TRansformation of Oceanic Plateaus Into ContinentS (TROPICS): Collaborative multidisciplinary international research and education program

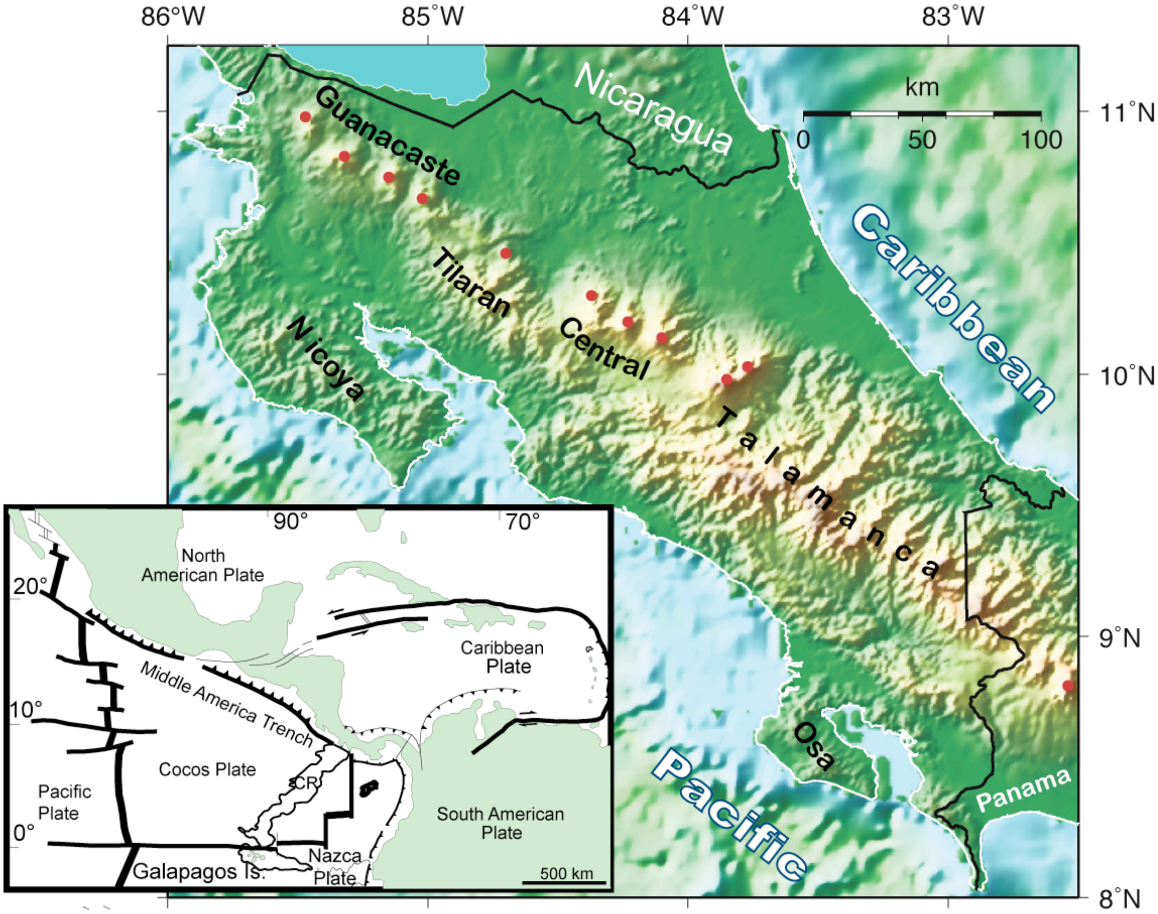


Figure 1. A map of Costa Rica topography showing names of main mountain ranges and largest peninsulas, and active volcanoes (red dots). The inset describes present-day tectonic setting of Central America. CR- Cocos Ridge.

SUMMARY BUDGET (7 institutions, 12 PIs, ~48K/year per PI)

Institution	Year 1	Year 2	Year 3	Year 4	Year 5	TOTAL
Rutgers	188885	287585	267935	183287	164558	1092250
Columbia	69557	118107	122230	126527	132547	568971
Cal Poly Pomona	51716	50249	52577	52714	53658	260914
CSU Stanislaus	36855	35899	36458	37034	37627	183873
Colorado	17412	74857	78715	72131	46782	289897
Michigan State	86760	87913	64442	23851	23963	286929
MIT	55346	59274	60205			174825
TOTAL						2857659

I. Overview of the Proposed Project

When compared to the other terrestrial planets, Earth's continents, large areas of thick silica-rich ("granitic") crust, are unique. Understanding the mechanical (accretion) and chemical (differentiation) processes of continent formation, and whether there has been secular change are fundamental problems of the earth science.

Any model for the formation and evolution of continents should explain their distinctive lithospheric structure and chemical composition. Ultimately, continental crust is derived from processing rocks formed by melting the upper mantle, although unlike the mid-ocean ridge environment, multiple stages of differentiation may be required. At present, some new continental crust may be created at the edges of existing continents, e.g. in the Andes. This process is, however, dependent on the prior existence of continental crust, and presents a classical chicken-and-egg problem for the origin of the continents. An alternative is to produce new continental crust through subduction-related magmatism. However, the bulk crustal composition inferred for most intra-oceanic arcs is basaltic and does not match either the geophysical structure or the composition of continental crust. To solve this conundrum, a two-step procedure is often envisaged, whereby thickened arc crust is melted and more silicic rocks are concentrated in the upper crust while the lower mafic crust with cumulates is removed via some mechanical process such as delamination.

Additional processes are necessary to account for the great thickness of the lithosphere beneath continents. These lithospheric mantle "roots" are 200-250 km thick under some cratons, the oldest (Archean) regions of the continents. While this root is believed to record protracted melt extraction, the volume of extracted melt is much larger then the volume of existing continental crust. Present-day melting at ridges and arcs produces smaller volumes of less depleted, residual mantle peridotite. Some authors have envisioned formation of cratonic mantle roots via collision and imbrication when arcs and other oceanic tectonic elements are accreted during plate convergence. This "underthrusting" scenario differs from regular subduction in that a part of the lithosphere of the downgoing plate do not sink into the mantle, but become attached to the overriding plate.

A number of lines of evidence suggest that oceanic plateaus, areas of voluminous submarine volcanism, may play a significant role in the formation of new continental crust. From a chemical standpoint, the trace-element budget of the bulk continental crust differs from that of subduction zone products, and can be matched by mixing them with a small but significant proportion rocks from oceanic plateaus. From the physical standpoint, some plateaus are "unsubductable" due to their combination of thick crust and buoyant residual mantle. Some present-day stable continental regions (e.g. the Arabian shield) are thought to represent agglomerations of oceanic plateaus. Edges of oceanic plateaus are a very likely locus for new subduction zone formation, suggesting that new arcs nucleate there. Finally, oceanic plateaus may have been more common during the Archean, as slightly hotter mantle temperatures would have been associated with a higher degrees of partial melting and higher magmatic productivity at ridges.

Southern Central America - and especially Costa Rica - is a region of thick crust of oceanic origin that is undergoing both subduction and underthrusting and that is also developing features characteristic of continents, including the emplacement of arc magmas that are unusually similar in composition to continental crust. The simultaneous presences of these three attributes, as well as the absence of material derived from established continents, make Costa Rica an ideal place to study the processes form continental crust and upper mantle. In particular, Costa Rica is an ideal place to constrain the role of oceanic plateaus in the origin of continental lithosphere.

The original crust of the Caribbean region is oceanic in origin and thicker (10-35 km) on average than the global average (6-8 km). Much of the crust is part of the Caribbean Large Igneous Province (CLIP), an oceanic plateau that formed in the mid-Cretaceous (~100 Ma). Plate tectonic reconstructions indicate that the CLIP was originally formed to the west of its present position and then migrated eastward as the Antilles subduction zone, which bounds the CLIP on the east, has moved into the Atlantic due to the slab roll-back. The Central American subduction zone, which bounds the CLIP on the west, began about ~75 Ma. We note, somewhat incidentally, that standard subduction is presently taking place only in the northern half of Costa Rica. In the southern half, no arc volcanism or intermediate depth earthquakes occur at present, although knowledge of recent volcanic history is sparse. No slab seems to be present, likely due to change in the plate tectonic configuration ~10 Ma. As we will discuss below, this north/south, subduction/no-subduction dichotomy will allow for informative comparisons between the two regions.

Originally, Central America was mainly submarine, like the bulk of the CLIP underlying the Caribbean Sea. It was exhumed to its present-day position during the past ~50 Ma. At least some of the landmass appears to be underlain by CLIP, as indicated by its outcrops on the Pacific coast west of the volcanic arc, and the CLIP isotopic signature found in modern-day volcanic rocks. Other parts of the landmass may have been built up of oceanic islands accreted to the western edge of the CLIP since the onset of subduction. The presence (or absence) of such accreted oceanic terrains pose no problem in the context of this proposal, for they too represent thick crust of oceanic origin. Of critical importance is the indication, from plate tectonic reconstructions, that the South American continent played no role in the development of Central America (despite its geographical proximity).

The Cocos Ridge offshore of southern Costa Rica represents a thickened trace of the Galapagos Hotspot, which may be thrusting beneath the CLIP at the southern terminus of the Middle America Trench. As discussed earlier, such events may be an important element of the continent-building process, because they provide a mechanism for thickening the mantle root.

The crust beneath Costa Rica has a number of geochemical and geophysical traits that are characteristic of continental crust. Like continents, the region is high standing and, compared to the oceans, the crust is unusually thick (> 30 km). As on continents, intrusive and extrusive silicic rocks are common, with the extrusives being associated with explosive volcanism similar to the Cascades and Andes. Furthermore, as in continental crust, many of the igneous rocks contain abundant Na_2O, K_2O, and light rare earth elements.

Processes that lead to silica enrichment and thickening of the continental crust, as well as development of a buoyant mantle root, all serve to lower the lithospheric density, and thus can be expected to produce an isostatic response. The subaerial character of Costa Rica is, of course, broadly consistent with such a response. Furthermore, geological evidence for recent – and extensive - uplift abounds in both northern and southern Costa Rica. Because of the absence of present-day arc volcanism in the south, and hence the absence of obscuring extrusive volcanic cover, uplift there is particularly evident, with Miocene marine sedimentary rocks now found at elevations of 3-4 km.

The processes operating to make Costa Rica more continent-like appear to have started in the relatively recent past, and appear to be continuing to the present-day. Igneous rocks older than about 30 Ma have unremarkable chemistries typical of oceanic basalts and intra-oceanic arcs. In contrast, younger (<10 ma) rocks are significantly enriched in Si, alkalis and light rare earth elements. The age and abruptness of the transition is not yet well established, but it represents a profound evolution in the character of the magmatic processes towards a continental state.

But what happened? Did the process start at 75 Ma, with the onset of Central American subduction? If so, why did more then 45 million years pass before the eruption of plutonic rocks with continental geochemical characteristics? Or was a triggering event, such as the underthrusting of the Cocos Ridge or the development of a slab window, a critical part of the process? And just how far along is this putative continent-forming process? Has the entire region been altered towards the continental "state", or just a few localities? We know enough now to be convinced that Costa Rica is telling us something extremely relevant to the continent-formation story, but not yet enough to understand exactly what. This proposal aims to supply the critical constraints required to make Costa Rica's continent-formation story clear.

II. Questions that we will address:

Question 1: What processes are responsible for creating and maintaining the topographically high-standing character of Costa Rica?

Hypothesis 1.1: Low crustal density associated with a silicic "continental crust" composition is responsible for creating Costa Rica's abnormally high topography.

Hypothesis 1.2: Low mantle density associated with an anomalously hot mantle is responsible for creating Costa Rica's topography.

Hypothesis 1.3: Low lithospheric mantle density associated with underthrusting of a buoyant depleted mantle residue is responsible for creating Costa Rica's topography.

Hypothesis 1.4: Low lithospheric mantle density associated with mechanical thickening of a basaltic crust is responsible for creating Costa Rica's topography.

Discussion. The high elevation of Costa Rica is a significant continent-like feature that distinguishes it from other regions with oceanic plateau-derived crust (e.g. Ontong Java, Kerguelen), and from oceanic arcs (e.g. western Aleutians, Izu Bonin), all of which are largely submarine. The high topography probably reflects isostatically compensated low-density material, but the character and depth extent of the low densities are not yet well understood. Is high topography a *consequence* of the continent-producing processes or is it associated with conditions (e.g. thickened crust or hot mantle) that were the necessary *antecedents* of the process.

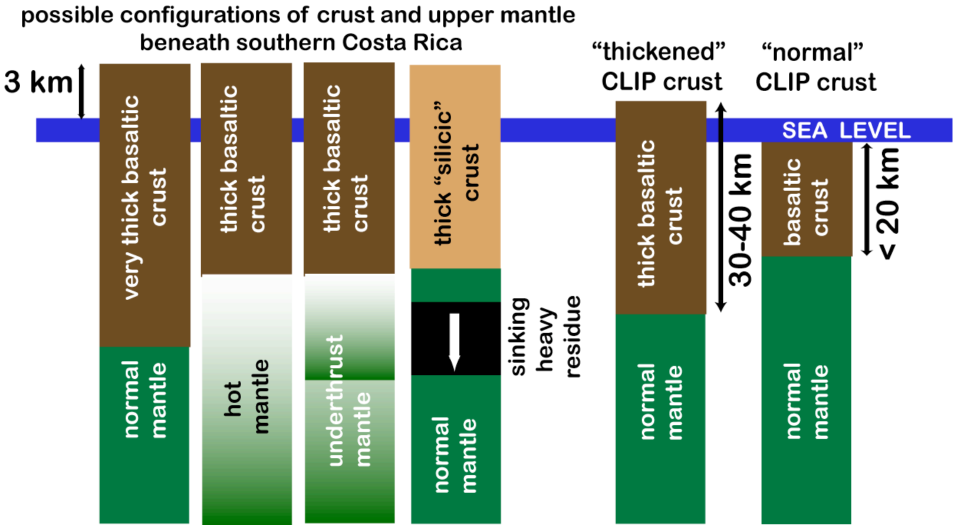


Figure 2. What keeps Costa Rica above water?

Question 2: Which processes in Costa Rica are essential for producing arc magmatic rocks similar in composition to continental crust?

Hypothesis 2.1: High-pressure crystal fractionation (or partial melting) in the lower part of a thickened crust is crucial for producing the silicic high-K magmas.

Hypothesis 2.2: Significant input of slab-derived melt is crucial for producing the silicic high-K magmas.

Hypothesis 2.3: Underthrusting and melting of the forearc material is crucial for producing the silicic high-K magmas.

Hypothesis 2.4: Interaction of the lower crust with an anomalously hot upper mantle is crucial for producing the high-K silicic magmas.

Discussion: Strongly calc-alkaline, andesitic to dacitic magmatic rocks are arguably the most profoundly "continental" aspect of Costa Rica, setting it apart from intra-oceanic arcs like Izu Bonin. The key issue here is to understand their origin, both in terms of geography and depth of generation, and in terms of the materials that are involved in their production.

Question 3: Are the processes that are giving Costa Rica a “continental” character evolving? What is the evolutionary sequence?

Hypothesis 3.1: The process began in the last 10 Ma due to a triggering event (and may be accelerating).

Hypothesis 3.2: The process has been occurring (possibly sporadically) since the onset of Central American subduction at 75 Ma.

Discussion: While Costa Rica definitely has continent-like characteristics, its relevance to understanding Archean crustal growth is speculative. A critical issue is the rate at which the process is occurring. Although many Archean cratons record histories of more than a billion years, smaller domains were constructed on much shorter time scales (10’s to 100’s of Ma). Thus, the ~75 Ma history of Costa Rica, will provide us a potential “snap shot” of crust forming processes.

Question 4: Is any part of Costa Rica *not* continental?

Hypothesis 4.1: All of Costa Rica has been made “continent-like”.

Hypothesis 4.2: Some parts of Costa Rica (e.g. the northern Caribbean coast) are underlain by thick basaltic crust (e.g. original CLIP-related crust) and has been less affected by arc magmatism in general and specifically by the continent-making process.

Discussion. The abrupt juxtaposition of two major lithospheric domains (the “original” plateau and the “transformed” continent-like area) in Costa Rica will allow us to compare and contrast their evolutions. This will allow us to understand the cause(s) of buoyancy and to evaluate whether it is related to differentiated upper crust.

