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Geochemistry and petrology of three granitoid rock cores from the Nicaraguan Rise, Caribbean Sea: implications for its composition, structure and tectonic evolution

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ABSTRACT

The Nicaraguan Rise is a major submarine structure of poorly known origin. Its lithologies have been studied from dredge hauls and land outcrops on the Greater Antilles and Central America and its structure from geophysical data. In this paper we present the first geochemical analyses for granitoids that were recovered during the 1970s from cores drilled on the Nicaragua Rise for oil prospecting. The three Nicaraguan Rise rocks are calk-alkaline granitoids, and lie in the high-K field for Caribbean granitoids similar to the Above Rocks, Jamaica and Terre Neuve, Haiti intrusions. All of these intrusions are considered to be of Late Cretaceous – Paleocene age. Key elements abundances - K, La, Ce, Nd, Hf, Zr and Sm - indicate that the three Nicaraguan Rise rocks present more affinity with mature oceanic arc rocks similar to other granitoids from the Greater Antilles rather than mature continental arcs. The Pb, Nd and Sr isotope data show no evidence of a continental component, thus indicating that the more eastern and northern submarine area of the Northern Nicaraguan Rise is not underlain by continental crust of the Chortis block. Although of similar age, the Nicaraguan Rise samples are different from the more depleted Cuban granitoids of the Sierra Maestra, though both show strong similarities in their $^{207}Pb/^{204}Pb$ composition. We postulate that the Northern Nicaraguan Rise was most likely a Caribbean oceanic arc system that may have interacted only at its margin with the continental blocks bounding the region to the west in the area of the Northern Honduran borderland.

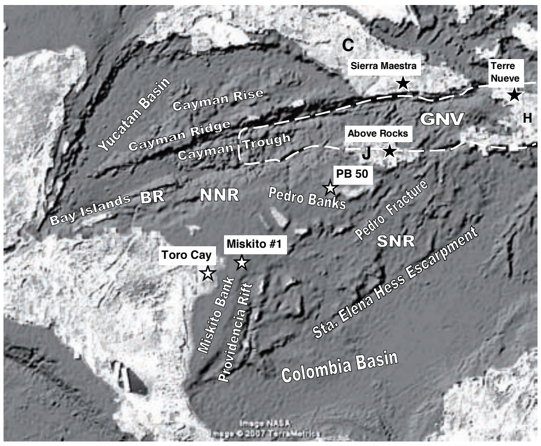
KEYWORDS Caribbean. Nicaraguan Rise. Granitoids. Geochemistry. Arc rocks.

INTRODUCTION

The Nicaraguan Rise (or Plateau) is a major submarine crustal feature that extends northeast across the Caribbean Sea from the coast of Honduras and Nicaragua to northeast of Jamaica where it meets with the southwestern part of the Southern Peninsula of Haiti.

The Nicaraguan Rise covers an area of some 413,000 km^2 in total (Fig. 1A, 1B). Little is known about its structure

A



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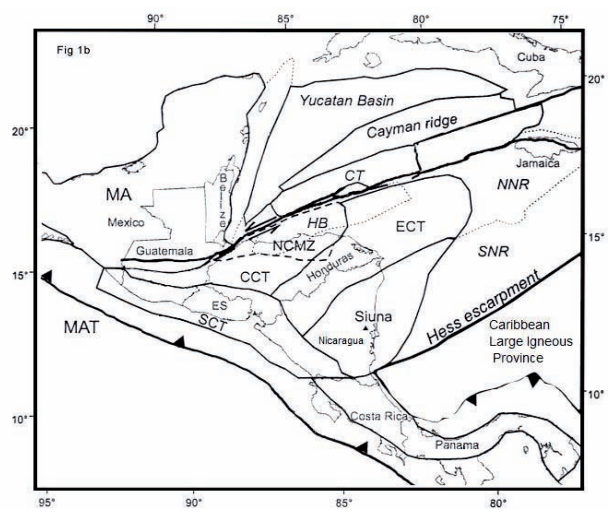

FIGURE 1 | **A) Image of the western Caribbean region, showing bathymetry and topography (base modified from Google Earth). Abbreviations for topographic features, plates, terranes and physiographic provinces are from names as given by Rogers et al. (2007); BR: Baccanao Ridge; GNV: Gonave Plate; NNR: North Nicaraguan Rise; SNR: South Nicaraguan Rise. White star represent drill core sites for the three samples. Black stars indicate the site of other Caribbean granitoid rocks referred to in text. B) Tectonic setting of northern Central America and southern Mexico showing the location and names of the terranes and physiographic provinces (adapted from Rogers et al., 2007): MA: Maya Block; MAT: Middle America Trench; YB: Yucatan Basin; NNR: Northern Nicaraguan Rise; SNR: Southern Nicaraguan Rise; MAT: Middle America Trench; ECT: Eastern Chortís Terrane; CCT: Central Chortis Terrane; HB: Honduras borderland; CB: Cuba; CT: Cayman Trough; SCT: Southern Chortís Terrane; ES: El Salvador.**

and lithological composition and it is probably the least understood major crustal feature in the whole Caribbean. Information about its composition and structure has come from four main sources; 1) geophysical investigations including seismic refraction (Ewing et al., 1960; Edgar et al., 1971) seismic reflection, gravity and magnetic profiling, and more recently aeromagnetic surveys (see below); 2) studies of the compositions of the cores drilled for petroleum exploration (Arden, 1975); 3) samples dredged from the walls of the Cayman Trench (Perfit and Heezen, 1978); 4) geology of the Bay Islands, northern Honduras and Jamaica (McBirney and Bass, 1969; Arden, 1975; Lewis and Draper, 1990). Most of the work prior to 1990 was summarized by Case et al. (1990) and Holcombe et al. (1990). Except for the seismic survey by Mauffret and Leroy (1997) and some seismic work and an aeromagnetic survey on the offshore areas of Nicaragua and Honduras summarized below, there has been little work done since the drilling and seismic surveys carried out by oil companies in the 1970s.

Synopses of the geology of the Nicaraguan Rise have been made by Arden (1969, 1975), Perfit and Heezen (1978) and Holcombe et al. (1990). Based on their recent compilations on the area of Honduras and Nicaragua, Rogers, Mann and colleagues (see below) and Baumgartner et al. (2008) have developed terrane models that have direct relevance as to the nature and origin of the Nicaraguan Rise. Recent models developed to account for the origin of the Nicaraguan Rise (Mann et al., 2006; Pindell and Kennan, in print) depend on the eastward movement and rotation of the Chortis block.

Three of the wells drilled in the 1970s for oil exploration along the northern Nicaraguan Rise sector (Fig. 1A) bottomed in plutonic rocks. Using up-to-date analytical techniques, we have determined the major and trace element, and Sr, Nd and Pb isotope compositions of the three granitoid rocks recovered. In this paper we show that these rocks are closely comparable in composition with those of the Above Rocks (Jamaica) pluton and the Terre Neuve (Haiti) stock but have lower amounts of the light rare earth elements (LREE), Ta and Nb. These data support the widely held view that most of the Nicaraguan Rise has evolved as island arc crust. The implication of these data as to the structure and composition of the Nicaraguan Rise are briefly discussed.

