Introduction

The Southwest evokes images of dusty desert landscapes beset with narrow mountain ranges, of the vast and colorful expanses of the Colorado Plateau and land of the Diné, of Monument Valley, and perhaps of the Spanish and Mexican cultural heritage. Terrains range from barren, seemingly lifeless, deserts to verdant, forested mountains, and vegetation zones from Sonoran to Alpine. Its varied landscapes have challenged explorers and settlers; beckoned artists and adventurers. They may elicit wonderment and awe but can be haunting, even intimidating. The beauty of the Southwest is often stark, typically subtle.

The Southwest of the United States is a region that defies precise geographic definition, eschewing neatly defined physiographic subdivisions. Most usages of the term ‘Southwest’ include the arid and semiarid region stretching from west Texas across New Mexico and Arizona to southern California (Fig. I.1; see also Plate 1). This vast expanse of desert, the heart of the Southwest, comprises dominantly the Basin and Range and Colorado Plateau physiographic provinces. The Basin and Range province, typifying the southern parts of New Mexico and Arizona and northern Mexico, is that region characterized by a distinctive physiography of narrow mountain ranges separated by broad, sediment-filled desert basins. In contrast, the Plateau is that region of *northern* New Mexico, *northern* Arizona, western Colorado, and much of Utah characterized by broad plateaus, deeply incised canyons, and mainly flat-lying sedimentary strata. In central Arizona, between the low desert basins of Phoenix and Tucson (330–730 m above sea level) and the high plateau of Flagstaff (2100 m) lies a region of ridges and valleys. This area, transitional in its physiography and exposed geology, is referred to by geologists as the ‘Transition Zone.’ These

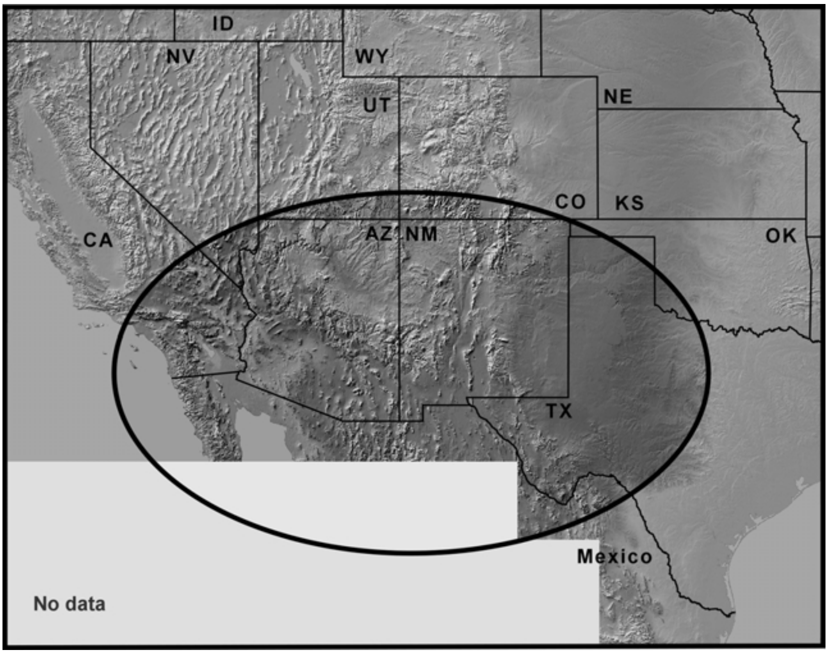

Fig. 1.1. Physiographic map of part of the western USA and northern Mexico compiled from digital elevation data. The Southwest of North America, as loosely defined in this book, is shown in the oval inset. Modified from world-wide web pages by Andrew D. Birrell. See also plate 1.

provinces acquired their physiography only a few tens of millions of years ago, long after most of the crust in the Southwest had formed. The region known as the Southwest includes, as well, part of the southern Rocky Mountains and western Great Plains, the latter being part of the stable core of North America. Arguably, the Southwest includes southern Nevada and Utah, and possibly southern Colorado. Naturally, the Basin and Range and Colorado Plateau provinces constitute a major focus of this book, but relevant parts of adjacent provinces are also included. These tectonic provinces are described further in Chapter 8. Geological features do not stop at international boundaries, and therefore many discussions and examples presented in this book lie in the states of Chihuahua and Sonora of northern Mexico. Typically, however, geological features are better studied on the northern side of the international border. These areas therefore garner more attention in this book.

