



# **HOFSTRA UNIVERSITY FIELD TRIP GUIDEBOOK**

**GEOLOGY 143A – Field Geology of Northern  
Arizona**

*27 March – 03 April 2010*



**View of the Great Unconformity of the Grand Canyon separating flat-lying Paleozoic strata from block-faulted and tilted Proterozoic strata. View southward from the less-traveled north rim of the canyon taken by the author July 2004.**

**Field Trip Notes by Prof. Charles Merguerian**

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**Hofstra University Geology 143A  
Northern Arizona Field Course, 27 March – 03 April 2010**

*Field Trip Guidebook by:  
Prof. Charles Merguerian  
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**Arizona – a Macro View**

Physically, he was not what you would call an imposing individual. He stood all of 5' 6" tall and weighed a mere and scrawny 120 pounds. His resume was as unimpressive as his physical stature. Thirty-five years old, a Civil War veteran who lost his right arm at Shiloh, a small time professor of geology at a no-name college with so few connections or clout that he had to finance his own makeshift excursion into a region dominated by a hellish landscape unseen anywhere else on the earth and a river best described as the river of no return. His name was John Wesley Powell and what he lacked in size he more than made up for in determination, energy, an incredible optimism and a natural skill for leading men (Figure 1).



**Figure 1** – John Wesley Powell in 1871.

The Lewis and Clark Expedition in the early years of the 19<sup>th</sup> century opened up large and unknown areas of the American frontier. By May of 1869, the transcontinental railroad joined east and west at Promontory Point in Utah. Miners, trappers and adventurers delved deep into the hidden recesses of the Sierra Nevada, Yosemite and Death Valley. The secrets of this vast wilderness hidden behind the isolation of the once uncharted areas of the western frontier were now common knowledge. Only one area of the American continent still remained a mystery and away from prying eyes. The maps merely said UNEXPLORED to the region of the American Southwest-an unbelievably immense area larger than most states or European countries. Adventurers knew that it was mostly arid and that the Colorado River ran through it. They knew that the ground was riddled with deep chasms that led to unknown and whispered dangers that would best be left to the mysterious forces that lurked just beneath the surface.

John Wesley Powell would not be put off by the vague rumors and the senseless feelings of uneasiness of lesser men and with 9 other courageous souls set off from the Green River Station in the Wyoming Territory at noon of May 24, 1869. On August 13, 1869, John Wesley Powell reached the Grand Canyon and the Colorado River in Arizona and the source of the vague whispers and fears of this mysterious land lay before him. He wrote in his diary of the dread that he felt.

“We are now ready to start our way down the Great Unknown...We are three quarters of a mile into the depths of the earth...We have an unknown distance yet to run; an unknown river yet to explore. What falls there are, we know not; what rocks beset the channel, we know not; what walls rise over the river, we know not. Ah, well! We may conjecture many things. The men talk as cheerfully as ever...but to me the cheer is somber and the jests are ghastly.”

And now, a century and a quarter later, the mystery still remains for most of us as it did for Powell and his men. It seems that the more we learned over the years about Arizona, the more mysteries that were solved, the greater our fascination became. It is truly an enchanted place with far more treasures than we will be able to see.

With over 2 Ga (billion years) of geological history, Arizona has a very complex and intense story to tell. From afar, Arizona appears a most inhospitable place. It is truly an exotic painting constructed by an especially harsh brush (Figure 2). Consider the sun-bleached Sonoran and Mojave Deserts, the torn and furrowed surface replete with thousands of canyons, some merely feet across and hundreds of feet deep, and other hidden places, eerily desolate and holding a fatal attraction to the unwary. Arizona is nature's cruel way to introduce you to oppressive and exhausting summer heat, rivers that may flow for up to two weeks in a good year and a flora and fauna that adapt to extreme climatic challenges and outlandish physical demands. Yet this place still retains, even in its overwhelming harshness, a miraculous beauty. To be sure, if life exists anywhere in Arizona, it is tenacious!

Humans have existed in Arizona for well over 10,000 years. The earlier Paleo-Indians were essentially nomadic, always in search of woolly mammoths, bison and bear on what was then the grasslands of southern Arizona. Hanging on by their fingertips on the ragged edge of survival, they left no art, no artifacts, and no architecture.



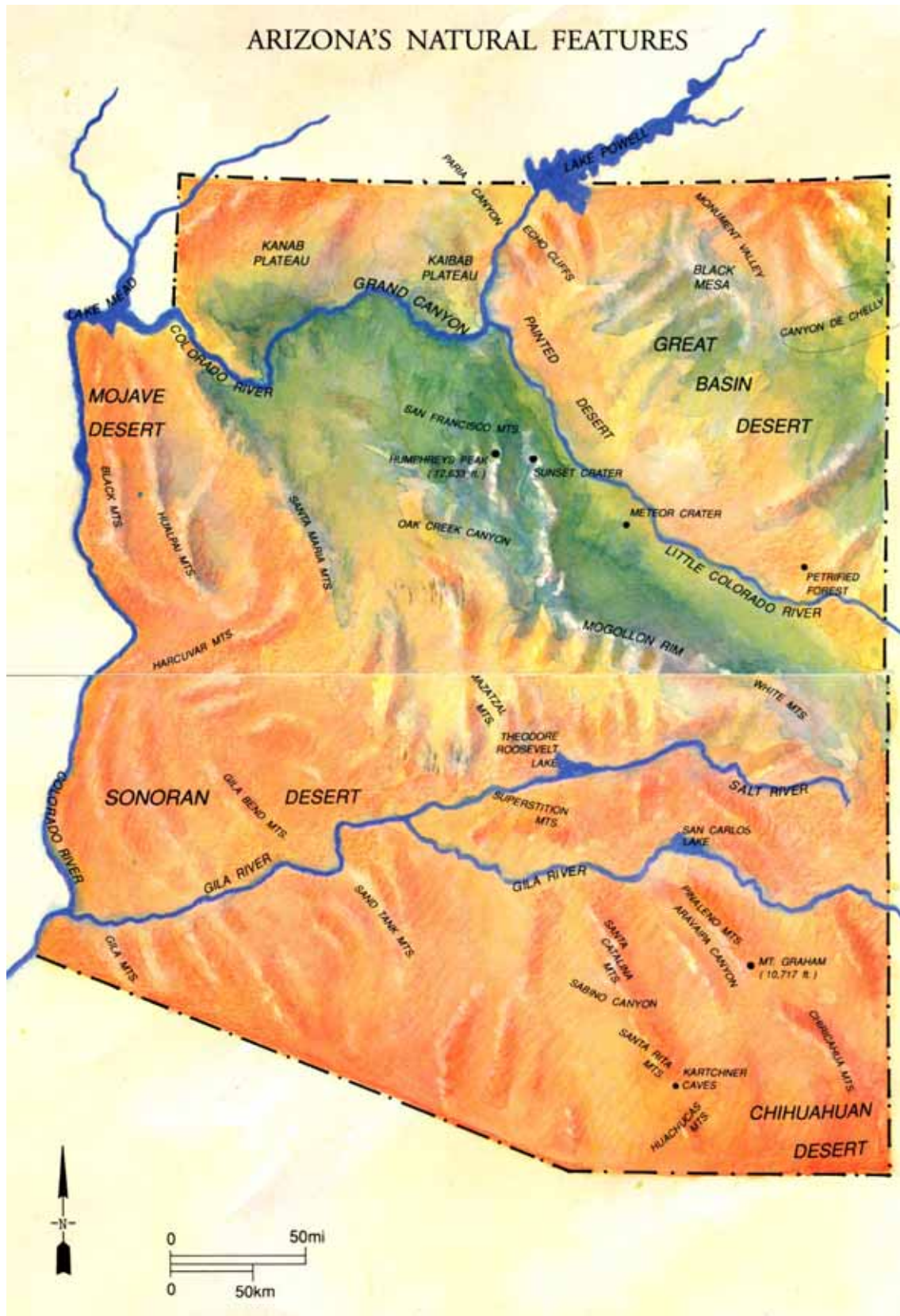


Figure 2 – Map showing Arizona’s natural features (Check, 1991, p. 46-47).



About 300 B.C., inhabitants of this region were cultivating food, most probably an idea that originated in Mexico. Interaction between peoples of the different regions became more commonplace and by 1000 A.D., several very important cultures were firmly established in Arizona. These cultures consisted of the Salt River valley desert **Hohokam** Indians, the **Mogollon** Indians of the mountains, the highly enigmatic **Anasazi** Indians of the high desert of northeastern Arizona, and the **Sinagua** tribesmen of the Verde Valley and southern Colorado Plateau. Clinging to life in an otherwise lifeless land, the Hohokam created a huge system of irrigation canals miles from the river. Nearly a thousand years later, the city of Phoenix rose from the ashes and the success of the Hohokam canals.

Arizona's present day Indians, the Hopi, are undoubtedly descendants of a prehistoric culture dating back 2,500 years. Called the Anasazi by the Navajos, it was a term originally thought to mean "the ancient ones." A newer translation of the term carries a more ominous message, "enemy ancestors". Modern day scholarship seems to suggest that cannibalism in the later years of the culture may have fostered an intense dislike of the Anasazi by neighboring tribes (their meat was tough and expensive!).

Evidence suggests that sometime around 1300 to 1400 A.D., life among the dominant tribes became increasingly unstable. These prehistoric peoples died off, wandered off, or were assimilated elsewhere. Anasazi communal cities and Sinagua settlements along with Hohokam lands gave evidence that these people had begun to develop defensive postures in the construction of their pueblos. The Casa Grande of the Hohokam has the undeniable air of a ringed fortress. Yet their records show nothing about the uneasiness that caused these cultures to abandon their existence at nearly the same time in history. Coincident cultural demise does not seem to be an alternative here. There must be some unifying theme that escapes the modern mind to explain or rationalize the departure of what were essentially successful and enterprising tribes.

Now well versed in Arizona history (the abridged version), we will begin our field trip by traveling north on US 17 from Phoenix, a town originally conceived as an oasis in the Valley of the Sun (Figure 3). Phoenix has long fought against and been reluctant to accept its desert environment. Tapping into both the Salt and Verde Rivers as the Hohokam Indians did, Phoenix created an enormous watershed that has fed its gluttonous appetite for verdant golf courses. Numerous suburbs rose out of the desert sands with fanciful names as Fountain Hills and, of course, Scottsdale. We can expect temperatures in the 100° range but, of course, we are led to believe that it does not feel hot because the humidity is so low. This must be some sort of Arizonian desert humor! Easterners know the difference between a humid New York summer in July and the conditions inside a pizza oven.

## **Acknowledgements**

No trip of this scope and magnitude is possible without the help of many individuals and agencies. Help from people on the ground in AZ is always an important part of any off-campus experience. In this connection, my colleagues **Starr Lanphere** and **Thomas McGuire** have provided great input into the localities and resources I have included in this field trip guidebook

and they will hopefully join us on parts of our trip. None of these trips would have been possible without the assistance and fortitude of the late **John Gibbons** of Hofstra University who first implored me to organize and conduct such undertakings. This series is continued in his honor. The assistance of the National Park Service in granting admittance into Grand Canyon National Park, Sunset Crater and Wupatki National Monuments and the Petrified Forest National Park is gratefully acknowledged. In addition to these individuals and agencies, the rollicking staff at Duke Geological Laboratories and especially **G. Glasson** and **H. Manne** have been instrumental in completing the guidebook in a timely manner.

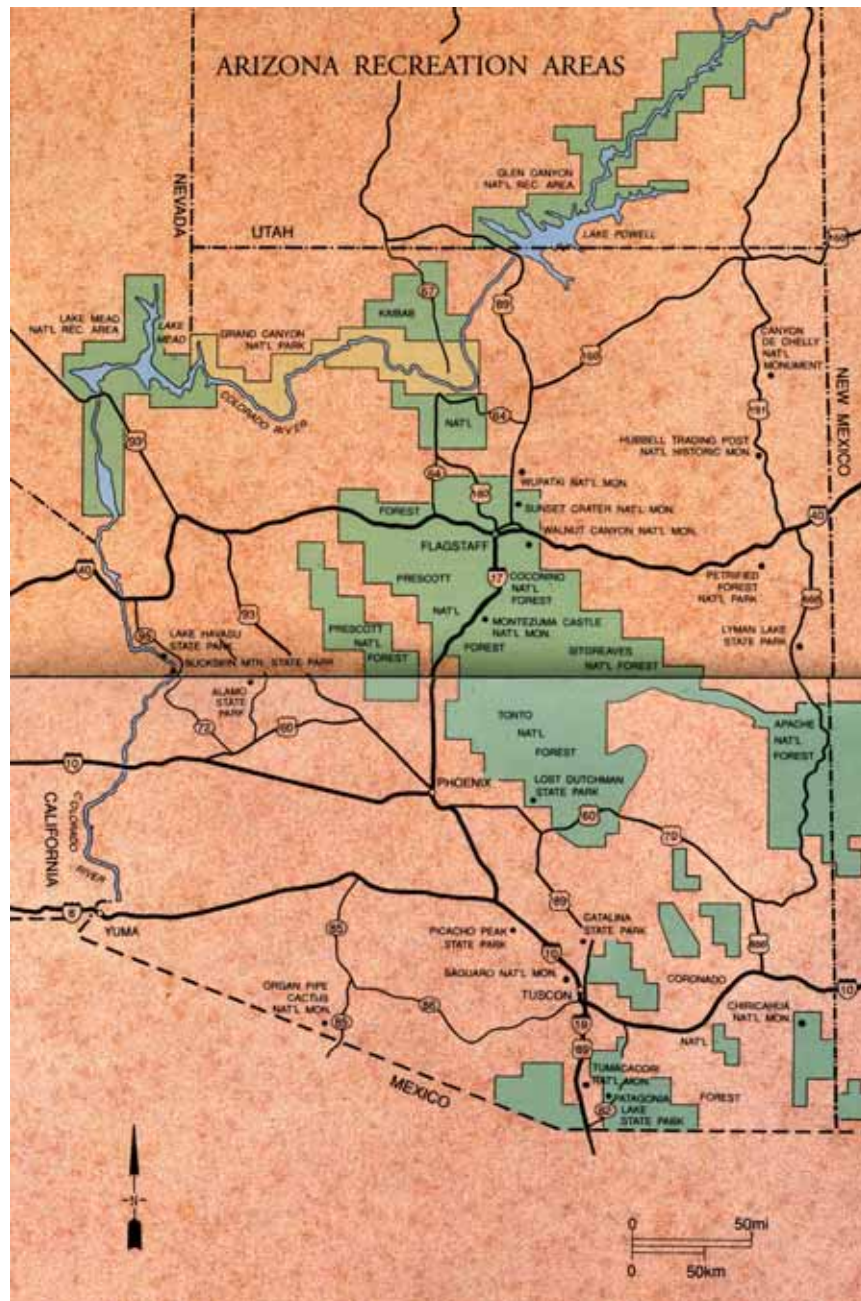


Figure 3 – Map of Arizona’s recreational areas (Cheek, 1991, p. 224-225).

# Field Geology: Northern Arizona

Geology 143A – Hofstra University  
Prof. Charles Merguerian

**Purpose and Goals:** Geology 143A is an undergraduate level introduction to field interpretation of volcanic and sedimentary sequences and geological structure of the southern **Colorado Plateau** and the related **Basin and Range**, through the **Transition Zone** geologic provinces. Emphasis will be placed on the tectonic, volcanic and sedimentary depositional processes observed and what conclusions can be derived from the field data gathered. The primary goal of this field trip is to provide a hands-on introduction to geologic field observation and the methods needed to integrate conclusions based academic learning, data collection, and observed field relationships.

## Final Itinerary

**Pre-trip: Wednesday, 17 March 2010** (4:00 PM – 6:00 PM) – Class meeting (162 Gittleson) to discuss regional geology of Arizona and to give out trip information packages.

**Saturday, 27 March 2010** – US Airways Flight 90 to Phoenix departs JFK Airport at 9:45 AM [**You Will Arrive at Airport 2-1/2 hours early = 7:15 AM SHARP!**] and will later arrive at Phoenix Sky Harbor Airport at 12:32 AM (AZ time). Secure van and drive north toward **Sedona**, AZ. Time permitting, along the way examine exposures at **Sunset Point** where the **Shylock Fault Zone** which separates two Proterozoic metamorphic terranes and the related Transition Zone topography. The **Bradshaw Mountains** are visible to the west (~7000' elev.) from the Sunset rest area. Stop north of Camp Verde to observe the southern exposure of the **Mogollon Rim**. Passing into and out of three National Forests called the Tonto, Prescott, and Coconino, elevation changes from a high desert environment to forest and mountain with an elevation of over 7,000' in Flagstaff. As we rise higher into the mountains, just east of I-17 and the Little Colorado River lies the Petrified Forest and Meteor Crater near Winslow, Arizona - a good town for standing on any corner. After passing through Sedona for a brief pit stop and time permitting do some food shopping for the week. After a brief tour of Sedona, we will secure our lodging in **Cottonwood** for the next three evenings and have a fine dinner together. Watch for the rabbit as we enter each night.

**Logistics for the First Three Nights:** Stay at the **Dead Horse Ranch State Park** campground in Cottonwood, AZ. We have a reservation for three cabins (Antelope [1], Bobcat [2], and Hawk [8]). Bed frames and mattresses are in the cabins but sleeping bags (good down to 20°F) and towels will be necessary. Electricity is provided for recharging batteries and a cookout area is on site for our use. (675 Dead Horse Ranch Road, Cottonwood, AZ 86326; (928) 634-5283; <http://www.azstateparks.com/index.html>).

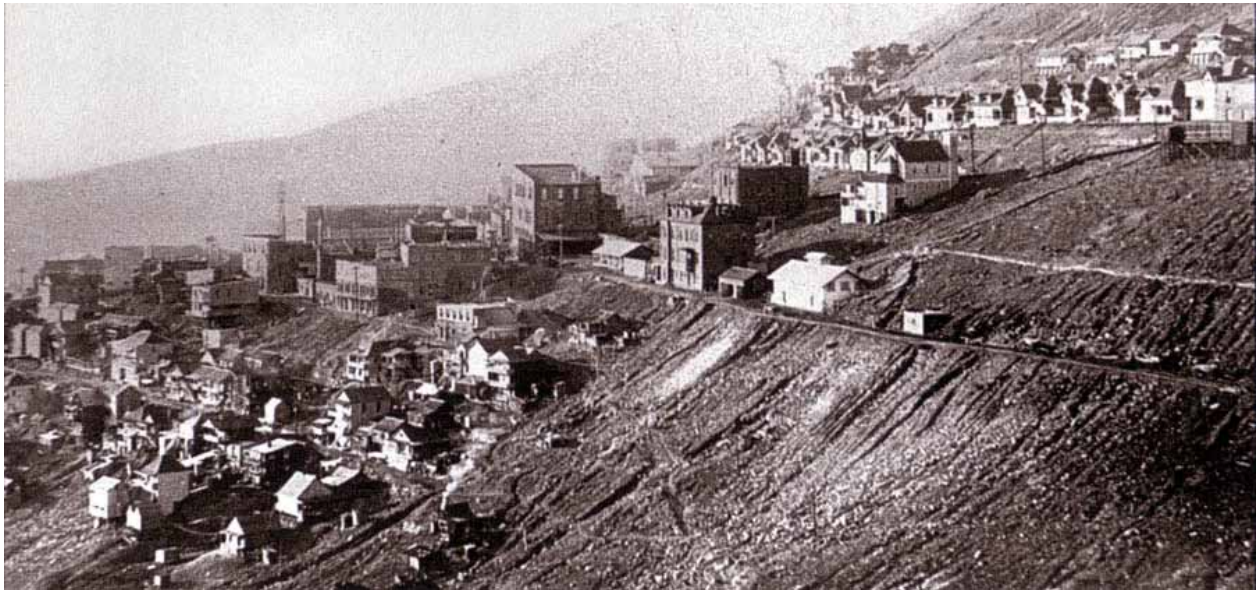
**Sunday, 28 March 2010** – Today we'll start with the Proterozoic geology of **Jerome** including theories concerning copper mineralization, visit mining museum and tour historic Jerome. Study the economic geology of the Jerome Mining District at **Jerome State Park** and enjoy the video.



While inside, be sure to see the mineral museum and outside observe mining equipment and a view of metamorphic rock types of the Transition Zone Terrain. Later we will examine the structural and metamorphic geology of Mingus Mountain on Route 89A including road cuts of the Cleopatra meta-rhyolite and associated submarine metamorphic rocks.

The **Yavapai** were first native American miners in the area of what is now called Jerome. Later the Spanish came looking for gold but found copper instead. Modern mining history dates back to 1876 and prospectors started the **United Verde Copper Company** by staking a claim in 1883. The high costs of operating caused the company to fold two years later in 1885. Senator William A. Clark in 1888 buys the **United Verde Mine** and built the **Montana Hotel** (which burned in 1903). By 1889, Clark successfully ran the mine and built a RR connecting Jerome and Clarkdale to the Santa Fe-Prescott-Phoenix line.

One of many to follow, a destructive fire started underground in 1894 when massive sulphide ore ignited and created uncontrolled heat and pollution. “Fire Eaters” (specially trained Spaniards from the Rio Tinto tin mines), could not control the disaster. Starting in 1897 fires erupted in tunnels and mining ceased for long periods. By 1914, a major fire erupted at the 400’ level and mining came to a halt. As a result, surface mining techniques replaced underground methods. Now, 87 miles of tunnel underlie the city of **Jerome** so watch your step!



**Jerome Arizona, circa 1907.**

Mining in Jerome for 77 years resulted in a tremendous economic boom for the area. By the end of 1930, the mines produced 20,314,000 tons of ore, yielding:

1,959,098,900 pounds of copper  
1,009,800 ounces of gold, and,  
34,586,000 ounces of silver

Over \$1 billion dollars of copper, gold, silver, zinc, and lead were mined here at a significant human toll. Many injuries and deaths resulted from the mining efforts. Indeed, United Verde (and later, Phelps-Dodge) provided its own hospital and doctors.

After our visit to Jerome and vicinity, drive westward on Route 89A over **Mingus Mountain** to examine metamorphic Proterozoic rocks and to see the fabulous jointed granite dells of **Prescott** and **Watson Lake Park**. We plan to do some hiking in these areas. Return back to Cottonwood via Route 89A back across Mingus Mountain where we will do some hiking at the peak (Woodchute Trail # 102 at Summit Picnic Area [MP366.5; 7023' Elev.]). Later we will examine road cuts of the uplifted Paleozoic section while we backtrack past Jerome to Cottonwood for our last night at Dead Horse (where's that rabbit?).



**Granite dells of Watson Lake Park. (CM 2008 image.)**

**Monday, 29 March 2010** – Today's excursions will take us on Route 89A east to **Sedona**, AZ where we will examine road cuts that show local Paleozoic units cut by faults and mafic dikes. Then we'll travel along back roads through Red Rock State Park to see the Mesozoic "Red Rock country" of **Sedona**. We'll have no worries about water (except for possibly too much in March) and plan to take a few hiking trails near **Bell Rock**, the **Midgley Bridge** area, **Red Rock**



**Crossing, the Vortex, and Slide Rock State Park.** After a brief visit in town to gawk at the tourists and tank up on ice cream, we'll head for food and lodging back at the Dead Horse Inn.



**Typical view of “Red Rock Country” near Sedona, AZ. (CM 2004 image.)**

**Tuesday, 30 March 2010** – Drive northeastward out of Cottonwood past **Sedona** and **Oak Creek Canyon** toward **Flagstaff** on Route 89A. We'll wind up in **Oak Creek Canyon** where Laramide and younger faulting has jostled large blocks of the countryside. There are many good hikes in this area - the best in the summer is along West Fork Canyon about 10 miles north of Sedona. This is a nice trail with very gradual elevation changes, allowing eastern sea-level dwellers the chance to adapt to ~7,000' elevation range. Oak Creek and the West Fork are the only streams running in the summer unless Arizona has a very wet monsoon season. Flagstaff sits on the southern flank of the highest point in Arizona, the 12,633' high Humphreys Peak of the **San Francisco Mountains**.

Today we travel eastward from Oak Creek Canyon to take a hiking tour of the geological features of **Sunset Crater Volcano National Monument** which includes the Recent (as in 1065



AD) Bonito lava flow. They have created a mile long trail of volcanic features to study recent volcanic eruption features and lava flow morphology.

**Sunset Crater**, named by John Wesley Powell for its orange colored rim and which overlooks a brood of baby cinder cones with bizarre lava flows and ice caves, lies just 15 miles out of Flagstaff on Route 89. Sunset Crater last erupted in 1065 (945 years ago) – barely a finger snap in geologic time.

In the afternoon, continue north through the **Strawberry Crater Wilderness** and visit **Wupatki National Monument**. Here, take a slight break from geology and study Sinagua adaptation of topography to 12<sup>th</sup> century agrarian culture, and discuss the effect of Sunset crater volcanism on agriculture. Wupatki National Monument, home of the Sinagua Indian ruins and the largest stand of ponderosa pine in the world. Less than 25 miles away is **Walnut Canyon**, where 300 rooms were built into a limestone cliff by the Sinaguans (kind of an early Motel 8). Oak Creek Canyon rips into this same plateau only about 10 miles south of the city. The fabulous Grand Canyon is roughly 80 miles north but we'll wait to see it later in the field trip, after we've acclimated to the thin air.



**View of Sunset Crater and Bonito Lava Flow. (CM 2004 image.)**

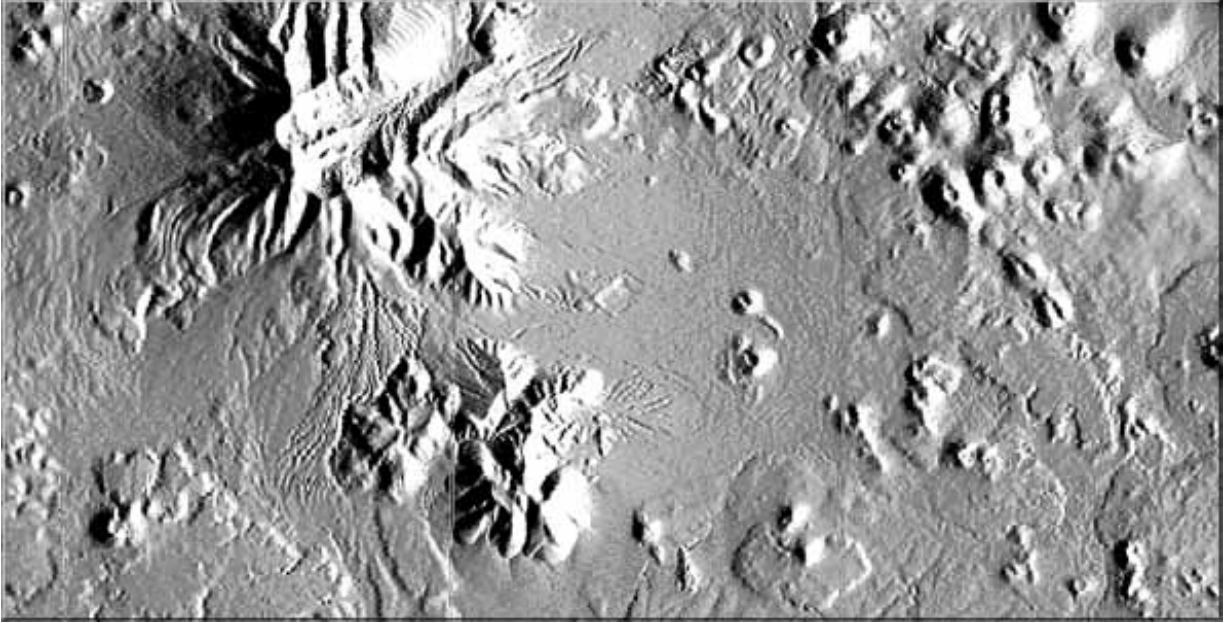


**View of Wupatki Ruins. (CM 2004 image.)**

Time and weather permitting we plan to travel north and then west past **Flagstaff** for a tour of the western San Francisco volcanic field. The drive from Oak Creek Canyon to Flagstaff should take under an hour. Here, we plan to study a local **cinder cone** in Parks, AZ (near your pal Starr Lanphere's home), visit the **Government Hill obsidian locality** (be on the lookout for horned toads – the area is thick with 'em), see a rhyolitic caldera and rhyolite ash flow structures on **Sitgreaves composite volcano**, and visit a dissected cinder cone at **Red Mountain** (if we can squeeze 32 hours into the day).

Just west of Flag (as the natives call it), Percival Lowell and wife constructed the **Lowell Observatory**. Planning to map Mars, the astronomer theorized that the patchwork of crisscrossed lines on the Martian surface were really canals to carry water from the polar icecaps to the red deserts. He redeemed himself before his death in 1916 by predicting the existence of a ninth planet. Clyde Tombaugh, an assistant in 1930 using Lowell's telescope at this very observatory discovered the planet.





**Digital Elevation Model (DEM) of San Francisco Peaks Volcanic District, AZ.**

**Logistics:** We have a reservation for three cabins as we change our evening venue to the fabulous Super 8 Motel in Flagstaff where we will stay for the next four nights.

**Super 8 Motel**

3745 Kasper Avenue  
Flagstaff, AZ 86004  
(888 324-9131)

**Wednesday, 31 March 2010** – Drive east from **Flagstaff** on I-40 toward **Meteor Crater** and spend the morning viewing the remains of a devastating nickel-iron bolide impact about 50,000 years ago whose shock wave would have leveled and obliterated everything within a twenty miles radius. All this from a metallic meteor no more than 150' across whose celerity approached 43,000 mph. A plane flying that speed would make it from NYC to Los Angeles in 4 minutes time (but you'd still have to pay for baggage)! The crater is about 600' deep, 0.75 mile across and 3 miles in circumference. Because of its location in a desert environment, it is the best-preserved crater on this planet. We will take part in a guided tour with **Eduardo** (if we are lucky) and watch a movie before investigating the crater where we will see crypto-explosion structures, faulting and inverted Mesozoic stratigraphy.

A closer examination of the area south and east of Flagstaff could convince most people that the bolide that struck and created Meteor Crater was merely one meteor in a rather extensive barrage that struck this area at or about the same time. A curious pattern of rings are found in the area and are thought by scientists to be the result of that meteoritic barrage. Incoming bolides tend to break up upon entry into the Earth's atmosphere because they are very cold and experience blow-torch-like, intense uneven heating. According to some sources, the circular rings have yielded large concentrations of gold, silver, copper and other minerals which have played an integral part in the economic life of Arizona.



Time permitting we will visit the **Canyon Diablo ghost town** about 5 miles north of I-40 near Meteor Crater along a terrible, gut-wrenching, axle-warping desert road. The ghost town is across the RR tracks! Nobody lives anywhere near it as you might surmise upon first exposure ([www.ghosttowns.com/states/az/canyondiablo.html](http://www.ghosttowns.com/states/az/canyondiablo.html)). Look down for reddish agate and jasper eroded from nodules within the Kaibab Limestone. Look up for somewhat lonely, friendly cows.



**Aerial View of Meteor Crater, AZ.**

In mid-morning continue east on I-40 to visit the **Petrified Forest National Park and Painted Desert** for the remainder of the day. Here we will examine Mesozoic strata and the geomorphology of the famous unearthly landscape that has produced huge variegated agate tree trunks. In late PM, stop at Jim Gray's Petrified Wood warehouse in **Holbrook** (928 524-1842) at south end of Petrified Forest and Route 180 for some purchases. The warehouse is a very impressive place - not too touristy but somewhat overpriced on some items. Can't miss with their petrified wood at \$2.00/pound.

From here we back-track to the fabulous Flagstaff Motel 8, where our evening accommodations are all set. Early start tomorrow, so get to bed early and rested.



**View of Painted Desert in the Petrified Forest, AZ. (CM 2004 image.)**

**Thursday, 01 April 2010** – Early AM drive west on I-40 then north to the south rim **Grand Canyon** through **Williams**, Arizona. At Williams drive north on Route 64 past **Tusayan** and enter **Grand Canyon National Park** for two days of intensive study of stratigraphy and geomorphology of the canyonlands. Farther north of Flagstaff, civilization has encroached upon John Wesley Powell's greatest achievement, his ride on the wild side through the Grand Canyon. Growing numbers of people are eschewing the South Rim with its vast crowds and crass commercial enterprises. The north rim, however, is more isolated and offers a favorable and more intimate setting. The north rim's higher elevation of 8,200' versus 6,900' (south rim) allows the rim to be open only from mid-May to mid-October. It would add an additional two days driving to our tour so we will let you visit the north rim on your own (best in summer) and urge you to swing by the **Vermillion Cliffs** near sundown or sunrise.

Our day at the canyon will be spent examining the geology exposed on the north and south rims of the canyon with a series of stops from west to east along the south rim. We will discuss geological time, unconformities, depositional environments, transgression and regression, regional tectonics and the control of Cordilleran tectonics on sedimentation. All this will set up the highlight of the field trip, tomorrow's hike a long ways down the canyon to get close and personal with the rock strata. We will make many stops along the south canyon rim from west to east before we head on southward toward Cameron.



Drive SE from the exit of the Grand Canyon along Route 64 toward **Cameron** where we will drive along the upturned monoclinical **Coconino Rim** of the **Coconino Plateau** with spectacular views into the gorge of the **Little Colorado River**. Before Cameron we'll try to stop to see an explosion breccia along the north wall of the Little Colorado river canyon. In any case we will pull over to examine the Little Colorado River canyon just past MP 280 on Route 64. Farther along we'll stop (Route 64; MP 290) to collect petrified wood and agate and to make a stop at the famous **Cameron Trading Post** before we head back to our Motel 8 for the evening.

**Friday, 02 April 2010** – Early AM departure along Route 180 to intercept with Route 64 and continue exploration of the Grand Canyon with a long hike down the **Bright Angel Trail** where we'll observe and discuss depositional environments, transgression/regression, and sedimentary structures, faulting, and erosional patterns among other topics during our hike. After an exhausting day hike, backtrack toward our campground area through **Williams** for the evening (our last night in Arizona). But before we hit the famous Flagstaff Super 8, plan for a huge Mexican dinner with rice and huge bowls of black beans at Pancho McGuillicuddy's in Williams in order to make the long van and plane rides tomorrow just so much more interesting for the group.



**Southward View of the Grand Canyon from the less-traveled North Rim. CM 2004 image.**



**Saturday, 03 April 2010** – Assuming you can still walk after our capstone hike down the canyon, early AM departure from our campground in Flagstaff (Phoenix Sky Harbor airport is about 2 hours away and we do have to drop off the van and equipment about two hours before our Noon flight time!) Time permitting we will consider stops at **Montezuma’s Castle National Monument** cliff dwelling (about 2 miles east of I-17). Also **Montezuma’s well** is about 5 miles north – an impressive big limestone sinkhole that vents lots of water. Both can be accessed from the same I-17 exit. Continue drive south to **Phoenix Sky Harbor** airport in time to drop off the **Happy Van** and get a flight back to **JFK** airport in NYC.



**Montezuma’s Castle National Monument. (CM 2004 image.)**

### **Return Flight Details:**

Depart **Phoenix Sky Harbor airport** on US Air Flight 14 at 12:05 PM and arrive at **JFK** at 7:45 PM. You will need to make arrangements for pickup from the airport unless we get a group van or cab.

## **Debriefing, Papers, and Presentations:**

Debriefing will occur during the last few days of the trip and on the plane ride back home (no exams!) for final selection of individual projects for the term paper and allied **Powerpoint presentation**. I would think a 15-page paper with a few diagrams or images to support your research topic would be a reasonable expectation. See detailed information on your papers in a separate handout or on Blackboard. The date for the Powerpoint potluck dinner class and deadline for papers is Thursday evening, **22 April 2010** at 7:00 PM in 162 Gittleston Hall. You may want to invite friends and family to this dinner and presentation. All students should bring something to share with others at the dinner – I will provide soft drinks and some pizza.

Papers should be double spaced for ease of readership with 1” margins all around and font size no larger than 12 pt. They can be mailed to me at the University ahead of the Powerpoint dinner for comments and review before your presentation or handed in immediately afterward. Please do not email papers as I will not print them out for you. You should email outlines for comment before the deadline. Students taking the course for credit will be graded on their research papers and Powerpoint presentation.

### **The following dates pertain to the field trip and the post-trip experience:**

**17 March 2010** (Wednesday; 4:00 PM – 6:00 PM) – Class meeting (162 Gittleston) to discuss regional geology of Arizona and to give out trip information packages and US Airways eTickets. In early February I will need an accurate list of names (exactly 100% as it appears on your license or other valid photo ID), and your date of birth.

**27 March – 03 April 2010** (in Arizona) – Elements of field report will be assigned in the field.

**05 April – 21 April 2010** – E-mail brigade ([charles.merguerian@hofstra.edu](mailto:charles.merguerian@hofstra.edu) or [charlesm@dukelabs.com](mailto:charlesm@dukelabs.com)) to help answer your questions about finalizing course work and to help you with your field reports. Students who contact me the day before the paper is due and say – “*I’m stuck Doc! What am I gonna do?*” ordinarily get the response “*Take two weeks off ... then quit.*”

**22 April 2010 (7:00 PM)** – Ultimate, final, drop-dead, figedabowht (silent “t”) deadline for submission of field reports and class presentation via PowerPoint of your field reports as assigned during the trip based on your interest.

