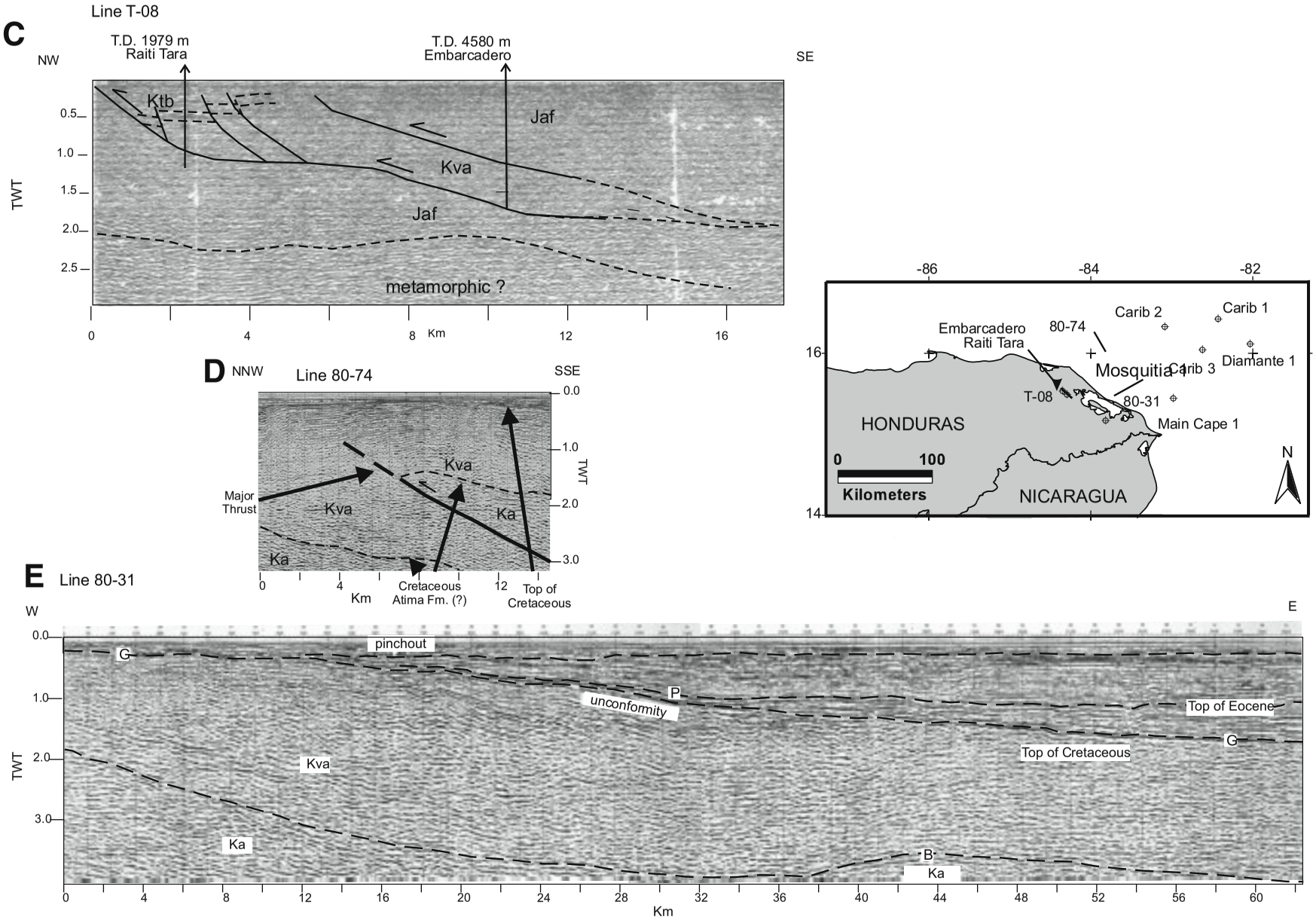

Figure 6 (*continued*)

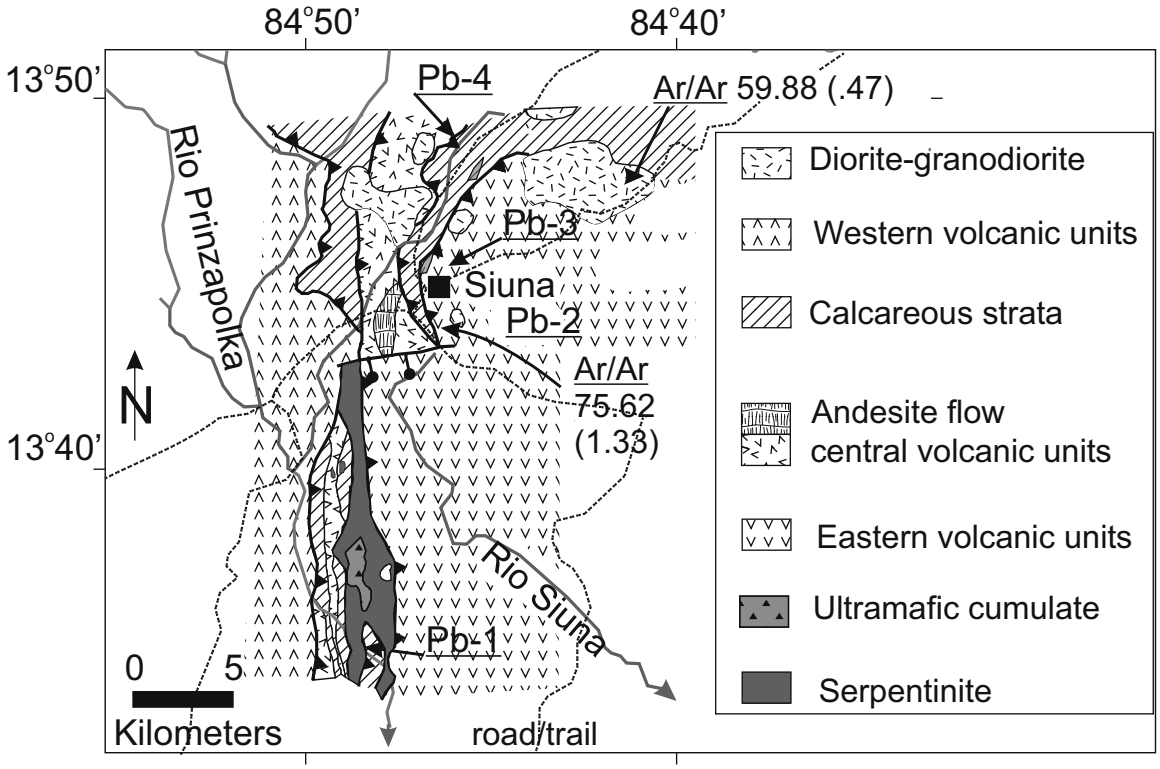

Figure 7. Geology of Siuna mining district, Nicaragua, modified from Venable (1994) showing distribution of thrusted ultramafic and igneous rocks. Location of map is shown on Figure 2. Locations of samples analyzed for Pb isotopic ratios (see Fig. 10 and Table 2) and of sample dated by argon-argon (Ar/Ar) are indicated.