The Southwest is a land of contrasts. Human presence ranges from log hogans and pre-Columbian adobe villages to state-of-the-art radio telescopes imaging the edges of the universe. Indigenous, Hispanic, and Anglo cultures mingle. Similarly, rocks exposed in the Southwest are diverse and varied. They range from ancient sediment and lava, now recrystallized by burial in the Earth's crust to depths exceeding 20 km, to lava flows so young that they devastated Anasazi cornfields. Volcanism ranged from passive effusion of basalt flows, similar to that occurring in Hawaii today, to catastrophic explosions of silicic magma that devastated wide regions of the continent and probably had global consequences. Sedimentary depositional environments ranged from deep marine to inland sea to, of course, terrestrial. In the Southwest the geology is youthful. Faulting remains active, with its consequent hazard for human existence. Volcanism occurred as recently as one thousand years ago and will happen again. The intersection of geology with social issues is manifest.

Geologic time scale, modified from the Geological Society of America 1998 Geologic Time Scale (A. R. Palmer, compiler). Permian-Triassic and basal Cambrian boundaries are from Bowring and Erwin (1998). Names and ages of subdivisions of the Proterozoic conform to international convention. Only the major time intervals are shown. The shaded region on the time scale that precedes each chapter indicates the time interval discussed in the chapter. Significant geologic events are indicated along the side. The ages of some of the major boundaries remain considerably uncertain, thus undoubtedly the time scale will continue to be modified with the results of more precise age determinations.

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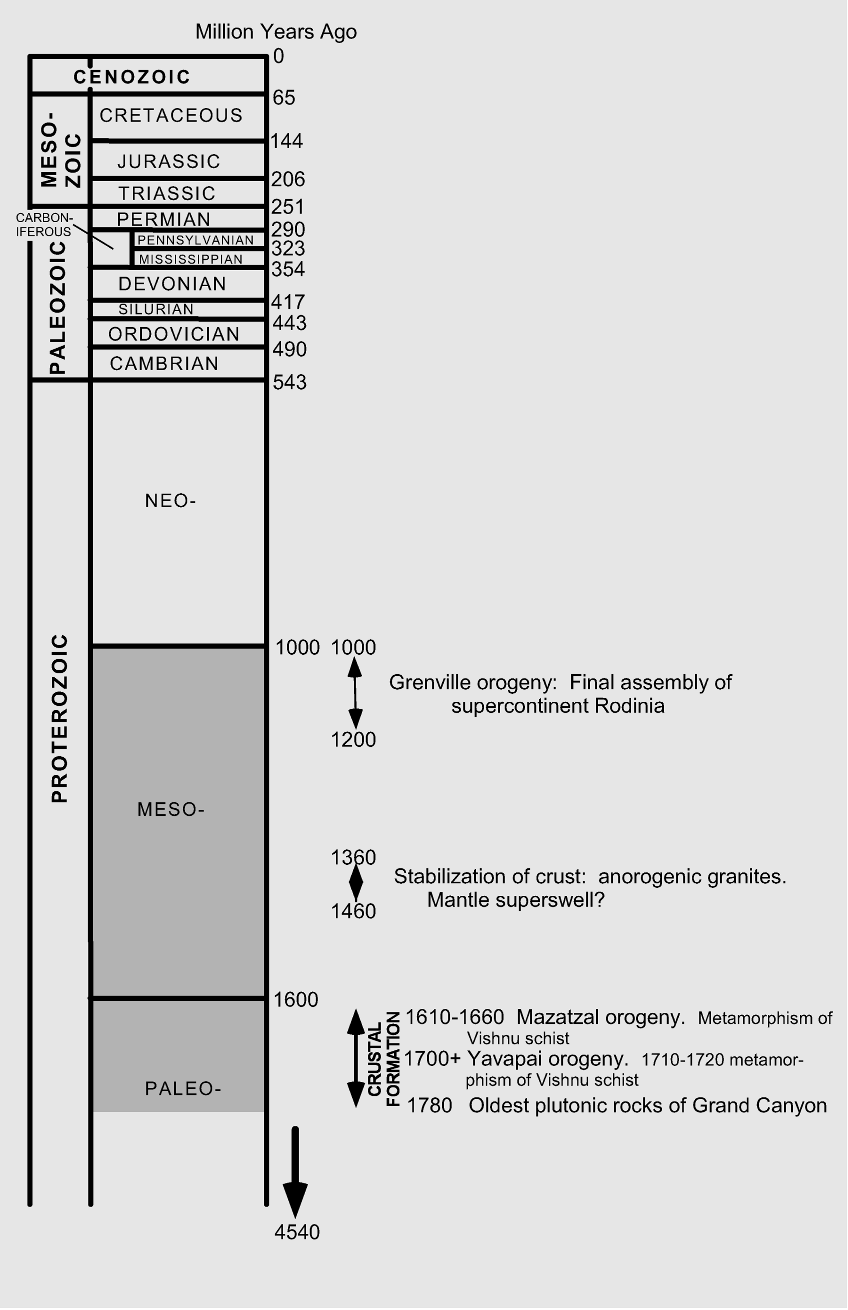