GEOLOGICAL SETTINGS

Nature and composition of the Nicaraguan Rise and relationship to Chortis Block

Fig. 1A is a map of the main topographic features of the Nicaraguan Rise and adjacent features. For more details of the topography and structural features as determined by geophysical measurements, the reader is referred to Case et al. (1990) and the references below.

The broad shelf area of the Nicaraguan Rise to the northeast of the land areas of Honduras and Nicaragua and extending to Jamaica (the upper Nicaraguan Rise of Holcombe et al., 1990) is here termed the Northern Nicaraguan Rise (NNR of Fig. 1A). The southern boundary of the Northern Nicaraguan Rise is the Pedro Fault (or Fracture) zone. Morphologically the Northern Nicaraguan Rise is characterized by a series of carbonate banks and shelves separated by channels and basins that have evolved from a continuous carbonate "megabank" established over basement highs (Arden, 1975; Mutti et al., 2005). In essence, the submarine shelf area of the Northern Nicaraguan Rise is a topographic extension of the Precambrian-Paleozoic continental Chortis block (Dengo and Bohnenberger, 1969; Dengo, 1973; Couch and Woodcock, 1981; Donnelly et al., 1990). For this reason Meyerhof (1996) and others maintained that a considerable part of the Nicaraguan Rise must be underlain by Pre-Mesozoic continental crust. All the information, however, indicates that most of the basement rock of the Northern Nicaraguan Rise is not of continental composition but consists of island arc crust and is likely to be of similar composition to the island of Jamaica near the northern end of the Rise (Arden, 1975; Perfit and Heezen, 1978; Lewis and Draper, 1990). With the exception of the northern Honduran borderlands (HB of Fig. 1B; see below) no rocks older than Cretaceous in age are known on Jamaica or have been reported from any part of the Nicaraguan Rise.

In their review of crustal types and crustal provinces in the Caribbean, Case et al. (1990) identified three main types of crust: continental, oceanic and accretionary found in different regions of the total area of the Nicaraguan Rise. They also considered the presence of "indeterminate crust" that results "where geologic events have obscured crustal processes" (Case et al., 1990).

Based largely on a regional aeromagnetic survey of the Honduras land surface and the region off the north coast of Honduras with a compilation of geological information, isotopic dates and lead isotope data of both Honduras and Nicaragua, Rogers et al. (2007) subdivided the Chortis block into three tectonic terranes, namely the Central Chortis terrane, the Eastern Chortis terrane and the Southern Chortis terrane as shown on Figure 1B. The Central and Eastern Chortis terranes are continuous to the northeast beyond the coastline on to the submarine Northern Nicaraguan Rise. The third terrane, the Siuna terrane (Venable, 1994) is exposed in northern Nicaragua and extends northeast on to the Nicaraguan Rise (Fig. 1B). The Siuna's eastern boundary against the Southern Nicaraguan Rise is defined topographically by the Providencia Rift but its north-east trending boundary is not defined by Rogers et al. (2007) as following any topographic or geologic feature (Fig. 1). Venable (1994) concluded that the Siuna terrane consists of an Early Cretaceous island arc developed on oceanic basement that was accreted to the Chortis terrane in the Early Cretaceous.

The Southern Nicaraguan Rise (termed the lower Nicaraguan Rise by Holcombe et al., 1990) is the large block that separates the Northern Nicaraguan Rise from the Colombian Basin (Holcombe et al., 1990; Mauffret and Leroy, 1997; Fig. 1). This structure is some 200-240km wide and approximately 1200km long along its southern boundary. Its northern boundary against the Northern Nicaraguan Rise is the Pedro Escarpment (Fault or Fracture Zone). The well-defined lineament that forms the southern boundary to the Southern Nicaraguan Rise against the Colombian basin is the Saint Elena-Hess Escarpment.

Although each of the terrane segments and provinces that have been suggested has its own structural and morphological features, the divisions between the segments have not always been clear, as pointed out by Case et al. (1990). New multichannel seismic surveys and a re-evaluation of existing geophysical data have resulted in a better characterization of the three of the segments. Case et al. (1990) concluded that, like southern Central America, the Southern Nicaraguan Rise is composed of oceanic crust. Based on multichannel seismic data collected on the 1992 Casis cruise and the reprocessing of older data, using modern techniques, Mauffret and Leroy (1997) found that the Southern Nicaraguan Rise is underlain by oceanic plateau crust. The upper Layer 2V (V for volcanic plateau) is composed of a thin basaltic layer that overlies layer 2 of the original oceanic crust. This is underlain by Layer 3V which is divided into two crustal layers, an upper intrusive gabbroic layer about 6km thick that overlies a 10km thick layer of picrite and mafic cumulates. Recognition of this lithology is based on a seismic velocity of 7.2-7.4km/sec for this layer and the occurrence of picrite on Curacao with which it is correlated. If the interpretation that all of the Southern Nicaraguan Rise is composed of volcanic plateau crust is correct then this area is the largest and thickest plateau crust in the Caribbean Sea.

Unfortunately, there have been no new seismic or other geophysical measurements made across the Northern Nicaraguan Rise segment nor has there been any further drilling since the mid 1970s on the northeastern region of the Nicaraguan Rise. Seismic velocities recorded for the lower layer of the Northern Nicaraguan Rise range from 6.2 to 6.7km/s (Ewing et al., 1960), in strong contrast with the high velocities for the lower layer of the Southern Nicaraguan Rise. These lower velocities for the lower layer of the Northern Nicaraguan Rise are in agreement with an island arc type of crust. Only a few measurements of crustal thickness (depth to the Moho) have been made in different parts of the Northern Nicaraguan Rise. Case et al. (1990) gave the thickness of the Northern Nicaraguan Rise at 20-23km. Revised thickness measurements, based on the older refraction data for the Northern Nicaraguan Rise and compiled on a regional map of the Caribbean area, range from 15 to 20km (Mauffret and LeRoy 1997, Fig. 2). Thickness measurements of the crust recorded for the area over the submarine Nicaraguan Rise between Jamaica and the mid-distance along the Rise to the coast of Central America varied from 15.3 to 18.5km (Mauffret and LeRoy, 1997). This differs decidedly from the estimates of the depth to the M-discontinuity by Case et al. (1990). These thicknesses are more typical of oceanic island arc crust, not of continental crust. Rogers et al. (2007), however, showed their Eastern Chortis terrane to extend for a considerable distance to the northeast, as part of the submerged plateau of the northern Nicaraguan Rise. In contrast, the new terrane map proposed by Baumgartner et al. (2008) shows the area of the Chortis block (underlain by definition by continental crust) to be reduced in area considerably compared with that suggested by Rogers et al. (2007) and is more in line with that proposed by Case et al. (1990).