TABLE 1. STRATIGRAPHIC CORRELATION OF THIS STUDY AND MILLS AND BARTON, 1996

Mills and Barton (1996)	This study	Lithology described by Mills and Barton (1996)
Ahuas beds	Tabacon Formation	Soft to hard, medium to fine grained, reddish sandstone siltstone, and conglomerate; volcaniclastic
Río Riba Formation	Valle de Angeles Formation	Red, fine-grained argillaceous hard sandstone and shale
Not observed	Krausirpe Formation	
Not observed	Atima Formation	
Agua Fria Formation	Agua Fria Formation	Dark tightly cemented sandstone and shale
Paleozoic (?) metasedimentary	Agua Fria Formation metamorphosed	Dark grey phyllite

thrust front. This contrasts with the footwall and foreland of the Colon belt, which is dominated by high-amplitude (>200 gamma) broad wavelength (20–30 km peak to trough distance) anomalies that range in color from magenta to dark blue in the area to the north and northwest of the thrust front.

Superimposing the thrust front known from mapping in the Colon Mountains and the Mosquitia subsurface study onto the aeromagnetic map clearly shows a northeast-trending deep basement structure expressed on the aeromagnetic map that is consistent with the shallow structure observed on the seismic data and by field mapping. This alignment implies involvement of the underlying magnetic basement in the shortening either as an inversion of the rifted Jurassic margin (Rogers et al., this volume, chapter 4) or as a backstop preventing further advancement of the thin-skinned thrusting.

THE COLON FOLD-THRUST BELT BENEATH THE NICARAGUA RISE, CARIBBEAN SEA

The Nicaragua Rise is a shallow-water (<100 m), tectonically stable, Cenozoic carbonate platform overlying both continental and arc crust (Arden, 1975; Case et al., 1990). Areas along the Honduran coast are dominated by terrigenous sedimentation related to major deltas of the Patuca and Coco Rivers (Fig. 2).

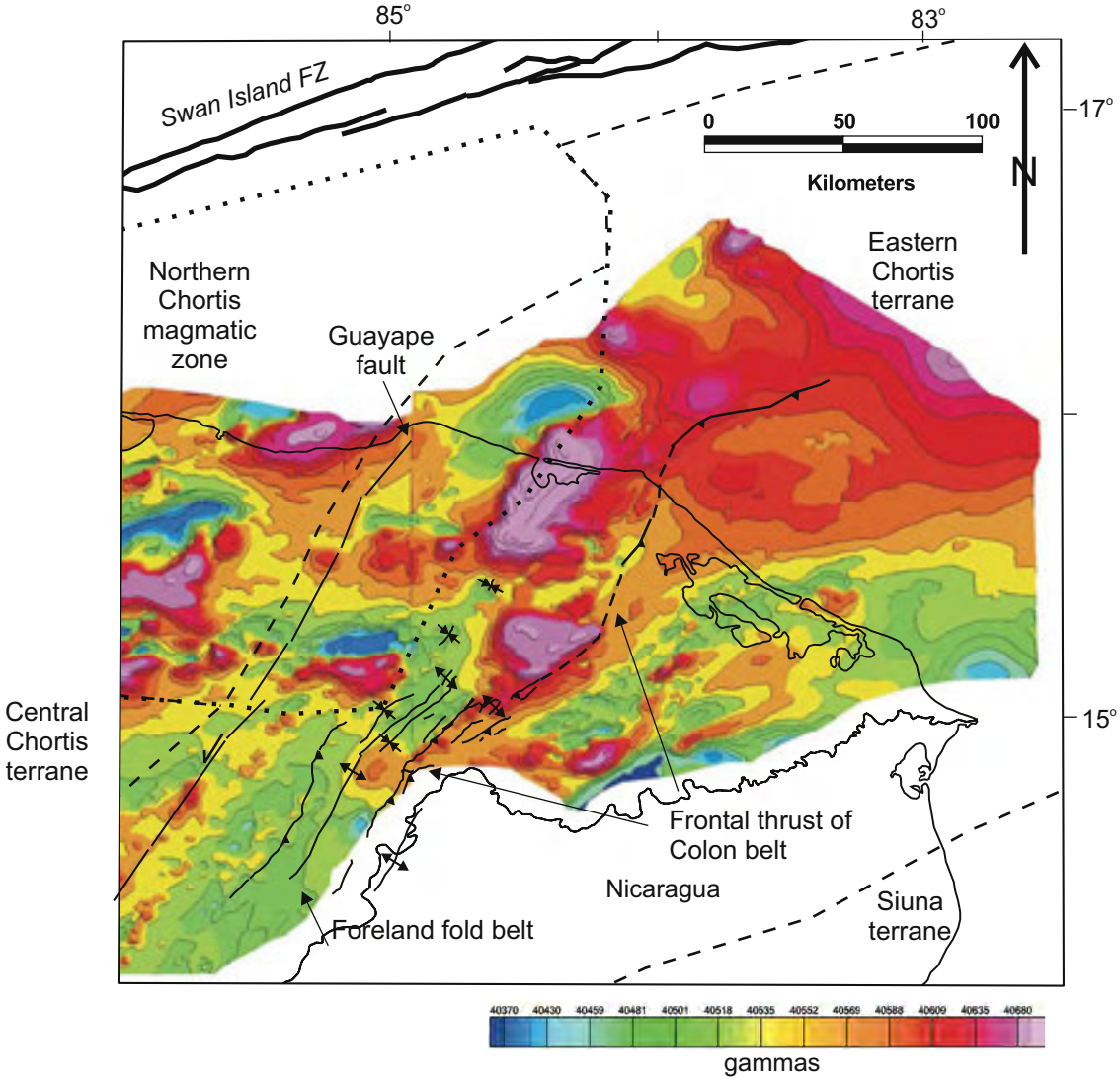

Figure 8. Aeromagnetic map of eastern Honduras modified from Dirección General de Energia (Honduras) (used with permission). Scale is in gammas. Thrust front from the geologic map in Figure 2 is superimposed to show the abrupt change in magnetic patterns that coincides with the leading edge of the Colon fold-thrust belt and the parallelism of surface thrust with magnetic trends in basement rocks. FZ—fault zone.

