The Tectonic Evolution of the Madrean Archipelago and Its Impact on the Geoecology of the Sky Islands

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Abstract—*While the unique geographic location of the Sky Islands is well recognized as a primary factor for the elevated biodiversity of the region, its unique tectonic history is often overlooked. The mixing of tectonic environments is an important supplement to the mixing of flora and faunal regimes in contributing to the biodiversity of the Madrean Archipelago. The Sky Islands region is located near the actively deforming plate margin of the Western United States that has seen active and diverse tectonics spanning more than 300 million years, many aspects of which are preserved in the present-day geology. This tectonic history has played a fundamental role in the development and nature of the topography, bedrock geology, and soil distribution through the region that in turn are important factors for understanding the biodiversity. Consideration of the geologic and tectonic history of the Sky Islands also provides important insights into the "deep time" factors contributing to present-day biodiversity that fall outside the normal realm of human perception.*

Introduction

The "Sky Island" region of the Madrean Archipelago (located between the northern Sierra Madre Occidental in Mexico and the Colorado Plateau/Rocky Mountains in the Southwestern United States) is an area of exceptional biodiversity and has become an important study area for geoecology, biology, and conservation management. No single factor is responsible for the biological richness of the Madrean Archipelago. Rather, numerous biologic, geographic, and geologic factors have fortuitously combined to create the unique setting of the Sky Islands, including: (1) Geographic setting at the convergence of four major ecoregions: two major floristic zones (Neotropic and Holarctic) and two major faunal realms (the Neotropic and Nearctic); (2) location at the convergence of three major climatic zones (tropical, subtropical, and temperate); (3) predominantly NW - SE trending topography, which encourages northward movement of neotropical species (the product of regional tectonic forces); (4) Complex topography combined with large elevation gradients (resulting from the interaction between geology and weathering factors); and (5) A bimodal annual rainfall distribution (due to geographic and climatic factors). Many of these are the result of the continental-scale deformation that has occurred over the past several hundred million years in response to plate tectonic activity. Thus, "deep time" processes that operate over timescales of tens to hundreds of million years need to be appreciated when considering the various sources responsible for the elevated biodiversity of the Sky Islands. The discussion of the relationship between topography and the biodiversity of the Sky Island region is continued in the companion paper (Coblentz and Riitter, this proceedings).

Tectonic Evolution of the Southwest

The Sky Islands form a sub-region of the Southern Basin and Range province which bridge the low elevation saddle in the North American Cordillera between the Sierra Madre Occidental and the Colorado Plateau – Southern Rocky Mountains (figure 1). This part of the Cordillera has been created by the interactions between the Pacific, North American, Farallon (now entirely subducted under North America) and Juan de Fuca plates and is rich in geology features, including major plateaus (The Colorado Plateau), large elevated areas that are actively extending (The Basin and Range), a major continental rift system (The Rio Grande Rift), an active hot spot (Yellowstone), and the remnants of a Paleozoic mountain belt of Himalayan proportions.

The tectonic history of the Sky Island region can be divided into three general stages: (1) Deposition of thick Paleozoic limestone sequences about 300 million years ago during a period when the area was sea floor, (2) A predominately compressional phase associated with Mesozoic to early Cenozoic (200 to 60 million years ago) as the North American Plate converged with and overrode the Farallon Plate and the East Pacific Rise, and (3) A transition from compressional to extensional tectonics in the mid-Cenozoic (about 30 million years ago) in response to the ending of the Farallon Plate subduction and the transition to transcurrent motion between the Pacific and North American plates along the Western North American margin.