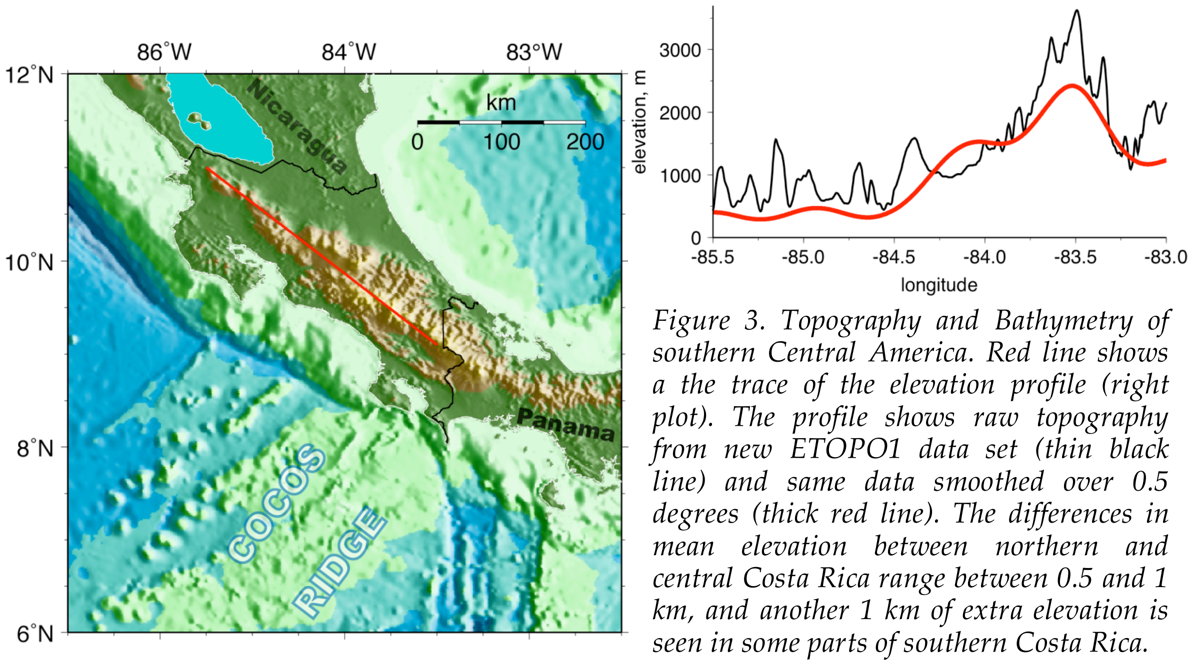


Figure 3. Topography and Bathymetry of southern Central America. Red line shows a the trace of the elevation profile (right plot). The profile shows raw topography from new ETOPO1 data set (thin black line) and same data smoothed over 0.5 degrees (thick red line). The differences in mean elevation between northern and central Costa Rica range between 0.5 and 1 km, and another 1 km of extra elevation is seen in some parts of southern Costa Rica.

1. BACKGROUND I: COSTA RICA TECTONIC HISTORY.

1.1 Modern tectonic setting of Costa Rica. Costa Rica today is a narrow landmass with a convergent margin on the western side, and a largely passive margin on the eastern side. Subduction of the Cocos plate takes place beneath the northern and central parts of the country, with a corresponding line of volcanoes extending halfway along the country's length. Intermediate-depth (foci below 50 km) earthquakes are seen beneath the volcanic chain, but are not observed beneath the southern part of the country. Elevations away from volcanoes are relatively low in the north, and progressively higher to the south, where the Talamanca Mountains comprise a high elevation (nearly 4 km) range extending into Panama. There are few if any currently active volcanoes in the Talamanca Mountains, though reconnaissance geochronological data on lavas and plutonic rocks reveal extensive magmatism there during the past five million years. A region of elevated seafloor called the Cocos Ridge extends from the Galapagos Islands to the Middle America Trench, where it may be underthrusting southern Costa Rica. However, there are no present-day manifestations of subduction (active volcanoes, deep earthquakes) east of the location where the Cocos Ridge impacts the coast.

The area of elevated seafloor approximately corresponds to the extent of the Talamanca Mountains inland. Offshore of eastern Costa Rica a zone of complex deformation extends approximately halfway along the coastline coincident with the Talamanca Mountains. In addition to the active volcanic arc, Costa Rica has experienced recent back-arc volcanism where compositionally unusual lavas contain mantle xenoliths.

1.2 Plate tectonic reconstruction indicates an oceanic plateau origin.
Mid-Cretaceous initiation of South Atlantic opening aligned South America plate motion with the slow westward trajectory of the North America plate (Ladd, 1976; Klitgord and Schouten, 1986; Mueller et al., 1993; Mann et al., 2006, Pindell et al., 2006). This caused the end of Middle Jurassic to Aptian spreading between the Americas that first opened the proto-Caribbean seaway (Pindell and Dewey, 1982; Duncan and Hargraves, 1984; Burke, 1988; Pindell et al., 1988; Pindell and Barrett, 1990; Meschede and Frisch, 1998; Pindell and Kennan, 2001). East dipping subduction of Farallon oceanic lithosphere occurred along the western margins of the Americas and the primitive island arc spanning the Americas (Figure 5) (Draper, 1986; Pindell et al, 1988; Lewis and Draper, 1990; Pindell et al, 2005; 2006; Kesler et al., 2005). During or shortly after the end of proto-Caribbean spreading, Cretaceous flood basalts thickened part of the Farallon plate west of the primitive island arc forming what is now the "Caribbean plateau" (Sinton et al., 1997; Kerr et al., 1998; Hauff et al, 2000; Hoernle et al., 2004). Incipient subduction of this oceanic plateau at the Farallon – proto-Caribbean arc margin choked the trench and ended east-dipping subduction (Figure 5) (Pindell et al., 1988; Kerr et al., 2003). This initiated west-dipping subduction of the proto-Caribbean oceanic lithosphere under the Caribbean Plateau until the proto-Caribbean lithosphere was consumed. This subduction continues in modified form to this day along the Lesser Antilles Island Arc (Pindell and Barrett, 1990).

With the Caribbean Plateau wider than the entrance between the Americas, resistance along its edges slowed the plateau relative to the normal Farallon oceanic lithosphere to the west (Kerr and Tarney, 2005; Pindell et al., 2006). Normal Farallon lithosphere began subducting eastward beneath the Carribean Plateau by the late Cretaceous (Dengo et al., 1985; Pindell and Barrett, 1990). It is along this western margin of the Caribbean Plateau in Costa Rica that an island arc developed (Sinton et al., 1997; Dengo, 1985; Duncan and Hargraves, 1984).

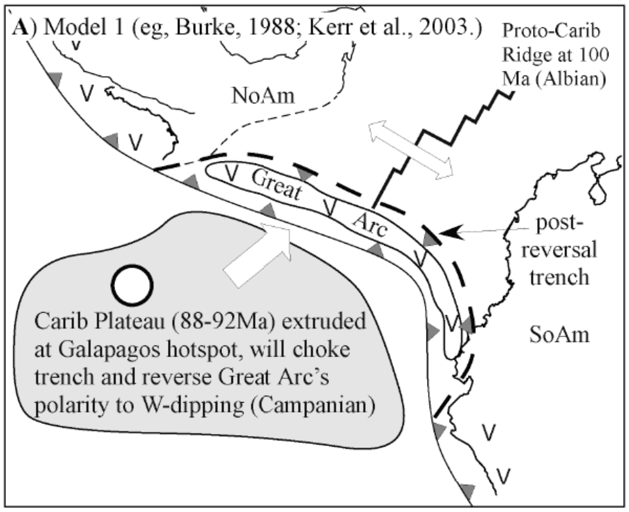


Figure 4. Possible evolution of the Caribbean, from Pindell et al. (2006)

Farallon subduction beneath the Costa Rican Arc resulted in late Cretaceous age subduction-related magmatism as recorded in the sedimentary record since the Albian in the Loma Chumico Formation (Calvo & Bolz, 1994). The oldest in situ remnants of arc activity are represented by the Sarapiqui Arc (22.2-11.4 Ma, Gazel et al., 2005), located behind the modern volcanic front of central Costa Rica, and the Talamanca Range (17.5-10.5, DeBoer et al, 1995, MacMillan et al., 2004). OIB terranes with Galapagos affinity were accreted between 70 and 17 My along the Pacific Margin of Costa Rica and Panama as buoyant incoming seamounts and ridges originating at the Galapagos hot spot arrived at the trench (Werner et al., 1999; Hoernle et al., 2002).

1.3 Upper mantle xenoliths in Costa Rica – pieces of a mantle plume head?.

Ultramafic xenoliths are rare in active volcanic arcs; even more exceptional are samples of the mantle section of an oceanic plateau within an arc system. However, mantle xenoliths were discovered in alkaline basalts in ~1 Ma old lavas at Cerro Mercedes (Vargas and Alfaro, 1992), about 70 km in the back-arc of the volcanic front and the western edge of the Caribbean plateau. More recently, Esteban Gazel (PhD candidate at Rutgers University), discovered mantle xenoliths in 5 other back-arc alkaline volcanoes of Costa Rica. We have reasons to believe these xenoliths are pieces of the mantle lithosphere from the Caribbean Large Igneous Province (CLIP), fossil mantle plume fragments. All mantle peridotite xenoliths are found in alkali basalts within the back-arc. Geochemically, most of the back arc magmas do not show a typical arc signature and HFSE (eg. Ti, Zr, Nb) depletions are rare (Carr et al., 2003), which suggest low input of the subduction component. Preliminary petrological work on peridotite whole rocks indicates that they might be fragments of the lithospheric mantle from the westernmost Caribbean plateau. The most fertile of these have FeO that is lower and Al_2O_3 that is higher than residues expected of ambient mantle having a potential temperature of about 1350ºC (Herzberg, 2004; Herzberg et al., 2007). The data are more consistent with residues of melt extraction below a hotter oceanic plateau. However, there is considerable variability. For example, MgO, FeO, and Al_2O_3 whole rock variations point to 10-25% melting as inferred from diagrams in Herzberg (2004), mantle potential temperatures in the 1450-1550ºC range as inferred from complementary primary magma compositions (Herzberg et al., 2007), and observed olivine Mg numbers generally range from 90.0 to 91.7. Many xenoliths of cratonic mantle have similar FeO contents, but MgO is higher and olivines have Mg numbers in the 92-94 range. Inferred mantle potential temperatures for xenoliths from Archean cratons and Costa Rican xenoliths are similar, but the higher MgO and more forsteritic olivine in cratonic mantle can be explained by higher extents of melting. Bernstein et al. (1997) and Herzberg (2004) have estimated 30-40% melting for cratonic mantle, and Herzberg (2004) suggested melting might have been more extensive in the Archean owing to thinner lithosphere and decompression to lower pressures. These preliminary petrological findings support a hot residue origin for the Costa Rican xenoliths, consistent with the Duncan and Hargraves (1984) model that the CLIP was produced by melting of a mantle plume.

2. BACKGROUND II: THE ORIGIN OF CONTINENTAL CRUST.

2.1 Chemical composition of the continental crust and models for its origin. Earth's continental crust has a bulk composition of andesite to dacite (Taylor, 1967, Rudnick, 1995; Rudnick and Gao, 2003), while the process of melting the upper mantle peridotite in "normal" conditions (i.e. under a mid-ocean ridge) yields basalt (Kelemen, 1995), a melt with much less silica. The crust formed at ridges is also relatively thin, exceeding 10 km only under special circumstances, while the crust of stable continents is ~ 40 km thick on average. Where vigorous melting at a mid-ocean ridge or a hot-spot does produce thick crust, as beneath Iceland or Hawaii, the bulk composition inferred from seismic observations remains basaltic (Staples et al., 1997; Menke et al., 1998; ten Brink and Brocher, 1987; Lindwall, 1988). Thus understanding the origin of continents requires a scenario that begins with melting of mantle peridotite but yields an appropriate thickness and composition for continental crust. The bulk of continental crust may have formed in the Archean (Patchett and Arndt, 1986; Taylor and McLennan, 1995; Hawkesworth and Kemp, 2006), so that a fundamental question is whether new (*aka* juvenile) continental crust is ever formed under present conditions.

A natural candidate for the formation of new continental crust is an intra-oceanic subduction zone, with both subducting and overriding plates having basaltic crust, but the resulting crust beneath the arc containing a significant fraction of andesitic material. However, seismic studies of many island arcs suggest that they have basaltic crust (e.g., Holbrook et al., 1999; Fliedner and Klemperer, 2000; Shillington et al., 2004) although recently examples of both fossil (Talkeetna: Behn and Kelemen, 2006) and active (Izu-Bonin-Marianas: Suyehiro et al., 1996; Kodaira et al. 2007) arcs with continent-like seismic structure have been found. An additional challenge writing a present day recipe for continental crust resides in the composition of arc andesites. For a given amount of silica most oceanic arc lavas have Mg# (molar Mg/(Mg+Fe)) lower than bulk continental crust, and oceanic arc lavas generally have lower abundances of key trace elements such as Th and light rare earth elements (e.g. Kelemen et al., 2003a).

Kelemen et al. (2003c) discussed one scenario that can solve the Mg deficit problem, including melting of subducting sediment and basaltic crust, not just upper mantle, in a subduction-zone environment. The presence of a ubiquitous component formed by partial melting of subducting sediment and/or basalt in arc magmas worldwide (e.g, Plank & Langmuir, 1993; Elliott et al., 1997; Class et al., 2000) is now widely accepted, and modern thermal models indicate that temperatures above the aqueous fluid saturated solidus are common along the top of most subducting plates worldwide, including beneath Central America (e.g., van Keken et al., 2002; Kelemen et al., 2003b; Conder, 2004; Peacock et al., 2005). However, only in the western Aleutian arc – and perhaps at the southeast end of the Costa Rican arc – is it clear that isotopically juvenile lavas with "continental" trace element compositions are commonly produced at present (Kelemen et al., 2003a,c), whereas other intra-oceanic arcs produce mainly basaltic lavas with major and trace elements very distinct from continental crust. In this regard, even the Izu-Bonin-Marianas arc falls short: andesitic magmas have major and trace element characteristics very different from the composition of continental crust.

Any recipe for making continental crust in intra-oceanic arcs has to contend with the problem of "dense residues" that form when more buoyant magmas (such as andesites) are produced by crystal fractionation from primitive melts of upper mantle peridotite. Such dense residues do not form significant proportions of the continental crust. Specifically, compressional wave speeds, Vp, predicted for the magnesium- and iron-rich rocks of the residue are high (about 7.5 km/s at lower-crustal depths, Behn and Kelemen, 2006), while typical lower continental crust has Vp < 7 km/s (Christensen and Mooney, 1995). A preferred solution to this problem is to remove the lower part of the island arc crust via some mechanical process driven by the density contrast between the dense residues of andesite differentiation and less dense upper mantle peridotite (Herzberg et al., 1983; Kay and Kay, 1988; Arndt and Goldstein, 1989; Jull and Kelemen 2001). Ducea and Saleeby (1996), Lee et al. (2000), and Kelemen et al. (2003a) discuss observational evidence for this having taken place in the past. Behn and Kelemen (2006) estimate the likely seismic properties of arc lower crust that is denser than underlying mantle for comparison with observed seismic profiles of modern arcs. They conclude that most arcs do not include much dense crust, and suggest that such material has already foundered into the underlying mantle, or else is “hidden” beneath the crust-mantle transition since its high seismic velocities approach those of mantle peridotite. Davidson and Arculus (2005) and Takahashi et al. (2006) also favor the notion that dense by-products of andesitic crust production in arcs are simply not recognized as such since their geophysical properties are close to those of the mantle.

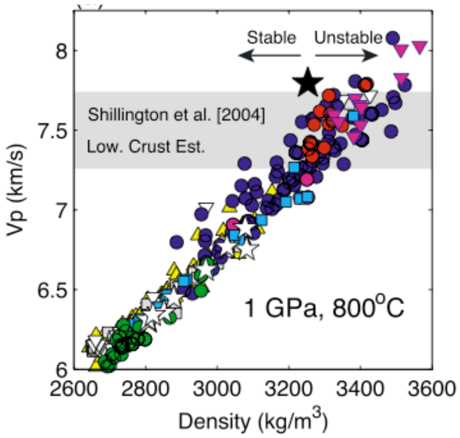


Figure 5. A relationship between the compressional wave speed, Vp, and density of typical lower crustal arc rocks (Behn and Kelemen, 2006). A grey zone shows a range of Vp in the central Aleutian Arc. In Costa Rica all estimates of crustal Vp are lower than 7.5 km/s.