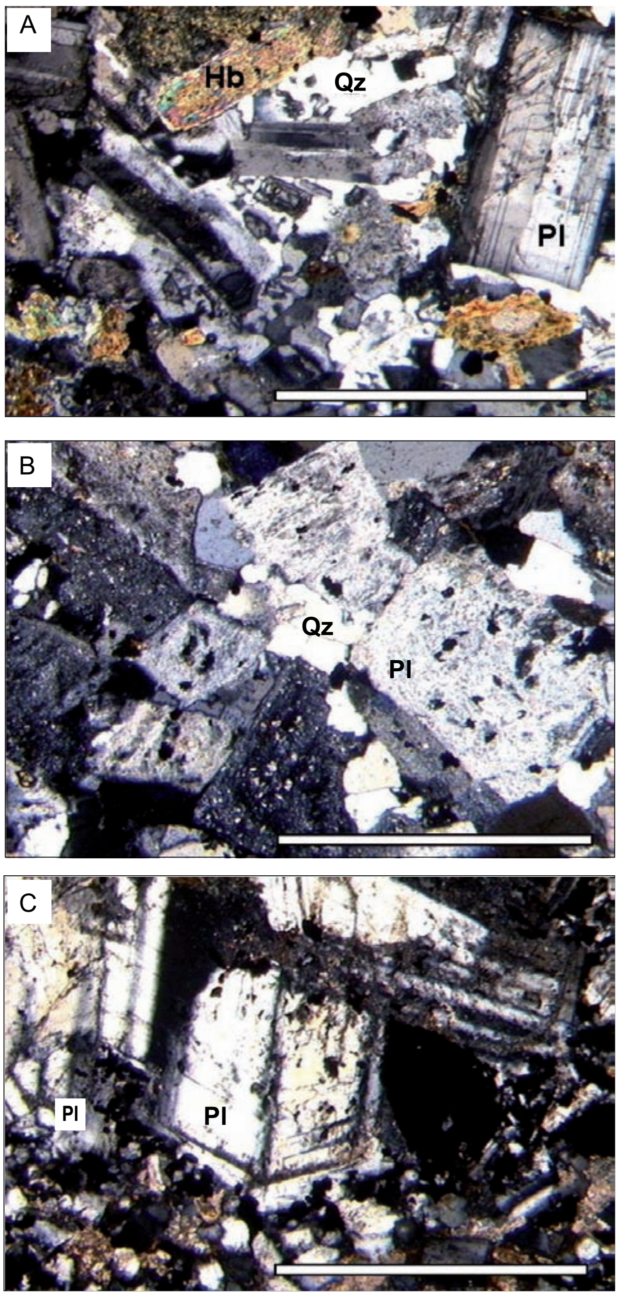

FIGURE 2 | **Thin section images of the three Nicaraguan Rise samples, White bar scale corresponds to 1mm. See text for description and discussion. A) Sample PB50. B) Sample Miskito 1. C) Sample Toro Cay.**

Baumgartner et al. (2008) have proposed a new terrane subdivision of Nicaragua and northern Costa Rica based on a detailed biostratigraphic study of Radiolaria and studies of the ultramafic and mafic rocks in the area. They identified the new terrane as the Mesquito Composite Oceanic Terrane , which includes the Siuna terrane in Nicaragua. The Mesquito Composite Oceanic Terrane extends from Guatemala in the west and forms the Southern Nicaraguan Rise (Fig. 1 and discussed above). It is considered to be underlain by accreted Pacific terranes and to extend into the “basement” units of the Greater Antilles islands of Jamaica, Hispaniola and Puerto Rico, composed essentially of island arc crust.

Northern Honduran Borderland

The one area in the northwestern part of the Nicaraguan Rise for which there is strong evidence that it is underlain by continental crust is the northern Honduran Borderland physiographic province (Fig. 1B). This is the marginal area between the Cayman Trough and the Northern Nicaraguan Rise and is the narrow offshore portion of the northernmost section of the Central Chortis terrane. It shows topographic and geological structures not seen elsewhere on the Chortis block or the Nicaraguan Rise. Swan Island, Guanaja, Utila and Roatan (the Bay Islands, Fig. 1) lie on a series of ridges that run parallel to the south wall of the Cayman Trough and are collectively known as the Bonacca Ridge. Gravity and bathymetry indicate a North and a South Bonacca Ridge separated by the Bonacca Basin (Rogers and Mann, 2007). Rocks exposed on Guanaja and Roatan islands include gabbro, pyroxene hornblendite, serpentinite, dacite and sodic granite together with a metamorphic sequence of schists, amphibolite and marble, the latter cut by the sodic granite; mudstones, chert and greywacke were reported to grade into the main metamorphic sequence (McBirney and Bass, 1969). Many structures seen in the offshore Honduran borderlands region can be traced onshore into the Cordillera Nombre de Dios and the Omoa to the southwest

(Horne et al., 1976; Holcombe et al., 1990: Rogers and Mann, 2007). The metamorphic rocks in the Bay Islands are similar to Paleozoic rocks in the Cordillera Nombre de Dios of northern Honduras. It has also been suggested that the amphibolites and associated serpentinites in the Bay Islands are the equivalent of the El Tambor amphibolites and associated serpentinised peridotites in the Motagua Valley and their emplacement may be related to the same obduction events (Donnelly et al., 1990).

Kornicker and Bryant (1969) and Pinet (1975), using single channel seismic profiling, outlined the series of elongated basins and ridges that make up the northern Honduran borderlands. Based on both multichannel and single channel seismic, together with gravity and an aeromagnetic survey and drilling, Rogers and Mann (2007) have described the structures and stratigraphy in considerable detail. They mapped 21 different basins that form a belt that narrows toward the Mid-Cayman spreading center. The four exploration wells drilled to depths of 2379-3790m together with the seismic data supported the rift interpretation of Pinet (1975) that documented "two stratigraphic sequences above an angular conformity disrupted by normal faults that form horsts and grabens filled by turbidites" (Rogers and Mann, 2007). The basement rocks penetrated in two wells consisted of black slate and quartzite and metasedimetary and volcanic rocks of Cretaceous age. These lithologies were interpreted to have an igneous source, although no intrusive or volcanic rocks were intersected. It is reasonable to assume that the basement lithologies in the wells correlate with the basement rocks exposed on Guanaja and Roatan because these islands are the exposed upper part of the ridges (Bonacca Ridge). In these wells a major unconformity separates the basement from a Middle Miocene pre-rift sequence consisting of sub-aerial redbeds to coastal or coastal shelf deposits.

