STUDENT'S MANUAL

for

2000

NORTH CAROLINA UNIVERSITIES

SUMMER FIELD COURSE

in

GEOLOGY

by

P. Geoffrey Feiss
Richard Mauger
Kevin G. Stewart

Acknowledgments

This manual has evolved over a decade with the help and assistance of many faculty, TAs, and staff — some forgotten, some not. Among those who deserve thanks are John Bartley, Mary Crump, Cathy Cash, Allen Glazner, Stephen Harper, Richard Spruill, Charles Daniel, Jim Reynolds, Terri Woods, Rick Wooten, and Patsy Webb.

© copyright USA 2000
All rights reserved

Schedule for 2000 Field Course

Date	Day	Activity
12-May	Fri	leave North Carolina; Trip West; camp at Cedars of Lebanon State Park, TN
13-May	Sat	Trip West; camp at Red Rock Canyon State Park, Hinton, OK
14-May	Sun	Trip West; arrive Abiquiu, NM camp site
15-May	Mon	Abiquiu, NM; Intoductory Geologic Mapping Project
16-May	Tue	Abiquiu, NM; Intoductory Geologic Mapping Project
17-May	Wed	Abiquiu, NM; Intoductory Geologic Mapping Project
18-May	Thu	Abiquiu, NM; Intoductory Geologic Mapping Project
19-May	Fri	Taos, NM mapping and landslide project
20-May	Sat	Taos, NM mapping and landslide project
21-May	Sun	Taos, NM mapping and landslide project
22-May	Mon	Taos, NM mapping and landslide project
23-May	Tue	Taos, NM mapping and landslide project
24-May	Wed	Taos, NM mapping and landslide project
25-May	Thu	Taos, NM mapping and landslide project
26-May	Fri	Field trip, Great Sand Dunes , CO and Raton Basin, NM
27-May	Sat	Field trip, Great Sand Dunes , CO and Raton Basin, NM
28-May	Sun	Field trip, Great Sand Dunes , CO and Raton Basin, NM
29-May	Mon	Cuba, NM, Mapping and hydrology projects
30-May	Tue	Cuba, NM, Mapping and hydrology projects
31-May	Wed	Cuba, NM, Mapping and hydrology projects
1-Jun	Thu	Cuba, NM, Mapping and hydrology projects
2-Jun	Fri	Cuba, NM, Mapping and hydrology projects
3-Jun	Sat	Cuba, NM, Mapping and hydrology projects
4-Jun	Sun	Cuba, NM, Mapping and hydrology projects
5-Jun	Mon	Cuba, NM, Mapping and hydrology projects
6-Jun	Tue	Cuba, NM, Mapping and hydrology projects
7-Jun	Wed	Field Trip, Mesa Verde, CO and Creede, CO
8-Jun	Thu	Field Trip, Mesa Verde, CO and Creede, CO
9-Jun	Fri	Field Trip, Mesa Verde, CO and Creede, CO
10-Jun	Sat	Gunnison Projects, East Elk Creek campground
11-Jun	Sun	Gunnison Projects, East Elk Creek campground
13-Jun	Mon	Gunnison Projects, East Elk Creek campground
14-Jun	Tue	Gunnison Projects, East Elk Creek campground
15-Jun	Wed	Gunnison Projects, East Elk Creek campground
16-Jun	Thu	Gunnison Projects, WSC dorms
17-Jun	Fri	Gunnison Projects, WSC dorms
18-Jun	Sat	Gunnison Projects, WSC dorms
19-Jun	Sun	Gunnison Projects, WSC dorms
20-Jun	Mon	Gunnison Projects, WSC dorms
21-Jun	Tue	Gunnison Projects, WSC dorms
22-Jun	Wed	Gunnison Projects, WSC dorms, pack for trip east
23-Jun	Thu	Trip East, camp at Wilson Lake State Park, Sylvan Grove, KS
24-Jun	Fri	Trip East, camp at Cedars of Lebanon State Park, TN
25-Jun	Sat	Trip East; arrive Raleigh/Chapel Hill, NC late afternoon

MAILING ADDRESSES

Before June 1

UNC System Geology Field Course
c/o Circle A Ranch, Box 2142, Cuba, NM 87013

After June 1

UNC System Geology Field Course
c/o Aspinall-Wilson Center
Western State College, Gunnison, CO 81230

CHAPTER 1 - GENERAL INFORMATION

ACADEMIC MATTERS

Grading Policy - Independent Work

If a student is found to have in his/her possession a copy or copies of map(s) or reports(s) from previous years, the student will be immediately dismissed from the field course.[1]

All material submitted by you for a grade will represent independent work. This is not as simple as it sounds. In all field exercises you will be working with a field partner and, in addition, we wish to encourage the free exchange of ideas in the field and in "bull sessions" - whenever the spirit moves you. Operationally, the concept of independent work boils down to this:

- **All data on your maps and in field notes was observed by you.**
- **All work submitted for grading was done by you.**

An example may suffice. Suppose that in a discussion with another group in the field, you and your partner become aware of an important structure that you had missed in your mapping. On that basis alone, it would not be appropriate to enter that structure on your map or submit your map with that structure shown. You would be advised to enter the idea in your field notebook properly acknowledged as to the source of the idea. However, there is no reason why you and your partner could not, on the basis of that discussion, return to the area in question, see the structure, and then enter the appropriate data on your map (in fact, you may return to the area in question and decide that the other group is completely wrong!).

What you call your work must be your own work. We encourage the sharing of ideas and observations (not data) with one another. This is integral to the learning experience. Here's an example: you encounter a couple of students measuring a strike and dip on an outcrop. You, too, plan to measure the strike and dip of this formation. As you approach, you hear one partner say to the other, "Strike N38W, Dip 51 SE". What do you do? Hint: you do not enter that in your field notes and walk on. You inspect the outcrop yourself and make your own measurements. After all, they might have measured a foliation, not bedding, or been wearing a highly magnetic belt buckle and got the dip in the wrong direction.

Problems may arise if you are not careful and circumspect with your maps and field notes during the evenings and other times. Should you leave your map in open view and unattended, you are nearly as guilty as someone who copies from that map — in a court of law you would be held accountable for entrapment. Keep your maps and notes secure and out-of-harm's way. Do not tempt your colleagues.

Unfortunately, it is not unusual for us to hear, six months later, that "so-and-so" copied every map — "everybody knew this". The problem is that "everybody" but the faculty and TAs know. If you know of such cheating, it is your responsibility to stop it — by confronting the student or reporting it. Why should you expect a TA or faculty member to confront an unknown student not known to have committed grievous acts of unreported dishonesty.

[1] For UNC-CH students, this is also an Honor Code violation.

Due Dates

Course grades are determined on the basis of assigned field course projects. Due dates (subject to revision at the instructor's discretion) for these projects will be made abundantly clear at the beginning of each exercise. The specific requirements for each of these projects will be spelled out at the same time. Generally speaking, an inked and colored geologic map, a stratigraphic column, and possibly one or more structure cross-sections will be required. In some instances a narrative or a description of the lithologic units may also be necessary.

The grade reported is based on submitted, graded work combined with the faculty's subjective impressions of your performance in the field. This latter is based on observation and discussions with each of you in the field by the instructors. The faculty are not grading you on what you know or do not know in the field. They are aware of your motivation, your willingness to contribute to the mapping project, your interest and enthusiasm, your developing field skills and many other factors. The instructors are there to supply guidance, answer questions, and observe your progress. It is unlikely that circumstances exist in which it would be advantageous to avoid the instructors while in the field (a course some individuals have chosen in the past). If the instructors never see you, they can neither help you nor give you the benefit of the doubt in grading.

This Course Manual

This manual should be your Bible/Koran/Torah. It contains instructions, a guide to field methods, guidelines for preparing maps and cross-sections, and lots of useful geological information. We appreciate constructive comments for future editions.

Your instructors may give reading assignments and hold you responsible, at any time, for short quizzes on the manual contents. Be forewarned.

We assume that you will have read the manual thoroughly prior to leaving on the trip west from North Carolina.

Policy on Making Up Missed Field Work

If, because of illness or injury, a student misses a portion of the field work, arrangements will have to be made with the faculty in charge of that project as to how this work is to be made-up so that you can submit a complete map. If a student misses a large portion of field time, it is left to the judgment of the faculty and the field camp director to suggest that the student withdraw from all or a portion of the course and repeat the work in a subsequent field season.

If injury occurs as a result of carelessness or negligence on the part of the student, especially if that injury occurs during the student's free time, the faculty will be notably less sympathetic about making special arrangements than if the student is injured in the normal course of field work.

RULES AND REGULATIONS

Over the years, we have developed a set of rules and regulations to govern various aspects of behavior at field camp. These are not intended to be onerous and, on the whole, are based on common sense. We demand no more of you than is normal of other groups of individuals (discounting such precedents as the Mongol hordes of Genghis Khan). In general, our philosophy is that you are adults and geologists. Do not disappoint us. The staff (faculty, camp manager, and TAs) are not camp counselors and will not act *in loco parentis*.

The following general regulations need to be spelled out for a variety of reasons (some legal):

1. No Firearms.

2. No Alcoholic Beverage consumption during the working day. Technically, that means from wake-up in the morning until we return to our base camp on field work days or travel days. Federal, state, and local laws and regulations apply!

3. No Drugs/Illegal Substances. The Field Course is **drug free**. No exceptions.

4. There is no formal "lights-out" in the evenings. However, if inconsiderate individuals force the issue, they may be banished to *terra incognito* to permit appropriate quiet and rest for others. Whenever there is "common space" for working on maps, drafting, and other "appropriate" behaviors, the **working few will always have priority** over those of a more jovial bent.

5. Policies on State/Field Course Vehicles

- North Carolina state law requires that state vehicles be driven only by state employees. These include instructors, TAs, camp managers, and any on-the-payroll drivers (if you do not know your driver status, you probably aren't authorized to drive).
- No alcohol or controlled substances are to be used at any time, under any circumstances, in a state-owned vehicle. Failure to comply with this policy will result in an immediate, nonnegotiable reduction of your course grade by one full letter grade. A second offense will result in a one-way ride to the nearest bus station and an "F" in the course. Faculty, camp manager, and TAs are not only empowered but obligated to enforce this policy - SO **DO NOT TEST OUR WILL**. This rule will apply equally to offenders and **other occupants** of the vehicle who can be shown to have been aware of the offense.
- State vehicles will, on occasion, be available for evening trips to town for shopping or laundry. If the trip is an official one, i.e., the faculty or camp manager authorize a trip to town for camp supplies or other official purposes, you are free to tag along at the convenience of the individual making the trip. If the trip is to be an unofficial one, the gasoline used must be replaced by the individuals making the trip.
- If a state vehicle is used for such trips, the driver must satisfy the requirements noted above for driver's of state vehicles, AND must refrain from consuming alcohol or any other controlled substance during the duration of the trip. Permission for "unofficial" trips can come only from a faculty member.
- Each state vehicle has an individual responsible for having that vehicle gassed up each morning and for routinely checking tires, fluid levels, etc. He/She will record all gas charges, save all gasoline receipts, and keep track of the keys to his/her assigned vehicle. They **<u>are not</u>** authorized to turn those keys over to anyone else nor will they be allowed to make unauthorized use of their vehicle without faculty or camp manager permission. So - DON'T ASK.

6. We have many housekeeping duties on the road, at Cuba, and at various campgrounds. Assignments will be made for such duties and rotated in an equitable manner. **No one is exempt.** Failure to cooperate will result in the assignment of additional, more demanding (and demeaning) duties. Repetition of slack behavior will result in public flogging.

7. With reference to all matters of keeping the camp operating, the camp manager is **THE BOSS**. All must bend to the camp manager's will.

8. While working on mapping projects, you will work with at least one partner. A certain amount of protocol is involved in this partnership. To wit:

- You and your partner must stay together at all times. Failure to remain within shouting distance is a serious breach of field safety and will not be taken lightly.
- You are expected to act like adults and get along with your partners in the field.

9. Any deliberate act which is potentially dangerous to life and/or limb will be severely punished. In particular, **DELIBERATE ROLLING OF BOULDERS WHILE OUT IN THE FIELD IS EXPRESSLY PROHIBITED** and will be punished in a fashion similar to that described for the consumption of controlled substances in state-owned vehicles. While rock-rolling is a popular pursuit in many circles, it is extremely dangerous and destructive. It is simply not possible to know if anyone is below you.

If you accidentally dislodge a rock while walking (undesirable and, we hope, unusual though inevitable), call out "ROCK!" — loudly. If you hear someone else call "rock," find cover. Standing still or looking up before moving enhances the possibility of returning to the camp or dorm with your features seriously rearranged (usually not for the better).

10. Unruly behavior will not be tolerated and may result in expulsion from the course. If you are unsure as to what constitutes unacceptable behavior, ask your professors. Please remember that we do not consider drunkenness, stupidity, etc. to be valid excuses for unacceptable behavior. If your behavior gets you in trouble with the law, you are on your own. In fact, we will probably side with the police.

11. Smoking Policy. All field course vehicles are smoke free!! In shared rooms, all occupants must agree to allow smoking unless prohibited by local regulations. Smoking in the field is strongly discouraged; many of our field areas are dry and fire-prone and smoking may be prohibited on BLM and Forest Service lands. **There is absolutely no smoking allowed inside the Circle A Ranch at Cuba.** This 100-year old ranch is a private home and the owners do not permit smoking in their house. In addition, tossing cigarette butts on the grounds of the Circle A is not just inconsiderate, it is a serious fire hazard. In all other situations, personal courtesy and respect for clean lungs should be the overriding principles governing smoking/nonsmoking behavior.

12. Geologists were among the first environmental scientists. It is incumbent on us to behave as if we wanted no one to ever know we were in the field. Pack out all litter (orange and banana peels can last a decade in dry areas). Do not deface outcrops and, of course, **collecting rocks and hammering on outcrops are absolutely prohibited in National Parks and Monuments.**

SAFETY

Natural Hazards

Geological field work involves travel over rough terrain, commonly taking you places that you would not dream of visiting for the fun of it, in weather which may be less than optimal. This is, to quote a cliché, "the price of science". To do this without taking unnecessary risks, you need to acquire some expertise and judgment in dealing with various natural hazards. While there is no substitute for common sense or experience, the following may be helpful.

1. Electrical storms. Afternoon thunder showers are common. Should an electrical storm begin while you are in the field, get away from high, projecting objects such as trees or power poles, which may serve as lightning rods. Further, avoid being a high, projecting object yourself: sit down, preferably in a topographically subdued and irregular area such as a talus slope. Try to look like just another boulder. If you feel a tingling sensation, drop flat immediately; that is a sign that you are about to become a lightening-rod.

Sheltering in a cave often seems like an attractive alternative to getting wet when the rain starts, but do this ONLY if the cave is deep and you can get well inside. The ground current induced by a lightning strike can arc across the mouth of a shallow cave and through you with tragic consequences.

2. Loose rocks. Talus and scree are abundant in the arid to semiarid areas where we will be working. This poses hazards to yourself (falling down because of uncertain footing) and to others (kicking loose rocks down on those below you). Obviously, there is no substitute for simply being careful. However, a few pointers may help:

- Keep your body vertical, i.e., your center of gravity should remain directly above your feet at all times. In particular, avoid the temptation to lean into the slope - this will cause your feet to slip out from under you, but we agree, you will fall upslope!
- Avoid placing yourself directly downhill from anyone else, and try not to traverse above others.
- As noted above, if you dislodge a loose rock, shout out "ROCK!" DO NOT check to see if there is anyone below you before shouting - shout IMMEDIATELY. You might not be able to see a person below you because she/he might be out of sight yet still vulnerable.

First Aid

You should be familiar with the general first aid procedures that would be applied in any hiking or camping setting. In general, unless the individual is not breathing or is bleeding from an artery, the best policy is to cover the person up, make them comfortable, and stay with them until help arrives. We will know of your general whereabouts during the day. If you do not show up at the prearranged time, we can probably find you within an hour or so.

Leave an injured person only if you have reason to believe that help will not catch up with you in the normal course of events. If you do leave an injured person, **your first responsibility is to be able to lead help back to them** - so do not panic. **Note your location!**

We always leave a set of vehicle keys hidden in a magnetic box on one or more vehicles - to be used in case of medical emergency in the field. They are there if you need to evacuate someone from the field or go for help during the working day when a staff member or authorized driver is not around. This is an emergency procedure only.

Some specific hints that might be of use to you in doing field work in the Southwest are as follows.

1. Snakes. The only poisonous snake that you will be at all likely to encounter is the rattlesnake. They usually give a lot of warning. Heed that warning and **STAY AWAY FROM THEM**. Most people who get bitten accomplish this task by their own stupidity. Do not try to kill them; they were here first. If you or your partner do get bitten, the best policy depends on where you are and the circumstances. If you are near others or the vehicles,

calm the Bitee, make him or her comfortable, and seek help. If it is a long distance from the vehicles and you do not think that you will be discovered in the course of the next few hours, you and the Bitee should calmly and quietly walk out; being aware that if the Bitee begins to show signs of physical stress, it is time to sit down and reevaluate the decision to walk out. There is no reason to resort to heroic measures - a normally healthy adult can survive a snake bite with no permanent damage. You typically have six hours for administration of anti-venom and we are never more than an hour's drive from a medical clinic.

2. Allergies and Serious Medical Conditions. Please notify us of any serious allergies (e.g., penicillin, bee stings, aspirin) and of any medical conditions (e.g., asthma, "football" knees). Tell your field partner if he/she needs to be familiar with your condition or with any emergency procedures (like where in your pack you keep your inhaler or anti-venom for insect bites).

If you feel ill at any time, convey that to a staff member. We will always be no more than an hours drive from medical help, but we can only seek help if you tell us in a timely manner.

3. Heat. The project areas around Prescott can be very hot. Your best defense is light, loose-fitting clothing that covers you (including, and especially, your head) and water - lots of water. Personal needs will vary with individuals, but if you perspire a great deal, you can easily need up to two quarts of water a day. If you feel dizzy, lightheaded, disoriented, nauseous, or chilled, sit in the shade, drink water (slowly), loosen your clothing, and rest. A bout of heat exhaustion is debilitating and will result in the loss of a good deal of field time. We keep extra water in the vehicles for emergencies. It is not there to allow you to carry only one quart of water and manage your traverses to have lunch at the vehicles with a nice cold draught of water. Misuse of that emergency water is a very serious offense.

4. Breaks and Sprains. Sprains are the most common injuries each summer (especially during the first week or so as you get your "sea legs". Be cautious, use a good set of well broken-in boots, and avoid dangerous situations where you will risk such injury.

5. Insects. Bring a good insect repellent that works for you. Skin chemistries differ and different repellents work different ways for different people. In general, preparations with n,n-diethylmetatoluamide as the active ingredient are most effective; others may find the infamous Skin-So-Soft formula works best. There may be a few times when a good bottle of Cutter's is the only thing between you and temporary insanity.

6. Sunburn. If you sunburn easily (and even if you do not), plan on bringing a good sunscreen (only those rated at >24 provide protection from cancer-causing UV) and some sort of chapstick with sunscreen. The hot, dry desert air and the high elevations of the southwest can do wonders to your epidermis. Be prepared to get a million-dollar tan, but remember you have six weeks in which to get it. A good pair of sunglasses is highly recommended, but be sure they have a UV filter and are shatterproof. Bandannas and scarves are useful for protecting the back of your neck from the low angle sun in the morning and afternoon — they make nice napkins to use with your lunch too. If your skin is naturally dry, you may want a good moisturizing lotion.

7. Cold. We will be at elevations of 500 to 10,000 feet; nights can be very cool at these elevations, even during the summer months. In the Taos/Cuba and Gunnison areas, the weather can get cold and nasty very quickly. Bring a good, lightweight rain jacket and warm clothes, particularly wool in preference to cotton (we recommend the layered-look,

i.e. undershirt, shirt, sweaters, vest, and jacket, since you can strip off the layers as the day gets warmer either by solar heating or exertion).

Bring a warm sleeping bag, but do not invest in a bag appropriate for an expedition to Denali or Everest. It will not be that cold. You will be plenty warm in a good quality bag rated to 0° C (a "three-season" bag) if you have clean clothes to sleep in, perhaps a light blanket, and a foam pad instead of an air mattress (you don't have to blow up a foam pad and it will not go flat!). Some Sno-Seal or other silicone-based waterproofing for your boots will keep your feet relatively dry while working on snow. For the hydrology project, bring along an "expendable" pair of tennis/running shoes. They will keep your feet from getting abraded, bruised, or cut while wading. You will have to have appropriate footwear to do the hydrology project.

8. Cacti. All field areas are well-populated by numerous species of cacti and other ripping/slashing/cutting plants with varying degrees of friendliness. Long pants are often the best defense; even gaiters can help. For the same reasons, leather boots are preferable to canvas, gore-tex and other easily penetrated materials. A pair of tweezers in your backpack may make a long day bearable.

WHAT TO BRING

Equipment

You may already have been given an equipment list; but in the event that you have not or have misplaced it, one follows. Listed are items needed in addition to personal effects. You can do laundry about once a week, Items in bold are things that people have forgotten in the past or wrongly assumed they could pick up at a K-mart the first day. Be warned — you will be a long way from a K-Mart in Cuba, NM and major credit or cash cards won't help.

Your belongings must be packed in **no more than two** bags or packs. No suitcases, trunks, or external-frame backpacks are permitted; these items are very difficult to pack in a truck or atop a van. On the drive out you will be allowed access to only one of your bags. Make sure that your camping gear and clothing for the 2.5 day trip are in your accessible bag.

A solar-powered, handheld calculator is a must this year!!

Unofficial Equipment List for Field Camp
(all packed in soft duffels or back packs)

Clothing Items

2-3 sets of field clothes	boots[2] and sneakers	5-6 pairs of heavy socks
rain jacket	sweater(s) or sweatshirts	swim suit
jacket or warm coat	light, leather gloves	2 towels
hat	sock/boot liners	one "nice" outfit
underwear, t-shirts & socks		belt; to carry compass & hammer ex-
pendable pair tennis or running shoes		

Other

laundry bag	toiletries	sunglasses
sleeping bag[3]	air mattress or foam pad[4]	2 one quart canteens

insect repellent	sunscreen & chapstick	safety glasses
bandannas	flashlight	camera and film
first-aid kit & tweezers)	reliable watch	alarm clock
whistle for signaling	silverware	plate and cup

plastic sandwich container; prevents terminal lunch deformation in your pack

Geological Gear (cannot readily be purchased after you leave)

rock hammer	hammer holster, optional	sturdy day pack
hand lens	field notebook	small triangles
cm. and in. rulers; scale	protractor	erasers for pencil and ink
pocket knife	pencil sharpener	drafting tape
colored pencils	can-opener	pocket calculator
clip-board or flat board	permanent marker	pencils; HB or harder

size 00, 0 & 1 drafting pens; you need pens for fine, regular, and heavy lines

sealable plastic bags for waterproofing field maps and notes

waterproof black ink

Optional Items

cards	walkman	frisbee
backgammon	escape literature	stamps & stationary

2-person tent & ground cloth — Mom or Dad's credit card

Financial issues

Bring enough cash (preferably as widely negotiable traveler's checks in small denominations) to pay for meals, laundry, telephone calls, toiletries, and stamps. At least $200-$300 is recommended.

It will be virtually impossible to cash personal or payroll checks. If people plan to send money, have them send a postal money order or a certified check. Even so, it will be difficult to get to a bank on a business day; try to bring enough cash and traveler's checks with you.

Remarks on Weather

You can assume that temperatures will range from 30° to 95° F; there may be snow, certainly afternoon thundershowers. All of this may happen in the same day. The best approach is the layered look, e.g. T-shirt, turtleneck, sweater, rain jacket, and light jacket which can be shed as the day proceeds.

Shorts, especially heavy-duty canvas types, are great but remember there are lots of

[2] Get knowledgeable advice on what kind of boots to buy, get them from a reputable supplier, and do not skimp on cost. **Buy them early and break them in**. The vast majority of foot ailments at field camp result from cheap boots or boots not properly broken in.

[3] You do not need a four-season sleeping bag rated for polar expeditions. A three-season (rated to, say, 25-30° F) is fine for the conditions we will see. However, get a real sleeping bag — no pheasants or Sesame Street characters on a flannel liner.

[4] Recommendation: Therma-Rest (best), various types of foam pads (OK), air mattress (worst; takes too much time and air to blow up, cold to sleep on).

cacti and the sun is ruthless. In some places, the bugs can even drive you to distraction. You'll have a great tan, in between the scabs. You will not need good clothes. Dressing up at field camp is putting on clean, dry T-shirts and jeans after washing your feet.

If you have the gear to do geological field work in sun, wind, rain, snow, insects, cold and can put it all in two duffels/back packs, you'll be fine.

Brunton Compass

You will have been issued a Brunton or Silva compass and case for your use. We expect only a minor amount of normal wear and tear. Loss of a compass or irresponsible breakage will cost you dearly. A Brunton retails at about $185. The compasses are remarkably rugged but they are precision instruments and must be treated accordingly. When you are first issued your compass, wait for proper instruction in its use before trying to follow some of the techniques described later in this handbook. A few simple tricks will save a broken mirror or cover.

<<PLEASE READ THIS>>

SOME WORDS ABOUT THIS MANUAL

This manual has three chapters. We have worked very hard to prepare it for you. This is not an accident. We think it is important.

You have just completed **Chapter One** which gives you all the bookkeeping details, the rules and regulations, and a lot of advice that you may or may not heed.

Chapter Two covers a whole set of field skills and lots of wise advice from your instructors. Remember: between them, these people have, though they would rather not admit it, pretty close to a hundred years of field experience. There are a whole lot of **very important** insights, recommendations, demonstrations, etc. in Chapter Two that we will expect you to know on the first day in the field. Take time to read this in the van and be sure you understand it all. Ask questions of the TAs and faculty on the way out. It will help pass the time — and believe us by the time you get to Oklahoma City you will want to pass the time!

Chapter Three is a field guide of sorts. It contains narrative information about most of our long distance drives and some of the field trips as well as important background on regional geology and tectonics of the Colorado Plateau and surrounding areas that we will take for granted as the summer proceeds.

This is an important reference and we expect you to read it before the course begins and frequently thereafter. Be familiar with it. The manual includes stratigraphic sections and columns that will be extremely helpful in a number of your mapping exercises.

CHAPTER 2 - GEOLOGICAL FIELD TECHNIQUES

INTRODUCTION

Geological field study of an area consists of three parts:

1) making a geologic map of the area,

2) recording in a field notebook observations regarding the rocks and structures present, and

3) analyzing and interpreting your field data, i.e., the map and notes.

The first two parts of the field study proceed together simultaneously while you are actually in the field. The third will involve considerable thought and analysis of data after you leave the field. This text is intended to give you some basic procedures for each aspect of field study, including techniques and helpful pointers in their application.

This handbook is intended as a general introduction to field methods, and is not meant to be an exhaustive compendium of techniques. Nor could it be one: the practice of field geology is strongly dependent on experience, which is why this course cannot be taught in a classroom. This is really a guide for getting started in acquiring your own fund of experience. In the course of fieldwork, you inevitably will encounter situations not addressed in any text. Thus, you will at times have to rely on your own insights to find a solution. "Thrashing it out" on your own is an indispensable part of learning to be a field geologist.

This first portion of this chapter covers data collection while in the field: what to do out there among the rocks. Succeeding portions cover map-making procedures in the field and back at camp.