2.2 Oceanic plateaus and their role in the formation of continents

Oceanic plateaus are areas of massive submarine volcanism that stand above the surrounding seafloor (Coffin and Endholm, 1994), and that have crust which may be 3 or more times thicker than the average 7 km of the oceanic crust (Kerr, 2003). Seismic properties of oceanic plateau crust are similar to those of oceanic crust, but often with a prominent lowermost layer of faster wave speed likely representing more dense magnesium- and iron-rich rocks (Walther, 2003). Plateaus are believed to result from initiation of mantle plumes within oceanic lithosphere, and, along with areas of subaerial basaltic flood volcanism, they are termed Large Igneous Provinces (LIPs).

A number of lines of evidence link oceanic plateaus to formation of continents. First, plateaus represent abrupt mechanical discontinuities in oceanic plates. They are heated, and hence elevated, upon formation, and then slowly subside, remaining much shallower than the oceanic lithosphere on which they are built (Ito and Clift, 1998). Thus plateau edges represent compositional buoyancy contrasts that are likely to serve as the locus of new subduction zones (Stein and Goldstein, 1996; Niu et al., 2003). Furthermore, as plateau crust becomes thicker due to higher degrees of melting and/or fast mantle upwelling, the respective volume of depleted (and thus buoyant) mantle rock beneath oceanic plateaus grows as well. Abbott et al. (1998) suggest that at a critical thickness of about 25 km, oceanic plateaus become "unsubductable", and thus *must* become a part of a future continent. However, only one present-day plateau (the Ontong-Java) is known to have crust in excess of 25 km thick (Gladczenko et al., 1997; Miura et al., 2004; Walther, 2003).

Budgets of some trace elements in the bulk continental crust are different from those found in intra-oceanic volcanic arcs. Rudnick (1995), as updated by Plank & Langmuir, (1998) Barth et al. (2000), and Rudnick & Gao (2003) suggested that 5 to 20% of the bulk continental crust could have originated through "intraplate volcanism". The intraplate input could have occurred via incorporation of oceanic plateaus. And indeed, a number of examples of former oceanic plateaus within stable continental crust are described in the literature, including the classic example of the entire Arabian plate, the smallest and youngest craton on the planet (e.g., Stein and Goldstein, 1996). On a smaller scale, the

Wrangellia terrane of western North America is recognized as a former plateau (e.g., Ben-Avraham et al., 1981).

2.3 Modern oceanic plateaus - analogs of the continental origin in the Archean?.

There are a number of observational parallels between continent construction in Costa Rica and in cratons of Archean age. In both cases, mantle xenoliths studies imply that a granitic crust is underlain by lithospheric peridotite of unusually depleted composition. Archean "granitic" rocks, which are actually tonalite-trondhjemite-granodiorite (TTG), and the depleted peridotites below the Moho are not complementary melts and residues, but have different origins.

Samples of the cratonic lithospheric mantle consist of highly depleted peridotite, and are understood to be residues that were subsequently modified by subduction zone magmas/fluids (Bernstein et al., 1998; Boyd, 1989; Griffin et al., 1989; Herzberg, 1993; 2004; Kelemen et al., 1992; 1998; Kopylova & Russell, 2000; Rudnick et al., 1993). Being cold but compositionally buoyant (Boyd and McAllister, 1976; Kelly et al., 2003; Lee, 2003), these rocks have behaved as buoyant unsubductable rafts isolated from the convecting mantle (Jordan, 1978; Pollack, 1986).

It has been estimated that cratonic mantle was initially formed as residues after 30 – 40% partial melting (Bernstein et al., 1997; Herzberg, 2004). Such extensive melting must have produced a very thick oceanic crust of broadly picritic composition (i.e., ~ 20% MgO; Herzberg, 2004; see Figure 6a). Given 30-40% melting to produce cratonic mantle, there should have been about $2.9\text{-}4.4 \times 10^9$ km^3 of "basalt", based on area dimensions of all cratons given in de Wit and Ashwall (1997) together with roots that extend from a 40 km Moho to the bottom of the ~ 250 km lithospheric keel. However, exposures of Archean granite-greenstone terrains reveal the predominance of TTG granitic rocks over basalts. Globally, there is ~ 3.8×10^7 km^3 of "greenstone" as metamorphosed basalts, picrites, and komatiites of diverse origins (de Wit and Ashwall, 1997; Condie, 1981; Thurston and Chivers, 1990; Polat and Kerrich, 2001). This is about 100 times less than the $2.9\text{-}4.4 \times 10^9$ km^3 of "basalt" expected as complementary magmatic products of cratonic mantle peridotite. *Where is all the Archean basalt?* One way to get rid of it is by delamination at the bottom of a thickened crust (Herzberg et al., 1983; Kay and Kay, 1993; Rudnick, 1995; Behn and Kelemen, 2006; Percival and Pysklywec, 2007). Another is by melting to form TTG, which stayed in the crust (Foley et al., 2002; Kemp and Hawkesworth, 2003; Rollinson, 2007). However, a substantial mass fraction of residual garnet amphibolite or eclogite is expected in the formation of TTG (Rollinson, 2007), but is not observed in Archean granite-greenstone terrains, favoring a mechanical removal mechanism.

Peridotite xenoliths from the CLIP (Lindsay et al., 2006) have many similarities to those from the Ontong Java Plateau (Ishikawa et al., 2004), and both differ from cratonic mantle (see section 1.3). However, they are all similar in that they are residues of extensive melt extraction. Additionally, both CLIP and cratonic peridotite have been modified by interaction with subduction zone magmas/fluids. In both cases, the peridotite residues were complementary to thick basalt-picrite (basaltic) crust formed in a hot mantle environment. However, whereas most of the thick basaltic crust in the CLIP remains, in an altered state, almost all the original Archean basaltic crust has been replaced by ~ 40 km of "granitic" rocks as discussed above. Understanding silicic crust development in Costa Rica might be a way to time travel back into the Archean.

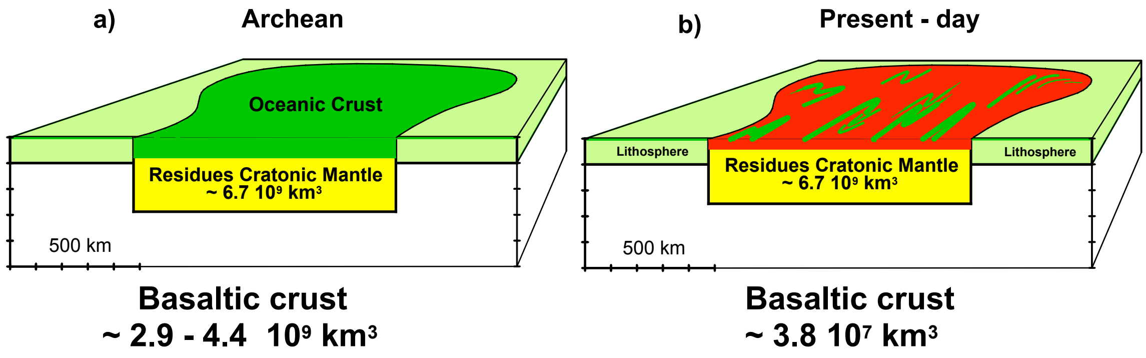


Figure 6. Cartoon illustrating the deficiency of basaltic rocks in present-day Archean cratons as inferred from the amount of cratonic mantle.

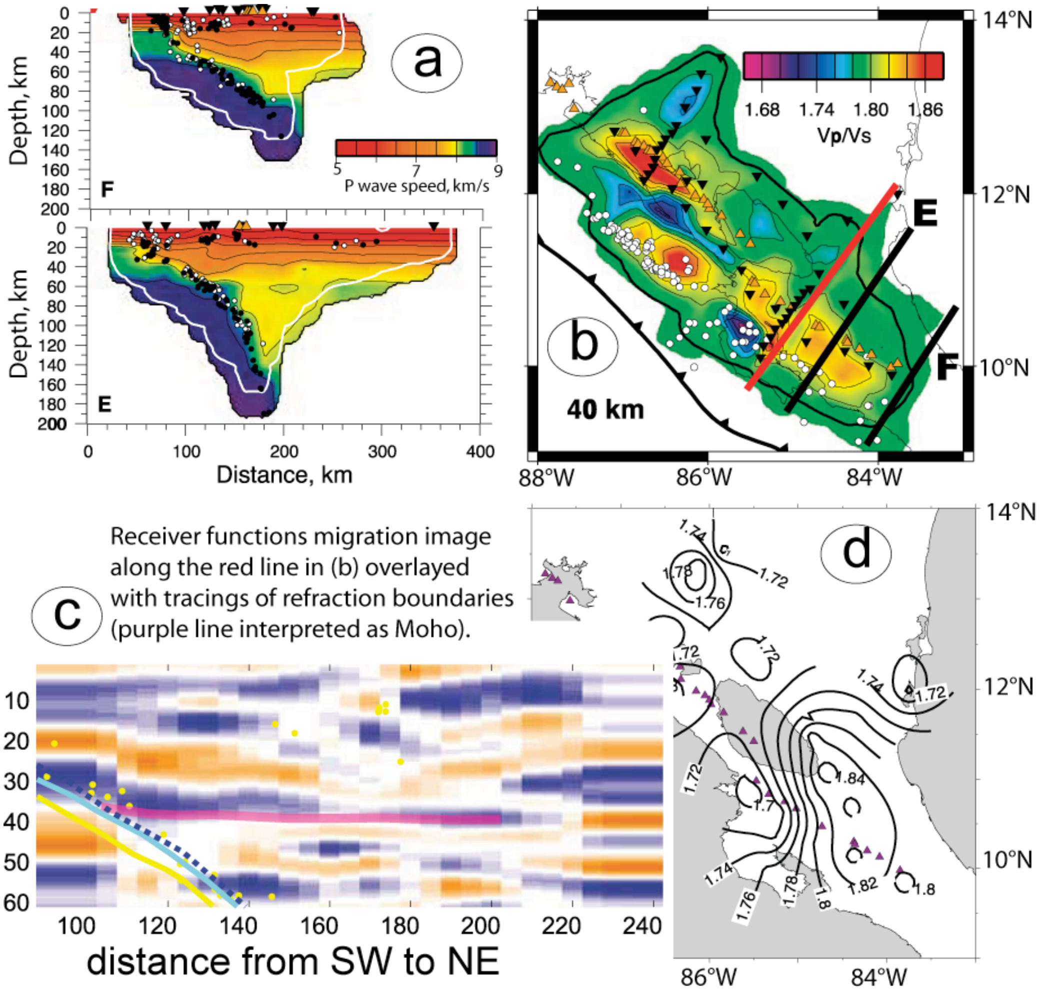
3. BACKGROUND III: CONTINENTAL(??) CRUST IN COSTA RICA

3.1 Seismic evidence for continent-like crust and upper mantle structure. Most seismic investigations of the crust and upper mantle in Costa Rica targeted the central and northern parts of the country near the Nicaragua border (Matumotu et al., 1977; Sallares et al., 2001; Holbrook et al., 2007; Salas-de-la-Cruz et al., 2007; MacKenzie et al., 2008; Syracuse et al., 2008). The low-lying regions along the Caribbean coast, possibly underlain by unmodified CLIP lithosphere, have received much less attention. Recent studies by a German group considerably improved the state of knowledge in the central part of the country (e.g., Dzierma, 2008; Dinc et al., 2008). The highland areas of southern Costa Rica are largely unstudied.

"Continent-like" compressional velocities were recently observed in central and northern Costa Rica (Holbrook et al., 2007; Lizzaralde et al., 2007). Tomographic inversion indicates that low Vp, less than 6.6, extends to mid-crustal depths of 15 km or more. This velocity is significantly lower than the 7.0-7.2 km/s values typically found in basaltic plateaus such as Icleand (Menke et al., 1998).

Sallares et al.'s (2001) observations of Moho reflections provide strong evidence for crustal thickness ~ 40 km, much thicker than in most oceanic arcs (e.g., Suyehiro et al. 1996; Holbrook et al., 1999; Fliedner & Klemperer, 2000; Shillington et al., 2004; Kodaira et al., 2007). Sallares's work, based on an active source profile across northern Costa Rica, is still the only documented Moho reflection in the region. Other important features of the profile are low (<7 km/s) lower-crustal Vp and low (< 8 km/s) mantle Vp. Crustal thickness and velocity are consistent with a "continental" structure, and the low mantle velocity is typical of those found in active volcanic arcs. A preliminary analysis ofa a less well documented, second profile, across southern Costa Rica, (Stavenhagen et al., 1998) notes a lack of reliable reflections from anything deeper than 17 km and does not constrain crustal thickness.

Crustal velocity structure in parts of Costa Rica has also been determined using travel times of regional earthquakes (Matumotu et al., 1977; Protti et al., 1995, 1996; Quintero and Kulhanek, 1999; Yao et al., 1999; Sallares et al., 2000; Quintero and Kissling, 2001; Husen et al., 2003; DeShon and Schwartz, 2004; DeShon et al., 2003, 2006; Syracuse et al., 2008; Dinc et al. 2008). The velocity structure varies from study to study, but mean Vp is generally <7 km/s in the upper 30 km, within the range of a typical "continental" velocity profile. All of these studies yielded crustal thickness estimates ranging from 30-40 km, and low (<8 km/s) Vp in the uppermost mantle.



Receiver functions migration image along the red line in (b) overlayed with tracings of refraction boundaries (purple line interpreted as Moho).

Figure 7. Results of the TUCAN project (Syracuse et al., 2008; MacKenzie et al., 2008), showing P wave velocity (a), Vp/Vs ratio (b and d) and an image of crustal and upper mantle structure (c). Refraction line tracings from Sallares et al. (2001).

Tomographic imaging efforts developed progressively more detailed maps of crustal Vp, with best resolution typically in the 10-30 km depth range (Protti et al. 1996; Yao et al. 1999; Sallares et al. 2000; Husen et al. 2003; Dinc et al. 2008). These studies do not define boundaries between regions underlain by "continental" and CLIP-related "oceanic plateau" material. Differences in techniques and data character make these studies hard to compare, and individual elements in them are hard to reconcile. Thus, for example, the Talamanca Mountains are underlain by a low-velocity crustal anomaly in one tomographic image (Protti et al., 1996), but a high-velocity feature in several others (Husen et al., 2003; Dinc et al., 2008).

A study of regional surface wave (Lg) attenuation (Ottemoller, 2002) found efficient propagation of this phase throughout Costa Rica, which suggests uniform crustal properties. Syracuse et al. (2008) map Vp and Vp/Vs ratio in the lowermost crust and the upper mantle. Their images contain intriguing hints of likely east-west differences across Costa Rica. However, their study (Figure 7ab) is largely focused on the Costa Rica-Nicaragua border region, so he central and southern parts of Costa Rica are not covered.

While the issue of the location and sharpness of regional boundaries within Costa Rica is unresolved to date, numerous studies have indicated that the structure of the

Caribbean plate to its east is quite different from that of Costa Rica, implying that a major structural boundary exists. Caribbean structure was first investigated by Ewing (e.g. Ewing et al., 1960), with the most recent work offshore of Venezuela (e.g., Guedez et al., 2006). Reported crustal thickness reaches 20 km, but are closer to ~15 km east of Costa Rica, with velocity values typical for oceanic crust. Thus the Costa Rican crust, at least in the better studied northwest, is nearly twice as thick as the rest of the CLIP.

Crustal shear wave velocity structure was studied using regional S waves (Sg) by Quintero and Kulhanek (1999). They did not report S wave speeds,, Vs, focusing instead on Vp/Vs, which is ~ 1.77. This is typical of Vp/Vs in oceanic plateaus, and different from Vp/Vs in the continents (Zandt and Ammon, 2002). Shear wave velocity structure has also been determined using receiver function methodology (MacKenzie et al., 2008, Linkimer et al., 2007). Available data cover central and northern Costa Rica. Results are broadly consistent with a thick (35-40 km) crust and a relatively high (~1.8 or higher) Vp/Vs ratio. Interestingly, the unambiguously oceanic Nicoya peninsula on the Pacific coast has Vp/Vs ratios lower than the interior (MacKenzie et al. 2008, see Figure 7), a pattern also confirmed by the tomographic inversion of Syracuse et al. (2008). Thus available Vp/Vs measurements are not consistent with a "continental" interpretation, but do not cover SE Costa Rica where magmatic arc rocks most closely resemble continental crust compositions. This is an important issue that needs to be addressed further as new data become available.