# The Geology of Arizona

## Location of Arizona

As planned, our geological field course will be held in Arizona, a part of the Intermontane Division of the SW Cordillera of the United States (Figure 4). The Arizona landscape varies greatly in climate and relief from desert in the south (Basin and Range) to mountains (Upper Gila Mountains) across the central interior and vast uplifted dissected plateau lands (Colorado Plateau) at the northern part of the state where elevations approach 10,000' (Figure 5).

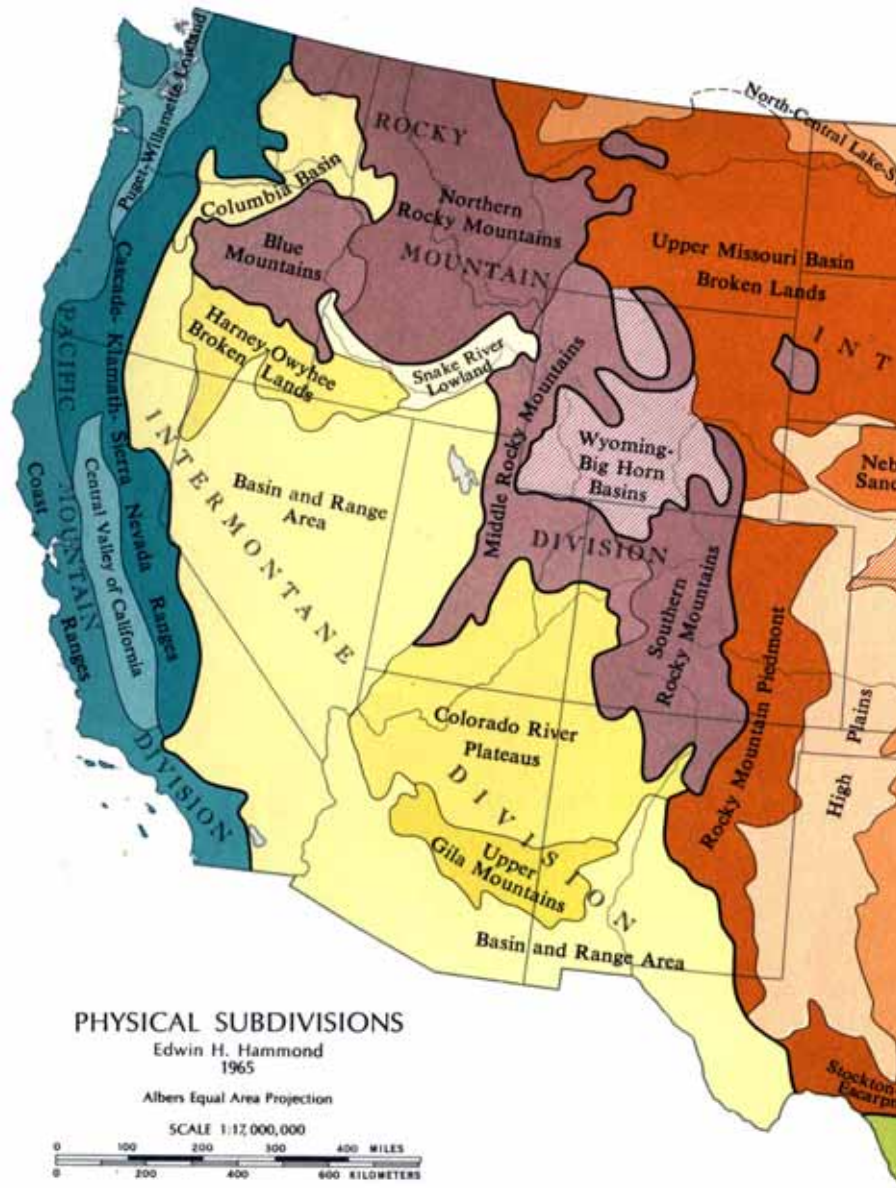


Figure 4 – Physical subdivisions of the Cordilleran belt of western North America (Hammond 1965).





Figure 5 – Physiographic map of the western United States.

Many modern highways transect the state from Phoenix northward and our eight-day itinerary will take us from the airport area northward into the higher plateau of Arizona (Figure 6).





Figure 6 – Physiographic location map of Arizona.



Figure 7 – Road map of Arizona.

Many features of cultural and historic interest will be encountered during our journey (Figure 7) and although not the central focus of our trip, whenever possible, time will be spent visiting these cultural features.

Our field course into the wilds of Arizona requires some introduction to the geology of the region. First we discuss the physiographic provinces of Arizona to set the framework for our field of study. Next, we describe the tectonic relationships of the Cordillera against the backdrop of geologic time and stratigraphy. Finally, we provide a simplified view of the geology of Arizona, choosing deliberately to subdivide the strata into discrete “Layers” and provide detailed descriptions of the rock units to be encountered on our trip. A bibliography and suggested resource list and two Appendixes are provided at the end of this guidebook. **Appendix 1** is a field- and structural geology primer and **Appendix 2** provides two tectonic maps and a series of developmental physiographic views of Arizona from Cambrian to Triassic time. **Appendix 3** provides a listing of Arizona’s mineral localities and a location map and **Appendix 4** lists the all important Geology Department Field Trip rules.

During our field course we will be working in rocks ranging in age from Proterozoic through Cenozoic and will see evidence for Recent volcanism. Thus, over 2 billion years of geology will be covered in just ten days. That means 200 million years of work for each day, so let’s get started.

### **Physiographic Provinces of Arizona**

The state of Arizona is nestled between the Sierra Nevada Range of California and the Rocky Mountain Range. (See Figure 5.) Arizona exposes three major NW-SE trending geological belts or provinces. The Colorado Plateau province is in the north and the Basin and Range province occurs to the south and west. Separating them is a transitional terrain containing exposures of ancient Proterozoic rock known as the Central Mountain Region or Mogollon Escarpment (Figure 8). We will travel through all three belts during our field trip.

The **Colorado Plateau** is the SW extension of the Great Basin, an enormous tract of land covering four states (UT, CO, NM, and AZ) that consists of mostly subhorizontal strata. In Arizona the SW margin of the Colorado Plateau is delineated by the **Mogollon Rim** (pronounced “muggy-own”). This boundary feature extends northwesterly across north-central Arizona to the Grand Wash cliffs of the western Grand Canyon (Figures 9, 10).

According to Stokes (1976) the Mogollon Escarpment (or “Rim”) may be continuous with a major fault along its western terminus raising the intriguing possibility that the prominent escarpment has a tectonic as well as erosional origin. Figure 11 shows NE-trending Paleozoic strata cut by a major right-lateral strike-slip fault (Walker Lane fault). The fault cuts miogeosynclinal and overthrust eugeosynclinal (Antler belt) Paleozoic rocks. Poole et al (1977) show the Las Vegas fault as a major right-lateral strike-slip fault that cuts Paleozoic strata and major Mississippian and Late Cretaceous overthrusts known as the Roberts Mountain and Sevier thrusts (Figure 12). Our trip should enable us to examine the escarpment to see if any evidence supports a right-lateral strike-slip model.

The spectacular beauty of the Colorado Plateau and Great Basin area is exemplified by the great number of National Parks found throughout the region. (See Figures 2, 3, 13.)

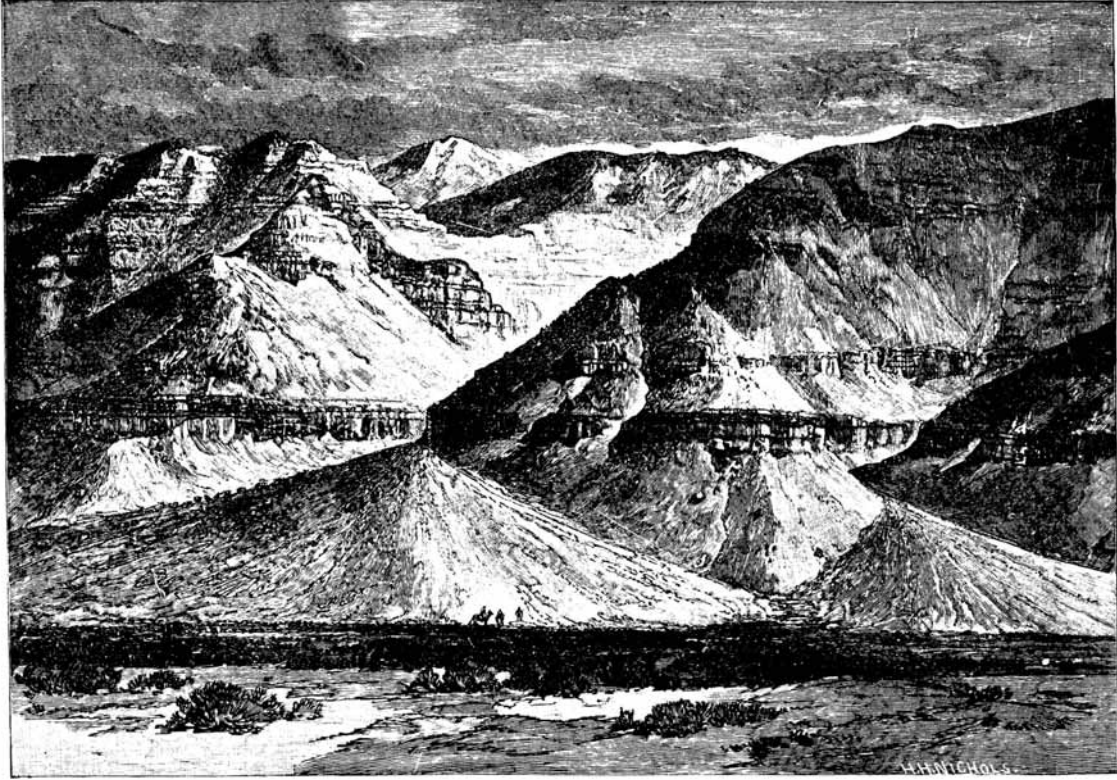


Figure 8 – Major Physiographic Provinces. (Ranney, 2005, p. 35.)

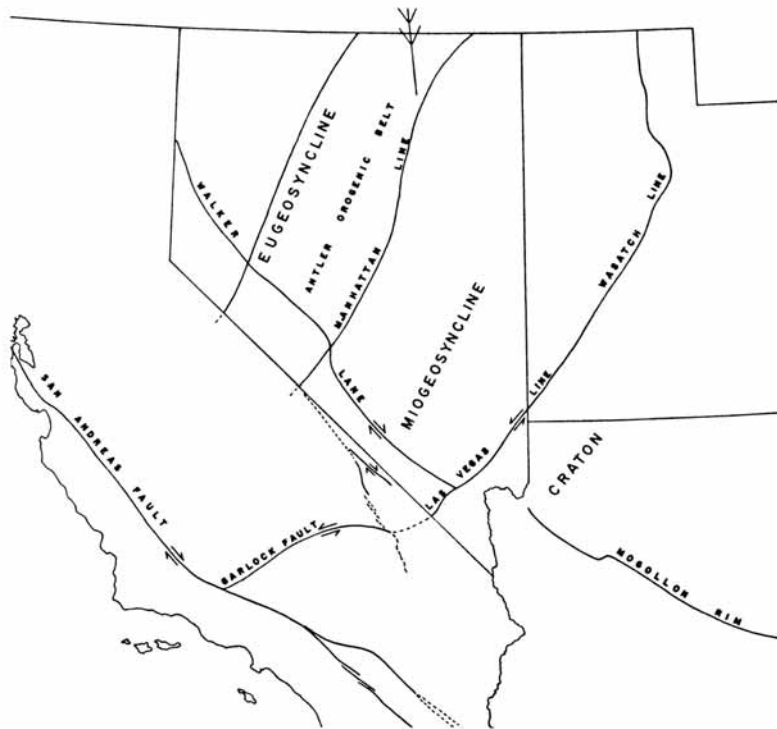




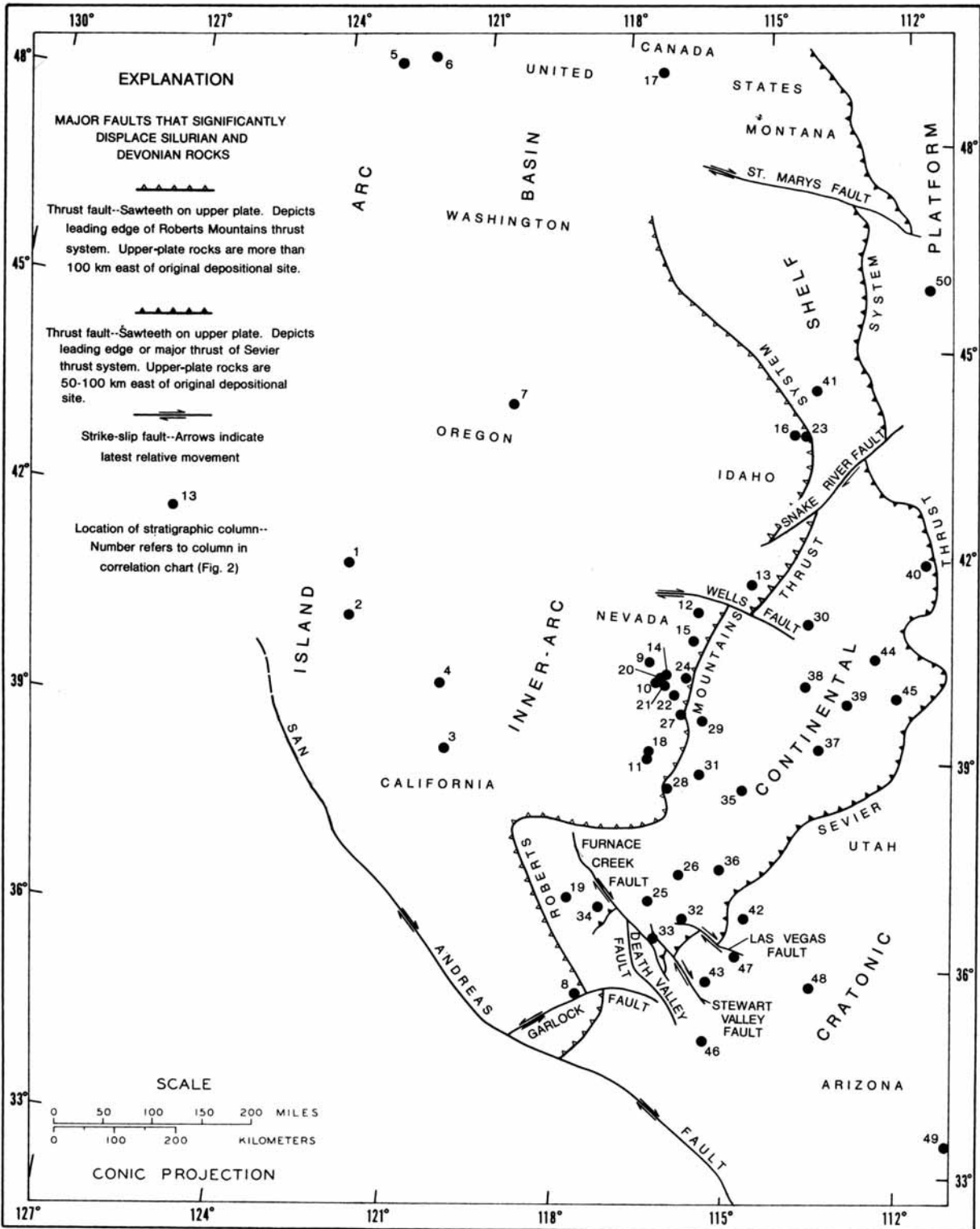
Figure 9 – Physiographic diagram of Arizona. (Nations and Stump, 1981, p. 81.)



**Figure 10** – H. H. Nichols drawing of the Mogollon Escarpment (in Powell, 1895).

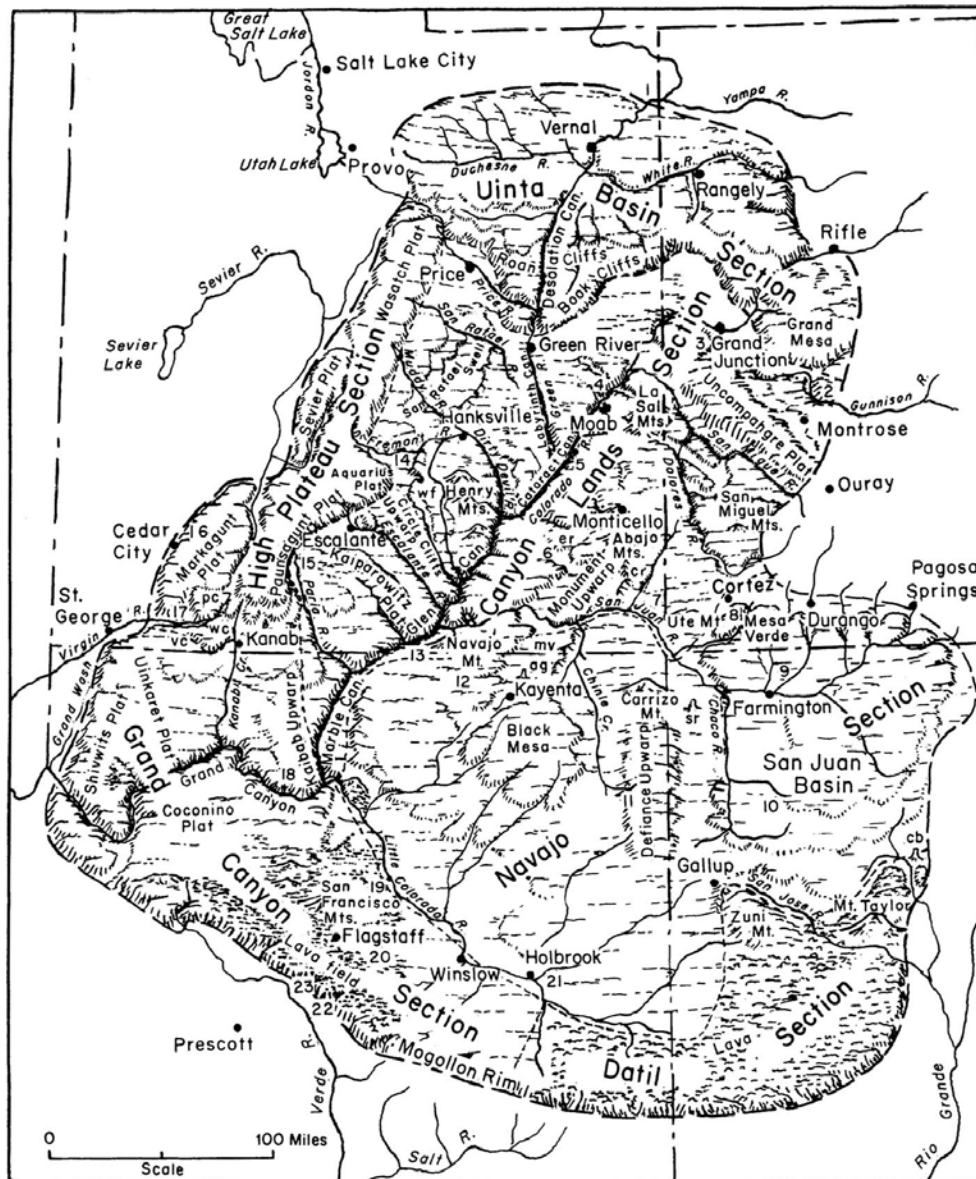


**Figure 11** – Alignment of the Mogollon Rim and the Walker Lane Fault (Stokes, 1976).



**Figure 12** – Map showing the Las Vegas fault and other strike-slip faults related to the Cenozoic San Andreas System (Poole et al., 1977).





*National Parks and Monuments*

- |  |   |
|--|---|
| 1. Dinosaur Nat. Mon.                          | 13. Rainbow Bridge Nat. Mon.                      |
| 2. Black Canyon of the Gunnison Nat. Mon.      | 14. Capitol Reef Nat. Mon.                        |
| 3. Colorado Nat. Mon.                          | 15. Bryce Canyon Nat. Park                        |
| 4. Arches Nat. Mon.                            | 16. Cedar Breaks Nat. Mon.                        |
| 5. Canyonlands Nat. Park                       | 17. Zion Nat. Park                                |
| 6. Natural Bridges Nat. Mon.                   | 18. Grand Canyon Nat. Park                        |
| 7. Hovenweep Nat. Mon.                         | 19. Wupatki and Sunset Crater Nat. Mons.          |
| 8. Mesaverde Nat. Park                         | 20. Walnut Canyon Nat. Mon.                       |
| 9. Aztec Ruins Nat. Mon.                       | 21. Petrified Forest and Painted Desert Nat. Mon. |
| 10. Chaco Canyon Nat. Mon.                     | 22. Montezuma Castle Nat. Mon.                    |
| 11. Canyon de Chelly Nat. Mon.                 | 23. Tuzigoot Nat. Mon.                            |
| 12. Navajo Nat. Mon. (Betatakin and Kiet Seel) |   |

*Escarments at South of High Plateaus*

- pc Pink Cliffs  
 wc White Cliffs  
 vc Vermilion Cliffs

*Other Prominent Features*

- wf Waterpocket Fold  
 er Elk Ridge  
 cr Comb Ridge  
 mv Monument Valley  
 ag Agathla Peak  
 sr Shiprock  
 cb Cabezon Peak

**Figure 13** – National parks and monuments in the vicinity of the Great Basin (Hunt, 1974, p. 426).

## Geologic Map of Arizona

The geologic map of Arizona (Figure 14) reveals the distribution of rock types in the state. Older and younger Precambrian terranes (Archean and Proterozoic in the modern usage) consist of highly deformed metamorphic, tilted sedimentary, and igneous rocks (colored in khaki and tan), occupy the Central Mountain Region (or Gila Mountains), and are also exposed in a few steep canyons, particularly in the northern part of the state (Grand Canyon area). The patchwork distribution of the older cratonic elements is the result of isolated fault-blocks and that most of the older rocks are blanketed by younger sedimentary rocks, volcanic constructs, and alluvium.

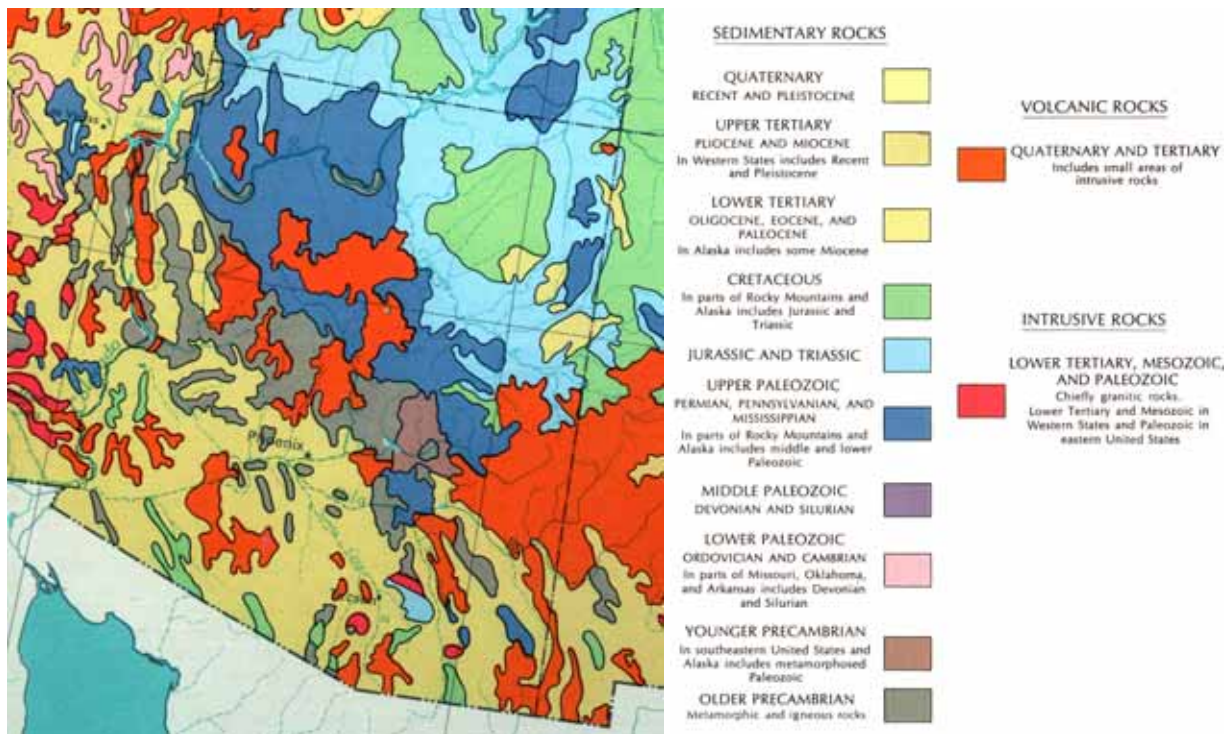
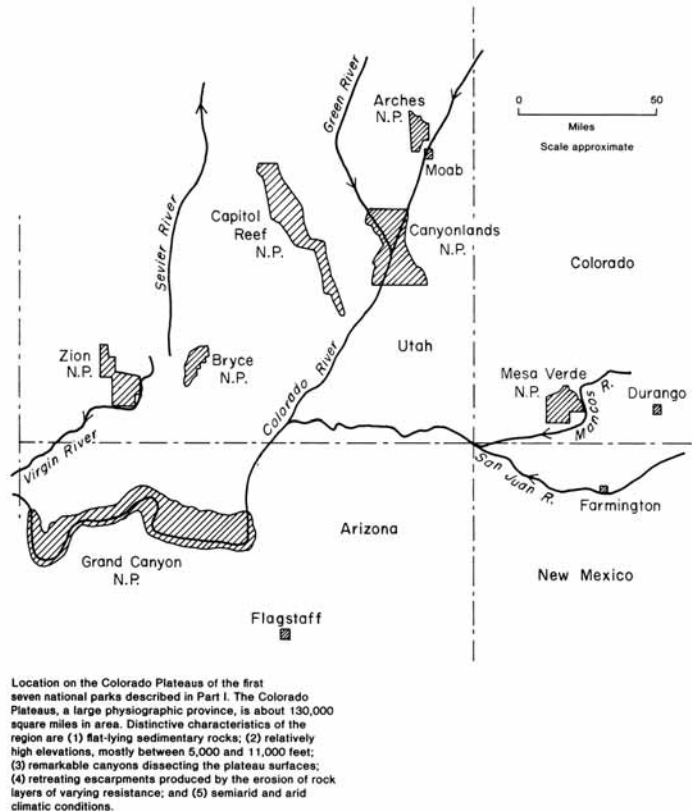


Figure 14 – Generalized geologic map of Arizona and adjacent areas.

Lower Cambrian to Devonian Paleozoic rocks (pink and purple in Figure 14) are sparsely exposed because they are generally thin or absent to start with and are largely covered by younger strata. Upper Paleozoic strata (dark blue) are well exposed in the north central part of the state (north of the Mogollon Rim) and form an important substrate northward into Utah along the basal portions of the Great Basin. Stratified Mesozoic rocks are also found in the Colorado Plateau province but they are best exposed north and east of the Grand Canyon (in Utah, Colorado, and New Mexico).

The Mesozoic strata in Arizona (light blue and green in Figure 14) are confined to the NE part of Arizona. Along with their counterparts to the north and east, the Mesozoic strata resulted from uplift and eastward erosion of the deformed internal zone of the western Cordillera. The result of rapid infilling of an enormous back-arc basin throughout that long interval, these

dominantly thickly bedded marine and non-marine sedimentary and volcanoclastic rocks are spectacularly exposed in the area of the Great Basin. Northward in Utah, prolonged erosion and dissection of these variegated subhorizontal strata have created unbelievable vistas in the form of Zion, Bryce, Capitol Reef, Arches, and Canyonlands National Parks (Figure 15).



**Figure 15** – Index map showing the location of National Parks of Arizona and Utah. (Harris and Tuttle, 1990, p. 3.)

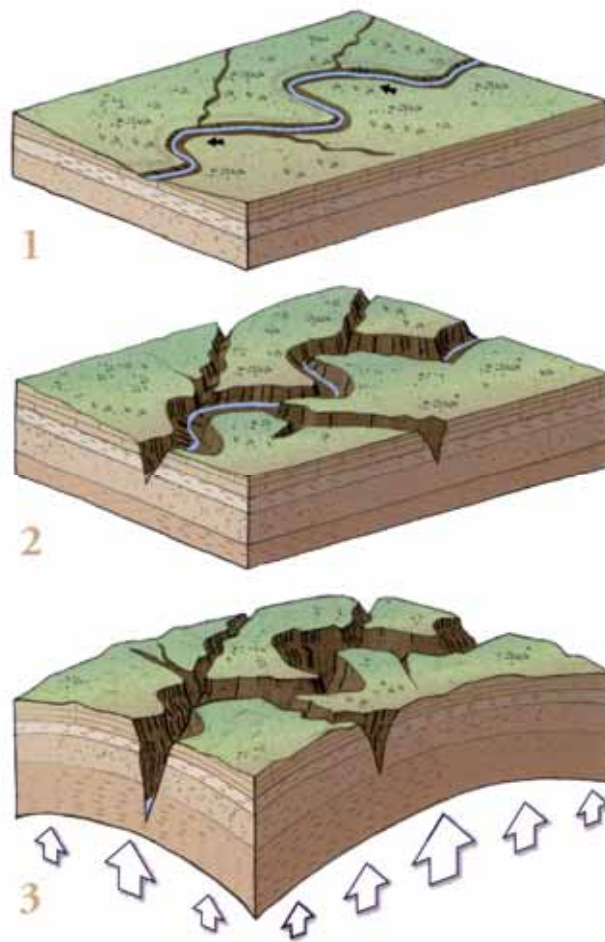
During the Cenozoic, the subduction of the spreading Pacific Ridge caused a changeover from pure to oblique subduction and development of a broad terrain of extensional tectonics. Indeed, right-lateral brittle deformation of the SW Cordillera produced the Basin and Range province and enabled openings for vast outpourings of Cenozoic volcanic rock and related volcanoclastic components. Cenozoic strata (various yellows in Figure 14) cover significant areas of the southern half of Arizona and are found in three large isolated patches in the NE corner of the state. The Cenozoic strata are cut by younger Cenozoic volcanic rocks (orange-red in Figure 14) in most areas except for the NE corner of Arizona.

Thus, rocks of vastly different age and tectonic ancestry are found in Arizona. They are found in three geological provinces – the Colorado Plateau, the Central Mountain Region, and the Basin and Range. Descriptions of these areas and how they fit into the regional geology follow.



## Colorado Plateau

The Colorado Plateau Physiographic Province is nearly circular and covers 130,000 square miles – a large tract of four states in the western United States. An area of thick Mesozoic sedimentation and subsequent broad uplift, the present elevation of the plateau province ranges from 5,000 to 11,000 feet above sea level (Figure 16). Consisting of horizontal to folded Paleozoic and Mesozoic strata underlain by crystalline and stratified rocks of great age, the plateau extends from Arizona northward into Utah and eastward into Colorado and New Mexico. In Arizona, the Grand Wash, Hurricane, Sevier, and Paunsaugunt faults have created regional upwarps, such as the Kaibab Upwarp that extends into the Grand Canyon (Figures 17 and 18). Uplift of the Colorado Plateau in northern Arizona and rapid downcutting by active rivers has carved a unique canyon topography consisting of steep, incised canyon walls and spectacular upland vistas with isolated buttes, mesas, and rock pinnacles. Especially appreciated by the card-carrying geologist, are features found in the area of the Grand Canyon, Mogollon Rim, Painted Desert, Vermillion Cliffs and the Petrified Forest (where you should be on the lookout for Duke Mantee – world famous killer on the lam!).



**Figure 16** – Block diagrams showing uplift and erosion of the Great Basin. (From Ranney, 2005, p. 43.)



**Figure 17** – Space view of the Grand Canyon showing the dissection of the Kaibab Upwarp (dark oval area near center of image) by the Colorado River. The dark area to the left is the Shivwits Plateau. North is to the top.

The Colorado Plateau has been the locus of significant Cenozoic volcanism (Figure 19). The region hosts an extensive history of Cenozoic volcanism, development of volcanic constructs, and coeval intrusive activity. Lava flows, lava tubes, calderas, cinder cones, composite volcanoes, aa, pahoehoe, domes, dikes, sills, apophyses, plutons, xenoliths, you name it and you will see it. Draping across the unique landscape of the Plateau Province are Cenozoic volcanic rocks of great diversity.

### **The “Transitional” or Central Mountain Region**

This mountainous landscape is dominated by complexly deformed and faulted Proterozoic crystalline rocks with subordinate Paleozoic strata as erosional remnants. Mesozoic and Cenozoic rocks are generally not found in this province although they may have been removed by erosion. According to Nations and Stump (1981), the best areas to examine these rocks are the Black Hills near Jerome and Prescott, the Mazatzal and Sierra Ancha Mountains near Roosevelt Lake, and the Salt River Canyon between Show Low and Globe. The famous copper mines in Morenci, Jerome, and Globe and uranium from the Dripping Spring Quartzite are found in the Proterozoic rocks of the transitional terrane. Minus the ore deposits, the transitional terrane is reminiscent of our own Proterozoic Hudson Highlands in New York and New Jersey. Scattered through the Hudson Highlands are fault-bounded inliers of deformed Paleozoic strata.

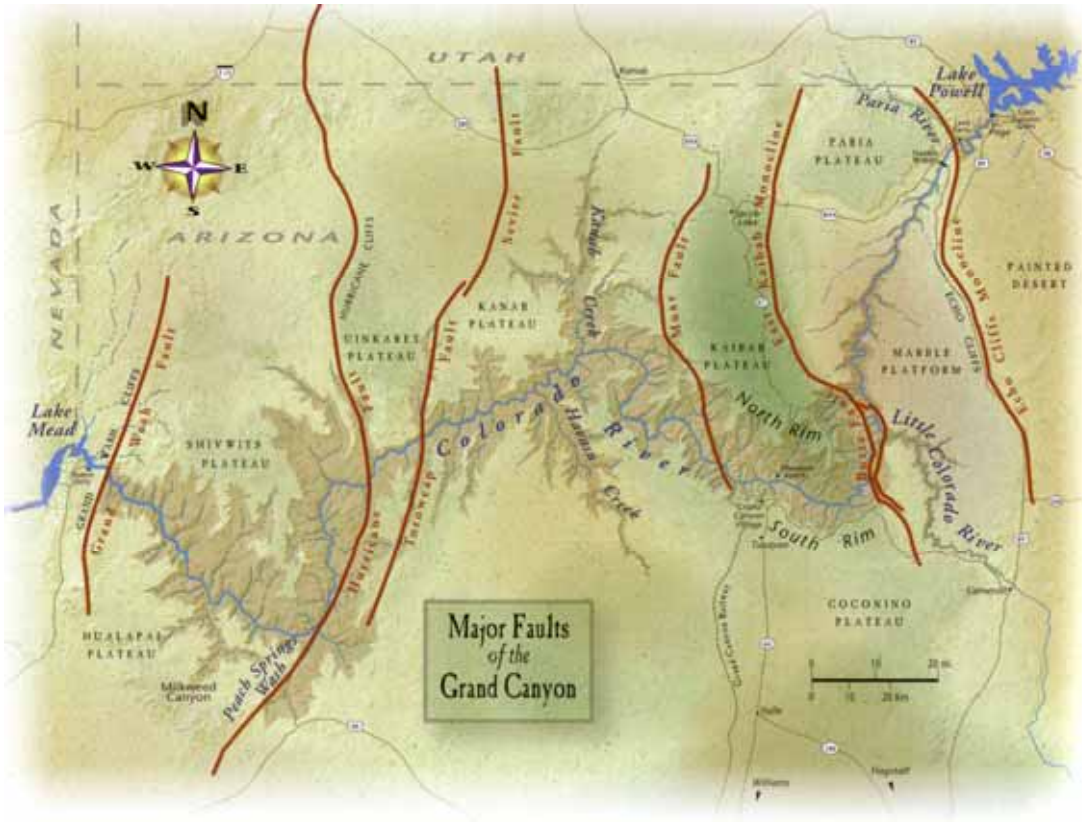


Figure 18 – Index map of the Grand Canyon region showing the major faults. (Ranney, 2005, p. 22).