NOTE: REMARKS WRITTEN IN BOLD CAPITALS AND HIGHLIGHTED (LIKE THIS ONE) ARE KEY POINTS TO BE REMEMBERED - "WORDS TO LIVE BY". IT WOULD NOT BE INAPPROPRIATE TO COMMIT THEM TO MEMORY, AT LEAST IN SOME FORM. THEY MAY SAVE A LOT OF WASTED TIME.

FIELD PROCEDURES

Introduction

The first thing we will consider is what to do when you get out into the field. Here's what to expect on your very first field day:

1. to be very confused
2. to take a long time to get oriented both topographically (where am I?) and stratigraphically (what is this rock I am looking at?)
3. to feel as if you are making no progress and that everyone else is
4. to be depressed by how little you have to show for a day's exertion
5. to fear that you will not complete the project in the time allotted

Each of these expectations is common and predictable. You are completely unfamiliar with the terrain, the geology, <u>and</u> the techniques you are trying to apply. The only difference when one of us goes into the field is that we are more familiar with the <u>techniques</u> that you are here to learn. We all, still, are lost and confused the first day into a new field area. So, relax:

1. your dismay is natural
2. assignments have been completed in their allotted time by preceding generations of students who felt just as lost as you

When you arrive at the beginning of your day's work, first record in your field notebook the date and a brief description of your work plan for the day. Optional information which often comes in handy later includes what geological problems you intend to solve that day, the weather conditions (which often put significant constraints on your performance which need to be kept in mind later), who your field partner is, and what map or photos you plan to be recording your data on. Sometimes enough anecdotal information in your early morning notes allows you to recall a field day when you are reviewing your field book and map six days, six months, or six years later.

What to do when you get to an outcrop

You walk to the first outcrop; what do you do now?

A reasonable sequence of procedures at the outcrop is as follows:

1. Locate yourself on your base map and record the outcrop on the map and the location in your notes.
2. Identify and describe the rock(s) present in the outcrop in your field notes, and plot the appropriate information (formation name and location of contact(s), etc.) on your map.
3. Collect samples, if any; number them with a permanent marker and record in your field notebook the sample numbers, and a brief description of the samples and why you collected them. Avoid the habit of collecting small chips of rock whose stratigraphic identity you cannot confirm, in lieu of determining a formation name in the field. While it is possible that someone can help you give a lithologic, mineral, or fossil name to such samples, stratigraphic position is far easier to determine in the field. Rock chips do not convey such information as bed forms, bed thickness, weathering, attitude, stratigraphic position relative to known units, etc.
4. Measure any rock structures or fabrics, including bedding, fault surfaces, slickenlines, fold hinges, etc., and record these measurements in your notebook. Plot bedding attitudes on your map.
5. In your notebook, sketch important exposed relationships, such as a contact or the shapes of small-scale folds, etc.; this includes any distant views which reveal structural or stratigraphic relationships.
6. Note any interpretive significance of the data that you have collected. It is important to be always thinking about the "cosmic" meaning of the relationships you are seeing, because this will be an important guide to what you should do next.

Your field notes should be a record of 1) observations, such as lithologies, bedding attitudes, and the like, and 2) interpretations and speculations which come to mind while on the outcrop. Important things may occur to you while you are actually looking at the rocks which may not be as apparent when you go back and look at your observations later. However, be sure to keep your observations (i.e., DATA) separate from your interpretations, both in your notes and in your thinking.

ALWAYS WRITE DOWN EVERYTHING WHILE YOU ARE ACTUALLY AT THE OUTCROP. NEVER SAVE ANYTHING TO BE WRITTEN DOWN LATER; THIS INCLUDES PLOTTING CONTACTS, STRIKES AND DIPS, AND OTHER STRUCTURAL DATA ON YOUR MAP.

Let's now review in detail most of the procedures (1-6) listed above.

Location

Locating yourself on the map (usually a topographic map or an airphoto) is perhaps the single most important skill in field geology; everything else depends upon it. The significance of any observation depends on its location relative to other features, so all these observations must be correctly located on the map.

IF YOU DO NOT KNOW PRECISELY WHERE YOU ARE, YOU MIGHT AS WELL NOT BE THERE!

For practical purposes, this means you must know your location within the precision of your ability to plot information on the map, i.e., the width of your pencil line. This brings up another important issue: the sharpness of your pencil!

THE PRECISION OF YOUR MAP IS DIRECTLY PROPORTIONAL TO THE SHARPNESS OF YOUR PENCIL. IF YOU USE A WOODEN PENCIL, KEEP IT SHARP; IF YOU PREFER A MECHANICAL PENCIL, BE SURE TO USE ONE WITH 0.5 MM LEAD OR FINER. DRAW ALL LINES ON THE MAP WITH A SINGLE SMOOTH LINE. LABEL ALL CONTACTS, FAULTS, ETC., WHEN YOU DRAW THEM.

Location Methods

While locating yourself can sometimes become a matter of some creative effort, you will ordinarily use one or more of three basic methods. It may be advisable to check one against another, especially when locating a particularly critical contact or relationship.

1) Location relative to a landmark - Sometimes a specific landmark can be identified as a unique point on the map. Examples include USGS benchmarks, tops of hills, intersections of roads or streams, or buildings if shown on the map. Beware of roads on topo maps. Dirt tracks are rarely shown and over a decade or two, the road patterns can change significantly.

Obviously, if you are precisely at a known landmark, you know your map location exactly. If you're near the landmark and want to determine your location precisely, use the pace-and-compass method:

1. Sight on the landmark with your compass (Fig. 1) to determine your direction from the landmark.

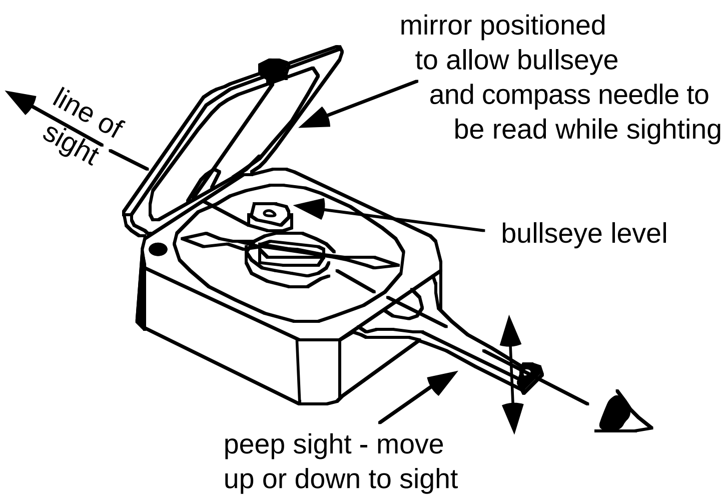


Figure 1: Measuring a bearing with a Brunton compass.

2. Using your protractor and a sharp pencil, draw a very light line (one you can easily erase) through the location of the landmark in the orientation of the compass bearing (Fig. 2). Your location must lie on this line; it remains to be determined where.

3. Pace out the distance from you to the landmark (you will already have measured your pace, so you can easily convert your number of paces into distance). If the slope is steep, you may have to adjust your measurement for shorter paces, although you should have measured a stride which you can maintain on almost any slope. Also, a steep slope will require a correction for the slope itself, because what you have measured is the actual surface distance; what the map shows is the horizontal projection of the surface distance. This correction is made by multiplying the distance you have paced by the cosine of the slope angle. Tables of trigonometric functions are usually included in field notebooks and on the case of your compass for this type of calculation. The slope angle can be determined by using the clinometer on your compass. The slope correction is not signifi-

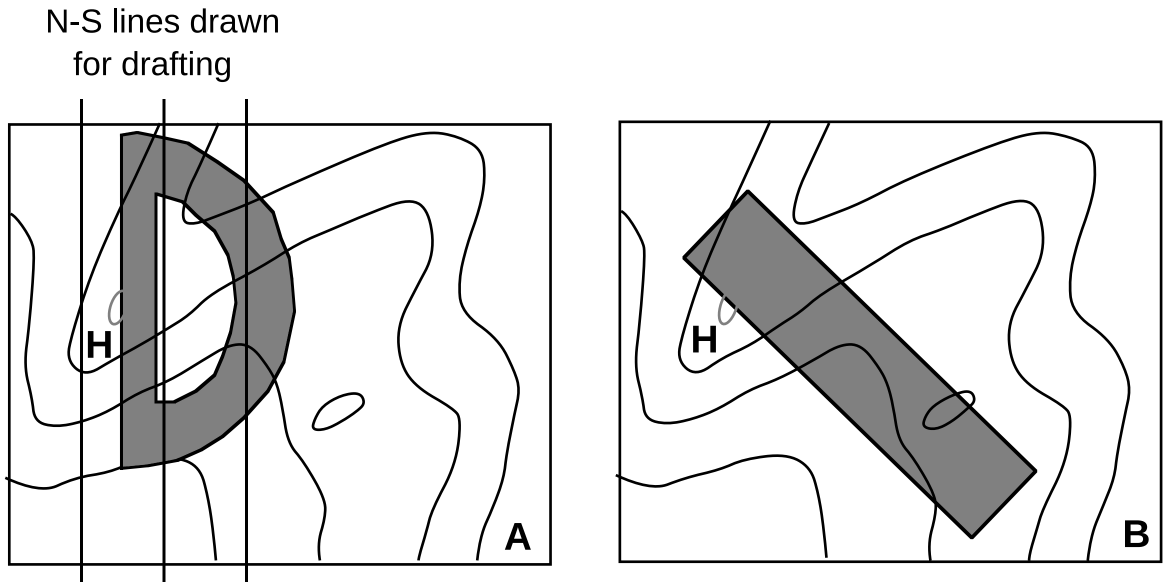


Figure 2: Plotting a compass bearing:
A. Locate landmark (hill H) on map; find the direction of the sight line with a protractor
B. Lightly draw in pencil the bearing of the sight line with a straight edge.
Your location lies somewhere on this line.

cant for slopes less than about 20 degrees, which is a moderately steep slope. You will thus only rarely need to worry about it.

4. Convert the real slope distance to the horizontal distance on the map using the map scale.
5. Using your scale, measure the distance you have paced along the line you drew on your map in step 2 above - this is your location!
6. Erase the line you drew in step 2. You should never let your map become cluttered with unnecessary marks.

++++++++++++++++++++++++++++

Advantages
Straightforward to Apply and Accurate

Disadvantages
Very Time-Consuming for any but nearby Landmarks
Requires Precisely Located Landmarks, of Which there may be Few
Accuracy Decreases as Distance from Landmark Increases

++++++++++++++++++++++++++++

2) Triangulation: This method is related to the former, in that it uses compass sightings on landmarks and geometrical construction on the map. It enables you to use distant landmarks, and eliminates time-consuming pacing. The principle is simply the geometrical axiom that two lines intersect in a unique point. Lines drawn on a map which extend along compass bearings from landmarks to you will thus intersect in a single point - your location. The procedure uses multiple sightings (at least three) to minimize errors, although in principle only two sightings would be adequate. The actual procedure is as follows:

1. Take compass bearings on at least three landmarks which can be precisely located on the map. The more landmarks you use, the more you can reduce the error of your location, although the point of diminishing returns is quickly reached.
   a. Maximize the spread of sighting directions to reduce error in location of line

intersections; optimal for three sightings is each at an angle of 120 degrees to the other two (Fig. 3).

b. Make sure the feature on which you are sighting is precisely the feature you are looking at on the map. In particular, a common error is to sight on the summit of a hill from below; it is rare to actually be able to see the top of a hill from below, so you are probably sighting on something near but not precisely at the summit. This can introduce significant error.

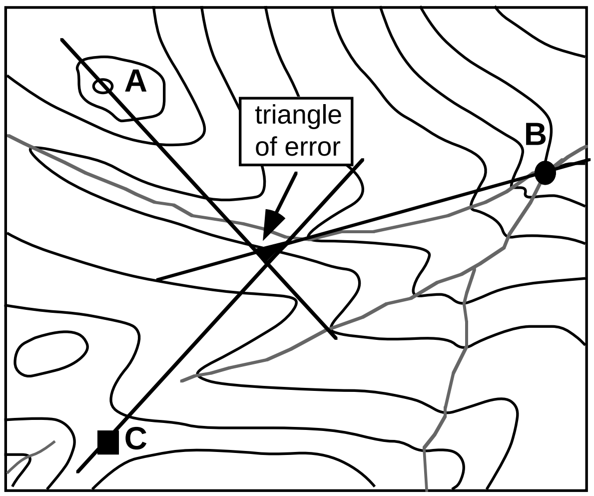


Figure 3: Triangulation -- compass bearings on hilltop A, stream confluence B, and structure C are plotted (see Figure 2). Your location is somewhere in the triangle of error.

2. Draw light, erasable lines through the landmarks on the maps in the directions of the appropriate compass sightings. These lines should intersect in a very restricted area; the area enclosed by three lines is referred to as the "triangle of error" (Fig 3).

3. Plot your position at the center of the triangle of error. An error triangle larger than a few millimeters is excessive. If this happens, you have probably made an error in identification of landmarks, measurement, or plotting. Check these until the error triangle is satisfactorily small.

4. Erase your construction lines from the map.

++++++++++++++++++++++++++++

Advantages
Accurate when Good Landmarks are Available
Less Time-Consuming than Pace-and-Compass Method in Areas Larger than a Few Tens of Meters

Disadvantages
Cannot be used when Distinctive Landmarks Can't be Identified
indistinct topography or obstructed vision
when at the bottom of a gully or in a forest
Relatively Time-Consuming

++++++++++++++++++++++++++++

3) <u>Interpreting the Topography on the Base Map</u> - The topographic contours on your base map represent the landscape on which you are standing. Therefore, you should relate the squiggles of the contour lines to peaks, valleys, ridges, gullies, astroblemes, and other topographic features you can see around you. With practice, you can use this information to locate yourself quite accurately. Furthermore, this method allows you to keep continuous track of your position. To do this with confidence requires a fairly good feel for the scale of the map, which requires a little practice, and you should be constantly consulting your map and comparing it to the landscape.

You might think of yourself as a Cruise missile — constantly monitoring elevation, slope conditions, and topography to adjust your path in order to arrive on target.

NEVER PUT THE MAP AWAY AND WALK OFF TO YOUR NEXT DESTINATION WITHOUT LOOKING AT IT - IT SHOULD ALWAYS BE HANDY, AND YOU SHOULD BE CONSULTING IT CONSTANTLY FOR INFORMATION ON LOCATION AND THE RELATIVE POSITIONS OF TOPOGRAPHIC FEATURES AROUND YOU.

++++++++++++++++++++++++++++

Advantages
Rapid
Can be used Anywhere, Regardless of Visibility

Disadvantages
Less Accurate than Surveying Methods
especially in areas of subdued topography where precision is strongly dependent on experience (that's why you're here, to gain experience!)

++++++++++++++++++++++++++++

Geologic field notes are usually taken in conjunction with key localities, which are plotted on the map and called "stations". A station is established whenever rock descriptions are entered, structural features are measured, and/or samples are collected. Each station is marked on the map and numbered. A trick to save cluttering your map with station numbers is to prick a hole in the map with a straight pin at the location of the station, turn the map over, and circle and number the station on the back of the map.

Stations allow you to relate your notes to the precise localities they describe, help in organizing your data, and provide a record of your traverse. However, DO NOT view fieldwork as a process of collecting data at a series of discrete key localities with your map in your pack and your mind in neutral.

DURING A TRAVERSE, YOU SHOULD AT ALL TIMES BE LOOKING AT THE ROCKS, KEEPING YOURSELF LOCATED, FILLING IN YOUR MAP, AND MAKING NOTES ABOUT WHAT YOU ARE SEEING AND WHAT YOU ARE THINKING .

Field notes, along with your map, are the basic data of field geology; you should think about them and respect them in exactly the same way you would treat a set of geochemical analyses. Field notes should NOT be a rambling diary of your adventures and misadventures; the notes should be entered in a methodical and precise manner, so that another geologist could pick up your notes and use them. Descriptions should be <u>printed</u> in terse English; any abbreviations should either be self-evident or explained parenthetically at the beginning of your notebook. Structural attitudes at each station should be written down in the form of a table, with a clear explanation of precisely what was measured. Attitudes which are approximate due to indistinct bedding or other causes should be annotated to that effect. Sketches should be as legible as possible; sharp pencils and a few colored pencils will greatly enhance their appearance and later utility.

You should keep in mind that in any work you do as a professional geologist, your field notes are your employer's property and will be stored as part of the data file on the area you are studying. Your supervisor clearly would not be pleased by chaotic and illegible notes. It is a good idea to form the lifelong notetaking habits of neatness, precision, and legibility now.

<u>NOTE</u> During the course, your field notes may be collected and graded.

Rock Descriptions (a fine art)

Once you are located, the next important step is to describe the rocks. We will assume you have a background in basic hand-specimen petrography, so this discussion will concentrate on aspects of description peculiar to fieldwork which are not typically addressed in a petrography laboratory. In particular, you will be observing rock units at a range of scales, extending from the submillimeter scale accessible with a good hand lens, up to hundreds of meters or more. These larger scales of observation will probably be less familiar to you, and will receive more consideration here. However, you must cover all scales of observation in your rock descriptions.

With this wide range of scales, it can help to approach the rocks systematically. Usually, it is best to work from large to small features. Start with the overall characteristics of the outcrops. Then, turn to features in outcrop, such as bedding, sedimentary or igneous structures, distribution of lithologic types, and fossil occurrences. Finally, look at one or more hand specimens. First describe the bulk characteristics and then use your hand lens to determine details of texture and composition. It can be important to use all your senses. Do the samples feel smooth or rough in your hand? Does the rock make a characteristic sound when struck with your hammer or emit a characteristic smell? The objectives here are twofold:

1) to generate a petrographic description of the rock for genetic interpretations, and

2) to determine a practical set of characteristics which can be used to distinguish this particular rock unit from others in the map area. The importance of the latter objective cannot be overstressed.

Fresh and weathered surfaces of rocks should be observed. Certain minerals, e.g., olivine, weather in a characteristic way, and may be more easily recognized on weathered surfaces than fresh. Textural and bedding features are often highlighted rather than obscured by weathering. This is especially true of fossils in limestones, which may be virtually invisible on a fresh surface while obvious on a weathered one. In low-grade metamorphic rocks (i.e., greenschist facies), fresh surfaces are, in some cases, virtually worthless for descriptive purposes and the descriptive information in the field may come entirely from examination of the weathered surfaces.

Outcrop Description: The objective is to summarize the characteristic features of the rock unit as a whole, and indicate the quality and nature of typical outcrops. For example, is the outcrop:

1. Resistant (a cliff-former) or nonresistant (a slope-former)?
2. Massive, ledgelike, platy (give typical thicknesses of ledges or plates)?
3. Characterized by a particular kind of vegetation? For example, sandstones often support pine trees preferentially.

Moving down a notch in scale, you should next describe and, if applicable, measure the following:

4. Bedding thickness noting its uniformity and continuity
5. Lithologic homogeneity or heterogeneity
6. Characteristics of bedding surfaces, e.g., planar or undulating, sharp or gradational
7. Primary structures and features, e.g., cross-stratification or fossils, noting information from primary structures regarding stratigraphic “up” direction
8. Structures, such as joints, folds, faults

Lithology. Once you have described these general characteristics, start describing the lithology of the rocks, recalling what you learned in basic petrology. Your descriptions should include information regarding:

1. Mineral composition: what minerals are present and their approximate proportions; in the case of conglomerates, the lithologies of the clast/matrix or phenocryst/matrix or porphyroblast/matrix ratio (again, where appropriate)
2. Other features such as color (on both fresh and weathered surfaces), hardness, density, fissility, etc.

YOUR ROCK DESCRIPTIONS MUST BE SUFFICIENTLY DETAILED SO THAT THEY SERVE THE TWO PURPOSES NOTED BELOW:

THEY MUST ALLOW EACH ROCK UNIT TO BE DISTINGUISHED FROM OTHERS IN THE FIELD AREA

AND

THEY SHOULD ALLOW SOME INTELLIGENT INFERENCES TO BE DRAWN REGARDING THE GENESIS OF THE ROCK IF POSSIBLE

Because you will not know the most distinctive features of each rock unit in the study area until you have gained some general familiarity with all the units, it is best to err on the side of over-describing until you have a clear idea of what is appropriate. Similarly, do not try to describe a unit or identify the formation to which it should be assigned on the basis of a single outcrop (unless you have only one outcrop with which to work). Rock units are commonly variable in their lithology, and often similar lithologies are repeated at more than one level in a stratigraphic sequence. Thus, you need to look around at the general area, at all available scales, when describing the rocks and making a formation assignment.

Rock Nomenclature: When you have described the rock upon which you are standing, the next logical step is to give it a name, i.e., basalt, limestone, garnet-mica schist, etc. Coming up with precisely the correct name on the basis of what you can see in the field is often difficult, especially in fine-grained rocks: Is it really a basalt or an andesite? Is it really an arkose or a litharenite? and so forth. The most important thing when you are in the field is to consistently distinguish one rock from another, regardless of what their correct names would be if you had a thin section and a bulk chemical analysis. After all, you do not want to be in the position that you cannot map the geology until you have spent several months in the lab!

Thus, give the rock an informal "field name" which seems reasonable on the basis of what you can see. As long as you apply that name to the same rock consistently, the name can always be changed on the basis of laboratory data, with no need to change anything but the label on your map. The contacts will remain the same.

Collecting Samples: Although in this course you will not be required to collect samples for petrographic or chemical study, you may wish to collect specimens to provide a more concrete record of the rock units you have seen. There are several significant points here. Freshness of the samples is vital; weathering can impart a completely different appearance to a rock (but note remarks above on the occasional helpfulness of weathered surfaces). Sample size is also important; the samples must be large enough to be truly representative of the rock unit. While one can get carried away collecting large samples, experience indicates that students more often err on the side of collecting samples which are too small to adequately characterize the outcrop from which they were taken.

A sample, once broken from the outcrop and trimmed of any excess weathered material, should be clearly marked with a permanent marker, and the number recorded in your field notes. While numbering systems vary from one geologist to another, you probably will want to adopt one which includes something to indicate in what geographic area the sample was collected. It is also helpful to make a note regarding your purpose in collecting the sample, because later it is often difficult to remember precisely why each of a number of samples was collected.

Measuring structural attitudes

A basic aspect of geologic mapping is collecting data regarding the orientations of structures in rocks and the three-dimensional arrangement of rock bodies. This means extending use of the Brunton compass from merely taking bearings to the collection of geological data including: measuring strike and dip of bedding and other planar structures such as fault planes, contact surfaces, and cleavage and measuring bearing and plunge of linear structures like slickenlines, fold hinges, and current indicators such as flute marks and ripple-mark crests. The following describes some useful methods for determining the orientations of rock structures; you may, with a little ingenuity, be able to supplement this list with alternative methods. However, these should be adequate for virtually every situation you will encounter.

Learn all of these methods; each has its limitations in accuracy and applicability. If you are uncertain of a measurement, repeat the same measurement by an independent method and compare the results. A good geological interpretation depends upon precise structural measurements!

Strike and Dip

The orientation in space (or attitude) of any PLANAR geologic surface is specified by its strike and dip.

The ***STRIKE*** is the compass direction (AZIMUTH) of a horizontal line lying within the plane of interest.

The ***DIP*** is the angle, measured in a vertical plane, between the horizontal and the line of greatest inclination within the plane (which will be perpendicular to the strike).

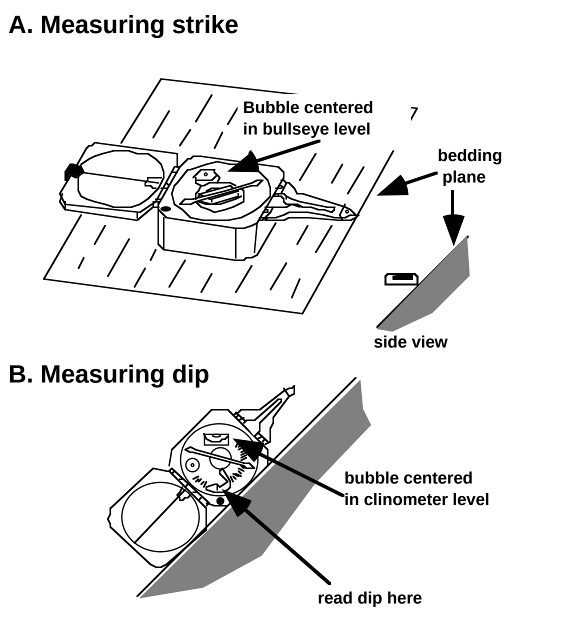


Figure 4: Measuring strike and dip of bedding by direct contact

Measuring Strike and Dip

The measurements fall into two categories (described below):

1) the compass is placed directly on the planar surface, or

2) the measurement is made by sighting on the planar surface from a short distance.

Direct Contact.

Three separate approaches for direct measurements are detailed next.

If a bedding plane or fault surface has been exhumed by erosion, so that the plane itself is well-exposed, a measurement can be made directly on that plane. The sequence of steps is as follows (See Fig. 4).

a. lay the compass on the plane so that the lower edge of the case is pressed firmly against the bedding surface (Fig. 4A). The edge of the compass is parallel with its sighting direction, meaning that the compass sighting direction now lies in the plane to be measured.

NOTE: If the bedding plane is slightly irregular (as is often the case), you should lay a flat object like a notebook or map board on the bedding plane to "even out" the irregularities.

DO NOT PLACE ANY STEEL OR OTHER MAGNETIC MATERIAL NEAR THE COMPASS DURING THIS OR ANY OTHER COMPASS MEASUREMENT, BECAUSE THIS WILL DEFLECT THE COMPASS NEEDLE, RESULTING IN AN ERRONEOUS READING.

---

b. keeping the compass in firm contact with the surface you are measuring, move the compass until the bull's-eye level inside the compass indicates that the compass is horizontal. This means that the sighting direction of the compass is horizontal and within the plane being measured, i.e., the compass is aligned with the strike.

c. Read the compass needle and record the direction in your field notebook. There are three common conventions for recording a strike direction, any of which you may use:

The acute angle between north and the strike line is recorded as, for example, N40E, which is read "north forty east," and refers to a strike line oriented forty degrees toward the east from due north.

The direction of the strike in 360 degree directional coordinates, where north is 0, east is 90, south is 180, and west is 270. N40E would be simply 40 in this method; N40W would be 140 (the "southerly" end of a N40E line) or 320.

The direction of the DIP, i.e. the compass orientation perpendicular to the strike in the direction DOWN the surface. This specifies the strike direction as precisely as the other two, but involves some arithmetic on the outcrop. It is thus is not used as much in the field, unless you are using a non-Brunton compass specifically designed for this method.

However, this convention has substantial advantages for computer treatment of data, and is thus commonly employed by oil-company geologists and in structural analysis. We do not recommend its use in this course, because it is more cumbersome in the field and less convenient for plotting attitudes on maps.

You now have the strike direction - what about the dip?

d. lay the compass on the surface with the compass body vertical (Fig. 4B) and oriented perpendicular to the strike (parallel to the dip or maximum inclination angle of the surface).

e. use the lever on the back of the compass to move the clinometer until the bubble in the clinometer level is centered.

f. lift the compass off of the surface, being careful not to disturb the position of the clinometer lever, and read the position of the clinometer on the scale on the face of the compass underneath. Be sure to read the scale calibrated from 90 to 0 to 90, i.e., the one that is calibrated in degrees.

g. record the amount **AND DIRECTION** of the dip; for any given strike, two dip directions are possible, so you must specify which is correct. This ambiguity does not exist if dip direction rather than strike direction is measured; thus mindless computers can handle dip-directions easily, strike directions alone pose problems.