TABLE 1 | **Stratigraphic summary of the three cores from the Nicaraguan Rise**

Pedro Banks - Occidental - Lat. 16°56.2' N - Long. 78°48 W	
Stratigraphic position in well	Depth (meters)
Water Bottom (top Middle Eocene)	100
Top Sst-conglomerates (base Middle Eocene)	1925
Top Granodiorite (base of Sst-conglomerates)	1934
Miskito-1 - Signal/Occidental - Lat. 14°.52.4' N - Long. 81°.42.2' W	
Stratigraphic position in well	Depth (meters)
Water Bottom (top of Pleistocene)	29.7
Top Upper Miocene (base Plio-Pleistocene)	55.7
Top Middle Miocene	135.7
Top Lower Miocene	280.7
Top Oligocene (base Miocene)	740.7
Top Upper Eocene (base Oligocene)	1144.7
Top Middle Eocene	1316.7
Top Upper Cretaceous (granodiorite)	1995.7
Total Depth	2025.7
Toro Cay - Mobil Oil - Lat: 14°.20.2' - Long: 83°.06.9'	
Stratigraphic position in well	Depth (meters)
Water Bottom (Top Lower Miocene)	15.2
Top Oligocene (Base Miocene)	400.2
Top Upper Eocene (Base Oligocene)	1146.2
Top Middle Eocene (Base U Eocene)	1268.2
Top Upper Cretaceous-top of diorite (Base Eocene)	2244.2
Total depth	2265.8

SAMPLE DETAILS AND ANALYTICAL METHODS

Drill core locations and stratigraphic details of the cores of three granitoid rock samples studied here are given in Fig. 1A and Table 1. Small pieces of rock were broken off from each of the core samples and thin sectioned. Pieces of rock, free of veining and alteration, were selected and crushed to powder using a ceramic shatter box. The samples were analyzed by several methods for both major and trace elements in different laboratories and at different times, allowing an interlaboratory check to be made. Sample PB 50 was analyzed by X-ray fluorescence for major elements in the 1970's along with samples of the Above Rocks granodiorite at the University of Montreal by B.M. Gunn. Sample Toro Cay was analyzed for major elements by X-ray fluorescence at the Geological Survey of Canada. Trace elements (except for Zr and Hf) for PB 50 and Toro Cay were determined by Inductively-Coupled Plasma – Mass Spectrometry (ICP-MS) at the University of Granada, Spain. PB50 was also analyzed for trace elements on an Element2 High Resolution - Inductively-Coupled Plasma – Mass Spectrometry (HR-ICP-MS) at the Department of Geological Sciences, University of Florida. The analyses were performed in medium resolution with Re and Rh used as internal standards. Quantification of the results was done by external calibration using a combination of USGS rock standards. Major elements on samples Miskito-1 were analyzed by Inductively-Coupled Plasma – Atomic Emission spectrophotometry (ICP-AE) and trace elements by ICP-MS at ACME Laboratories, Vancouver. In the technique used at ACME Laboratories, the sample powders are fused with lithium tetraborate and taken into solution with hydrofluoric and perchloric acids and hence solution of refractory minerals such as zircon should be complete. As a further check, samples were also analyzed for Rb, Sr, Ba, Nb, Zr, Cr, and Ni by X-ray fluorescence using the pressed pellet method at Activation Laboratories, Ancaster, Canada. All these analyses have been combined with the analyses of other Caribbean granitoids to give a consistent data set for 35 elements for most samples. The new analyses for the Nicaraguan Rise rocks are presented in Table 2. Since all three samples have undergone at least some degree of alteration the most significant results are based on the most immobile elements Th, Nb, Ta, Hf, Zr, Ti, Y and REE.

In carrying out the isotope analyses Sr, Pb and Nd were separated using standard chromatographic methods in a

TABLE 2 | **Major and trace element analyses of Nicaraguan granitoid rocks with comparisons from Above Rocks (Jamaica) and Neuve (Haiti)**

Major Elements Oxides	Toro Cay	Miskito #1	PB 50	WIR 154 Above Rocks	SK-9 Terre Neuve
SiO_2	54.31	61.38	62.87	62.92	62.77
TiO_2	0.79	0.49	0.54	0.67	0.79
Al_2O_3	19.2	16.24	17.23	16.45	15.32
Fe2O3	6.7	5.66	5.52		6.65
MnO	0.11	0.15	0.08	0.11	0.08
MgO	1.12	3.01	2.23	1.9	1.71
CaO	6.61	4.27	4.42	4.67	5.1
Na_2O	4.03	4.11	3.59	3.9	3.61
K_2O	3.15	2.15	3.41	3.69	2.9
P_2O_5	0.41	0.15	0.13	0.2	0.23
LOI	3.58	2.3	n.d	n.d.	1
TOT/C	n.d.	0.09	n.d	n.d.	0.14
TOT/S	n.d.	0.34	n.d	n.d.	0.15
Total	100.01	100.34	100.2	97.24	100.3
Trace elements ppm					
Sc	13.9	12	13.1		20.8
V	119	122	125	125	125
Cr	21.8	21	31.5	27.2	36.7
Co	13.2	11.7	14.5	12.9	16.2
Ni	5.6	7.3	8.1	5.3	6.8
Cu	53.6		41.6	905.7	1926.4
Zn	88.3	89	75.1	54.3	59.5
Ga	20.6	16.5	16.9	17.9	16.8
Rb	87	32.7	69.1	104.2	81.3
Sr	635	428.2	463	660.5	891.1
Y	19.6	18.2	14.1	19.4	15.9
Zr	132	73.7	30	143	128.9
Nb	4.1	2.7	4.9	13	15.6
Ba	626	695.3	790	1276	1009.7
La	15.9	10.9	15.2	25.2	25.6
Ce	32.8	22.2	29.4	47.2	46.5
Pr	4.6	2.83	3.8	5.8	5.48
Nd	20.1	12.6	15	22.2	21.6
Sm	4.53	3.2	3.11	4.38	3.8
Eu	1.39	0.92	0.87	1.19	1.3
Gd	4.06	3.05	2.55	3.59	3.7
Tb	0.62	0.54	0.41	0.58	0.51
Dy	3.53	2.81	2.45	3.3	3.02
Ho	0.72	0.62	0.5	0.68	0.56
Er	1.9	1.83	1.4	1.81	1.55
Tm	0.29	0.29	0.22	0.27	0.27
Yb	1.96	1.85	1.38	1.78	1.25
Lu	0.29	0.26	0.2	0.26	0.22
Hf	3.58	2.4	1.14	0.9	3.5
Ta	0.34	0.2	0.46	1.14	1
Pb	7.9	2.2	7.8	8.6	2.5
Th	5.3	1.7	5.6	9.27	3.5
U	1.3	0.6	1.8	2.61	1.4

Note: Major elements in wt %, trace elements in ppm; values not determined n.d.

clean laboratory at the Department of Geological Sciences, University of Florida. Sr isotopic compositions were determined on a Nu-Plasma Multi-Collector Inductively - Coupled Plasma – Mass Spectrometry (MC-ICP-MS) in static mode acquiring simultaneously ^{88}Sr on high-5, ^{87}Sr on high-4, ^{86}Sr on high-2, ^{85}Rb on axial and ^{84}Sr on low-2 Faraday detectors. $^{87}Sr/^{86}Sr$ ratio was corrected for mass-bias using exponential law and $^{86}Sr/^{88}Sr=0.1194$. All analyses were done by using on-peak measured zeros determined on clean 2% HNO_3 solution to correct for isobaric interferences of Kr impurities in the Ar gas. The long-term average value of NBS 987 $^{87}Sr/^{86}Sr$ is 0.71025 (+/-0.00003, 2σ). Nd isotope measurements were also conducted in static mode acquiring simultaneously ^{142}Nd on low-2, ^{143}Nd on low-1, ^{144}Nd on Axial, ^{145}Nd on high-1, ^{146}Nd on high-2, ^{147}Sm on high-3, ^{148}Nd on high-4 and ^{150}Nd on high-5 Faraday detectors. The measured ^{144}Nd, ^{148}Nd and ^{150}Nd beams were corrected for isobaric interference from Sm using $^{147}Sm/^{144}Sm = 4.88$, $^{147}Sm/^{148}Sm = 1.33$ and $^{147}Sm/^{150}Sm = 2.03$. All measured ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$ using an exponential law for mass-bias correction. Baseline was measured by electrostatic analyser (ESA) deflection of the beam. Repeated analyses of the JNdi-1 standard produced mean values of 0.512099 (+/-0.000015, 2σ). Pb isotopic analyses were also conducted on the Nu Plasma MC-ICP-MS using Tl normalization technique (Kamenov et al., 2004). The Pb isotope data are relative to the following values of NBS 981: $^{206}Pb/^{204}Pb=16.937$ (+/-0.004, 2σ), $^{207}Pb/^{204}Pb=15.490$ (+/-0.003, 2σ) and $^{208}Pb/^{204}Pb=36.695$ (+/-0.009, 2σ).