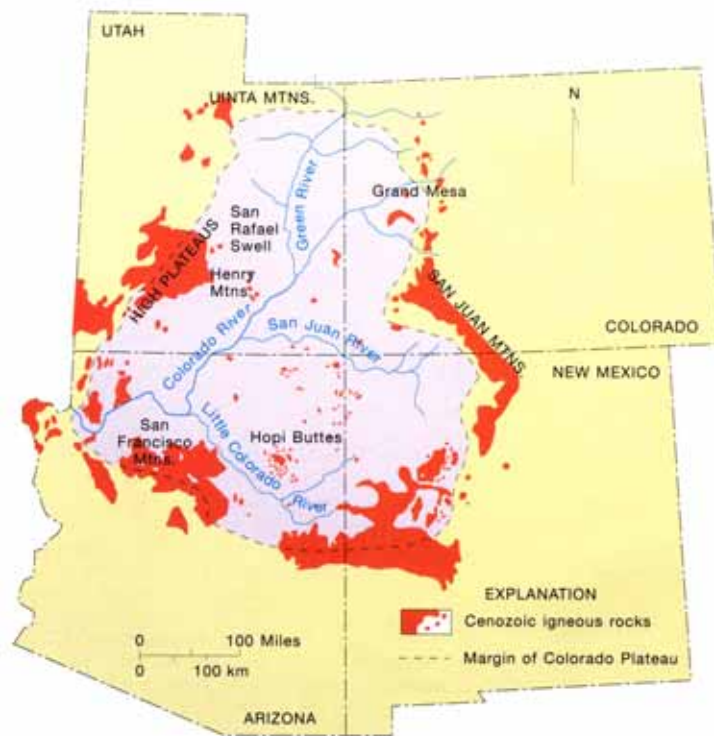


Figure 19 – Map showing Cenozoic igneous rocks (in red) associated with the Colorado Plateau.



## Basin and Range Province

Extending from eastern California and Nevada, the basin and range province extends into Arizona and bordering Mexico. In a nutshell, the province is dominated by normal fault blocks of upper crust produced by oblique slip and tensional fragmentation (Hamilton and Myers, 1966). The crust has been thinned by tension but thickened by Cenozoic surface volcanism and by intrusion at depth. Renowned for the stark character of the resultant landscape, Basin and Range topography is rooted in Cenozoic crustal extension related to the development of the San Andreas fault system, inland development of horst and graben structure, and coseismic erosion of the ranges and infilling of the basins. The horsts form the ranges and the basins get filled in with sediment from the uplift and erosion of the horsts. The results are elongate fault-bounded mountains protruding through broad valleys of intercalated alluvium and volcanic materials. In southern Arizona the trend of the ranges are NW-SE, essentially parallel to the San Andreas trend. In Arizona, the Basin and Range is best viewed in the Phoenix Mountains north of the airport, the Chiricahua and Tucson Mountains near Tucson, and the Hualapai Mountains south of Kingman.

The mountains are structurally complex and contain rocks of Proterozoic through Cenozoic vintage. Overlying the Proterozoic rocks, the early Paleozoic strata include shallow water marine limestone, shale, and sandstone. Late Paleozoic strata are of a deep-water marine facies, predominately shale and greywacke. Early Mesozoic rocks are igneous (both volcanic and plutonic) but these are either overlain by Cretaceous marine sandstone, shale, and carbonates or cut by Cretaceous (Laramide) granitoids.

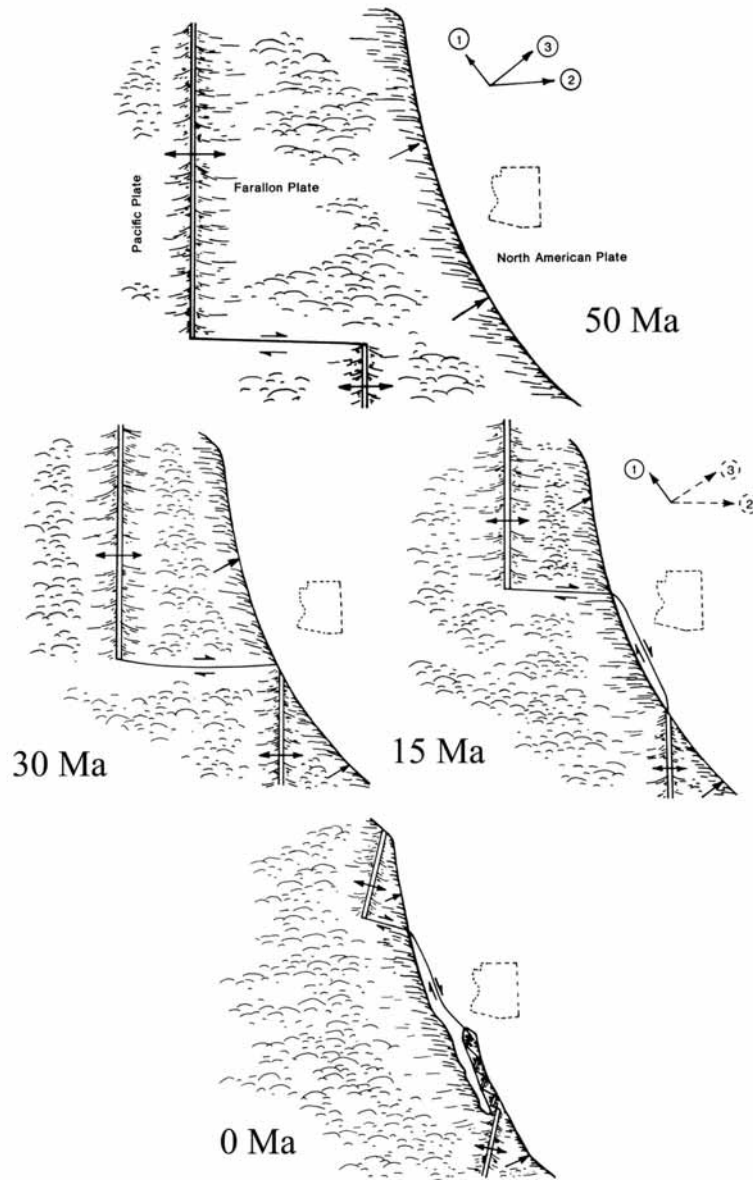
The Cenozoic rocks of the Basin and Range of Arizona are largely volcanic but include non-marine fluvial and lacustrine sediment and a minor patch of marine sediment along the southern Colorado River (Nations and Stump, 1981). The basins have accumulated thousands of feet of alluvium, volcanic, and lacustrine strata in response to regional extension.

A view of the Cenozoic tectonics of the region helps to understand the products of Cenozoic geologic development of Arizona. Subduction of the east half of the Pacific Ocean plate during the Mesozoic and Cenozoic resulted in the formation of the western Cordillera of the United States. Subduction of the Farallon plate and parts of the East Pacific Rise began during the later part of the Cenozoic Era. By the Eocene (roughly 50 Ma) the plate configuration involved subduction of an offset ridge crest that ultimately resulted in fragmentation of North American crust and development of the right-lateral San Andreas fault system (Figure 20). By 30 Ma, the NE-corner of the transform-ridge Farallon segment had collided with northern Mexico and from that noble area subduction of western half of the Pacific Ocean plate officially began. Parades, celebrations, and parties were held throughout the western Cordillera.

By 15 Ma the merrymaking had faded as the consequence of the subduction of an active ridge crest had become obvious – decreased volcanicity at first then continuous volumes of lava and explosive volcanoclastic debris all in the midst of active seismicity. Indeed, the result of subduction of the Pacific Ridge had far-reaching geological consequences. High heat flow and resulting volcanicity, extensional faulting, uplift, and seismicity can all be attributed to the

consequences of subduction and active ridge crest. The development of Cenozoic metamorphic core complexes, with low-angle ductile normal faulting, were formed by the same mechanism.

Starting about 5 Ma in Baja California our present plate configuration (compare Figure 20 at 0 Ma with Figure 21) has produced a sliver of North America (the Salinian block) that moves northwestward along the Cordilleran margin. As demonstrated by studies of the western Canadian Rockies, this scenario has played out many times in the past. Much of the western Canadian Rockies constitute a collage of accreted terranes that are linked to the SW Cordillera of the United States and Mexico. The Cenozoic dislocation and drift of the Salinian block provides a candidate for the next accreted terrane when the future tectonics change to convergence.

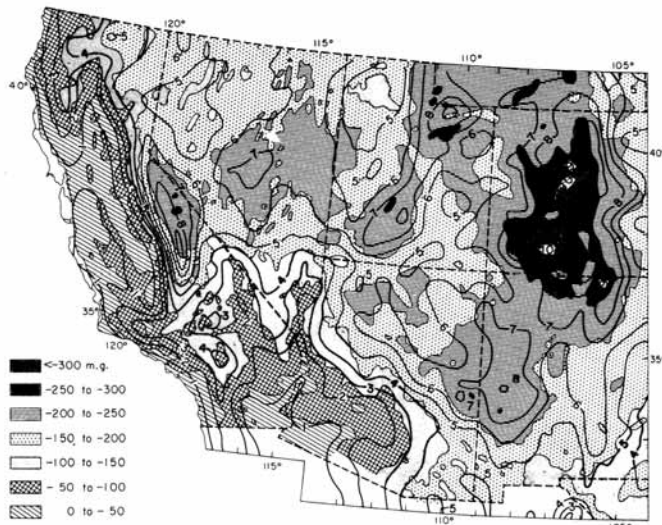


**Figure 20** – Four views of the post-Eocene plate tectonic evolution of the SW Cordillera. The position of Arizona is shown as a dotted outline. (Adapted from Nations and Stump, 1981, Figure 7-6, p. 75-77.)



**Figure 21** – Modern plate tectonic configuration of North America showing subduction of the East Pacific Rise beneath the Rocky Mountain range of the western Cordillera.

Our modern view of the western Cordillera indicates isostatic equilibrium in that the highest areas correspond with gravity lows (Figure 22). In other words the mountains have deep



crustal roots. The San Andreas system continues to evolve along the SW Cordillera. Because of the relative motion of the Pacific Ocean plate, the extension produced by the spreading of the subducted Pacific Ridge has resulted in an overall pattern of right-lateral oblique extension. As discussed earlier, this has produced Basin and Range structure throughout the American southwest.

**Figure 22** – Bouguer gravity vs. topographic map indicates that highest areas are above lowest gravity, an indication of isostatic equilibrium in the western Cordillera (Gilluly, 1973).



## Geologic Time and Stratigraphy

In the blink of a geological eye we draw your attention to the time scale below (Figure 23) that is specific to Arizona. The time scale indicates the era, period, and epoch subdivisions, lists fossil ranges, and generalizes the tectonic events. The geologic development of Arizona spans at least 2 Ga (“giga” or billion years). To simplify a complex story, we have taken the liberty of subdividing the geologic history of Arizona into major “Layers” or tectonostratigraphic units. Thus, building upon the concept of sequence stratigraphy as proposed by Sloss (1963, 1966), one can subdivide unconformity- and fault-bound geologic sequences to better understand the evolution of complex terranes. (See Appendix 1.) Thus, in the section below, we summarize the geology of 5 packages or “Layers” of strata forming Arizona. In much the same way that a layer cake is made, we start with the older rocks of Layer I at the base and move upwards in time and stratigraphy to Layer V. The details of the ingredients of each layer are described individually below where many stratigraphic charts and tables are provided for use in the field.

Figure 24 is another timescale that has more details about the formation and group names specific to the geology of the Grand Canyon area. Clearly the central focus of any trip to Arizona, the picture book of geologic time exposed in the walls of the Grand Canyon (despite a few missing chapters and groups of pages), is naturally arranged by Layers, starting with the oldest rocks found in Arizona.

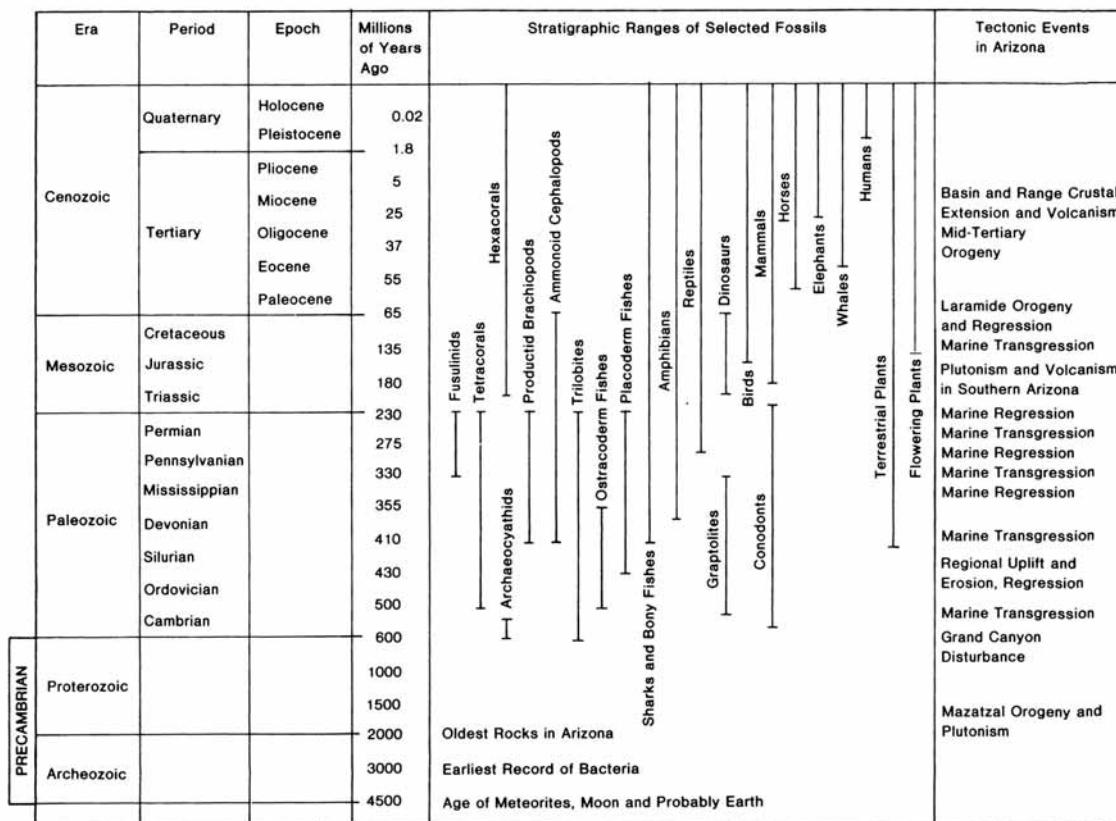


Figure 23 – Geologic time scale of Arizona (Nations and Stump, 1981, Table 4-1, p. 29).

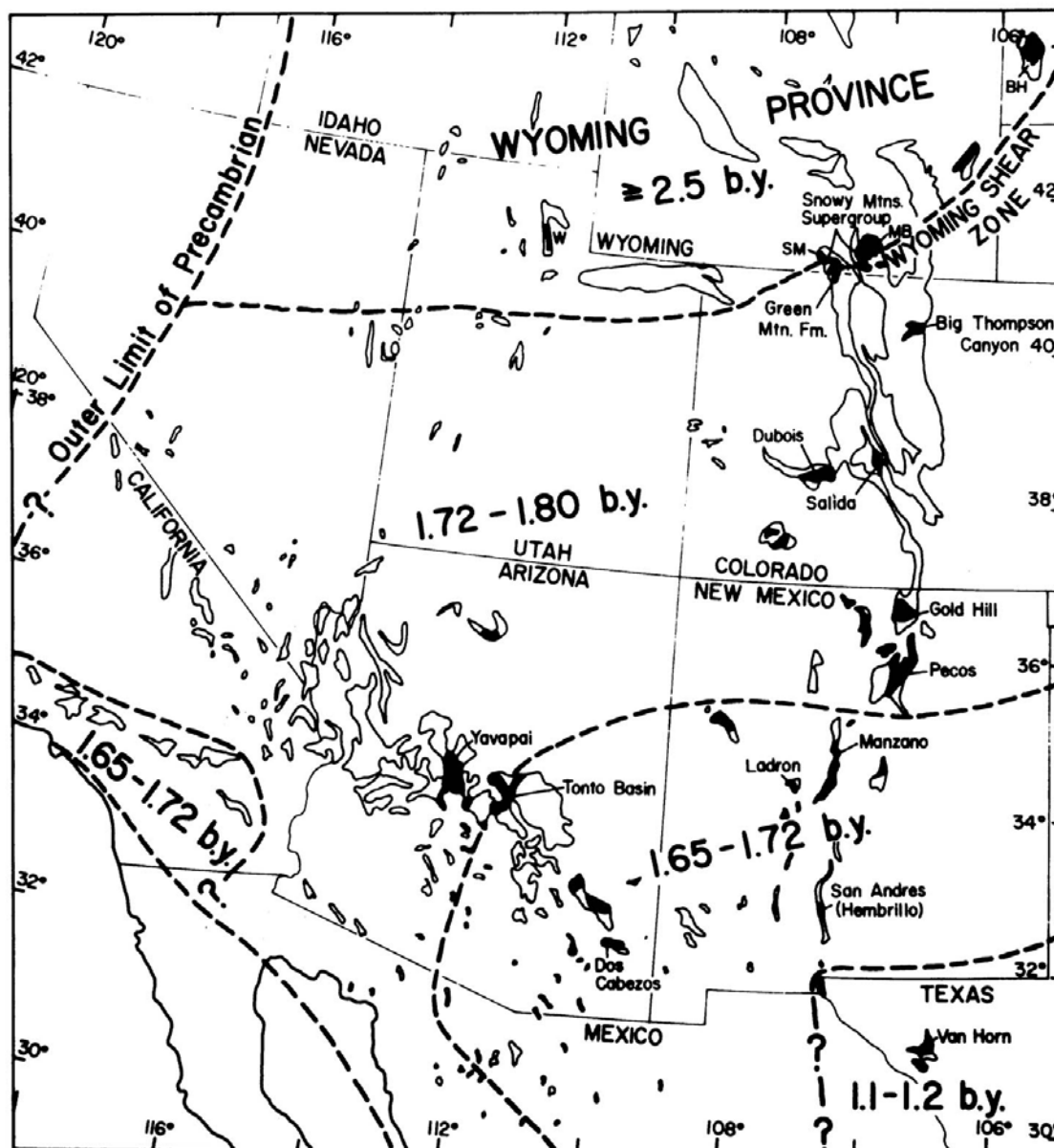
Time Units		Rock Units		Geologic Events		
Era	Period	Group & Super-group	Formation			
Cenozoic	Quaternary		Lavas	Minor lava flows Development of Grand Canyon by uplifting and tilting, accompanied by down-cutting. Uplift, erosion, minor deformation. Erosion		
	Tertiary		Slump and slide deposits, terrace gravels, river deposits, travertine.			
Mesozoic	Cretaceous			Moenkopi	Flood-plain deposition. Withdrawal of seas. Erosion	
	Jurassic			Kaibab Limestone	Transgression of shallow seas; regression. Erosion	
	Triassic			Toroweap	Transgression of shallow seas, flattening sand dunes.	
Paleozoic	Permian			Coconino Sandstone	Flood-plain deposits covered by migrating sand dunes. Erosion	
				Hermit Shale	Deposition on flood plain, lagoons. Erosion	
				Supai	Esplanade Sandstone	Flood-plain deposition
					Wescogame Manakacha Watahomigi	Retreat of seas Marine sedimentation
	Mississippian			Surprise Canyon	Erosion	
		Redwall Limestone		Channel deposits; uplift Erosion		
	Devonian		Temple Butte Limestone	Karst development Marine sedimentation Erosion		
				Marine deposits in channels Erosion		
	Cambrian		Tonto	Muav Limestone Bright Angel Shale Tapeats Sandstone	Deposition in a transgressing sea, forming a facies change in these formations Erosion	
	Late & Middle Precambrian time (Proterozoic)		Grand Canyon	Chuar	Sixty Mile	Stream Deposition Erosion
Kwagunt Galeros					Volcanic activity; Grand Canyon orogeny, block-faulting, thrust-faulting, folding. Erosion	
Nankoweap					Deposition in a shallow sea. Erosion	
Unkar				Cardenas Lava Dox Sandstone Shinumo Quartzite Hakatai Shale Bass Limestone (including Hotauta Conglomerate)	Faulting, igneous intrusions, lava flows Shallow sea deposits Deposited as a marine sandstone Temporary retreat of the sea Deposition in warm, shallow sea Transgression of seas; major unconformity Erosion	
				Trinity and Elves Chasm Gneisses	Block-faulting; uplift. Igneous intrusions; metamorphism Erosion	
Early Precambrian time (Archean)			Zoroaster Granite	Uplift of Mazatzal Mountains; orogeny, folding, faulting, intrusions, metamorphism		
			Vishnu Schist	Deposition of marine sediment; volcanic activity.		

Source: Modified after Huntoon et al. 1981, 1982, 1986.

**Figure 24** – Geologic time scale for the Grand Canyon region (Harris and Tuttle, 1990, p. 20).

## Layer I – Early Proterozoic and possibly “Archean?” rocks (2.5? Ga – 1.7 Ga)

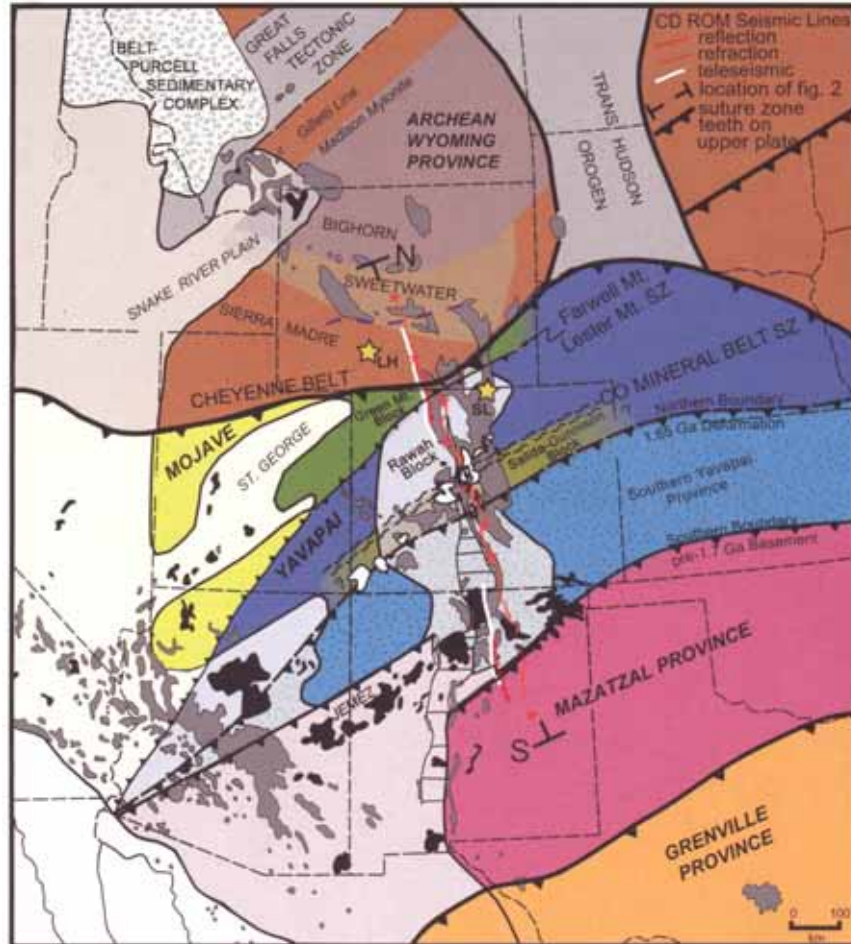
The oldest rocks found in Arizona are exposed in the Grand Canyon. Known as the Vishnu Schist, Brahma Schist, and Zoroaster Granite, the rocks form a NE-trending metamorphic complex deformed during the 1.7 Ga Mazatzal orogeny, based on radiogenic age dating of late-stage granitoids. Thus, the depositional age of the sequence is older and may be of Archean parentage. Because of internal shearing and the complex separation of ancient basement terranes during Cenozoic Basin and Range faulting in Arizona (Figure 25), correlation between Proterozoic and older terranes needs careful mapping and geochronologic data before a clear picture will ever emerge.



**Figure 25** – Distribution of two belts of Proterozoic rocks of slightly different age in the SW Cordillera. (From Condie, 1982, p. 38.)

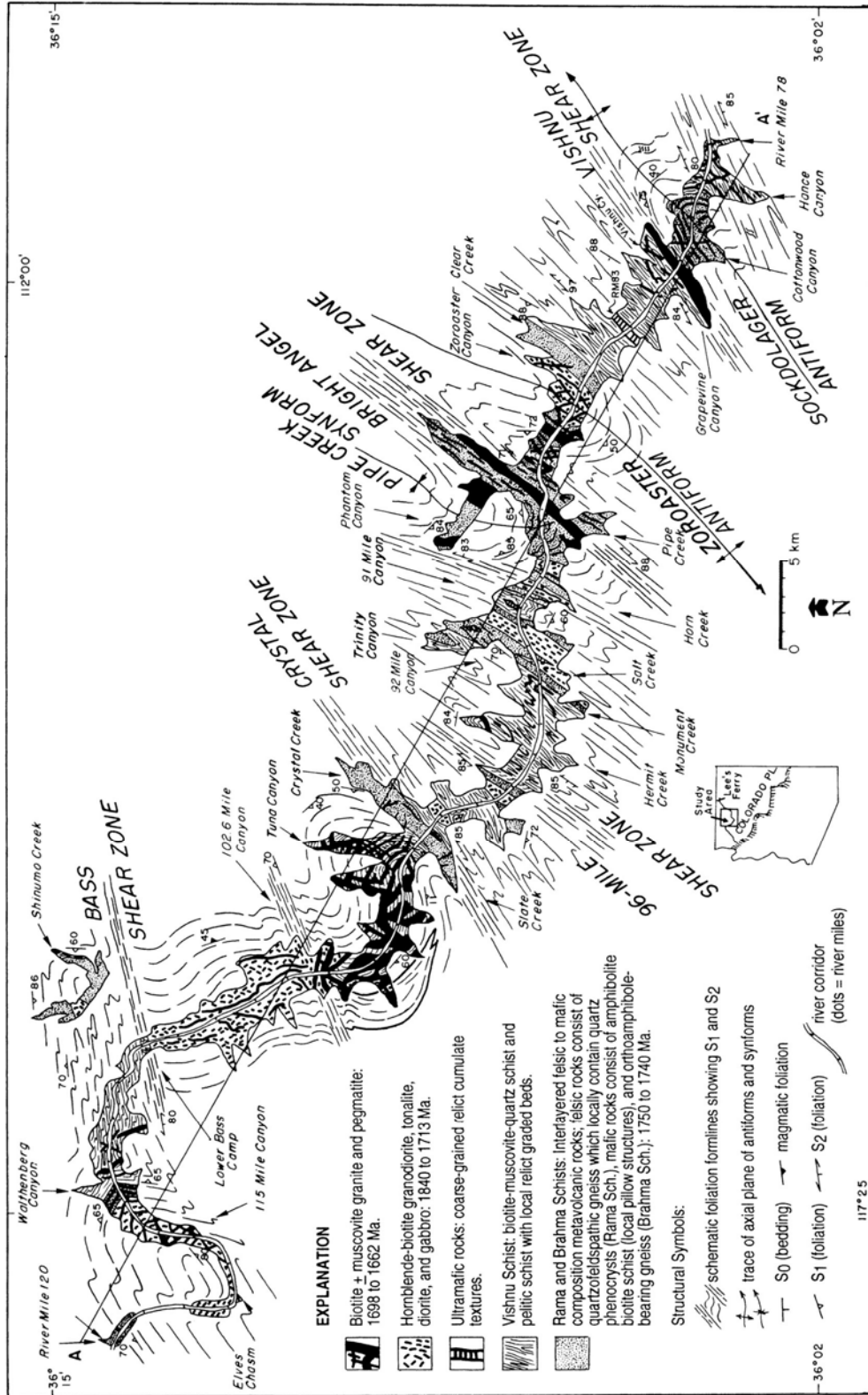


According to Condie (1982) two major NE-trending Proterozoic provinces occur in Arizona (Figure 25). The older of these (Yavapai province; 1.72–1.80 Ga) dominates most of the state and the younger sequence (Southern Yavapai province; 1.65–1.72 Ga) crops out southeastward from the Tonto Mountains. (See Figure 26 or simply ask for Keemosabbe.) Integration of seismic reflection, seismic reflection, teleseismic, and geological data has allowed the CD-ROM Working Group to publish an interpretive map of the crustal structure in the SW USA (Figure 26). Clearly the basement geology of the American SW contains many internally deformed tectonic blocks of great age (Hawkins and others, 1996).

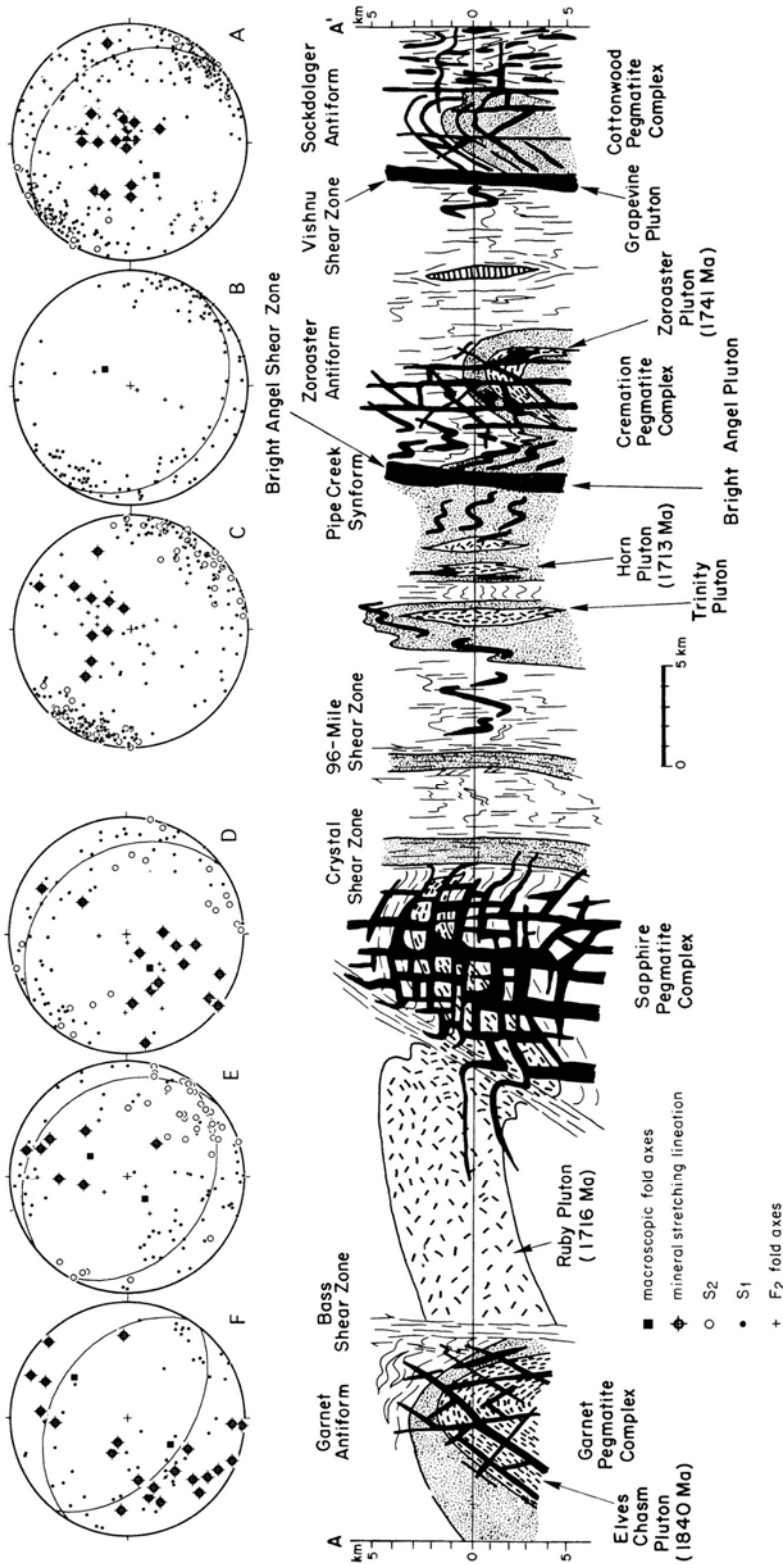


**Figure 26** – Terrane map of the SW Cordillera showing the convergence of the Yavapai and Mazatzal provinces (CD-ROM Working Group, 2002).

As best exposed in the Grand Canyon, the rocks of Layer I can be subdivided into sub-layers. The oldest of these is known as the Vishnu Schist but also include the Rama and Brahma schists. The rocks are best exposed in the steep v-shaped Granite Gorge near between Mileposts 78 and 120. Hamblin and Rigby (1969) describe the rocks as “characteristically dark somber gray”. According to Ilg and others (1996) and Dumond and others (2007), they consist of intensely deformed and highly foliated metasedimentary and metavolcanic rocks that were developed in the roots of an ancient convergent arc setting about 1.7 Ga (Figure 27a, b, c, d).

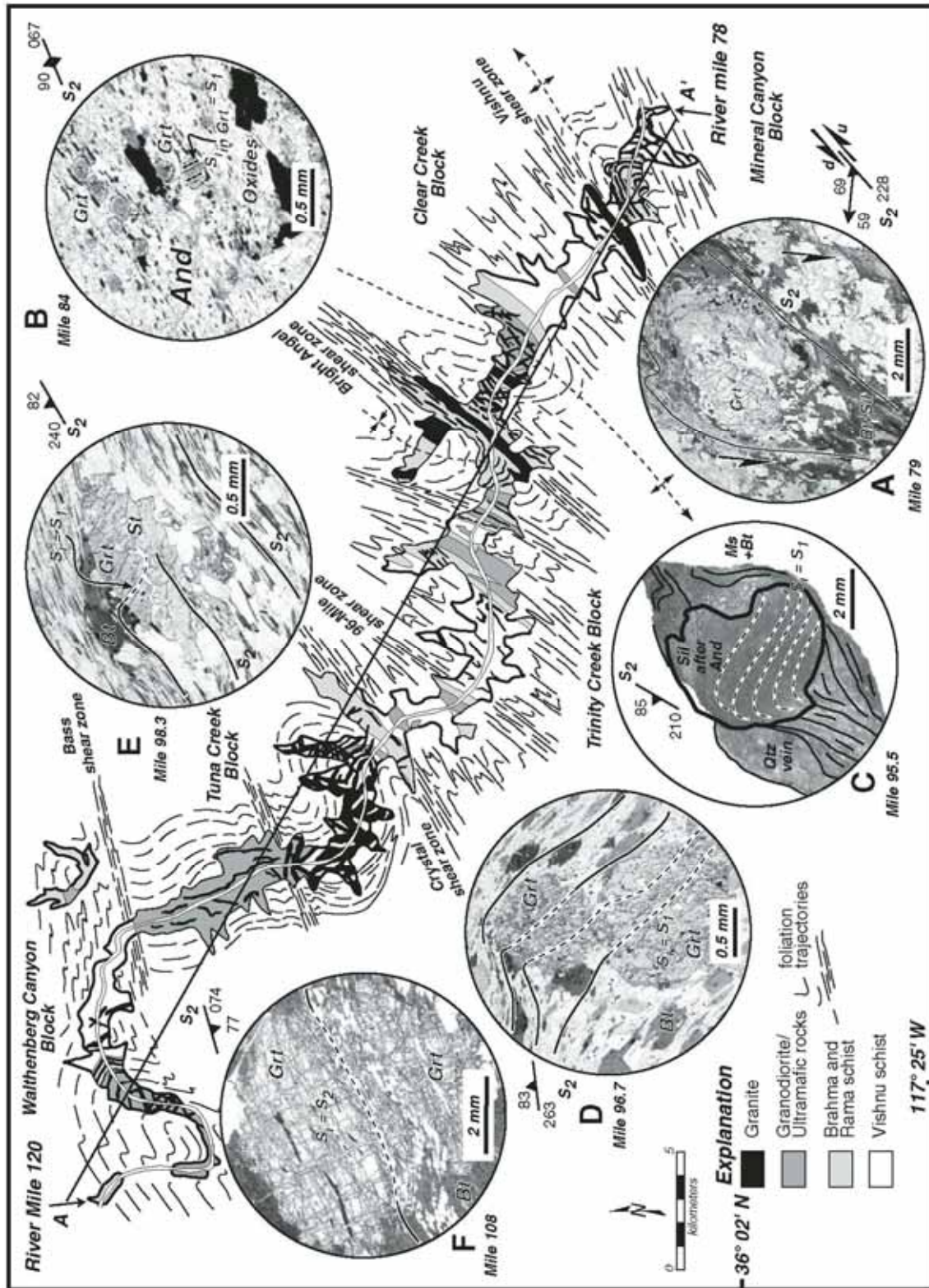


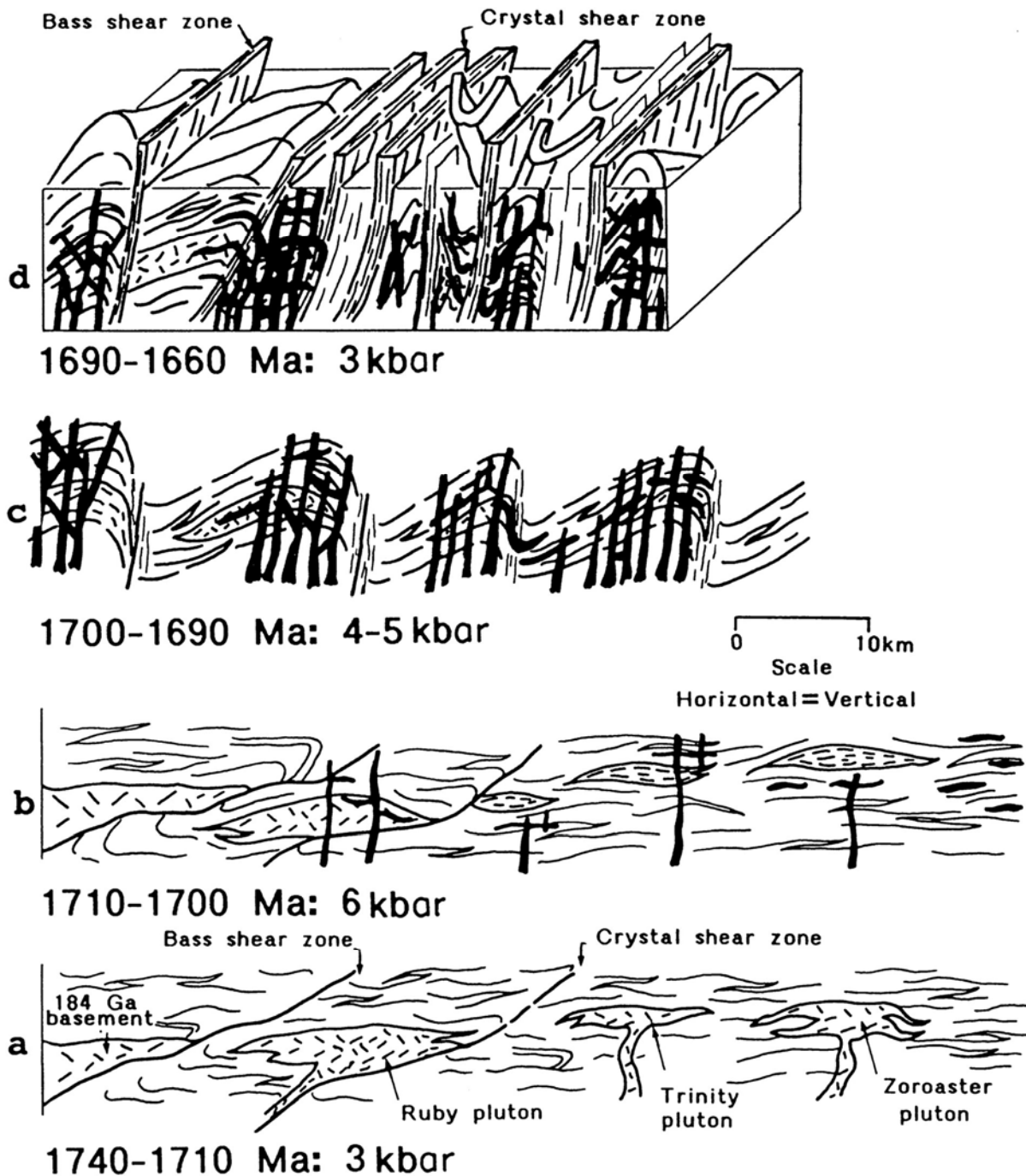
**Figure 27a** – Geological map of Paleoproterozoic rocks in the Upper Granite Gorge, Grand Canyon showing km-scale  $F_2$  folds and NE-trending  $S_2$  fabrics superimposed on variable dipping, NW-trending  $S_1$  foliation. (DFR0m IIg and others, 1996, Fig. 1, p. 1150.)