The final result you will record in your notes will thus take a form like (N52W, 67NE) or (128, 67NE). Note that the strike is written before the dip.

If a surface dips less than about 12 degrees, you will find that the compass cannot be leveled when you are measuring the strike, because the clinometer lever and the raised protective ring around it interfere with movement of the compass. Therefore, an alternative method to measure the strike is as follows:

a. set the clinometer to zero

b. place the compass (edge-on) on the surface in the approximate strike direction, keeping the plane of the compass as near vertical as possible while maintaining firm contact

c. rotate the compass around a vertical axis until the bubble in the clinometer is centered; because you set the level to zero, the compass is now level, and thus is aligned with the strike of the plane

d. mark this direction by laying a pencil, straight edge or other straight object parallel to the compass

e. sight along your marker with the compass to determine the strike direction

f. measure the dip as previously described

Massive resistant rocks, especially metamorphic rocks, commonly do not break preferentially along the structural surface you wish to measure, so direct measurement is not possible. In these circumstances, it is possible to make the measurement by aligning a planar object, such as a notebook or clipboard, with the plane to be measured, and then using the direct measurement techniques above to measure the orientation of the planar object. Alignment of your planar object with the surface of interest is in part a matter of judgment; it is often helpful to have two people look at the clipboard or notebook from different directions to see that it is correctly aligned. If you must do this alone, the following procedure may be helpful.

a) Identify the trace of a particular surface on two nonparallel joint surfaces (preferably joints which are approximately at right angles to the surface you wish to measure and to each other).

b) Lay the edge of your notebook or clipboard (aligned with the trace of your chosen bedding surface on that face) against one of the joint faces.

c) Sight down the edge of the notebook which is held against the rock, so that you can see the trace of the surface you are measuring on the other joint plane. Rotate the notebook around the edge which is held against the rock, until in this view the notebook lies on the extension of the bedding trace on this second joint surface.
At this point, the notebook should be aligned with two nonparallel lines which lie in the plane measured; thus the notebook is parallel to the plane.

d) Holding the notebook carefully in the same orientation, use technique A above to measure the strike and dip on the notebook.

Sighting method.

It is common for the bedding surfaces to be so irregular, or so diffusely defined, that it is not possible either to lay your compass directly on a surface, or to align your notebook with one. Nonetheless, you may be able to see bedding reasonably clearly when you stand back a bit from the outcrop. It is under these circumstances that the sighting method is especially useful.

There is one basic method for sighting to determine strike and dip; all differences are merely minor variations on the same basic procedure. The technique is as follows:

a. move your body, if necessary squatting or lying on the ground, until your eyes are actually positioned within the bedding plane which you wish to measure. An especially accurate means of doing this is possible if you can identify precisely the same bedding horizon in adjacent outcrops, such as on opposite sides of a gully or canyon. Stand or sit at one of the exposures so that your head is immediately adjacent to this bedding surface, and sight towards the exposure in the other outcrop. This assures that your eyes lie precisely in the plane to be measured.

Be very careful and precise in this first step, major errors can be introduced here.

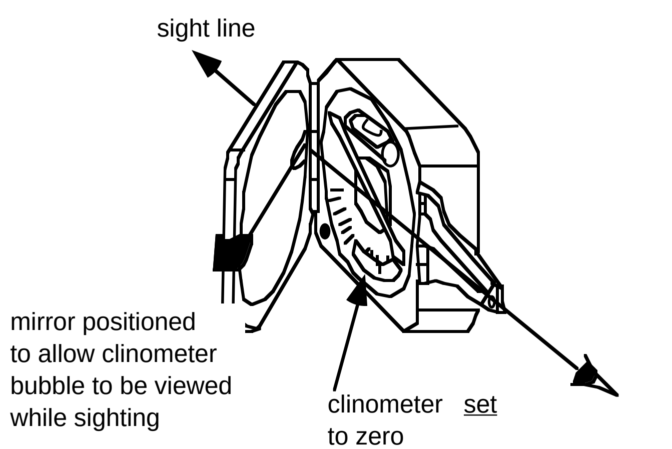


Figure 5: Sighting a horizontal line with the Brunton compass

b. set your clinometer at zero. Then, look through the peep sight of the compass, with the compass body vertical and the mirror positioned so that you can see the clinometer level (Fig. 5). Find the trace of the surface on which you are sighting in the peep-sight of the compass.

c. leaving the clinometer set at zero, move your sight line up and down the trace upon which you are sighting until the bubble in the clinometer level is centered. Note the exact spot that you see in the peep-sight when the compass is leveled, identifying a distinctive plant, fracture, or any other kind of minor landmark; if nothing else, your field partner can walk over and mark the spot.

This landmark you have just identified lies at precisely the same elevation as your eyes and also lies within the bedding plane. The line that connects your eyes to that landmark is therefore a strike line!

d. sight a compass bearing on your landmark: this is the strike direction.

e. hold the compass at arm’s length, with its face toward you, so that the plane of the compass body is vertical. While continuing to sight with your eyes on your landmark, rotate the compass until its sighting axis is parallel to the trace of the bed on which you are sighting.

f. level the bubble in the clinometer and read the dip.

Bearing and Plunge

The orientation of any linear geologic structure is specified by its bearing and plunge.

The ***BEARING*** is the compass direction or azimuth of the horizontal projection of the line of interest in the DOWNWARD direction. There is no ambiguity as with strike direction; bearing is always specified in the downward direction.

The ***PLUNGE*** is the angle between the horizontal and the line of interest, i.e., the angle between the line and its horizontal projection.

Methods of measuring bearing and plunge: In some cases, a linear structure is exposed well enough that it can be directly measured in a manner analogous to procedure A for strike and dip. Examples of this situation include flutes or parting lineation on bedding surfaces, slickenlines on a fault plane, and crenulations on a foliation surface. The procedure for measuring linear structures of this kind is as follows:

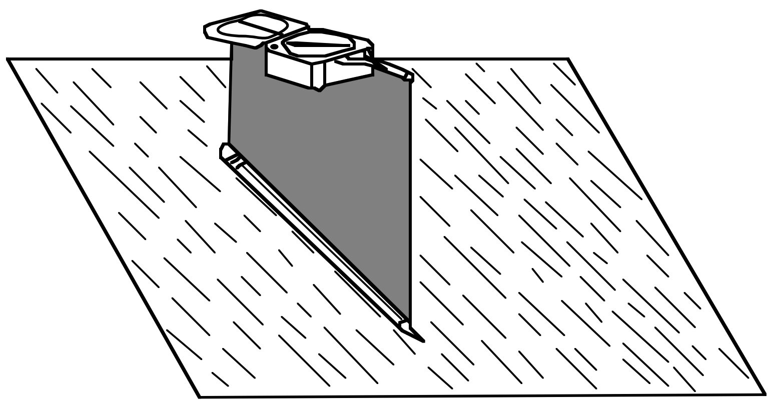


Figure 2-6: Measuring the bearing of a lineation

1) Stand above the exposure so that you are looking straight down on the lineation.

2) Holding your compass level, align the sighting axis of the compass with the lineation (Fig. 6). Often, linear elements define a reasonably unique direction but are not individually perfectly parallel. Your eye can be confused by these slight discordances. You can clear up this problem by laying a pencil on the surface and aligning it visually with the average direction, sighting on the pencil for your bearing.

3) Read the bearing from the compass, and record it in your notebook. Similar notation options exist for linear structures as planar structures:

a) You measure the angle between the bearing, the direction in which the line goes DOWN in ELEVATION and either due north or south, whichever is closer. Thus the bearing of a line plunging to the northeast would be recorded N45E, while a line plunging to the southeast is S45E.

b) Alternatively, you can record the direction of plunge bearing in 360 coordinates; note that there is no ambiguity here, because the bearing is always given in the downward direction.

4) Measure the plunge as you would measure a dip, aligning the compass directly with the lineation.

5) Record the plunge. Because there is no ambiguity of plunge direction, only the amount is recorded. A further precaution often taken to distinguish measurements of

lineations from those of planar structures is to write the plunge first, e.g., (45, N67E) would refer to a line plunging 45 degrees toward N67E).

A related method is used for linear structures which cannot be measured directly but for which it is possible to visualize the orientation in space nonetheless. This is especially common with fold hinges. In this case, align a pencil with the direction of the fold axis. Be sure to look at its orientation from the top and sides to be certain it is correctly aligned. Then measure the bearing and plunge of the pencil directly as described above.

Planning a traverse

Up to this point, the discussion has focused on what to do at an outcrop. However, the practice of field geology more usually involves examining areas of many square kilometers, commonly in a limited amount of time. Under these circumstances it is impossible for a geologist to examine every outcrop. Similarly, in an area of good exposure (which is true for many areas you will map in this course), it may take too much time to examine every outcrop. Therefore, some planning and consideration must go into deciding which outcrops you will visit.

It is important to maintain a balance between adhering to a planned traverse designed to address a specific geologic problem and making digressions to follow up significant and unexpected observations along the way. Any relationship which may make the planned traverse pointless needs to be followed up immediately. For example, if you start to measure a stratigraphic section and discover that the "section" contains a thrust fault, you might as well abandon the planned traverse and examine the relationships of the thrust; or, alternatively, you could measure thicknesses above and below the thrust, keeping in mind the limitations on the use of the resulting thicknesses.

You can use two basic kinds of traverses to cover the map area: 1) cross-strike traverses, where you walk transverse to the contacts, and 2) along-strike traverses, where you follow a contact, fault, or other key horizon. Both are necessary parts of the mapping process; the proportions you use depends on a variety of factors, including the structural style and complexity of the area, the specific objectives of the study, and the amount of time available.

<u>Cross-strike</u> <u>traverses</u>: Traversing across the strike gives the most general and specific information about an area in the shortest time:

1) The sequence and thicknesses of stratigraphic formations, and the locations and characteristics of their contacts;

2) The dip of the units and variations of the dip;

3) Structural repetitions or omissions in the stratigraphic section due to faults oriented parallel to the strike or unconformities;

4) The location of folds.

In a general way, a cross-strike traverse gives a good cross-sectional view of the geology, only limited by the fact that you have looked at the geology along but a single line. They do require, however, that you be comfortable with the stratigraphy of the region.

<u>Along-strike</u> <u>traverses</u>: Traverses along the strike are used generally as a supplement to cross-strike traverses, particularly in order to work out structural problems defined by previous cross-strike traverses. In most cases, along-strike traverses will involve walking out the surface trace of a particular contact or key marker-horizon. The primary objectives are to locate cross-strike faults, or trace out the geometry of folds. Also, it is often necessary to walk out the trace of a fault, dike, or other feature which is discordant with the stratigraphic units, in order to determine its extent. In the case of faults, the surface separation of stratigraphic units is critical as well. In areas of locally variable sedimentary facies, traverses along the strike may be important to working out the depositional patterns of stratigraphic units. In volcanic rocks, facies changes can be extreme over short distances, so mapping along strike becomes imperative.

Important information regarding the three-dimensional form of folds can be gained by working parallel to the regional strike, using what is called the <u>down-plunge</u> <u>method</u>.

Down-plunge method is based on the observation that, if a fold plunges, the map is a distorted (inclined, not strike-perpendicular) cross-section. Thus, by working along the strike, important changes of the structure with depth can be recognized.

A good deal of time can be squandered by painstakingly (and, perhaps, a little unimaginatively) walking every stratigraphic contact, back-and-forth, across the field area. This is a common error of neophyte field geologists. How then to decide which contact to walk? Distinct and easily recognized contacts are the best to follow. "Distinct" not just in the few outcrops that might happen to expose that contact, but distinct in the terrain you are mapping in. Some very subtle contacts in outcrop are well-displayed by differential weathering, by soil color changes, even by vegetation patterns. In contrast, some very clean and sharp contacts on a fresh surface (as between two carbonates of differing cementation or color) may be unrecognizable on weathered slopes. Finally, the overall structural complexity of the area should guide your decision as to which or how many contacts to walk out. Again, experience is the great teacher and you are here to gain that.

Filling In the Map: A planned traverse may include working both across and along strike. Another important consideration is filling in the map. Rarely, if ever, will you have unlimited time to complete a map, so you must budget your time accordingly. Thus, a systematic mapping plan needs to take into account the actual area to be covered. Such a plan typically will involve early cross-strike traverses to locate contacts, later along-strike traverses to connect the contacts located on the cross-strike traverses, and then detailed examination of critical problem areas to finish up.

Sky Mapping: "Sky mapping" refers to mapping the geology of the area surrounding you, on the basis of what you can see from a distance.

Unrestricted sky-mapping is obviously not recommended, but the distant view is nonetheless a vital part of the process of geologic mapping. Often there are relationships which cannot be recognized except from a distance. It is commonly difficult to "see the forest for the trees" when you have your nose on the outcrop. Also, sky mapping, constrained by firsthand knowledge of the rocks at which you are looking from a distance, can substantially expand the area you can cover without sacrificing accuracy. However, until you have a clear idea of the character of the geology of an area, it is best to err on the side of caution. Try to check by direct outcrop observation what you infer from a distance.

Plan to visit the best high vantage-point in the study area after you have spent part of the first day familiarizing yourself with the general character of the rocks and the kind of exposures you will be mapping. This will give you an overall feel for the amount of ground you have to cover, an idea of what access routes are available, and an excellent opportunity to plan systematically what your method of attacking the area will be.

Broadly speaking, you should record and make use of all the information available to you at all times. Wherever you are in the field area, look around you at all distances and scales: try to fit what you see in the outcrop in front of you together with what you see on the other side of the gully, on the ridge beyond, and the mountainside behind you. Be particularly aware of anomalies that appear at a distance: ledges of resistant units that end abruptly on a hillside or which are not concordant with adjacent ledges, valleys which take abrupt turns or which are unusually straight, and springs or boggy ground not in major valley-bottoms. These may be signs of a fault. Note them on your map and in your field notebook; plan to visit them later.

Time of Day: A final consideration in traverse-planning may be the orientation of the lighting of the outcrops. This is especially important if you are doing any sky-mapping, because a backlit slope may be totally indecipherable from a distance, whereas if the lighting were behind you it would be obvious what the geological relationships are. Therefore, we suggest that, whenever possible, you try to plan traverses so that you are looking at east-facing slopes in the morning and west-facing slopes in the afternoon. This has the disadvantage that shade may be hard to find at times, but it is more than compensated (or so we presume) by the greater efficiency with which you will be able to do the geology.

Some final homilies

TIME IN THE FIELD IS ALWAYS PRECIOUS; THEREFORE, AVOID VISITING OUTCROPS TWICE.

Try to gather all the data you will need from an outcrop, or an area, before moving on. It is a serious mistake to think that "you can always go back and check that outcrop again".

EXPECT TO BE CONFUSED AT THE BEGINNING OF A PROJECT (<u>EACH</u> <u>PROJECT!</u>); WE ALL ARE.

However, you do not need to understand the geology in order to describe what you see, or place contacts and bedding attitudes on the map. Record the data as you collect it; think about the interpretation as you go, but do not let confusion prevent you from covering the ground and making a map. Be confident that the geological picture will emerge and that you will be able to interpret and understand that picture

---

IF YOU FAIL TO PUT THE DATA ON PAPER, YOU MAY NEVER FIGURE IT OUT!

PLAN YOUR TRAVERSES TO TIE INTO EACH OTHER WITHOUT LEAVING HOLES IN YOUR MAP.

Walking for hours all over an area on your last day in the field, filling in holes left by poor planning is a waste of precious time.

MAKING THE MAP: FIELD TECHNIQUES

Introduction

One of the most difficult steps for a beginning field geology student is to start placing data on the map. This seems partly a lack of confidence in your own "inexpert" observations and is partly due to not having routine procedures for recording the data. Both problems can be solved with experience. However, acquainting you with some standard conventions used by field geologists in making a map in the field will help as well.

A GEOLOGIC MAP IS MADE WHILE YOU ARE IN THE FIELD, NOT BACK IN CAMP. RECORD THE POSITIONS OF CONTACTS, ATTITUDES, SAMPLES, AND ANY OTHER RELEVANT INFORMATION <u>WHILE</u> <u>YOU</u> <u>ARE</u> <u>ON</u> <u>THE</u> <u>OUTCROP</u>.

The purpose and procedures of "office work" in the evening after the day in the field will be discussed later; the techniques described in this section refer mainly to what you do while in the field.

Representation of contacts

A principal goal in geologic mapping is showing the locations of contacts between different rock units on the map. In fact, a geologic map ought to be an accurate representation of the contacts and map units. It is important to remember that a MAP unit need not be precisely equivalent to a LITHOLOGIC unit. For example, there may be a brecciated zone within a formation; it would be a perfectly valid (and probably wise) approach to map the contact between the unbroken and brecciated parts of that formation. On the other hand, you may be working with a complicated intrusive body where the lithology changes from diorite to granite over very short distances. If you are not mapping in great detail, you may want to "lump" the various intrusive lithologies into a single map unit.

Many different types of contacts can be distinguished on geological grounds: conformable and unconformable stratigraphic contacts, intrusive contacts, fault contacts, hydrothermal alteration zones, and so forth. Not all of these are distinguished by different standard geological symbols; the stratigraphic column accompanying your final map will contain some of this information. The main distinctions on your field map will relate to:

1) whether a contact is faulted or "primary," i.e., not a fault contact; and
2) how precisely you have located the contact in the field.

Primary vs. Fault Contacts: A primary contact is represented on the map by a thin, single, unadorned pencil line. Stratigraphic and intrusive contacts are not distinguished, although the distinction should be made in your notes, and will be clear in the stratigraphic column accompanying your map. If a contact may be faulted, note this in some informal fashion, and proceed to find out whether it is faulted or not.

A fault contact is represented by a somewhat heavier pencil line (but keep it as thin as possible while still distinguishable from a primary contact). You may add symbols to the fault trace to indicate the following types of information: dip of the fault (by direct measurement with your compass of a fault surface), slickenline directions, or slip sense and direction. In the case of thrust faults, barbs indicating the hanging wall should be added. Figure 7 illustrates a set of symbols to be used for this purpose.

Exposed, Approximate, Inferred, Concealed and Queried Contacts: If the earth had no soil, vegetation, or alluvial cover on the bedrock, this section would be unnecessary. Fortunately (from a cultural viewpoint), these hindrances are present to obscure the geological relationships you are generally trying to determine in geologic mapping. The result is that you cannot locate all contacts with equal precision and confidence. It is extremely important that the degree of confidence you can place in the location of any particular contact be clearly expressed. For example, if it is known in a mining district that ore deposits occur along the contacts between granitic plutons and limestones, exploratory drilling plans will be strongly affected by how precisely such contacts have been located in the field.

The following four types of contacts are drawn on the basis of the kind and quality of information used to locate the contact: exposed, inferred or approximate, concealed, and queried. The same usages apply to primary or fault contacts; the only difference on the map is the weight of the line.

1. Exposed Contacts

Exposed contacts are represented with a solid line. If this usage were rigorous, only contacts where you could actually put your finger on the precise spot would be shown in this fashion, which would make solid lines on geologic maps extremely rare. A more convenient operational criterion for a solid line is that the contact can be located within the precision that you can map it, which as noted previously depends on the width of your pencil line; it also depends on the scale of your map. For example, if you are mapping at 1:24,000 (USGS 7.5-minute quadrangle scale) and your pencil line in 0.3 mm wide, your pencil line corresponds to a line 7.2 meters wide on the ground. Thus, locating the contact to within less than 7.2 meters (about 25 feet) would be adequate to justify a solid line.

2. Approximate or Inferred Contacts

If you cannot locate a contact as precisely as you can plot it, and are not mapping the material that is concealing the contact as a separate stratigraphic unit, then you represent the position of the contact with a dashed line (———). This refers to an approximate or inferred contact; you have inferred from the outcrops that a contact must occur between here and there, but exposures are not adequate to locate it more precisely. A contact that is virtually always dashed is the contact between bedrock and younger alluvium (about which more anon). The alluvium generally "feathers out" against the bedrock, with vegetation and soil covering the bedrock surface, so the precise position of the contact is somewhat arbitrary.

It is common for beginning mapping students to dash too few of their contacts. There is no shame in admitting that the exposures do not allow you to locate a contact more precisely, and you should be scrupulously honest about this. On the other hand, you should work hard to locate precisely as many contacts as possible.

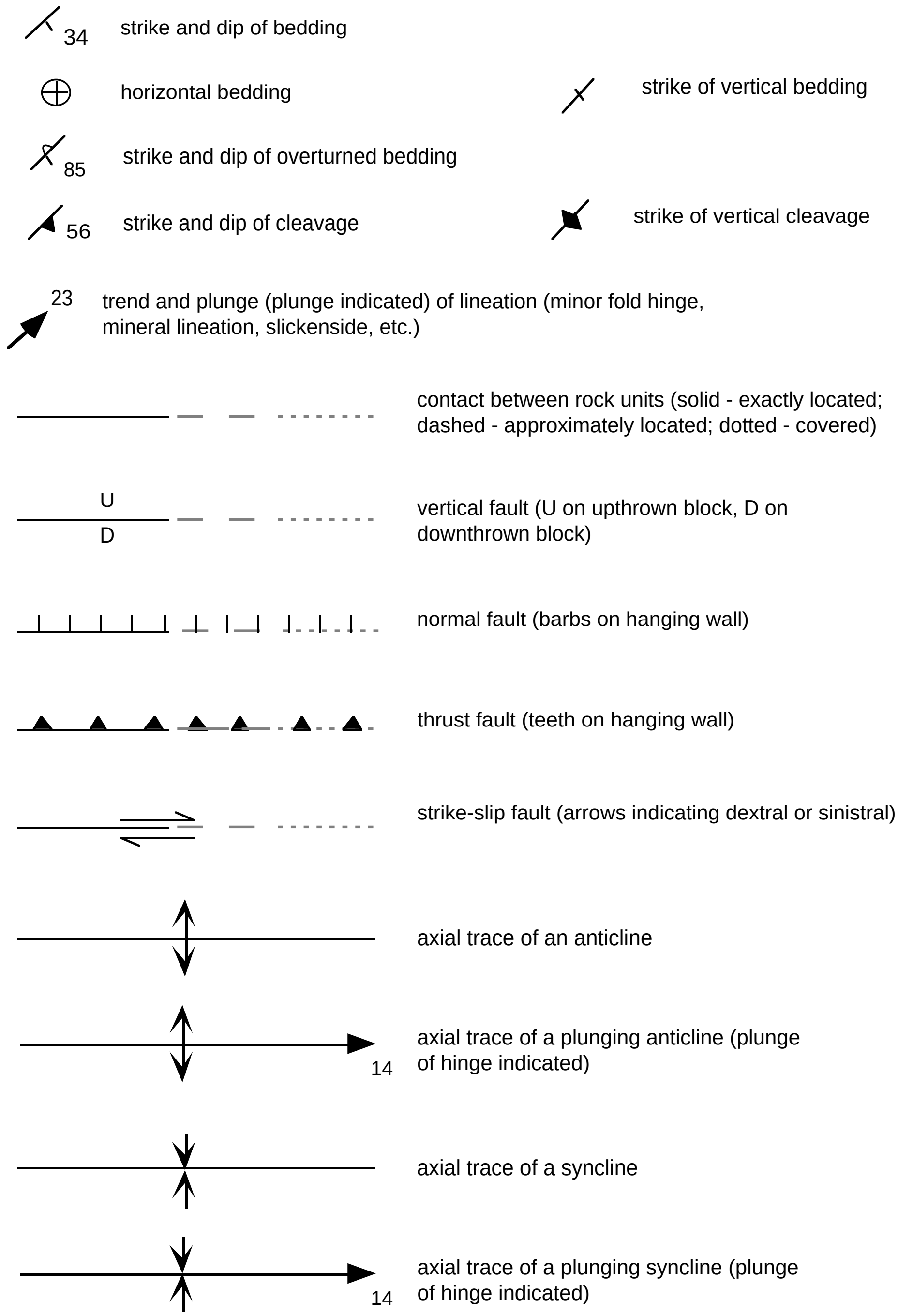


Figure 7: Structural and rock contact symbols for geological maps

3. Concealed Contacts

Often you will find situations in which one map unit conceals the contact between two others. The most common example is when Quaternary alluvial deposits overlap the contact between two bedrock map units. More generally, any unconformity may yield relationships of this kind. If you believe that you can infer the position of the concealed contact, and especially if you believe you can connect the same contact from one side to the other of an alluviated valley, you use a dotted line (...........). This indicates that the contact being represented is concealed by another unit which appears in the stratigraphic column of the map. This is not the same as a dashed contact, where the covering material is not shown on the map.

Dotted contacts are only commonly used for faults, partly just to avoid cluttering the map with dotted lines. However, primary contacts may be dotted when the relationships across an alluvium-covered area are not clear from the map, and there are important interpretive differences between alternate ways of connecting the contacts. However, in this case, the dotted line should be drawn only if you have good reason for making that particular connection.

4. Queried Contacts

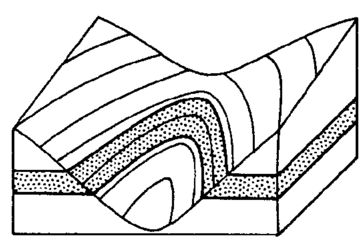
As noted, your field notes should include a certain amount of surmise and educated guessing. Similarly, it may be very useful to include on your map some educated guesses at connections you are not able to demonstrate with data. For example, you may think that faults on both sides of an alluviated valley are, in fact, the same fault. However, without subsurface data, you probably will not be able to prove this relationship; nonetheless, this would be a useful inference to record on the map.

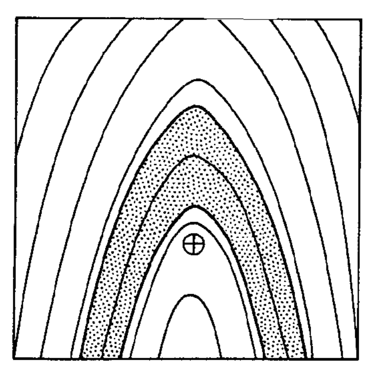
However, educated guesses must be carefully distinguished from demonstrable relationships. Thus, any contacts which are only guesses should be queried; that is, they should be drawn as dotted or dashed lines (depending on whether the contact is concealed or merely obscured by surficial deposits), interrupted by question marks (—?—?—, or ..?..?..). This is standard usage on your field map (liberally!) and final map when further field work has not allowed you to solve the problem.

Drawing contacts between outcrops

Most of the contacts on your map should be drawn in the field and should be based on well-located observations. Inevitably there are places in your field area where you cannot walk a contact or the contact is not exposed. In these instances you must extrapolate contacts between outcrops.

If the surface of the earth were perfectly smooth this wouldn't be a problem - contacts would simply continue as straight lines. But in a world with hills and valleys, the map pattern of a contact depends on the topography and the orientation of the contact. The relationship between the map pattern of a contact, the orientation of a contact, and topography is explained by the Rule of Vs.