Rockwell (1985) reported findings based on 850 km of seismic reflection airgun data (48 fold) and 315 km of original Texaco data collected by surveys from 1977 to 1980 (offshore survey area shown in Fig. 2). This area of the Nicaragua Rise is known as the Gracias a Dios platform. The objective was to reevaluate petroleum prospects in the area and plan additional, non-exclusive seismic surveys in the area. Specific objectives included the enhancement of pre-Tertiary reflectors and clarification of shallow structural and stratigraphic relationships. Reprocessing substantially improved data down to the base of the Tertiary and marginally improved pre-Tertiary data.

Three horizons were mapped: top of Eocene, top of Cretaceous, and top of Atima (mid-Cretaceous) (Figs. 6D and 6E). A tie to the Main Cape-1 well shown on Figure 2 on an adjacent seismic line of this vintage confirms the age of the first two horizons, but no well tie in this vintage was able to substantiate the top of the Atima Formation although this has been demonstrated by other industry wells and seismic profiles in the vicinity of the Gracias a Dios platform. Other wells on the Nicaragua Rise compiled by Robertson Research (1984) support the idea that direct correlation is possible between the Cretaceous stratigraphy in eastern Honduras and the Cretaceous stratigraphy underlying the Eocene-Recent carbonate platform. For example, the Caribe-1, Caribe-2, and Caribe-3 wells all encountered mid- to early Albian limestone below Late Cretaceous sandstone. This succession suggests the regional extent of Albian Atima Formation overlain by Late Cretaceous Valle de Angeles Formation. The Diamante-1 well penetrated Cretaceous limestone, no older

than late Albian, overlain by dark shale with minor sandstone. This succession suggests Krausirpe Formation overlying Atima Formation (Fig. 3B).

The top of Eocene horizon represents an unconformity between Eocene and Oligocene carbonate lithologies and shows that Eocene rocks pinch out in a westward and northwestward direction on the platform by erosion (Fig. 6E). The wedge of Eocene rocks is extended by a series of down-to-the-southeast normal faults. The relationship of the normal faults to the older shortening structures of the Colon belt is attributed to continued shortening thrusting and uplift along the thrust front and hanging wall of the Colon belt shown on Figure 2, or alternatively, to post-collisional collapse.

The top of Cretaceous unit dips east-southeast and is subparallel to an east-southeast–dipping frontal thrust. This fault aligns with the subsurface thrust mapped beneath the Mosquitia Plain and exposed in the Colon Mountains (Figs. 2 and 6D). The structure of this frontal thrust is similar in the Colon Mountains and in the Mosquitia plain: an anticlinal hanging wall block developed in mid-Cretaceous Atima limestone and overthrust clastic sedimentary units correlated to the Late Cretaceous Valle de Angeles Formation (Fig. 6D).

Offshore observations constrain the age of thrusting on the Nicaragua Rise as post-dating the deposition of the Valle de Angeles Formation, or Late Cretaceous–Tertiary (post-80 Ma). Tilting and normal faulting of the Eocene unit indicates that thrusting could have continued into the Eocene but ended by the beginning of the Oligocene.

Reconstructing the Southern Margin of North America in Latest Cretaceous Times

Restoring the Chortis block to its pre-translation (pre-Eocene) position adjacent to the truncated margin of southwestern México realigns the Colon fold-thrust belt of the Eastern Honduras with the fold-thrust belts and ophiolites north of the Motagua suture in Guatemala (Burkart, 1994; Donnelly et al., 1990) (Fig. 9A). The present day configuration of these elements is shown in Figure 9B. This reconstruction also provides a best fit of the following elements common to the Chortis block and SW México, which are discussed in detail in Rogers et al. (this volume, Chapter 4):

1. Influx of Late Cretaceous terrigenous sandstone and shale over Early Cretaceous shallow marine platform limestone of both southern México and Chortis;
2. Grenville-age basement common to both areas;
3. Late Cretaceous shortening structures common to both areas; and
4. Mid-Cretaceous arc volcanism that is geochemically similar in both areas (Rogers, 2003; Rogers et al., this volume, Chapter 5).

These common features of the two regions are used to reconstruct the Late Cretaceous position of the Chortis block against southwestern México in Figure 9A.

Three independent lines of evidence support our interpretation in Figure 9A that the eastern Chortis block records the collision of the Caribbean arc with the southern margin of North America in the Late Cretaceous. The first is the 350-km-long Colon fold-thrust belt with Late Cretaceous, northwest-directed shortening as described in this study. The second is the spatial association and inferred accretion of the intra-oceanic Siuna island arc complex on the southern margin of the Chortis block in the Late Cretaceous (Venable, 1994). The third is the Pacific origin of the Caribbean arc and its position at the leading edge of the Caribbean large igneous province (Pindell and Barrett, 1990; Sinton et al., 1997). The entry of this oceanic arc plateau into the proto-Caribbean Sea, as shown in Figure 9A, led to the subduction of proto-Caribbean oceanic crust and partial accretion of the Caribbean arc and the oceanic plateau at the "gateways" to the Caribbean in Colombia in South America (Kerr et al., 1998) and in southern Central America, where large areas of the crust appear to have been built on oceanic plateau material (Sinton et al., 1997).

In the reconstruction shown in Figure 9A, the Guayape fault system of eastern Honduras manifests collisional deformation by left-lateral strike-slip faulting and oroclinal bending of the inverted rift basins adjacent to the fault (Rogers, 2003; Rogers et al., this volume, Chapter 5).