**Figure 27b** – Equal area projections of structural features and geological section A-A' (see Figure 27a for location) showing Paleoproterozoic rocks of the Upper Granite Gorge, Grand Canyon. (From Ilg and others, 1996, Fig. 2, p. 1151.)







**Figure 27d** – Tectonic sketches showing 1.7 Ga – 1.66 Ga development of Paleoproterozoic rocks of the Upper Granite Gorge, Grand Canyon based on geochronology and P-T analysis of garnet core petrofabrics. (a) 1.74-1.71 Ga - Arc-type plutons intrude at ~3 kbar (~9 km) preserving NW-trending  $S_1$  fabrics. (b) 1.71-1.70 Ga - Rocks experienced 6 kbar pressure (18 km depth). (c) 1.70-1.69 Ga – SE-vergent shortening and transposition into  $S_2$  fabric with injection of magmas and metamorphic fluids at 4-5 kbar (12-15 km). (d) 1.69-1.66 Ga – Period of N-S shortening and stabilization at higher crustal levels (~3 kbar) with continued shearing and injection of granitoids until 1.662 Ga (Phantom Pluton). (From Ilg and others, 1996, Fig. 10, p. 1164.)

The **Vishnu Schist** originated as mostly thin-bedded fine-grained clastics (sand, silt, clay) and minor mafic volcanic rocks formed in a shallow-water marine environment. The protoliths of the Vishnu were overlain by mafic tuffs, pillow lavas, and fissure flows with subordinate intercalated fine-grained clastics. Originally called the Brahma Schist, most workers now group both metamorphosed units as the Vishnu, noting that the volcanic component dominated the later depositional history of the unit.

During the **Mazatzal orogeny** protoliths of the Vishnu were isoclinally folded along NE-trending axial surfaces and foliated and later intruded by the 1.7 Ga **Zoroaster Granite**, which crops out over an area of 40 square miles. The voluminous sheets and dikes of granite produced broad areas of migmatite, pegmatitization, contact metamorphism, and metasomatic replacement. Intrusives of probable Zoroaster age include the gray plagioclase granite in the western Grand Canyon and quartz diorite in the Shinumo quadrangle west of Bright Angel. Thus, no absolute age control exists for the base of the metamorphic sequence and therefore the original depositional age of Vishnu clastics may be Archean as suggested by Maxson (1961). Development of the Trinity and Elves Chasm Gneisses and associated intrusive activity closes the book on Layer I.

After the main phase Mazatzal orogeny, the region was cut by a crisscross fault pattern (NW-SE and NE-SW), filling of faults by quartz veins, and renewed faulting. A period of uplift and erosion followed which produced an extensive nearly flat regional planation, known as the **Arizonian erosion surface**. Post Arizonian fragmentation of Layer I would include uplift, erosion, subsidence, and deposition of Layer II in fault-bounded basins.

## **Layer II – Algonkian Grand Canyon Supergroup (1.6 Ga – 850 Ma)**

Post Mazatzal uplift and erosion set the stage for the deposition of Layer II (the **Grand Canyon Supergroup** which consists of the **Unkar** and **Chuar Groups** in Figure 24). Layer II consists of a vast sequence of intercalated sedimentary and volcanic rocks of predominately marine origin. The sequence starts with deposition of the **Hotauta Conglomerate** which grades upward into the **Bass Limestone**. The Hotauta contains fragments of igneous and metamorphic rocks of Layer I, preserved remnants of the older “Archean” sequence. The Bass Limestone (and dolostone) varies in thickness from 120’ to 340’ and forms the basal unit of the 3,000’ thick Proterozoic Unkar Group. The Bass Limestone is overlain by 580’ to 830’ of non-marine terrigenous clastics (**Hakatai Shale**) and by 1,100’ to 1,560’ of **Shinumo Sandstone** (“quartzite” in older publications). The Shinumo is overlain by roughly 3,000’ of intercalated marine sandstone and shale of the **Dox Formation**. Thus, an open ocean passive continental margin sequence had developed by the end of Dox sedimentation.

Faulting was then renewed on a pre-existing NW-SE and NE-SW network. After faulting, an 800’ to 1,000’ thick sequence of basaltic fissure flows (**Cardenas or Rama formations**) took place and diabase dikes and sills invaded both across and along faults, fractures, and bedding planes of older formations.

Although not exposed in the Grand Canyon, a thick sedimentary sequence of latest Proterozoic age overlies the **Unkar Group** in fault blocks to the west of Nankoweap Canyon.



Here, the **Chuar Group** consists of the **Nankoweap, Galeros, Kwagunt, and Sixtymile Formations**, a total of 5,000' of dominantly shallow water marine sediment.

Following deposition of the Unkar and Chuar Groups, block faulting, thrust faulting, development of monoclinical folds, and another period of regional uplift and erosion took place before deposition of the stream deposits of the Sixtymile formation. This final ratchet of uplift and erosion ultimately beveled the rocks of both Layers I and II and produced another extensive erosion surface known as the **Grand Canyon Peneplain**. Geologists point to it proudly and have named it the **Great Unconformity**. The Great Unconformity is both an angular unconformity and nonconformity that separates the rocks of Layers I and II (below) from subhorizontal Cambrian Paleozoic rocks of Layer III. It's as if 550 million years of time has just vanished between the time of their horizontal deposition and ultimate exposure in the same orientation. Cambrian sedimentation continued in the area with thick accumulations of sandstone, shale, and limestone in a transgressive environment. Thus, after the second orogenic cycle (**Grand Canyon orogeny**), the embryonic SW Cordillera returned to another trailing edge passive continental margin condition. It just can't seem to be able to make up its mind!

All of this extended passivity was about to change forever as looming to the west of us were the harbingers of fundamental change. Subduction had begun without warning in the present area of California and volcanic arcs and incoming exotic terranes were about to make their tectonic marks on the developing Cordillera. The sedimentary record of the Great Basin records the continentward expression of significant plate tectonic interactions throughout most of Phanerozoic time. Thus, in order to better understand the sedimentary story about to unfold, we would like to take some page space to alert you to the goings on to the west of us. After reading the digression on the Phanerozoic Tectonics of the Western Cordillera, kindly return to the descriptions of Layer III (below).

### **Digression 1 – Phanerozoic Tectonics of the Western Cordillera**

You've heard of Tora! Tora! Tora!, well ... Subduction, Subduction, Subduction! That would be the easiest way to describe the Phanerozoic tectonics of the western Cordillera (Appendix 2). Throughout the early Paleozoic development of an open-ocean passive margin formed an extensive miogeoclinal and deep-water eugeosynclinal couple formed adjacent to embryonic western North America. Starting with the **Antler orogeny** in late Devonian – early Mississippian time, a series of convergent margin events produced the present western Cordillera. An arc-continent collision was responsible for the Antler orogeny according to most modern workers. The Roberts Mountain Allochthon places deep-water facies atop coeval miogeoclinal rocks through central Nevada along east-directed overthrusts. Such overthrusts were produced within the walls of an accretionary prism that collided with the passive margin of North America.

After a period of uplift, erosion, and extension a marginal basin formed that filled with Pennsylvanian and Permian sediments. A piece of the late Devonian Antler volcanic arc that had already collided began to rift away from the suture zone, leaving a small oceanic "marginal" basin behind. Closure of that marginal basin along a west-dipping subduction zone resulted in a collision with the old Antler arc that had rifted away earlier. The **Sonoma orogeny** (late

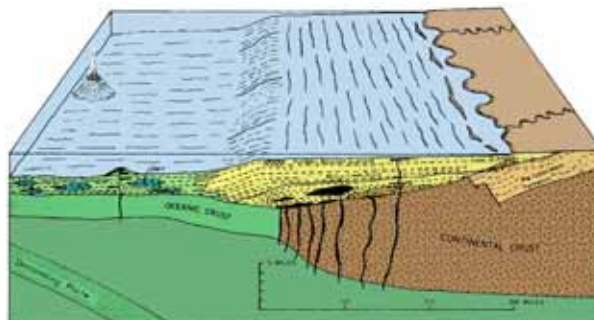
Permian - early Triassic) has produced by a collision that resulted from the composite arc that formed in the upper plate of the new subduction zone. (See Appendix 2.)

By the late Triassic, after some significant shifts in polar wander paths (indicating rapid plate reorganizations), the SW Cordillera looked quite different. Development of a NW-trending megashear zone cut across the Antler and Sonoma trends and prepared the newly arranged margin for an unprecedented epoch (Jurassic to present) of continuous continentward subduction. During the middle Jurassic **Nevadan orogeny**, island arcs were swept into the Cordilleran margin and subduction flips were common. The scattered volcanic island arcs of the SW Pacific may offer a modern analog to the conditions that must have prevailed along the active edge of the western Cordillera throughout the Mesozoic. By Cenozoic time subduction was in an Andean setting with development of an elongate volcano-plutonic complex parallel to the present coastline. With flattening of subduction angles in the Cenozoic, volcanogenesis broadened to include the Great Basin. Starting at about 30 Ma, destruction of the Farallon plate and development of the San Andreas plate boundary has dominated the tectonics of the region.

The major tectonic events occurring to the west of our field area have had an important effect on depositional patterns, faulting, and igneous activity. For example, continental borderland lithospheric flexure in response to marginal subduction or thrust loading produces important crustal depressions (basins) and upwarps (domes). The thermal effects and associated igneous and tectonic activity can vary in time and space depending upon subduction rate, angle, and direction. The digression above provides some backdrop to better understand the geology of Arizona and adjacent areas.

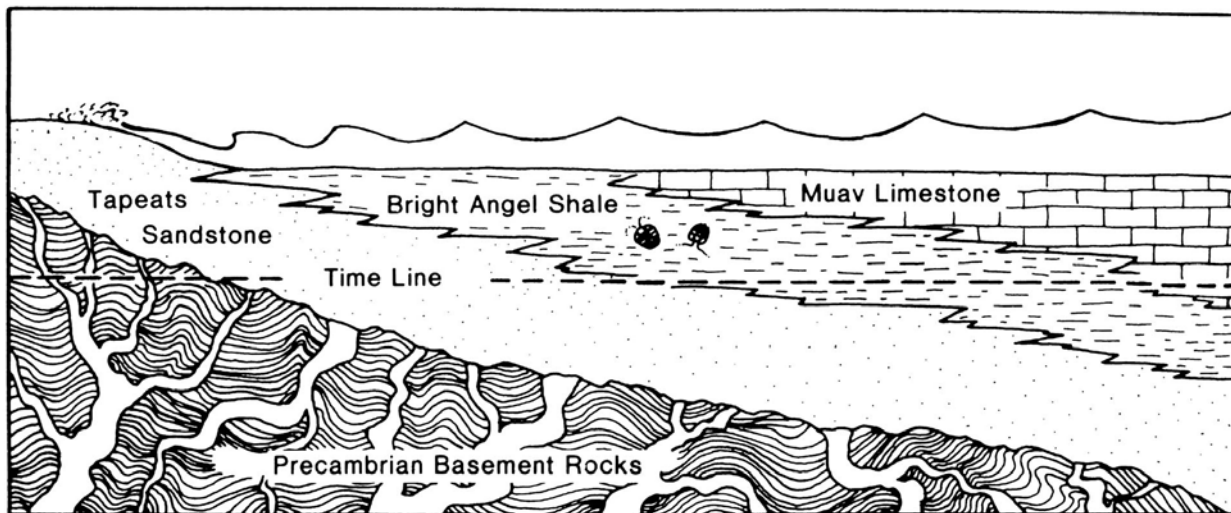
### **Layer III – Late Proterozoic and Paleozoic Strata (Proterozoic Z to Permian)**

The Grand Canyon of Arizona is one of the best places on Earth to study the geologic record of the Paleozoic (Figure 28). With the development of a trailing edge passive continental margin by latest Proterozoic Z time, the stage was set for Cambrian transgressive sedimentation. As a prelude to that, at around 850 Ma, diamictites (conglomeratic mudstone of possible glacial origin) formed a widely distributed but discontinuous basal unit to a sequence of siltstone, shale, argillite, quartzite, and conglomerate (Stewart, 1972). Tholeiitic basalt is found as flows and sills near the base of this late Proterozoic sequence but is sparse higher in the section. Because the strike of the Proterozoic Z strata cut across the trends of Layer I or II rocks but are parallel to the Paleozoic strata of Layer III, we include them in this layer. Stewart (1972) interprets the entire package as a rift-facies related to thinning and rifting of the crust during a period of continental separation that ultimately led to the formation of an open ocean, passive continental margin. These strata pinch out before reaching the Grand Canyon area and are therefore not shown on most stratigraphic sections. Yet, they set the stage for a rather impressive continentward transgression of the seas during earliest Cambrian time.



**Figure 28** – Late Proterozoic and upper Cambrian rocks of the northern Great Basin of Nevada and Utah (Stewart, 1972, Figure 3, p. 1346).

Roughly 550 Ma, with formation of an open ocean to the west, Cambrian clastics spread out over the edge of North America under shallow water conditions. Directly analogous to the transgressive lower Paleozoic facies of the Appalachian belt, with rising sea level, subsiding continental edge, or both, the Cambrian shoreline migrated eastward to sweep across Arizona. As time passed, the offshore depositional environments shifted continentward along with the transgression of the seas. This resulted in a fining upward sequence of strata where Cambrian sands (Tapeats) were overlain by shale (Bright Angel), then by carbonate (Muav) of the Tonto Group as shown in Figure 29.



**Figure 29** – Southward view along a profile section showing the discordant relationship between time lines and formational contacts in a transgressive environment. (Nations and Stump, 1981, p. 19.)

The **Tapeats Sandstone** varies from 200' to 300' thick, consists of cross-stratified coarse-grained quartz sand, and contains several types of Cambrian fossils. Interpreted as a near-shore shallow water marine facies, it is easily recognized in the Grand Canyon because it forms a prominent cliff beneath an easily eroded shale unit. The **Bright Angel Shale** ranges in thickness up to 450' and consists of thin-bedded, light greenish gray silty shale. Cambrian brachiopods, trilobites, and trace fossils have been found in the unit. Similar to the Tapeats but from farther offshore, the Bright Angel is the result of shallow water marine deposition.

The **Muav Limestone** is a sequence of intercalated gray limestone and greenish gray calcareous siltstone. Ripple marks and wave agitated sediment indicates shallow water depositional conditions. Fossil Cambrian trilobites are found in the unit. The top surface of the Muav is an erosional unconformity atop which rests either Devonian Temple Buttes Limestone or the Mississippian Redwall Limestone.

Ordovician and Silurian strata are absent in the Grand Canyon but Ordovician strata are found in the Virgin Mountains and in SE Arizona (Figure 30). Ordovician and Silurian sequences are well known throughout Nevada, in the foothills belt of the Sierra Nevada range of California and in the northern Sierra and Klamath Mountains of Oregon. Non-deposition during



that interval or removal of Ordovician strata during the Silurian, either model results in the same geological record at the Grand Canyon – an unconformity at the top of the Cambrian with Devonian and Mississippian sedimentary rocks above (Figure 31). Deep channels were formed in the Muav Limestone prior to deposition of the upper Devonian **Temple Buttes Limestone** that locally fills the channels. (Also see Figure 24.) The presence of channels in the Muav suggest that uplift and erosion is the cause of the missing lower Paleozoic strata. According to Harris and Tuttle (1990), the Temple Buttes is best exposed along the walls of Marble Canyon and is a prominent cliff former in the Grand Wash Cliffs where the thickness exceeds 1,000’.

The Temple Buttes was named by Walcott (1899) and consists of purplish-gray to pinkish gray, medium bedded limestone. They are lensoidal in form varying from 400’ across and 50’ thick to those that are only 10’s of feet across and are conglomeratic near the basal contact with the Muav. The Temple Buttes contains upper Devonian fossils.

	Virgin Mountains	Grand Canyon	Southeastern Arizona
Devonian	Muddy Peak Limestone	Temple Butte Ls.      Martin Formation	Martin Formation      Portal and Swisshelm Formations
Ordovician	Pogonip Limestone	No Ordovician Recognized Undifferentiated Dolomite	Longfellow Limestone
	Undifferentiated Dolomitic Limestone		El Paso Limestone
Cambrian	Peasley Limestone	Tonto Group	Muav Limestone
	Chisholm Shale		Bright Angel Shale
	Lyndon Limestone		
	Pioche Shale		
	Prospect Mountain Quartzite		Tapeats Sandstone
			Bolsa Quartzite

**Figure 30** – Stratigraphic correlation chart for the lower part of the Paleozoic in Arizona. (Nations and Stump, 1981, p. 111.)

Despite rumblings to the west in the form of the Antler orogeny, the arrival of the Mississippian (Figure 31) brought with it marine carbonate deposition to produce the **Redwall Limestone**, one of the most distinctive and prominent sequences of the canyon. Typically about 500’ thick and commonly stained red from percolation of hematite in groundwater from overlying terrigenous clastics (Supai and Hermit redbeds), the Redwall weathers into stark vertical cliffs. The limestone is medium gray in fresh hand sample and is typically well bedded with local beds of red jasper near the base and local chert nodules. Containing less than 1% sand and clay, this pure limestone was deposited in quiet, marine waters far away from clastics. Fossils include invertebrates including shells and corals.

During the Pennsylvanian and Permian, major changes in sediment type and volume took place in the Great Basin. Deposition of coarse terrigenous clastics resulted in regression of the seas and replacement by non-marine environments. The **Supai Group** is 600' to 700' thick and consists of mostly non-marine red sandstone, shale, and siltstone accumulated in a swampy, but oxygenated deltaic environment. Similar to the Devonian Catskill delta fan complex of eastern New York State, the sequence is crossbedded suggesting ancient deltas and coastal dunes. The middle and upper part of the formation yields fossil ferns and other primitive plants and quadruped amphibian footprints.

The Supai is overlain by the **Hermit Shale** of Permian age. Characteristically deep red and only 200' to 300' thick at the river level of the eastern Canyon, the formation thickens to more than 900' in the west. The Hermit has yielded 35 species of plant fossils, ripple marks, mud cracks, and insect remains that together indicate a savannah-type environment with long, dry seasons. Migrating sand dunes replaced the swampy flood plains of the Hermit interval with the arrival of the **Coconino Sandstone**. The Coconino Sandstone is a prominent, white-colored, homogenous cliff-former found beneath the Kaibab and Toroweap Limestones but is very thin in the eastern canyon. The Coconino consists of uniform, well-rounded and -sorted, pitted or frosted quartz grains arranged into elongate crossbeds, with angles of repose indicative of eolian deposition. Large dunes are indicated as the Coconino exceeds 400' in thickness. Twenty-two varieties of fossil reptile footprints indicate that animals traveled the dunes in search of fast food and would gladly settle for not-so-fast food. Thus, the swampy environment of the Pennsylvanian is replaced by a broad desert during the Permian. The outcrop extent of the Coconino (32,000 square miles) places it on par with the present-day Sahara or Arabian deserts.

Deposition of the **Kaibab and Toroweap Formations** during the later stages of the Permian have produced a broadly exposed cap rock in the Grand Canyon area. (See Figures 24 and 31.) Both formations are well-bedded marine limestones that mark a late Paleozoic marine incursion into the area of former terrigenous strata. Variable amounts of sandstone and chert are found in the Kaibab and the Toroweap contains some shale. They can best be described as a creamy, yellowish-gray limestones although local color variations exist. More than 80 genera of marine invertebrate fossils are reported from both formations as well as a few fossil fish teeth. Chert nodules are locally present and some are cored by silicified sponges.

Post-Mesozoic uplift of Layer III strata and subsequent rapid downcutting by active river systems have produced spectacular exposures in the dissected canyon lands of northern Arizona and adjacent Utah. Differential erosion of various horizontal rock types produces amazing terraces and slopes, as seen in the Grand Canyon (Figure 32). Profile sections (Figure 33), provide an important view into the scale of the downcutting and the geometry of the uplifted Great Basin sequence. Where did all that sedimentary material go? Why, back to the Pacific, of course. Despite the fact that archeological views that put doubt on the geologist's view of the age of Grand Canyon formation (Figure 34), we are confident that the rock record speaks for itself in these matters. A compilation stratigraphic column for the Grand Canyon is reproduced as Figure 35. In the event even more evidence of age is needed for the skeptical reader, Figure 36 shows that at 1.0 Ma the canyon existed in more or less its present shape although damming of the Colorado River by lava and cinder evidently took place at various times.

	Northwestern Arizona	Grand Canyon	Central Arizona	Northeastern Arizona	Southeastern Arizona		
Permian	Kaibab Limestone	Kaibab Limestone	Kaibab Ls. Coconino ss.	DeChelly Sandstone	Rain Valley Formation		
	Toroweap Formation	Toroweap Formation			Concha Limestone		
	Coconino Sandstone	Coconino Sandstone	Scherrer Formation				
	Hermit Shale	Hermit Shale	Schneibly Hill Fm.	Epitaph Dolomite			
	Supai Formation	Esplanade Sandstone	Hermit Shale	Colina Limestone			
Pennsylvanian	Callville Limestone	Supai Group	Esplanade ss.	Cutler Gp.	Earp Formation		
						Wescogame Formation	Organ Rock Fm.
						Manakacha Formation	Cedar Mesa ss.
						Watahomigi Formation	Halgaito Fm.
Mississippian	Redwall Limestone	Redwall Limestone	Redwall Limestone	Redwall Limestone	Paradise Formation		
					Escabrosa Limestone	Hachita Fm.	
						Keating Fm.	
						Black Prince Limestone	
					Horquilla Limestone		
Molas Formation							

Figure 31 – Stratigraphic correlation chart for the upper part of the Paleozoic in Arizona. (Nations and Stump, 1981, p. 117.)

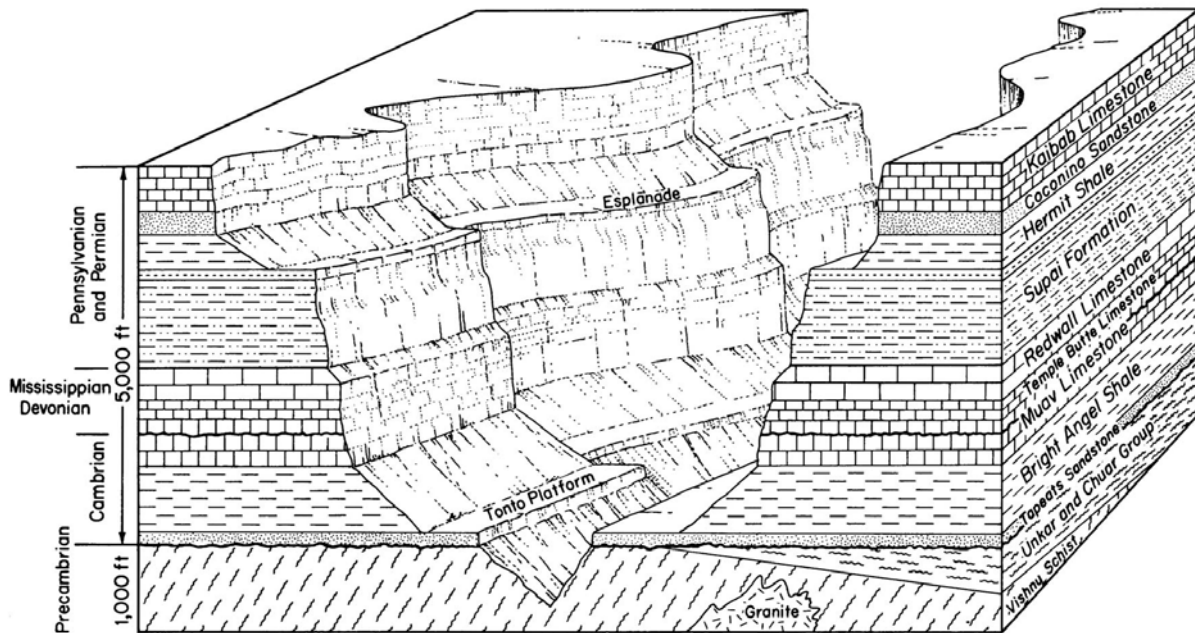


Figure 32 – Sketch showing the erosion angles of various strata in the Grand Canyon.



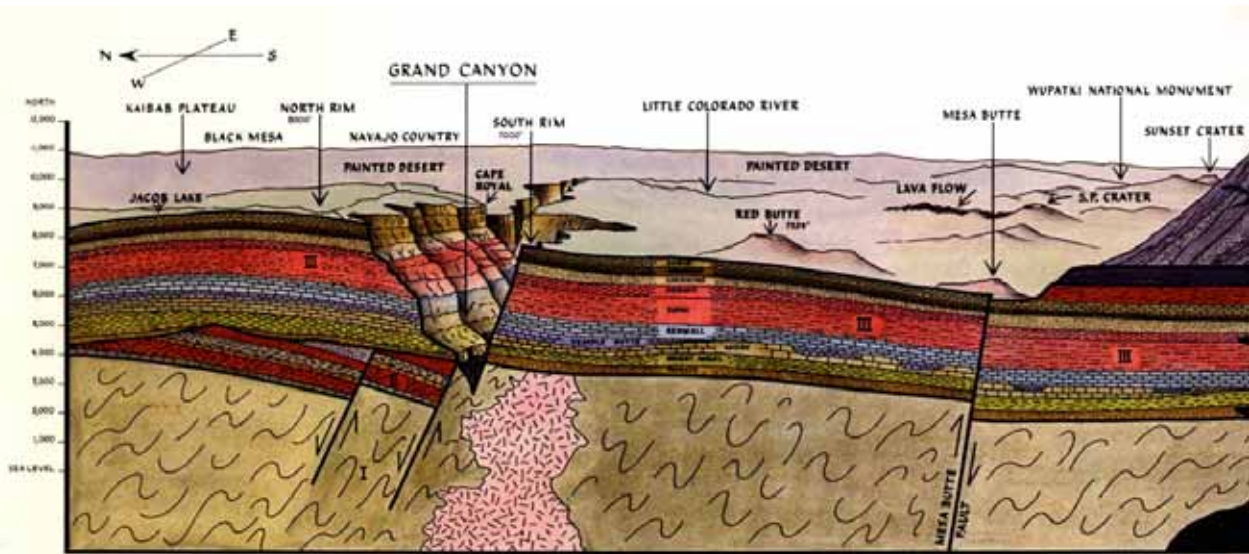


Figure 33 – Generalized profile section across part of the Grand Canyon and Kaibab uplift.



Figure 34 – Reproduction of rare J. Wesley Powell lithograph of “Early Work on the Grand Canyon”.

## GRAND CANYON, ARIZONA

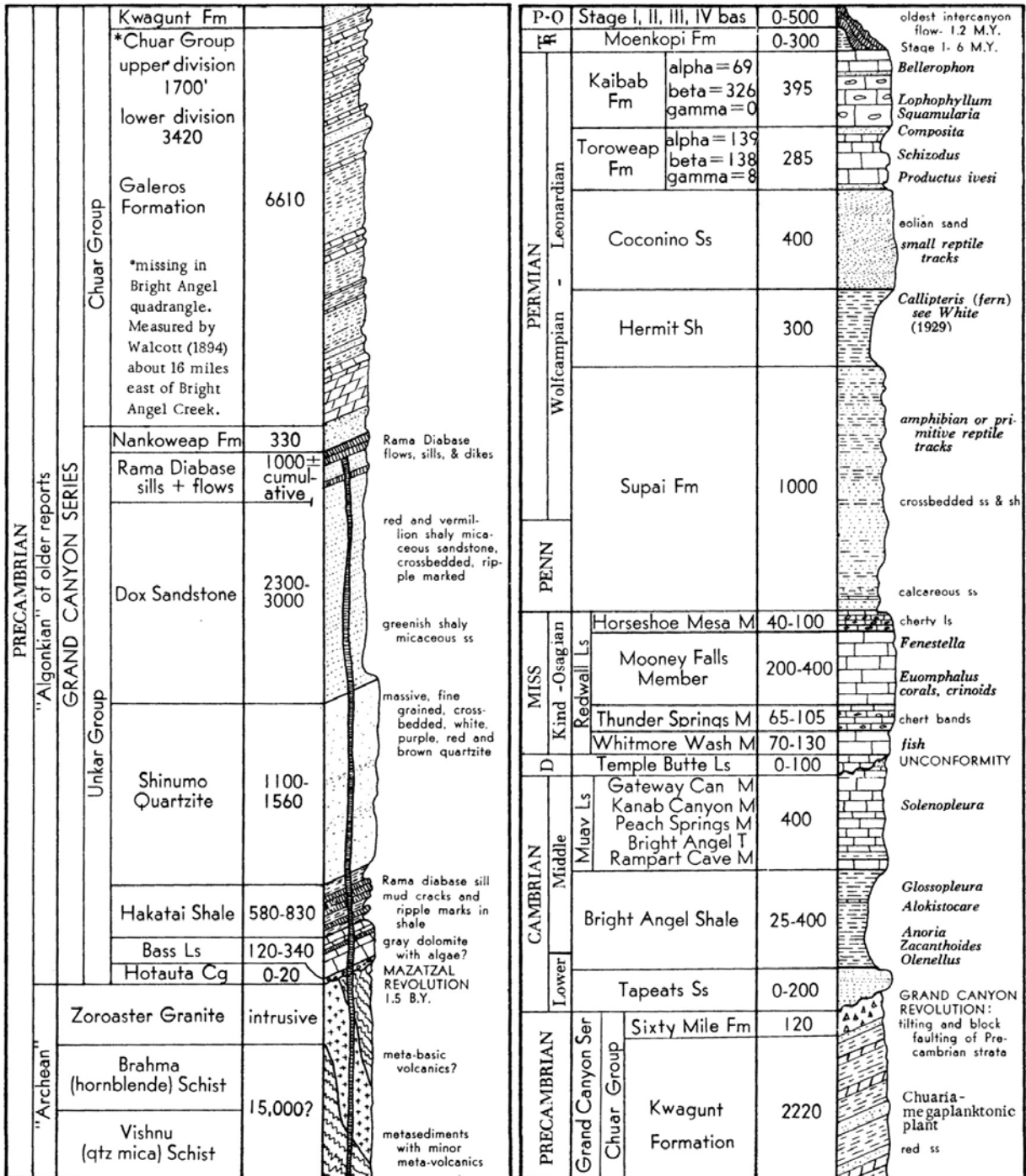
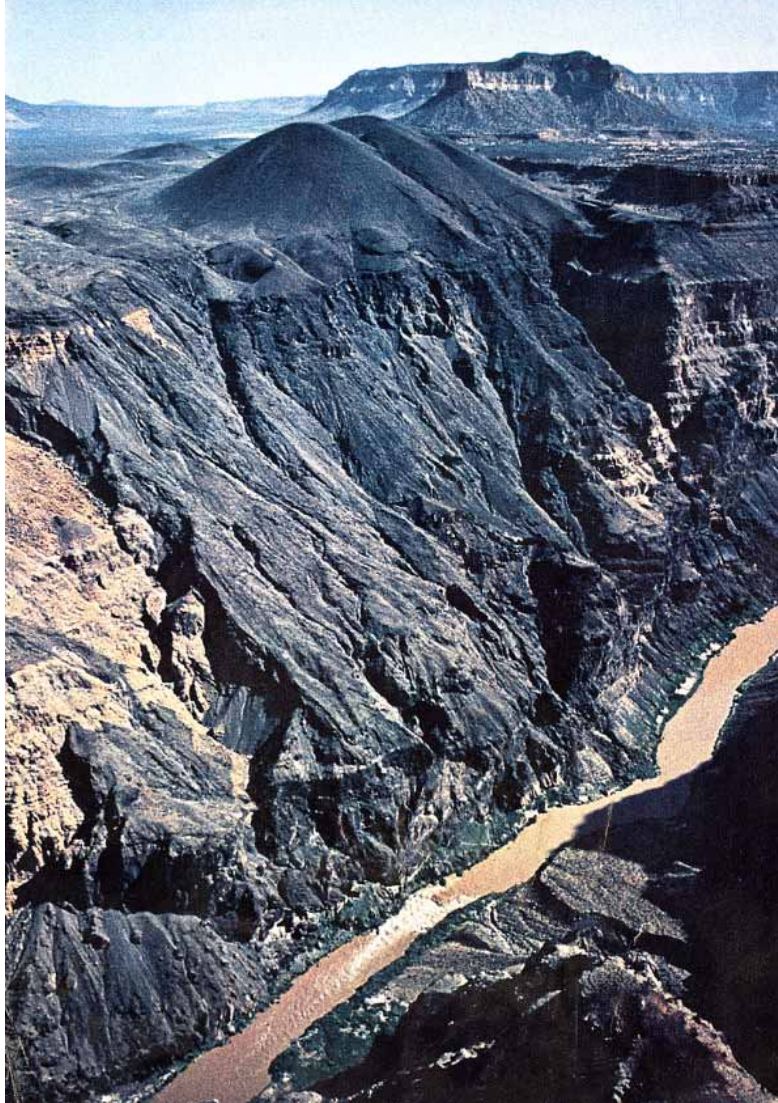


Figure 35 – Stratigraphic correlation chart for the Grand Canyon area. (Hintze, 1980, p. 163.)





**Figure 36** – Vulcan's Throne in the Grand Canyon, a 1.0 Ma lava flow and associated cinder cone.

A natural separation exists between Layers III and IV in the form of a transition from Paleozoic marine to Triassic non-marine conditions. This transition conveniently occurs at the Paleozoic-Mesozoic boundary, a natural subdivision where rocks and time merge.

#### **Layer IV – Mesozoic Strata (Triassic to Cretaceous)**

With all of the tectonic activity to the west (Permo-Triassic Sonoman orogeny and middle Jurassic Nevadan orogeny), infilling of the Great Basin in post-Paleozoic time produced thick sequences of beautifully variegated, predominantly non-marine sedimentary rocks. Starting with the Triassic **Moenkopi Formation**, terrigenous sediment began to overlay the marine Kaibab in broad floodplains and river systems. Subsequent deposition of the Shinarump Conglomerate, Chinle formation, and Moenave formation, and lower part of the Kayenta formation all took place during the Triassic (Figure 37).