PETROGRAPHY, STRATIGRAPHY AND AGE OF THE SAMPLES

Although all three Nicaraguan Rise rock samples are medium grained grayish rocks each has a distinctive appearance and texture (Fig. 2).

Pedro Banks Drill Core - Sample: PB50 (Granodiorite)

This pale grey rock is medium-grained and consists mainly of relatively fresh plagioclase feldspar, rare potash feldspar, biotite and hornblende. In thin section the overall texture is hypidomorphic granular. Fresh subhedral plagioclase (up to about 1.2mm) is the dominant mineral. Quartz and potassium feldspar (<0.5mm) are anhedral and intersertal. Hornblende and lesser amounts of biotite are present as single grains that rarely exceed 1mm in size. Apatite and iron oxide are the main accessory minerals (Fig. 2A).

Miskito-1 Drill Core - Sample: Miskito -1 (Granodiorite)

The rock is mainly pale grayish white but has a patchy appearance due to the pale rusty color of the sericitized plagioclase feldspar in comparison with darker grey colored areas where the plagioclase is only slightly altered. Thin quartz-calcite and epidote veinlets (1-2mm across) cut the rock. In thin section subhedral and anhedral plagioclase (mainly 0.8 to 1.6mm) is altered to sericite and potash feldspar (about 0.5mm) is similarly altered. Quartz is entirely interstitial to the plagioclase feldspar. Epidote is pervasive and both hornblende and biotite are altered almost entirely to chlorite. Textural features are shown in Fig 2B.

Toro Cay Drill Core: Sample - Toro Cay (Plagioclase Porphyry)

In hand specimen this rock is darkish grey and medium-grained but on closer inspection it has a rusty appearance due to oxidation to fine-grained hematite. The rock is best termed plagioclase diorite porphyry as it consists of abundant phenocrysts of relatively fresh plagioclase feldspar laths (up to 1.4mm in length) in a finer-grained granular matrix consisting of plagioclase, ferromagnesian minerals and hematite covered grains (Fig. 2C).

Of the 26 exploration wells drilled within the area of the Miskito Banks off the east coast of Nicaragua (Munoz et al., 1997), six wells penetrated the "economic" basement below the Cenozoic sedimentary rocks. Besides the granitoid rocks from the Miskito -1 and Toro Cay wells which were sampled, granitoid rock was reported from the Centeno-1 well located about 60km east of the coast of Nicaragua at latitude 12°N. The medium-grained texture of the three granitoids examined in this paper suggests the possibility that they are the marginal or high level facies of larger courser grained intrusions. Their intermediate compositions suggest that these samples are not high level late stage differentiates, but are part of the main intrusive phases. However there is no supporting evidence for either of these suggestions.

All three wells bottomed in the granitoid rocks interpreted in the drill core logs correspond to an igneous basement of Cretaceous age (Table 1). The granitoid rocks in the Pedro Banks, Miskito-1 and Toro Cay all uncomfortably underlie Middle Eocene sedimentary rocks. A short section of sandstone and conglomerate separates the Eocene carbonate from the granodiorite rock in the Pedro banks drill core. In the core logs there is no evidence of an intrusive contact between the granitoid rocks and the sedimentary rocks. The lower Eocene and Paleocene are missing in all three cores suggesting that this was an erosional interval or a time of no sediment deposition over a wide area with the exception of the Touché-1 well, located about 47km off the coast of Nicaragua between the Toro Cay and Miskito-I wells. There is a continuous Paleocene to Eocene section about 1,900m thick in the Touche-1 well that bottoms in calcareous shale of Paleocene age (Arden, 1975; Holcombe et al., 1990).

Only one approximate age determination of 48.6-57.4Ma (53 ± 4.4Ma) is available for the Pedro Banks sample (Meyerhof and Krieg, 1977). Because this is a K/Ar whole rock age, it is interpreted as a minimum age; still the age is consistent with the stratigraphic position in the well. Since the Pedro Banks well appears to lie along the same general arc structure as the Above Rocks intrusion in Jamaica, this age should be compared with the U/Pb age of 63 ± 3Ma (after adjustment by Harland et al., 1964) obtained on titanite from a sample of granodiorite (Chubb and Burke, 1963) and a fission track age of 60.4 ± 3.4Ma (Ahmad et al., 1987) for the Above Rocks intrusion. These determinations on the Above Rocks samples are interpreted as crystallization and minimum cooling ages respectively.

Because the Miskito-1 and Toro Cay samples appear to be from the same general stratigraphic level as the Pedro Banks sample, it is apparent that all three samples are probably of a similar age, that is, within the interval late Late Cretaceous-Paleocene. A number of the wells in the Miskito Banks area off the coast of Honduras and Nicaragua, intersected or bottomed in extrusive rocks of apparent Eocene age suggesting a significant igneous event at this time (Munoz et al., 1997; Emmet, 2008). There are no data on the nature and composition of these volcanic rocks. Greenschist rock with a thickness of 516m was penetrated in the Rama-12 hole, located about 30km off the coast of Nicaragua at latitude of 13° 12"N. This could represent an ancient imbricate subduction wedge of Cretaceous age consistent with its presence in the Siuna terrane (Munoz et al., 1997).

GEOCHEMISTRY

Major and trace element geochemistry

Major and trace element analyses for the three drill core samples from the Nicaraguan Rise are given in Table 2 along with two selected analyses of other Late Cretaceous granitoids from the Above Rocks intrusion, Jamaica (Jackson and Scott, 1994) and the Terre Neuve intrusion, Haiti (Kesler, 1971) for comparison. In terms of major elements the Toro Cay sample is slightly more basic in composition with 57% SiO_2 (volatile free) compared with the Pedro Banks and Miskito samples which are both intermediate in composition with about 63 % SiO_2 (volatile free). Samples PB50 and Miskito-1 closely match sample WIR154 from the Above Rocks and SK-9 from the Terre Neuve intrusion, Haiti (Table 2). The Toro Cay sample contains 19.20% Al_20_3 and 6.03% FeO total, but only 1.12% MgO, reflecting the high percentage of plagioclase feldspar and lack of ferromagnesian silicate minerals for a low silica rock. Most of the iron is now largely oxidized to hematite.