Comparison of Lead Isotopic Composition of Siuna Terrane with Chortis Terranes and Maya Block

Kesler et al. (1990) showed that the continental blocks of Central America and México display distinct clustering of lead isotopic ratios, which provides a useful basis for distinguishing among the complexly amalgamated terranes of the region. We follow their approach by utilizing lead data from Venable (1994) from the Siuna terrane (Table 2). As previously discussed, the crust of the Chortis block can be subdivided into (1) continental crust of the central and northern Chortis terranes with Precambrian-Paleozoic crystalline basement; (2) crust of the Eastern Chortis terrane, consisting of attenuated continental crust corresponding to exposed Jurassic metasedimentary basement (Agua Fria Formation); and (3) accreted oceanic island arc crust of the Siuna terrane (Fig. 10A).

The plot in Figure 10B of $^{207/206}$Pb versus $^{206/204}$Pb data from volcanic host rock displays distinctive clustering of common lead isotopes grouped by terrane. Also displayed on the plot are lead isotopic ratios from the Caribbean large igneous province (Sinton et al., 1997; Hauff et al., 2000; Hoernle et al., 2002), the Maya block of the North America plate (Cumming and Kesler 1976; Cumming et al., 1981; Sunblad et al., 1991), and the Miocene volcanic cover of western Nicaragua (Cumming et al., 1981). The lead ratios of the Siuna terrane cluster outside of the Caribbean large igneous province cluster, indicating that the Siuna arc is not underlain by the Caribbean plateau material. Instead, the Siuna arc probably developed as an arc terrane at the leading edge of the Caribbean oceanic plateau province.

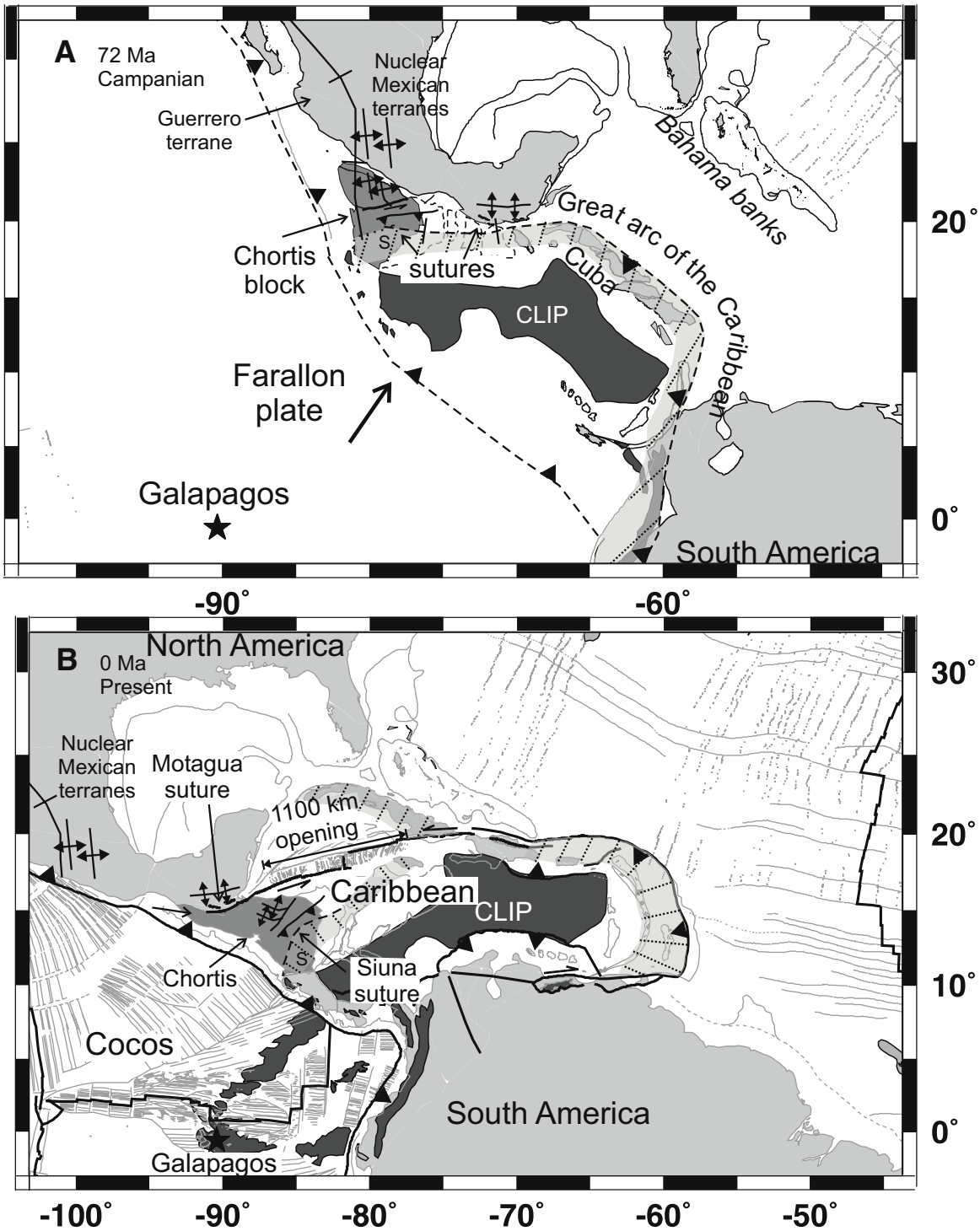

Figure 9. (A) Plate reconstruction during Campanian time (ca. 72 Ma). The reconstruction uses a mantle reference frame, and the Galapagos hotspot is held fixed. At this time, the Chortis block (gray area) forms the southwest corner of the North America plate. The Caribbean large igneous province (CLIP) formed ca. 88 Ma in the eastern Pacific Ocean as part of the Farallon plate and moved northeastward with the Caribbean arc at its leading edge. The Caribbean arc and trailing Caribbean large igneous province (dark area on figure) collided with the edges of North and South America on either side of the gap (proto-Caribbean Sea) formed by Late Jurassic–Early Cretaceous rifting and oceanic spreading between the two Americas. Accreted parts of the Caribbean large igneous province in South America are shown in medium-gray shading. Note the alignment of the Colon fold-thrust belt in the Chortis block with ophiolite belts to the east along the southern margin of North America (Motagua Valley, Guatemala). (B) Present-day position of the same tectonic elements shown in A. Note how rotation of the Chortis block has produced anomalous northeast trends in the Colon fold-thrust belt. S—Siuna.