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1

Growth of a continent: formation and stabilization of continental lithosphere

Paleoproterozoic to Mesoproterozoic

Cutting through the Gunnison uplift of western Colorado, the Gunnison River exposes rocks of Paleoproterozoic and Mesoproterozoic age in the famous Black Canyon. Seen here are schists and gneiss metamorphosed more than 1.7 Ga. These rocks are among the oldest in the Southwest, forming the basement upon which later, stratified rocks were deposited. Although their exact relationship to rocks exposed in central Arizona is uncertain, they are typical of rocks underlying all of the Southwest but exposed only discontinuously. The name 'Black Canyon' derives from the dark aspect the rocks present.

1.1 Progress in deciphering the Precambrian

The geologic story of the Southwest begins far back in the Precambrian, that period of the Earth's history prior to 543 Ma. It was during the Precambrian that the underpinnings of the crust were formed from the underlying mantle by a variety of processes. Yet events of this great age in the Southwest, as in most other areas of the world, have been difficult to interpret. For more than a century geologists have recognized that Precambrian rocks record events of regional and global importance, but it was not possible until relatively recently to make significant progress in deciphering these events. Earth's Precambrian history remained obscure for several reasons. Over great regions of the continents, rocks of Precambrian age are covered by younger sedimentary rocks, hiding them from direct observation except in deep wells. Where exposed, much of the Precambrian is highly metamorphosed and/or deformed on all scales, destroying or obscuring features of the original rocks that aid in interpreting their genesis. Most importantly, though, rocks of Precambrian age, even where unmetamorphosed, are nearly devoid of the fossils that were essential for the relative age determinations and regional correlations upon which an understanding of geological events was based. Only in the Cambrian period beginning around 543 Ma did organisms suddenly develop the hard body parts that enabled their remains to be preserved well.

Despite the difficulties, tremendous advances have been made in understanding Earth's history before the Cambrian and continue to be made at an increasing rate, not least in the Southwest. Significant progress in understanding the Precambrian awaited the advances in radiometric dating techniques made possible by development of the mass spectrometer. Although the modern mass spectrometer was pioneered in the 1930s, its refinement and commercial availability following World War II led to an explosion of information related to the Precambrian beginning in the 1950s (White and Wood, 1968; Nier, 1989). Several isotopic systems are now routinely used to date crystalline rocks of Precambrian age. Other tools and techniques, such as high-sensitivity electron and ion microprobes and precise $^{40}Ar/^{39}Ar$ dating, allow analysis of individual grains, and even of zones within grains, of minerals such as zircon, xenotime, and monazite. Microanalytical dating and analysis techniques have made it possible to unravel thermal histories and cooling rates of crystalline rocks. In addition, geologists now have a plate-tectonic framework, based on modern analogues, in which to interpret crust-forming events. As a result of these developments, great potential exists for refining our knowledge of the paleogeography and assembly of crustal building blocks, of the process by which newly formed crust is stabilized, and of relationships between plutonism, deformation, and metamorphism of lower and middle crust. Study of older and deeper levels of the crust allow geologists to better understand modern processes.