Mesozoic Rock Units in Arizona

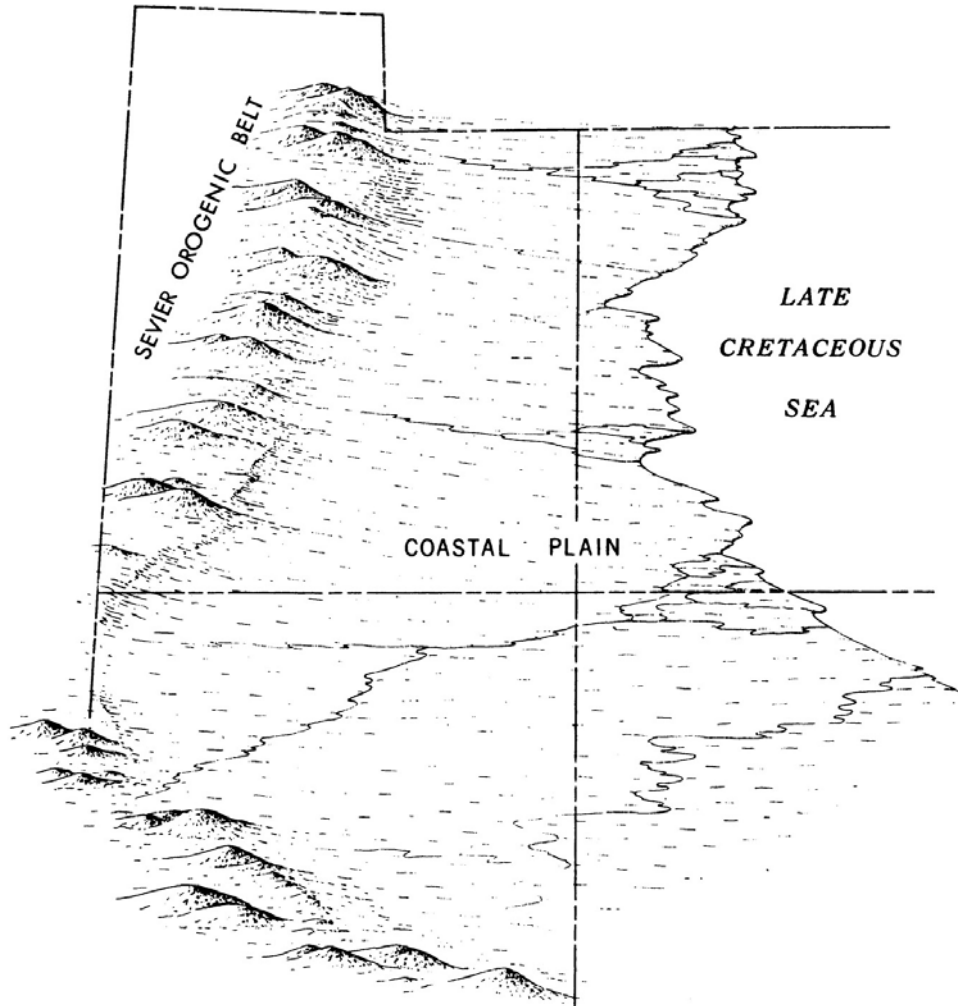
		Virgin Mountains	Black Mesa Basin	Southeastern Arizona			
Cretaceous	Upper	Cottonwood Wash Formation	Mesaverde Group	Andesite and Rhyolite			
				Yale Point Sandstone	Silverbell and Salero Fms.		
				Wepo Formation	Amole Arkose		
			Toreva Formation	Pinkard Formation			
			Mancos Shale	Fort Crittenden Formation			
	Dakota Sandstone						
	Lower	Jacobs Ranch Formation			Bisbee Group		
					Cintura Fm.		
					Mural Ls.		
					Morita Fm.		
Glance Cgl.							
Jurassic	Navajo Sandstone			Undifferentiated Volcanic and Clastic Units			
					Morrison Formation		
					San Raphael Group	Bluff Sandstone	
						Summerville Formation	Cow Springs Sandstone
						Todilto Limestone	
						Entrada Sandstone	
						Carmel Formation	
					Glen Canyon Group	Navajo Sandstone	
						Kayenta Formation	
						Moenave Formation	
Wingate Sandstone							
Rudolfo Fm. and Recreation Redbeds							
Triassic	Chinle Formation			Ox Frame and Mt. Wrightson Fms.			
					Wingate Sandstone		
					Chinle Formation		
					Moenkopi Formation		
	Moenkopi Formation						

Figure 37 – Stratigraphic correlation chart of Mesozoic rocks in Arizona. (Nations and Stump, 1981, p. 134.)

The **Moenkopi Formation** (200') consists of dark, reddish brown shale and siltstone. Coarse sand and gravel of the **Shinarump Conglomerate** produces a resistant formation ranging from 50' to 100' thick. The conglomerate is host for fossil wood rich in radiogenic carnotite. Known together as the "Chocolate Cliffs", excellent exposures are near Kanab, Utah near the Arizona state line.

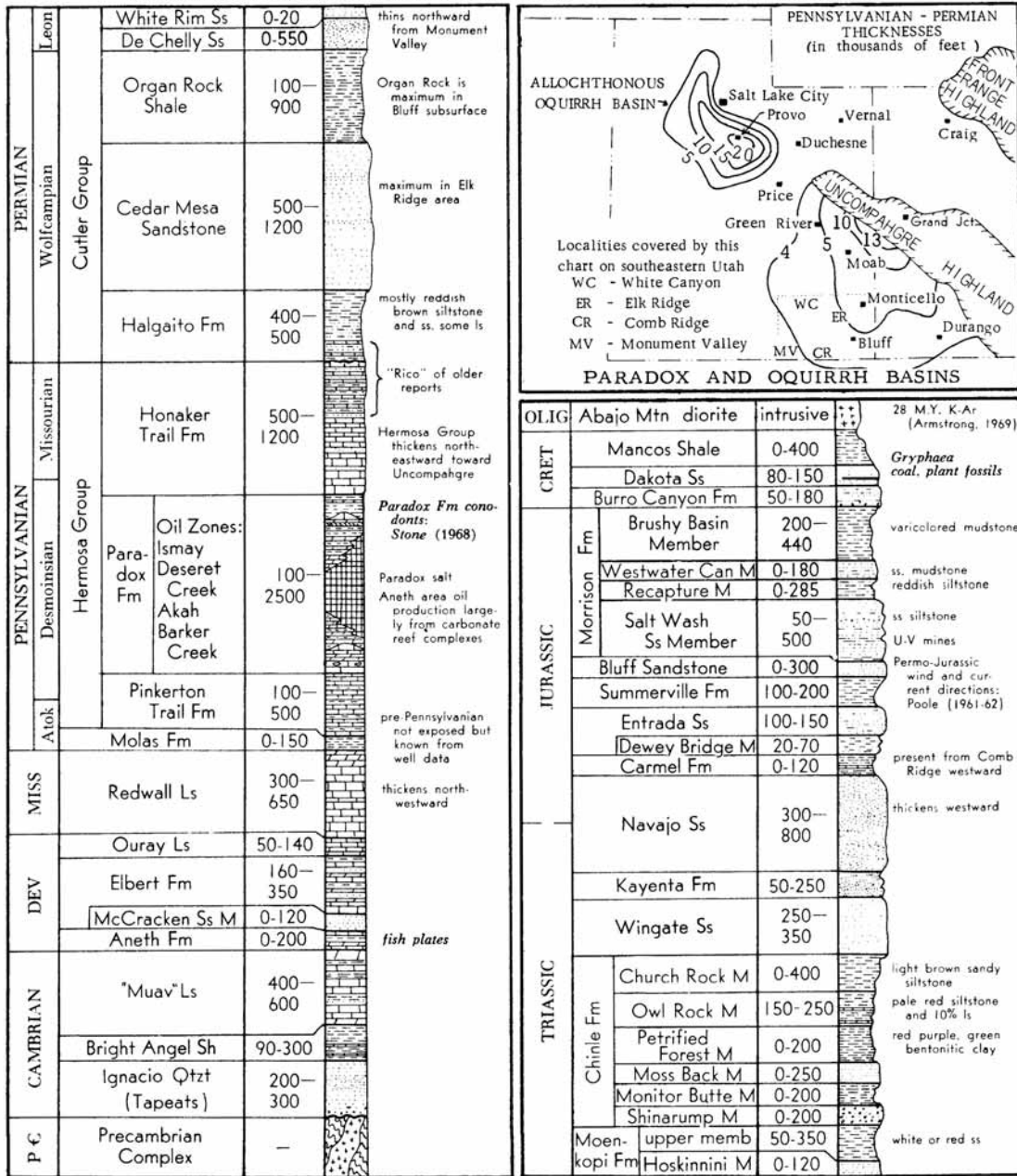
The **Chinle Formation** consists of a thick sequence of variegated shales that range in colors from blue, purple, green, pink, gray, maroon, to brown. This formation underlies the famous Painted Desert and the Petrified Forest. The **Moenave Formation** is 350' thick and consists of variegated shades of red, orange, and reddish brown. A cliff-former, the formation consists of lenticular sandstones produced by active stream systems. The Jura-Triassic **Kayenta Formation** is roughly 400' thick and consists of fine-grained sandstone and siltstone. Dinosaur tracks are found in the siltstones indicating non-marine conditions throughout the interval.

In Arizona, overlying Jurassic sedimentary sequences include the **Navajo Sandstone** and correlative **San Rafael Group** of strata followed by Cretaceous strata including the **Dakota Sandstone, Mancos Shale** and overlying **Mesa Verde Group**. The Great Basin, by late Cretaceous time, was fringed by the upraised Sevier highlands to the west, a configuration that provided an ample source of terrigenous sediment. To the north and east shallow water marine conditions prevailed (Figure 38) but not for long. Cenozoic alluvial sediment and volcanic materials have pushed back the Cretaceous seas from North America. By and large the Mesozoic sequences are best experienced in the awesome canyon lands of southern Utah (Figure 39).



**Figure 38** – Physiographic diagram of the Great Basin during the Cretaceous.

**SOUTHEASTERN UTAH  
MONUMENT VALLEY - COMB RIDGE - BLUFF - ELK RIDGE - MONTICELLO**



**Figure 39** – Stratigraphic correlation chart for southern Utah. (Hintze, 1980, p. 162.)

As we had mentioned earlier, the Mesozoic was a period of continuous subduction but many changes in tectonic plate subduction. For example, between the late Triassic to Cretaceous rapid tectonic suturing of exotic terranes and development of a broad tectonic welt occurred in the SW Cordillera (Figure 40). Thus, starting in Kimmeridgian (middle Jurassic) time and extending through the Cretaceous to present, continentward subduction has resulted in the truncation of all older geologic trends including Antler (Roberts Mountain), Sonoman, and



Sevier thrusts (Figure 41). The Cenozoic geology of Layer V is the product of continuous subduction against a complexly deformed Phanerozoic mobile belt.

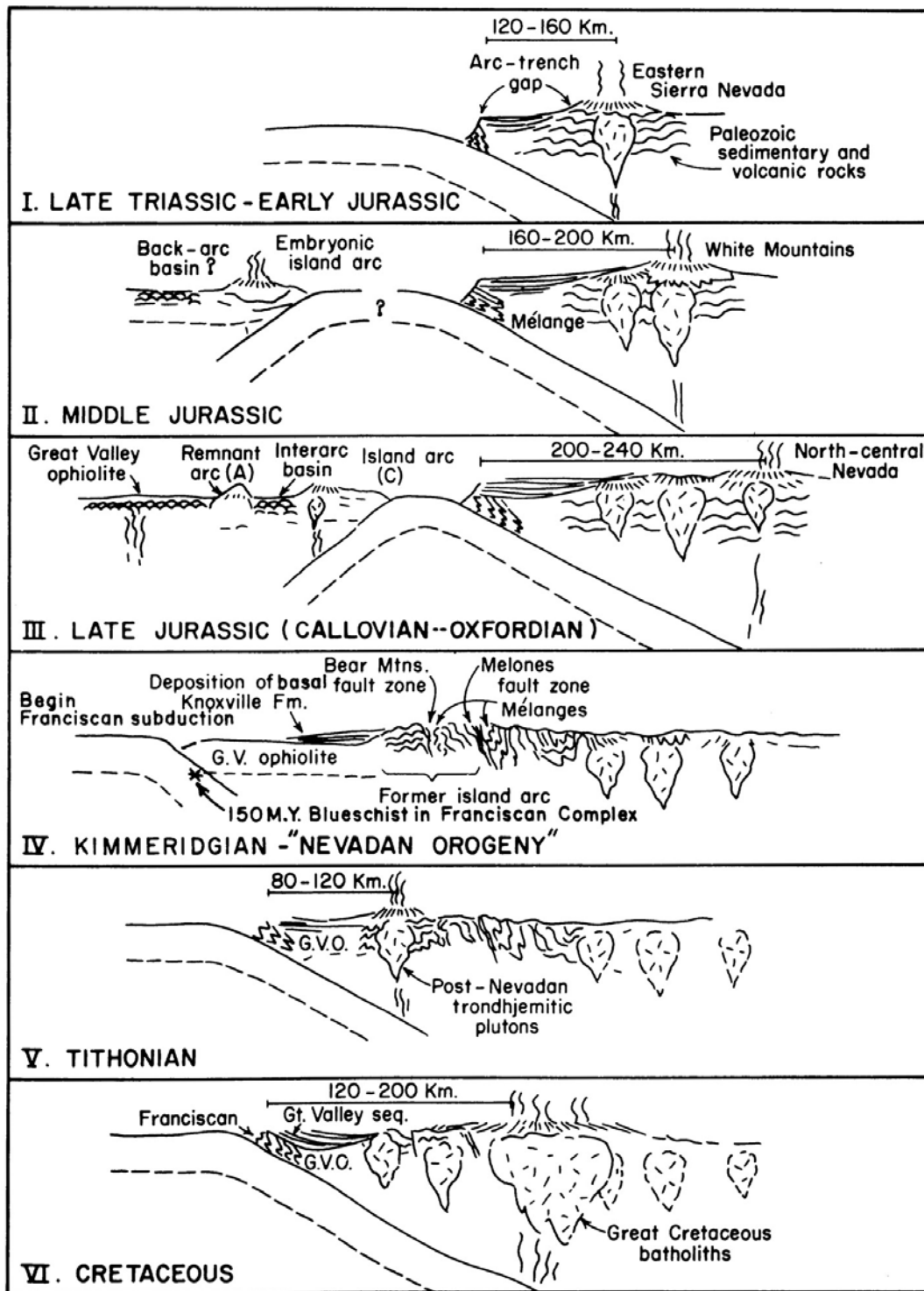
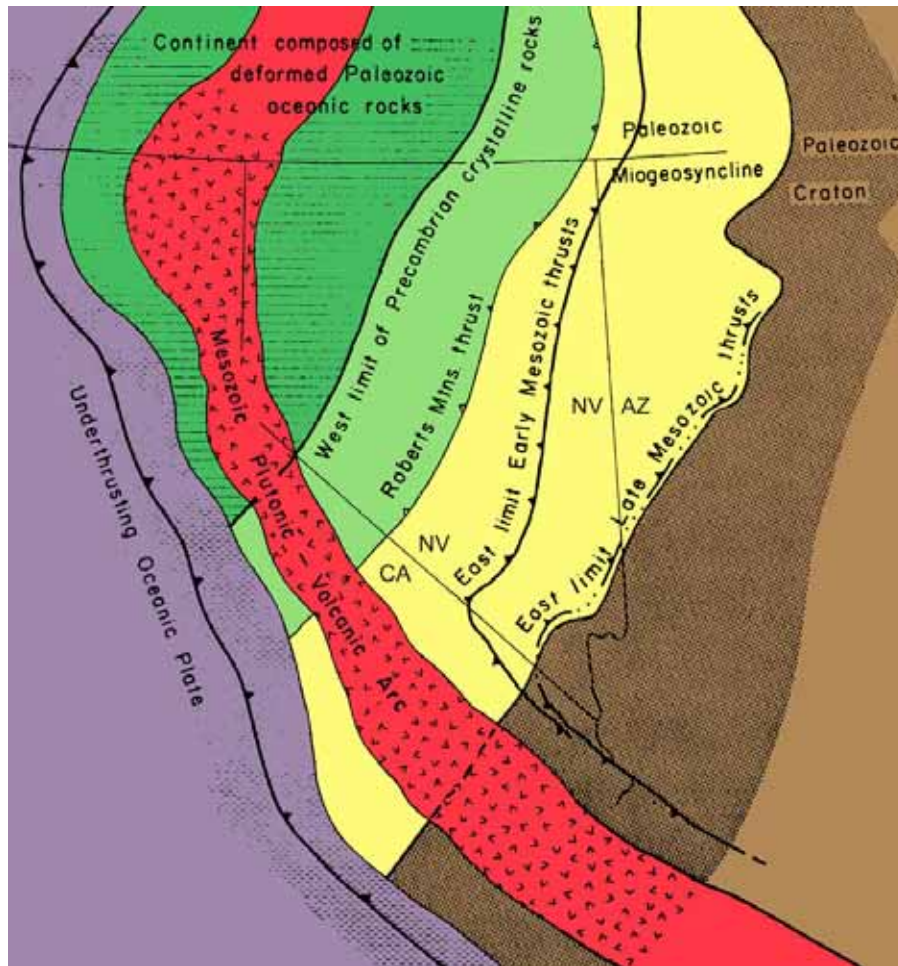


Figure 40 – Plate models to explain Mesozoic tectonics of the SW Cordillera. (Schweickert and Cowan, 1975, Figure 3.)



**Figure 41** – Geologic sketchmap showing the truncation of Antler, Sonoman, and Sevier thrusts. (Burchfiel and Davis, 1972, Fig. 7.)

### **Layer V – Cenozoic Strata (Tertiary and Quaternary)**

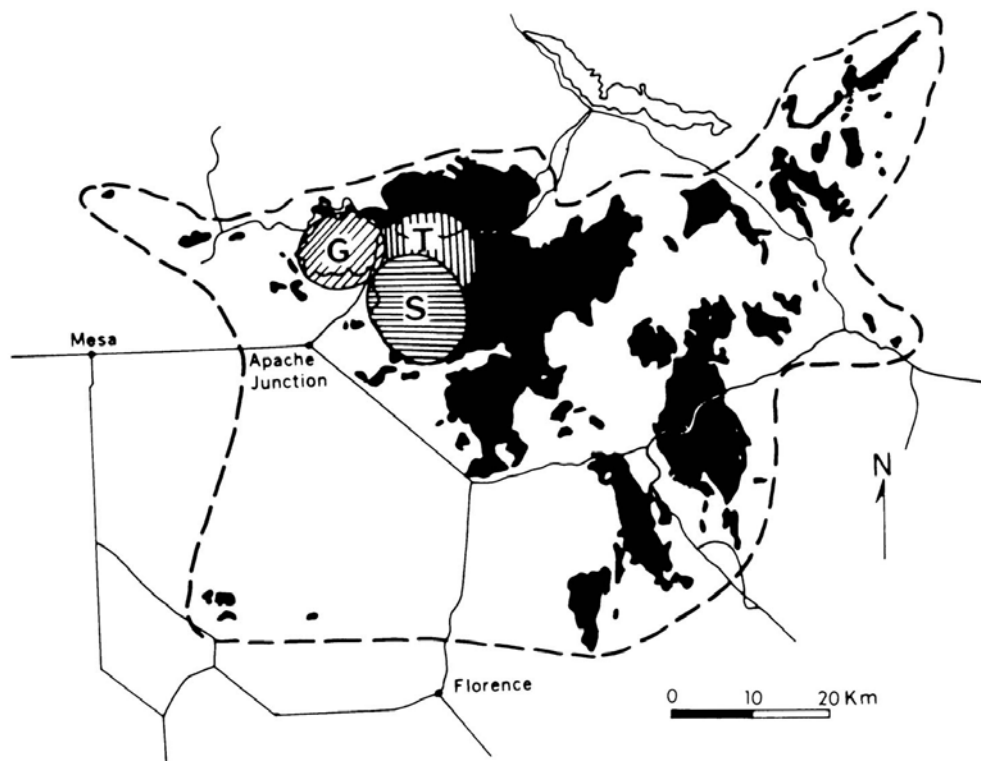
The Laramide orogeny affected the SW Cordillera between late Cretaceous and Eocene time. Arizona was tectonically active with upwarps and downwarps of the region controlling sediment patterns. That instability was followed by intermediate to silicic eruptive volcanism in response to continuous subduction along the active margin to the west. Lithospheric softening and NE-directed compression resulted in thermal collapse of internal core zones of the Laramide overthrusts where ductile thrusts show maximum offset of 100 km. Known as metamorphic core complexes to some, these areas exhibit mobilized amphibolite facies gneisses in massive overthrust sheets. In addition, large Cenozoic plutons invaded portions of southern Arizona but Basin and Range faulting has obscured many of the geologic relationships. The Cenozoic plutons provided mineralization into the wallrocks that have bolstered the economy of the region in the form of porphyry copper mines.

In northern Arizona, Layer V sediments were not deposited as the region was becoming arched along steep reverse faults, the results of uplift and compression. Faulting cuts the

crystalline substrate of northern Arizona with major faults showing 5,000' of offset in some places. As originally described by Powell, monoclinical folds formed at this time, the result of draped Paleozoic and younger strata over brittle fault blocks at depth.

Starting in the Eocene roughly 50 Ma, subduction of the Pacific ridge forever changed the geometry of subduction along the western Cordilleran margin. (See Figure 20.) The heat was off, so to speak, for a while and the southern part of Arizona was uplifted and eroded to a low relief terrain. During the early Oligocene, sediments were shed northward into Utah and Colorado. By late Oligocene time, a significant change in the geology took place.

Voluminous volcanism dominated the landscape in the Oligo-Miocene (between 30 Ma to 20 Ma) with the locus of activity drifting westward from New Mexico (32 Ma), to the eastern Arizona Basin and Range (26 Ma), to the Sonoran desert region (21 Ma). Such westward drift of the volcanic axis could be in response to oversteepening of the subducting plate and trenchward migration of the volcano-plutonic axis. Explosive ignimbritic deposits and caldera eruptions dominated during this catastrophic volcanic interval. The same subduction that yielded volcanism continued to weaken the lower lithosphere with the injection of numerous plutons. The mid Miocene saw the Arizona landscape built up high with volcanic materials. Development of the Superstition Mountains Caldera Complex took place at this time (Figure 42).



Distribution of volcanic rocks associated with the Superstition volcanic field. Superstition caldera (S), Goldfield Caldera (G), and Tortilla Caldera (T) are indicated by the line pattern. Reproduced from: Sheridan, M. F., 1978 *The Superstition Caldera Complex in Guidebook to the Geology of Central Arizona*, Az. Bureau Geol. and Min. Technology, Special Paper No. 2.

**Figure 42** – Volcanic rocks of the Superstition volcanic field. (Nations and Stump, 1981, p. 173.)

Basin and Range faulting began about 15 Ma, in response to the changing tectonic pattern that formed the Salinian block adjacent to the San Andreas fault (Figure 43). Normal faulting without a rotational component dominated during this phase with vertical offset in the range of 5,940' to 9,900' in some basins. Basin and Range extension, with the production of elongate ranges nestled between broad fault-bounded basins, lasted till about 8 Ma when most activity stopped. Basaltic volcanism in the San Francisco and White Mountain volcanic fields began about 4 Ma (Figures 44 and 45) and sporadic basaltic volcanism continues to this day. (See Figure 26.)

The down-dropped basins formed during the Basin and Range interval continued to receive sediment and volcanic materials and have allowed regional correlation across Arizona (Figure 46). Quaternary deposits are not shown in Figure 45 but consist of unconsolidated sand and gravel and lava flows of the San Francisco and White Mountain volcanic fields.

Appendix 2 contains eight time-slice physiographic views of Arizona from the Cambrian through Late Tertiary. Appendix 3 provides a listing of Arizona's mineral localities and a location map. The all important Appendix 4 provides field trip rules.



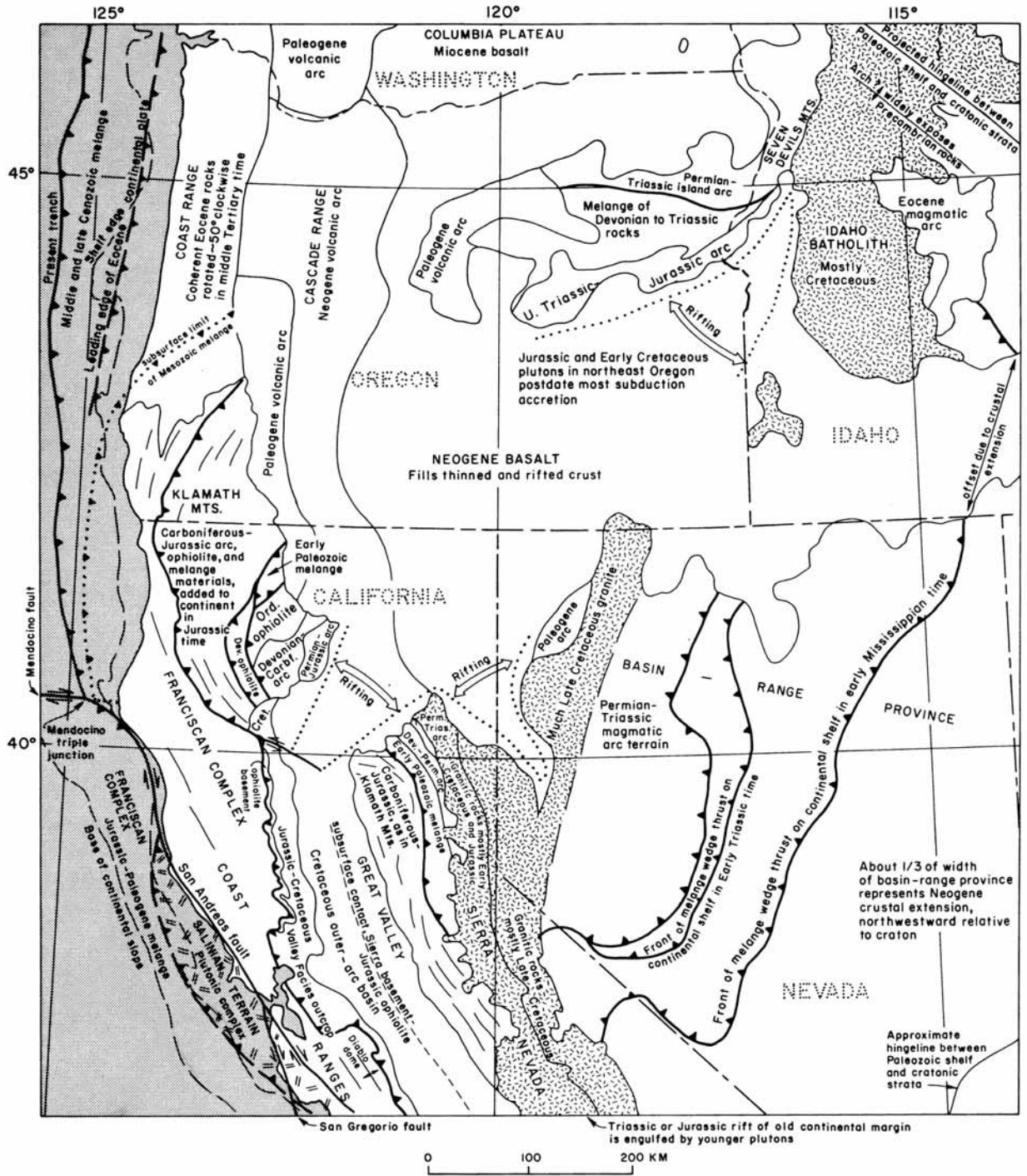
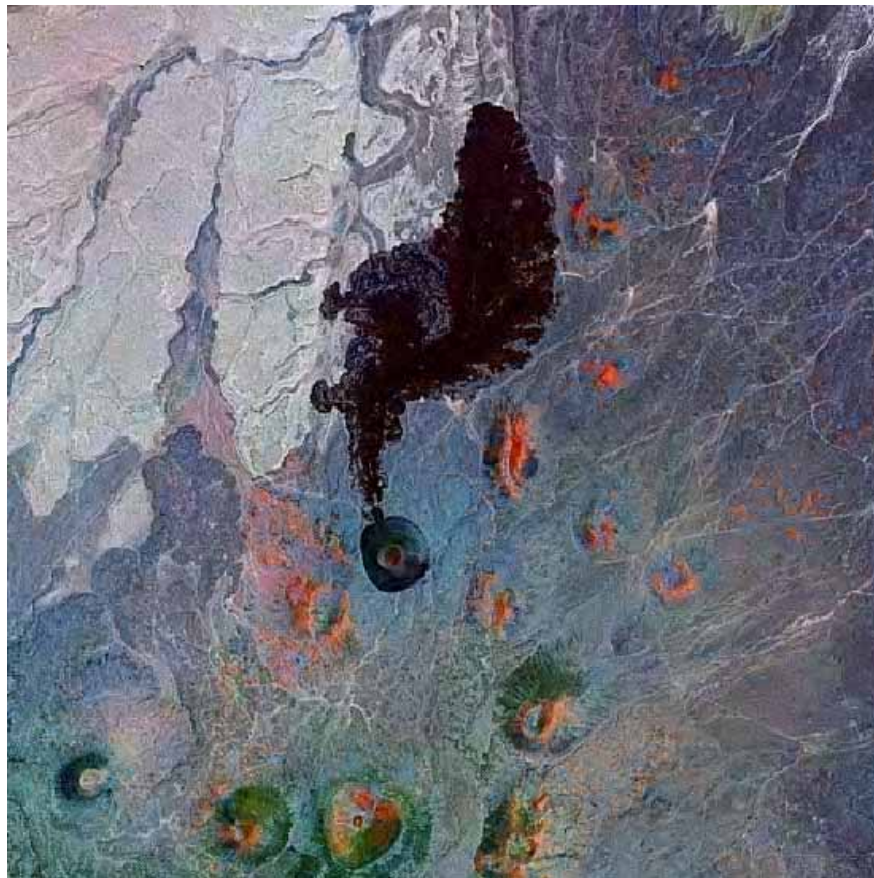


Figure 43 – Tectonic map of the western Cordillera. (Hamilton 1978, Fig. 4, p. 38.)



**Figure 44** – Photograph of SP Crater from the San Francisco Volcanic Field. Note spatter rampart at tip of crater extending partially into it. Lava flows erupted from side of cone at late stages of eruption. (Nations and Stump, 1981, p. 164.)



**Figure 45** – Landsat image of SP Crater and San Francisco volcanic field.

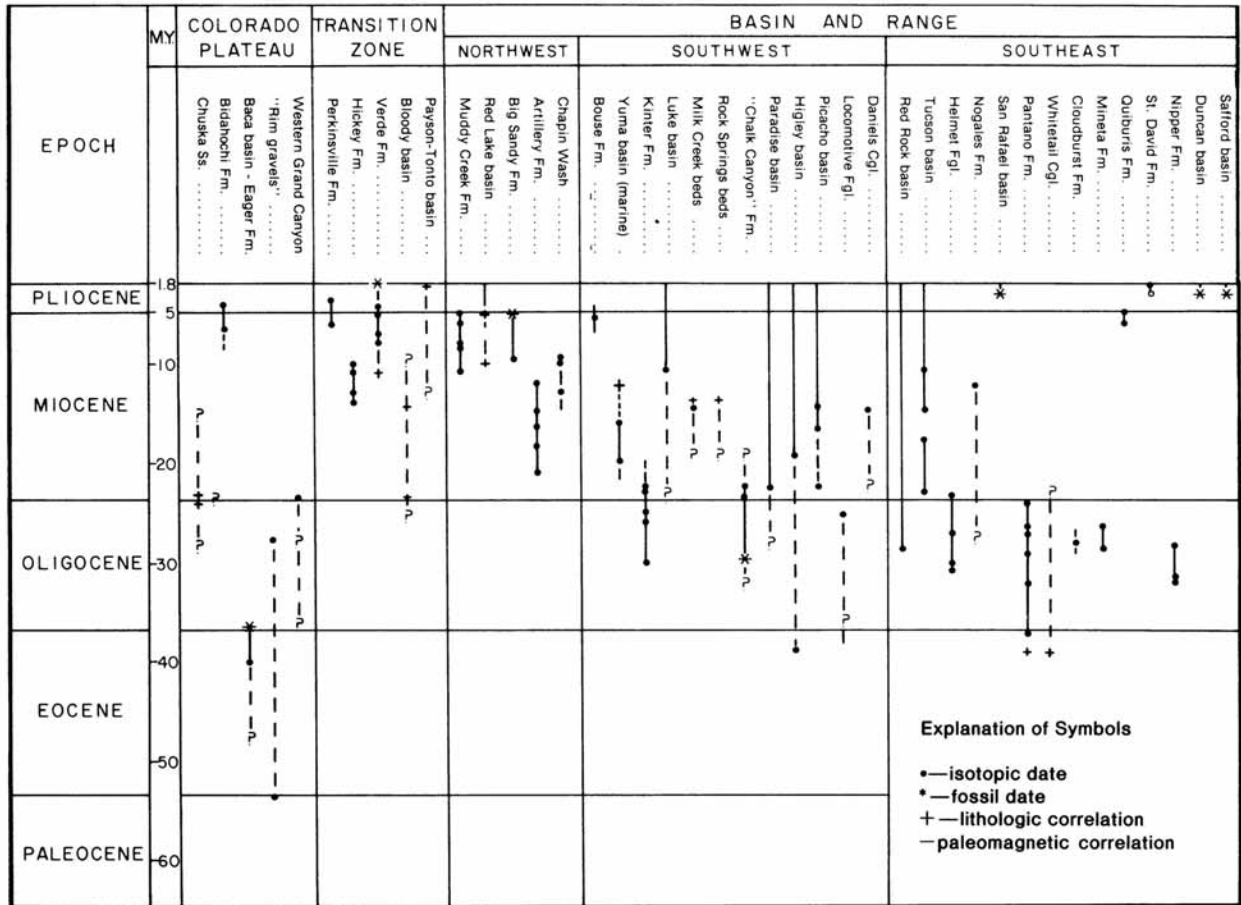


Figure 46 – Stratigraphic correlation chart of Cenozoic strata in Arizona. (Nations and Stump, 1981, p. 144.)

## Appendix 1 - Geologic Structure - a Primer

Geologists use terminology to confuse the layman and to enable them to amass a huge library of terms that are undeniably useless in most social situations. Luckily, our Geology classes and field trips are an exception. We will not try to bury you in a mountain (how about a deeply eroded mountain range?) of terms to help you understand the major types of structures and geologic features that you will read- and hear about today. But, if you are to understand what we are talking about, you need to know some important definitions. In the following section, we describe folds, faults, surfaces of unconformity, sedimentary structures, structures in sedimentary- vs. metamorphic rocks, and tectonostratigraphic units.

We begin with some concepts and definitions based on the engineering discipline known as **strength of materials**. Given today's sophisticated laboratory apparatus, it is possible to subject rocks to temperatures- and pressures comparable to those found deep inside the Earth.

Imagine taking a cylinder of rock out of the Earth and torturing it in a tri-axial compression machine to see what happens. Some geologists get a big charge out of this and tell us (the field geologists) that they really understand how rocks behave under stress. [CM thinks they need to perform these experiments over a longer time frame than a few generations of siblings will allow and thus relies more on field observation and inference than from rock-squeezing data to gain a feel for the complex nature of how rocks are deformed in nature.]

Despite the limitations of the experimental work, measurements in the laboratory on specimens being deformed provide some fundamental definitions. One key definition is the **elastic limit**, which is the point at which a test specimen no longer returns to its initial shape after the load has been released. Below the elastic limit, the change of shape and/or volume (which is known as **strain**) is proportional to the stress inside the specimen. Above the elastic limit, the specimen acquires some permanent strain. In other words, the specimen has "failed" internally. Irrecoverable strain manifests itself in the distortion of crystal lattices, grain-boundary adjustments between minerals composing the rock, and minute motions along cleavage- or twin planes.

When differential force is applied slowly (or, according to CM, over long periods of time), rocks fail by *flowing*. This condition is defined as behaving in a **ductile fashion** (toothpaste being squeezed out of a tube is an example of ductile behavior). Folds are the result of such behavior. If the force is applied under low confining pressure or is applied rapidly (high strain rates), rocks do not flow, but *fracture*. This kind of failure is referred to as rocks behaving in a **brittle fashion** (as in peanut brittle). The result is faults or joints. Once a brittle failure (fracture) has begun, it will propagate and may produce offset thus forming a fault surface. Joint surfaces commonly exhibit distinctive "feathers" which show the direction of joint propagation.

In some cases, during deformation, rocks not only undergo simple strain, but also recrystallize. New metamorphic minerals form and newly formed metamorphic minerals acquire a parallel arrangement. More on metamorphic textures later. From the laboratory studies of rock deformation, a few simple relationships are generally agreed upon regarding brittle- and ductile faulting and these are discussed below.