TABLE 2. LEAD ISOTOPIC COMPOSITION OF THE SIUNA TERRANE, NICARAGUA

	Sample	Mineral	Host rock	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Pb-1	417-231	galena	Cretaceous volcanic	18.613	15.591	38.399
Pb-2	403-196	galena	serpentinite	18.598	15.559	38.315
Pb-3	371-031	galena	Cretaceous volcanic	18.550	15.606	38.415
Pb-4	417-290	sphalerite	Cretaceous volcanic	18.583	15.575	38.341

Note: Sample locations shown in Figure 7; data from Venable, 1994. Analysis by A. Baadsgard, University of Alberta.

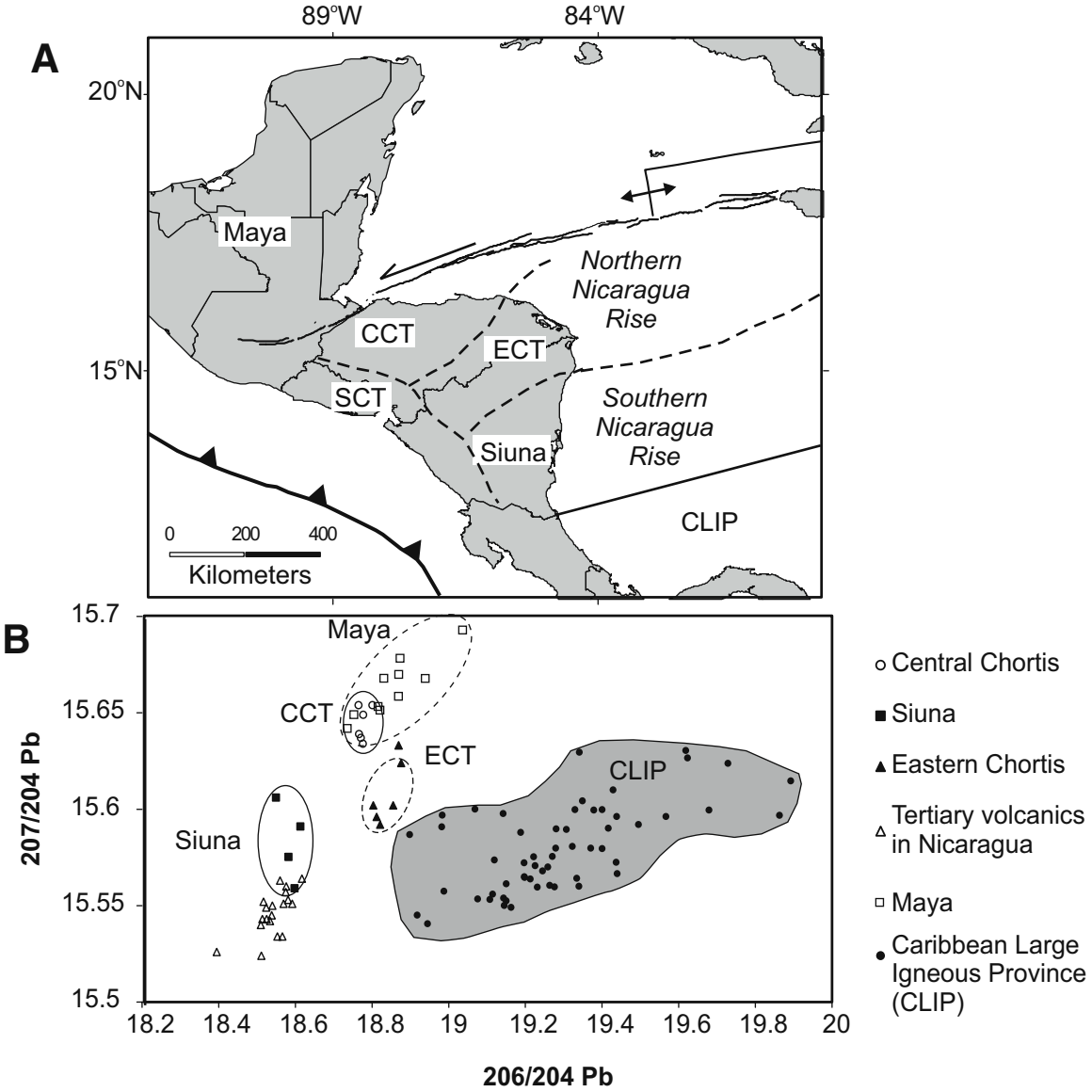

Figure 10. (A) Map showing Maya and Chortis blocks and proposed terranes of the Chortis block: CLIP—Caribbean large igneous province; CCT—Central Chortis terrane; ECT—Eastern Chortis terrane; SCT—Southern Chortis terrane; Siuna—Siuna terrane. (B) Comparison of common lead isotope data for Chortis block (including Siuna terrane) with surrounding terranes and Maya block. Note that lead data distinguishes the accreted Siuna terrane inferred to have originated in the Caribbean arc system from the Chortis block. (Lead data compiled from Cumming and Kesler, 1976; Cumming et al., 1981; Sunblad et al., 1991; Sinton et al., 1997; Hauff et al., 2000; Hoernle et al., 2002).

The isotopic ratios from the Miocene volcanic cover of western Nicaragua plot close to the Siuna cluster, suggesting that the volcanic pyroclastic deposits may bury the Siuna arc terrane to the southwest where Garayar and Viramonte (1973) described peridotite-bearing ultramafic rocks locally exposed beneath the Nicaraguan volcanic cover. Walther et al.'s (2000) observation of high velocity mantle material in an upper crustal position beneath western Nicaragua may also represent a part of the oceanic Siuna terrane.