The three Nicaraguan rocks fall into the category of calc-alkaline granitoids according to the alkali-lime index the most widely used criterion for classifying granitoid rocks (e.g., Brown, 1982; Brown et al., 1984). With their relatively high K content they are similar to the Above Rocks and Terre Neuve intrusions, and lie in the high-K field in a K_2O-SiO_2 plot for Caribbean granitoids (Lidiak and Jolly, 1996). In this way they contrast strongly with the low-K calcic group of granitoids as found in the Cordillera Central-Massif du Nord of Hispaniola and the intrusive rocks of Paleogene age from the Sierra Maestra of Cuba (Lidiak and Jolly, 1996; Kysar Mattietti, 2001; Rojas-Agramonte, 2004).

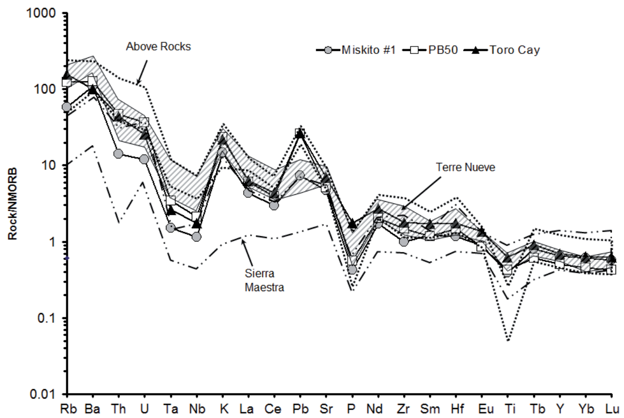

FIGURE 3 | **N-MORB- normalized trace element patterns for the three Nicaraguan granitoid rocks in comparison with granitoids from the Above Rocks and Terre Neuve plutons and intrusive rocks from the Sierra Maestra. Data for Above Rocks and Terre Neuve from unpublished data on Caribbean granitoids. Data for the Sierra Maestra from Kysar Mattietti (2001) and unpublished data.**

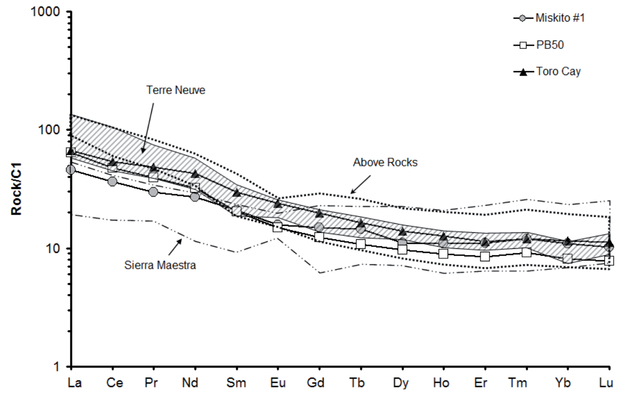

FIGURE 4 | **Chondrite-C1 normalized REE patterns for the three Nicaraguan granitoid rocks. Data for Above Rocks and Terre Neuve from unpublished data on Caribbean granitoids. Data for the Sierra Maestra from Kysar Mattietti (2001) and unpublished data.**

Trace elements for the Nicaraguan Rise samples together with the available data for the Above Rocks, Terre Neuve and Sierra Maestra intrusions have been plotted on an N-MORB normalized multi-element diagram (Fig. 3). The diagram shows the degree of subduction-derived enrichment in large ion lithophile elements (LILE) (Rb, Ba, Th, U and K) and the level above a line drawn through the high field strength elements (HFSE) (Pearce, 1983). The shapes of the patterns for all samples show similar trends with considerable enrichment in the LILE. This is less evident for the three Nicaraguan Rise samples compared with those from the Above Rocks and Terre Neuve plutons. The Sierra Maestra rocks show a more marked depletion for most elements in comparison with the other suites. This feature is typical of the more calcic or primitive type of oceanic arc Caribbean granitoid (Kysar Mattietti, 2001; Brown et al., 1984). Whereas all the samples plotted show a negative Nb -Ta anomaly with respect to Th, U and Ce, typical of subduction related rocks, the three Nicaraguan samples are all lower in Nb and Ta than the Above Rocks and Terre Neuve suites. The concentrations of Ta-Nb for the Nicaraguan samples are just above unity, that is slightly more than that of N-MORB, and the concentrations of Nd, Zr, Sm, Hf and Eu are similar and slightly higher than N-MORB for the Nicaraguan, Above Rocks and Terre Neuve suites.

The concentrations of HREE in the three suites are similar but slightly below that of typical N-MORB (Fig. 3). HREE concentrations in the Nicaraguan samples overlap with the other suites, particularly the Terre Neuve, but are lower than in many samples from the Above Rocks and Sierra Maestra.

The Nicaraguan rocks show enrichment of the LREE compared with average chondrite (Fig. 4). La/Yb in the three Nicaraguan Rise rocks ranges from 5.9 to 11, typical of the calc-alkaline group of Caribbean granitoids (Lidiak and Jolly, 1996). La values for the Nicaraguan rocks range from 10.9-15.9ppm, decidedly lower than in the Above Rocks (La = 21.33 to 31.55ppm) and Terre Neuve rocks (3.6 to 32.2ppm). Yb values for the Nicaraguan Rise rocks are in the same range as in the Terre Neuve rocks but lower than in some of the Above Rocks (Yb = 1.16 to 3.26ppm). There is only limited overlap of the LREE in the Nicaraguan rocks with those from the Sierra Maestra.

Further insight is gained by plotting the data on a multi-element mantle normalized diagram (Fig. 5) and

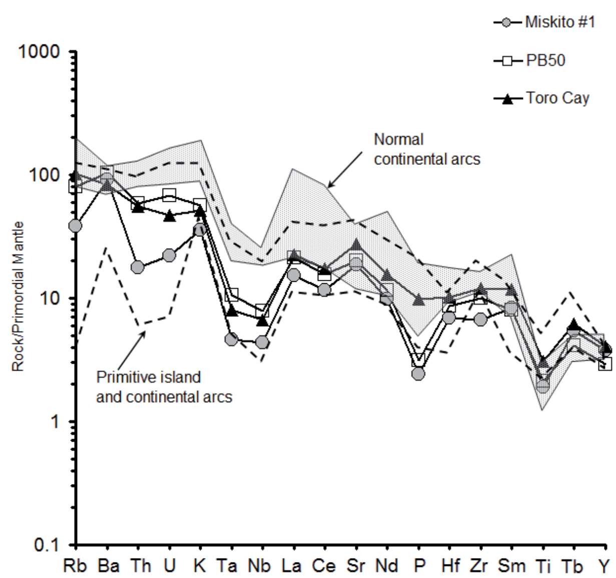

FIGURE 5 | **Primordial mantle-normalized trace element patterns for the three Nicaraguan Rise granitoid rocks in comparison with Mesozoic and Cenozoic arc granitoids. Data and terminology taken from Brown et al. (1984).**

comparing these data with two large groupings of arc-related rocks taken from the study of Brown et al. (1984). As Fig. 5 shows, there is considerable overlap, particularly for the LILE (Rb, Ba, Th, U and K) between the primitive island arc rocks and normal continental arc rocks. The normal continental arc rocks show higher concentrations of K, La, Ce, Nd, Hf and Sm than those from primitive oceanic island and continental arcs. All three Nicaraguan samples plot within the oceanic and primitive continental arc field, though there is some overlap with the normal continental arc field.