When subjected to differential forces, under high confining pressures and elevated temperatures, rocks (like humans) begin to behave foolishly, squirming in many directions and upsetting the original orientation of primary- or secondary **planar- and linear features** within them. Geologists try to sort out the effects of deformation by working out the order in which these surfaces or linear features formed using a relative nomenclature based on four letters of the alphabet: D, F, S, and M. Episodes of deformation are abbreviated by ( $D_n$ ), of folding by ( $F_n$ ), of the origin of surfaces (such as bedding or foliation) by ( $S_n$ ), and of metamorphism by ( $M_n$ ), where  $n$  is a whole number starting with 1 (or in some cases, with zero). Bedding is commonly designated as  $S_0$  (or surface number zero) as it is commonly overprinted by  $S_1$  (the first foliation). To use this relative nomenclature to describe the structural history of an area, for example, one might write: "During the second deformation ( $D_2$ ),  $F_2$  folds formed; under progressive  $M_1$  metamorphic conditions, an axial-planar  $S_2$  foliation developed."

In dealing with the geologic structures in sedimentary rocks, the first surface one tries to identify positively is **bedding** or **stratification**. The boundaries of strata mark original sub-horizontal surfaces imparted to sediments in the earliest stage of the formation of sedimentary rock. Imagine how such strata, buried by the weight of overlying strata and laterally compressed by the advance of lithospheric plates, are subjected to the differential force necessary for folds to form. Contrary to older ideas, we now realize that vertical burial cannot cause regional folds (although small-scale slumping, stratal disharmony, and clastic dikes are possible). Rather, resolved tangential force that creates differential stress must be applied to provide the driving force to bring about folds and faults.

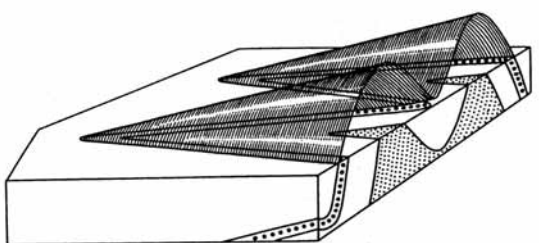
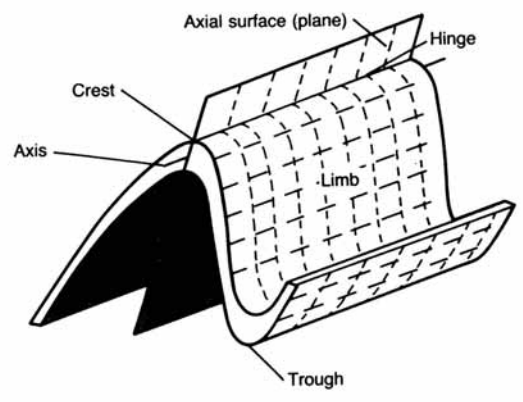
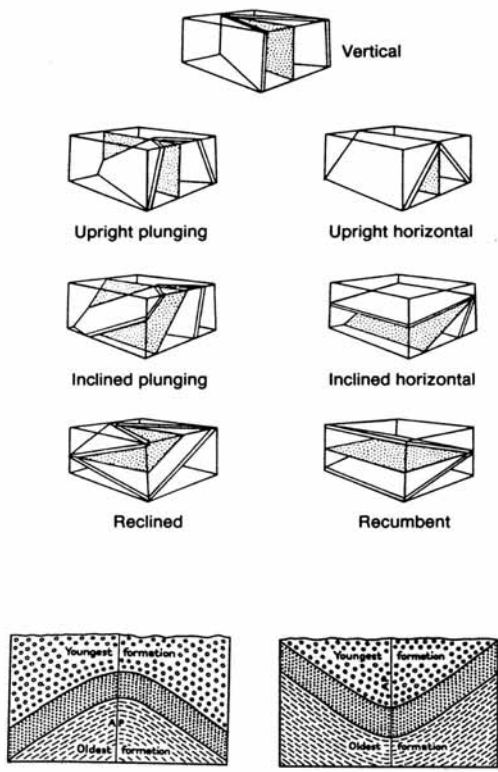
It's now time to turn to some geometric aspects of the features formed as a result of deformation of rocks in the Earth. We start with folds.

## Folds

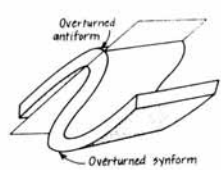
If layers are folded into convex-upward forms we call them **anticlines**. Convex-downward fold forms are called **synclines**. In Figure A1-1, note the geometric relationship of anticlines and synclines. **Axial planes** (or **axial surfaces**) physically divide folds in half. Note that in Figure A1-1, the fold is deformed about a vertical axial surface and is cylindrical about a linear **fold axis** which lies within the axial surface. The locus of points connected through the domain of maximum curvature of the bedding (or any other folded surface of the fold) is known as the **hinge line** (which is parallel to the fold axis). This is geometry folks; we have to keep it simple so geologists can understand it.

In eroded anticlines, strata forming the limbs of the fold *dip away from* the central hinge area or core (axis) of the structure. In synclines, the layers forming the limbs *dip toward the hinge area*. Given these arrangements, we expect that in the arches of eroded anticlines, older stratigraphic layers will peek through whereas in the eroded troughs of synclines, younger strata will be preserved.

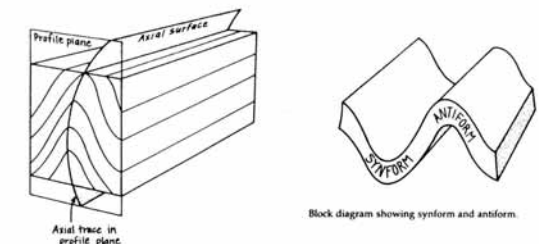
Fold classification by attitudes of hinge and axial surface.



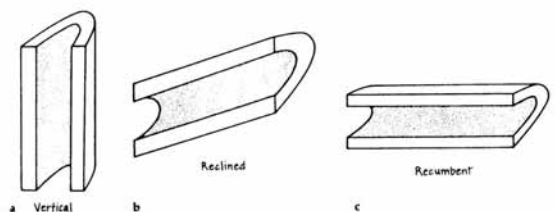
Plunging folds. Plunge is about 10° to the left. One bed is shown by open circles; the part of this bed that has been removed by erosion is shown by lining.



Block diagram showing overturned folds.



Profile plane and axial surface of folds.



Vertical (a), reclined (b), and recumbent (c) folds.

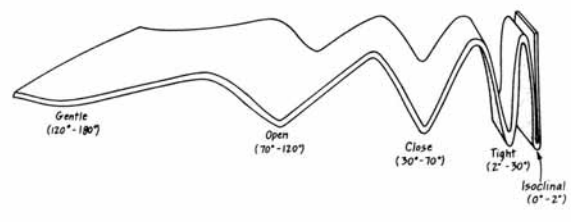
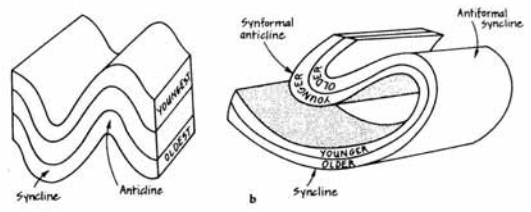


Figure A1-1 - Composite diagram from introductory texts showing various fold styles and nomenclature as discussed in the text.

In metamorphic terranes, field geologists are not always sure of the correct age relationships of the metamorphosed strata. Therefore, it is helpful to make use of the general terms **antiform** and **synform** which describe the folds by whether they are convex upward (antiform) or concave upward (synform) but do not imply anything about the relative ages of the strata within them.

Realize that in the upright folds shown in Figure A1-1, axial surfaces are vertical and fold axes, horizontal. Keep in mind that folding under metamorphic conditions commonly produces a penetrative mineral fabric with neocrystallized minerals (typically micas and amphiboles) aligned parallel to the axial surfaces of folds. Such penetrative metamorphic fabrics are called **foliation**, if primary, and **schistosity**, if secondary. Minerals can also become aligned in a linear fashion producing a **metamorphic lineation**. Such features can be useful in interpreting a unique direction of tectonic transport or flow direction. Because folds in metamorphic rocks are commonly **tight-** to **isoclinal** (high amplitude-to-wavelength aspect ratio) with limbs generally parallel to axial surfaces, a penetrative foliation produced during regional dynamothermal metamorphism will generally be parallel to the re-oriented remnants of stratification (except of course in the hinge areas of folds). Thus, in highly deformed terranes, a composite foliation + remnant compositional layering is commonly observed in the field. Departures from this common norm are important to identify as they tend to mark regional fold-hinge areas.

Folds could care less about the orientation of their axes or axial surfaces and you can certainly imagine that axial surfaces can be tilted, to form inclined or **overturned folds**. Or the axial surfaces may be sub-horizontal, in which case the term **recumbent folds** is used. In both overturned folds and recumbent folds, the fold axes may remain subhorizontal. (See Figure A1-1.) It is also possible for an axial surface to be vertical but for the orientation of the fold axis to range from horizontal to some angle other than 0° (thus to acquire a plunge and to produce a **plunging fold**). Possible configurations include plunging anticlines (or -antiforms) or plunging synclines (or -synforms). **Vertical folds** (plunging 90°) are also known; in them, the terms anticline and syncline are not meaningful. In **reclined folds**, quite common in ductile shear zones, the fold axes plunge directly down the dip of the axial surface.

In complexly deformed mountain ranges, most terranes show the superposed effects of more than one set of folds and faults. As a result of multiple episodes of deformation, the ultimate configuration of folds can be quite complex (i. e., plunging folds with inclined axial surfaces and overturned limbs).

We need to mention one additional point about the alphabet soup of structural geology. Seen in cross section, folds fall into one of three groups, the S's, the M's, and the Z's. Looking down plunge in the hinge area of a northward-plunging anticlinal fold, for example, dextral shearing generates asymmetric Z folds on the western limb and sinistral shearing forms S folds on the eastern limb. Usually only one variety of small, asymmetric folds will be found on a given limb of a larger fold. Therefore, if one notices a change in the pattern from S folds to Z folds (or vice versa), one should be on the lookout for a fold axis. The hinge area is dominated by M folds (no sense of asymmetry).

One final note on folding -- it is generally agreed, in geologically simple areas, that axial surfaces form perpendicular to the last forces that ultimately produced the fold. Therefore, the orientation of the folds give some hint as to the direction of application of the active forces (often a regional indicator of relative plate convergence). In complex regions, the final regional orientation of the structures is a composite result of many protracted pulses of deformation, each with its unique geometric attributes. In these instances, simple analysis is often not possible. Rather, a range of possible explanations for a given structural event is commonly presented.

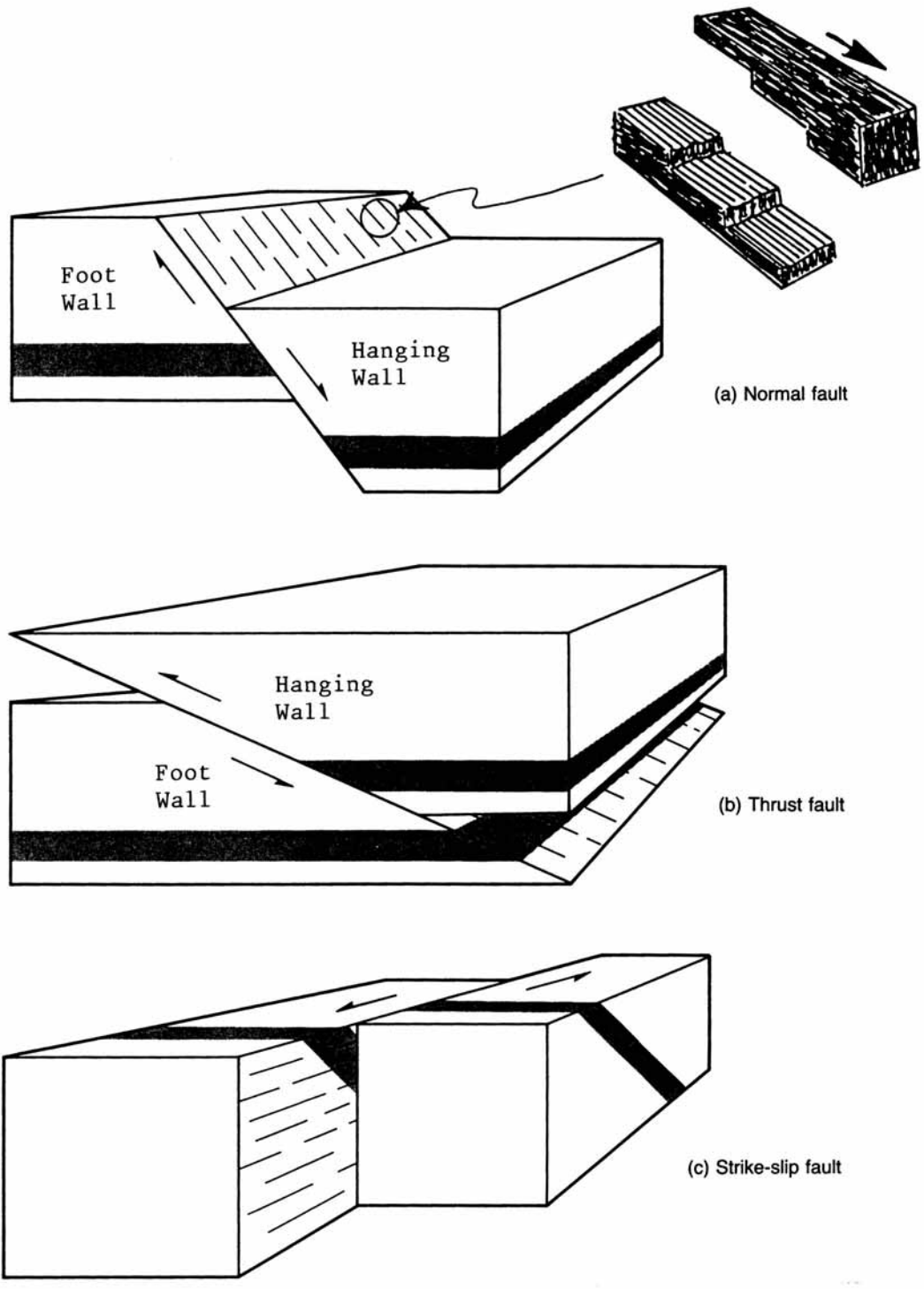
## Faults

A **fault** is defined as *a fracture along which the opposite sides have been displaced*. The surface of displacement is known as the fault plane (or fault surface). The enormous forces released during earthquakes produce elongate gouges within the fault surface (called **slickensides**) that may possess asymmetric linear ridges that enable one to determine the relative motion between the moving sides (Figure A1-2, inset). The block situated below the fault plane is called the **footwall block** and the block situated above the fault plane, the **hanging-wall block**. Extensional force causes the hanging-wall block to slide **down** the fault plane producing a **normal fault**. [See Figure A1-2 (a).] Compressive forces drive the hanging-wall block **up** the fault plane to make a **reverse fault**. A reverse fault with a low angle ( $<30^\circ$ ) is called a **thrust fault**. [See Figure A1-2 (b).] In all of these cases, the slickensides on the fault will be oriented more or less down the dip of the fault plane and the relationship between the tiny "risers" that are perpendicular to the striae make it possible to determine the relative sense of motion along the fault. Experimental- and field evidence indicate that the asymmetry of slickensides is not always an ironclad indicator of relative fault motion. As such, displaced geological marker beds or veins are necessary to verify relative offset. Fault motion up- or down the dip (as in normal faults, reverse faults, or thrusts faults) is named **dip-slip motion**.

Rather than simply extending or compressing a rock, imagine that the block of rock is sheared along its sides (*i. e.*, that is, one attempts to rotate the block about a vertical axis but does not allow the block to rotate). This situation is referred to as a shearing couple and could generate a **strike-slip fault**. [See Figure A1-2 (c).] On a strike-slip-fault plane, slickensides are oriented subhorizontally and again may provide information as to which direction the blocks athwart the fault surface moved.

Two basic kinds of shearing couples and/or strike-slip motion are possible: **left lateral** and **right lateral**. These are defined as follows. Imagine yourself standing on one of the fault blocks and looking across the fault plane to the other block. If the block across the fault from you appears to have moved to the left, the fault is **left lateral** [illustrated in Figure A1-2 (c)]. If the block across the fault appears to have moved to the right, the motion is **right lateral**. Convince yourself that no matter which block you can choose to observe the fault from, you will get the same result! Naturally, complex faults show movements that can show components of dip-slip- and strike-slip motion, rotation about axes perpendicular to the fault plane, or reactivation in a number of contrasting directions or variety. This, however, is no fault of ours.





**Figure A1-2** - The three main types of faults shown in schematic blocks. Along a normal fault (a) the hanging-wall block has moved relatively downward. On a thrust fault (or reverse fault) (b) the hanging-wall block has moved relatively upward. Along a strike-slip fault (c), the vertical reference layer (black) has been offset by horizontal movement (left-lateral offset shown here). Inset (d) shows segments of two blocks along a slickensided surface show how the jagged "risers" of the stairsteps (formed as pull-apart tension fractures) can be used to infer sense of relative motion. [(a), (b), (c), Composite diagram from introductory texts; (d), J. E. Sanders, 1981, fig. 16.11 (b), p. 397.]

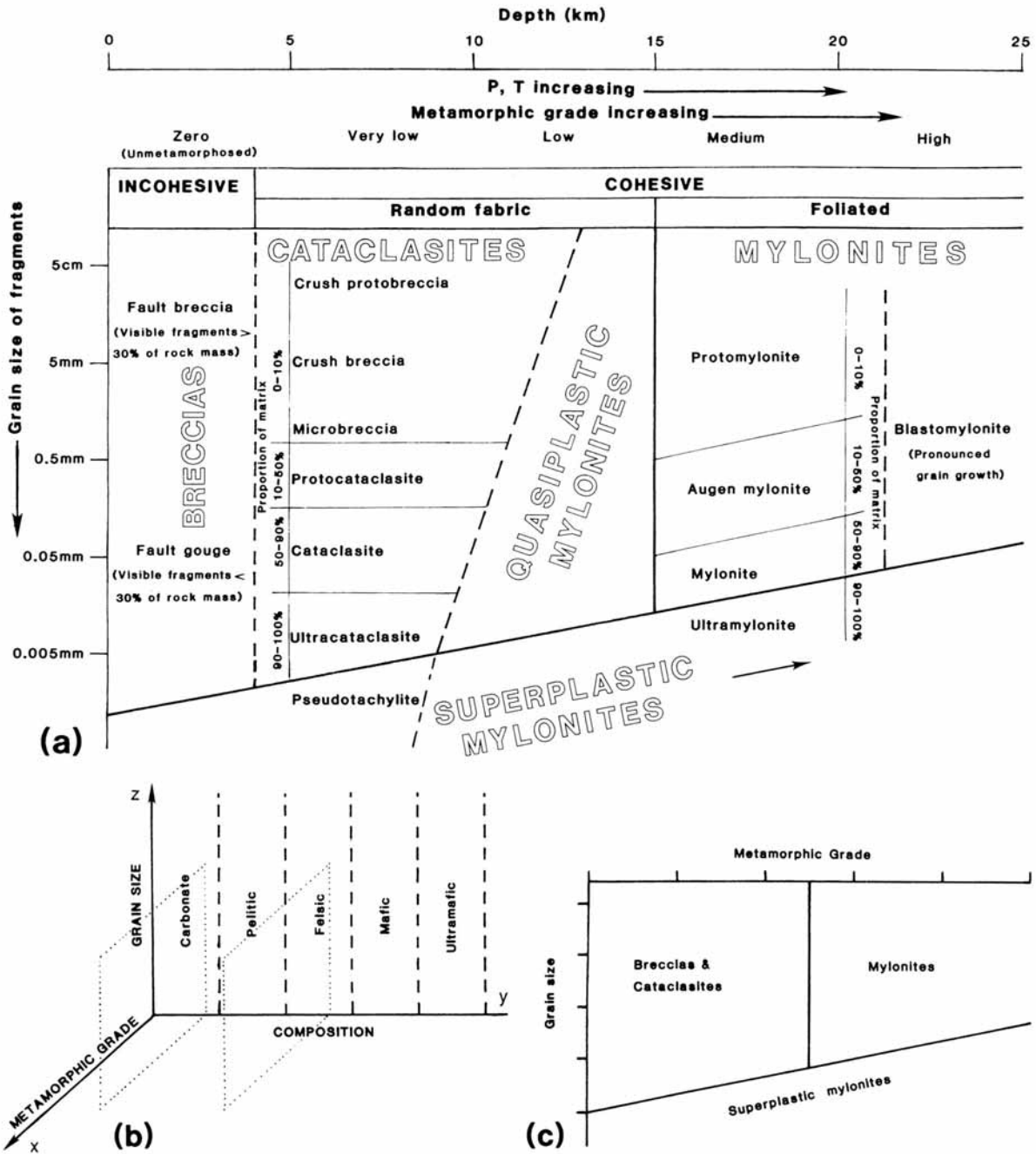
Tensional- or compressional faulting resulting from brittle deformation, at crustal levels above 10 to 15 km, is accompanied by seismicity and the development of highly crushed and granulated rocks called **fault breccias** and **cataclasites** (including fault gouge, fault breccia, and others). Figure A1-3 lists brittle- and ductile fault terminology as adapted from Sibson (1977) and Hull et al. (1986). Beginning at roughly 10 to 15 km and continuing downward, rocks under stress behave aseptically and relieve strain by recrystallizing during flow. These unique metamorphic conditions prompt the development of highly strained (ribboned) quartz, feldspar porphyroclasts (augen), and frayed micas, among other changes, and results in highly laminated rocks called **mylonites** (Figure A1-3).

The identification of such ductile fault rocks in complexly deformed terranes can be accomplished only by detailed mapping of metamorphic lithologies and establishing their geometric relationship to suspected mylonite zones. Unfortunately, continued deformation under load often causes early formed mylonites to recrystallize and thus to produce annealed mylonitic textures (Merguerian, 1988), which can easily be "missed" in the field without careful microscopic analysis. Cameron's Line, a recrystallized ductile shear zone showing post-tectonic brittle reactivation, is an original ductile fault zone (mylonite) having a complex geologic history.

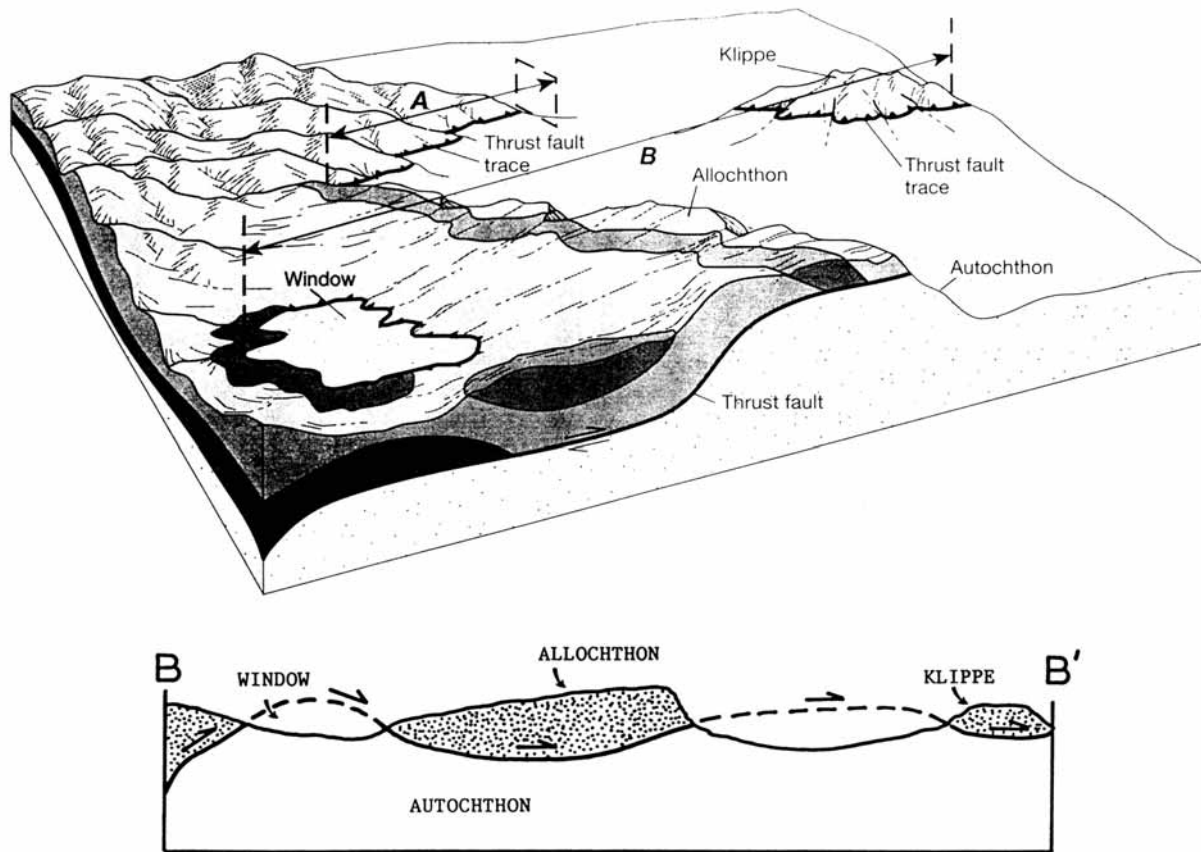
Over the years, field geologists have noted special geologic features associated with thrust faults. Because they propagate at low angles with respect to bedding, thrusts commonly duplicate strata. In addition, thrust faults can displace strata for great distances and wind up transporting rock deposited in one environment above rocks deposited in markedly disparate environments. In such cases, we call the displaced strata of the upper plate above a thrust fault an **allochthon** or describe an entire displaced sequence of strata as an **allochthonous terrane** (see Tectonostratigraphic Units below). In other words, *allochthonous rocks were not originally deposited where they are now found*. By contrast, regions consisting of rock sequences that were originally deposited where they are now found constitute an **autochthon** or **autochthonous terrane**.

Interesting geometric patterns result from the erosion of overthrust sheets of strata that have been folded after they were overthrust. When the upper plate (allochthon) has a "hole" eroded through it, we can peer downward through the allochthon and see the autochthon exposed in a **window**, **inlier**, or **fenster** surrounded by the trace of the thrust fault that was responsible for the dislocation (Figure A1-4). By contrast, if most of the upper plate has been eroded, only a remnant **outlier** or **klippe** may remain. (See Figure A1-4.) Both klippen and windows produce similar map-scale outcrop patterns. The difference is that the thrust surface typically dips *toward* the center of a klippe (a remnant of the allochthon) and *away from* the center of window (which shows a part of the underlying autochthon).

Bedding-plane thrusts are more-localized features but are geometrically the same as thrust faults in that they involve layer-parallel shortening of strata and produce low-angle imbrication of strata. They can easily be "missed" in the field but result in overthickening of strata and can produce anomalous stratigraphic thickness in sedimentary units. The field geologist can identify them by careful bed-by-bed examination of known sequences based on duplication of key- or marker beds and by identification of highly veined dislocation surfaces.



**Figure A1-3 - Fault-rock terminology.** (a) Classification of fault rocks that have been derived from quartzofeldspathic lithologies (e. g. granite) (adapted from Sibson, 1977); (b) the grain size - metamorphic grade - lithologic composition grid used for classifying fault rocks (after Hull et al., 1986); (c) fault-rock diagram for marl showing expanded mylonite and superplastic mylonite fields as compared to those shown on the diagram for granite in (a) (from Marshak and Mitra [1988]).



**Figure A1-4** - Block diagram illustrating the relationships between allochthons, autochthons, klippen, and windows. (Twiss and Moores, 1992, p. 99) with section B-B' drawn by CM.

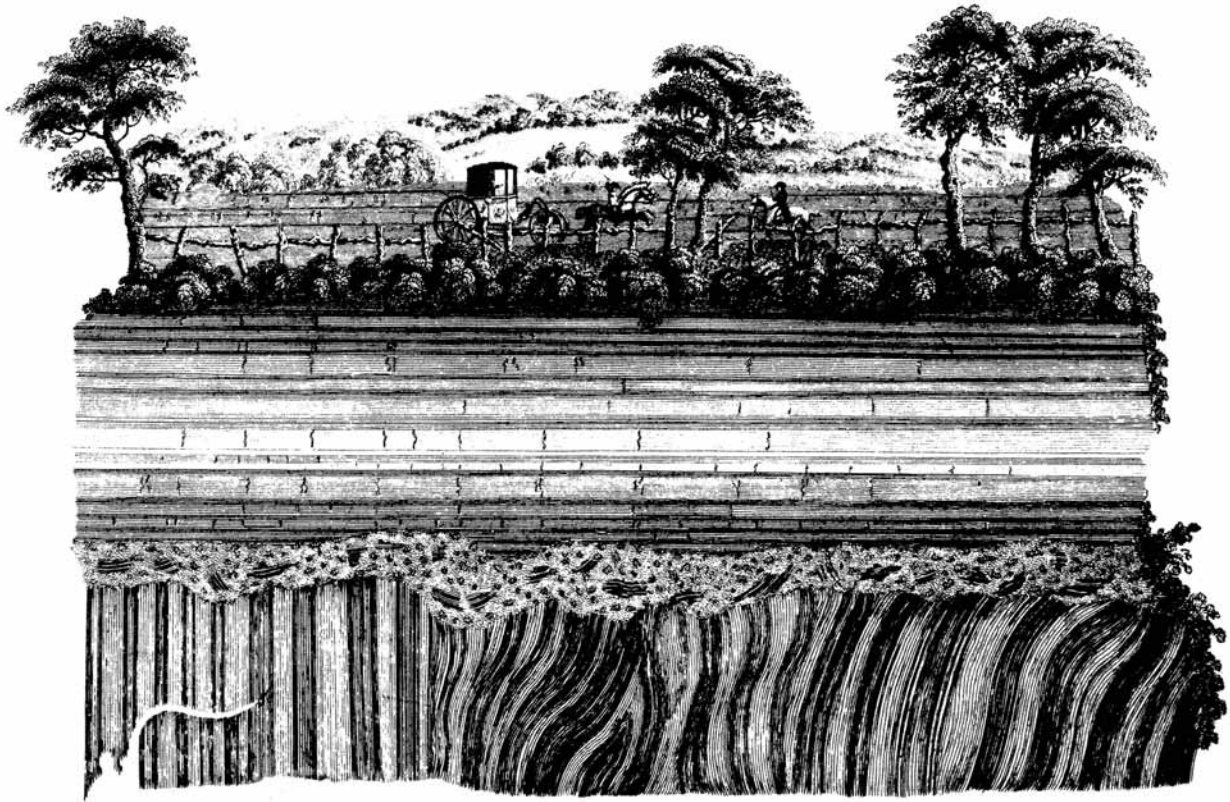
During episodes of mountain building associated with continuous subduction and/or collisions near continental margins, thrusting is typically directed from the ocean toward the continent. Accordingly, one of the large-scale effects of such periods of great overthrusting is to impose an anomalous load on the lithosphere that causes it to subside and form a **foreland basin**. These basins receive tremendous quantities of sediment that fill the basin with debris derived from erosion of uplifted areas within the active collision zone. In the late stages of convergence, forces transmitted from the collision zone into the developing foreland basin create a diachronous secondary stage of folding and continent-directed overthrusting of the strata filling the foreland basin. Thus, a thrust may override debris eroded from it.

### **Surfaces of Unconformity**

Surfaces of unconformity mark temporal gaps in the geologic record and commonly result from periods of uplift and erosion. Such uplift and erosion is commonly caused during the terminal phase of regional mountain-building episodes. As correctly interpreted by James Hutton at the now-famous surface of unconformity exposed in the cliff face of the River Jed (Figure A1-5), such surfaces represent mysterious intervals of geologic time where the local



evidence contains no clues as to what went on! By looking elsewhere, the effects of a surface of unconformity of regional extent can be recognized and piecemeal explanations of evidence for filling in the missing interval may be found.



**Figure A1-5** - Unconformity with basal conglomerate along the River Jed, south of Edinburgh, Scotland. From James Hutton's "Theory of the Earth", (1795).

Unconformities occur in three basic erosional varieties - angular unconformities, nonconformities, and disconformities (Figure A1-6). Angular unconformities (such as the River Jed) truncate dipping strata below the surface of unconformity and thus exhibit angular discordance at the erosion surface. Nonconformities separate sedimentary strata above the erosion surface from eroded igneous- or metamorphic rocks below. Disconformities are the most-subtle variety, separating subparallel sedimentary strata. They are commonly identified by paleontologic means, by the presence of channels cut into the underlying strata, or by clasts of the underlying strata in their basal part. The strata above a surface of unconformity may or may not include clasts of the underlying strata in the form of a coarse-grained, often bouldery basal facies.

Following the proposal made in 1963 by L. L. Sloss, surfaces of unconformity of regional extent within a craton are used as boundaries to define stratigraphic sequences.

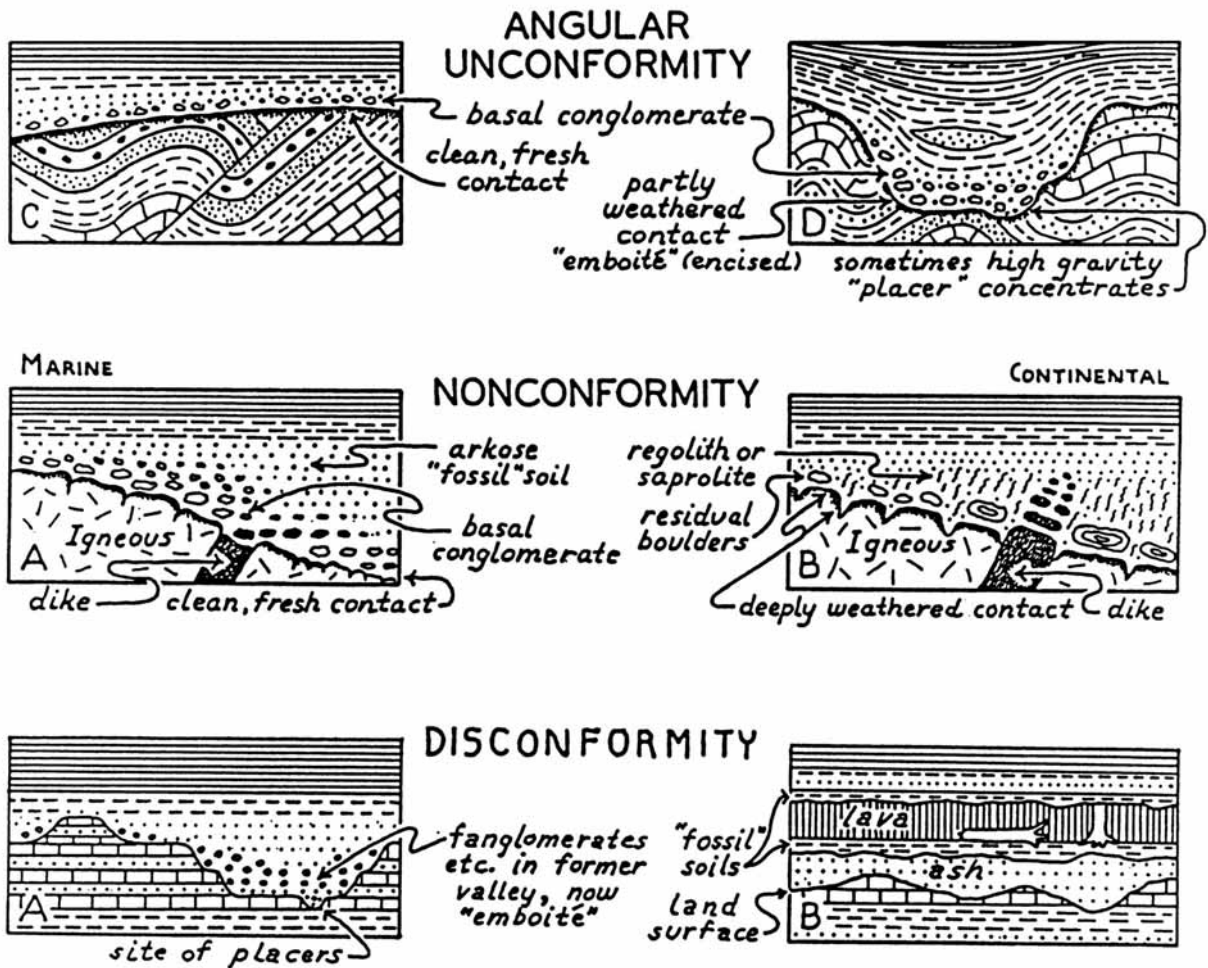


Figure A1-6 - Various types of unconformities, or gaps in the geologic record. Drawings by Rhodes W. Fairbridge.

## Sedimentary Structures

During deposition in a variety of environments, primary- and secondary sedimentary structures can develop above-, below-, and within strata. During normal deposition, or settling from a fluid in a rainfall of particles, massive, essentially poorly stratified successions may result. The presence of **strata** implies a change in deposition and as a result most geologists appreciate the significance of layering in sedimentary rocks as marking **CHANGE** in big letters, be it a change in parent area of the sediment, particle size, or style of deposition. Thus, **bedding** can best be viewed as marking the presence of mini-surfaces of unconformity (diastems). During high-energy transport of particles, features such as **cross beds**, **hummocky strata**, **asymmetric current ripple marks**, or **graded beds** result. Cross- and hummocky bedding, and asymmetric current ripple marks are deposited by moving currents and help us unravel the paleocurrent directions during their formation. Graded beds result from a kind of a "lump-sum distribution" of a wide range of particles all at once (usually in a gravity-induced turbidity flow).