Although the age of the Earth is now known to be about 4.54 Gyr (Dalrymple, 1991) (Fig. 1.1), the oldest known rocks, from the Northwest Territories, Canada, are 4.055 Gyr old and zircon crystals, from western Australia, are as old as 4.40 Gyr (Froude *et al.*, 1983; Bowring *et al.*, 1989; Wilde *et al.*, 2001). In the United States, the oldest dated rocks are 3.6–3.7 Gyr, although zircons from older rocks incorporated into quartzite are as old as 3.96 Gyr (Mueller *et al.*, 1992). Thus, the term 'Precambrian,' simply assigned to rocks lying stratigraphically below rocks of Cambrian age, incorporates over four thousand million years – almost 88% – of the Earth's history, and the Proterozoic spans almost two thousand million years. Successively younger time units (both eras and periods) tend to represent shorter intervals of time, reflecting simply the greater preservation of younger rocks and the enhanced ability to resolve and interpret more recent events. In the Southwest, rocks are no older than a mere two thousand m.y. (Proterozoic Eon), the age of crustal formation in this region. For this age, the terms 'Precambrian' and 'Proterozoic' are interchangeable (Fig. 1.1).

This chapter, and the next two, focus on Proterozoic rocks of the Southwest. The present chapter describes the formation of continental crust in the Southwest, which occurred in the Paleoproterozoic and Mesoproterozoic. In understanding crustal formation, surface volcanic and tectonic processes must be inferred. Yet most of the Precambrian rocks exposed in the Southwest were formed or metamorphosed, not at or near the surface, but rather in the middle crust, at depths typically of 10–20 km, during assembly of the continent. Thus, a challenge presented to geologists is to interpret surface events from a middle crustal record. Crust-forming events recorded in the Southwest were part of the formation of the larger continent of Laurentia. Laurentia comprised the ancestral **craton** (Box 1.1) of North America, Greenland, parts of Scotland, Scandinavia, and possibly Argentina. For part of the Proterozoic, Laurentia was embedded in a still

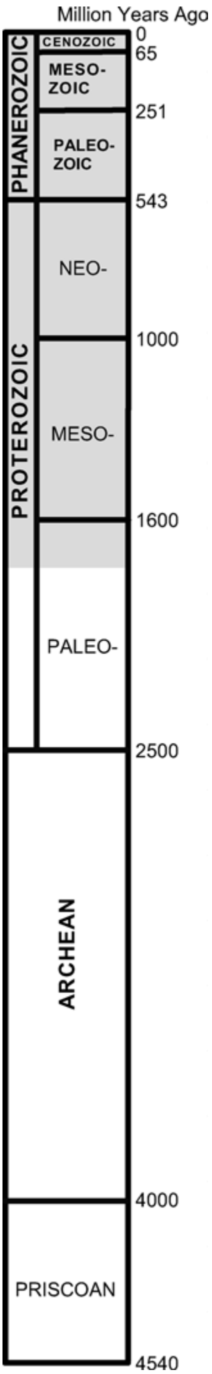

Fig. 1.1. In this simplified time scale is shown the period of the Earth's history (shaded) covered in this book. Time before the lowermost unit of the Paleozoic (Cambrian) is typically referred to by the more general term 'Precambrian.' The oldest rocks in the Southwest (approximately 1.84 Gyr old) (Hawkins *et al.*, 1996) are much less than half the age of the Earth.

Box 1.1 Craton The relatively stable interior of a continent, typically composed of Archean and Proterozoic rocks. These ancient rocks are exposed in areas called 'shields' because of their subdued topography and low domal forms, but are elsewhere buried beneath younger sediments and sedimentary rocks. Because of its buoyancy and strength, the craton generally does not experience the rapid subsidence and uplift, and the deformation, which occur at continental margins. Cratons are not wholly without deformation, however. Structural basins, domes, and arches do form on cratons, and major deformational events initiated at margins may extend onto the cratons.

larger continent, a *super*continent. It persisted as a continental entity until it was fragmented at the end of the Proterozoic, when the present continents began to take their forms (Dalziel, 1997). Thereafter, the largest part of the original continent of Laurentia retained the name 'Laurentia' until the reassembly of continental fragments into the supercontinent of Pangea.