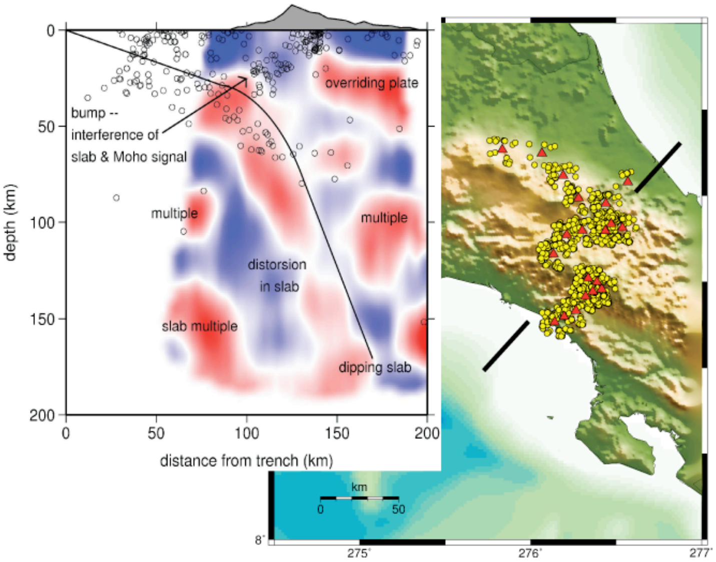


Figure 8. A smoothed image of the seismic structure beneath central Costa Rica obtained by migration of P-S converted waves. Colors show location of gradients in seismic velocity (red corresponds to a change from fast to slow going up). Open circles show seismicity. Dzierma (2008) interprets the red band dipping eastward as the Moho of the subducting Cocos plate. Stations (red triangles), piercing points at Moho (circles) and the trace of the vertical section (black lines) are shown on the map.

The mantle beneath Costa Rica has been explored primarily along the western coast, where local earthquakes offer a convenient source of energy. The most recent work (Syracuse et al., 2008, Dinc et al., 2008) shows Vp below 8 km/s in the region above the subducting Cocos plate. In an earlier effort, Quintero & Kulhanek (1999) used travel times of head waves (Pn, Sn) from local and regional earthquakes to show that the uppermost mantle beneath Costa Rica has Vp of 7.81 km/s and Vp/Vs=1.77, with no Pn velocity anisotropy being detected. Relatively low Pn velocities of ~7.8 km/s are often interpreted as indicating hot but sub-solidus conditions (e.g. Hearn et al. 1994). However, the low Vp/Vs ratio may not be consistent with near-solidus conditions (where one would expect Vp/Vs > 1.85), so that this issue needs to be further addressed.

Quintero & Kulhanek's (1999) isotropic mantle is unusual in a plate-boundary setting and is contradicted by a recent study of shear wave splitting (Hoernle et al., 2008). Their result suggests a complex vertical stratification of anisotropic properties, with a preference for trench-parallel fabric in northern Costa Rica and Nicaragua. Dzierma (2008), on the other hand, finds a trench-normal orientation in central Costa

Rica based on receiver functions. Her other finding, of a slab-like feature dipping to over 100 km depth beneath the northernmost Talamanca Mountains (Figure 8), differs significantly from previously published results (e.g., Husen et al., 2003) that did not find the slab south of the volcanic arc. Thus, different authors paint radically different pictures of the state of the mantle beneath Costa Rica, raising yet another issue that we plan to address with new and more comprehensive data, particularly for SE Costa Rica.

3.2 Continent-like Chemistry of the Costa Rica crust.

3.2.1Explosive Volcanism. Known ignimbrites in Costa Rica range from Early Miocene to Pleistocene and occur in three main areas in northern and central Costa Rica. Ignimbrite compositions range from basaltic andesite to rhyolite, but are dominated by rhyolite. The chemical variation of these ignimbrites is reviewed by Vogel and coworkers (Vogel *et al.*, 2004, Vogel *et al.*, 2006) and much of this chemical review is taken from these references. The silicic deposits in Costa Rica display the common large ion lithophile element (LILE) enrichment and high field strength element (HFSE) depletion observed in magmas generated by subduction processes, which are not characteristic of melts generated from oceanic plateaus (Fig. 9). Incompatible trace elements of ignimbrites are similar to the continental crust. They are slightly enriched in the most incompatible elements (Rb, Ba, Th and U) and depleted in P and Ti.

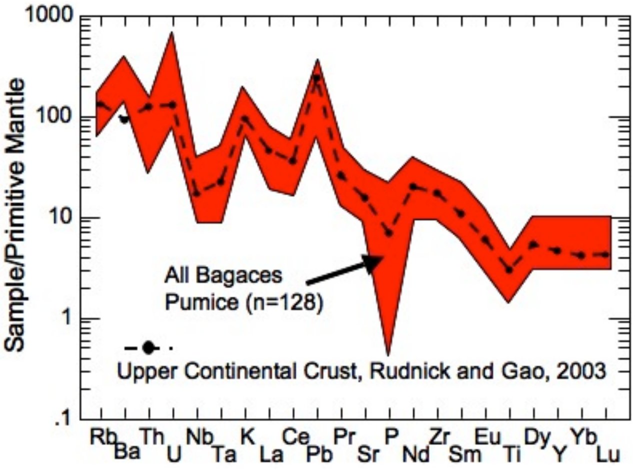


Figure 9. *Spider diagram of the composition of silicic magmas from Costa Rica. An estimated, average composition for the upper continental crust (Rudnick and Gao (2003) is shown with the dashed line, and reveals the similarity in the patterns, including characteristic subduction-zone depletions in HFSE (e.g. Nb, Ti).*

Along-arc chemical variations for the silicic deposits and mafic lavas are similar and this is particularly important for key trace element ratios such as Ba/La, Ce/Pb and U/Th, which have been used to infer contributions from the slab and mantle in arc-related magmas. Although these trace element ratios are similar, the silicic deposits are more enriched in incompatible trace elements than the mafic lavas. The silicic deposits are remarkably similar to continental crust (Figure 9).

The along-arc isotopic variations of Sr, Nd and oxygen are also similar in the silicic deposits and mafic lavas. From these data we conclude that the silicic magmas are genetically related to the basaltic magmas that were produced in the mantle wedge and that there has been little or no interaction with old, evolved continental crust (see also a later section on isotopes). The isotope data do not exclude assimilation of young, igneous rocks that crystallized deep in the crust, into yet younger, primitive arc magmas. However, the oxygen isotope compositions show no evidence for hydrothermal alteration, supporting the conclusion that assimilation of altered volcanic rocks or shallow intrusive rocks can be ruled out (these would be more subjected to hydrothermal alteration and then would be shifted in δ^{18}O).

Overall, isotopic and trace element ratios make a clear connection between mafic lavas and silicic deposits in northwestern Cost Rica. However, the silicic deposits are similar to the continental crust, whereas the mafic lavas in NW Costa Rica are more like island arc lavas, deficient, relative to continental crust, in the most highly incompatible elements.

3.2.2 Composition of lavas. There is an along arc geochemical trend from Nicaragua to Costa Rica to western Panama, with increasing SiO_2, Na_2O, K_2O, large ion lithophile elements (e.g Ba, Rb, Th and U) and light rare earth elements. Examples of this trend are shown in Figure 10a. This trend is distinct from the well known NW to SE decrease in subducted sediment tracers (e.g. Ba/La) extending from Nicaragua into NW Costa Rica.

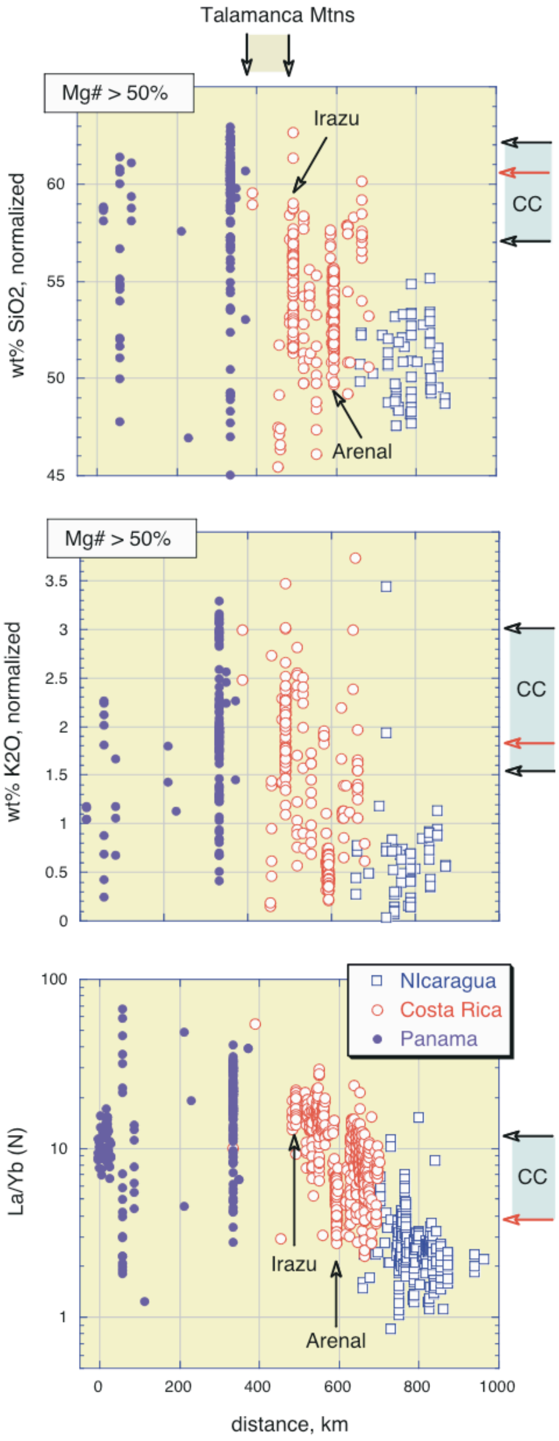


Figure 10a. Data on arc lavas less than 5 Ma (mostly from active volcanoes) compiled by Kelemen et al 2003a, from GeoRoc, literature data, and unpublished data from PI's Carr, Vogel, and their colleagues. CC: Range of estimates for contintal crust compiled by Kelemen (1995). Red arrow, estimate by Rudnick & Gao (2003, 2007).

On the right side of Figure 10a is the range of estimated compositions for bulk continental crust (Mg# ~ 0.5). Clearly, lavas with similar Mg# in the northwest, (distance > 500km) are distinct from continental crust in their major and trace element compositions, while there is a marked overlap between continental compositions and lavas in the 500-300 km range. There is a substantial gap in data (about 390-450 km) in the Talamanca Mountains, where compositions similar to continental crust might be expected to be most common, because the intermediate plutonic rocks and lavas there are little studied.

These scatterplots (Figure 10a) provide an honest view of regional variability, but tend to obscure the covariance in the data, diminish the data in clusters and over-emphasize outliers. Thus, the histograms in Figure 10b supplement Figure 10a. The regional data are divided into two distinct groups, with the southeastern group extending to Irazu volcano, and the northwestern group from there to the border with Nicaragua. Clearly, lava compositions similar to continental crust are well represented in the southern group (300-500 km) and poorly represented in the northern group (500-700 km). In turn, the lavas of the northern group are more similar to continental crust than lavas of the Izu-Bonin-Marianas island arc in the western Pacific.

The question arises, whether the igneous rocks in southern Costa Rica and Panama that resemble continental crust are a recent phenomenon, or have been erupted throughout the lifetime of the arc. Plank et al. (2002) found that from the Miocene to the present the regional variation in Nicaragua did not change, except for U which has recently increased, reflecting change in the sediment being subducted. In contrast, the early Miocene lavas in central Costa Rica are like the western Nicaraguan lavas shown in Figure 10c (Gazel et al., 2005), not like the present day lavas that partly cover them, and the long-term geochemical continuity in ratios like Ba/La and La/Yb in Nicaragua did not occur in Costa Rica (Gazel et al. submitted). Preliminary ^{40}Ar/^{39}Ar age data from Gazel & Carr (Gazel et al. submitted) do not show significant age evolution along the arc, but do show geochemical evolution towards more "continental" lava compositions in SE Costa Rica and Panama over the past 20 Ma.

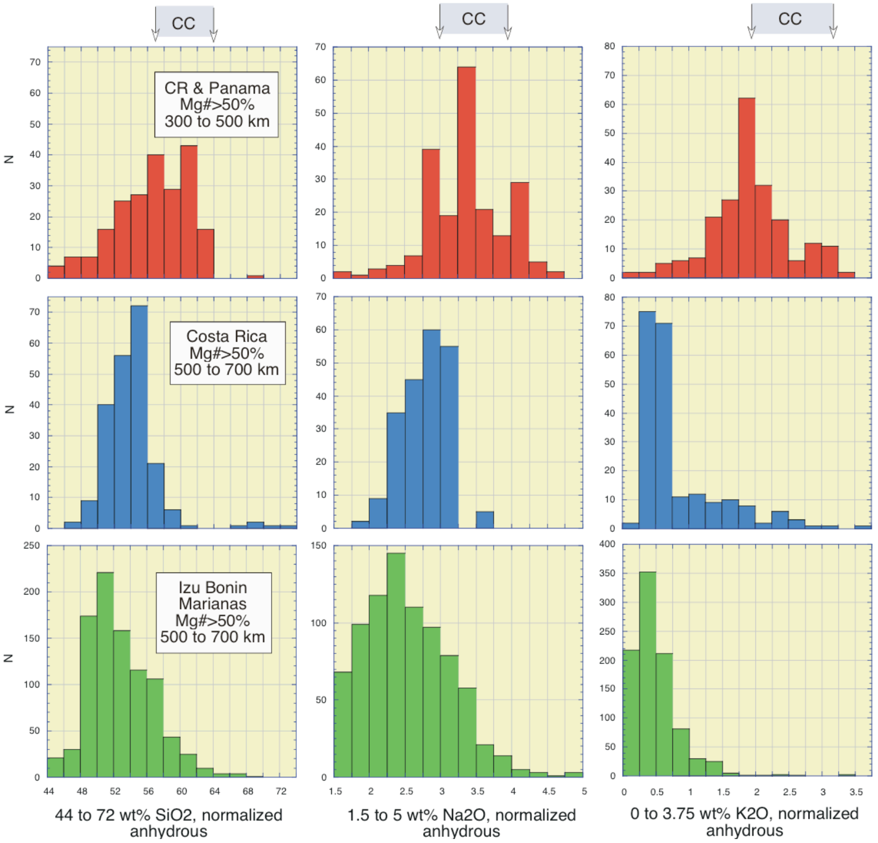
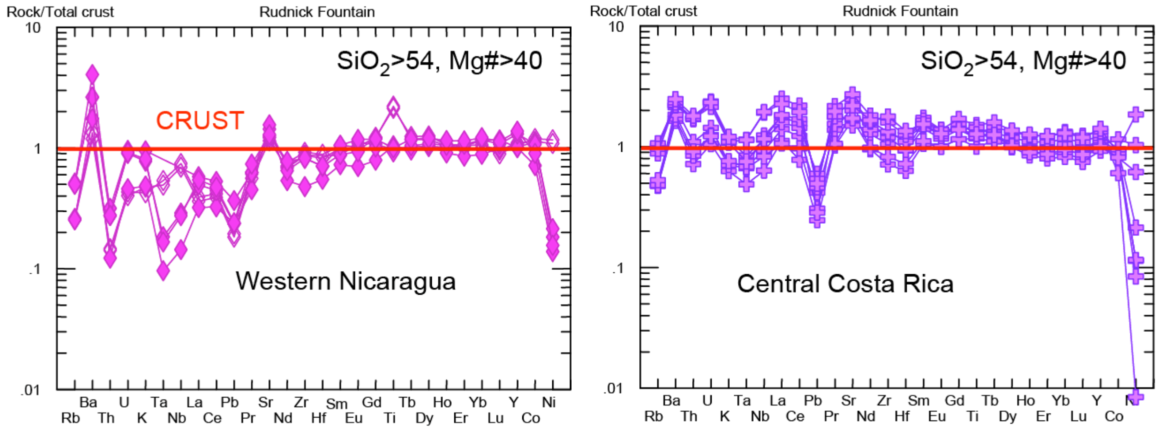


Figure 10b: Data compilation as for Figure 10. Evidence for distinct major element chemistry in high Mg# (molar Mg/(Mg+Fe)) lavas of central and NW Costa Rica compared to southern Costa Rica and western Panama. In the southern group, Si, Na and K contents of most high Mg# lavas are similar to estimates for continental crust, whereas in the northern group, high Mg# lavas have lower SiO_2, Na_2O and K_2O contents than continental crust. Almost all lavas from Costa Rica and Panama are more similar to continental crust than any lavas from the Izu-Bonin-Marianas island arc.