Thus, graded beds show larger particle sizes at the base of a particular layer "grading" upward into finer particles.

Secondary sedimentary features are developed on already deposited strata and include **mud (or desiccation) cracks, rain-drop impressions, sole marks, load-flow structures, flame structures, and rip-up clasts**. The last three categorize effects produced by a moving body of sediment on strata already in place below. A composite diagram illustrating these common structures is reproduced in Figure A1-7.

Together, these primary- and secondary sedimentary structures help the soft-rock structural geologist unravel the oft-asked field questions - namely.... **Which way is up?** and **Which way to the package store?** The direction of younging of the strata seems obvious in horizontal- or gently tilted strata using Steno's principle of superposition. But steeply tilted-, vertical-, or overturned beds can be confidently unravelled and interpreted structurally only after the true topping (stratigraphic younging) direction has been determined. As we may be able to demonstrate on this field trip, simple observations allow the card-carrying geologist to know "Which way is up" at all times.

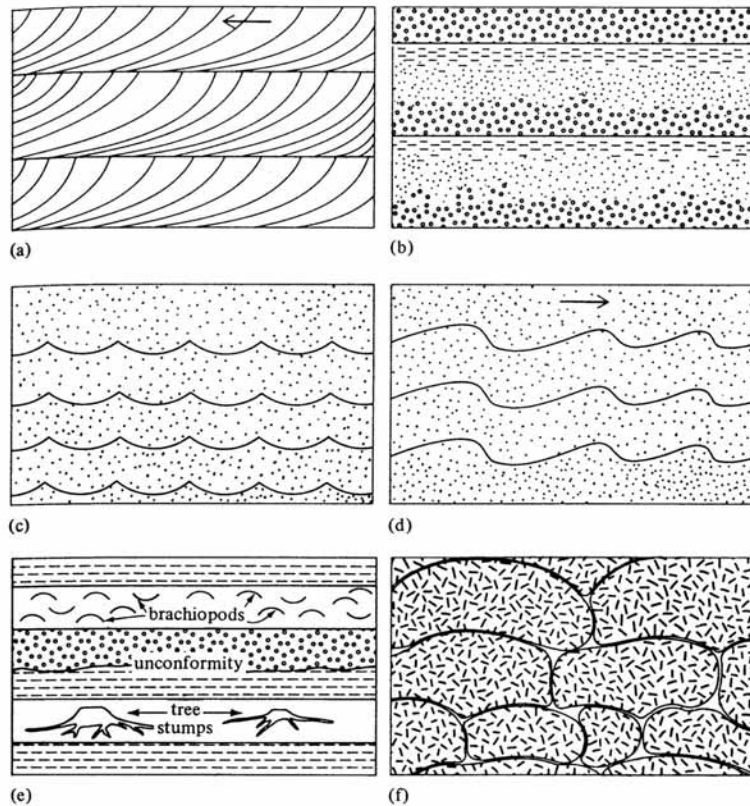
### **Structures in Sedimentary- vs. Metamorphic Rocks**

For hard-rock geologists working in metamorphic terranes, simple sedimentary observations will not allow the card-carrying geologist to know "Which way is up" **at all**. Rather, because of intense transposition and flow during ductile deformation, stratification, fossils for age dating, tops and current-direction indicators are largely useless except to identify their hosts as sedimentary protoliths. Thus, according to CM, "*at the outcrop scale, metamorphism can best be viewed as the great homogenizer.*" Commonly during metamorphism, the increase in temperature and -pressure and presence of chemically active fluids severely alter the mineral compositions and textures of pre-existing rocks. As a result, in many instances, typical soft-rock stratigraphic- and sedimentologic analysis of metamorphic rocks is not possible.

### **Tectonostratigraphic Units**

In metamorphic terranes, **tectonostratigraphic units** can best be described as large-scale tracts of land underlain by bedrock with similar age range, protolith paleoenvironment, and structure. Such terranes are generally bounded by ductile-fault zones (mylonites), surfaces of unconformity, or brittle faults. Unravelling the collisional plate-tectonic history of mountain belts is greatly facilitated by identifying former cratonic (ancient crustal), continental-margin, continental-slope-, and rise, deep-oceanic, and volcanic-island tectonostratigraphic units. The major distinction in unravelling complexly deformed mountain belts is to identify former shallow-water shelf deposits (originally deposited on continental crust) and to separate them from deep-water oceanic deposits (originally deposited on oceanic crust). The collective adjectives *miogeosynclinal* (for the shallow-water shelf deposits) and *eugeosynclinal* (for the

deep-water oceanic deposits) have been applied to the products of these contrasting depositional realms.



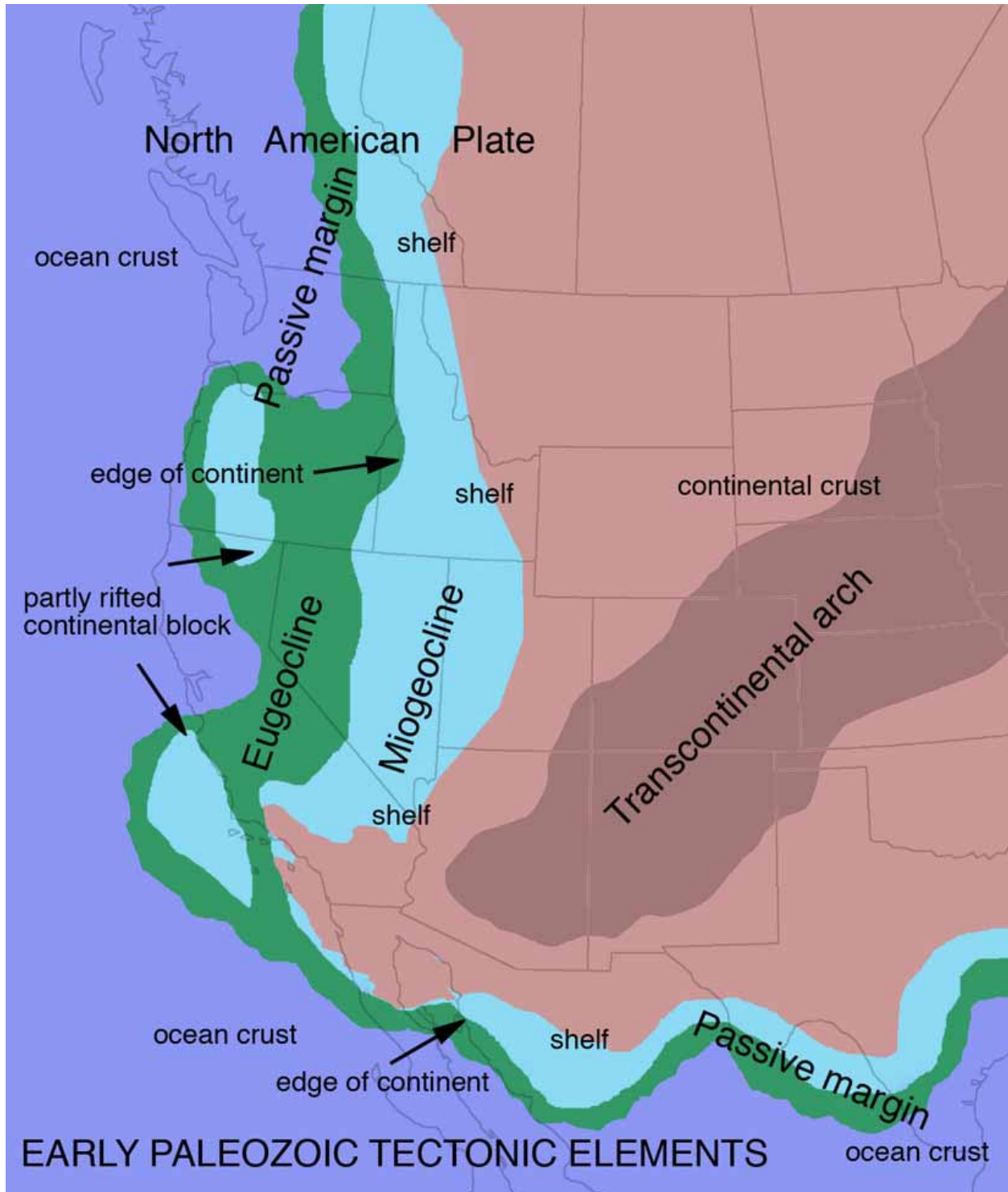
**Figure A1-7** - Diagrammatic sketches of primary sedimentary structures (a through e) and cross sections of pillows (f) used in determining topping (younging) directions in rocks.

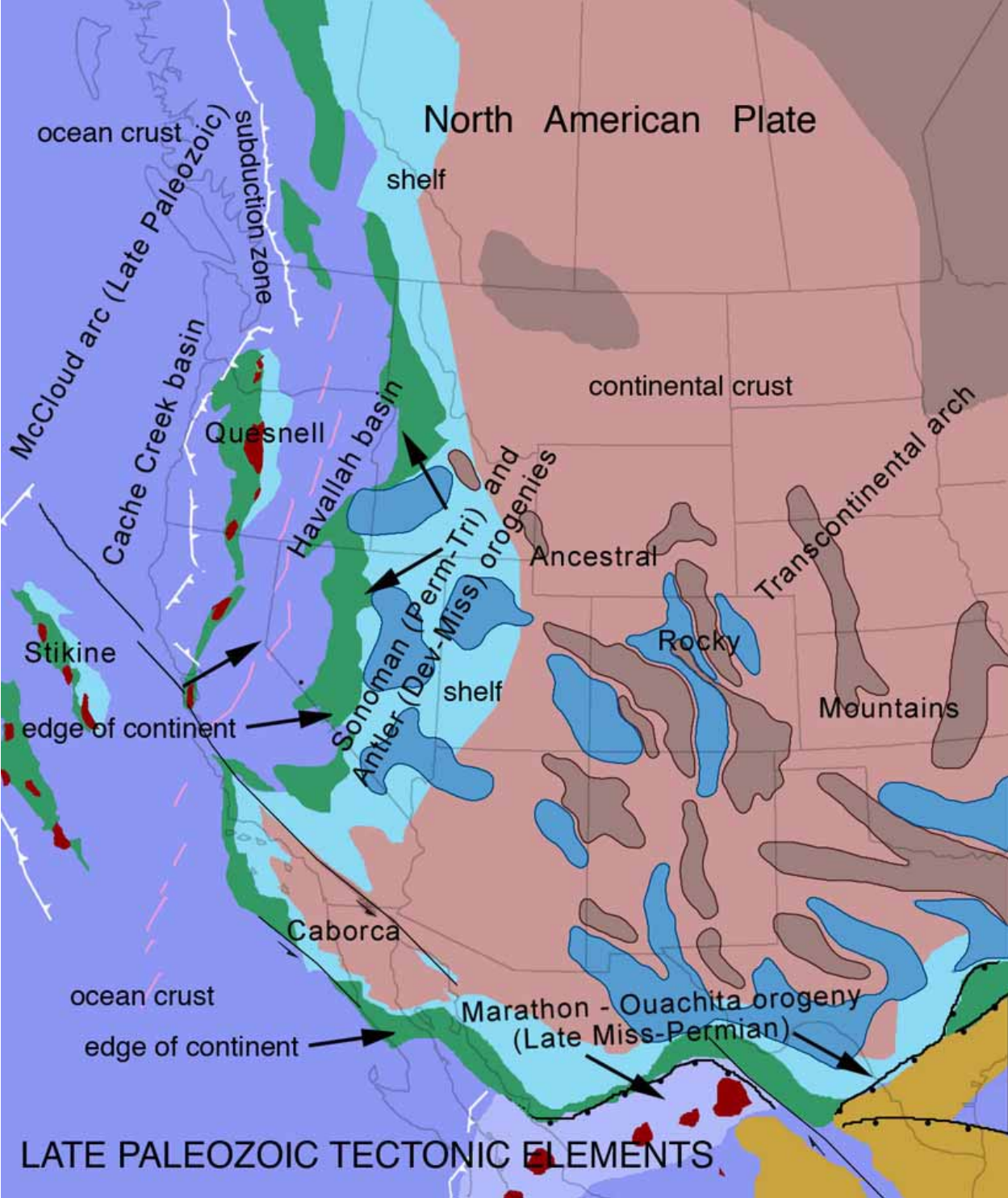
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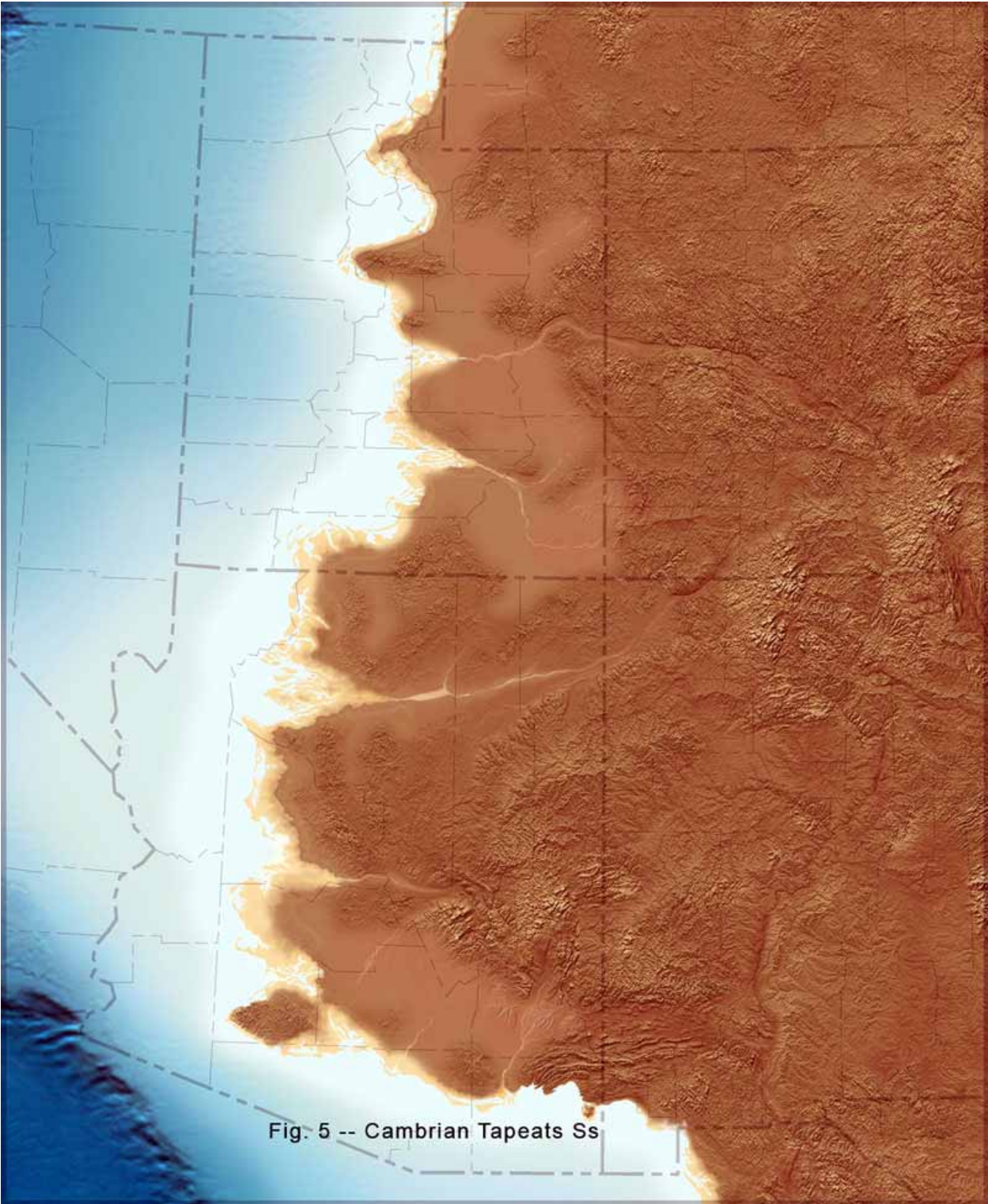