During most of the Cretaceous and the early Tertiary, subduction of the Farallon plate beneath North America produced widespread compressional tectonics throughout most of the region. As this subduction evolved, a zone of deformation propagated eastward producing "thin-skinned" deformation (often referred to as the Sevier Orogeny) where the lithosphere was sufficiently weak. The characteristic style of this deformation phase was folding and thrusting of Paleozoic and Mesozoic sedimentary rocks from west to east along steep westward dipping thrust faults. The Sevier thrust faulting formed a large mountain system of north-south trending topography that has subsequently collapsed due to the weakness of the lithosphere in this region. Some Sevier topographic features are preserved in the faulted Basin and Range

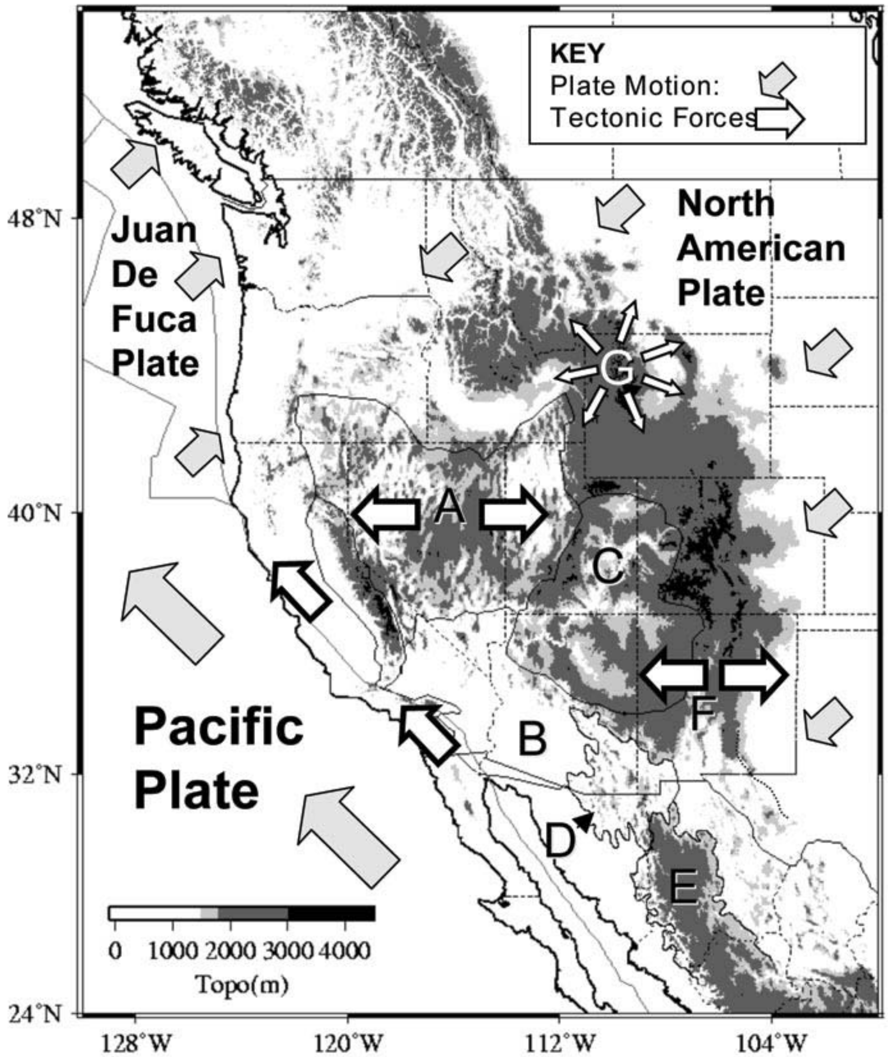

Figure 1—Tectonic setting of the Western United States Cordillera. Gray arrows indicate absolute plate motion of the North American, Pacific, and Juan de Fuca plates; white arrows schematically illustrate approximate present-day tectonic motion. Note that the tectonic setting of the Sky Island regions needs to be viewed in the context of the surrounding four provinces: The Basin and Range (A and B), the Colorado Plateau (C), the Madrean Archipelago (D), the Sierra Madre (E), and the Rio Grande Rift (F), (G) is an active hotspot (Yellowstone).