Figure 10c Trace element compilations showing continental affinity of silicic lavas in Costa Rica, and a different pattern in Nicaragua.



3.3 Isotopic evidence rules out pre-existing continental crust in Costa Rica.

Strong evidence that central Costa Rican lavas are unaffected by continental crust derives from Pb, Sr and Nd isotopes. Guatemalan lavas clearly show the effects of crustal contamination on Nd-Pb isotope diagram (see Fig. 11). Throughout Central America, the influence of continental crust is indicated by trend lines away from mantle values on all isotope diagrams. On a Sr-Pb isotope diagram, all lavas along the volcanic front are removed from mantle values because both continental crust and the subducting sediment package shift ^{87}Sr/^{86}Sr towards high values (Feigenson et al., 2004). However, the subduction components have no appreciable effect on ^{143}Nd/^{144}Nd, so only lavas contaminated by continental crust are displaced from mantle values. This is evident for several lavas in northwestern Guatemala (marked by the oval in the plot), but is not the case in lavas either from the volcanic front or the back arc of central Costa Rica, nor in the Talamanca lavas, demonstrating the lack of continental influence for this segment of the Central American arc.

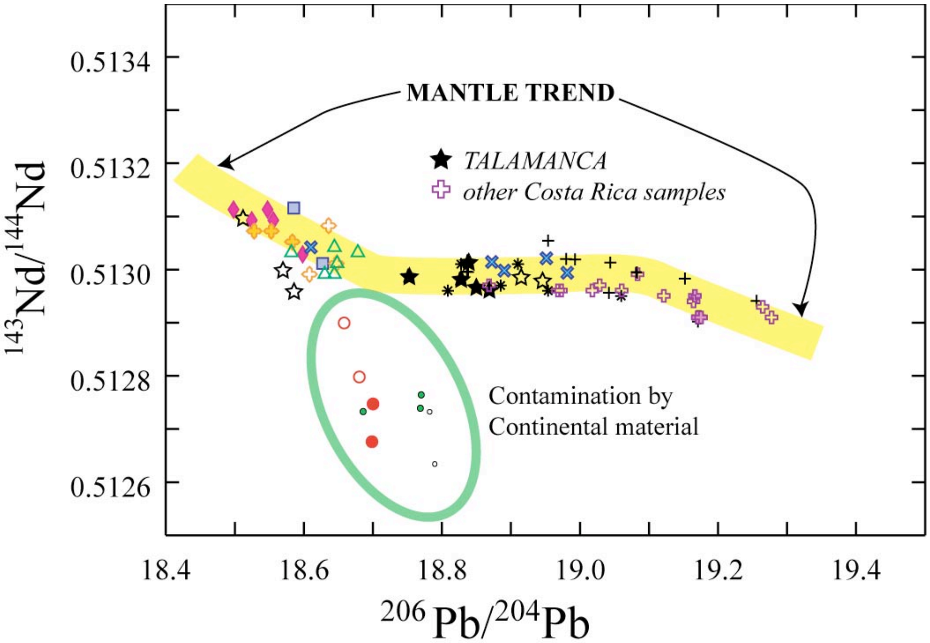


Figure 11: Nd-Pb isotope diagram for Central America. Lavas from central Costa Rica, the Caribbean back arc, and Panama are shifted to higher ^{206}Pb/^{204}Pb than the rest of Central America. In addition, only some samples from Guatemala and from the pre-Quaternary volcanic front in Nicaragua (plotted inside the oval) are affected by continental crust.

3.4 **A view into recently transformed crust in uplifted Southern Costa Rica.**

In the southern part of Costa Rica, erosion of a recently elevated mountain range has exposed rocks of upper-to-middle crustal origin. Here it is possible to sample the "plumbing system" of the recently active volcanic arc directly, but without drilling, and to access the degree of transformation of the upper crust of the former plateau. This section reviews basic facts about the less well-studied southern Costa Rica.

Subduction may not be occurring beneath southern Costa Rica. No earthquakes deeper than ~60 km occur there (Figure 12 and Quintero & Kissling, 2001; Husen et al., 2003), tomographic evidence for a slab is weak (though see Dzierma, 2008), and no arc volcanoes are active. Timing of the cessation of volcanism is uncertain, most ages from Ar/Ar analysis are in the 11-14 Ma range (MacMillan et al., 2004). Ages as young as 5 Ma have been obtained using K/Ar analysis (DeBoer et al., 1995; Drummond et al., 1995). Notably, the mean elevation in the south is 1 to 2 Km above that in the north, with a very sharp lateral transition (Figure 3). The Talamanca Mountains, which reach elevations of about 4 km, are asymmetric in cross-section (Grafe et al., 2002). The Pacific flank, dominated by reverse and normal faults, is steep, whereas the Caribbean slope is moderately inclined, and laced with thrust faults.

The Talamanca mountains constitute a magmatic axis in the southeast part of Costa Rica. Granites and aplite granites are common in the upper section, and gabbros in the lower section. The silica content of these intrusive rocks ranges from 46 to 72 wt. %, and most are calc-alkaline. Limited geochronological studies have been done on these rocks (Abrattis and Wörner, 2001; Grafe et al., 2002; MacMillan et al., 2004).

Uplift and erosional unroofing have long been recognized as important processes affecting the crust in this region (e.g., Dengo, 1962). However, the timing, rates, and mechanisms remain poorly constrained. A broad range of different ages has been reported for the initiation of Talamanca uplift (1 to 8 Ma), each based on disparate lines of evidence (e.g., Gardner et al., 1992; de Boer et al., 1995; Abratis and Wörner, 2001; MacMillan et al., 2004). Many studies associate this uplift with the Cocos Ridge, proposing either underthrusting of buoyant Cocos Ridge lithosphere beneath Costa Rica, or mechanical thickening of the Costa Rican crust due to lateral compression. An alternative hypothesis is that the absence of a slab – a so called “slab window” - facilitates buoyant upwelling of hot asthenospheric mantle to shallow depth. Current seismic data are insufficient to discriminate between these hypotheses. Better understanding of the relative timing of uplift, silicic volcanism and the impact of the Cocos Ridge are required to resolve this issue.

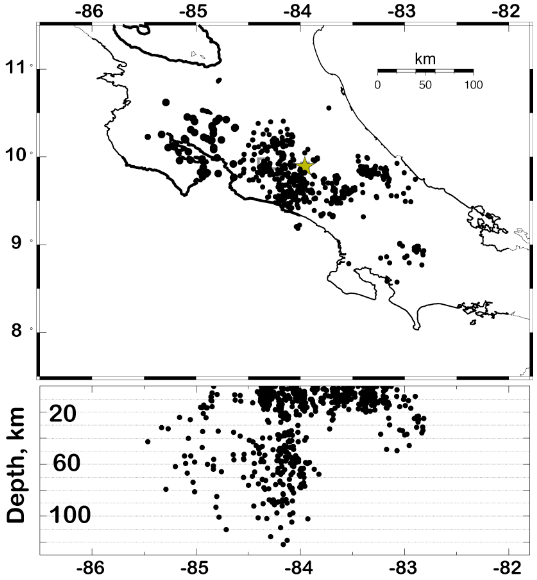


Figure 12. Plots of ~800 well-located regional earthquakes (adapted from Quintero and Kissling, 2001), illustrating a lack of deep seismic activity beneath southern Costa Rica.

3.4.1 Adakites in Costa Rica. The term “adakite” is used here for consistency with previous publications on southern Costa Rica (Abratis and Worner, 2001, McMillan et al., 2004; Drummond et al., 1995). “Adakitic” signatures include strongly fractionated REE patterns with very low heavy REE contents, and very high Sr/Y. These probably require garnet at some stage in the origin of adakites, as a residual phase or an early crystallizing phase to account for the steep REE patterns. However, whether the source is in lower arc crust (e.g. Smith & Leeman, 1987; Petford & Atherton, 1996) or subducted oceanic crust (e.g. Defant & Drummond, 1990; Stern & Kilian, 1996; Bourdon et al., 2002) is still a matter of debate. Adakite-like compositions have been produced by high-pressure experiments on a hydrous, oxidized, primitive basalt that crystallized amphibole and garnet (Prouteau and Scaillet, 2003). Adakitic (in the above sense) lavas <5 Ma in age are exposed as individual domes or minor lava flows in the Talmanca area, and in western Panama (MacMillan et al, 2004, Abratis and Worner, 2001). Also, recent geochemical work in a ~5.6 Ma alluvial fan, shows evidence of an “adakitic” signature (e.g very steep REE patterns, and high Sr/Y>50, E. Gazel, unpublished data). The presence of these unusual rocks is significant, and will play an important role in our understanding of the geodynamic processes that formed this continental-like crust.

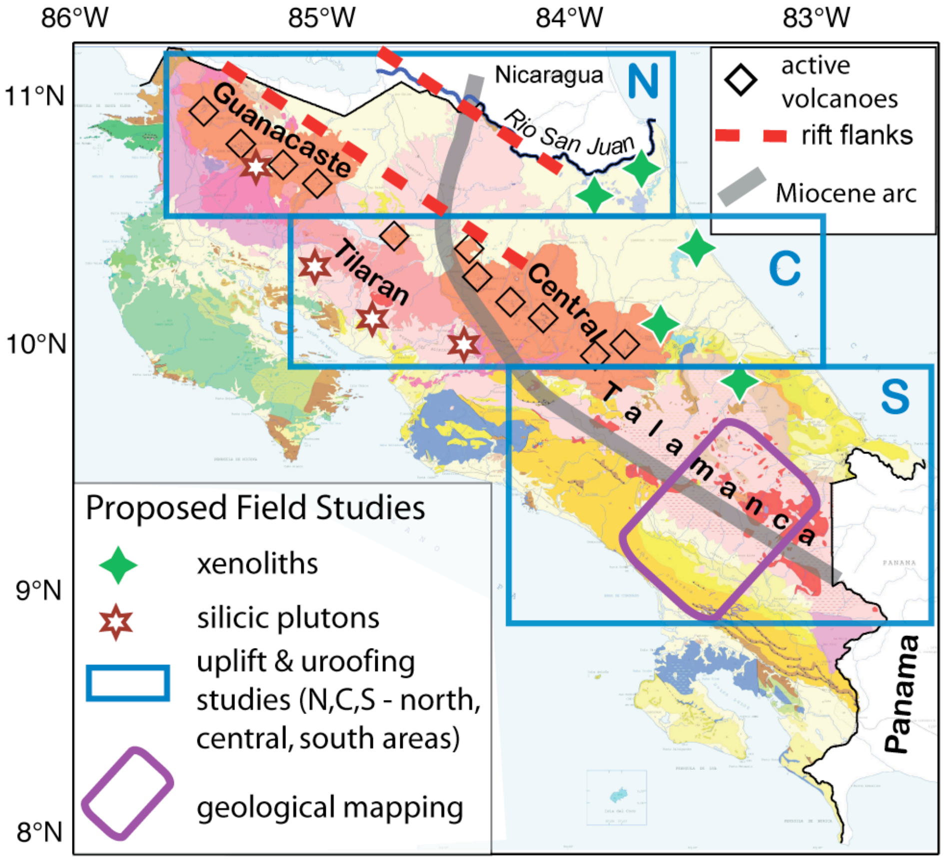


Figure 13. A geologic map of Costa Rica and a schematic depiction of locations for various sampling and mapping campaigns, and morphotectonic studies

4. Overview of the Research Plan

New observations are a key component of our research plan, and are vital for testing the hypotheses set out in Section II. Key observables include: bulk composition of the crust; crustal thickness; thickness of the lithosphere; composition and physical state of the upper mantle; the history of magmatism, unroofing and surface uplift.

Our research plan integrates geophysical, geochemical and geomorphological methods relevant to each observable, and has major observational efforts in each of these three areas:

1. Extensive sampling and analysis (geochemical, petrological, mineralogical) of crustal rocks, and where available, lower crustal and mantle xenoliths;
2. A passive seismic array targeting the structure of poorly studied southern and eastern Costa Rica;
3. Geomophological studies of landforms that constrain uplift history.

Knowledge of the bulk composition of the crust, and its geographic variation, is key to defining the degree to which it has become continent-like. Seismic observations are one important component, since basaltic rocks can be distinguished from more silica-rich rocks via seismic wave velocities and Poisson ratio. Available seismic results, though broadly consistent with a crust of continental composition, are deficient in two respects: away from the seismically active western coast they are largely limited to rather shallow depths (<15 km), and the coverage in eastern and southern Costa Rica is poor. Thus our research plan calls for studies of both body wave travel times and receiver functions to fill in those gaps of knowledge. Some data for this exist, but areas most critical for the present study (Caribbean coast, Talamanca Mountains) are poorly sampled, and we plan to collect new data there. Equally important will be searching for lower crustal xenoliths, that will provide direct evidence of lower crustal composition. Finally, geochemical and mineralogical studies of plutonic rocks of a broad range of compositions will constrain the P-T conditions under which they formed, and hence help us interpret seismological observations.

Crustal thickness, when coupled with bulk composition, is key to understanding the relative importance of crustal buoyancy and mantle buoyancy as agents responsible for uplift. Crustal thickness is also related to melt generation and magmatic differentiation. Our plan calls for mapping crustal thickness, especially in poorly studied southern and eastern Coast Rica, with receiver function analysis and wide-angle Moho reflections from local earthquake sources.

It is unclear whether Costa Rica has a continent-like mantle root beneath its continent-like crust. Buoyant lithosphere thickened by underthusting (e.g. of the Cocos Ridge) will have a seismic signature distinct from the warm partially molten buoyant asthenospheric material. Our plan calls for mapping of lithospheric thickness using Receiver Functions and seismic surface waves. Studies of mantle xenoliths, and the P-T conditions under which they were formed, will also contribute to this subject.

We also expect to be able to constrain the composition of the uppermost mantle and its physical state, in order to address the degree to which it might represent original CLIP-derived material, peridotite derived from the arc's mantle wedge, "hidden" residue of crustal transformation etc. Composition will mainly be constrained by chemical analysis of rocks derived from primitive magmas and studies of mantle xenoliths. Thermal state will be studied by using both seismic observations of shear wave attenuation and petrological estimates related to degree of partial melting. The degree and direction of deformation will be determined through observations of seismic anisotropy.

Two interrelated evolutionary relationships are extremely important, the history of silicic magmatism, and the history of surface uplift and unroofing. Currently, there is a ~20 Ma uncertainty in the onset of silicic magmatism, and a ~5 Ma uncertainty in the onset of uplift. We will determine a new set of ages for a regionally representative set of samples, with tight geological controls that we will improve through new mapping efforts if necessary. The geomorphic and thermochronologic analyses will allow us to discriminate whether some or all of the uplift and unroofing in Costa Rica is a consequence of continent-producing processes, is a necessary antecedent of these processes, or is largely unrelated. For example, the generation of continental crust is commonly thought to be associated with the removal of dense lower crustal residue, and that this delamination requires isostatic adjustment and uplift of the remaining more buoyant crust. This regional epeirogenic uplift and consequent erosional unroofing would leave a recognizable signal on the landscape that can be differentiated from localized horizontally-directed tectonic forcing (e.g., Cocos Ridge collision).

5. SPECIFIC PLANS, METHODS, TECHNIQUES

5.1 Seismic properties of the crust and the upper mantle.

The primitive basaltic oceanic plateaus and arcs and a silica-rich continent are very different in mean crustal Vp, with the low value of 6.45 being characteristic of continents (Christensen and Mooney, 1995) and a much higher value of 6.8-7.0 being observed in areas of thick basaltic crust (e.g. in Iceland (Menke et al., 1998) and the Aleutians (Shillington et. al, 2004)). Poisson's ratio varies significantly too, owing to the extremely low value for the mineral quartz, with values of 0.24 (corresponding to a velocity ratio of 1.71) being characteristics of a silicic crust, while higher values, often exceeding 0.27 (velocity ratio of 1.78) are typical of basaltic terrains (Zandt and Ammon, 2002). Seismology thus provides an extremely effective way to gauge the degree to which the bulk crust beneath Costa Rica has become "continental", and the geographical extent of this change.

Seismology will also contribute to understanding elevation gradients in Costa Rica, and especially in discriminating between three end-members, in which the highland topography is alternatively compensated by: anomalously low crustal density due to its continental nature; anomalously high mantle buoyancy due to either temperature of chemical depletion; or anomalously thick crust, due to mechanical thickening of a still largely basaltic material (Figure 2). In the crust, the correlation of seismic velocity with density is mainly due to petrology, with the faster, more mafic minerals being denser than the slower, more felsic ones. In the mantle, seismic velocities are most strongly controlled by temperature, especially in areas (such as southern Costa Rica) where no present-day volcanism is occurring, and hence where the complicating effects of partial melt are likely to be absent. A seismically-derived density structure (e.g. applying Christensen and Mooney’s (1995) formula for inferring density from crustal velocity) that includes crustal petrology, crustal thickness and mantle thermal buoyancy effects will provide a means for discriminating the alternative models.