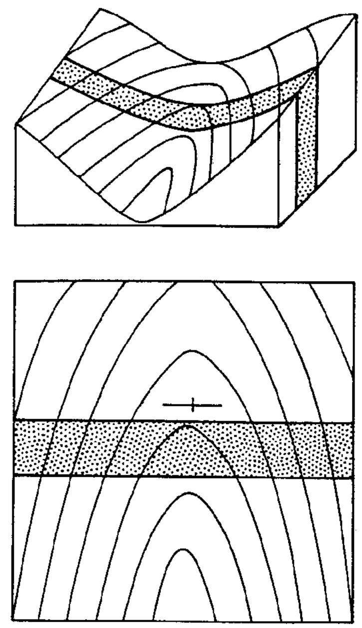


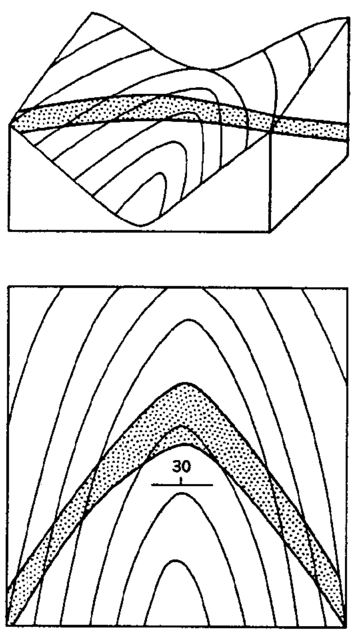
Horizontal contacts (dip=0°)

Topographic contour lines connect points of equal elevation and are therefore horizontal lines. The trace of a horizontal contact must be parallel to the topographic contours.

Vertical contacts (dip=90°)

The map pattern of a vertical contact is a straight line parallel to the strike of the contact. Topography has no control on the map pattern of a vertical contact.





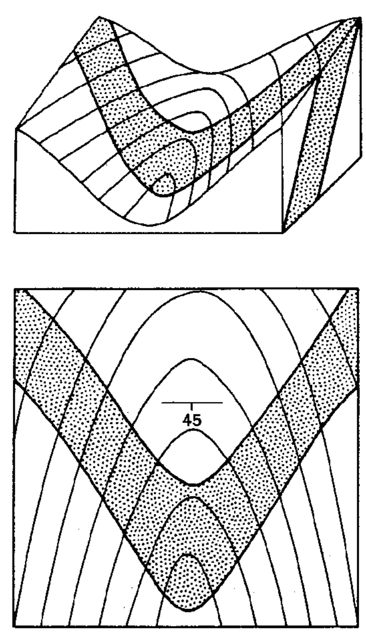
Contacts which dip upstream

The contact will make a "V"-shaped pattern as it crosses the stream valley (hence the Rule of Vs!). The point of the "V" will be pointing upstream and the steeper the dip, the shorter the "V". If the stream valley is bounded by ridges the contact will also make a "V" as it crosses the ridges except the "V" will point downstream on the ridges.

Contacts which dip downstream

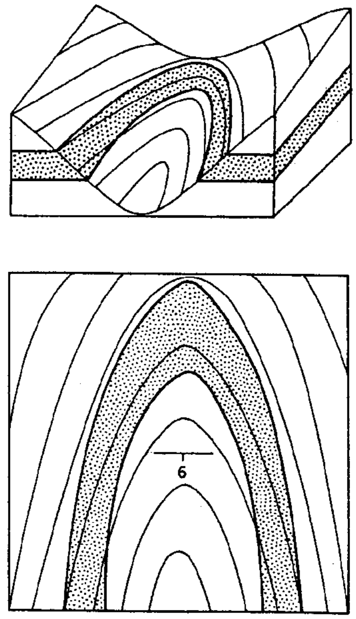
Case 1: Contact dips more steeply than the stream gradient

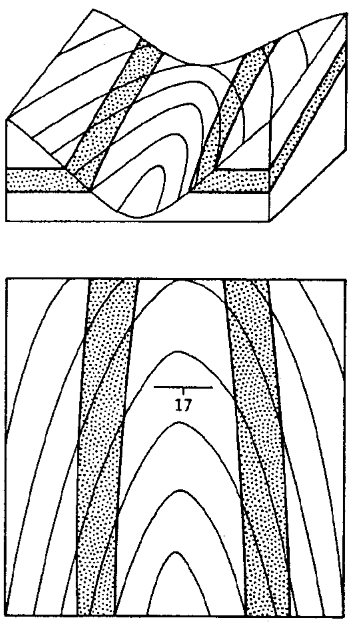
The contact will make a "V" which points downstream as it crosses the stream valley. Again, the steeper the dip, the shorter the "V".



Case 2: Contact dips less steeply than the stream gradient

The contact will make a "V" which points upstream as it crosses the stream valley. In this case, the steeper the dip, the longer the "V".





Case 3: Contact dips the same as the stream gradient

In the unusual case of a contact dipping the same as a stream gradient, the contact won't cross the stream valley.

Checking map patterns using the strike measurement

You can check to see if the contact you have drawn is consistent with the measured strike and dip. Remember, the strike line of a contact is a horizontal line. If the contact crosses the same topographic contour at two different points, the line connecting those points is a horizontal line and should be parallel to the measured strike.

Mapping alluvium

In geologic mapping, the emphasis placed on any particular geologic unit depends on the objectives of the project. A study of Quaternary glacial deposits will tend to treat all bedrock as undifferentiated "basement," even if some of the "basement" is scarcely lithified. On the other hand, a study of Precambrian metamorphic rocks in Minnesota where periglacial deposits cover much of the bedrock, may lump into "undifferentiated glacial deposits" the units that geologists have spent their entire careers studying. In other words, "one geologist's basement is another geologist's overburden". In any study, however, it is important to show as much as possible the actual distribution of the materials you are emphasizing on the map. This often means mapping the obscuring cover as a separate stratigraphic unit.

The usual procedure in regional geologic mapping of bedrock lithologies is to show Quaternary deposits as a separate map unit wherever they are extensive enough to show conveniently. This will commonly mean neglecting the surficial soil and slope deposits which often partially obscure the outcrops on valley walls and ridge crests. This is the usual style of USGS quadrangle maps, for example.

Blob mapping

Most geologic rock bodies take the form of layers. This not only includes sedimentary and volcanic rocks, which are actually deposited as layers at the surface, but also many intrusive forms as well, including dikes, sills, laccoliths and lopoliths. When these rock bodies are metamorphosed, a layer-like form is retained and may be enhanced by strain. However, plutons commonly have non-tabular forms.

A rock layer crops out as a linear or curvilinear band on a map. This band may curve either due to folding or due to intersection with topography, and it may be disrupted by faults. Nonetheless, the only case where the band-like outcrop pattern will not be expected is when an erosional remnant of a flat-lying layer is perched on top of a hill. In virtually any other situation, rock layers will crop out as continuous bands unless interrupted by faults.

It is common for beginning mapping students to show rounded blobs of various formations on their maps, having drawn contacts around areas where they saw outcrops of a particular unit. Except in certain special cases like the erosional remnant mentioned above, this is in direct conflict with what we know about the form of geologic bodies, and therefore is almost certain to be erroneous; usually, the layers prove either to be continuous along the strike but less well-exposed, or even have been truncated by a fault. In the latter case, the fault should be mapped as another more-or-less straight-line feature which truncates the stratigraphic units.

Keep in mind that the outcrop pattern shown on your map should make geological sense, in terms of logical geometrical forms for the rock units and relationships between structures.

Dikes, sills, and marker beds

Rock layers which are significant to your interpretation will sometimes be inconveniently thin. In particular, dikes and sills are often only a few meters thick. This means that, if your pencil line is equivalent to a several meters on the map, a single line is wider than the thickness of the feature you want to show. A usual way of dealing with this is to show such thin rock bodies as a single line, overlaid with “x” marks, “o’s” or some other similar symbol to allow you to distinguish these lines from contacts or faults (Fig. 7).

When you are making along-strike traverses to locate faults, it is often useful to follow a single thin, but distinctive sedimentary layer. Such a layer is referred to as a “key bed” or “marker bed”. This technique gives you the ability to locate faults which are difficult to find if you are only mapping formation contacts, because your resolution becomes equal to or even less than the thickness of your key bed. With a marker bed 2 m thick, you can locate any fault with separation as small as 2 m. Marker beds should be shown on the map in a manner similar to that described above for dikes and sills, that is, with a single ornamented line.

Structural symbols

We have previously described techniques for measuring structural attitudes. When you have made a measurement and recorded it in your field notebook, it should be plotted on the map <u>immediately</u> (i.e., NOT back at camp in the evening). Plotting the measurements while in the field is important for at least three reasons:

1) it prevents any possible later confusion about the location at which the measurement was made;

2) it gives you indispensable help in visualizing the expected surface continuation of a rock unit or structure (i.e., where would you expect to see the same rocks on the next hill) by comparing the plotted attitude with the topography. This is particularly important because you may be unable to locate folds and faults unless you have a clear understanding of what the outcrop pattern should be were it not affected by later structures; and

3) it allows changes in dip to be quickly recognized and helps you to organize your thinking about the geological significance (e.g., the presence of a fold or fault) of changes in dip.

Symbols for various types of structural features you should measure (i.e., bedding, cleavage, faults, etc.) are given in Figure 7. The strike and dip symbol is plotted so that the point of intersection of the strike line with the tick mark, barb, or other ornament corresponds to the exact location on the map where the measurement was made.

The number of structural attitudes to plot on a geologic map is dependent on the structure. Beginning students almost never make as many measurements as they should; if you are not certain whether you should stop and measure bedding, do it. The goal is to have enough data to draw a cross-section, in any direction and to have enough measurements along the line of section for reasonable accuracy. In reality, there are often not enough outcrops to achieve this result, but you should strive to come as close as you can. Plot enough structural data to clearly define each structure.

If we give you a line along which to do a cross-section (as we will often do, especially early in the course), it is wise to accumulate enough structural data along that line to be able to draw a reasonable geologic cross-section.

Folds

The two principal structures you must map are faults and folds. Folds may sometimes be directly observed from a distance in the field (see under "Sky Mapping), but more often are recognized by a change in dip or by the outcrop pattern of layers. We will assume you know enough about structural geology to be able to recognize a fold in this way. Topography is also useful at times. The focus here is on the use of symbols to represent folds on the map.

Folds are generally represented on the map by the trace of the axial surface. The axial surface is the planar or curviplanar surface which includes the line of sharpest curvature of each layer affected by the fold. Practically speaking, you can locate the fold axial-surface trace by a "connect the dots" procedure: locate the point on the map along each folded contact where the curvature is greatest, and draw a line through these points. The appropriate symbol for the type of fold, i.e., anticline and syncline, should be placed on your axial-surface trace (Figure 7)[5]. Do not forget to show the plunge of the fold if it can be determined; remember that the plunge will not be parallel to the axial-surface trace of a fold with an inclined axial surface, so the plunge arrow will point away from the axial-surface trace in this particular case.

Make certain that your representation of the folds makes sense. This may seem obvious, but it is not trivial. In general, two synclines will have an anticline between them, and vice versa. The axial-surface trace separates the limbs of the fold from each other, so the dips on each side should more or less go together and be distinct from those on the other side of the axial-surface trace. If this is not the case, you need to reconsider either the location or orientation (or both) you have chosen for the axial-surface trace.

MAKING THE MAP: OFFICE TECHNIQUES

Introduction

Collection of field data, while important, is only the first step in the geological study of a field area. Much of the thinking and interpretation goes on back in camp, long after you have left the field. However, the more thinking you can accomplish during the field work, the better. Ideas can be followed up immediately, and you are able to use your time

[5] The hinge line of a monocline is a special case. Rather than being the line connecting the points of sharpest curvature, it connects the inflection point where the dips on the limb begin to become less steep.

far more effectively if you have figured out precisely what you should search for and where. In order to do a good job, both in this course and in the future, you will need to spend a significant amount of your time in the evenings going over the day's mapping and planning the next day's traverse.

After the last day's mapping, it is time to report on what you have done. The map is the foremost ingredient of any report on a mapping project.

What to do back at camp in the evening

Before you crack open a beer (or at least too many for you to hold a steady pen), ink in what you consider to be reliable mapping, using a technical drawing pen. Do not ink lines which are dashed or queried unless you have finished working on those areas. Recommended pen sizes are 00 for primary contacts and strikes and dips and 0 or 1 for faults. It is best to use pen points at least two sizes apart to clearly distinguish faults and primary contacts. You have good reasons for inking-in your field map on a daily basis:

1) It prevents hard-earned contacts and bedding measurements from being accidentally erased or rubbed off by a sweaty palm.

2) It takes you back over the ground you have covered; the first step in planning your next day's traverse. See what is left to do and consider what connections you need to make and where and how you can make them.

3) It gives you a sense of completing part of your fieldwork. Mapping is like piecing together a puzzle; as each part of the area is finished, you have one more piece in place. Ink in what you have and move on!

Before inking your map, go back over your field notes; make certain everything is legible and clear. You may add comments to the day's observations, based on your ideas while inking the map. Then, with your map, notes, and your field partner, you should a) identify the foremost geologic questions remaining to be worked out in the area, b) settle on where you need to go to look for the relationships which will answer those questions, and c) decide on a practical plan of attack which will allow you to complete the remaining mapping. Keep in mind the time constraints, the size of the area, and the pointers in this manual regarding traverses.

Drafting your final map

Figure 8 is a sample map, showing the general format for a geologic map. You will probably find it useful simply for guidance in drawing your final map. However, certain points should be emphasized:

1. **Any geologic map should have the following**, neatly and prominently displayed, as shown in Figure 8:

a. bar scale and fractional scale

b. north arrow (true and magnetic; grid if applicable)

c. title, including clear geographic information needed to locate the map area. E.g., latitude and longitude, county and state, and/or township and range

d. explanation of lithologic units placed in correct stratigraphic order (that is, oldest at the bottom and youngest at the top), with a color scheme and lettered labels for different rock units, placed both on the map and in the stratigraphic column. The stratigraphic column should also indicate the ages of the units and any unconformities should be noted

e. legend with map symbols, such as contacts, faults, folds, etc.

2. Lay out the map in pencil before you start inking. Make certain that your letter sizes and pen widths will give a legible and attractive balance between the map itself, the stratigraphic column, the title, and the other explanatory material.

3. You will ordinarily be drafting your final map on either semitransparent drafting paper or Mylar® or on a clean copy of the topo map on which you did your field mapping. Draw lines in pencil first, then go over them in pen; it is very easy to trace the wrong line accidentally, with traumatic results even if you do have another piece of paper.

4. In addition to the geology, you should also show the following on the map (if not already present):

a. major drainages and peaks (for topographic reference)
b. section boundaries and numbers and township and range numbers

5. The following should be drawn **with a straight edge**:

a. boundaries of the field area
b. bar scale
c. pencil guidelines for lettered labels (to be erased after inking)
d. strike-and-dip symbols
e. boxes in the stratigraphic column

6. The following should never be drawn with a straight edge:

a. FAULTS - Only a fault which is perfectly planar (never happens) and perfectly vertical (also never happens) would have a truly straight trace on a map. Faults should be drawn to show the location and trace you determine by walking them out in the field.
b. CONTACTS - same as for faults
c. FOLD AXIAL-SURFACES - same as for contacts and faults

7. Use colored pencils. Your map will look better and be far more legible if you color lightly and stick to pastel colors. Standard color usages are as follows:

a. yellow for Quaternary alluvium (Qal)
b. red and orange for igneous rocks
c. other colors for sedimentary and metasedimentary rocks

We will ignore the standard USGS colors scheme for rocks of different ages. However, the faculty will recommend simple coloring schemes on field course projects. This makes map grading much easier on the staff.

Aside from the above traditional restrictions on use of red, orange, and yellow, if you choose your own color scheme, it is important to:

ACHIEVE GOOD CONTRAST BETWEEN ADJACENT ROCK UNITS SO THAT THE MAP IS LEGIBLE.

If you have a small number of colored pencils, go ahead and use red and orange for sedimentary units if it helps. It is far more important to make a readable map than to adhere to color conventions.

You will be pleasantly surprised with the professional appearance of your map if you take the time to be careful.

8. You will be graded on neatness and legibility. This will be direct (a map that looks shoddy will be graded accordingly), and indirect (if we can't figure out what you meant, we assume you did not know what you meant).

KEEP IN MIND THAT THE OBJECTIVE IS TO SHOW THE GEOLOGY OF THE AREA. STANDARD DRAFTING PROCEDURES AND NEAT AND LEGIBLE WORK CONTRIBUTE TO COMMUNICATE THE GEOLOGY TO OTHERS IN THE MOST EFFECTIVE MANNER.

A note on budgeting time

You will be turning in a final map for each project (although faculty have been known to collect maps in the field for grading or for photocopying in the evening; this diabolical practice is intended to reinforce by fear the practice of placing contacts, strikes and dips, and other information on your map in the field, as you go). This means that in most cases, you must come in from the field on the final mapping day and produce a drafted and colored map in six to twenty-four hours, depending on time and scheduling.

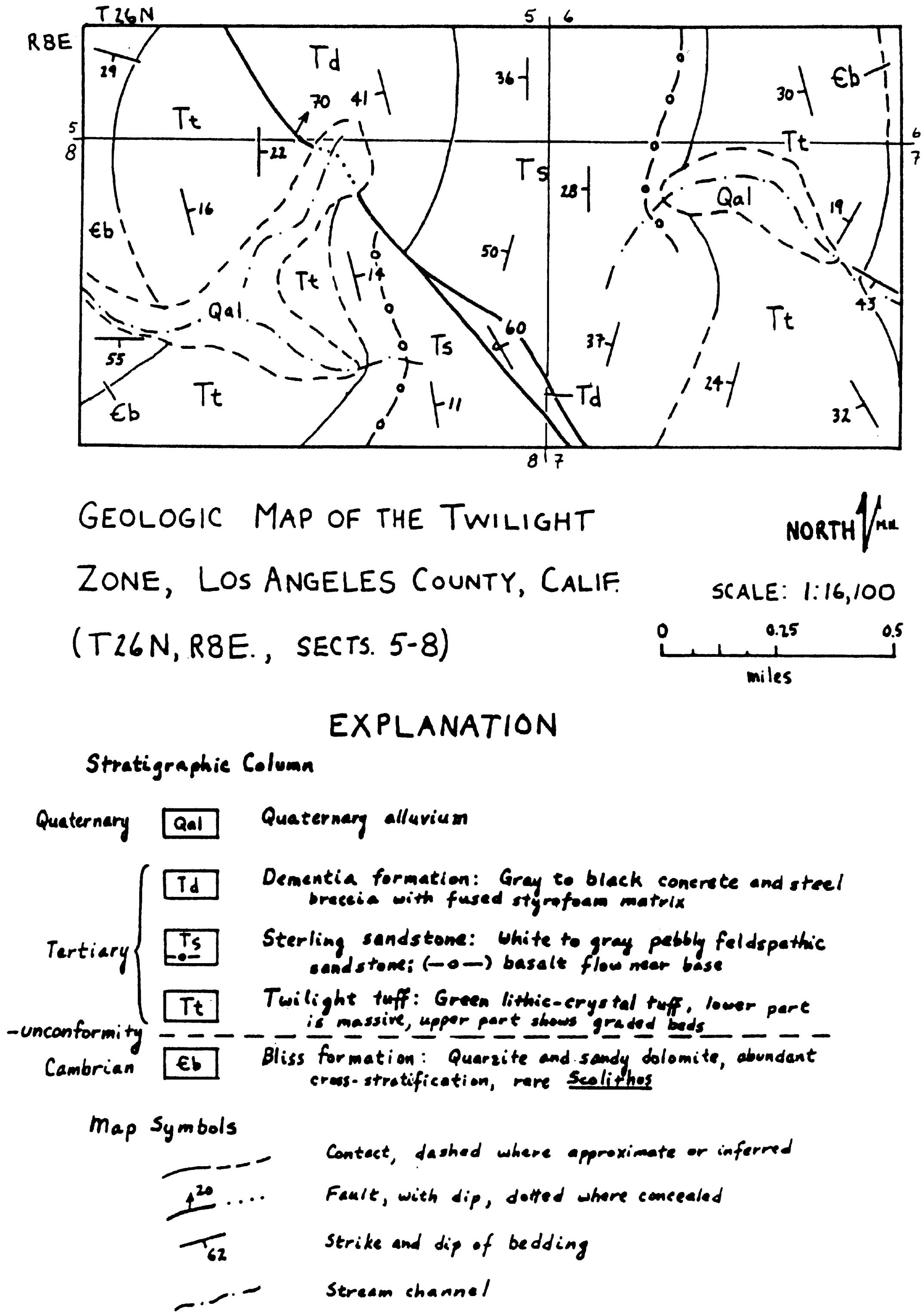


Figure 8: Sample map

You can do two or three critical things to reduce the final night panic and to allow you some deserved R&R. These are:

1. **Update your map every evening**. This way you will not have to spend long hours on the final night figuring out the geology and arguing with your field partner. This should have be done anyway to plan your next day's traverses and you will have a head start on your final map.

2. **Sketching out geologic cross-sections as soon as you have sufficient map coverage.** Students commonly wait until about 3 a.m. of the night before maps are due to start their cross-sections. Tired and sleepy, they are not at their critical best and realize too late that they should have gone to the top of that hill in the southeast corner of the map area after all.

3. **Get a final map sheet and ink significant parts of the legend, stratigraphic column, etc. long before the final night.** This way you avoid last minute routine drafting and can concentrate on the geology.

Use of drafting equipment

For most of you this will be the first time you have been asked to draft a publication-quality map. Here are some helpful pointers about the use of your drafting equipment.

There are many technical drawing pens available. Some are more dependable than others. You will only be using black ink. Of those on the market, a relatively new brand of drafting pens known as Ceramicron® are inexpensive and durable. They come in several sizes and one holder suffices. Many other inexpensive drafting pens have the disadvantage of soft tips which flatten with hard use.

A traditionally popular brand with geologists is Rapidograph®. These can be temperamental and considerable care must be taken in handling them. If you decide to use these pens, read the manufacturer's instructions that came with the pens, and follow them! Some particularly important points:

1) After filling the ink reservoir (a plastic cartridge in virtually all current models), shake the pen gently parallel to its length. You should be able to hear the plunger inside the point shaking back and forth. Mounted to this plunger is a cleaning needle which runs up inside the pen tip. Shaking the pen both helps shake the ink up into the point due to pumping action of the plunger, and helps to dislodge any dust or dried ink which may be in the tip. Thus, shaking the plunger back and forth in the point is the first remedy to attempt if the ink is not flowing well. N.B., a Tupperware® box is great for storing pens and other graphics weaponry.

DO NOT SHAKE THE PEN OVER YOUR NOTES, MAP, OR ANYTHING ELSE YOU WANT TO KEEP FREE OF INK BLOBS: OCCASIONALLY INK WILL BEGIN FLOWING SUDDENLY, RESULTING IN A LARGE DROP FALLING DIRECTLY ON YOUR MAP!

---

2) Keep a small scrap of drafting paper or Mylar next to your working map or diagram to test your pen's writing performance. Make sure that ink does not collect on the tip, as this will generate too wide a line. Write very lightly; pressure will not make the pen write better, and the tip may be bent or ruined.

3) The pen should be washed periodically. If you are using it daily (as you should be during the course), every 2-3 weeks is usually adequate. If you will not be using it for an extended period of time, wash and dry the pen thoroughly and store it empty of ink. When using the pen regularly so it contains ink, the following precautions will prevent clogging:

a. Screw the cap on firmly BUT NOT TOO HARD. The cap must be sealed airtight to prevent evaporation, but it cracks with ease and can be ruined by putting it on too tightly. Always put the cap on when not using the pen.

b. Store the pen upright with the point up. This prevents ink from pooling in the point. Keeping the point up is especially important if you set the pen down momentarily with the cap off (but try to avoid setting the pen down without the cap at any time).

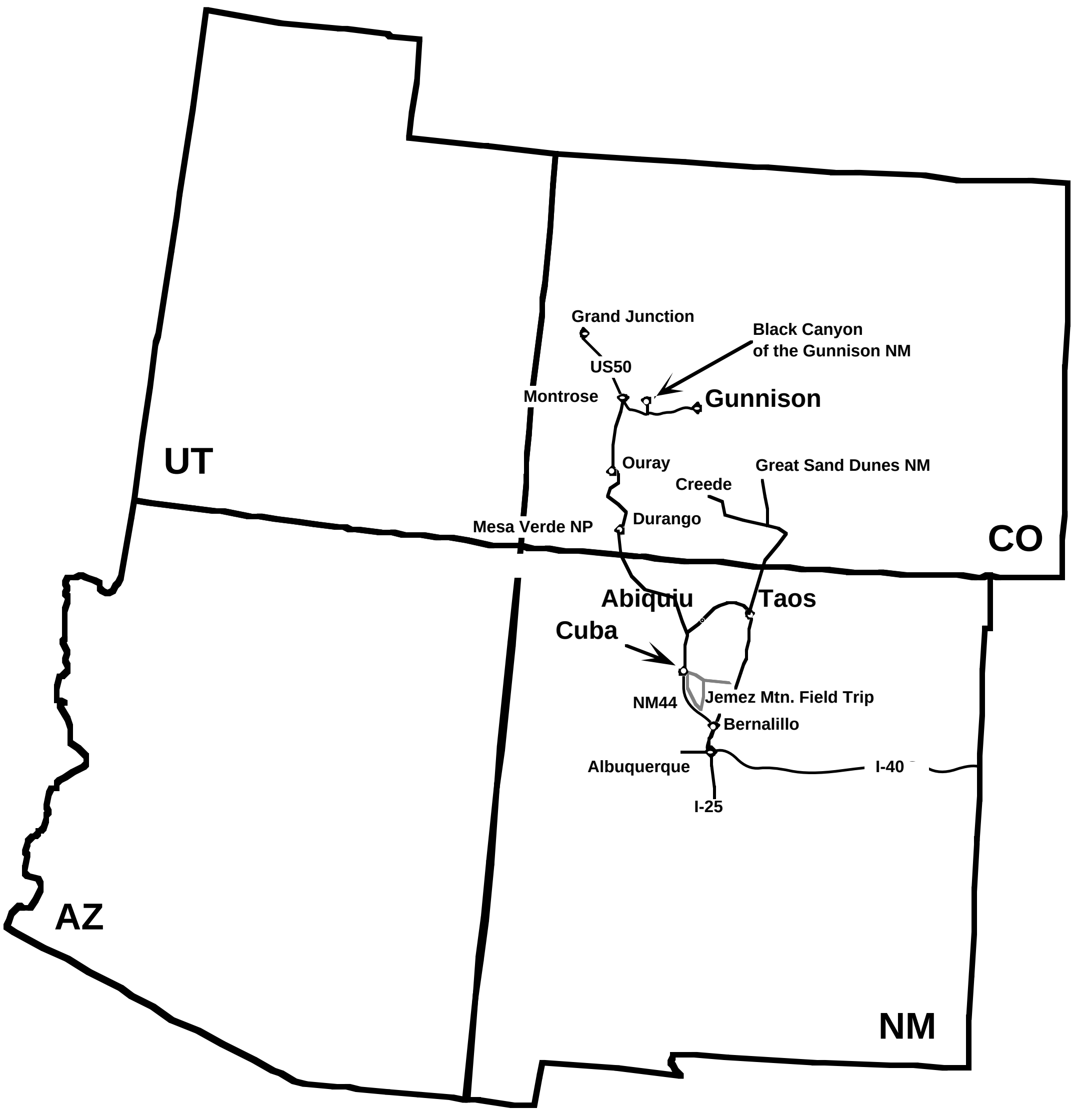
4) BE CAREFUL! Technical drawing pens are fragile and expensive. They can easily be ruined by dropping them, leaving them sitting on the dashboard of a truck in the sun, or a variety of other abuses. In addition, the finer points (000, 00, or 0) are harder to keep unclogged. Be particularly careful with these pens.