sequences as well as along the western margin of the Uinta and Wind River Mountains. As the deformation progressed further east during the Late Cretaceous and Early Cenozoic (c. 60 Ma) into stronger parts of the North American plate, deeper parts of the crust become involved (often referred to as the Laramide Orogeny). Mountain ranges formed during this deformational phase include the Rocky Mountains, the San Juans, the Gore Range and the Sawatch Range in Colorado; the Sangre de Cristos and Sandias in New Mexico; the Uintas and Wasatch Range in Utah; the Black Hills in South Dakota; the Bitterroot Range in Montana and Idaho; the Bighorns and Wind River Range in Wyoming; and the Franklin Mountains of West Texas. This topography is characterized by uplifted blocks of crust that include Phanerozoic sedimentary rocks as well as the underlying Precambrian igneous and metamorphic rocks that make up the core or basement of the continental crust. In the Huachucas, Precambrian granite, Paleozoic limestones, and Cretaceous sedimentary and volcanic rocks are together along faults that date back to the Laramide Orogeny. These Laramide structures are presented in dissected and isolated form due to subsequent Basin and Range faulting and are evident in many of the Sky Islands of southeastern Arizona.

Starting about 30 Ma the elevated topography of the cordillera began to collapse in response to a transition from compression-dominated subduction of the Farallon plate off the western coast of North America to transcurrent motion between the Pacific and North American plates. Extensional tectonics produced by this gravitational collapse is responsible for the dominant present-day topographic fabric of *en echelon* north-south oriented mountain ranges separated by valleys filled with erosional detritus. Extensional processes during this period also formed the several large mountain ranges including the Tetons in Wyoming and the Sierra Nevada in California.

Present-day Physiography of the Southwest

The Southwest can be roughly divided into five provinces based on tectonic history and topography (figure 2). A brief description of each of the provinces follows.

The Colorado Plateau is a major tectonic and physiographic province in the Southwestern United States that has behaved as a relatively stable, coherent block during much of Phanerozoic time. The plateau is roughly circular with an area of about 240,000 km^2 centered on the Four Corners region of the Southwest United States. The southern edge of the province roughly correlates with the Mogollon Rim in Arizona. To the east, the bounding edge of the plateau extends into New Mexico, though Tertiary volcanic rocks of the White Mountains and the Gila Highlands obscures its exact location. A site of marine deposition during Cretaceous time, the Colorado Plateau now stands about 2 km above sea level, implying that nearly 2 km of uplift occurred during Cenozoic time. The greatest amount of uplift has apparently been along the southwestern margin of the Plateau, where elevations are often 0.5 km greater than in the center (Lucchitta 1989). Study of vesicular basalts indicates that the southwest Colorado Plateau stood at least 1 km above sea level during Oligocene time (Sahagian and Proussevitch 2000). The Colorado Plateau has apparently remained a relatively rigid block, resistant to faulting, a view reinforced by paleomagnetic studies that show coherent rotation of the plateau (e.g., Bryan and Gordon 1986; Wells and Hillhouse 1989). Given that the Colorado Plateau is in isostatic equilibrium now (the free air gravity anomaly is nearly zero; Thompson and Zoback 1979), and assuming that it was in the past, then some growing mass deficiency at depth must have compensated for its uplift. Several mechanisms have been proposed to account for the most recent phase of uplift, including thermal expansion, crustal thickening, and delamination of the lithosphere (Bird 1979, 1984; McGetchin et al. 1980; Morgan and Swanberg 1985; Spencer 1996; Thompson and Zoback 1979).