Mantle flow-induced fabric, determined via seismic anisotropy, can also be used to constrain models of crustal evolution. We would expect delamination of a dense crustal component to be associated with large-scale vertical flow in the mantle. Vertical flow implies a vertical fast direction, and a negative transverse anisotropy parameter (i.e. Gaherty’s (2001) parameter, ΔVs, which is a straightforward seismic observable). However, should this flow have a strong horizontal component (e.g., Behn et al., 2007), its azimuth will also be diagnostic. Models that involve a slab widow in southern Costa Rica, and call for the transport of hot Pacific mantle northward beneath Costa Rica (e.g., Hornle et al., 2008) imply a flow direction roughly perpendicular to that envisaged by models in which Cocos Ridge is subductig, and high topography is achieved by pure-strain shortening and thickening of the highlands.

The hypotheses that we are testing all require knowledge of ‘bulk earth properties’: the thickness of the crust and the velocity structure of the crust and mantle, and their geographical variation, especially at wavelength of tens of kilometers. Developing such a seismic model is more challenging than first appears, since uniformity of coverage, over both geographical region and depth interval is paramount. Even a cursory survey of the seismic literature will find copious examples of studies that produced nice results, say for the upper crust, but were unable to image the lower curst or even to detect Moho, or that produced interesting tomographic images, say, of slabs in the upper mantle, but without constraining the "background" velocity. Our focus here must be on data acquisition and analysis that can provide the right kind of information.

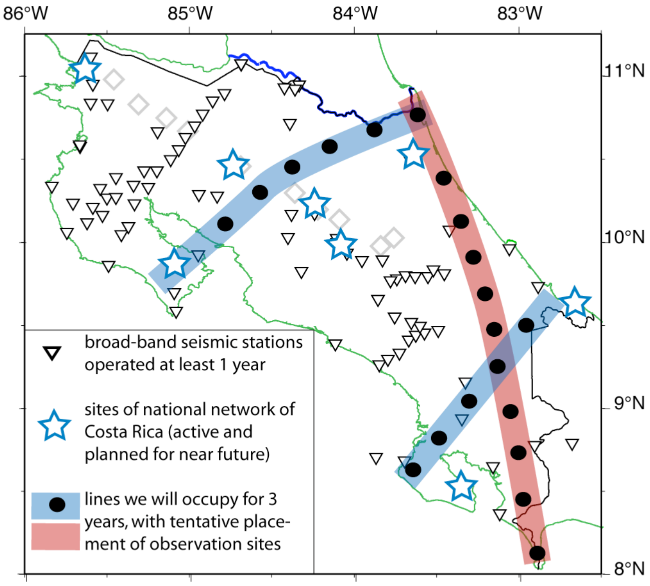


Figure 14. Existing broadband seismic observations in Costa Rica include past temporary seimic deplyment (triangles, squares) as well as the permanent network of Costa Rica (open stars). Our planned experiment (lines with dots) will complement this coverage, emphasizing eastern and southern Costa Rica.

Existing data (Figure 14), though often of high quality, is insufficient for our purposes, mostly because of limits in geographical coverage. We are thus proposing a 3-year deployment of an array of 20 broadband seismometers, arranged on a set of 3 lines (Figure 14). The long duration of observations is, in our opinion, necessary to successfully apply modern body-wave analysis methods, especially those relying on directional variations in observations. Simultaneously collected data from Costa Rica's national broadband network will supplement this array and allow us to probe all the important tectonic provinces. The southern end of the proposed north-south line (red in Figure 14) coincides with a region of intense shallow seismicity offshore in the Pacific (figure 15), facilitating the array's use in passive seismic refraction experiment (discussed further below).

Supplementary data are available from the numerous temporary experiments that have been performed in Costa Rica in the last 10 years (e.g. the 20-station Costa Rican half of the TUCAN array in the northern part of the country, also Swiss and German deployments). These are currently available to us (see supplementary documents), or they will become open in the near future according to the PASSCAL data policy.

The seismological toolset that we will employ focuses on techniques that will allow us to map out the "bulk properties" of the crust and upper mantle: Receiver Function (RF) analysis, body wave refraction, Love/Rayleigh wave dispersion and shear wave splitting. RF analysis relies on near-vertical seismic waves from distant sources and probes the seismic structure directly beneath a station. It has proven very effective in a variety of settings in detecting Moho and upper mantle discontinuities. We rely on it for mapping out lateral variations in crustal thickness. While not being particularly sensitive to Vp, RF analysis provides constraints on the crust and mantle shear wave velocity, and on the Poisson's ratio (Zandt and Ammon, 1995; 2002). Combining our new data with already existing results (e.g. MacKenzie et al., 2008) we will construct maps of crustal thickness and Poisson's ratio for the entire Costa Rican landmass.

We will supplement the RF analysis with observations of crustal-refracted and Moho-reflected body waves from earthquake sources (“passive source refraction”, PSR). This method is not limited to probing the immediate vicinity of the station, and can thus be used to fill in gaps between stations. Being a higher-frequency technique than RF, it may also be able to provide information on “Moho character”, which may help in understanding whether mechanical deformation processes have been active there. PSR also provides a better control on Vp than does RF. The comobination of these two tectniques and will yield superior maps of variations in seismic wave speed and Poisson’s ratio.

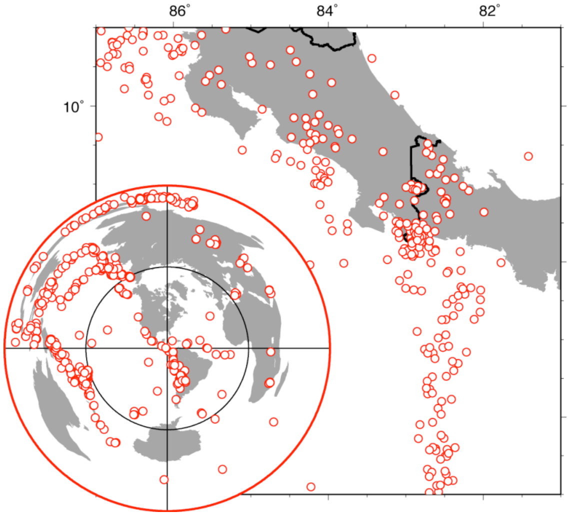


Figure 15. A likely arrangement of seismic sources to be recorded in 3 years. Local earthquakes of M>4 and global sources of M>6 are shown.

Love/Rayleigh dispersion (LRD) (especially in the 20-120 second period range), is our main tool for measuring upper mantle shear velocity and anisotropy. Geographically, it is a relatively low-resolution technique, limited to features of ~100 km or greater in size. But its strength is in being able to determine mantle shear velocity, especially in the 75-150 km depth range, with great precision. Surface-wave derived mantle velocity models will provide an estimate of mantle temperature (since shear velocity strongly varies with temperature) and hence of mantle density. Surface wave measurements are also likely to detect upper mantle seismic wave speed inversions associated, say, with lithosphere underthrusting events.

Finally, seismic anisotropy may give insight into mantle flow directions, and hence the modes of deformation and their regionalization. Anisotropy will be inferred on the basis of splitting of shear body wave phases (SKS and similar, and local S from slab sources), which are useful in determining the azimuth of horizontal anisotropy, and also from differences in Love and Rayleigh wave velocities, which are useful in discriminating "vertical" from "horizontal" anisotropy. Gaherty (2001), for example, uses this later technique to test models of active and passive convection on Reykjanes Ridge. Additional constraints on anisotropic properties within the lithosphere are available from RF analysis (e.g., Levin et al., 2002ab). Most methods aimed at resolving seismic anisotropy depend for their success on obtaining observations from as many directions as possible. Our interest in resolving anisotropic properties largely motivates a 3 year-long deployment, to facilitate numerous observations from all major subduction zones.

At least one member of the proposal team is well-versed in each of these techniques. Levin has previously used RF methodology to map out crustal structure variations in Kamchatka and Italy (Levin et al., 2002ab, Piana et al. 2008). Menke has previously employed the PSR technique in Iceland to measure P, S, PmP and SmS traveltimes and produce “whole-crust” models of that basaltic plateau (Menke et. al., 1998). He also has developed 3D traveltime inversion codes for modeling such data (Menke, 2005). Both Menke and Levin have experience in measuring LRD on regional networks of seismographs, and in using these data to infer mantle velocity structure (Menke and Levin, 2002). They also both have experience in measuring splitting parameters and interpreting them in a variety of tectonic settings (Levin et al., 1999, 2004, 2006, 2008), and have developed special tools that help in cases of complex mantle patterns, as expected here (Menke and Levin, 2003).

The southern Costa Rica is a setting very similar to one in which Levin has previously worked – the junction of Kamchatka and Aleutian arcs. There he and co-workers successfully used shear-wave splitting observations to discriminate between possible mantle flow scenarios (Peyton et al., 2001).

5.2 Geochemistry and petrology of mantle rocks.

Our main hypothesis is that upper mantle xenoliths found in Costa Rica are pieces of the mantle lithosphere from the Caribbean Large Igneous Province (CLIP), the fragments of a fossil mantle plume. Studying them will allow us to test, through direct sampling, the regional tectonic model that the CLIP represents the basement of southern Central America (Hauff et al, 2000; Denyer et al., 2006). The xenolith study is also important for testing the more general theory that subduction can be initiated at the edge of an oceanic plateau (Niu et al., 2003; Stein and Goldstein, 1996). In this way, oceanic plateaus can act as nuclei for the formation of new continental crust. Furthermore, evidence for modification of the samples by subduction zone fluids/melts provides insights into subduction development and evolution.

We need to examine our preliminary findings more carefully by detailed geochemical studies on whole rocks and clinopyroxene mineral separates that preserve the geochemical identity of the protolith before and during subduction. Work will be done on the five new xenolith localities (See Figure 13) that were discovered in the back arc region, and new samples will be prospected for in this region. This will be done by Esteban Gazel at Rutgers University, as part of his work in a postdoctoral position. Preliminary work shows considerable variation in both major and trace element geochemistry, like the Cerro Mercedes occurrence. We need to distinguish variations that occurred due to melting in the mantle plume from variations that occurred later by melt-rock reaction during subduction. The plume model predicts large variations in peridotite residue composition from the hot core to the cool periphery, and our current hypothesis is that the xenoliths are heterogeneous in part because they are samples from the western edge of the plume. In order to properly evaluate this hypothesis, we need to work on samples collected over a wide geographical area in the back arc region. We are optimistic that continued prospecting will provide a wealth of more xenoliths.

One practical difficulty that we have encountered is that xenoliths are in some cases too small for whole rock analysis. For these we are reconstructing whole rock geochemistry from mineral chemistry and mineral modes. This is a time-consuming effort, requiring a considerable amount of time on the electron microprobe.

Recent work shows that Pb and Nd isotope ratios of Cretaceous rocks distributed from most of the Caribbean plateau (Hauff et al., 2000; Thompson *et al*., 2003; Geldmacher *et al*., 2003) are essentially identical to those of lavas from the modern heterogeneous Galápagos plume (Werner *et al*. 2003). We will determine the isotopic ratios of clinopyroxene separates from selected peridotite xenoliths to see if they can be identified with any of the part of the present-day Galápagos plume.

New major, trace element and isotopic (Sr, Nd, Pb) data of the alkaline basalts that host the mantle xenoliths have already been collected as part of Esteban Gazel's PhD thesis. Based on this data, Gazel suggests that the host basalt has no subduction signature, therefore the major and trace element and isotopic data collected in the xenoliths will provide petrological information about the mantle composition before subduction metasomatism. Trace element analyses will be obtained on clinopyroxenes in the xenoliths using the LA-ICP-MS at the Institute of Marine and Costal Sciences at Rutgers University or at the LA-ICP-MS at Michigan State University. Mineral chemistry data will be obtained from thin sections using the Electron Microprobe Laboratory at the Department of Geological Sciences at Rutgers University. Isotopic data will be obtained using the Thermal Ionization Mass Spectrometer at the Department of Geological

Sciences at Rutgers University. Geochronology of the host basalts will be done using $^{40}Ar/^{39}Ar$ mass spectrometry with the MA215-50 at the Department of Geological Sciences at Rutgers University.

5.3 Comprehensive analysis of plutonic rocks.

5.3.1. Geochemistry/petrology. We will determine the chemical and mineralogical variation of the plutonic rocks and the contact metamorphosed wall rocks. The plutonic rocks are abundant in the Talamanca Mountains, and much of our effort will be directed to sampling these plutons. However, limited exposures of plutonic rocks (red stars in Figure 13) also occur elsewhere to the northwest in Costa Rica and these will also be sampled. Splits of these samples will be allocated for isotopic analyses (see below). Our overall goal is to compare the chemical composition of these samples to "bulk" or upper continental crust (for example Rudnick and Gao, 2003). We will also compare the compositional variation of the Talamanca plutonic rocks to the variations observed in silicic volcanic rocks (Deering *et al.*, 2007, Vogel *et al.*, 2004, Vogel *et al.*, 2006). All of the whole-rock chemical analyses will be done by Vogel at MSU using XRF and LA-ICP-MS techniques. We also will analyze the minerals in the plutons with the electron microprobe in order to determine the intensive parameters for these plutons – this work will be coordinate with all PI's evaluating geobarometry and geothermometry.

5.3.2 Sr, Nd and Pb. We plan to analyze a representative suite of samples (30 per year) for Sr, Nd and Pb isotopes. Previous research has shown that these isotopic systems are indispensable for characterizing and modeling melt production and evolution from a variety of mantle domains and for evaluating the role crustal contamination. This work will be overseen by Mark Feigenson

5.3.3 Geobarometry. The geobarometry effort will use well known hornblende barometers for felsic plutonic rocks with the necessary mineral assemblage (Anderson and Smith, 1995; Anderson, 1996; Ague, 1997), together with less well known barometers involving plagioclase (plag), clinopyroxene (cpx) and quartz via the reactions NaAlSi3O8 (in plag) = NaAlSi2O6 (in cpx) + SiO2 and CaAl2Si2O8 (plag) = CaAl2SiO6 (cpx) + SiO2 (Markl et al., 1998). We will evaluate phase relations of contact rocks associated with the intrusive rocks to determine depth of emplacement. There are many possible metamorphic geobarometers, one example is the Grt-Pl-Ky-Qtz geobarometer. The choice of the particular approach will depend on our success in finding the proper samples. At the moment our knowledge of Talamanca geology is not good enough, but will improve dramatically once the mapping effort gets underway. Kelemen will direct a student project on this topic, primarily using Rutgers microprobe facility as a tool. Determination of crystallization pressures will be essential for understanding (a) the mechanism(s) of crustal differentiation via mid- or lower crustal crystal fractionation and melting, and (b) the extent of uplift from mid-crustal depths to the current erosional surface.

5.3.4 U-Pb, $^{40}Ar/^{39}Ar$, $\delta^{18}O$ Geochronology. Establishing a high-precision sequence of events is crucial for deciphering the history of arc construction, unroofing, uplift and relief development. We plan to accomplish this through an integrated U-Pb, $^{40}Ar/^{39}Ar$, and $\delta^{18}O$ effort that will greatly expand the existing geochronological dataset in the region. Samples that are collected for geochronology and thermochronology will be distributed to other members of the team for geochemical and isotopic characterization. We will use these data to build a geochronological and geochemical database that allows the relationships between plate tectonics and magmatism to be evaluated.

U-Pb geochronology (Bowring, MIT) of key igneous rocks will be essential for understanding the growth and possible conversion of CLIP to continental crust. Our work will explore the full spectrum of compositional diversity, from gabbro to granite. Of particular interest will be establishing the presence or absence of inherited zircons in any of the rocks as indicators of within arc reprocessing or the involvement of much older lithosphere. This will involve chemical characterization of zircons in polished grain mounts and physical isolation of small inherited components. The high precision offered by IDTIMS analyses will ensure that even subtle amounts of inherited zircon can be detected and analyzed. The lab at MIT has experience obtaining high precision U-Pb dates on zircon even from rocks less than 1 Ma.