Straight edges and templates: You will be using a straight edge for a many purposes (see above), so some simple advice may help:

1) Most straight edges and templates are plastic, and you are going to be working in some dusty, gritty places. Even metal drafting equipment requires care under these circumstances; but plastic is particularly susceptible to damage. If the edge becomes cracked, chipped, pitted, or otherwise maimed, it will not be straight and is no longer useful. Plastic drafting tools warp if exposed to excessive heat, so do not leave them in the sun on the dashboard of a truck. In short, keep your drawing tools in a safe, protected place, preferably in a box or other protective container.

2) When using a straight edge or template with a pen, you must keep a significant space between the paper and the edge of the implement. Otherwise, capillary action will cause the ink to spread out under the implement, making a horrible mess. Some straight edges are beveled or have a cork base to prevent this problem. If your equipment is not manufactured this way, two or more strips of drafting tape on the underside of the implement will open a space between it and the paper.

2000 NC Universities Field Camp



Travel Days:

May 12-14:	**NC to Abiquiu, NM**
May 19:	**Abiquiu, NM to Taos, NM**
May 26-28	**Taos, NM to Cuba, NM via Great Sand Dunes, CO**
June 8-11:	**Cuba, NM to Gunnison, CO via Mesa Verde and Creede**
June 11-14:	**Prescott to Flagstaff**
	Flagstaff to Grand Canyon
	Grand Canyon to Mesa Verde, CO
	Mesa Verde to Gunnison, CO
June 23-25:	**Gunnison to NC**

Figure 9: 2000 Field Camp itinerary

CHAPTER 3 - REGIONAL GEOLOGY & FIELD TRIP NOTES

INTRODUCTION

The North Carolina Universities Field Course involves projects and field trips in the Four Corners Region (so-named for the common point where Colorado-New Mexico-Arizona-Utah meet, Fig. 9). The main objective of a field course is to teach the field methods that you will need in your geological career. A dividend is that we take you to a part of the world with classic geology. You will see a wealth of rock types, a spectacular record of tectonic events, and geomorphic features you likely have not seen before. If "the best geologist is the one who has seen the most rocks," then our field camp will not only teach you techniques, but will begin a lifetime of exposure to new rocks in new geological settings.

In that context, the course will be more meaningful if you do two things:

1. Always know where you are (who knows, you may want to come back again) and
2. Be aware of how local geology fits into the regional structure and history.

Thus, this section of the manual emphasizes the regional and local geological setting of places we visit. There will be synopses of the geological history and tectonics. We provide maps, cross-sections and stratigraphic columns. The text is built around our itinerary so you can follow your progress as we move about the region. Our goal is to present a broad overview of the regional geology, and to encourage a rewarding interest in the rich historical and cultural background of the region.

REGIONAL SETTING

Figure 10 shows the broad geologic provinces of the United States. What most people think of as the Rocky Mountains (i.e., Pikes Peak and the high country of Colorado) is but one small part of the western, North American Cordillera that extends from Alaska to Mexico to Central America.

In the course of our six weeks, we see that portion of the Cordillera that consists of the Western Interior Platform (including the Colorado Plateau, "C.P". in Fig. 10) where it is bordered by the Front Range of the Rockies on the east and by the Basin and Range on the south and west. We will see crystalline rocks as old as Archean and volcanic rocks as young as six or seven hundred years. Our project areas include sedimentary, volcanic, and metamorphic rocks, complex surficial deposits, and influent streams. We will have ample oppor-

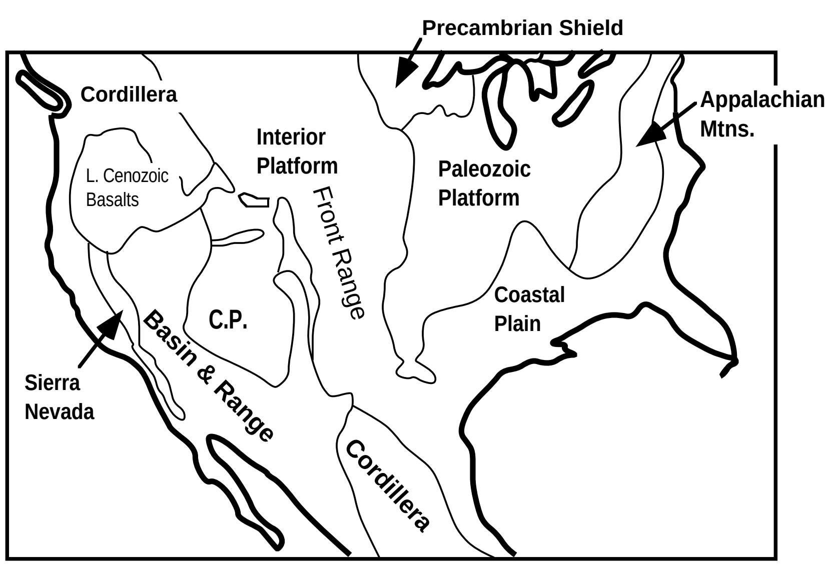


Figure 10: Physiographic provinces of southern North America

tunities for studying classic geologic localities such as the Grand Canyon, the Jemez Volcanic field, and the Black Canyon of the Gunnison.

We confine our studies to the states of New Mexico, Arizona, Utah, and Colorado (Fig. 9). Much of the terrain is semiarid, and we will see classic arid-land geomorphology. The influence of elevation and western- vs. eastern-facing slopes on rainfall, vegetation, and the perennial/intermittent nature of the rivers and streams will be apparent. You will see high mountainous areas that were glaciated during the Pleistocene.

We work in the drainage basins of the Rio Grande and Colorado Rivers (Fig. 11). The Rio Grande drains to the south and southeast and entering the Gulf of Mexico at Brownsville, Texas. The Colorado River drains west through the Grand Canyon and then south, forming the California-Arizona border before entering Mexico and ending in the now-desolate Colorado River delta lands at the north end of the Sea of Cortez. Our mapping areas near Cuba, NM, are in the drainage basin of the Rio Puerco which joins the Rio

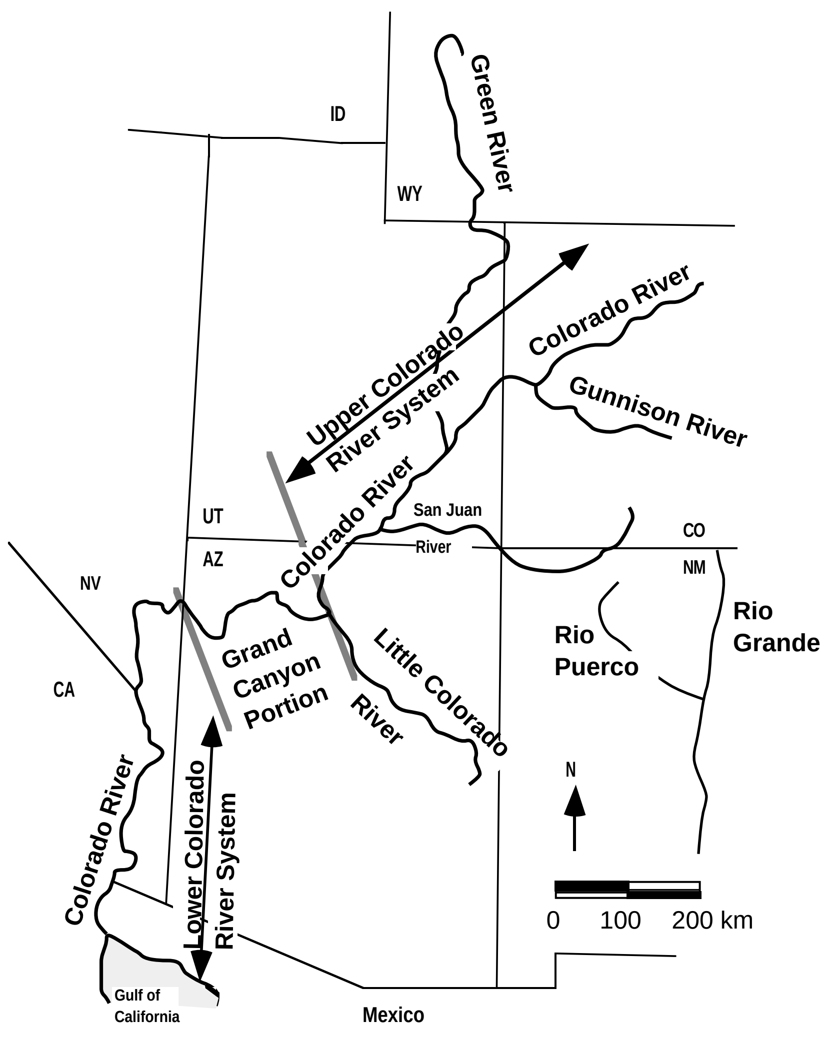


Figure 11: Colorado River drainage system

Grande north of Albuquerque. When we leave Cuba, we cross the continental divide into the Colorado River Basin and work there for the remainder of field camp.

This area is strongly influenced by the mixing of Spanish, Mexican, Pueblo, Navajo, and Anglo cultures. Native American settlements date to c400 A.D., the beginning of the Anasazi Period, and were followed by nearly 800 years of development, culminating in the wondrous cliff-dwellings at Mesa Verde.

Europeans first arrived in the area in 1539. Before the first Americans arrived by the

Santa Fe Trail in significant numbers (in the late 1820's and 1830's), a thriving Spanish/Mexican/Native American culture had been here for 200 over years. The more remote areas were explored in the 1870's and 1880's by geologic greats like John Wesley Powell, the one-armed Civil War veteran who twice ran the Colorado River in wooden boats, and G. K. Gilbert, still the finest writer of geological prose in the English language (excepting, perhaps, John McPhee).

The area is rich in important mineral resources. There has been extensive mining of copper, molybdenum, lead, and zinc, precious metals, uranium, and salt. Coal, oil, and natural gas are produced. Today, the area's economy is based on agriculture, forestry, mining, oil and gas, tourism, and outdoor recreation (skiing, river-rafting, boating, biking, hunting, and fishing).

Geologically this area is dominated by the Colorado Plateau (Fig. 12). The Colorado Plateau is a huge piece of real estate about 600 km on a side (about the size of Utah). The plateau is a mile-high, broad, arid tableland with isolated mesas and high cliffs where more resistant, flat-lying to shallowly dipping beds come to surface. The plateau is cut by spectacular canyons, suggestive of recent uplift, and, here and there, is pierced by diatremes and volcanic conduits. The surficial rocks are shallow marine and fluvio-deltaic sedimentary rocks ranging in age from Cretaceous and younger in the east to Permian in the west.

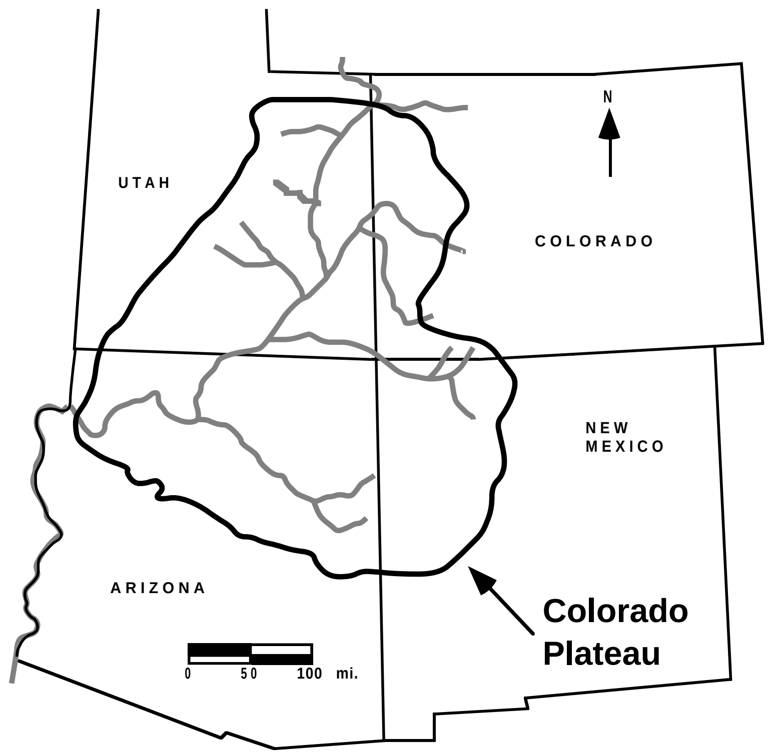


Figure 12: The Colorado Plateau

At the edges of the Plateau, the topography is considerably modified by extensive Cenozoic volcanism.

Imagine yourself progressing east to west across the Plateau. You descend a series of steps, each step representing a more resistant, older Mesozoic and finally upper Paleozoic rock formation. However, this is not just layer-cake geology. Within the sedimentary cover of the Plateau is a complex sedimentary and tectonic history — one of successive subsiding basins rimmed by uplifts throughout the late Proterozoic and the Phanerozoic. Structural complications are present, but subtle. Except at the margins of the Plateau, such structures are mostly limited to large, basement-rooted high-angle faults across which overlying sediments are draped into monoclines.

Along the margin of the Plateau, the transition to several major geological provinces — the Rocky Mountain Foreland in Colorado and the Basin and Range Province in central Arizona (Fig. 10) — will be the subject of much of our detailed mapping.

We now begin our regional overview in chronological sequence.

ENTERING NEW MEXICO

After two days of traveling from North Carolina we will finally get our first glimpse of the Rocky Mountains; but that will come later in the day. First we have to cross about half of New Mexico (Fig. 13). High points of the trip, for sure, have been crossing the Mississippi at Memphis (did you see the pyramid on Mud Island?), noting the buried Cadillacs in Oklahoma City (north side of I-40), and hoping to catch glimpses of the Helium Monument and billboards for 42 oz. steaks in Amarillo. Now is our time to focus on geology.

West from Amarillo in the Texas panhandle, we cross one of the most interesting hydrogeological regions in the southwest. The Spanish called this moderately high, incredibly flat country el Plano Estacado, "the staked plain," for reasons uncertain. This area and the high plains of eastern New Mexico, now called the Pecos Slope by geologists, support a thriving agricultural economy based on groundwater from the Miocene Ogallala Formation. This aquifer was first tapped about the turn-of-the-century, providing plentiful, deep artesian water to the town of Artesia, NM (the origin of its name should no longer be a mystery) about 120 miles south of Santa Rosa. Not until many years later after artesian pressures and water tables had dropped did geologists realize that the Pecos River had long ago incised its way through the Ogallala sands, thus severing the eastern portions of the aquifer from its former recharge area in the Sacramento Mountains near Alamagordo and Ruidoso, NM (Fig. 14).

Pleistocene downcutting of the Pecos River had converted the Ogallala formation from a confined artesian system to a perched aquifer whose only natural recharge is now from rainfall on the Pecos Slope east of the Pecos River. Streams on the east side of the Sacramento Mountains no longer recharge the Ogallala aquifer. Continued withdrawal of water for irrigation has caused water tables to drop as much as 30 meters. The saturated zone in the Ogallala is, in many areas, only half of what it was originally. The groundwater is being mined as a nonrenewable resource!

Watch as you drive through the Texas panhandle and eastern New Mexico. In a few years, some of the irrigated fields will revert to dry prairie lands, as the groundwater gets scarcer, deeper, and more expensive to pump. About one hundred miles west of Amarillo, the Plano Estacado abruptly ends in a maze of rugged, highly dissected slopes. This hang glider's heaven marks the western rim of the High Plains and the beginning of the dissected, mesa-studded semiarid Pecos Slope of eastern New Mexico. You will feel that you've finally entered the West of Clint Eastwood, Hondo, and John Wayne.

After crossing into New Mexico, we drive for the next 200 miles on the Pecos Slope. Near Santa Rosa, NM, depending on weather and time of day, the southern terminus of the Front Range of the Rocky Mountains should appear at one to two o'clock. Even if you can't see the mountains, you often as not can see the clouds building up above the high peaks.

In New Mexico, the frontal range of the Rockies is called the Sangre de Cristo Mountains (Figs. 13 and 15). The Front Range is a nearly continuous wall of high (most above 10,000') mountains, bounded by high-angle reverse faults, that extends north-south for 350 miles from Laramie, Wyoming, through Colorado, to Santa Fe. North and south of the Front Range, there is no such continuous mountain front. Instead, one sees isolated fault-block mountains of the Northern Rockies in Wyoming and Montana or Basin and Range type topography in New Mexico. If you follow I-40, you pass south of the Sangre de Cristo and cross the Sandia Mountains just east of Albuquerque.

The Sandia Mountains define the eastern margin of the Rio Grande Rift, a north-south, continental rift through central New Mexico. The San Luis, Española, and Albuquerque basins (Fig. 13) comprise the northern New Mexico section of the rift. Figure 15 shows

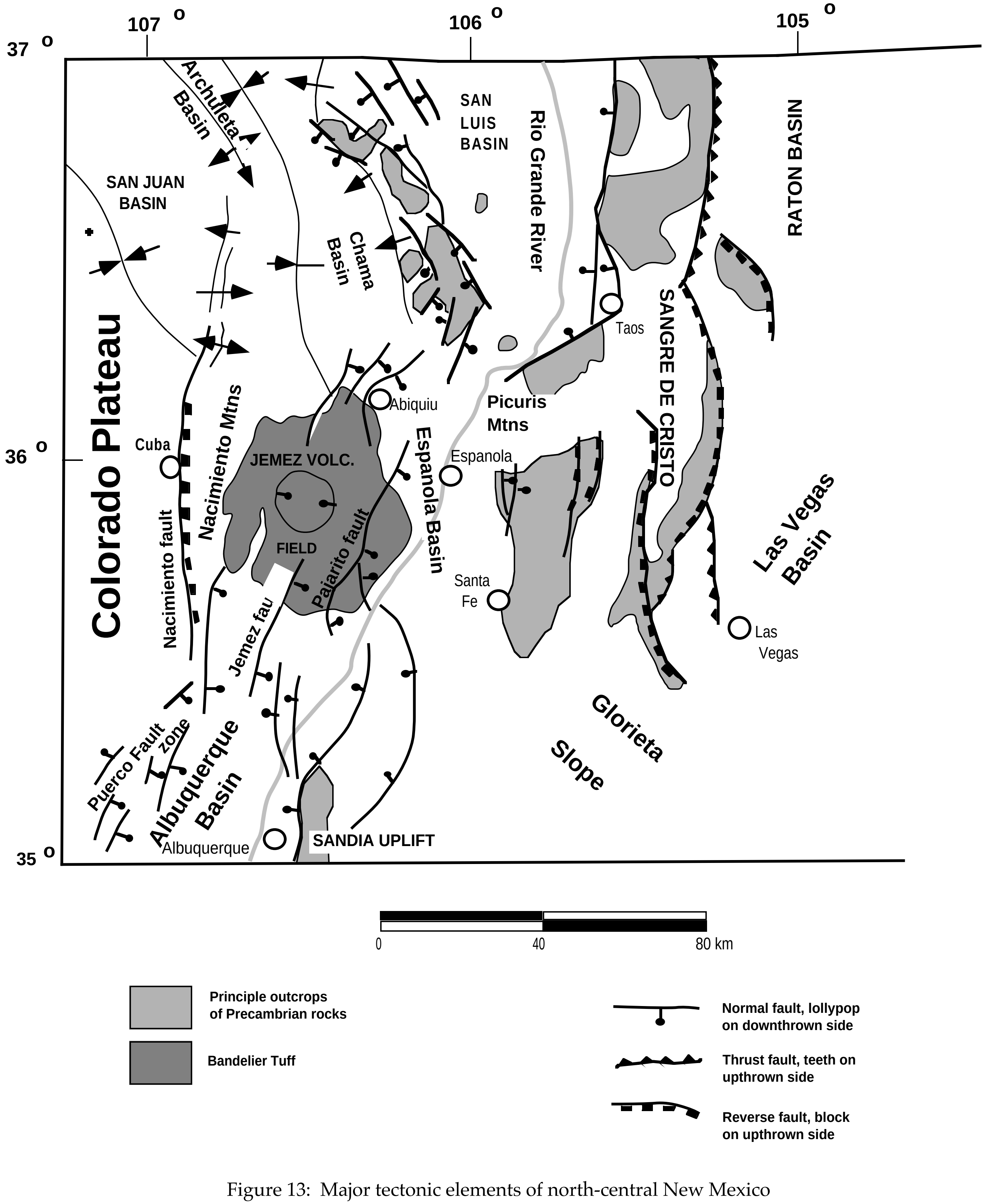


Figure 13: Major tectonic elements of north-central New Mexico

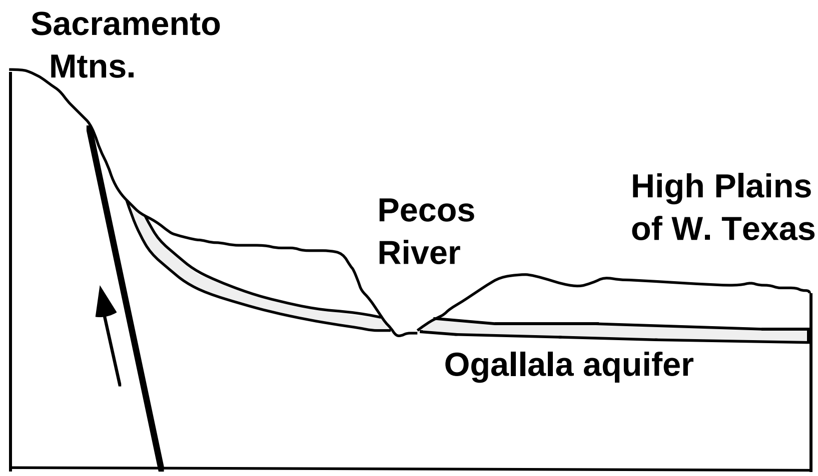


Figure 14: Schematic diagram of the Ogallala confined aquifer

the relationship of the Rio Grande Rift and Sangre de Cristo Mountains. Figure 16 is a detailed cross-section of the rift valley in the vicinity of Albuquerque. Here, the rift valley is about 40 km wide and well-defined on the east by the Rincon Fault along the western base of the Sandia uplift. The western margin of the rift, across the Llano de Albuquerque (Albuquerque plain), is very subtle because basement rocks are not exposed on the western boundary faults. Driving west from Albuquerque, one finds that the western rift margin gradually merges with a terrain much like the Pecos Slope, called the Mogollon (pronounced “mug ee yun”) Slope to the south and the Chaco Slope to the north. Both are part of the Colorado Plateau province. Farther south, near Socorro, and north toward Taos, the western margin of the rift is well-defined by basement uplifts similar to the Sandias (Fig. 13).

Be alert as you cross the Sandias, especially watch the 8-mile stretch west of the Zuzax I-40 exit. In the roadcut you’ll see exposures of the Pennsylvanian-Permian section disconformably resting on Precambrian granites. This relationship is shown schematically in the easternmost portion of the cross-section in Figure 16. Numerous high angle faults exposed in the I-40 roadcuts suggest that this area is far more complex than one might at first imagine. The beds are dipping east, we are descending in elevation, and we generally move downsection in an orderly progression. First we see Permian strata, consisting of red-brown sandstones, shales, and mudstones with some gypsum. This section becomes more carbonate-rich until we are in the Pennsylvanian Madera Limestone, a thick, massive gray marine limestone. At the base of the Madera a thin, basal sandstone of the Pennsylvanian Sandia Formation lies unconformably on Precambrian granites, gneisses, and greenstones in the core of the Sandia Uplift.

At Albuquerque, we finally leave I-40 (though we shall see it again in ten days or so) and head north on I-25 to Bernalillo and Santa Fe, NM. As we drive north on the Llano de Albuquerque (elevation about 1500 m above sea level), the Sandia crest to the east (elev. about 3000 m above sea level) makes an impressive skyline. The ledge at the top of the mountain consists of 200 m of Pennsylvanian sedimentary units, the Madera Limestone, and mixed sandstones, shales, and limestones of the Sandia Formation that we saw along I-40 (Fig. 16). These rest with profound unconformity on a smooth erosion surface of the Precambrian Sandia Granite (1.4 Ga). If we were to proceed south along the eastern margin of the rift basin, we would find older and older rocks resting on this Precambrian basement until reaching El Paso, where quartz-rich Cambrian sandstones lie in paraconformity with Precambrian rhyolites in the Franklin Mountains.

If the light is right, spectacular pegmatite dikes can be seen cutting the Sandia Granite on the west-facing cliffs of the mountains. The structural relief on the Rincon Fault (the

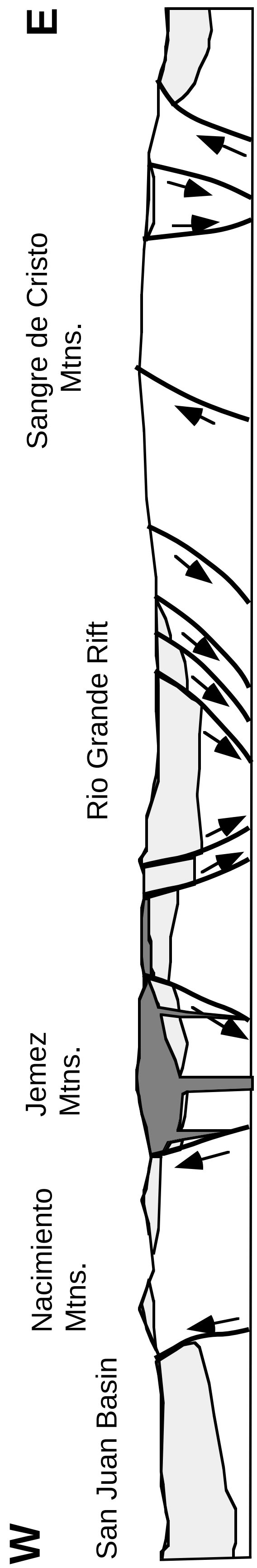


Figure 15: Schematic geological cross-section from the Sangre de Cristo front to the San Juan Basin

distance from the Precambrian-Pennsylvanian contact on top of Sandia Crest to the same contact beneath many thousands of feet of basin-fill sediments) is close to 6 km or nearly 20,000' (Fig. 16). This is the estimated throw on the west side of the Sandias. This movement has all taken place in the Neogene, probably within the past 20 million years. The “bottom is falling out” of the Rio Grande Rift at an average rate of about 0.1 inches a year. Nearly as fast as the rift has gone down, it has filled — mostly with coarse sands and gravels shed off the uplifted blocks. The young Tertiary basin-fill, clastic sediments are often lumped together as the Santa Fe Formation. Interbedded lavas and pyroclastic units can be age dated.

Bernalillo to Cuba, NM: Within a mile or so of the interstate exit at Bernalillo, we cross the Rio Grande. Its full name was once El Rio Grande del Norte, the Great River of the North. It was so named by the Spanish who penetrated this area along the Rio Grande in the first decades of the sixteenth century. The west Texas town of El Paso derives its name from the fact that the Rio Grande passes between the Franklin Mountains and the Sierra de Juarez, thus allowing easy passage north along the river. Franciscan missions in the area of Albuquerque and of Santa Fe just 50 miles north of here were active nearly one hundred years before the Jamestown settlement in Virginia!