The Rio Grande Rift is one of the major continental rifts in the world and a major structural element of the Southern Rocky Mountain region. The rift was recognized as a major continental rift in the 1970's (e.g., Riecker 1979), and since has been extensively studied from both a geologic and geophysical perspective (e.g., see the extensive review in Baldridge et al. 1995). The physiography of the rift is the product of three principal factors: (1) extensional tectonics (that began between 27 and 32 Ma and lasted 10 to 12 Ma) when regional extension reactivated the southern Rocky Mountains, which are a major north-trending zone of weakness that had developed during Sevier and Laramide orogenies; (2) volcanism (that increased slowly after a hiatus in the middle Miocene, 20 to 13 Ma); and(3) regional uplift of the Southern Rocky Mountains and adjacent areas between about 7 and 4 Ma (Chapin and Cather 1994). The current topography along the rift is characterized by broad flat lying topography along the rift axis, bounded by sharp escarpments (e.g., the Sandia, Manzano, and Sacramento Mountain ranges in New Mexico) that expose Paleozoic sedimentary rock and formed major NS alignment of topography.

The Sierra Madre Occidental is a large volcanic plateau in Western Mexico extending parallel to the Pacific coastline for more that 1,200 km from the United States-Mexico border (31°N) to the Trans-Mexican Volcanic Belt (21°N). The total aerial distribution of the volcanic rock is more than 300,000 square kilometers. The volcanics resulted from the eastward subduction of the Farallon Plate along the western Cordillera of North America prior to the mid-Tertiary. By the mid- to late-Tertiary subduction gradually ceased and a broad zone of normal faulting, more than 3,000 km long, was developed in the Western United States and in Northern Mexico. This extension formed the Basin and Range Province in present-day Nevada, Utah, and Arizona. The topography of the Northern Sierra Madre is characterized by high average elevation (~1900 meters) and large topographic range (~2800 meters). In contrast to the other Southwestern tectonic provinces, the topographic relief of the Sierra Madre is not the product of elevated mountain ranges, but rather incised canyons (e.g., the Barranca de Cobre)—reflected in the largest elevation standard deviation of all the Southwestern tectonic provinces (~340 m). The western edge is quite steep while the eastern topographic gradients from the Sierra Madre into the central Mexican Plateau are relatively small. The elevation distribution is fairly flat about the mean value and shows a skewness to lower elevation values, reflecting a sampling of lower elevations along the coastal plain of Sonora. The regional fabric of the Sierra Madre is aligned in a NW-SE orientation (N11°W +/- 9°) and is thought to facilitate dispersal for tropical flora and fauna moving in response to climatic change.

The Madrean Archipelago spans the region formed by the common borders of Arizona, New Mexico, and the Northern Mexican States of Sonora and Chihuahua. The term "archipelago" metaphorically reflects the insular nature of the roughly 40 isolated mountain ranges (Sky Islands) in this region. The topography of the Archipelago is characterized by isolated mountain ranges elongated in a NNW-SSE direction; the average orientation for the entire province is N10°W +/- 11°. There are many area of locally very large vertical relief (more than 2,000 m across the Santa Catalina and Pinaleno Mountains), with a topographic range of about 2,000 meters, a mean elevation of about 1,300 meters with a standard deviations of about 200 meters. The mean elevation of the Sky Islands is significantly lower than the Colorado Plateau (~1900 m) and the Sierra Madre (~1910 m) leading to its identification as a physiographic "pass" that has facilitated the longitudinal mixing of flora and fauna between the Sonoran and Chihuahuan Deserts.

The Basin and Range province, characterized by its disrupted crust, lies to the west and south of the relatively coherent Colorado Plateau and west of the Sky Island region (note that the Sky Islands are a part of the Southern Basin and Range). Topography in this region is characterized by isolated mountain ranges elongated along a northwest-southeast oriented axis (N15°W +/-16°). While elevations in this province approach 3,400 m (e.g., in the Spring Mountains near Las Vegas), the average elevation of the province is relatively low (333 m) with many parts slightly above or below sea level (e.g., in the Salton Trough of Southern California). The area has been stretched and extended as much as 100% since the early Tertiary. The earliest stages of extension began by latest Oligocene time in the southern parts of California and Arizona in the United States, and in Durango, Chihuahua, and Oaxaca, Mexico. By early Miocene time, strong extension had begun on major normal faults across much of Mexico (e.g., Henry and Aranda-Gomez 1992), and metamorphic core complexes were forming along the Colorado River between California and Arizona (Howard and John 1987) and along the southern edge of the Colorado Plateau in southern Arizona (Rehrig and Reynolds 1980). Pliocene and Quaternary eruptions accompany incipient rifting in the Jalisco block that lies at