Isotope compositions

Present day $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios determined for the three granitoids from the Nicaraguan Rise are listed in Table 3. The values, corrected for age to 60 Ma (common range of all ages determination available for the samples) are plotted in Figs. 6 and 7. Data for the Above Rocks and Terre Neuve plutons (unpublished) and for the Sierra Maestra intrusions (Kysar Mattietti, 2001) are plotted for comparison. The Pb isotope ratios for the samples from Toro Cay and Miskito-1 are very similar suggesting that these two rocks were derived from the same magma or at least came from the same source, consistent with their close proximity beneath the Miskito Banks. In Fig. 6 the values for the three Nicaraguan samples, the Above Rocks and Terre Neuve samples plot in a narrow band parallel to the Northern Hemisphere Reference Line (NHRL). These factors suggest a genetic link and common mantle source for these three groups of granitoid rocks. Similarly, the overlap of the Nicaraguan samples with those from the Sierra Maestra on the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram (Fig. 6) suggests a similar source for these rocks also. The close proximity of the isotopic data to the NHRL line and the overall distribution of the data on the Pb plots in Figs.6 and 7 suggest little Atlantic sediment contamination in the generation of the granitoid magmas. However, plotting of the values of $Pb\Delta^{207/204}$ and $Pb\Delta^{208/204}$ of 4.07,4.47,4.95 and 17.77,16.97,17.45, respectively, calculated for the three Nicaraguan granitoid samples (Table 3), on Figure 5 of Jolly et al. (2006), suggests an Atlantic sediment contribution of just less than 2% (Lidiak, pers. comm.). In contrast Terre Neuve has a $Pb^{\Delta 207/204}$ ratio of only 0.91.

A number of studies have shown that the lead ore samples hosted by Paleozoic and Precambrian rocks of Central America and Mexico show Pb isotopic ratios distinctive for each of the terranes from which they have been derived (Cumming et al., 1982; Kesler et al., 1990). If the granitoid magmas have assimilated any of the host rock of these continental terranes, this lead component should be reflected in the lead isotopic composition of the granitoid rocks. Such is the case for the granitoid rocks with a continental compositional affinity dredged from the northwest wall of the Cayman Trough (Fig. 7; Lewis et al., 2005; Kysar Mattietti et al., 2009). In contrast, there is no evidence of such a continental crustal component present in the granitoid rocks from the three areas of the Nicaraguan Rise studied here.

The Sr isotopic ratios for the Nicaraguan Rise samples have an average value ($^{87}Sr/^{86}Sr = 0.7041 \pm 1$) (Table 3, Fig. 8). These values are well framed within the comparative sets of Jamaica, Haiti, Southern Cuba and the Cayman Ridge. This indicates no significant contribution of isotopically

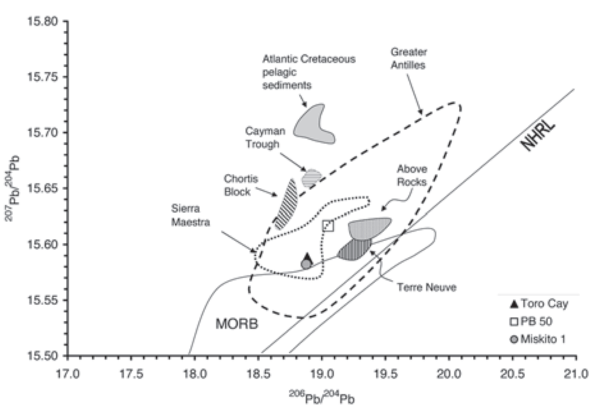

FIGURE 6 **Measured ^{207}Pb data for the Nicaraguan Rise samples. Data for Above Rocks and Terre Neuve from unpublished data on Caribbean granitoids. Data for the Sierra Maestra from Kysar Mattietti (2001) and unpublished data. Greater Antilles field drawn from GeoRoc database. Fields for|Cretaceous Atlantic pelagic sediments and MORB from Jolly and others (2006). NHRL: Northern Hemisphere Reference Line.**

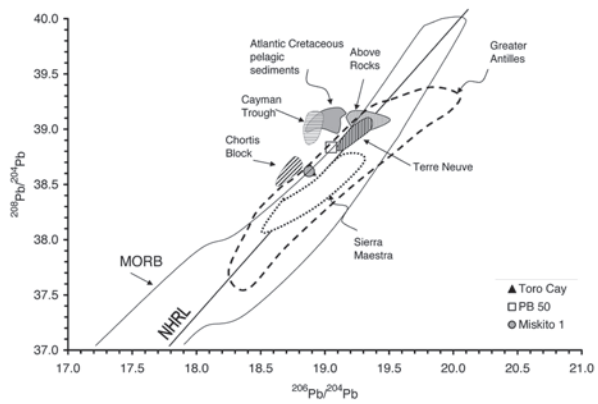

FIGURE 7 **Measured ^{208}Pb data for the Nicaraguan Rise samples with comparisons. Data source: Greater Antilles field drawn from GeoRoc database. Fields for Cretaceous Atlantic pelagic sediments and MORB from Jolly and others (2006) and from Wilson (1989). Fields for Chortis block from Cummings and others (1981) and for the Above Rocks and Cayman Ridge from unpublished data. Field from the Sierra Maestra from Kysar Mattietti (2001) and unpublished data. NHRL: Northern Hemisphere Reference Line.**

TABLE 3 | **Isotope analyses of Nicaraguan rocks**

Samples	PB50	Miskito #1	Toro Cay
SiO2	62.87	61.83	54.31
$^{206}Pb/^{204}Pb$	19.0491	18.877	18.885
$^{207}Pb/^{204}Pb$	15.6166	15.582	15.5876
$^{208}Pb/^{204}Pb$	38.8351	38.619	38.6335
Rb ppm	69.1	32.7	87
Sr ppm	463	428	635
$^{87}Rb/^{86}Sr$	0.431655	0.220971	0.39626
$^{87}Sr/^{86}Sr$	0.704249	0.704045	0.704128
ISr	0.703881	0.703857	0.70379
Sm(ppm)	3.1	3.2	4.5
Nd(ppm)	15	12.6	20.1
$^{147}Sm/^{144}Nd$	0.125394	0.153598	0.136304
$^{143}Nd/^{144}Nd$	0.512784	0.512997	0.512936
INd	0.512735	0.512883	0.512937

note: 63Ma was used to calculate Initial Sr and Initial Nd

evolved components such as older sedimentary material and/or seawater alteration across this area of the Northern Caribbean. Initial Sr isotope ratios range between 0.703790 and 0.703857 and are closest to those of the Above Rocks and Terre Neuve (Jones et al., 1979).