1.2 Distribution of Proterozoic rocks

Rocks of Proterozoic age *underlie* most of the Southwest. In contrast, they are *exposed* only in limited areas, where uplift creates elevation differences and allows younger rocks to be thinned and stripped away, either by erosion or tectonic processes. Such is the case in many mountain ranges throughout the Southwest. In some places, such as the Grand Canyon of the Colorado River and the Black Canyon of the Gunnison River, a combination of uplift and deep erosion by rivers has exposed Proterozoic rocks.

In the Southwest, Proterozoic rocks are exposed in two major transects that fortuitously strike perpendicular or nearly so to major age boundaries (Fig. 1.2). The first of these is a northwest-trending belt stretching 500 km from Sonora, Mexico, and southeastern Arizona to Nevada and southeastern California. Much of this area lies in the physiographic region referred to as the 'Transition Zone' between the Colorado Plateau in northern Arizona and the Basin and Range province to the south. The second major outcrop belt comprises exposures in the cores of various ranges of the Rocky Mountains extending from southern Wyoming through Colorado and New Mexico to west Texas and northern Chihuahua (Karlstrom and Bowring, 1993). Proterozoic rocks crop out in other areas of the Southwest, of course, but not with the continuity and lateral extent that have allowed major crust-forming events of the Proterozoic to be discerned.

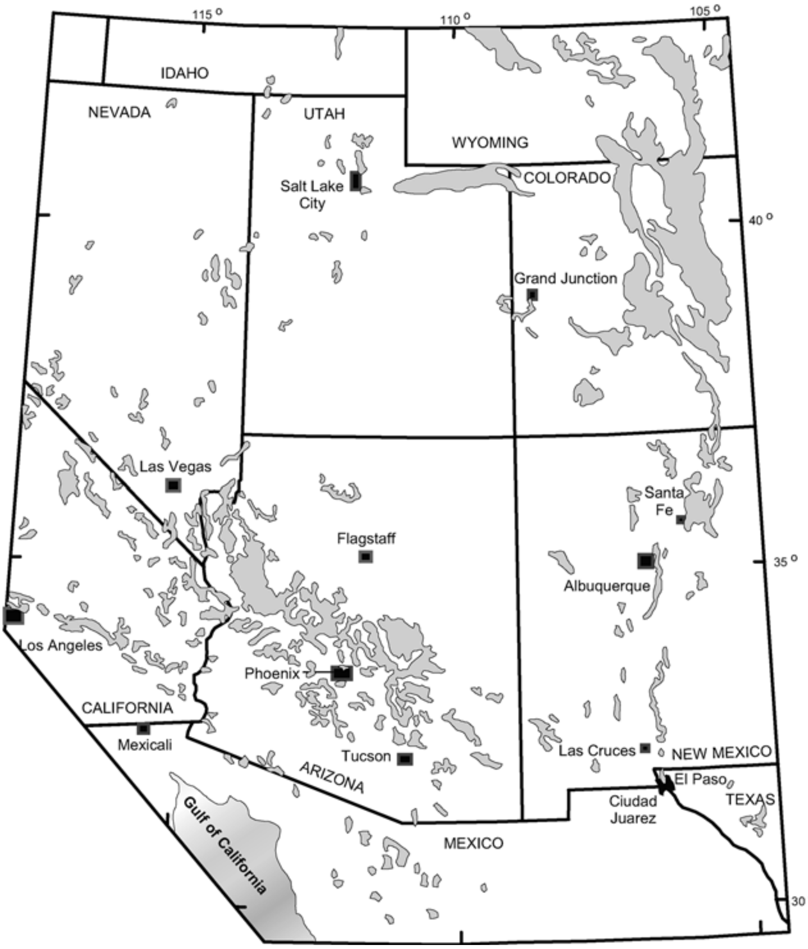

Fig. 1.2. Rocks of Precambrian age underlie younger rocks throughout the Southwest and adjacent regions. They are exposed mainly in two belts, a northwest-trending belt through central Arizona and in ranges of the Rocky Mountains from west Texas to Wyoming. Simplified from Condie (1981).

1.3 Age provinces

To better understand these rocks and to appreciate their significance, it is necessary to relate them to the Precambrian rocks that make up the North American craton as a whole and to understand how the craton was constructed. Much of the present understanding of the processes by which