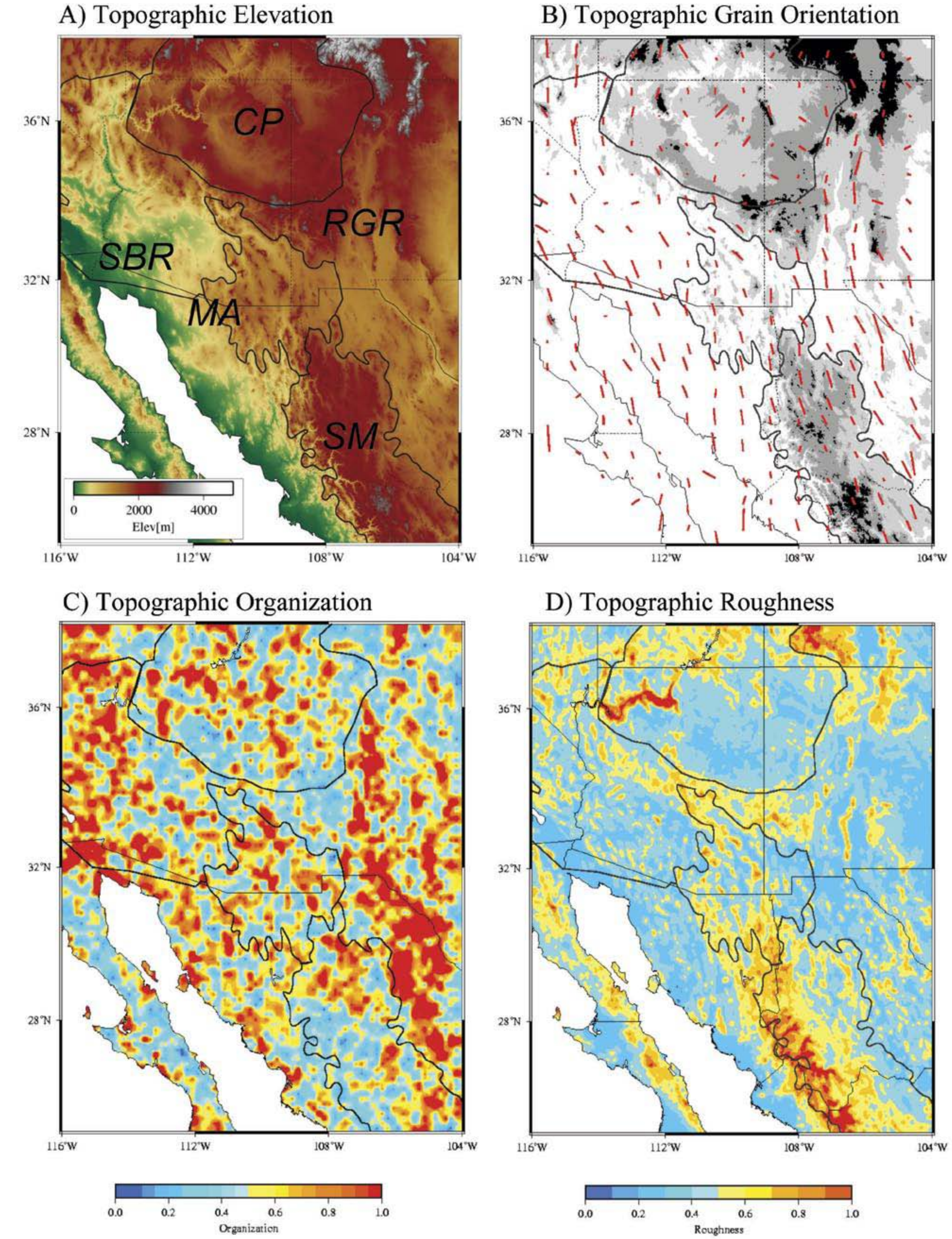

Figure 2—Spatial distribution of various descriptive topographic quantities calculated using the algorithms discussed in the text. (A) Topography of the study. (B) Vectors of the topographic fabric orientation computed for the topography for a 80 km x 80 km analysis window. Vector lengths are scaled by organization with longer vectors indicating greater organization. (C) Topographic organization computed within a 10 km x 10 km window. (D) Topographic roughness computed within a 10 km x 10 km window. Tectonic province abbreviations: CP: Colorado Plateau; RGR: Rio Grande Rift; SM: Sierra Madre Occidental; MA: Madrean Archipelago; and SBR: Southern Basin and Range.

the southern edge of the Sierra Madre Occidental in Mexico (Wallace et al. 1992), possibly indicating that the Basin and Range province is growing to the south.

Topographic Analysis

Topography is a fundamental geophysical parameter that contains valuable information about the geodynamic, tectonic, and climatic history of a region. It is also by far the most readily measurable data and most accurately known information used to describe the Earth. As a consequence, topographic features have historically invited many studies that have sought to extract the information contained in the "character" of the Earth's surface.

The complex tectonic history of the Western United States invites a closer look at the character of the topographic fabric with the aim of evaluating its relative contribution to the remarkable biodiversity of the Sky Island region.

The topography of the Madrean Archipelago (figure 2a) is characterized by insular mountain fabrics that bridge the relatively low elevation gap between the Sierra Madre Occidental and the Colorado Plateau (note the variation in the mean elevation for the elevation distribution shown in figure 3e). Using the topographic analysis method discussed in Coblentz and Riitter (this proceedings), the