CONCLUSIONS

1. The Colon fold-thrust belt of eastern Honduras and the Nicaragua Rise is comprised of southeast-dipping imbricate thrusts and folds, which record a Late Cretaceous northwest-southeast tectonic shortening event (present geographic coordinates).
2. The Late Cretaceous Siuna oceanic island arc complex of northern Nicaragua consists of calc-alkaline volcanic strata, serpentinite, and ultramafic cumulates. The Siuna terrane is inferred to represent the leading edge of the Caribbean arc system that was accreted onto the southern edge of the Chortis block in latest Cretaceous time.
3. Coeval, Late Cretaceous deformation of the Colon belt and the accretion of the Siuna complex are attributed to collision between the intra-oceanic Caribbean arc and the continental Chortis block.
4. This collision is coeval or slightly older than the collision of the Caribbean arc with the Maya block in Guatemala. This event emplaced the northern subduction complex of the Motagua valley and produced widespread shortening deformation to the north of the Motagua valley in Guatemala.
5. We propose that the collision belts of Guatemala and the Colon belt were originally collinear features that have now been offset by the Cenozoic rotation and translation of the Chortis block by 1100 km to the east relative to the deformed Maya block in Guatemala, providing the first pre-Tertiary piercing line oriented east to west across this margin.

ACKNOWLEDGMENTS

Funding for R. Rogers and P Mann was provided by the Petroleum Research Fund of the American Chemical Society (grant 33935-AC2 to P. Mann). We thank Dirección de Energia, of Honduras and JAPEX Geoscience Institute for releasing data for this study. Roger Barton of True Oil Company provided seismic data. Lisa Gahagan at Institute for Geophysics provided plate reconstructions. This is University of Texas Institute for Geophysics contribution no. 1869. The authors acknowledge the financial support for publication costs provided by the University of Texas at Austin's Geology Foundation and the Jackson School of Geosciences.

REFERENCES CITED

Arden, D., 1975, Geology of Jamaica and Nicaraguan Rise, *in* Nairn, A.E.M., and Stehli, F.G., eds., The ocean basins and margins: New York, Plenum Press, v. 3, p. 616–661.

Azéma, J., Biju-Duval, B., Bizon, J.J., Carfantan, J.C., Mascle, A., and Tardy, M., 1985, Le Honduras (Amerique Centrale Nucleaire) et le bloc d'Oaxaca (Sud du Mexique): Deux ensembles comparables du continent Nord-Americain separés par le jeu decrochant senestre des failles du systeme Polochic-Motagua, *in* Mascle, A., ed., Géodynamique des Caraibes: Paris, Editions Technip, p. 427–438.

Bullard, E.C., Everett, J.E., and Smith, A.G., 1965, The fit of the continents around the Atlantic: Philosophical Transactions of the Royal Society of London, v. A258, p. 41–51.

Burkart, B., 1994, Northern Central America, *in* Donovan, S., and Jackson, T., eds., Caribbean geology: An introduction: Jamaica, University of the West Indies Publisher's Association, p. 265–284.

Burkart, B., and Self, S., 1985, Extension and rotation of crustal blocks in northern Central America and effect on the volcanic arc: Geology, v. 13, p. 22–26, doi: 10.1130/0091-7613(1985)13<22:EAROCB>2.0.CO;2.

Carpenter, R.H., 1954, Geology and ore deposits of the Rosario Mining District and the San Juancito Mountains, Honduras, Central America: Geological Society of America Bulletin, v. 65, p. 23–38, doi: 10.1130/0016-7606(1954)65[23:GAODOT]2.0.CO;2.

Case, J., MacDonald, W., and Fox, P., 1990, Caribbean crustal provinces; seismic and gravity evidence, *in* Dengo, G., and Case, J. E., eds., The Caribbean Region: Boulder, Colorado, Geological Society of America, The Geology of North America, v. H, p. 15–36.

Cumming, G., and Kesler, S., 1976, Source of lead in Central America and Caribbean mineralization: Earth and Planetary Science Letters, v. 31, p. 262–268, doi: 10.1016/0012-821X(76)90218-1.

Cumming, G., Kesler, S., and Krstic, D., 1981, Source of lead in Central America and Caribbean mineralization: II. Lead isotope provinces: Earth and Planetary Science Letters, v. 56, p. 199–209, doi: 10.1016/0012-821X(81)90127-8.

DeMets, C., Jansma, P., Mattioli, G., Dixon, T., Farina, F., Bilham, R., Calais, E., and Mann, P., 2000, GPS geodetic constraints on Caribbean–North American plate motion: Geophysical Research Letters, v. 27, p. 437–440, doi: 10.1029/1999GL005436.

Dengo, G., 1973, Estructura geológica, historia tectonica y morfologia de America Central (Geologic structure, tectonic history and morphology of Central America): Guatemala City, Instituto Centroamericano de Investigacion Tecnologia Industrial, p. 1–52.

Dengo, G., 1985, Mid America: Tectonic setting for the Pacific margin from southern Mexico to northwestern Columbia, *in* Nairn, A., and Stehli, F., eds., The Ocean Basins and Margins, vol. 7: New York, Plenum Press, p. 123–180.

Donnelly, T., Horne, G., Finch, R., and López-Ramos, E., 1990, Northern Central America: The Maya and Chortis blocks, *in* Dengo, G., and Case, J.E., eds., The Caribbean Region: Boulder, Colorado, The Geological Society of America, The Geology of North America, v. H, p. 37–76.

Finch, R., 1981, Mesozoic stratigraphy of central Honduras: AAPG Bulletin, v. 65, p. 1320–1333.

Finch, R.C., and Ritchie, A.W., 1991, The Guayape fault system, Honduras, Central America: Journal of South American Earth Sciences, v. 4, p. 43–60, doi: 10.1016/0895-9811(91)90017-F.

Garayar, J., and Viramonte, J., 1973, Hallazgo de peridotitas en Nicaragua, Informe y trabajos técnicos presentados en la IV Reunión de Geólogos de América Central: Publicaciones Geológicas del ICAITI, p. 31–42.

Gordon, M.B., 1990, Strike-slip faulting and basin formation at the Guayape Fault–Valle de Catacamas Intersection, Honduras, Central America [Ph. D. dissertation]: Austin, Texas, University of Texas at Austin, 259 p.

Gordon, M.B., 1993a, Revised Jurassic and Early Cretaceous (Pre-Yojoa Group) stratigraphy of the Chortis block: Paleogeographic and tectonic implications, *in* Pindell, J., and Perkins, R., eds., Mesozoic and Early Cenozoic Development of the Gulf of Mexico and Caribbean Region: A Context for Hydrocarbon Exploration*:* Austin, Texas, Gulf Coast Section Society of Economic Paleontologists and Mineralogists Foundation, p. 143–154.