## Appendix 2 – Developmental Geology of Arizona



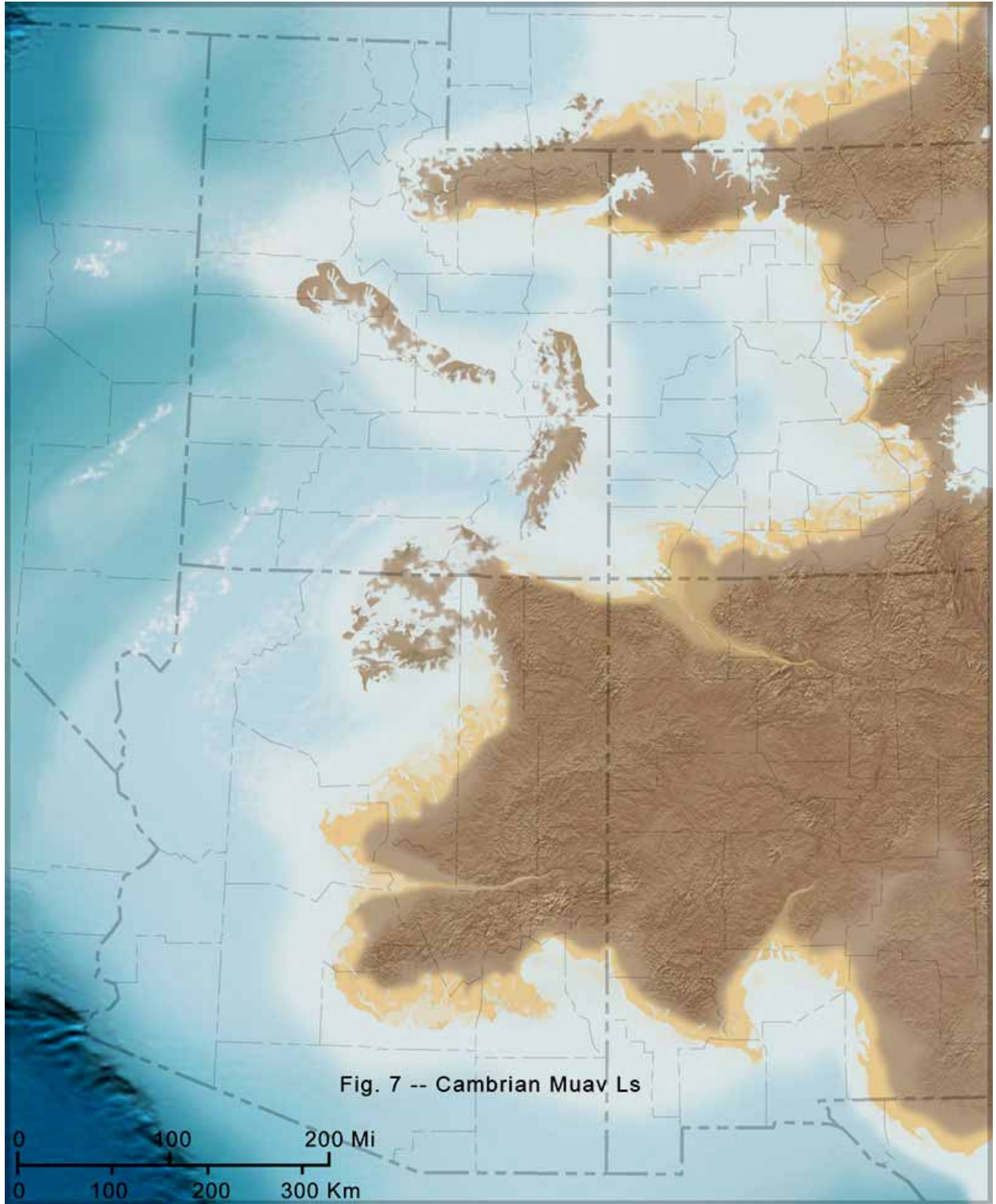


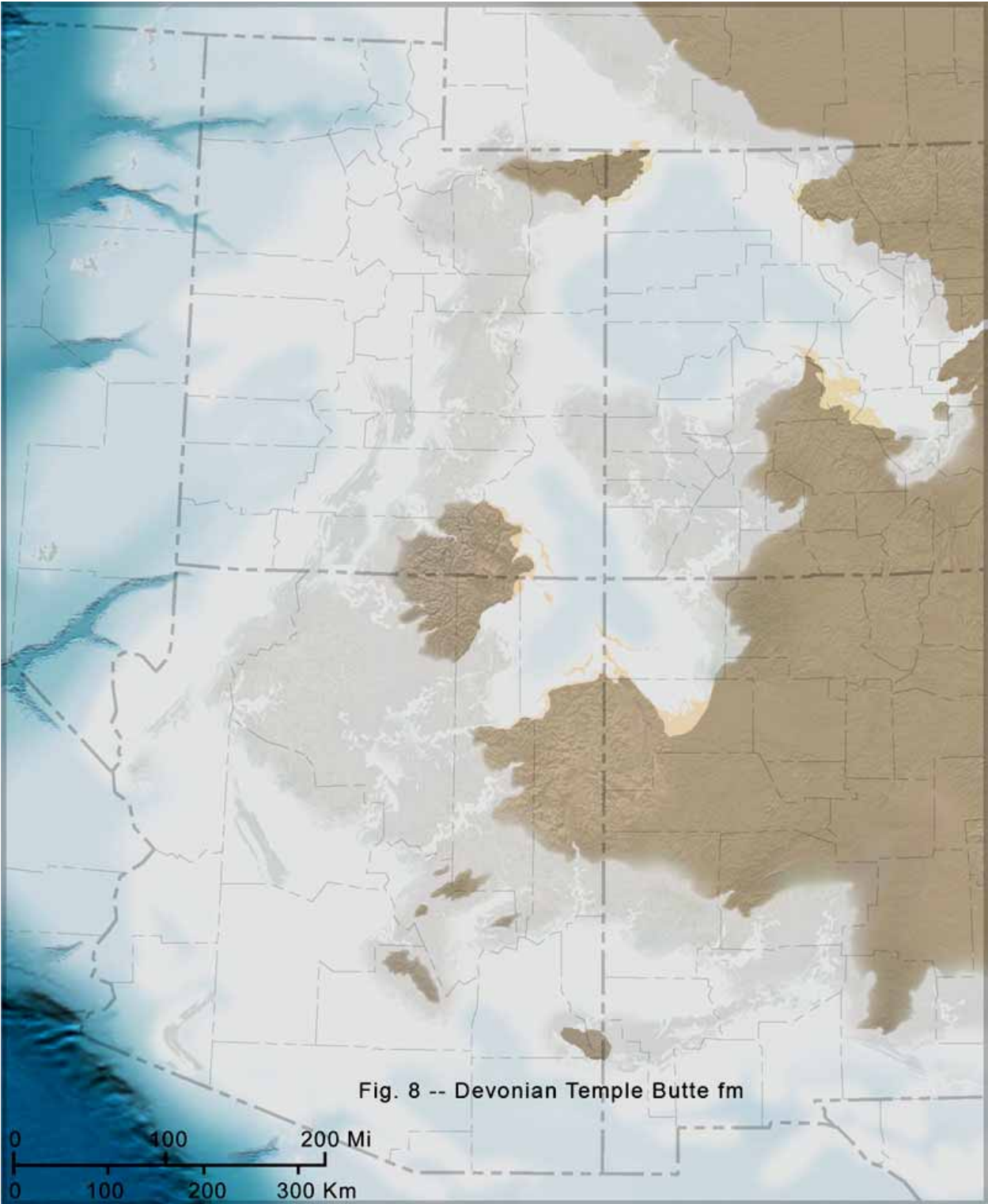


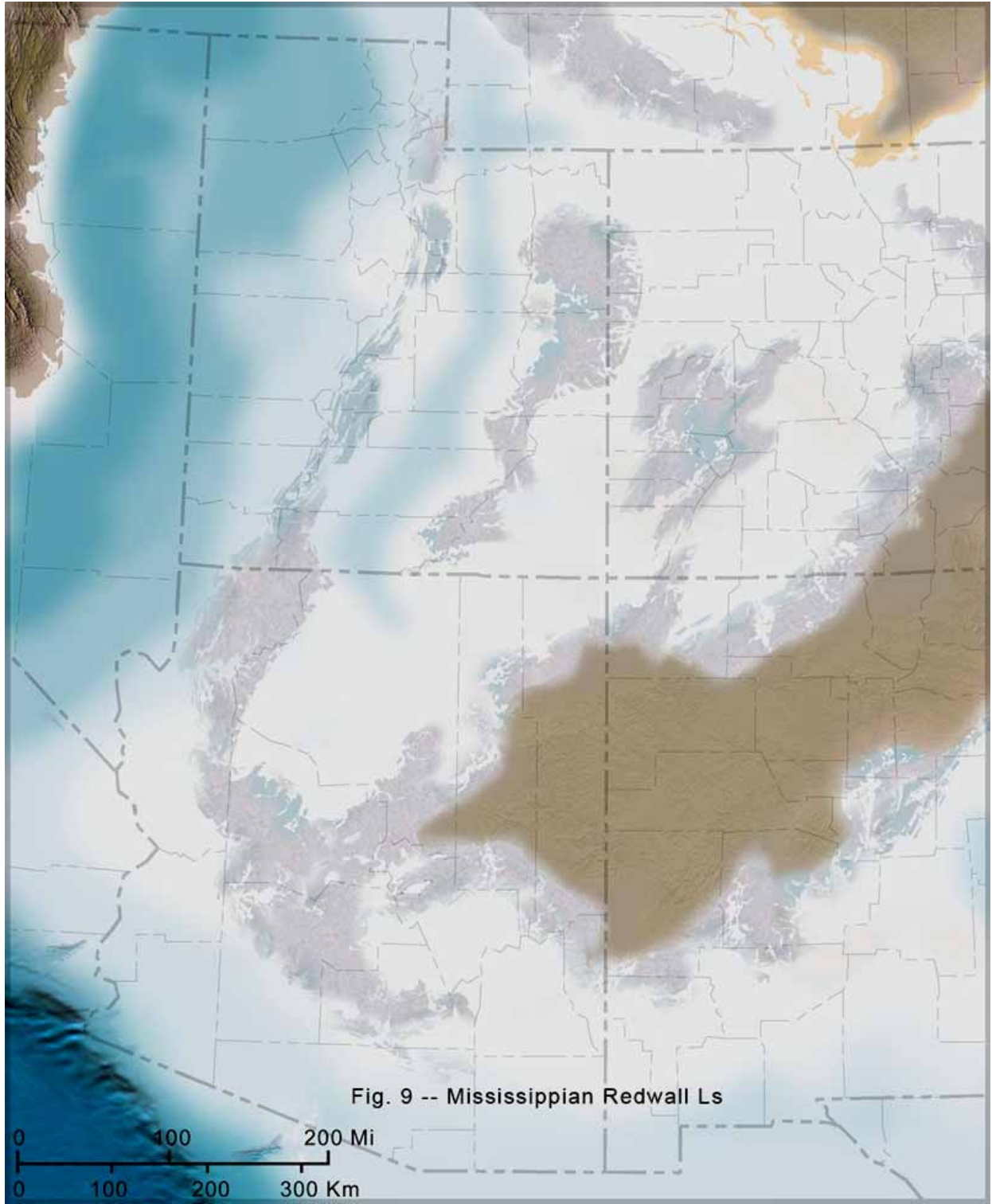




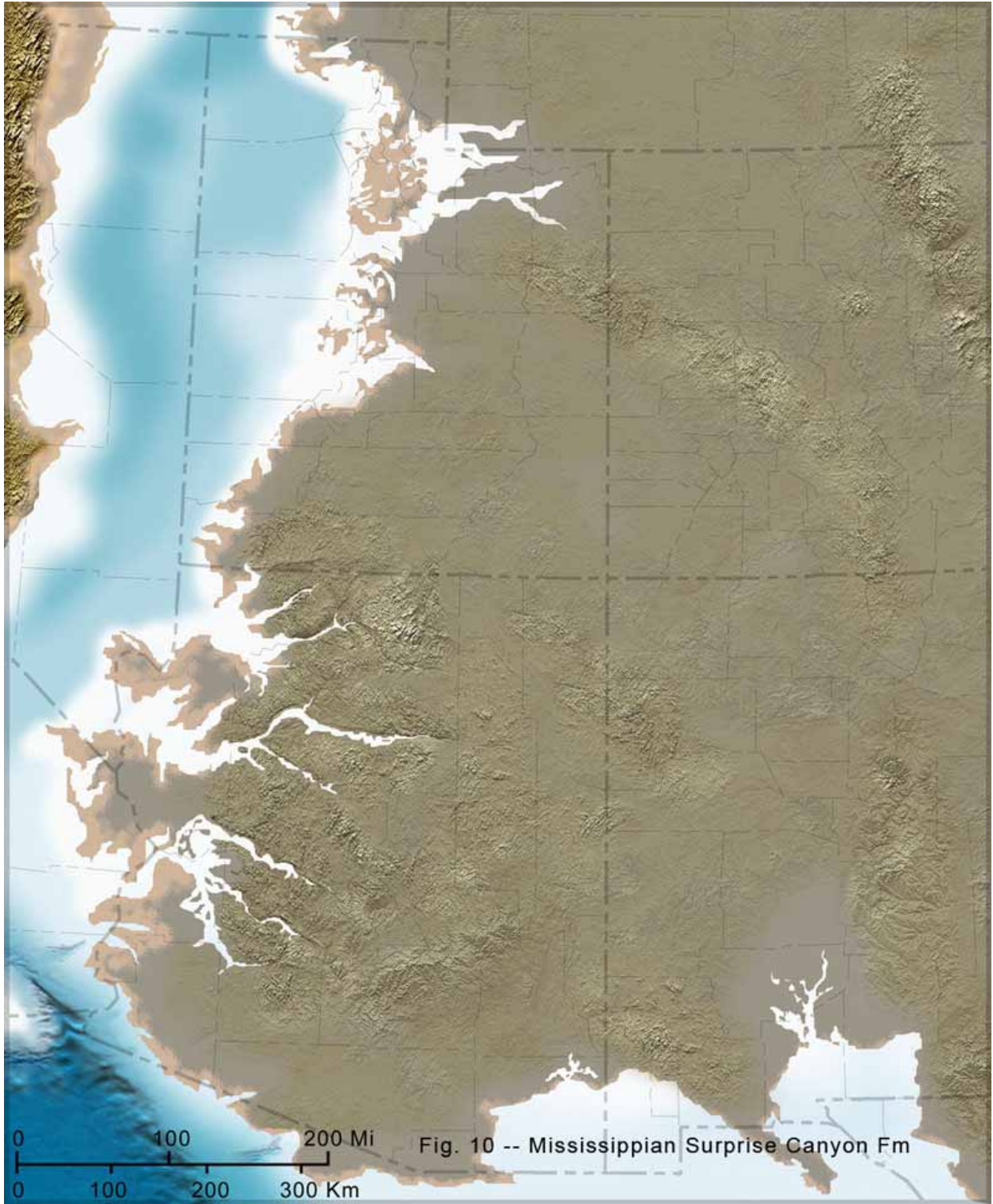




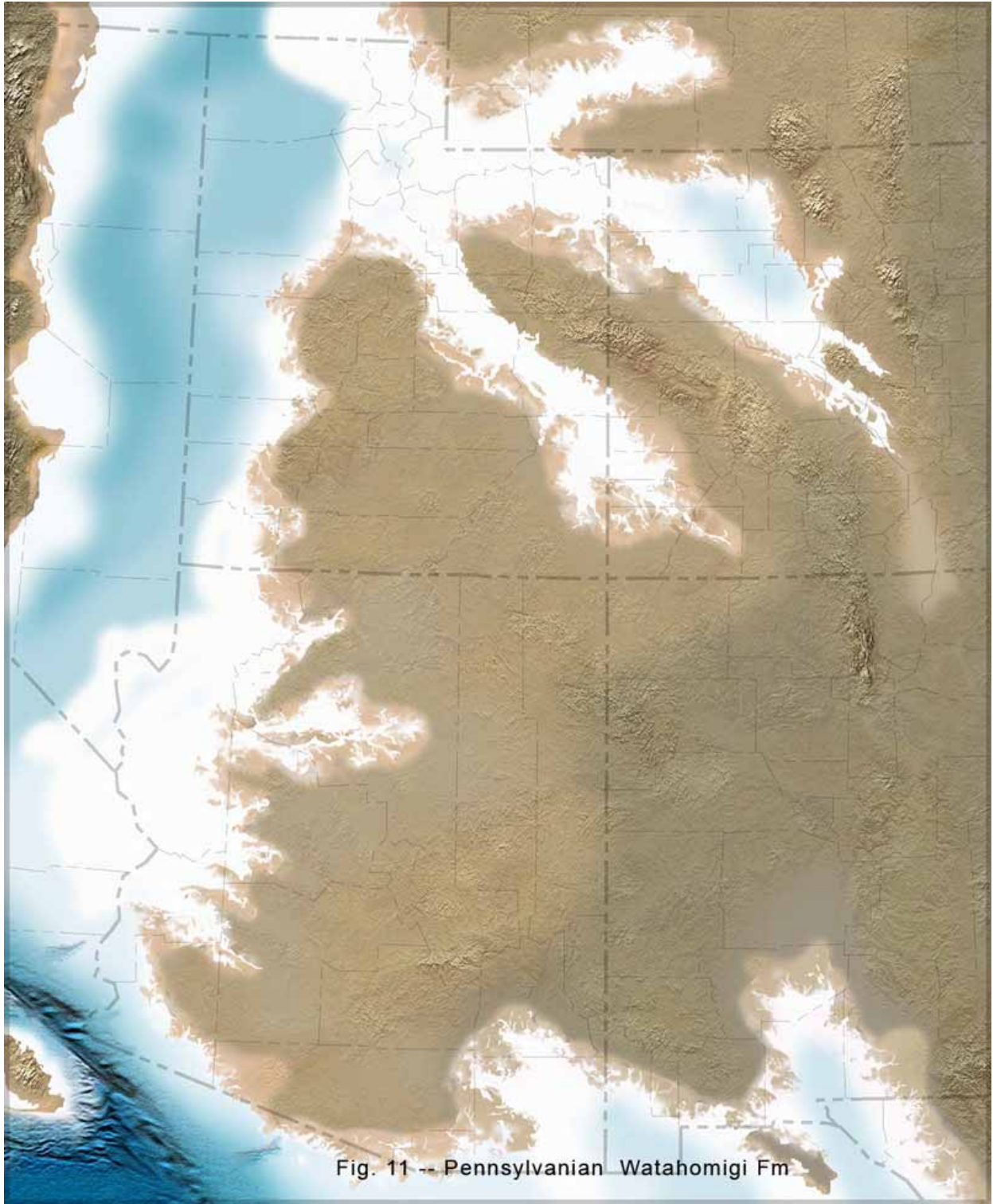


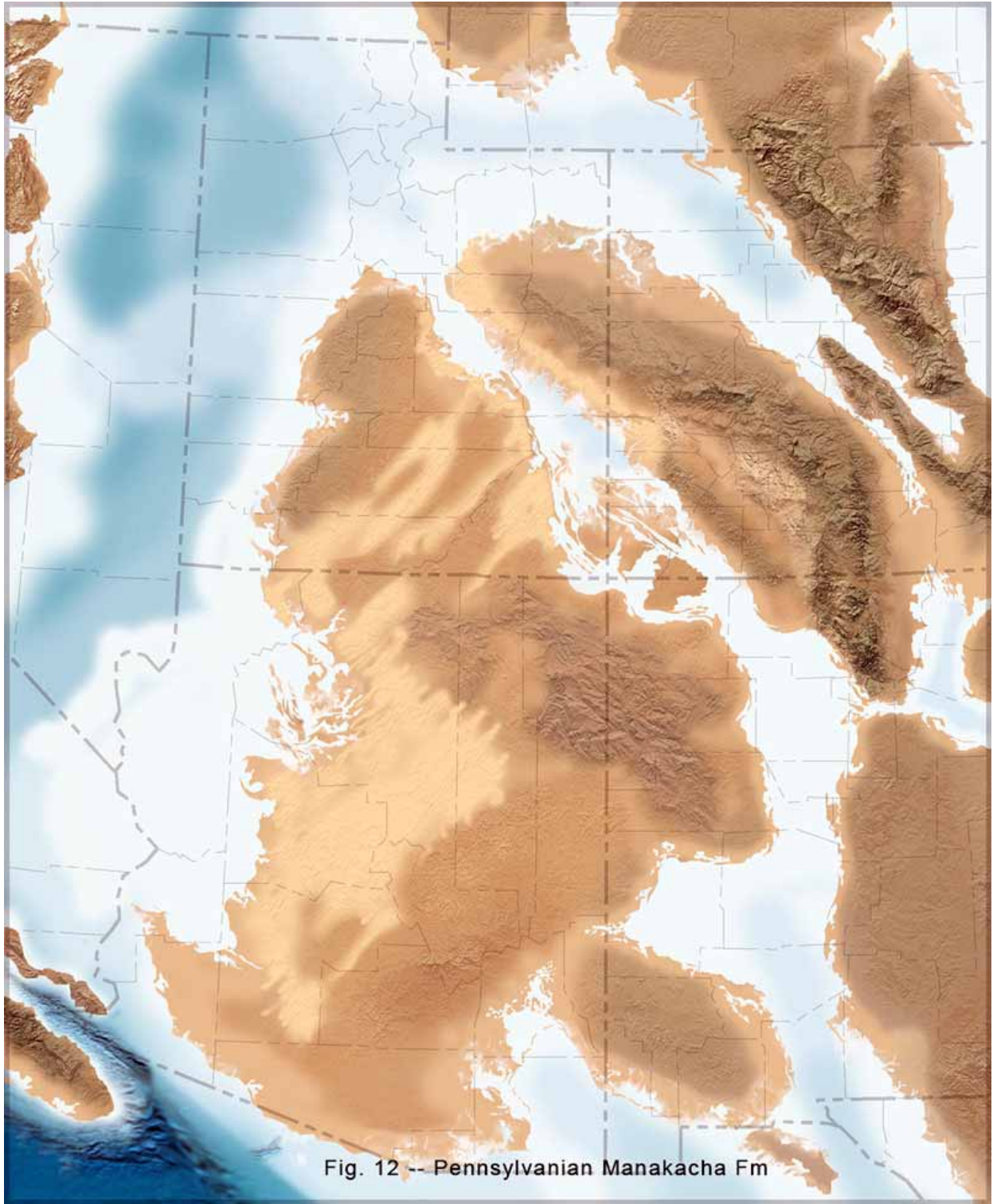




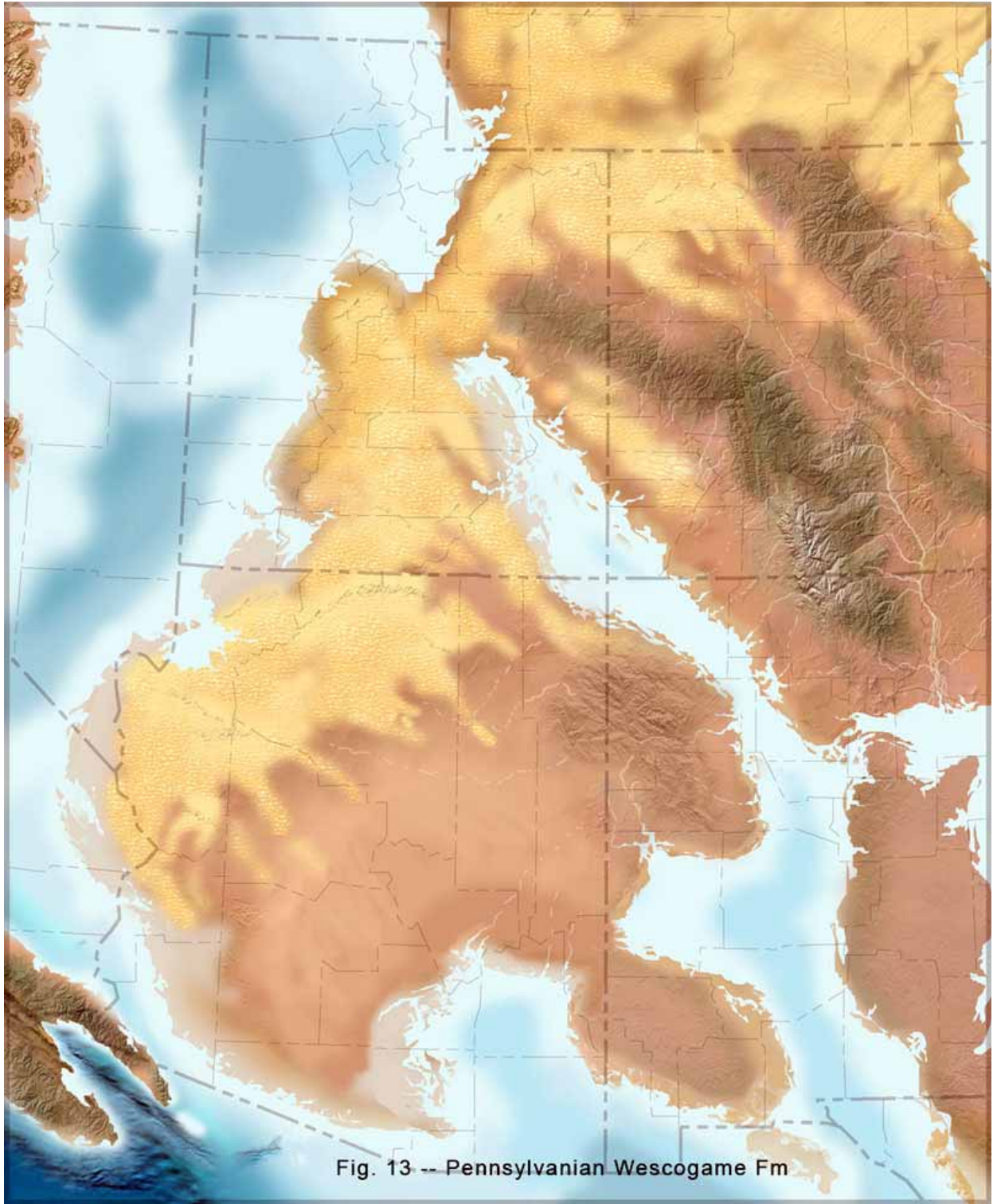


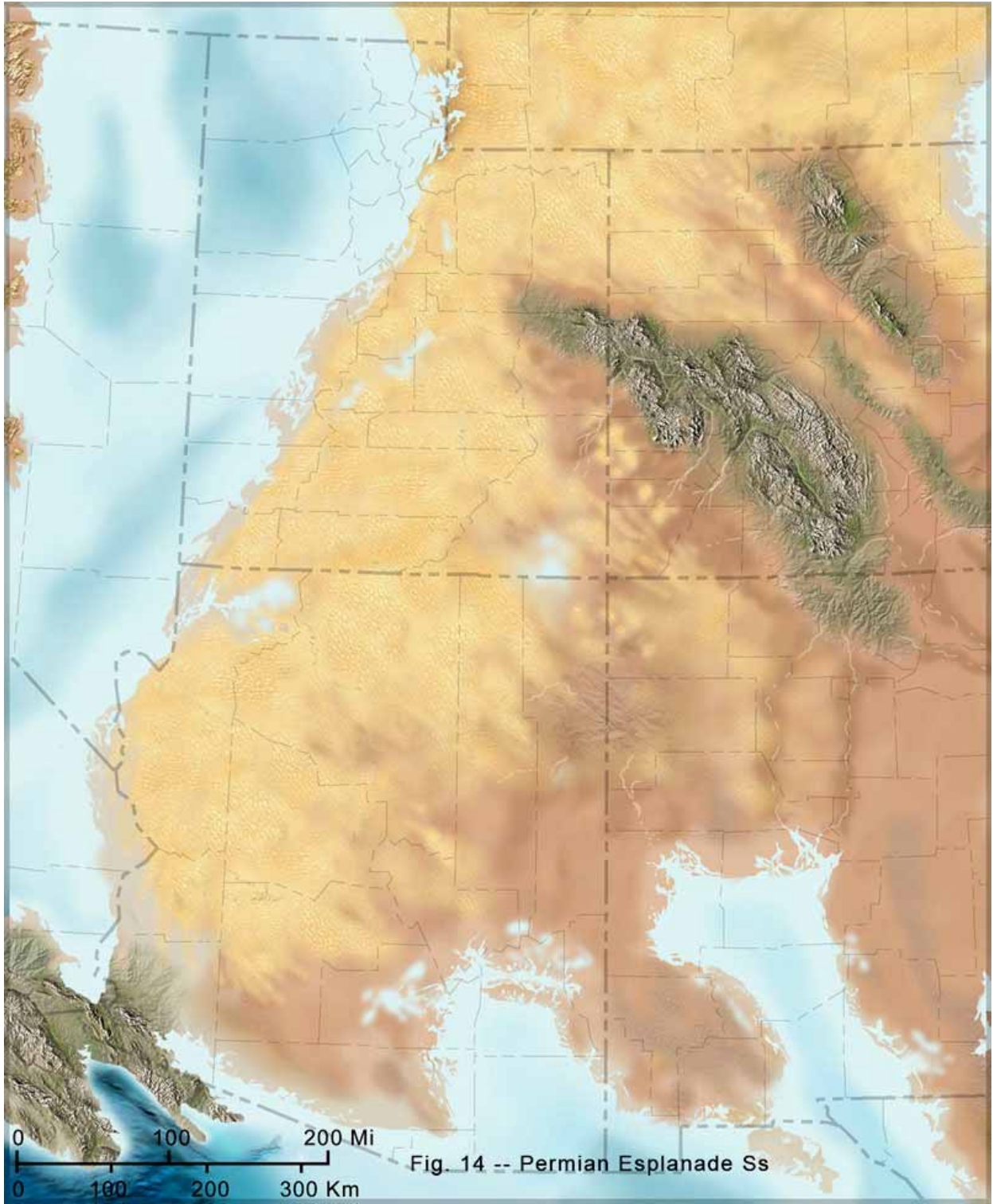




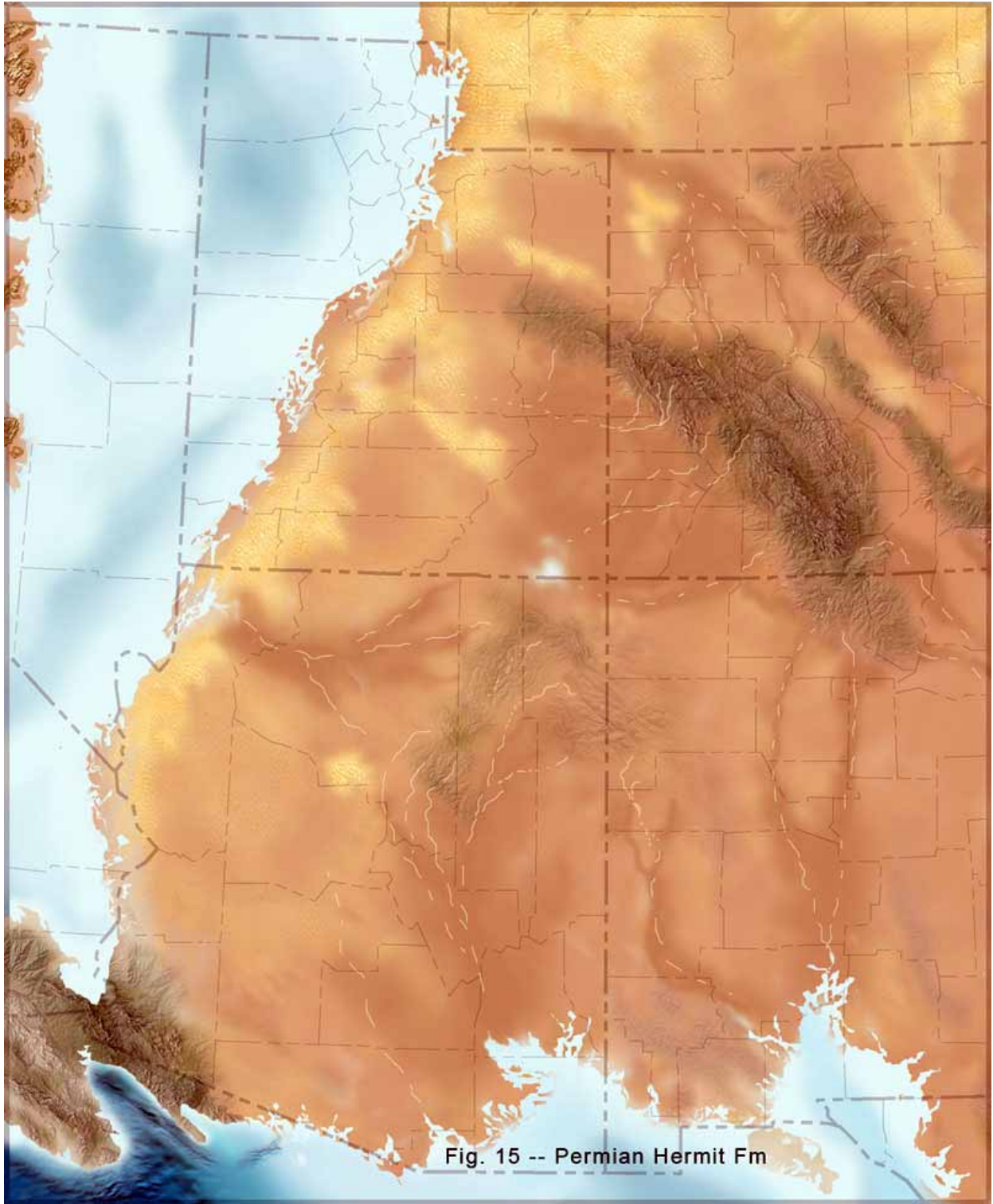


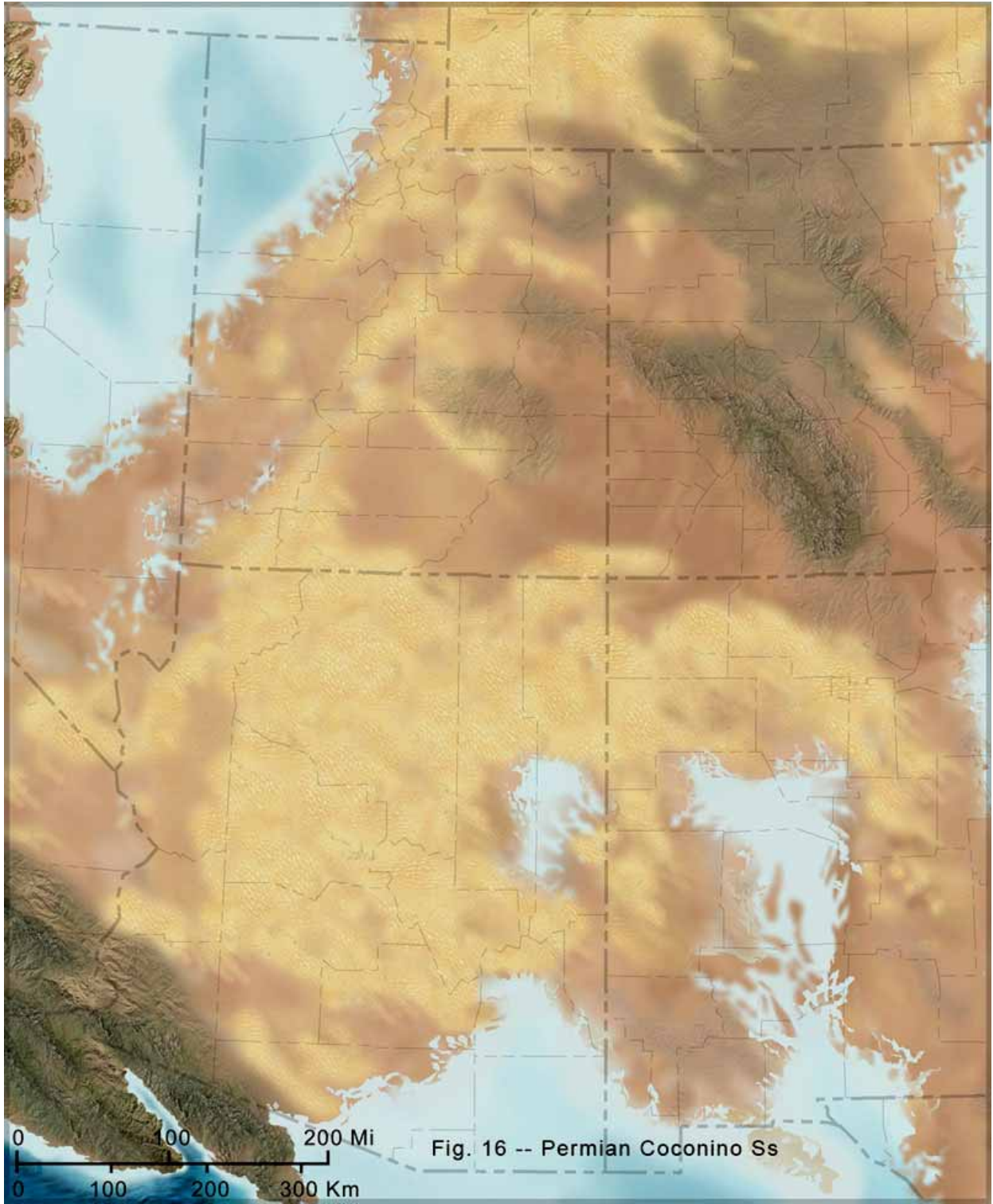




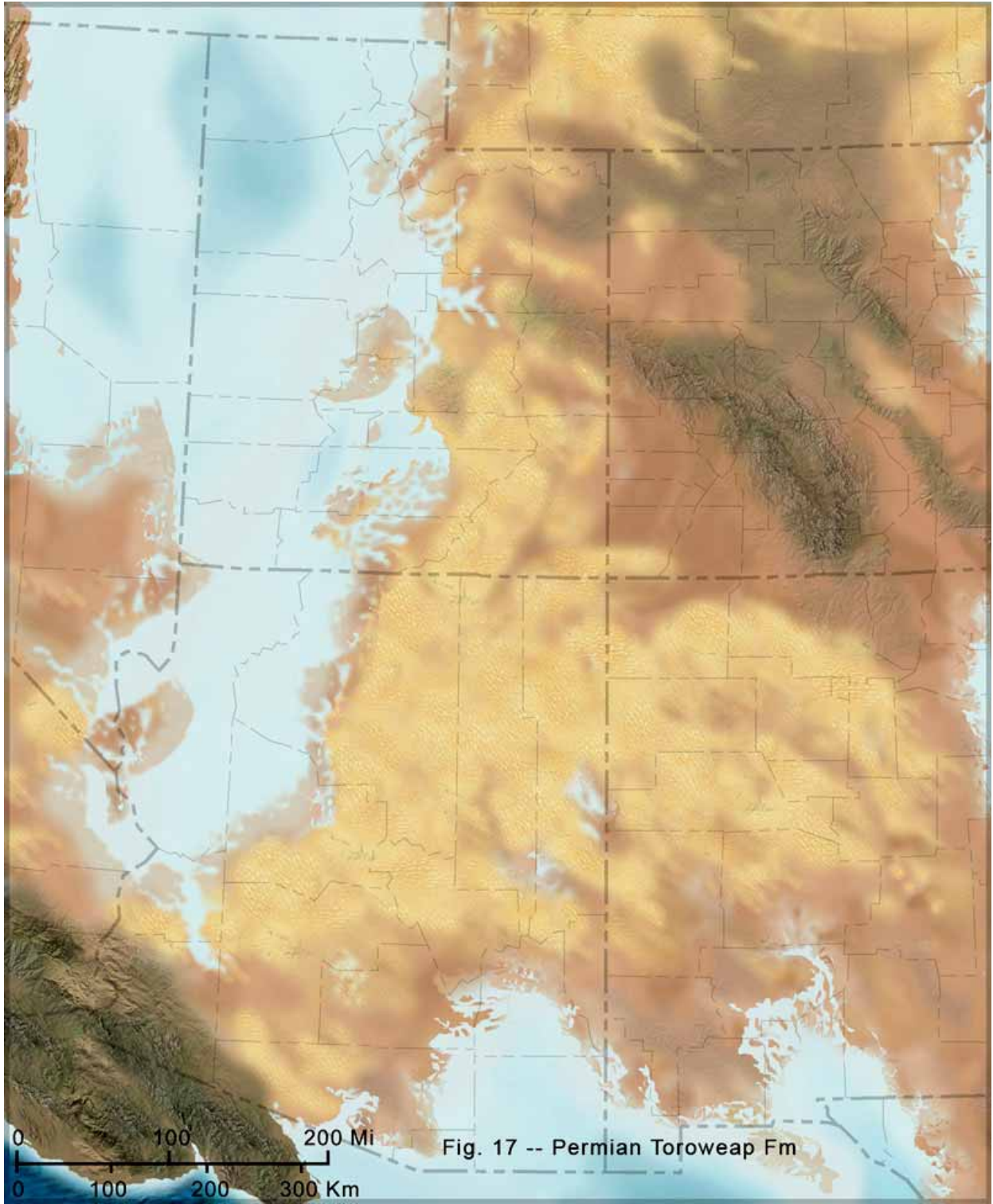


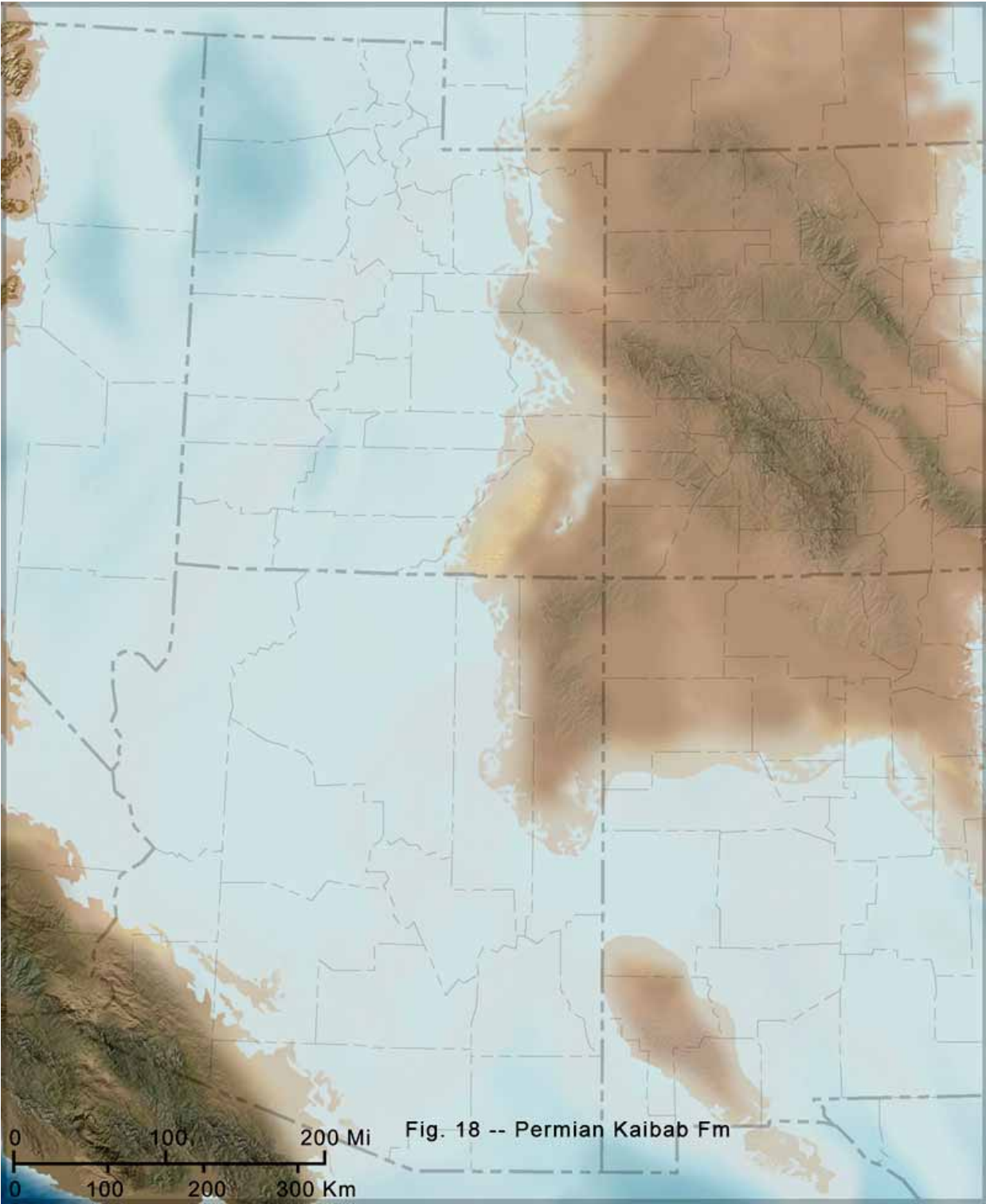




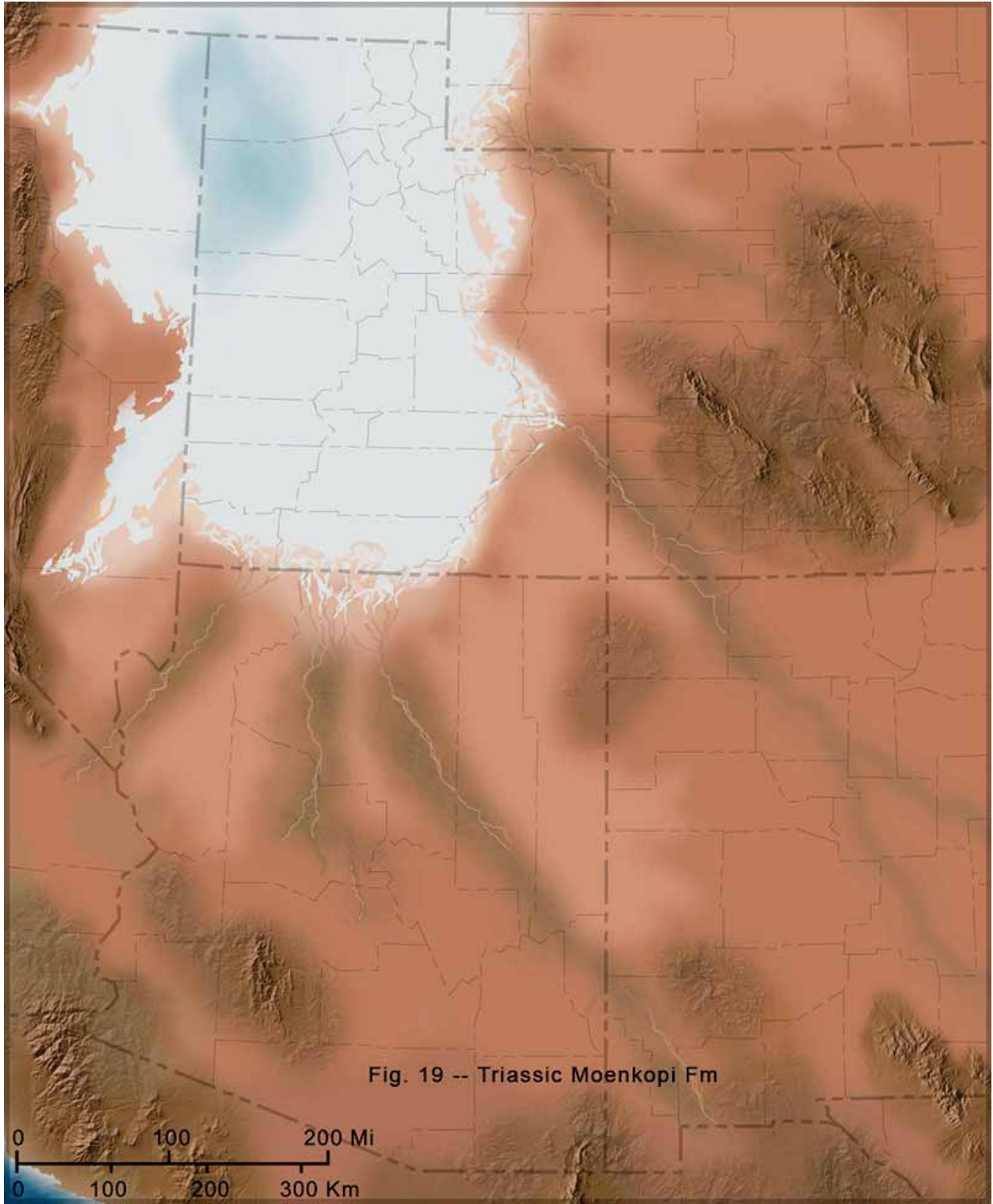








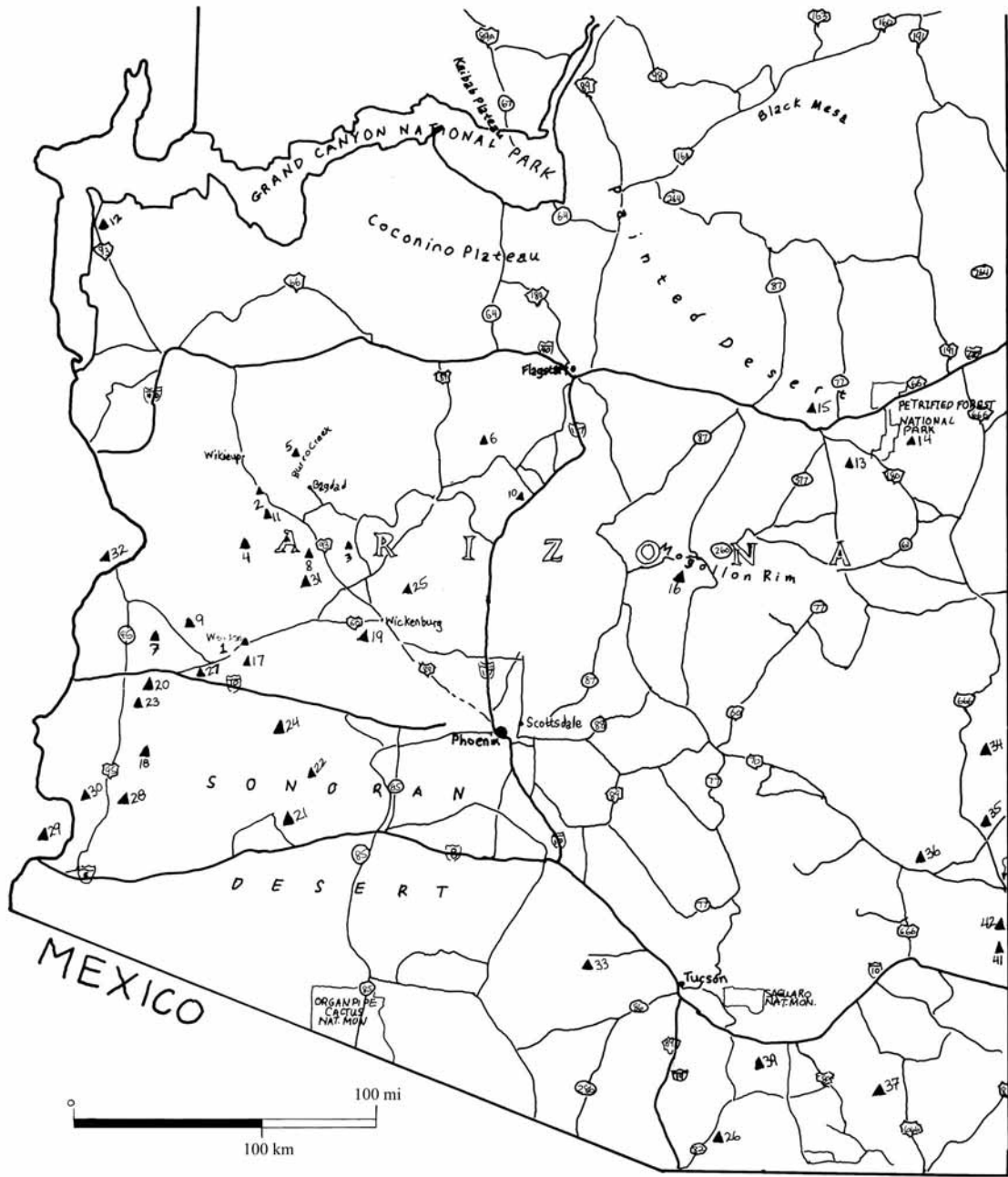






### Appendix 3 - Arizona Mineral Localities

1. Dendritic Agate and Palm Wood
2. Brecciated Jasper
3. Quartz Crystals
4. Rhyolite, Jasper, Saganite Agate
5. Pastelite
6. Perkinsville Agate
7. Hematite, Jasper
8. Palm Bog
9. Agate
10. Salt Mine, Agate, Selenite, Glauberite, Kyanite
11. Apache Tears
12. Selenite
13. Petrified Wood
14. Agatized Wood-----\$1 Entrance Fee \$0.15 Per Lb.
15. Petrified Wood
16. ??? Crystals
17. Chrysocolla, Pseudomalachite, Diopside, Pyrite, Azurite?
18. Fire Agate
19. Apache Tears, Geodes, Gold Panning, Quartz Crystals
20. Chalcedony roses, Quartz Crystals (double terminated, scepter crystals)
21. Agate, Wulfenite, Mimetite, Cerussite (Slightly Dangerous site)
22. Agates, Geodes, Apache Tears
23. Pastelite, Orbicular Jasper
24. Red Jasper
25. Quartz, Pyrite, Bornite, Black Tourmaline, Epidote, Actinolite, Chalcocite
26. Pyrite, Copper Ore, Lead, Silver, Tourmaline, Epidote, Garnets
27. Jasper
28. Vanadinite, Fluorite, Calcite, Anglesite, Cerussite
29. Fire Agate ---- CLOSED AFTER APRIL 30.
30. Calcite, Barite, Vanadium, Fluorite, Wulfenite --- COLLECT AT DUMPS, MINE IS  
CLOSED DUE TO HAZARDS
31. Chalcedony Roses
32. Chalcedony Roses
33. Malachite, Azurite, Auricalcite, Pyrite, Wulfenite
34. Agate
35. Fire Agate, Geodes, Desert Roses
36. Fire Agate, Apache Tears, Palm Root
37. Wulfenite, Auricalcite, Rosacite, Turquoise, Agate, Geodes, Bornite (Peacock ore)
38. Fire Agate
39. Selenite clusters
40. Pyrite, Amethyst, Jasper
41. Fire Agate, Chalcedony Roses
42. Agate, Geodes, Desert Roses



**Figure A3-1** – Location map of mineral localities keyed to Desert Gem Trails Mineral Guide. Compilation and drafting by Marc Bieler (May 2002).



## Appendix 4 - GEOLOGY FIELD TRIP RULES

**The following rules, first organized by Kevin Higgins and Brendan Jordan and then modified by the words and deeds of other Hofstra students, apply to all departmental field trips in which you will participate. As many of these rules apply to life in general, you should heed all rules.**

1. Never ever ask "what's next?", "where are we going?", "when will we get there?", or "when are we getting back?"
- Rule 1a. (*The Regan Corollary*)** – Never break Rule #1 while backing away from the Gittleson Hall loading dock on the initial day of any field trip.
2. Don't bother anyone before breakfast unless you are a morning person and have acquired special permission.
3. Never speak at breakfast unless spoken to.
4. Never approach a surface outcrop before the professor. Students may enter any subsurface adit, pit, cavern, or mine shaft, first, however.
5. Do not stand so that you will be at a greater elevation than the professor while he or she is lecturing.
6. Avoid standing in front of the professor at any time.
7. While in the van or bus do not sit in Dr. Merguerian's seat.
8. Never attempt to borrow money from a professor.
9. Never end the semester owing a professor money. The converse is, however, acceptable.
10. Leave the jokes to the professor.
11. No back seat driving. Unless you are the navigator or have been specifically asked, do not give the driver **any** instructions.
12. Never read the comics out loud at breakfast or while driving in the van.
13. The President and Vice-President/Chief Decision Maker sit in the primary van seats. At a certain point on all field trips, certain seats become most desirable. Avoid being in the way at these times.
14. Loud music and smoking are strictly forbidden during the vehicular phase of all field trips unless you provide a personal walkman and portable iron lung or decompression chamber.
15. All club officers, past and present, are exempt from all fire duties. These include such things as finding wood, starting the fire, and maintenance.
16. Always get receipts for all expenses for subsequent donation to the professor.
17. When in natural surroundings, pack out what you pack in.
18. Read the rules carefully. Never ask, "What are the rules?"
19. Never be the last person to board the van more than once in a row.
20. Special rules are invoked during long-duration return trips in the driving rain or in heavy traffic. These include the following:
  - A) Absolutely no singing of grunge-rock, hip-hop, rap, or heavy metal while seated near Dr. Merguerian.
  - B) Use of the radio is limited to the driver's discretion and the front speakers.
  - C) Discussion of social issues is limited to one fifteen-minute period per field day.
  - D) The Hess Rule – Never talk for more than 30 minutes straight without eliciting some form of feedback from the person you are speaking to.
21. Never complain and always remember the famous saying, "If you don't like it, too bad".
22. Never be the one to ask, "Is this the last stop?" on the last day of any weekend field trip.
23. When you are 15 minutes late, never walk towards the van at a leisurely pace.
24. Never complain to the Professor that he or she is late when the van is pre-parked in the lot.
25. Cell phone calls from family members inquiring as the timing of trips are strictly forbidden.
26. Never buy two cups of coffee within 2-3 minutes of one another.
27. Most importantly, what happens in the field stays in the field. There is no need for the circulation of tall tales here on campus. If, however, these tales enhance greater student participation or professional neck rubs, talk as much as you like, and lastly,
28. Refrain from applying scented creams, oils, or tinctures while riding in the van unless you are over age 80 and have a note from your parents.
29. Obey all rules!

***Rules Last Updated 25 August 2008***

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