spatial variation in the topographic orientation, organization, and roughness are shown in figure 2. Histograms for the topographic fabric orientation, organization, roughness, land cover diversity (see discussion) and elevation for the five tectonic provinces are shown in figure 3. The character of the topographic parameters is discussed in the following sections.

The orientation of the topographic fabric (figures 2b, 3a) is primarily controlled by crustal deformation in response to tectonic motion between the North American and Pacific plates, and the resulting tectonic stresses have resulted in boundary-parallel topographic fabric, most evident in the California Coastal Ranges and the Baja California Peninsula. This observation is corroborated by the good correlation of NW-SE regional orientation of the topographic fabric within the five provinces with their proximity to the North American-Pacific plate boundary. In general, the strength of the topographic fabric with the various provinces reflects the degree of active tectonics. In the relatively undeformed Colorado Plateau, the topographic fabric shows considerable scatter about the mean orientation (N1.5^{o}W +/-17^{o}) and poor topographic organization (0.79 +/- 0.22). In contrast, topography along the Rio Grande Rift is closely distributed about a mean orientation of N3.2^{o}W+/-9^{o} with a relatively high degree of organization (1.07 +/- 0.35). The orientation of the topographic grain in provinces geographically closer to the plate margin (Sierra Madre, Madrean Archipelago, and Southern Basin and Range) are rotated toward the NW, subparallel to the relative motion between the North American and Pacific plates. There is a high coherence of the topographic grain within the Sierra Madre and Madrean Archipelago provinces that are also characterized by low standard deviations about the mean grain orientation N10^{o}W +/- 11^{o} and N11^{o}W +/- 9^{o}, respectively.