Accessory minerals such as zircon contain a wealth of information and once separated from rocks of interest will be distributed to other members of the team for U-Th-He thermochronology, oxygen isotopic studies. Oxygen isotope studies will be coordinate by Vogel (MSU) in cooperation with Valley (UWis – see letter in supplemental material). We will analyze $\delta^{18}O$ of minerals such as magnetite, hornblende and zircons using laser fluorination techniques in Valley's laboratory. It is possible that we will find evidence of oxygen isotope zoning within single minerals such as zircon. We have the capability in Valley's lab to analyze $\delta^{18}O$ with a 10-micron diameter spot (1 micron deep, +-0.2‰) in situ from a thin section or grain mount using the Wisc-SIMS CAMECA 1280 ion microprobe (Page et al. 2007, Moser et al. 2008). When possible the same zircon crystal will be used for oxygen studies and the U-Pb studies. Oxygen isotope ratios of refractory minerals have been particularly useful in determining source areas for Central American ignimbrites (Vogel et al. 2006) and in other rhyolite terrains, in situ analysis of zircons reveals thermal and fluid histories that are otherwise unknown (Bindeman et al. 2001, 2008). The mineral separation work will be coordinated by Bowring and Flowers (MIT and Colorado) and one of the long term goals of the project will be to aid our Costa Rican colleagues in establishing a state-of-the-art rock crushing and mineral separation facility. Bowring and Flowers will coordinate their activities and share samples. The graduate student from University of Colorado will work in Bowring's lab learning U-Pb geochronology.

We are also particularly interested in identifying accessory minerals in lower crustal/upper mantle xenoliths that can be dated using U-Pb geochronology with an eye toward establishing the age and thermal history of the lower crust and upper mantle. While few lower crustal xenoliths have been described, searching for and characterizing them will be an aspect of the proposed research.

In order to further constrain the uplift and magmatic history of the Talamancas, detrital zircon age populations from Cenozoic basinal strata adjacent to the Talamancas and elsewhere in Costa Rica will be determined (see letter in supplementary material). This work will be coordinated by MSU and the U-Pb analyzes done at the LA-MCA-ICP laboratory at the University of Arizona.

5.4 Uplift and unroofing history from geomorphic analysis, stratigraphic study, and thermochronology

A key question that we will address is which processes are responsible for creating and maintaining the subareal nature and abrupt topographic relief of Costa Rica. Options include: 1) low crustal density associated with the development of continental crust and removal (delamination) of a dense crustal root; 2) upwelling of hot mantle from a slab window; 3) mechanical underthrusting of low density, hotspot-thickened lithosphere (i.e., Cocos Ridge), and/or 4) the presence of original CLIP of sufficiently low density to explain the modern topographic relief. Options 1 and 2 result in vertical epeirogenic uplift associated with either delamination of the lower crust, or mantle derived volcanism, respectively. Option 3 involves significant horizontal forcing, which would be predicted to coincide with or postdate the onset of Cocos Ridge collision with Costa Rica. Option 4 does not require progressive uplift and is simply the result of volcanic arc formation atop the pre-existing CLIP. Resolving the timing and patterns of surface uplift and erosional unroofing of Costa Rica is crucial for discriminating between these options.

We will focus on three different segments of Costa Rica with distinct geomorphic and geologic characteristics (see Figures 2, 3 and 13):

1) Northern Costa Rica (Guanacaste volcanic range and backarc lowlands between it and the Caribbean), where elevations are low, and Miocene lavas show no evidence of a "continental" signature, but some silicic plutons are present;

2) Central Costa Rica (Tilarán and Central volcanic ranges, and lowlands east of them), where present mean elevation and exposure of granitoid plutons suggest some uplift and unroofing. Here evidence for the continental nature of the crust comes from the geochemistry of ignimbrites (see section 3.1) and seismic studies (see section 3.2);

3) Southern Costa Rica (Talamanca Mountains and the Caribbean coast east of them), where we find widespread continental lithologies, significant uplift and unroofing (Figure 3, also see section 3.4), as well as evidence for crustal shortening (Fisher et al., 2004). The collision of the Cocos Ridge with Costa Rica affects this region, but the details of how the collision influenced unroofing and surface uplift are not yet clear.

Our geomorphic and thermochronologic studies in these three distinct areas will allow us to isolate the uplift associated with continental crust formation from that associated with underthrusting of the Cocos Ridge hotspot-thickened crust, and will enable us to determine whether lithospheric delamination has occurred beneath part or all of Costa Rica. Thus, the goals of the TROPICS surfical process team (tectonic geomorphology: Rogers and Marshall, and thermochronology: Bowring, Flowers, and Turrin) are to identify the extent and age of the signals associated with Cocos Ridge impact, delamination, or other processes driving crustal uplift.

Northern and central Costa Rica present ideal locations to test whether an isostatic response (Options 1 and 2) has occurred and to establish its age. The volcanic arc and back arc region of northern Costa Rica and southern Nicaragua is likely underlain by island arc crust. Despite some silicic volcanism, this region lacks the geochemical signatures of continental crust formation (see sections 3.3). A major change in the nature of the crust-mantle boundary is seen crossing from Nicaragua into Costa Rica (MacKenzie et al., 2008). In contrast, the adjacent volcanic arc and back arc region of central Costa Rica exhibits more "continental" geochemistry of lavas, as well as evidence of uplift and unroofing in the form of higher average topography and surface exposures of silicic intrusive rocks (See Figure 13). If delamination (Option 1) has occurred, then central Costa Rica may have experienced an isostatic response or uplift event distinct from northern Costa Rica and southern Nicaragua. In Nicaragua, Lakes Managua and Nicaragua occupy an intra- to back-arc rift basin (red dashed lines in Figure 13). This rift extends southeastward into Costa Rica and crosses the suspected boundary between island arc and continental crust in northern Costa Rica. Rift fill deposits have been exhumed in north-central Costa Rica and form a drainage divide within the rift valley separating rivers draining northwest toward Lake Nicaragua and rivers flowing southeast toward the Caribbean Sea. This divide is at the boundary between non-continental crust to the north and the candidate continental crust to the south. It appears that the southern part of the rift, coincident with the continental crust, has been uplifted. Landscape analysis across the crustal boundary will help us determine whether the uplift is a delamination signal. This analysis can then be extended into southern Costa Rica, where any potential delamination related uplift in the Talamanca range can be differentiated from tectonic uplift and crustal shortening driven by sub-horizontal subduction of the Cocos ridge (Option 3).

5.4.1 Geomorphic Analysis (Rogers, CSU Stanislaus; Marshall, CalPoly Pomona)

The configuration of the rift crossing the tentative continent/non-continent boundary at a high angle between northern and central Costa Rica is advantageous for discerning the isostatic response to delamination (Option 1) and separating this signal from the tectonic forcing associated with Cocos Ridge collision. A number of tectonic geomorphic techniques ("morphometric analyses") are applicable to this setting (e.g., Keller and Pinter, 2002; Bull, 2007). For example, hypsometric analysis of river basins entering the rift should display greater disequilibrium towards the south reflecting the isostatic response to delamination. Area and shape analysis of these watersheds should display minimal evidence of tilting along the rift axis if uplift is near vertical. Where rivers enter the rift, the river valley height/width ratio should be greater in the south reflecting uplift in response to delamination. Longitudinal profiles of rivers entering the rift may display subtle but significant differences on each side of the crustal boundaries. Base level lowering should be greater in areas above the delamination, resulting in increased gradients and stream-length gradient indices while not significantly altering the form of the rivers' longitudinal profile. We will complete regional-scale topographic and morphometric analyses utilizing 90-m SRTM (Shuttle Radar Topography Mission) and new 30-m TERRA digital topographic data for Costa Rica. This will allow us to identify discrete geomorphic domains with varying patterns and histories of landscape evolution, uplift, and exhumation. The morphometric analyses will provide a first order test of the hypothesis that continental crust has formed in central Costa Rica, and will provide a critical tool in distinguishing the isostatic signal from tectonic forcing. Co-PI Rogers has utilized similar techniques to separate and map landscape responses produced by tectonic forcing (extensional and transtensional) from a mantle upwelling event in northern Central America (Rogers et al., 2002 and Rogers and Mann, 2007).

Guided by the morphometric analyses, we will utilize maps, aerial photos, and remote sensing imagery to identify particular landforms (fluvial terraces, erosion surfaces, alluvial fans) associated with regional isostatic uplift. We will target these landforms for detailed field study and sampling for datable material to determine the patterns, rates, and timing of isostatic uplift. Geomorphic surfaces and deposits will be mapped in the field (1:25,000 scale) and topographic transects will be surveyed for local elevation control using differential GPS and barometric altimetry. Samples will be collected for isotopic dating using radiocarbon, optically stimulated luminescence, and/or cosmogenic radionuclides. Soil profiles will be described at key locations for age correlation with existing Costa Rican soil chronosequences (Kesel and Spicer, 1985; Marshall et al., 2001). In conjunction with field investigations, locations for thermobarometry will be identified in both the northern (non-continental) and central (continental) areas.

In southern Costa Rica, while the isostatic response is likely to be strongly overprinted by tectonic uplift associated with Cocos Ridge collision (Option 3), we expect to be able to trace landforms associated with isostatic uplift from central Costa Rica into the Talamanca range. By isolating the isostatic signal from tectonic effects, we intend to determine the extent of delamination beneath southern Costa Rica. Several regional low-relief erosion surfaces have been identified at mid to higher elevations in the Talamanca range. These surfaces will be the target of morphologic and field analyses to determine if they are related to the isostatic response (options 1 and 2) or solely Cocos Ridge underthrusting (option 3). In southern Costa Rica, we anticipate relying on hypsometric (volume) analysis that can "trace" erosion surfaces in watersheds and on landform mapping, mainly of erosion surfaces. Ideally, these surfaces will appear progressively elevated along the Talamanca range crest, reach a maximum elevation directly above the underthrust Cocos Ridge lithosphere, and decrease in elevation to the south. The southernmost extent of these surfaces is expected to mark the southern extent of continental crust. Erosion surfaces in the Talamanca Mountains, where accessible, will be field verified and datable material sampled to ensure that the surfaces are associated with the isostatic event. This effort will be coordinated with the thermochronology effort to separate the Cocos ridge uplift event from the isostatic response to delamination.

5.4.2 Stratigraphic Study of Basins. Sediments eroded from the Talamanca range are stored in the forearc and backarc basins, preserving an inverse record of unroofing and exhumation. We will correlate existing stratigraphic data contained in geologic maps, seismic profiles, and well logs (e.g., Astorga et al., 1991; Brandes et al., 2007) to evaluate the sedimentation history of range-flanking basins (e.g., Limón, Valle General, Terraba basins). Using digital topographic data, we will characterize the geometry of range-front alluvial fans and basin fill. Through field study, we will examine the distribution of clast lithologies in sedimentary deposits. As described further below, we also will carry out an exploratory detrital thermochronologic study of targeted basinal deposits. The results of these efforts will allow us to evaluate eroded sediment volumes, spatial and temporal denudation patterns, and regional unroofing history of the Talamanca Mountains.

In addition, Co-PI Rogers is in discussion with Black Hills Corporation (BHC) Costa Rica subsidiary, Mallon Oil Company Sucursal (see attached letter of support) concerning data sharing in north-central Costa Rica's back arc basin. BHC holds hydrocarbon concessions in the rifted region where there is existing multichannel seismic data and two existing wells, logs and core. BHC is planning new seismic acquisition and drilling in 2009-2010. Data sharing discussions are in early stage; however BHC has indicating that they are agreeable to making MSC and well data available in exchange for access to crustal geophysics and landscape evolution results. Integration of industry data may allow identify the sediment pulse from the delamination event in the subsurface (anticipated being a pulse of clastic sediment over the continental parts of the rift). Identification of this event in the seismic and well data can provide confirmation of the age of the delamination event and because BHC MCS data extend to the coast, it may be possible to identify and trace the delamination pulse of sediment offshore into the Limon basin and in front of the Talamanca. If successful this would provide an additional constraint on the extent of the delamination extent to the south. We anticipate no additional cost associated with sharing data with BHC and if data sharing is not possible, then the affect on the proposal is negligible.

5.4.3 Thermochronology Studies. The thermochronology efforts will be focused on the north-south topographic transition between northern and central Costa Rica that has undergone lesser unroofing and surface uplift, and southern Costa Rica that has experienced more substantial unroofing and the development of over 3 km of relief (Figure 3). The spatial extent of the Cocos Ridge offshore coincides with the elevated Talamanca Mountains region in the south, strongly suggesting that Cocos Ridge collision plays a role in current surface uplift. This pattern raises the possibility, for example, that the entire north to south region was unroofed (but perhaps not elevated) during whatever geodynamic scenario lead to the formation of the continental signature (Options 1, 2 or 4), with subsequent uplift and additional unroofing of the southern part caused by Cocos Ridge collision (Option 3). Notably, the relative timing of the Cocos Ridge impact and the rise of the Talamanca is uncertain (see section 3.4). Deciphering the cooling history of the northern area will constrain unroofing associated with pre-Cocos Ridge "normal" subduction along the entire length of Costa Rica. Integrating these efforts with thermochronology studies in the south should enable us to unravel the superimposed effects of the pre-Cocos Ridge and Cocos Ridge unroofing and uplift phases in the Talamanca Mountains. The detailed timing and patterns of these unroofing phases, when integrated with the geomorphic constraints on the uplift history, will further help constrain the driving mechanisms discussed above.

^{40}Ar/^{39}Ar dating (Turrin, Rutgers) will be used to help constrain the cooling history of the granitoid rocks of the Talamanca Mountains. Suitable material for ^{40}Ar/^{39}Ar dating (hornblende and biotite, see Grafe et al., 2002) is present in the granitic rocks of the Talamanca. In this proposed study, ^{40}Ar/^{39}Ar ages on hornblende will provide the limits on the cooling age in the ~550° C range while ${}^{40}Ar/{}^{39}Ar$ ages on biotite will provide similar limits on the cooling age in the ~300° C range.

(U-Th)/He thermochronology (Flowers, Colorado) of apatites will be used to constrain the cooling history of rocks from ~ 75°C to 40 °C, with analyses of zircons applied in targeted areas to determine the timing of cooling through temperatures of 170-195 °C. The only existing low temperature thermochronological dataset is a zircon and apatite fission-track study in the Talamanca (Grafe et al., 2002). The data for two vertical transects yielded 9-10 Ma zircon dates that indicate rapid cooling through ~260 °C, and 5-2 Ma fission-track dates for chlorine-rich apatites that could either represent initial cooling below 170 °C or reheating associated with subsequent pluton emplacement. Acquisition of zircon (U-Th)/He data should help us distinguish between the initial cooling and reheating models of Grafe et al. (2002), and the apatite (U-Th)/He data will provide access to the crucial lower temperature portions of the thermal history.

Specifically, we plan 1) to resample and extend to higher and lower elevations the two vertical transects for which complementary fission-track data have already been acquired in southern Costa Rica (~12 samples per vertical transect), and 2) to acquire data for a suite of granitic basement samples in northern and central Costa Rica (12-15 samples). We also recognize the potential of the rich detrital record in adjacent basins, discussed above, to yield key, complementary insights to the basement thermochronology efforts. We will use part of the initial field effort to identify and sample promising sedimentary outcrops with which to carry out a reconnaissance detrital thermochronology effort (10-15 samples, mica ${}^{40}Ar/{}^{39}Ar$, apatite (U-Th)/He, double-dating by U-Pb and (U-Th)/He of zircon) to more fully explore the potential of the detrital record for constraining the evolution of surface uplift and unroofing in the region.

5.4.4 Integrated uplift and exhumation model. The results of our geomorphic and thermochronologic studies will be used to develop an integrated model for uplift and exhumation along the Costa Rican volcanic arc. This model will allow us to characterize the background signal of regional tectonics, and isolate the footprint of crustal displacements associated with continental crust formation (e.g., delamination). We will accomplish this by 1) linking the results of morphometric analyses, field geomorphic studies, and thermochronologic work, 2) placing our data within the developing geochronologic framework for Costa Rica, and 3) integrating our results with recent investigations of Costa Rican tectonics, seismology, and geodesy (e.g., Marshall et al., 2000, 2003; Fisher et al., 2004; MacMillan et al., 2004; Norabuena et al., 2004; LaFemina et al., 2006, 2007; Brandes and Winsemann, 2007; MacKenzie et al., 2008, Morell et al., 2007) as well with the results of the other research components of this project.

5.5 Geological mapping.

An important element in the proposed research program will be a set of geological surveys in the southern part of Costa Rica. Denyer and Alvarado, our co-PIs at the University of Costa Rica (UCR), have recently compiled a new geological map of the country. While quite detailed, it lacks uniform control in poorly accessible parts of the Talamanca Mountains. New targerted geological mapping studies will provide necessary structural background for the planned sampling campaigns, and for morphotectonic studies. This work will be organized and coordinated by Denyer and Alvarado..