From here, the Rio Grande flows over a thousand miles to the Gulf of Mexico. The Rio Chama enters the Rio Grande north of here (Fig. 11). It is the last perennial stream in the U.S. to enter the Rio Grande. The Rio Grande’s headwaters are near Creede, Colorado, about 50 miles south of Gunnison where we end the field camp.

To our right (on the northern horizon as we head out of Bernalillo) are the Jemez Mountains, a Neogene caldera complex. Just past the tiny crossroads of San Ysidro where NM Highway 4 heads north into the caldera, NM Highway 44 snakes back and forth between spectacular variegated mesas comprised of Permian through Jurassic strata (Fig. 17). This stratigraphic section (Fig. 17) should become second nature to you now; you are urged to commit to memory the names and ages of the units from the Permian at least to the Cretaceous-Tertiary (K-T) boundary. The mesa area is in a complex zone of normal faulting known as the Puerco Fault Zone (Fig. 13). Just past the Puerco Fault Zone, the highway swings nearly due north along the western margin of the Nacimiento Mountains. As we approach Cuba, we are
driving on Cretaceous strata and Tertiary basin-fill sediments of the San Juan Basin — the easternmost part of the Colorado Plateau (Figs. 13 and 15).

Not surprisingly, this plateau/basin terminology confuses students. The term Colorado Plateau was originally a geographer’s term, referring to the broad, flat highlands of the Four-Corners region. Geologists then borrowed the term to refer to the geologic province that roughly coincides with the topographic plateau. A geologic province is an area where the rocks are of similar ages and share similar tectonic styles and geologic histories.

Geological provinces typically coincide with geographic provinces of the same name, but need not do so in detail. Think of the Blue Ridge geologic and geographic provinces in the Appalachians. Parts of the Colorado Plateau, such as the San Juan Basin, consist of uplifted sections of thick, Tertiary, basin-fill sediments. Thus the geologic basin is part of the geographic plateau. As we drive north along the mountain front, the Nacimiento Fault is to our right; it forms the western edge of the Nacimiento Mountains. The Nacimiento is a high-angle, reverse fault which sets Precambrian and Paleozoic rocks on the east against Mesozoic and Tertiary rocks of the

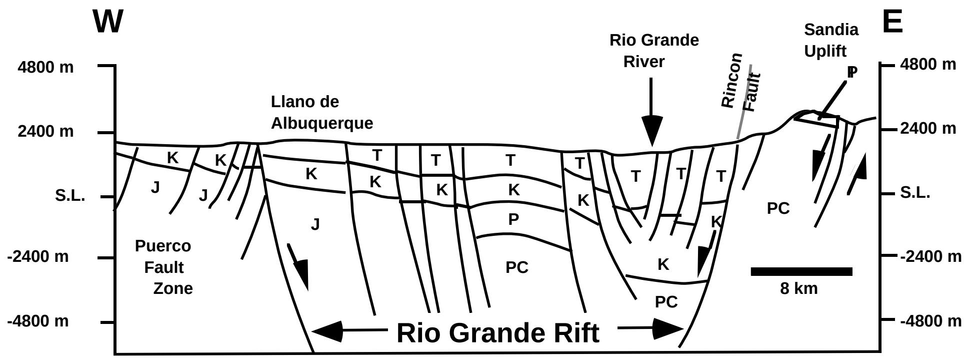


Figure 16: Diagrammatic cross-section of the Rio Grande Basin at Albuquerque, NM

San Juan Basin on the west. Be sure to get a good look at the Landsat photo of New Mexico at this stage (several should be available in the vans). The fifty-mile long, razor-sharp Nacimiento Fault is hard to miss.

NORTHWESTERN NEW MEXICO

We do a mapping and hydrogeologic project on the western flank of the Nacimiento Mountains. The local stratigraphic section is given in Figure 17. Short, local field trips are critical for learning the stratigraphy in the project areas and for beginning to utilize local and regional geological concepts. The geologic history of this area is complex. Precambrian exposures are limited, consisting mostly of granites and granitic gneisses with a few small inliers of metasedimentary and metavolcanic rocks. During mid- to late Paleozoic, a large uplift known as the Uncompahgre Uplift dominated the paleogeography of northern New Mexico and southern Colorado (Fig. 18). This upland was eroded down to Precambrian basement rocks so that nowhere in the Nacimiento mountains do we see Phanerozoic rocks older than Permian.

Remember, as we crossed the Sandias at Albuquerque, we saw Pennsylvanian sedimentary rocks exposed on the crest of the uplift and pointed out that to the south units as old as Cambrian rest on basement rocks. Now, we know why! The Precambrian-Paleozoic unconformity climbs up-section from south to north in the area of the Uncompahgre Uplift. A broad depocenter, the Paradox Basin, developed on the west side of the Uncompahgre Uplift (Fig. 18). It was a restricted basin in Pennsylvanian-Permian time and contains abundant evaporites.

During and following the active phase of the Uncompahgre Uplift, erosion and deposition of clastic debris shed off of these highlands dominated the sedimentary record. Permo-Triassic sedimentation in this area is characterized by fluvial, lacustrine, and shallow deltaic marine facies (the Cutler and Chinle Formations). These units are dominantly fine to coarse-grained clastic sediments. In the Jurassic, similar units like the Morrison Formation intertongue with other units that indicate an arid environment, e.g., evaporite sequences in the Todilto Formation and eolian dune sands in the Entrada Sandstone. The end of the Jurassic marks the end of this regional arid cycle. The Cretaceous period was marked by two episodes of sea-level advance and retreat. The basal Cretaceous unit is the Dakota Sandstone, a sheetlike sand that was undoubtedly a marine transgressive sand not

Erathem	System	Rock units	Measured thickness (ft)	Symbol
CENOZOIC	Quaternary	Bandelier Tuff	0–650	Qbt
CENOZOIC	Tertiary and/or Quaternary	terrace and pediment deposits	0–30	TQtp
CENOZOIC	Tertiary and/or Quaternary	travertine	0–50	QTt
CENOZOIC	Tertiary	Paliza Canyon Formation	0–45	Tpc
CENOZOIC	Tertiary	Abiquiu Formation (Ta) 0–400; Zia Sand (Tz) 0–1,000; volcaniclastic rocks (Tv) 350–450		
CENOZOIC	Tertiary	San Jose Formation	800–1,400	Tsj
CENOZOIC	Tertiary	Nacimiento Formation	500–800	Tn
CENOZOIC	Tertiary	Ojo Alamo Sandstone	70–125	Toa
MESOZOIC	Cretaceous	Kirtland Shale and Fruitland Formation undivided	85–240	Kkf
MESOZOIC	Cretaceous	Pictured Cliffs Sandstone	0–65	Kpc
MESOZOIC	Cretaceous	Lewis Shale	1,500–2,000	Kl
MESOZOIC	Cretaceous	Mesaverde Group (Kmv): La Ventana Tongue of Cliff House Sandstone	15–900	Klv
MESOZOIC	Cretaceous	Mesaverde Group (Kmv): Menefee Formation	265–700	Kmf
MESOZOIC	Cretaceous	Mesaverde Group (Kmv): Point Lookout Sandstone	40–275	Kpl
MESOZOIC	Cretaceous	Mancos Shale	2,000–2,200	Km
MESOZOIC	Cretaceous	Dakota Formation	80–210	Kd
MESOZOIC	Jurassic	Morrison Formation	400–1,020	Jm
MESOZOIC	Jurassic	Todilto Formation	14–150	Jt
MESOZOIC	Jurassic	Entrada Sandstone	100–300	Je
MESOZOIC	Triassic	Chinle Formation (Ŧc): upper shale member	400–600	Ŧu
MESOZOIC	Triassic	Chinle Formation (Ŧc): Poleo Sandstone Lentil	0–135	Ŧp
MESOZOIC	Triassic	Chinle Formation (Ŧc): Salitral Shale Tongue	0–335	Ŧs
MESOZOIC	Triassic	Chinle Formation (Ŧc): Petrified Forest Member (upper shale member, Poleo Sandstone Lentil, Salitral Shale Tongue)	1,070	(Ŧpf)
MESOZOIC	Triassic	Chinle Formation (Ŧc): Agua Zarca Sandstone Member	0–210	Ŧa
PALEOZOIC	Permian	Bernal Formation	0–80	Pb
PALEOZOIC	Permian	Glorieta Sandstone	0–100	Pg
PALEOZOIC	Permian	Yeso Formation	10(?)–525	Py
PALEOZOIC	Permian	Abo Formation	100(?)–2,900(?)	Pa
PALEOZOIC	Pennsylvanian	Madera Formation	0–1,775	IPm
PALEOZOIC	Pennsylvanian	Sandia Formation	0–225	IPs
PALEOZOIC	Pennsylvanian	Osha Canyon Formation	0–71	IPoc
PALEOZOIC	Mississippian	Log Springs Formation	0–50	Mls
PALEOZOIC	Mississippian	Arroyo Peñasco Formation	0–120	Map
PALEOZOIC	Cambrian–Ordovician	syenite		€Os
PRECAMBRIAN		metamorphic and plutonic igneous rocks		p€

Figure 17: Stratigraphic column for the Nacimiento Mountains and eastern San Juan Basin (from Woodward, 1987)

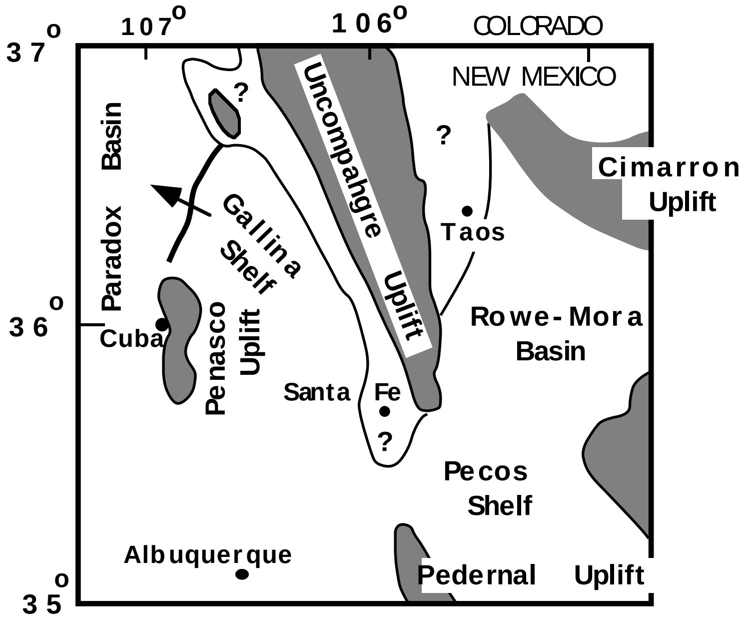


Figure 18: Paleotectonic map of northcentral New Mexico during late Pennsylvanian time

unlike those we see on the North Carolina Coastal Plain. Both Cretaceous sea level excursions, rises and falls, are marked by thick marine shale and siltstone sequences (Mancos and Lewis shales) overlain by coal-rich, fluvial-deltaic clastic sequences (the Mesaverde Group including the Pictured Cliffs/Fruitland Formations).

By early Tertiary (Fig. 19), the Nacimiento Uplift was rising along the Nacimiento fault. This fault is well-exposed in the area around Cuba. North of Cuba, near Gallinas (where we will spend a morning studying the stratigraphic section), the Nacimiento Fault did not break up through the Mesozoic section. However above the tip of the fault, the overlying rocks were deformed into a large anticline known as the Gallinas-Archuleta Arch.

Beginning in the Eocene, clastic sediments from the Nacimiento Uplift were shed west into the San Juan Basin. These are the multicolored, sandy units that you see near to and west of Cuba. In latest Tertiary, the influence of the Rio Grande Rift begins to be seen with development of the Jemez Volcanic Field farther east (Fig. 13).

Some formations seen in the Cuba mapping projects appear in other field areas, although thicknesses, internal units, colors, etc., may change. Learn the stratigraphic section! Know the ages, names, stratigraphic sequences, and lithologies of these formations; this information will give you a solid grasp of their of sedimentological and paleographic significance. Study Figure 17!

<u>Bernalillo to Taos</u>: The trip to Taos parallels the Rio Grande, although we soon pull away from the river as it heads west toward the Jemez Mountains on the northern horizon. We swing northeast to Santa Fe. You will rejoin the river at Española in a few hours and from there stay in close contact until tonight, when you may bathe in the river should the spirit move you. The river's Spanish name is El Rio Grande del Norte, the Great River of the North. It was so named by Spanish missionaries and explorers who penetrated this area during the first decades of the sixteenth century. El Paso, TX, derives its name from the fact that the Rio Grande <u>passes</u> between the Franklin Mountains and the Sierra de Juarez, thus allowing easy north-south passage along the river. Franciscan missions at Albuquerque and Santa Fe were active almost one hundred years before Jamestown, Virginia, was settled!

From Bernalillo, the Rio Grande flows over a thousand miles to the Gulf of Mexico. Its headwaters are near Creede, Colorado, about 50 miles south of Gunnison where our field course ends. The Rio Chama, a major tributary, enters the Rio Grande just north of Española (Fig. 11).

The Rio Grande Rift: Let's review some major points on the rift. The river follows a north-south trending, fault-bounded valley known as the Rio Grande depression or rift (some prefer to not use the word "rift" since it carries connotations of crustal thinning and rift tectonics) from El Paso to southern Colorado. The present-day basin began to form about 10 Ma (late Miocene-Pliocene), although extensive volcanic and clastic units as old as latest Oligocene or early Miocene (20 Ma) suggest localized tectonic subsidence prior to the actual formation of the basin.

As the basin subsided, Paleozoic and Precambrian rocks were exposed in the surrounding highlands (Fig. 13). These mountains in the southern half of the rift, from Santa

Fe south, are mostly restricted to the eastern side of the rift. An example would be the Sandia Mountains east of Albuquerque (Fig. 16). North of Santa Fe, the highlands have structural relief of as much as 24,000' on both the eastern and western margins of the depression. The present-day topography of this area is controlled almost exclusively by this young, ongoing "rift" basin formation. This is "neotectonics". Volcanic rocks and faults less than 100,000 years old cut the older rocks.

Don't forget the record of earlier, regional, tectonic events. These include extensive Proterozoic crustal shortening sometime prior to about 1.6 Ga, a late Paleozoic event that produced the Uncompahgre and other uplifts from western and central Colorado to north-central New Mexico (Fig. 18), and Late Cretaceous-Early Tertiary uplifts of the Laramide Orogeny (Fig. 19) that foreshadowed the modern Brazos uplift and Sangre de Cristo Mountains.

Elmer Baltz, a USGS gurus on this part of the country, once said:

> *The Neogene Rio Grande depression in north-central New Mexico is a series of northerly elongate, tilted, sagged, and faulted blocks that are collapsed parts of a broad area of Laramide structural uplift between the Great Plains and the Colorado Plateau.*

Refer to Figure 13 and see what he meant. The Raton and Las Vegas basins are foreland basins in the western Great Plains. They are bounded on the west by Laramide-age, Precambrian-cored, structural uplifts, the Sangre de Cristo Mountains in New Mexico and the Front Range in Colorado. The area (Fig. 13) between the thrust faults on the eastern flank of the Sangre de Cristo and the Nacimiento reverse fault near Cuba is the Rio Grande rift proper. The cross-section (Fig. 16), drawn at Albuquerque, is typical of the southern rift. The eastern boundary is a major fault with throw of thousands of meters that brings Precambrian rocks to the surface. The western boundary is wider and marked by a series of steplike fault blocks; Precambrian basement rocks are not lifted high enough to be exposed. The character of the western side of the rift changes as we move north.

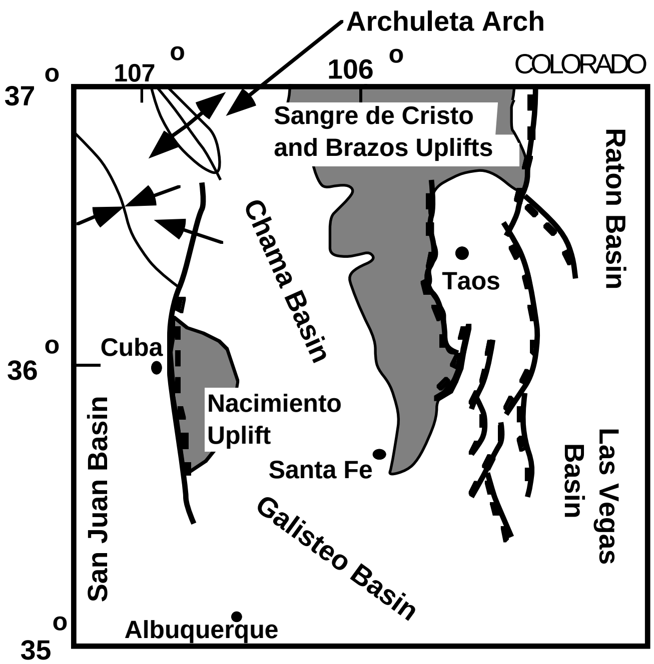


Figure 19: Paleotectonic map of northcentral New Mexico during late Eocene time

From Bernalillo to Santa Fe to Velarde, a little town of north of Española, the highway follows young, basin-fill sediments of the Santa Fe Group. These are Miocene through Pleistocene in age and include sands, gravels, fanglomerates, and interbedded volcanic rocks. You will see river terraces, badlands topography, a few cinder cones, and some volcanic domes. This area is tectonically and volcanically active.

We follow the Rio Grande north from Albuquerque (Fig. 13) and skirt the Jemez Volcanic Field to the west. Just north of Santa Fe, we enter the Española Basin. Santa Fe is tucked in the elbow of the Santa Fe Range of the Sangre de Cristo Mountains. These high, snow-capped peaks are held up by Precambrian metamorphic and igneous rocks and overlain on the east flanks by Pennsylvanian and younger sediments. The structure is very similar to the Sandia Mountains east of Albuquerque. At Velarde, we enter the narrow canyon of the Rio Grande where it is confined between Miocene to Recent basalts flows and a small reentrant of Precambrian rocks known as the Picuris Mountains (Fig. 13), the site of our Taos mapping projects. This narrowing of the Rio Grande depression is known as the Embudo constriction. North of the Picuris Mountains and the turnoff to Orilla Verde, our Rio Grande Canyon campsite, the highway climbs to the top of the Taos Plateau.

Now, let's follow a semi-road log: About 10 miles north of the Bernalillo exit on I-25, you begin to catch glimpses of the snow-capped Santa Fe Range of the Sangre de Cristo to the north and east. Here the highway route diverges from the Rio Grande. The river flows through White Rock Canyon (a stop on our Jemez Mountain trip) and the highway climbs a long pediment surface toward Santa Fe. To the west lie the Jemez Mountains. Most road-cuts along this stretch of I-25 expose Santa Fe Group fluvial sands and gravels that include some buried paleosurface horizons stained by iron and manganese oxides. Relatively thin volcanic ash beds related to eruptions from the Jemez volcanic center are also exposed.

About 20 miles north of Bernalillo you begin seeing Mesozoic units exposed along subtle fault scarps. These include dark Mancos Shale, white to yellowish Dakota Formation sandstones, and underlying red to purple Morrison Formation (Fig. 17). Some roadcuts expose dikes that cut through the Mesozoic units and faults placing Mancos shales against Morrison strata.

Just past the Waldo exit (Where's Waldo?) about milepost 268, the highway crests a hill, allowing a good view of the Sangre de Cristo Mountains. The southernmost high peak is Santa Fe Baldy (12,622'). Soon, we'll arrive in Santa Fe, the capital of New Mexico and the oldest "European community west of the Mississippi," founded in 1610. It was quietly occupied in 1848 by American forces commanded by General S. W. Kearney and became part of the United States after the Mexican War. Santa Fe is a richly, interesting city. Its old downtown, presidio area is classic, southwestern adobe architecture blended with a modern adobe-style often referred to as the Pueblo revival style. Sante Fe is an arts and crafts center, home to many artists and craftsmen, and of course, noted for Pueblo jewelry, pottery, and textiles. Just south of Sante Fe, we exit I-25 and continue north to Taos on secondary roads. North of Santa Fe, one of the more obvious landmarks is Camel Rock, which, as you may imagine, looks like its namesake desert animal. The feature is an erosional remnant of the Skull Ridge Member of the Tesuque Formation, Santa Fe Group. Farther north, we'll descend onto the Pleistocene terraces of Rio Grande valley and enter Española, the low-rider capital of New Mexico.

Many of the small towns between Santa Fe and Española are Pueblos, meaning that the lands were originally granted to the Indians granted by the Spanish crown. These Pueblo grants are still honored today. They are not reservations, but self-governing, independent tribal entities. Many are world-famous for their distinctive pottery styles, e.g., Santa Clara, San Juan, Jemez, and Acoma.

North of Española toward Taos, the Rio Grande basin narrows where the Picuris Mountains jut westward into the Rio Grande depression, marking the Embudo constriction. Find Taos on Figure 13 and notice the Precambrian rocks on both sides of the Rio Grande depression southwest of Taos. The Precambrian rocks shown immediately southwest of Taos are the Picuris block (you will be mapping there). The mountains east of Taos are the Santa Fe Range in the south and Taos Range to the north; both are parts of the Sangre de Cristo range. The Tusas and Nacimiento Mountains lie west of the Española and San Luis basins. The latter feature is the topographic basin in the Rio Grande depression in northern New Mexico and southern Colorado. The San Luis Basin is a geological basin; it is fault-bounded on both side and filled with young sediments and volcanic rocks. The Taos portion of the San Luis Basin is called the Taos Plateau. Confused? Here, the San Luis Basin rocks form a topographic plateau — an extensive plain, underlain by basalts, at an elevation of 5000'. The Taos Plateau is significantly higher than the Española Basin which filled with more easily eroded clastic units, not basalt flows.

North from Española to Velarde you have been riding on river terraces with the Sangre de Cristo to the east and 2.8 Ma tholeiitic basalts of the Servilleta Formation capping Black Mesa to the west and northwest (the southern limit of the Taos Plateau basalts). Velarde is a charming little agricultural center famous for its chili peppers. You often see colorful rastras of dried red chilies hanging from shop rafters along the road. Just north of Velarde, the Rio Grande valley narrows and the highway enters a canyon cut down through the Servilleta basalts. A low dam here ensures a constant flow of irrigation water

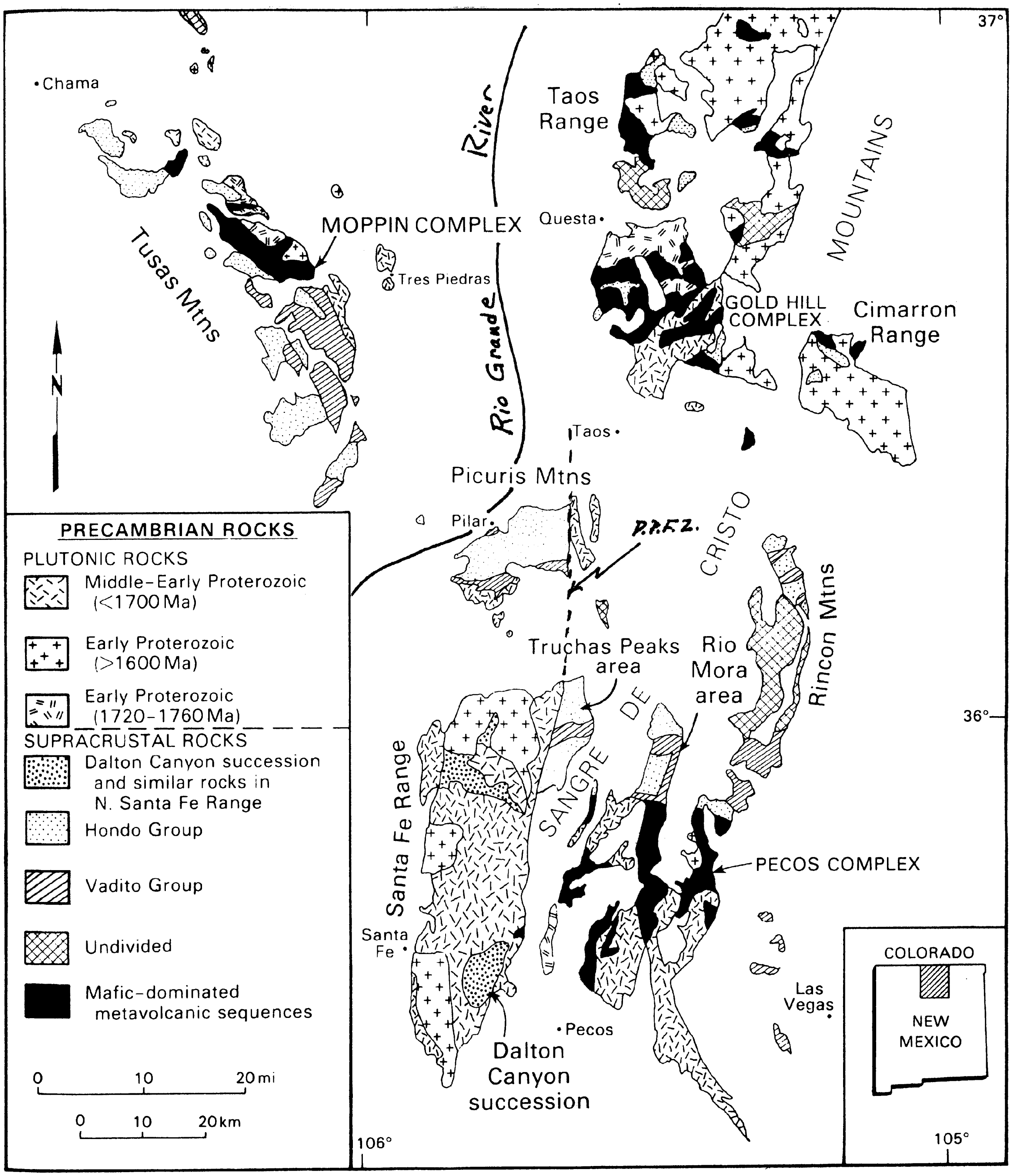


Figure 20: Outcrops of Precambrian metamorphic rocks in the Taos-Santa Fe segment of the Rio Grande basin. From Williams, 1990.

for the farmers in Velarde Valley. Keep your eyes on the river for the next ten miles or so. This is prime rafting water, and unless the river is dangerously high, you should see rafters galore.

About 2.5 miles north of where the highway enters the canyon, a monument in a left turnout marks the first USGS river gaging station, constructed in 1889. As we continue north along prime Rio Grande “whitewater”, the highway skirts the Picuris Mountains (Fig. 20), a Precambrian-cored uplift much like the main ranges of the Sangre de Cristo. As Figure 20 shows, the Picuris are on “strike” with the north-northeast trend of the Santa Fe Range. The Rio Grande River (sketched in Figure 20), given the “choice” of incising into the Servilleta basalts or metamorphic rocks of the Proterozoic Hondo and Vadito Groups (Fig. 21), chose the basalts. The downcutting river exploited weakened rocks along a major normal fault (like that in Fig. 16) that forms the northwest boundary of the Picuris block. This fault is related to formation of the Rio Grande depression.

About 10 miles north of Velarde, just after the highway passes through the little village of Rinconada and several miles north of the intersection with NM 75, the south wall of the valley consists of 1000' high, steep cliffs of whitish Ortega quartzites of the Hondo Group (Fig. 21). If you stay alert, you should notice an outlier of these quartzites across the river. These rocks are highly fractured and badly sheared, indicating that the river downcut directly into the fault zone.