Topographic organization (figures 2c, 3b) is a measure of the strength of the fabric, with regions of good orientation coherence having high organization levels. The two tectonic provinces with the strongest tectonic activity (Rio Grande Rift and Southern Basin and Range) have the highest levels of organization (mean values of 1.07 +/- 0.35 and 1.02 +/- 0.32, respectively). The insular nature of the mountain ranges of the Madrean Archipelago province results in an intermediate organization level (0.85 +/- 0.27), while the high level of drainage-related incisement in the Sierra Madre effectively lowers its organization level to that of the Colorado Plateau (0.76 +/- 0.22 and 0.79 +/- 0.22, respectively). The distributions are all skewed toward higher organization, indicating the existence of highly organized topographic regions within each of the provinces. The low level of topographic organization in the Sierra Madre province (0.76 +/- 0.22) is attributable to the high level of drainage-related incisement present in this region; in general, the development of drainage networks has the effect of lowering the organization relative to topography of tectonically active areas. The organization distributions are all skewed toward higher organization, indicating the existence of highly organized topographic regions within each of the provinces.

Topographic roughness (figures 2d, 3c) correlates with relief, standard deviation of elevation, average slope, and standard deviation of slope. A number of tectonic and geomorphic processes can contribute to topographic roughness including high heat flow (tectonically young regions), high erosion, and incision rates. Because no single process is responsible for topographic roughness it is possible to draw only first-order generalizations from figure 2d. The Sierra Madre and the Madrean Archipelago have the highest mean roughness values (0.23 +/- 0.06 and 0.20 +/- 0.04, respectively) reflecting the large amount of topographic relief in these two provinces. In the case of the Sierra Madre province, this is particularly evident in the high roughness region along the southwestern margin of the mountain range. It is interesting to note that the incision-related processes that are responsible for low organization levels in the Sierra Madre province are also responsible for its high level of roughness—in general, canyon cutting by rivers generates rough but poorly organized topography. The Colorado Plateau has a low mean roughness value, which is also evident in figure 2d (with the obvious exception of the very rough Grand Canyon region—which has the largest roughness value in the data set). Similarly, the Rio Grande Rift, dominated by the relatively smooth rift valley, shows a relatively low roughness values (0.16 +/- 0.04), though the negative kurtosis value for the distribution indicates significant spread about the mean value (skewed towards rougher values), reflecting the existence of rough escarpments along the margin of the rift. We note that all the provinces have similar standard deviations, indicating that the spread of the roughness values about the mean roughness values. All distributions are skewed toward higher roughness, suggesting the existence of rough outliers in the distribution (particularly for the CP and SM provinces).

Discussion

This contribution has been an attempt to summarize the geologic and tectonic history and a presentation of how this history has shaped the topographic landscape of the Sky