Two broad goals of the mapping efforts are: 1) improved control for collected samples, especially in the high Talamanca Mountains. This work will be performed by UCR personnel and advanced students working on their theses; 2) detailed mapping of the western foothills of the Talamanca, with the goal of unraveling the sedimentary depositional history. This work will be supervised by UCR faculty, but most of the actual mapping will be done by students enrolled in annual field schools.

5.6 Logistics.

One of the key aspects of our research plan is to conduct a well-coordinated rock sampling and analysis campaign. We intend to carry out as many of our proposed analyses as possible on the same samples (or at least the same geological units, proximate outcrops etc.), thus avoiding the common difficulty of relating the insight from disparate analyses of rocks collected by different people with different goals. Furthermore, sampling locations for volcanic/plutonic rock analyses will be spatially coordinated with seismological sites, and with areas of morphotectonicfield surveys. Besides scientific integration, this strategy will allow us to use field work funds and personnel more efficiently. This will be specifically the case when deploying and servicing seismic stations.

Our main base of operations will be at the UCR in San Jose. We plan to acquire necessary equipment, and set up a state-of-the art rock samples preparation facility at the UCR. We will use facilities of the regional seismic monitoring network jointly operated by UCR and ICE (the national power authority) to store equipment used in the seismological field campaign, to carry out necessary repairs and maintenance, and to perform the preliminary seismic data manipulation. We will rely on UCR for field vehicles, and on ICE for potential sites where to place seismographs in the field.

Our field campaign in the south of Costa Rica will have logistical challenges, mainly having to do with rugged terrain and lack of passable roads in the jungle, as well as with environmental sensitivity of the area. The feasibility of the proposed fieldwork in the Talamanca Mountains has been extensively discussed with both the UCR co-PIs and with members of the science department of ICE. Dr. Denyer conducted consultations with the national police force responsible for operating helicopters, and secured a promise of cooperation. In addition, members of the UCR School of Geology will carry out a reconnaissance field campaign (funded by UCR and Rutgers) in the Talamanca region in the winter of 2009. Along with the initial survey of the geological structure, they will conduct discussions with authorities of the indigeneous population and the management of national parks and preserves in the area.

5.7 Work Plan and Timeline.

The proposed research program will start with field campaigns aimed at collecting relevant rock samples (volcanic, plutonic, xenoliths). These campaigns will be accompanied by efforts to improve existing geological maps, especially in the southern part of Costa Rica. Where possible, the basic geological mapping work will be integrated with the training element of the field schools. Most sample collection efforts are envisaged in the first two years of the project. Additional collection, if needed, will be done in years 3 and 4 of the project in conjunction with geophysical and geomorphological field campaigns. Rock samples analysis will proceed on pace with the field campaigns, and should be largely completed in the first 3 years of the project.

Scouting of locations for seismic deployment, and installation of 2-3 sites (using equipment owned by PIs) will take place in the first year. Also in the first year existing seismological data sets will be assembled, and analyzed for crustal structure and composition. Together with existing literature, these preliminary analyses will help guide the final designs of the seismic array. The bulk of the PASSCAL equipment (20 sensors) will become available after the summer of 2010 (per communication with B. Beaudoin, Director, PASSCAL), thus we plan installing the main seismic array during the second year of the project. The array will then stay in Costa Rica for 3 years, with periodic maintenance performed by UCR staff and Rutgers and LDEO participants (PIs and students). Deployment and service of the array (likely to require helicopter support in the high elevation areas of the Talamanca) will be coordinated with the rock-sampling program.

Morphotectonic and thermochronologic investigations will start with the analysis of existing maps, aerial photos, and DEM data to determine and quantify the landscape response to tectonic forcing and isostatic forcing in each of the three regions of Costa Rica, starting in the north. Digital terrain analysis using ArcGIS will be conducted primarily in the first three years of the project. Fieldwork (ground truthing of quantitative morphologic analysis, field mapping and sampling) is planned for each year of the project, and will proceed from north to south, covering field sites dictated by the map and digital terrain studies. Integration of morphotectonic and thermochronologic studies with BHC exploration investigations will occur primarily in the first three years of the project.

Field Schools will be held every year, either during the winter break in early January, and/or in early-middle June. Field school participants will collect data in support of the main research program, primarily on the western slope of the Talamanca Mountains, but also in other areas where large amounts of basic field mapping and/or sample collection are required.

6. Educational plan and Broader Impacts

This proposal provides a strong, well-integrated and international learning experience for participating students and faculty that has three elements: 1) a series of annual Research and Educational Workshops; 2) a Field School for participating U.S. and Costa Rican students, and 3) a Research Experience for Undergraduates Program (REU). The workshops and field schools will be held in Costa Rica, and will strengthen the already-excellent collaborative partnership between North American and Central American geoscientists. They will serve to foster a high-degree of communication and understanding between scientists from different disciplines. In addition, they will provide students with both intellectual and physical access to cutting-edge research.

6.1 Research and Educational Workshops

The annual Research and Education Workshops that will be held at the University of Costa Rica's Central American School of Geology (ECG-UCR) serve three purposes: 1) presentation and discussion of results, 2) project coordination among research groups, and 3) education and professional growth of participating students. These workshops will be based on the successful model of an NSF funded science-planning meeting held at ECG-UCR in January 2007 that developed ideas for this proposal. As the premiere geosciences degree-granting institution in southern Central America, ECG-UCR has excellent facilities and support infrastructure for hosting the planned workshops. Participants will submit abstracts in advance, and the meeting schedule and agenda will be well advertised. Invitations and financial assistance will be extended to a broad selection of faculty, graduate students and undergraduate students from participating US and Costa Rican institutions, and the meetings themselves will be open to the public. Talks and poster presentations in both English and Spanish will allow participants to share results. Focused group discussions and planning sessions will provide a venue for assessing progress and coordinating ongoing research efforts. A brief summary report and workshop agenda will be distributed. These workshops will be followed by a fieldtrip to one or more field-research sites that will emphasize the way in which field observations contribute to solving the specific geological problems engendered by the overall research program.

The workshops will contribute to the education and professional development of participating graduate and undergraduate students. In addition to research presentations and discussion, Mini-Short Courses will be offered in which faculty and graduate students provide hands-on training in research skills (e.g. preparing abstracts and posters that effectively communicate research; planning, conducting and documenting a research program in both laboratory and field settings; technical training to use seismometers, GIS-systems and other research-enabling technologies; etc.) Undergraduate and graduate students from both the U.S. and Costa Rica will experience firsthand the impact of collaborative international research. We are fortunate to have involved in this project several US-based graduate students who were undergraduate students at ECG-UCR. These individuals will play a prominent role in the workshops and will serve as important role models for a new generation of young scientists.

6.2 Field Schools

The geological mapping element of this proposal is especially amenable to student involvement, so much so that we plan to broaden it to include a formal educational element. Recognizing geological structures and developing models for their interrelationship and history is an extremely important aspect of the earth sciences, and one that has traditionally served as an entry point into the discipline for students. Field Schools will thus have some of the elements of a traditional field camp, in that they will teach students the basics of field observation, mapping and interpretation. They will differ from such camps in being focused on hitherto unmapped regions of Costa Rica, for instance in the Talamanca Range. The goal is to have students make real contributions to defining the geological relationships and to collectively produce a new geological map of publishable quality. Since 1976 the Geology School of UCR has operated a field camp course as one of the last requirements of Bachelor in Geology. This course consists of fieldwork lasting 2 to 3 weeks, working on detailed geologic mapping of a specific area of about 12 km^2. The scale of work is 1:10 000, and the final maps vary from this scale to 1:25 000. This course is typically guided by at least three professors specialized in the particular of the area. After this field camp, the students are guided to make a report, where they describe the geology, geomorphology, petrography, structural geology and other aspects of the area. Building on this framework, TROPICS field school students will work in two-to-three person teams, each supervised by a scientist skilled in fieldwork. Results of their work will contribute to the overall research program, and will provide them with opportunities to further their professional development, e.g. through presenting these results at workshops and conferences.

6.3 Research Experience for Undergraduates Program (REU Supplement)

Undergraduate participation in this project will be enabled through a multi-student REU directed by PI's Marshall (Pomona University) and Rogers (CSU Stanislaus). Funds for this are included primarily in the Rutgers budget. Marshall is a Geosciences Councilor with the Council on Undergraduate Research (CUR), and has supervised several undergraduate research projects in Costa Rica (Marshall et al., 2005; Marshall 2005; 2008). Both of the participating universities are designated Hispanic Serving Institutions (HSI), with predominantly underrepresented minority student populations. The REU program will actively recruit these students, and will leverage existing NSF funded minority recruitment programs at these campuses (e.g. NSF S-STEM Scholarship; Louis Stokes Alliance for Minority Participation). The program will cover the students' travel to Costa Rica, provide a stipend for the duration of field school, and support their participation in professional meeting to present research results. Additional funds will be available for materials and supplies for student research and meeting presentations. A team-mentoring program will be developed at participating institutions, including bi-monthly meetings of students and research advisors, goal oriented research agendas, and progress reports and presentations. Where possible, graduate students involved in the proposed research will also serve as mentors for undergraduates. In addition to the annual project workshops, REU students will present their research results at professional conferences such as AGU, GSA, and SACNAS (Society for the Advancement of Chicanos and Native Americans in Science).

7. Dissemination of Results.

Data sets and data products collected by this project will be archived according to the policies of specific disciplines, e.g. seismic data from the PASSCAL array will be placed in a data management system of IRIS consortium. Rutgers University will host a web site, which will inform the Earth Science community about the preliminary findings of the project. We will present our work at typical venues (AGU, GSA), and publish results in major peer-reviewed journals.

8. Project management.

This project includes 12 PIs from 7 US institutions representing very diverse subfields of Earth Science, and numerous collaborators in Costa Rica. The success of the project requires several different kinds of management: operational management, field-specific management, and synthesis (integration of results). By operational management we mean the routine administrative tasks required for fieldwork, workshops etc., and in fostering communications between participants. Operational management will be performed by Rutgers University (Levin) and University of Costa Rica (Denyer). By disciplinary management we mean first and foremost supervision and training of students, coordination of activity by PIs in different institutions, lab operations, fieldwork planning, data and samples archiving etc. We envisage frequent (3-4 times a year) PI coordination conferences using telecommunication and/or online tools. In the table below we associate individual PIs with specific elements of the proposed research program. The integration of results from different components of the project will naturally arise from yearly workshops, which will include an annual session in which we will synthesize our results.

Topic	Key personnel	work	Yr1	Yr2	Yr3	Yr4	Yr5
Coordination	Levin, Denyer	admin.	X	X	X	X	X
Xenoliths	Herzberg, Gazel	Field & analysis	X	X	X		
Seismics	Menke, Levin,	field	X	X	X	X	
		analysis		X	X	X	X
Mapping	Denyer,Turrin,Alvarado,	field	X	X			
Sampling	Alvarado, Feigenson, Turrin, Flowers, Kelemen, Vogel	field	X	X	X		
Geochemistry/petrology	Vogel, Carr, Alvarado	analysis	X	X	X		
Isotopes O,U-Pb detrital zircons	Vogel	Analysis	X	X	X		
Isotopes	Feigenson	analysis	X	X	X		
Geobarometry	Kelemen	analysis	X	X	X		
Age Dating	Turrin, Flowers, Bowring	analysis	X	X	X	X	
Morphotectonics	Marshall, Rogers	Field and analysis	X	X	X	X	X
Workshops	Levin, Marshall, Denyer, Menke	training	X	X	X	X	X
Field Schools	Denyer, Marshall, Menke	training	X	X	X	X	X
REU	Marshall, Rogers	training	X	X	X	X	X

PRIOR NSF SUPPORT (full statements in the supplementary documents)

BOWRING Collaborative Research: The Anatomy of an Archean Craton: The Evolution of the South African Continental lithosphere EAR –9526702 total $396,774 07/01/1996-08/31/2003 (with extension). Supported a PhD thesis (Schmitz). Publications: Schmitz and Bowring, 2001, 2003abc; Carlson et al., 2000; Hanson et al, in press; Hanson et al., 2004; Schmitz e al., 2004ab.

CARR, FEIGENSON, TURRIN co-Pi Carl Swisher EAR-0507924: $287K 07/05 – 06/07, Volcanic growth rates and elemental fluxes from Central America. Significant publication Carr et al., 2007.

LEVIN EAR 0242291 Retreating-trench,extension and accretion tectonics (RETREAT). 10/02/-10/08 (no-cost extended), $269,000 Papers supported by the grant include: Levin et al., 2002; Plomerova et al., 2006; Levin et al., 2007; Salimbeni et al., 2007,2008; Piana et al. 2008

MENKE NSF OCE 02-21035; Integrating Geophysical Data into New Axial Volcano Magma Chamber Model, 10/01/02-09/30/05; $163,658; 2 years with additional 1 year extension.Papers published: Menke et al., 2007; Menke et al., 2006; Menke, 2005; West et al., 2003.

HERZBERG: NSF EAR 0228592 Petrology and mineral chemistry of crust and mantle fragments in an Archean ophiolite from the North China Craton 01/2003-12/2004, $74,562; Two publications resulted from this grant: Herzberg (2004), Polat, et al., 2006

FLOWERS. EAR-071145, Tectonics, Collaborative Research: Quantifying the stability of continents using advances in apatite (U-Th)/He, ^{4}He/^{3}He, and U/Pb thermochronology, 09/01/07 to 08/31/09, $193,144. Publications supported by this grant are Flowers (in press) and Flowers et al. (in review,), and Ault et al. (in review) (Ault is Flowers' first PhD student).

MARSHALL has not served in the PI capacity before. His PhD was supported by the grant Tectonic Escape of the Panama Microplate? Kinematics Along the Western Boundary, Costa Rica (EAR-9214832), 1993-1995. Also, Marshall is "senior personnel" on the grant *Comprehensive Scholarship Program for Mathematics, Physical, Biological, and Computer Science Majors*, (S-STEM) National Science Foundation, Scholarships in Science, Technology, Engineering, and Mathematics Program, $584,000 2007-2010, P.I. Barbara Burke.

VOGEL Structure, conditions and magmatic processes within an active Volcano: Analysis of samples from boreholes drilled into the conduit of Unzen Volcano. EAR-0309773, 2003-2007 $100,624, Publications resulting from this award: Browne et al., 2006ab; Almberg et al., 2007; Vogel et al., 2008.

KELEMEN NSF grants to Kelemen as PI (lead institution) active in 2000-07 are OCE 0426160: … *Thermal Histories of Fast- and Slow-Spreading Oceanic Crust* (Kelemen, 8/04, 24 mos, $516,557); EAR 0337677: *Rhenium Osmium … and PGE Systematics of Lower Oceanic Crust* (Kelemen & Peucker Ehrenbrink, 1/1/04, 36 mos, $299,725); EAR-0125919: *Convection of the Mantle Wedge in Subduction Zones* (Kelemen, Hirth & Billen, 5/15/02, 24 mos, $99,971); OCE-0118572: *Detailed Study of Focused Melt Transport in the Upper Mantle …* (Kelemen & Hirth, 11/15/01 24 mos, $134,265); EAR-0087706: *Tectonic Consequences of Lower Crustal Convective Instability* (Kelemen & Jull, 3/1/01, 24 mos, $126,516); and EAR-9910899: *… Genesis of Continental Crust via Arc Magmatism* (Kelemen & 8 others, 7/1/00, 48 mos, $1.7M). Kelemen was lead proponent and co-chief on ODP Leg 209, "*… Mantle Peridotite along the Mid-Atlantic Ridge from 14 to 16°N*". 50 papers and two books were published in 00-07 on these projects and other grants with Kelemen as co-PI, with many presentations at meetings. During 00-07, one PhD thesis supervised by Kelemen was completed (Braun, WHOI/MIT). Kelemen is advisor or co-advisor to 5 grad students at Columbia (Collier started 04, VanTongeren 05, Homburg 06, Crowley 07, Streit 07). Kelemen supervised projects in 00-07 for 16 at WHOI, MIT, Brown, UCSB, UWW, & Columbia (**Postdoc**: Hanghøj, Jull, Müntener, Billen, Montesi, Holtzman, Hersum; **PhD**: Behn, Rioux, Kelly; **MSc**: Greene; **in progress**: Warren, Morgan, Austin, Coon) and sat on PhD (Katz 06, Elkins, Waters, Jackson, Renick) and MSc (Johnsen 07, Buono, Du) committees.

ROGERS had no prior NSF support

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