Gordon, M., 1993b, Mapa Geológica de Honduras, Hoja de Santa Maria del Real: Tegucigalpa, Honduras, Instituto Geográfico Nacional, escala 1:50,000, 1 sheet.

Gordon, M., and Young, K., 1993, Bathonian and Valanginian fossils from Honduras: Géobios, Mémoire Spécial, n. 15, p. 175–179.

Gordon, M., and Muehlberger, W., 1994, Rotation of the Chortís block causes dextral slip on the Guayape fault: Tectonics, v. 13, p. 858–872, doi: 10.1029/94TC00923.

Harlow, G., Hemming, S., Avé Lallemant, H., Sisson, V., and Sorensen, S., 2004, Two high-pressure-low-temperature serpentinite-matrix mélange belts, Motagua fault zone, Guatemala; a record of Aptian and Maastrichtian collisions: Geology, v. 32, p. 17–20, doi: 10.1130/G19990.1.

Hauff, F., Hoernle, K., Tilton, G., Graham, D., and Kerr, A., 2000, Large volume recycling of oceanic lithosphere over short time scales: Geochemical constraints from the Caribbean Large Igneous Province: Earth and Planetary Science Letters, v. 174, p. 247–263, doi: 10.1016/S0012-821X(99)00272-1.

Horne, G., Atwood, M., and King, A., 1974, Stratigraphy, sedimentology, and paleoenvironment of Esquias Formation of Honduras: AAPG Bulletin, v. 58, p. 176–188.

Hoernle, K., van den Bogaard, P., Werner, R., Lissinna, B., Hauff, F., Alvarado, G., and Garbe-Schoenberg, D., 2002, Missing history (16–71 Ma) of the Galapagos hotspot: Implications for the tectonic and biological evolution of the Americas: Geology, v. 30, p. 795–798, doi: 10.1130/0091-7613(2002)030<0795:MHMOTG>2.0.CO;2.

INETER (Instituto Nicaragüense de Estudios Territoriales), 1995, Mapa Geológica Minero de la Republica de Nicaragua: Managua, Nicaragua, escala 1:500,000, 5 sheets.

Jordan, B.R., Sigurdsson, H., Carey, S., Lundin, S., Rogers, R., Singer, B., and Barquero-Molina, M., 2007, this volume, Petrogenesis of Central American Tertiary ignimbrites and associated Caribbean Sea tephra, *in* Mann, P., ed., Geologic and tectonic development of the Caribbean plate in northern Central America: Geological Society of America Special Paper 428, doi: 10.1130/2007.2428(07).

Kerr, A., Tarney, J., Nivia, A., Marriner, G., and Saunders, A., 1998, The internal structure of oceanic plateaus: Inferences from obducted Cretaceous terranes in western Colombia and the Caribbean: Tectonophysics, v. 292, p. 173–188, doi: 10.1016/S0040-1951(98)00067-5.

Kesler, S., Levy, E., and Martín, F., 1990, Metallogenic evolution of the Caribbean region, *in* Dengo, G., and Case, J. E., eds., The Caribbean Region: Boulder, Colorado, The Geological Society of America, The Geology of North America, v. H, p. 459–482.

Kozuch, M., 1991, Mapa Geológica de Honduras: Tegucigalpa, Honduras, Instituto Geográfico Nacional, 1:500,000, 3 sheets.

Leroy, S., Mauffret, A., Patriat, P., and Mercier de Lepinay, B., 2000, An alternative interpretation of the Cayman Trough evolution from a reidentification of magnetic anomalies: Geophysical Journal International, v. 141, p. 539–557, doi: 10.1046/j.1365-246x.2000.00059.x.

Mann, P., 1999, Caribbean sedimentary basins: Classification and tectonic setting from Jurassic to Present, *in* Mann, P., ed., The Caribbean Basin: Sedimentary Basins of the World series: Amsterdam, Elsevier, v. 4, p. 3–31.

Manton, W., 1996, The Grenville of Honduras: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. 493.

Manton, W., and Manton, R., 1999, The southern flank of the Tela basin, Republic of Honduras, *in* Mann, P., ed., Caribbean Basins, Sedimentary Basins of the World series: Amsterdam, Elsevier, v. 4, p. 219–236.

Mills, R., and Barton, R., 1996, Geology of the Ahuas area in the Mosquitia Basin of Honduras: Preliminary report: AAPG Bulletin, v. 80, p. 1627–1640.

Mills, R., Hugh, K., Feray, D., and Swolfs, H., 1967, Mesozoic stratigraphy of Honduras: AAPG Bulletin, v. 51, p. 1711–1786.

Mills, R., and Hugh, K., 1974, Reconnaissance geologic map of Mosquitia region, Honduras and Nicaragua Caribbean Coast: AAPG Bulletin, v. 58, p. 189–207.

Nelson, B., Herrmann, U., Gordon, M., and Ratschbacher, L., 1997, Sm-Nd and U-Pb evidence for Proterozoic crust in the Chortis block, Central America: Comparison with the crustal history of southern Mexico: Terra Nova, v. 9, p. 496.

Paz-Rivera, N., 1963, Reconocimiento geológico de la costa Pacífico de Nicaragua: Boletín Servicio Geológico Nacional (Nicaragua), v. 8, p. 69–87.

Pindell, J., and Dewey, J., 1982, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: Tectonics, v. 1, p. 179–211.

Pindell, J., and Barrett, S., 1990, Geological evolution of the Caribbean region; a plate-tectonic perspective, *in* Dengo, G., and Case, J.E., eds., The Caribbean Region: Boulder, Colorado, The Geological Society of America, The Geology of North America, v. H, p. 405–432.

Riller, U., Ratschbacher, L., and Frisch, W., 1992, Left-lateral transtension along the Tierra Colorada deformation zone, northern margin of the Xolapa magmatic arc of southern Mexico: Journal of South American Earth Sciences, v. 5, p. 237–249, doi: 10.1016/0895-9811(92)90023-R.

Ritchie, A.W., and Finch, R.C., 1985, Widespread Jurassic strata on the Chortis block of the Caribbean plate: Geological Society of America Abstracts with Programs, v. 17, no. 7, p. 700–701.

Robertson Research, 1984, A biostratigraphic study of wells in Honduras: Tegucigalpa, Honduras, unpublished report to Dirección General de Minas e Hidrocarburos, 112 p.