At the small community of Pilar, we turn off to Orilla Verde, our campsite for the next five days or so. The campsite is on the river with steep canyon walls of Servilleta basalts rising some 600' above us. Had we continued north toward Taos, we would climb a five-mile grade and eventually arrive on top of the Taos Plateau. Road cuts at several creek crossings expose portions of the faults that bound the frontal zone of the Picuris block. These are interpreted as left-lateral strike slip faults, but many that you see in outcrop are low-angle faults (perhaps they are in blocks rotated on deeper, hidden faults and thus their present-day attitudes do not represent their original orientation). These faults cut very young, unconsolidated, boulder and cobble fanglomerates of the upper Santa Fe Group. After emerging from the last arroyo crossing, you arrive at a picnic turnout (both sides of the road) called the Hondo Canyon Overlook. This is a must, a photo opportunity! From here, you look up the Rio Grande depression for forty or more miles. As you face north, Picuris Peak, the highest point in the Picuris Mountains (10,901'), is at 4 o’clock and the town of Taos is nestled at the foot of the Taos Range at 2 o’clock. At dusk, the lights of Taos twinkle in the dry desert air like a fairyland scene.

Many of you have heard of Taos. It is the site of the Taos Pueblo, one of the most fiercely independent of the New Mexico pueblos. Still inhabited, it is the picture postcard, four-story adobe pueblo which most tourists associate with New Mexico. The revolt of 1680 that temporarily drove the Spanish back to Mexico for 13 years began here.

The Pueblo revolt in which the American Governor Bent was killed also started here. Taos was famous in the 1830’s for the annual get-togethers of fur-trappers, Indians, and traders, the latter having crossed the Santa Fe Trail to buy the beaver pelts trapped the previous winter in the Rockies. These “fairs” were week-long brawls full of trading and knife-fights, consumption of vast amounts of Taos Lightening, and a good deal of general immorality followed by the Mountain Men returning, usually broke and hungover, to the mountains for another season of trapping. The Taos Pueblo is north of the modern town. Taos proper has a touristy main plaza surrounded by curio, gift, and t-shirt shops (there are several good outdoor/camping stores in Taos as well as your basic K-Mart on the strip to the south of town). Taos is famous too for its literary/artistic tradition. There are many fancy art studios surrounding the Plaza and lots of shops which sell southwestern jewelry, pottery, and weavings. D. H. Lawrence and Georgia O’Keeffe lived here, among many others.

As you drive toward Taos, which we will probably do on several occasions , you pass through Ranchos de Taos, once the Mexican farming center for town. On the right, across from the Post Office, is the famous St. Francis of Assisi mission. This is the classic pueblo-style Franciscan missions of New Mexico — much photographed and often painted, particularly by Georgia O’Keeffe. Half of the paintings for sale in Taos are of this mission or the Taos Pueblo!

Let's continue with the view from Hondo Canyon Overlook. Rising above Taos is the snow-capped Taos Range of the Sangre de Cristo. The highest mountain in New Mexico, Wheeler Peak (13,161') is at 1:30 o'clock. At 12:00 o'clock due north up the valley, the Rio Grande Gorge looks like a knife gash through the plateau. Many of the low, subdued hills in the mid-distance between 8 and 10 o'clock are young, volcanic rocks.

Geology of the Picuris Mountains: Your main mapping project(s) are in the Picuris Mountains. The Picuris (Fig. 20) are an isolated fault-block of Proterozoic rocks between the Santa Fe and Taos Ranges. As we have seen, the northern and western margin of the Picuris block is a normal, down-to-the-west fault, related to the Rio Grande basin development. The eastern margin is thought to be a major shear zone with dextral strike-slip movement that apparently occurred in the mid-Proterozoic. This is the Pecos-Picuris Fault Zone (crudely labeled the P.P.F.Z., Fig. 20). It appears that this shear zone was reactivated during rift-basin development.

Our mapping project involves units of the Hondo Group in the Picuris Mountains (Fig. 21). You will have to describe these units in some detail in the field.

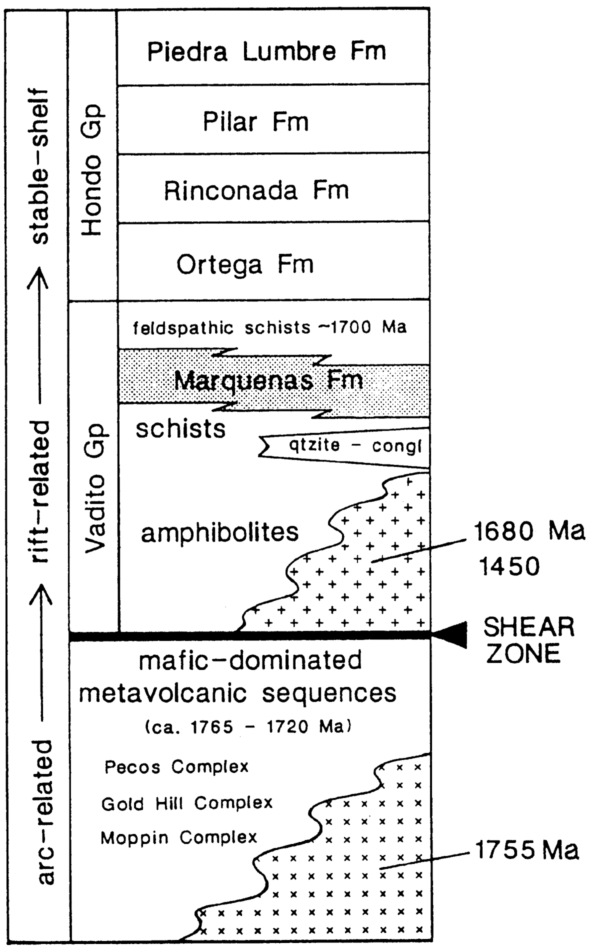


Figure 21: Generalized stratigraphic column for the Proterozoic rocks of northern New Mexico (Bauer, 1989)

Hondo Group (Proterozoic)

Piedra Lumbre Formation: garnetiferous muscovite-biotite crenulated schists and calc-silicate rocks
Pilar Formation: black, graphitic phyllites
Rinconada Formation: pelitic schists and two, massive, cross-bedded quartzite units; divided into six informal stratigraphic units (R1-R6) for mapping purposes
R6 - silvery gray, crenulated, garnet-muscovite schist.
R5 - massive, sugary-textured, pale-bluish, ledge-forming quartzite; some cross-bedding
R4 - muscovite-biotite-garnet schist with <= 2 ft-thick quartzite beds; contact with R5 is gradational
R3 - pale-bluish to tan, cross-bedded, fine-grained, ledge-forming quartzite; beds and outcrops less massive than R5
R2 - muscovite-biotite-staurolite-garnet schist; twinned staurolite grains up to 1" in dia.; some cordierite in upper units; basal bed is a prominent, pale-blue quartzite. R2/R3 contact is gradational.
R1 - medium to coarse grained, muscovite-biotite schist grading upward into staurolite, mica schist
Ortega Fm - tough, massive, thick-bedded, white to pale-blue quartzite; includes prominent horizon containing viridine (Mn-rich andalusite) and piemontite (Mn-rich epidote) and zones of copper mineralization (malachite/cuprite).

Taos Plateau, San Luis Valley, and the San Juan and Sangre de Cristo Mountains

Harding Pegmatite

The Harding pegmatite and mine, presumably named for President Warren G. Harding, is located just about one-half mile south of NM highway 75, 8.5 miles east of the junction of NM highways 75 and 68 at Embudo. Isotopic dating shows that the pegmatite was emplaced into Proterozoic metasedimentary strata during mid Proterozoic time. Pegmatites are small intrusive masses crystallized from magmas unusually rich in water and other volatiles, such as fluorine, that radically lower silicate magma melting and crystallization temperatures and promote growth of unusually large mineral grains. Some pegmatites with granitic compositions like the Harding, exhibit strong internal compositional zoning and enrichment in rare elements such as uranium, lithium, rubidium, beryllium, tantalum, and niobium. Major common rock-forming minerals include quartz, muscovite, albite (sodium-rich plagioclase), and microcline (K-feldspar); other normally-rare minerals found in unusual abundances in the pegmatite include lepidolite, apatite, spodumene, beryl, garnets, and tantalum-niobium minerals (Table 1).

Table 1; Prominent Minerals of the Harding Pegmatite Mine

albite	$NaAlSi_3O_8$	white, cleavelandite variety
apatite	calcium fluorophosphate	green, bluish green
beryl	$Be_3Al_2Si_6O_{18}$	white at Harding
lepidolite	K, Li, Al mica	distinctive lilac color
muscovite	K, AL mica	pale pink color common at Harding
microcline	$KAlSi_3O_8$	white to pale greenish blue at Harding
microlite pyrochlore	$(Na, Ca)_2 (Ta, Nb)_2 (O, F)_7$	isometric; microlite, the Ta-rich variety, is brown to black and pyrochlore, the Nb-rich variety, is light tan to yellow
tantalite columbite	$(Fe, Mn) (Ta, Nb)_2O_6$	bladed to blocky, tabular crystals; Fe-Ta varieties are black; Mn-Ta varieties are deep reddish brown
spodumene	$LiAlSi_2O_6$	colorless to pale green
garnets	$(Mn, Fe)_3Al_2(SiO_4)_3$	isometric; red to pink dodecahedral crystals; varieties include spessartine (Mn-rich; pink, light colors) and almandine (Fe-rich; deep red)

The pegmatite was first mined during the 1920s for coarse-grained lepidolite used in the formulation and manufacture of specialty heat-resistant glasses. During World War II, the pegmatite became an important domestic source for tantalum, a relatively rare strategic metal desperately needed by the emerging high-tech electronics industry during World War II. Finally during the 1950s, beryl-bearing zones in the pegmatite were exploited as an ore of the lightweight metal beryllium.

In 1974, the long time mine owner and developer, Arthur Montgomery, a geology professor who had since retired from Lafayette College, Easton, PA, donated the property to the Geology Department of the University of New Mexico with the expressed intention of preserving the area for research, earth science education, and mineral collecting.

Taos Plateau North to San Luis Valley

The Rio Grande rift zone consists of separate fault-block basins strung together in a north-south linear pattern from El Paso, TX, to the upper Arkansas River valley in Colorado. The individual basins connect through relatively constricted openings at their northern and southern ends and flare out to much wider dimensions in their central zones. The Embudo fault zone, a strand of which passes through Pilar, NM, forms the western flank of the northern Española basin and eastern flank of the southern San Luis basin. It crosses from one side of the rift zone to the other through the area of the narrow, bedrock gorge of the Rio Grande between Pilar and Velarde. This narrow canyon segment thus forms the connecting zone between the two basins, and shows that the Taos Plateau segment of the Rio Grande rift zone is actually the southern part of the San Luis basin.

From Taos northward toward the Colorado border, the river has incised a deep canyon through resistant late Pliocene basalt lava flows and interbedded clastic strata of the Sante Fe formation. Playa sediments, dune sands, alluvial fan deposits, palagonized basalts (hydrated basaltic glass), and pillow basalts are all generally consistent with sediment deposition/lava extrusion into a closed hydrologic basin containing seasonal lakes and/or more persistent, longer-lasting bodies of standing water. A N-S strip of Quaternary alluvial deposits overlies the basalts along the eastern margin of the valley. This relationship reflects ongoing eastward tilt of the basin. Hill masses projecting above the flat surface of the plateau, particularly north of Taos and west of the Rio Grande gorge, consist mainly of rocks (basalt through dacite) associated with Pliocene volcanism, but may include patches of Miocene and late Oligocene volcanic rocks. These outcrops typically lie along localized uplifted fault blocks, known as intra-basin horsts, that rise from the floor of the larger, downdropped basin.

Proterozoic rocks and small areas of mid-Tertiary felsic intrusions and welded tuffs form the eastern edge of the plateau and comprise the foothills of the Sangre de Cristo range. Evidence for Quaternary faulting can be seen in the San Luis valley near Mesita, CO (access via CO 248 from CO 159 south from San Luis, CO), in the eastern part (east of the Rio Grande) of the San Luis Hills. Here, fault scarps document an interval of down-to-the-west offset that lasted from the late Pliocene/early Pleistocene (mafic lavas from a nearby cinder cone are displaced from 8-10 m) to late Pleistocene (alluvial fan deposits are displaced by 1 m). The modern stream channel and floodplain sediments of Costilla Creek show no displacement, suggesting that the last movement was late Pleistocene in age. Offset late Pleistocene alluvial deposits north of Great Sand Dunes National Monument also prove Quaternary faulting along the western flanks of the Sangre de Cristo range.

Molycorp Mine and Questa Caldera

The Molycorp Mine at Questa, NM is a subsidiary enterprise of UNOCAL, the west coast petroleum giant. The mine produces molybdenite (MoS_2) concentrate which is shipped elsewhere for processing into Mo_2O_3 for use in making high strength steels and other specialty steel products. The mine has recently reopened after about a ten-year shutdown. As in many western mining camps, original prospecting interest focused on placer gold and lode gold and silver deposits. Just before the start of World War I, prospectors found outcrops of molybdenite-bearing veins in Sulfur Gulch, an extensive area of yellowish, hydrothermally altered rock on the north side of the Red River. These veins were exploited via underground mining until the late 1950s, when increasing mining costs and decreasing ore grades necessitated a new look at mining in the area. Thereafter, a large tonnage of near-surface, low grade ore in the headwaters area of Sulfur and Goat Gulches was developed as an open-pit. As open-pit mining was reaching its end, a deeper, low-grade, ore body southwest of the open pit was blocked out by drilling, and subsequently exploited by underground block caving methods.

The low-grade ore, in reality, is aplitic granite and fine-grained, porphyritic granite from tops of high-level, mid-Tertiary, stocks intruded along the ring fracture zone of the Questa caldera, a major collapse structure associated with eruptions of large-volume ash-flow tuffs. The Amalia Tuff is the major outflow sheet known to have been erupted from the Questa caldera. The host rocks contain disseminated molybdenite grains and are cut by numerous, crisscrossing veins, veinlets, and cracks. A first set of veinlets contains quartz, potash feldspar, biotite, pyrite, and molybdenite and a slightly later set contains mainly quartz and molybdenite. Central zones of the later veinlets contain small quantities of calcite, fluorite, and lead and zinc sulfides.

The bright yellow mineral ferrimolybdite $(Fe^{3+})_2(MoO_4)_3 \cdot 8H_2O$ at the surface is a telltale signal of molybdenite mineralization at depth, but it is retained only in oxidized outcrops where primary molybdenite in the unoxidized, mineralized rock was accompanied by relatively limited amounts of pyrite. In the presence of larger amounts of pyrite, the pH of percolating waters during oxidation is lowered enough to solubilize and transport Mo as the anion $HMoO_4$(1-). Thus under these condition, ferrimolybdite is absent from the oxidized zone.

The mined, mineralized rock is crushed and ground to a fine-silt size powder and the molybdenite is concentrated by floatation. Sulfide and silicate mineral grains and grains of different sulfide minerals have different surface properties and are "wetted" or "not "wetted" to different degrees by various liquid floatation agents. Frothing of the floatation liquids causes the non-wetted grains to concentrate in the surface froth while wetted grains sink to the bottom of the flotation tanks, thus providing for separation of the desired sulfide mineral from silicate grains and from other, unwanted sulfides such as pyrite. The tails (tailings) or waste mineral grains from the flotation process are carried as a slurry through large diameter pipes to tailings ponds on the west side of the Rio Grande near Questa. The tailings disposal areas need to be well-stabilized against erosion by wind and running water.

No Agua Perlite Deposit

Glassy rhyolite/dacite lavas and lava domes in the No Agua Hills, north of Tres Piedras, NM, are mined for perlite, a hydrated siliceous volcanic glass. Hydrated glass with the proper silica and water contents will fragment explosively, or "pop", when heated rapidly to the glass softening temperature. The resulting product, known as popped perlite, has a very low bulk density, is chemically inert and stable, and has low thermal conductivity. Thus the bulk, granular product is useful commercially as a lightweight aggregate.

Great Sand Dunes National Monument

The monument lies against the lower, western flank of the Sangre de Cristo Range in south-central Colorado. The broad and relatively flat San Luis Valley stretches for 40 or so miles to the west where it ends against the higher, rugged terrain of the southeastern San Juan Mountains. Most prominent peaks in the Sangre de Cristos exceed 13,000 feet in elevation; a few such as Blanca Peak, between the monument and Fort Garland, CO, and Crestone Peak on the skyline about 10 miles north of the monument, exceed 14,000 feet. The San Luis is a high, dry valley; valley floor elevations generally exceed 7500 feet and annual precipitation ranges from about 6 inches in the interior areas to 10 inches or more in the monument and other higher areas along the perimeter of the valley. Interior drainage characterizes the valley north of the Rio Grande alluvial fan that extends eastward from Del Norte, CO. Perennial streams on the east flank of the valley, such as Medano and Sand Creeks, are fed by melting snows in the Sangre de Cristos. As these streams cross from bedrock onto alluvial fans and sandy areas flanking the mountains, water infiltrates to the groundwater system and stream discharge declines. Evaportranspiration takes and additional toll on streamflow. Thus these streams generally dry up within a few miles of the mountain front or at times of high flow, they may discharge into low-lying playas, shallow lakes, and marshes.

The monument dune field is nestled in an eastward-directed reentrant in the Sangre de Cristo mountain front. After blowing without obstruction across the flat terrain of the

Dune Type	Description/Explanation/Distribution
parabolic, deflation, & accumulation	A dune ridge in the shape of a parabola encloses a shallow basinlike interior area on three sides; tips of the dune ridge point into the prevailing wind direction; winds blow through the open end of the shallow basin and transport sand to the crest of the slip face at the closed end of the dune. The slip face is always inclined downhill in the downwind direction. Parabolic dunes occur as multiple dunes in "dune fields". In parabolic dunes of deflation, sand is eroded from the bare, basinlike interior area of the dune and the dune ridge is usually vegetated. Depth of erosion may be limited by vegetation, a surface concentration of particles coarser-grained than fine sand, or the water table. In parabolic dunes of accumulation, the basinlike interior areas of the dune is a surface of transport (no net erosion) and the dune ridge is usually unvegetated.
barchan	The dune ridge is crescent shaped like a quarter moon, usually with a wider open end than a parabolic dune; ridge tips point downwind. Barchans occur in small groups of isolated dunes. Barchans are mobile dunes; sand is driven up the gently inclined transport surface and slides (avalanches) down the steeper slip face, causing the dune to gradually move laterally while preserving the form and configuration of the dune. Migrating dunes such as barchans are usually unvegetated.
longitudinal	The dune is long and narrow; the ridge and perimeter are aligned parallel to the prevailing wind direction. Small-area, cuspate slip faces are distributed along the sloping, lateral flanks of the dune.
transverse	The dune crests and flanks are aligned more-or-less at right angles to the prevailing wind direction. These are the dominant dunes at the monument.
star	These dunes have a high, central apex that connects with three or more, sharp-crested, radial, dune ridges. Star dunes form in response to "multiple prevailing wind directions". These dunes are very active, but because the sand is blown back and forth over the central apex zone during successive episodes of different wind directions, the dunes tend to remain more-or-less at the same location. In general, star dunes are not vegetated.

valley, prevailing southwest winds are funneled into the reentrant and impeded by the mountain front. As the moving air masses slow down and rise, velocities and turbulence remain competent enough to transport dust and fine silt particles on across the mountains; however sand-sized particles are left behind to accumulate in dunes.

Windblown sand moves mainly by saltation or bouncing. The sand grains are lifted by localized turbulent updrafts, rise a short distance into the air, usually no more than a few feet or so, and fall back to the surface, all the while being carried laterally by the forward motion of the wind. The falling grains impact the surface with enough momentum to dislodge or eject one or more other grains, thus providing a ready supply of easily lifted grains for the next updraft. In unusually strong winds, the number of saltating grains increases to the point that the entire surface sand layer is more-or-less set in a continuous rolling motion by the impacts of falling, saltating grains, greatly increasing the net rate of sand transport.

Sand for the dunes is mainly derived from an area between the modern channel of the Rio Grande and the San Luis Lakes State Wildlife Area. The ephemeral lakes and marshes of the wildlife area mark the final sump for the south-flowing San Luis Creek and also delimit an area of fluvial sediments associated with abandoned, migrating channels of the Rio Grande. Fed by melting snows in the mountains, the Rio Grande winds its way eastward through the San Juans, enters the valley at Del Norte, and then gradually changes direction toward the south. This southward turn is completed about ten miles east-southeast of Alamosa, CO, and the river is finally poised for its nearly one-thousand mile-long southward run to the Gulf of Mexico. Originally, the river evidently flowed due eastward across the valley from Del Norte to a point about five miles east of the state wildlife area. Here, encountering the distal edges of the extensive alluvial fans building westward from the Sangre de Cristos, the river turned abruptly south and connected with the northernmost, due-south channel segment of the modern river. During its migration, the river left behind a surface veneer of fluvial sediments, such as point bar, natural levee, and floodplain deposits that contain abundant, fine-grained sand. Most of the sand now piled up in the monument dunes has been supplied by deflation of these sediments.

This area of wind erosion is identified by numerous parabolic dunes of deflation. Remember, the term "deflation" is synonymous with wind erosion and the term" blowout" describes a shallow, basinlike depression excavated by deflation.

The monument dunes are unusually high transverse dunes; the crests stand 500-700 feet above Medano Creek and the area of parabolic dunes of accumulation in the western part of the monument. As would be expected for eolian deposits, the sand is fine-grained (ave. dia. 0.2 to 0.3 mm) and well sorted. A majority of grains are lithics derived from rocks of the San Juan volcanic field. These impart the medium-brown color so evident in the dunes, especially at low sun angles in the early morning and late afternoon. The remaining grains are quartz plus a percent or so of heavy minerals, mainly magnetite. Its fine grain size and volcanic provenance support the conclusion that the sand is deflated from nearby fluvial deposits of the Rio Grande.

Although sand is seemingly being continually blown toward the mountain front, the dunes are not migrating any closer to the mountain front. Why? The explanation involves short periods during the winter months when the normal, prevailing southwest winds are replaced by winds from the east and northeast. These develop from large, very cold, Arctic, high pressure systems that spread from central Canada southward and eastward into the western plains. As the cold air flows southward along the eastern front of the Rockies, some spills over the Sangre de Cristos, sinks into San Luis Valley, and continues moving west as strong, very cold, surface winds. During these periods of easterly winds, transport directions are reversed and slip faces sloping to the west are constructed along the high dune ridges. This cold, dry, Arctic air is substantially more dense than air associated with the warmer, southwest prevailing winds. For equal pressures and zero humidity, air at -60 °F is nearly 50 % more dense than at 100 °F. Thus colder air masses can move larger-size sand grains and a larger quantity of finer-grained sand than warmer air masses with equivalent wind speeds and turbulence. Evidently enough sand is transported to the west during these relatively short periods of cold easterly winds to undo the net eastward transport occurring during the rest of the year. As the sand moves back and forth in response to reversing wind directions, the dunes grow to unusually high elevations, but remain more or less in place.

Small patches of lighter-colored, medium- to coarse-grained quartz sand are evident in some dunes near Medano and Sand Creeks. This sand is derived from Proterozoic rocks of the Sangre de Cristos and is mainly deflated from braided stream deposits. It only saltates with the very strongest, cold, winter winds; vegetation and near-surface water tables along the creeks further limit deflation and sand transport.

The Sangre de Cristo Range

The Sangre de Cristo range stretches nearly two hundred miles north-south from Poncha Pass at the extreme north end of the San Luis Valley to Sante Fe, NM. Proterozoic rocks visible in roadcuts along Interstate 25 just south and east of Sante Fe mark the southern geologic boundary of the range. In New Mexico and southern Colorado, the Sangre de Cristos are the easternmost of the Laramide-age (late Cretaceous/early Tertiary) basement uplifts of the Rocky Mountains; the eastern flanks of the range border on the westernmost parts of the High Plains. North of Fort Garland, CO, the Wet Mountain Valley and the Wet Mountain basement uplift are interposed between the Sangre de Cristos and the High Plains.

On the less-steep, east-sloping flank of the range, Proterozoic basement rocks are still largely covered with late Paleozoic clastic strata roughly equivalent to those (Belden, Gothic, and Maroon Formations) in the Gunnison area. Proterozoic and late Paleozoic rocks comprise the crest of the range; younger rocks are limited to localized patches of Oligocene and Miocene volcanic rocks and a few felsic stocks. Proterozoic basement rocks almost exclusively comprise the precipitous, west-facing flank of the range.

The late Paleozoic clastic strata were derived by vigorous erosion of Proterozoic basement blocks that had been uplifted in late Pennsylvanian-early Permian time to form the Ancestral Rockies. Thin, mainly continental, Triassic and Jurassic clastic strata, such as the Morrison Formation, were deposited over the deeply eroded Proterozoic and Paleozoic rocks. These are overlain by a major, Cretaceous, marine sequence, including a transgressive beach sandstone (Dakota Sandstone), a very thick marine shale (the Pierre Shale; equivalent to the Mancos Shale farther west), and a regressive beach and fluvial sandstone and included coals and coastal swamp shales (Vermejo Formation; equivalent to the Mesaverde Group farther west).

Structurally, the Sangre de Cristos can be visualized as a "perched thrust tip" or isolated frontal remnant of a Laramide-age uplifted block that originally extended much farther to the west, perhaps as far as the San Juan uplift north of Durango. Crystalline

Proterozoic rocks with a thin veneer of late Paleozoic sedimentary strata were shoved upward and to the east along a major, west-dipping, thrust fault and monoclinal zone that forms the eastern boundary of the range. Eastward from the village of Cuchara, CO, vertical Morrison and Dakota beds along the mountain front give way to subhorizontal Pierre Shale and younger strata within a short west-to-east distance. The zone of rapid, lateral, dip flattening marks the eastern limit of the Laramide uplift.

The San Luis Valley is an important, northern segment of the Rio Grande rift zone. The San Luis rift segment is a half graben tilted downward to the east; thus maximum vertical fault displacements (at least 13,000 ft) and thicknesses of Plio-Pleistocene valley-fill sediments (7000 ft or more) are associated with the eastern valley margin. Oligocene and Miocene volcanic rocks, once continuous with those of the southeastern San Juans to the west, underlie the basin-fill sediments. Thus graben collapse initiated in early Pliocene or late Miocene time has left the older rocks of the frontal tip of the Laramide thrust block juxtaposed against overridden younger strata to the east and against very young, valley-fill sediments accumulating in the downdropped, graben depression to the west. Faulted Pleistocene alluvial fan deposits along the west flank of the range attest to Quaternary normal-fault uplift of the Sangre de Cristo block.

Spanish Peaks

The Spanish Peaks area is 5 to 10 miles east of the eastern Sangre de Cristo front from Cuchara, CO and about 30 miles WNW of Trinidad, CO. The name derives from two prominent mountains, West (13,600 ft) and East (12,700 ft) Spanish Peaks. Mid-Tertiary (24 +/-1 Ma) plutons comprise the mountains; a granite-granodiorite stock is centered at East Spanish Peak and a somewhat smaller and less felsic syenodiorite stock underlies West Spanish Peak. The surrounding area is well-known for its extensive swarms of mid-Tertiary dikes. A radial swarm of andesite dikes (24 +/- 1 Ma) converges toward the West Spanish Peak stock. Slightly older alkali lamprophyre (26 Ma) and younger minette (phlogopite lamprophyre; 21 Ma) dike swarms also exhibits some radial convergence toward the central stocks, but almost parallel EW- and ENE-trending dikes are prominent in areas beyond 10 to 15 km north, south, and east of the central stocks.