Nd isotope ratios for the Nicaragua Rise (Table 3, Fig. 8), in contrast, show a significant spread of values from the more radiogenic Miskito-1 sample - comparable to that of the Sierra Maestra and close to the MORB domain - to the less radiogenic Pedro Banks sample. The Toro Cay and Pedro Banks samples are similar to the Above Rocks and Terre Neuve. The Sr-Nd isotope ratios for the Nicaraguan samples plot within the field of arc related materials. Toro Cay and Miskito-1 plot in the oceanic arc field whereas PB50 plots on the margin or outside the continental arc field (Fig. 8). A more detailed discussion of this feature will be made in a future paper on the granitoids in the northwestern Caribbean. In contrast Sr-Nd ratios for the

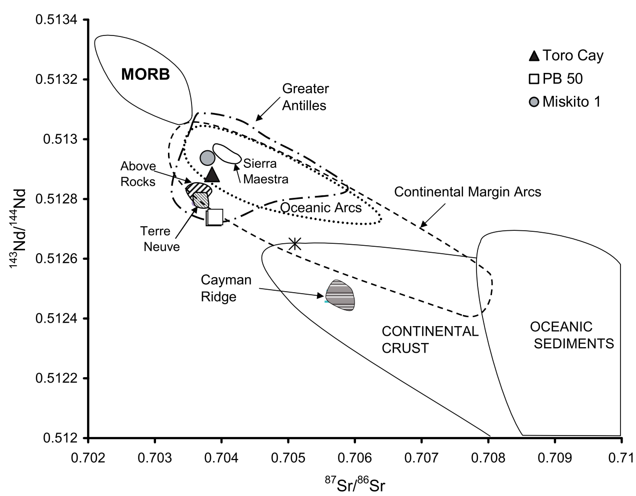

FIGURE 8 | **Measured Sr-Nd isotopic ratios for the Nicaraguan Rise samples, with comparisons. Data source: Greater Antilles field drawn from GeoRoc database; data for Cayman Trough samples unpublished. Other reference fields from Jolly and others (2006) and from Wilson (1989). Star symbol represents Bulk Earth Composition.**

granitoids dredged from the northwestern Cayman Trench (Perfit and Heezen, 1978; Lewis et al., 2005; Kysar Mattietti et al., 2009) plot well within the continental crust field consistent with their Pb isotopic composition (Figs. 6 and 7) and their origin in relation to the Chortis block as discussed above.

DISCUSSION

The Pedro Banks sample PB50 comes from the shallow bank on the median axis of the upper Nicaraguan Rise, some 90km southwest of Jamaica (Fig. 1A). The seismic and geological information clearly indicate that the Pedro Banks are the southwestern extension of the Jamaican crustal structure (Arden, 1975). The stratigraphy seen in the Pedro Banks drill core directly reflects that of Jamaica (Arden, 1975; Lewis and Draper, 1990). These are strong pieces of evidence supporting the hypothesis that the crustal rocks underlying Jamaica and the Pedro Banks are genetically related and had the same tectonic history (Arden, 1975).

The lithologies drilled at the Miskito-1 hole located north of the Pedro Fault zone on the main plateau of the upper Nicaraguan Rise are consistent with the presence, in this area, of a basement of island arc crust. The Toro Cay well is located at latitude 14° 20.2'N, about 10km off the Nicaraguan coast, immediately north of the eastward extension of the Pedro Fault zone. However, it is possible that this sample is located within the Siuna terrane, at least according to the boundary given on Fig. 1B, modified from Rogers et al., (2007). This is reasonable since this is an arc terrane and the granitoid rock is fine-grained porphyry of dioritic composition. The alternative is that the boundary between the Siuna and Eastern Chortis terrane as shown on Fig. 1B of Rogers et al. (2007) is too far to the north. If this second interpretation is correct, then this lithology represents island arc crust related to the Northern Nicaraguan Rise. The projection on Fig. 1B of the northern boundary to the Siuna terrane out into the Caribbean Sea over the Nicaraguan Rise also places the Moskito-1 drill core in the Siuna terrane. In our opinion the boundary between the Siuna terrane and the Northern Nicaraguan crust (Fig. 1A) should lie along the western Pedro Fracture zone, the eastern extension of which separates the Northern Nicaraguan Rise from the Southern Nicaraguan Rise (Fig. 1A). Based on a detailed biostratigraphic study of Radiolaria and studies of the geochemistry of mafic and ultramafic rocks in the area of Nicaragua and northern Costa Rica Baumgartner at al. (2008) identified the Mesquito Composite Oceanic Terrane, which includes the Siuna terrane, as a collage of Pacific terranes covered by Tertiary to Recent arc rocks. Both the Toro Cay and Miskito-1 well sites lie at the same latitude and the close similarity between the trace element and isotope geochemistry of the Toro Cay and Miskito-1 samples strongly supports the view that these were derived from the same magma reservoir and belong to the same terrane.

CONCLUSIONS

The three granitoid rocks of apparent Late Cretaceous-Paleocene age from the Northern Nicaraguan Rise analyzed for this study show the same overall chemistry in terms of both major and trace elements and fall into the category of the high K calc-alkaline type for Caribbean granitoid rocks. They closely resemble in composition the Above Rocks and Terre Neuve granitoids but are lower in Ta, Nb and LREE. Like the Above Rocks and Terre Neuve intrusions, which lie within the Gonave microplate (Fig. 1A; Mann et al., 1995), the Nicaraguan intrusive rocks studied here are also apparently of Late Cretaceous-Paleocene age, considerably younger than most of the low K intrusive activity in the Cordillera Central-Massif du Nord in Hispaniola (Lewis, 1982; Kesler et al., 1991; Escuder et al., 2006) and the intrusions in central Cuba (Hall et al., 2004). This suggests that the eastern boundary to the Gonave microplate in central Hispaniola is a reactivated tectonic boundary initially formed in the Late Cretaceous that defined a distinct terrane at that time.

The Pb isotopic compositions of the three Nicaraguan granitoid rocks plot in the same general field as other plutonic rocks from the western Caribbean, suggesting that the mantle reservoir and source for the Pb components is the same. Consistent with a common depleted mantle source, the Nicaraguan Rise, Above Rocks and Terre Neuve rocks plot along the NHRL line and fall within the MORB field on Pb isotope plots.

There is no evidence from the Pb isotope data that there has been any significant contamination from the Atlantic sediments. Nor is there evidence of a Pb component in the granitoid rocks derived through contamination from Paleozoic or Precambrian crustal rocks in the Chortis block. Even at Toro Cay only 10km from the present Nicaraguan coast there is no evidence from the chemistry of the granitoid rock sampled that Paleozoic-Precambrian crust underlies the Cenozoic-Cretaceous sedimentary platform in this area. To date, no granitoid intrusive rocks nor other ”basement rocks” have been sampled and analyzed from the main area immediately offshore north of Honduras or from the Honduran borderland, both areas which are likely to be underlain by crustal rocks of the Chortis block.

We postulate that the Southern Nicaraguan Rise represents oceanic crust that was subducting below the Northern Nicaraguan Rise and was the cause of the Late Cretaceous magmatism along the Nicaraguan Rise. This subduction continued until the thick plateau crust collided with the lighter island arc crust of the Northern Nicaraguan Rise. This agrees with the conclusion of Pindell and Kennan (in press) that no more subduction was occurring by the end of the Eocene. The structure must be more complex along the Honduran borderland with the Cayman Trough, since granitoid rocks dredged from the northern wall of the Cayman Trough do show evidence of a Chortís block continental component.

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