Rockwell, D., 1985, Interpretation of marine seismic data, Gracias a Dios platform, offshore northeast Honduras: Tegucigalpa, Honduras, unpublished report to Direccion General de Minas e Hidrocarburos, 13 p.

Rogers, R., 1995, Mapa geológica de Honduras, hoja de Valle de Jamastran: Tegucigalpa, Honduras, Instituto Geográfico Nacional, escala 1:50,000, 1 sheet.

Rogers, R., 1996, Geología a lo largo del Río Patuca y Wampu, La Mosquitia, Honduras: Tegucigalpa, Honduras, Instituto Geográfico Nacional, Revista, v. 4, p. 86–106.

Rogers, R., 2003, Jurassic–Recent tectonic and stratigraphic history of the Chortis block of Honduras and Nicaragua (northern Central America) [Ph.D. dissertation]: Austin, Texas, University of Texas at Austin, 264 p.

Rogers, R., and O'Conner, E., 1993, Mapa Geológico de Honduras: Hoja de Tegucigalpa (segunda edición): Tegucigalpa, Honduras, Instituto Geográfico Nacional, escala 1:50,000, 1 sheet.

Rogers, R., Kárason, H., and van der Hilst, R., 2002, Epeirogenic uplift above a detached slab in northern Central America: Geology, v. 30, p. 1031–1034, doi: 10.1130/0091-7613(2002)030<1031:EUAADS>2.0.CO;2.

Rogers, R., and Mann, P., 2007, this volume, Transtensional deformation of the western Caribbean-North America plate boundary zone, *in* Mann, P., ed., Geologic and tectonic development of the Caribbean plate in northern Central America: Geological Society of America Special Paper 428, doi: 10.1130/2007.2428(03).

Rogers, R., Mann, P., and Emmet, P., 2007, this volume, Tectonic terranes of the Chortis block based on integration of regional aeromagnetic and geologic data, *in* Mann, P., ed., Geologic and tectonic development of the Caribbean plate in northern Central America: Geological Society of America Special Paper 428, doi: 10.1130/2007.2428(04).

Rogers, R.D., Mann, P., Scott, R., and Patino, L., 2007, this volume, Cretaceous intra-arc rifting, sedimentation and basin inversion in east-central Honduras, *in* Mann, P., ed., Geologic and tectonic development of the Caribbean plate in northern Central America: Geological Society of America Special Paper 428, doi: 10.1130/2007.2428(05).

Rosencrantz, E., Ross, M., and Sclater, J., 1988, Age and spreading history of the Cayman Trough as determined from depth, heat flow, and magnetic anomalies: Journal of Geophysical Research, v. 93, p. 2141–2157.

Rosenfeld, J.H., 1981, Geology of the Western Sierra de Santa Cruz, Guatemala, Central America: An ophiolite sequence [Ph.D. dissertation]: Binghamton, New York, State University of New York at Binghamton, 313 p.

Schaaf, P., Morán-Zenteno, D., Hernández-Bernal, M., Solís-Pichardo, G., Tolson, G., and Kohler, H., 1995, Paleogene continental margin truncation in southwestern Mexico: Geochronological evidence: Tectonics, v. 14, no. 6, p. 1339–1350, doi: 10.1029/95TC01928.

Scott, R., and Finch, R., 1999, Cretaceous carbonate biostratigraphy and environments in Honduras, *in* Mann, P., ed., Caribbean Basins, Sedimentary Basins of the World series: Amsterdam, Elsevier, v. 4, p 151–166.

Simonson, B., 1977, Mapa Geológico de Honduras, El Porvenir: Tegucigalpa, Honduras, Instituto Geográfico Nacional, escala 1:50,000, 1 sheet.

Sinton, C., Duncan, R., and Denyer, P., 1997, Nicoya Peninsula, Costa Rica: A single suite of Caribbean oceanic plateau magmas: Journal of Geophysical Research, v. 102, p. 15,507–15,520, doi: 10.1029/97JB00681.

Southernwood, R., 1986, Late Cretaceous limestone clast conglomerates of Honduras [M.S. thesis]: Dallas, Texas, University of Texas at Dallas, 300 p.

Sundblad, K., Cumming, G., and Krstic, D., 1991, Lead isotope evidence for the formation of epithermal gold quartz veins in the Chortis block, Nicaragua: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 86, p. 944–959.

Tardy, M., Lapierre, H., Freydier, C., Coulon, C., Gill, J., Mercier de Lepinay, B., and Beck, C., Martinez-R., Talavera-M., Ortiz-H., E., Stein, G.,

Bourdier, J., and Yta, M., 1994, The Guerrero suspect terrane (western Mexico) and coeval arc terranes (the Greater Antilles and the Western Cordillera of Colombia): A late Mesozoic intra-oceanic arc accreted to cratonal America during the Cretaceous: Tectonophysics, v. 230, p. 49–73.

Venable, M., 1994, A geological, tectonic, and metallogenetic evaluation of the Siuna terrane (Nicaragua) [Ph.D. dissertation]: Tucson, Arizona, University of Arizona, 154 p.

Viland, J., Henry, B., Calix, R., and Diaz, C., 1996, Late Jurassic deformation in Honduras: Proposals for a revised regional stratigraphy: Journal of South American Earth Sciences, v. 9, p. 153–160, doi: 10.1016/0895-9811(96)00002-8.

Walther, C., Flueh, E., Ranero, C., von Huene, R., and Strauch, W., 2000, Crustal structure across the Pacific margin of Nicaragua; evidence for ophiolitic basement and a shallow mantle sliver: Geophysical Journal International, v. 141, p. 759–777, doi: 10.1046/j.1365-246x.2000.00134.x.

Weiland, T., Suayah, I., and Finch, R., 1992, Petrologic and tectonic significance of Mesozoic volcanic rocks in the Río Wampú area, eastern Honduras: Journal of South American Earth Sciences, v. 6, p. 309–325, doi: 10.1016/0895-9811(92)90049-5.

Zoppis Bracci, L., and del Giudice, 1958, Un reconocimiento geológico del Río Bocay y parte del Río Coco: Boletín del Servicio Geológico Nacional de Nicaragua, v. 2, p. 81–102.

Manuscript Accepted by the Society 22 December 2006