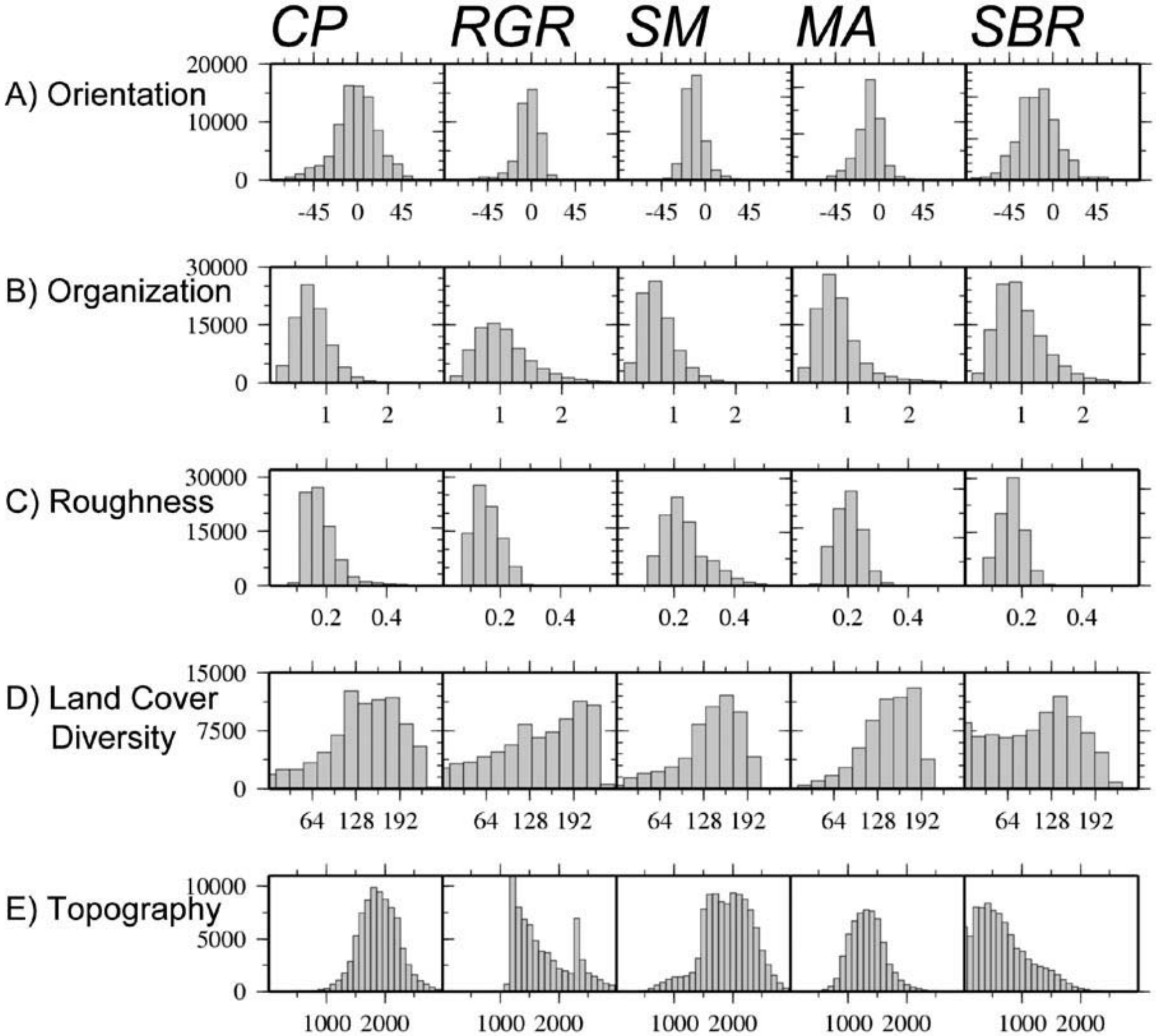

Figure 3—Histograms of the (A) topographic orientation, (B) organization, (C) roughness, (D) land cover diversity (see discussion in Coblentz and Riitter, this proceedings), and (E) elevation for the five tectonic provinces shown in figure 2a. See figure 2 for tectonic province abbreviations.

Islands. In doing so, I have sought to bring into sharper relief the important role played by "deep time" processes in the geoecology of the Sky Islands. The complex tectonic history of the Sky Island region has produced a unique ensemble of topography and geology, which is an important contribution to the biodiversity of the region. The Sky Islands are characterized by a unique mix of bedrock geology spanning several hundred million years of geologic history, and all three principal rock types are present including (1) Igneous rocks in the form of Precambrian and Tertiary granites as well as Mesozoic to Quaternary volcanics; (2) Metamorphic rocks of Precambrian and Mesozoic age including gneisses and schists; and (3) Sedimentary rocks of mostly Paleozoic, Mesozoic and Cenozoic age in the form of limestones, sandstones, quartzites, and shales. The bedrock geology has been mixed by several stages of tectonic deformation, and the diverse soil types resulting from this heterogeneous rock mix invariably has influenced the biodiversity in the Sky Island region.

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