At the modern land surface, the dikes and stocks crosscut Paleocene and Eocene clastic sedimentary strata derived from the Laramide-age, Sangre de Cristo uplift and deposited along the western edge of the High Plains. Some of the lamprophyre dikes are unusually thick (up to 100 ft) and laterally extensive (many miles). Due to differential erosion, the harder plutonic and dike rocks stand substantially higher than the adjacent softer, sedimentary wallrock, and in places, outcrops of the thicker dikes have evolved into "vertical walls" that stretch prominently across the landscape.

The radial andesite dikes are similar in age and composition to the syenodiorite of the West Spanish Peak stock, and the radial fracture pattern is compatible with the stress field imposed by an inflating magma chamber at depth. The andesite and lamprophyre dikes exhibit laterally unconnected, en-echelon segments and abrupt thickening and thinning along strike. These observations favor magma injection from below rather than lateral injection from a centralized source. However, significant compositional differences preclude derivation of the lamprophyres from either of the central stock magmas.

Lamprophyres are a highly diverse group of dark-colored igneous rocks. In comparison to common igneous rocks such as rhyolite and basalt, they are rare and only occur in small-volume masses such as dikes, intrusive pipes, and small laccoliths. They are characterized by one or more abundant ferromagnesian minerals as phenocrysts; feldspars are typically restricted to the finer-grained matrix enclosing the phenocrysts. The compositional varieties and textural peculiarities are almost endless; thus only a terse, non-inclusive classification of the quartz-bearing and/or quartz-normative varieties is provided in Table 2.

Table 2; Common Quartz-Bearing/Quartz Normative Lamprophyres

minette	dominant phenocrysts are phlogopite/Mg-rich biotite; may also contain diopsidic augite and/or Mg-rich olivine phenocrysts; olivine is typically altered to talc or chlorite; matrix is mainly fine-grained to aphanitic alkali (K, Na) feldspar and the dominant mafic phenocryst mineral(s)
kersanite	dominant phenocrysts same as in minettes; matrix is mainly fine-grained to aphanitic plagioclase (Na, Ca) feldspar and the dominant mafic phenocryst mineral(s)
vogesite	dominant phenocrysts are hornblende; may also contain diopsidic augite and/or Mg-rich olivine phenocrysts; olivine is typically altered to talc or chlorite; matrix is mainly fine-grained to aphanitic alkali (K, Na) feldspar and the dominant mafic phenocryst mineral(s)
spessartite	dominant phenocrysts are same as in vogesite; matrix is mainly fine-grained to aphanitic plagioclase (Na, Ca) feldspar and the dominant mafic phenocryst mineral(s)

Failure by brittle fracture, chilled dike-rock margins, and age-stratigraphic considerations (dikes, Miocene; sedimentary wallrocks, Eocene and Paleocene) all suggest "cold" wallrock and shallow emplacement depths. Some dikes show different interior compositional/textural zones, suggesting injection of two or more, successive batches of magma. The dike orientations and patterns favor simultaneous or near-simultaneous dike-wall rupture and magma injection. The idea that the rising magma fortuitously encountered preexisting, pre-patterned, vertical fractures at depth is a little too contrived to justify a strong defense.

Because of their diversity, small volume, and relative scarcity, lamprophyres have not attracted broad petrologic and geochemical interest. Traditionally, they were regarded as fluid-rich by-products of shallow partial melting in wallrock aureoles around batholiths and stocks. Although many lamprophyres do show elevated contents of volatile components, particularly carbonates, newer evidence does not support the older ideas. For example, mantle xenoliths have been found in minettes of the Navajo volcanic field (northeastern Arizona including Monument Valley) and elsewhere. Also, experimental studies have shown that minettes and other common lamprophyres have low-pressure liquidus temperatures comparable to those of basalts (1150-1200 °C), and many regionally-extensive lamprophyre dike swarms are not even remotely related spatially to a central batholith.

Preservation of high-pressure mineral assemblages and textural patterns in mantle xenoliths force the conclusion that at least some lamprophyres (minettes) rise very rapidly from lower crustal/upper mantle depths. Such rapid ascent rates insure minimal heat losses and in tandem with rapid cooling of the dikes, prevent the xenoliths from re-equilibrating with their new, low-pressure surroundings. Some intrusive lamprophyre pipes and volcanic necks in the Navajo volcanic field are known to have merged upward into explosive, surface diatremes; other associated intrusive pipes in that area, once regarded as "kimberlite", are now recognized as fine-grained breccias and microbreccias comprised predominantly of mantle and lower crustal lithic fragments. Both observations call attention to the explosive power of expanding gases, probably carbon dioxide, during emplacement.

Minette and perhaps other lamprophyre magmas are probably formed in the upper mantle by partial melting of small masses of compositionally-distinctive, subducted, parental material. Examples might include pelagic/hemipelagic sediment, pieces of seamounts, or masses of highly altered seafloor basalt. The melt, including abundant dissolved carbon dioxide and other gases, accumulates in small magma chambers in the upper mantle or near the crust-mantle boundary. Slow crystallization eventually causes a CO2-rich fluid phase to form in the magma chamber. Sudden failure of the chamber initiates explosive breakout and decompression of the fluid phase and high-speed collapse of the chamber. The imploding walls impart an explosive acceleration to the magma, propelling it upward just behind the breakout gases boring and cracking their way toward the surface. Thus the magma arrives suddenly and without substantial heat loss to fill both old and newly-opened fractures (dikes) or fracture intersections (pipes) in the upper crust. Upward movement as a fluidized emulsion of expanding gases, magma particles, and crystals allows for very rapid ascent rates.

San Juan Volcanic Field

The San Juan Volcanic field extends across south-central and southwestern Colorado from the San Luis Valley to the towns of Ouray and Telluride. The volcanic field is conveniently divisible into three major portions.

Divisions of the San Juan Volcanic Field; Major Calderas and Ash-Flow Units

southeastern — San Luis Valley westward to South Fork, CO

Platoro caldera and nested, younger Summitville caldera; multiple named units of the Treasure Mountain Tuff (28 to 32 Ma); mainly high-silica dacite; the La Jara Canyon member (29.3 Ma; 20-35 % phenocrysts; plagioclase > biotite > augite > sanidine) is the most voluminous (500 to 1000 cubic km)

central — Area from South Fork, CO, westward toward Lake City, CO

Includes the Creede and five other major calderas; numerous widespread ash-flow sheets include the Snowshoe Mountain Tuff (26.6 Ma; zoned upward from high silica dacite to andesite; Creede caldera), Carpenter Ridge Tuff (27.4 Ma; zoned upward from rhyolite to dacite; Bachelor caldera), and Fish Canyon Tuff (27.8 Ma; dacite; La Garita caldera); the Fish Canyon is the most voluminous ash-flow tuff in the San Juan field (about 3000 cubic km) and is notable for its unusually high content (40-50 %) and diversity of phenocrysts (plagioclase > sanidine > biotite > quartz > hornblende)

western — area from Lake City, CO, westward to Telluride and Ouray, CO

Includes two major calderas plus the Silverton and Lake City calderas, nested in the older, much larger Uncompahgre caldera); the Sapinero Mesa Tuff (28 Ma; low-silica rhyolite; 5 % phenocrysts, sanidine > plagioclase > biotite > augite; Uncompahgre caldera) is the most voluminous (> 1000 cubic km) ash-flow sheet

Stratovolcano building from early through middle Oligocene time characterized the initial phase of volcanism. Volcanic products, dominantly intermediate in composition (mafic andesite to andesite), included lava flows, flow breccias, feeder dikes, near-vent fragmental deposits, air-fall and pyroclastic-flow tuffs, mudflow deposits, and epiclastic sedimentary units. The latter two characterized the lower flanks of the volcanoes and intervening alluvial valleys. As stratovolcano building continued, batholithic-size, felsic magma bodies (granodiorite to granite) grew beneath the major clusters of stratovolcanoes. Mineral exploration drill holes in the western San Juans intersected the uppermost tips of a batholith about a mile below base elevations of the Oligocene stratovolcanoes. Continued engorgement of the batholiths effectively shut down stratovolcano growth and set the stage for the major episode (Oligocene through early Miocene) of explosive, silicic, ash-flow volcanism and caldera collapse. The most voluminous of the ash-flow sheets are dacitic in composition but lessor volumes of andesite, low-silica rhyolite, and rhyolite were erupted. During the closing stages (late Miocene) of volcanism, basaltic lavas were erupted from vents beyond the calderas while rhyolite ash-flow tuffs were being erupted from the caldera complexes.

Ash-Flow Tuffs, Welded Tuffs, and Calderas

Large-volume, ash-flow tuffs and caldera formation have spawned a specialized descriptive terminology and many complex, novel, geologic concepts. These are briefly reviewed in the following section.

Pyroclastic flows move far beyond the confines of the source caldera and deposit a comparatively thin, widespread sheet of ash-flow tuff. These are known as outflow sheets. Mineralogic and chemical characteristics, although somewhat variable laterally and vertically, are usually consistent enough to allow the same outflow sheet to be identified and traced over a wide geographical area.

Liquid magma fragments and pumice lumps in a hot pyroclastic-flow deposit are capable of deformation by flowage. As the individual particles flatten and pore spaces are closed, the glassy particles are squeezed into close contact, causing them to join (weld) together. Subsequently, fast cooling preserves the glass as a basal vitrophyre or slower cooling promotes crystallization (devitrification) to an aphanitic/microcrystalline textured tuff. Phenocrysts and lithic fragments are preserved in tact, but may be altered to varying degrees. Eutaxitic texture describes the discontinuous layering pattern caused by compression and flattening of pumice lumps.

A significant, but highly variable percentage of the erupted pyroclastic-flow material accumulates inside the associated caldera, especially if subsidence is initiated early during the course of the eruption. These deposits are defined as intra-caldera or caldera-fill units. Given such huge eruption volumes and deep subsidence, intra-caldera deposits are usually very thick (thousands of meters) and substantially thicker than outflow sheets deposited during the same eruption. However, outflow tuffs originating elsewhere may accumulate (pond) to unusual thicknesses in a nearby caldera, thus complicating the process of assigning specific tuff sheets to specific source calderas. Tuff deposits inside a caldera are much more likely to be hydrothermally altered than outflow sheets. Thus outflow tuffs and intra-caldera or ponded outflow deposits from the same eruption may be difficult to identify with certainty. Toward the perimeter of the caldera, intra-caldera tuffs may grade abruptly into mass wasting deposits (landslide breccias and megabreccias) derived by collapse of the caldera walls.

A cooling unit is defined as a pyroclastic-flow deposit that cools as a single entity. Cooling units may represent a single deposit from one major eruption or an accumulation of deposits from multiple flows erupted in rapid succession. Cooling units develop distinctive, subhorizontal, lithologic zones that at first glance might be misidentified as "internal stratigraphy"; however, keep in mind that these zones evolve in situ from the pyroclastic-flow deposit and do not represent original, stratigraphic variations.

Simplified, Major Lithologic Zones of an Ash-Flow Tuff Cooling Unit

Devitrified (Crystallized) Upper Zone (Thick; Hard; Well Indurated)

Comprises the bulk of the cooling unit. May contain open cavities lined with drusy crystals grown from a hot, gas phase rich in water vapor. Original glassy particles have crystallized (devitrified).

Basal Vitrophyre (Usually Thin: Hard; Well Indurated)

A glass (obsidian) sheet with embedded phenocrysts and lithic fragments is formed toward the base of a cooling unit by compression and welding of originally hot, glassy fragments. The glassy zone is preserved because vapor loss and fast cooling prevent crystallization.

Basal Non-Welded Zone (Very Thin; Soft; Weakly Indurated)

Non-welded, uncompacted accumulation of original, pyroclastic-flow particles (glassy fragments, pumice lumps, phenocrysts, and lithic fragments) at the base of the cooling unit; contact with cool, original land surface promotes rapid heat loss, preventing post-depositional welding, compaction, and crystallization.

Many outflow ash-flow tuff sheets have upper portions that are more mafic than the bulk of the deposit. Examples from the San Juan field include the Snowshoe Mountain Tuff (high silica dacite capped with andesite) and the Carpenter Ridge Tuff (lower rhyolite and upper dacite zones). Keep in mind that relative vertical positions of pyroclastic-flow material in the tuff sheet are in reverse order to their depths in the source magma chamber; magma originally at the top of the chamber is erupted first and deeper magma is tapped later toward the end of the eruption. Compositional zoning is thus strong evidence for density stratification of the magma chamber at the time of the eruption. In general, less dense, more siliceous magmas (rhyolite/dacite) overlie denser, more mafic dacite/andesite magmas at depth.

Gradual filling and engorgement of the batholith are accompanied by broad doming and stretching of the rocks above the magma chamber. Radial stretching induces vertical to near-vertical, arcuate, circumferential fractures to form above the domical surface of the buried magma body. These fractures are known as ring fractures. Lengthened laterally and vertically, they eventually provide direct channelways from the magma body to the surface. Relatively small-scale, pre-caldera eruptive vents, eruptive vents and subsidence associated with catastrophic eruptions, and thick, moundlike, post-collapse, intra-caldera lava flows are all to some extent localized by ring fractures. During the brief catastrophic eruption episode, extrusion rates far exceed rates of magma-chamber recharge, resulting in temporary evacuation of the upper part of the magma chamber. Rocks above the chamber, already bounded by earlier-formed ring fractures, are thus left unsupported and collapse into the vacant space. Landslides and other mass wasting events during and soon after the catastrophic eruption enlarge the near-surface dimensions of the caldera and destroy its original, vertical-walled form.

Following a catastrophic eruption, additional magma often "recharges" the batholith, renewing inflation of the caldera region. In response, part of the subsided zone bulges upward as a resurgent dome. The domed rocks are extended and broken by normal faults. An apical or keystone graben forms along the crest of the dome. Growth of a central resurgent dome produces a circular to elliptical valley just inside the perimeter of the caldera. This valley is called a moat; derivation of the term is self evident to anyone familiar with medieval castles, knights, and battlements. The moat is eventually filled with a remarkably diverse rock assemblage, including fine-grained lake beds, hot spring deposits, landslide debris, lava flows, ash-flow tuffs, and products of extensive hydrothermal alteration. Snowshoe Mountain, just south of Creede, CO, is a resurgent dome in the center of the Creede caldera, and near Creede, the Rio Grande follows a semicircular course through a valley cut into soft lake beds of the Creede caldera moat.

Redondo Peak, in the center of the Jemez caldera between Taos and Cuba, NM, is another well-documented example of a resurgent dome. The Jemez caldera moat is still easily recognized as Valle Grande, the extensive, open valley encircling Redondo Peak.

Mineralization and Mining in the Creede District, Colorado

Commercial-scale mining in the Creede District began in 1889. Extremely-rich "bonanza-type" silver ores, encountered at shallow depths, turned the Willow Creek Valley into an instant "strip city" replete with all the amenities, the good, the bad, and the ugly, associated with a turn-of-the-century, western, silver boom town. The district survived the silver panic (silver price collapse) and disastrous fires of the early 1890s, and returned to prosperity as the high-grade silver ores kept coming. Gradually, however, ore grades declined as mining reached deeper levels and the strongly enriched ores of the oxidized zone were mined out. Lead and zinc production with some silver, characterized deeper mining activities from the 1920s on. The great heyday of quick fortunes and fabulous silver ores thus lasted about 30 years. From 1889 to 1964, the district had produced about $66 million in metals, over half in silver and the rest in lead, zinc, gold (about $3 million) and copper. Most ore was produced from the Amethyst vein system. Like many old mining camps in the west, Creede is blessed with a beguiling history and spectacular scenic surroundings. Thus hard-rock mining with its honky-tonk saloons and get-rich-quick clientele has given way to wholesome outdoor activities, such as hiking, fishing, hunting, geology field trips, and family vacations.

The mineral deposits at Creede are contained in N- to NNW-trending fissure veins of the Creede graben, a downdropped block about 5 km in width (E-W) and 9 km in length (N-S). The drainage basin of Willow Creek provides a rough approximation to the surface dimensions of the graben-and-vein system. The fissures extend northward from the walls of the Creede caldera at Creede into the southern portion of the San Luis caldera. However, the main portion of the graben and fissure system evidently developed originally as extension fractures (an apical graben!) on a resurgent dome in intra-caldera welded tuffs of the slightly older Bachelor caldera. "Ponding" and post-depositional flowage suggest that the original graben fissures developed while the wallrock tuffs were still accumulating and hot.

The deeper, unoxidized portions of the veins consist mainly of quartz and metal sulfide minerals (Table 3) as open space fillings between chloritized, brecciated fragments of welded tuff. Repeated faulting movements during the two or so million years following collapse of the Creede caldera evidently kept the vein system "open" and allowed for more or less continuous hydrothermal circulation. Mineralization was completed by about 25 Ma. Detailed studies of fluid inclusions and stable isotopes suggest that two, very different fluids were involved in the mineralization. One was a hot, very saline brine that originated at depth from the moat and moat sediments of the Creede caldera; the other was derived from meteoric water in the high terrain near the continental divide north of Creede. Metal sulfides and quartz were slowly deposited in the fissure veins by the rising saline brine. Unusually rich concentrations of silver minerals were probably deposited where mixing with the shallower, cooler, less-saline fluid destabilized highly soluble metal chloride complexes dissolved in the brine, allowing the metals to precipitate as metal sulfides (Table 3). Native silver and other secondary, silver-bearing minerals accounted for the unusually high silver values in the near-surface, oxidized portions of the veins. However, the silver halides (Table 4) and some of the native silver may also have been primary minerals of the mixing zone between the two, different, hydrothermal fluids.

At Wagon Wheel gap, a few miles east of Creede, the Colorado Fuel and Iron Company had developed a mine for fluorite (fluorspar). The mineral was used as a fluxing agent in iron ore smelting and steel making at a now-defunct plant at Pueblo, CO. In addition, the deposit contains rhodochrosite, manganese oxides, and two, rare, fluorine-bearing minerals, creedite and gearksutite (Table 5).

Table 3; Creede District; Deeper Mine Levels
Primary Vein Minerals Unaffected by Near-Surface Oxidation and Weathering

chalcopyrite	$CuFeS_2$	copper iron sulfide
pyrite	FeS_2	iron disulfide; isometric
marcasite	FeS_2	iron disulfide; orthorhombic
galena	PbS	lead sulfide
sphalerite	ZnS	zinc sulfide
argentite	Ag_2S	silver sulfide
stephanite	Ag_5SbS_4	silver antimony sulfide

Table 4; Creede District; Shallow Mine Levels
Sulfur in Primary Sulfide Minerals Oxidized to Sulfate

cerargyrite	AgCl	silver chloride
bromyite	AgBr	silver bromide
native silver	Ag	silver metal
cerussite	$PbCO_3$	lead carbonate
anglesite	$PbSO_4$	lead sulfate
chrysocolla	$CuSiO_3 \cdot 2H_2O$	copper silicate hydrate
goslarite	$ZnSO4 \cdot 7H_2O$	zinc sulfate hydrate
melanterite	$(Fe, Zn, Cu, Mg)\ SO_4 \cdot 7H_2O$	magnesium, copper, zinc, and iron (2+) sulfate hydrate
jarosite	$KFe_3\ (OH)_6\ (SO4)_2$	potassium iron (3+) hydroxy sulfate
argentojarosite	$AgFe_3\ (OH)_6\ (SO4)_2$	silver iron (3+) hydroxy sulfate
pumbojarosite	$PbFe_3\ (OH)_6\ (SO4)_2$	lead iron (3+) hydroxy sulfate

Table 5; Rare Fluorine Minerals of the Wagon Wheel Gap Fluorspar Mine

creedite	$Ca_3Al_2F_4\ (OH)_6\ SO_4 \cdot H_2O$
gearksutite	$CaAl\ (F, OH)_5 \cdot H_2O$

Jemez Mountains

On the trip from Taos to Cuba and the Circle A, both groups will inspect the spectacular Jemez volcanic center (Fig. 13) and gaze into the Rio Grande Rift from high on its western margin. Before this trip be sure to study the Landsat image of New Mexico (the Jemez volcanic center is the erupted blister just southeast of Cuba) and the marvelous map of the Jemez Mountains by Smith, Bailey, and Ross (USGS Map I-571). Don't get too depressed by this map, note it is the result of 21 years of mapping!
The location of the Jemez volcanic center (JVC) is controlled by the geometry of the Rio Grande Rift, so let's review rifts for a moment. A characteristic of continental rift valleys such as the Rio Grande, the East African (Kenya, Tanzania), and the Baikal (central Siberia, Russia) is high heat flow. Heat flows of 2-2.5 HFU (two to two-and-a-half times crustal averages) are common in the Rio Grande rift (Fig. 22). Higher values (6 to 16 HFUs) are reported in a few very young volcanic centers (such as the JVC) or near faults which act as conduits for rising heated waters.

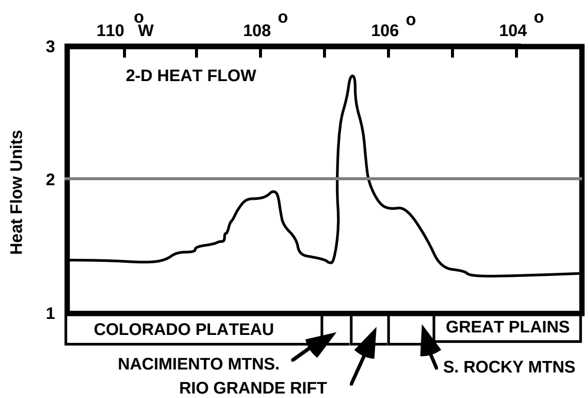


Figure 22: Measured heat flow: the Rio Grande Rift at 36 deg N

Seismic and gravity data indicate a thinner-than-typical continental crust beneath the rift. From west to east, the North American continent is 40 km thick under the Colorado Plateau, 33 km under the rift, and 50 km under the Great Plains. If one combines crustal thinning (reduced load pressure) with a steady-state thermal model based on the heat flow data (Fig. 22), it is reasonable to infer that mantle peridotites beneath the rift have crossed above solidus temperatures and are partially melting at depths of only 30-35 km. One rift formation model (based primarily on Bridwell, 1978) is as follows:

1. an asthenospheric thermal pulse initiates adiabatic, upward flow of mantle peridotite, resulting in partial melting in the upper mantle

2. buoyant uplift and arching of the overlying lithosphere and thinning of the continental crust

3. extensional normal faulting along the crest of the arch, formed keystonelike blocks in the thinned crust

4. injection of primitive, mantle-derived, basaltic magmas along deep faults caused melting of lower crustal rocks and magma mixing, generating basaltic andesite and more evolved, hybrid, magma compositions

5. continuing uplift; rocks beneath the rift become hotter

6. development of deep, elongate, and often en echelon graben segments at the surface which rapidly fill with clastic and volcaniclastic debris and volcanic rocks.

Remember that while the central portions of the rift may be structurally lower than the margins, the total motion of the rift system is up relative to the mantle diapir below and nonextended crust in the Great Plains.

Let's get back to the Jemez Mountains (Fig. 23). The JVC consists of two nested calderas, the older Toledo and the younger Valles calderas. Each collapsed during a huge ignimbrite or ash flow eruption. The eruptive events are responsible for many of the volcanic rocks and landforms we see in the region. The JVC is notable for its youth, excellent preservation, and for the fact that it represents an unusually large accumulation of felsic volcanic rocks associated with a continental rift margin; such volcanic centers more typically erupt mafic and/or alkalic mafic magmas.

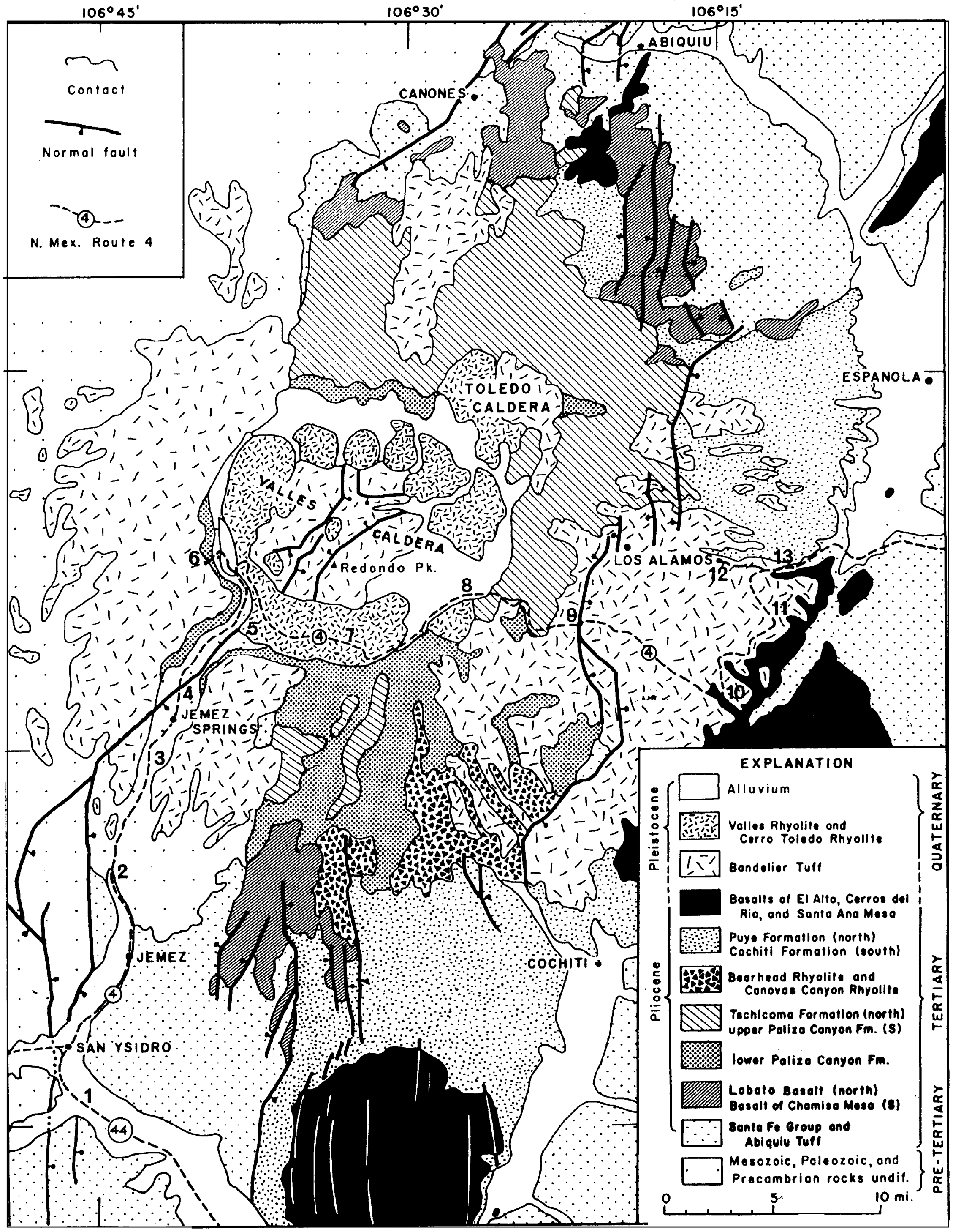


Figure 23: Geologic map of the Jemez Mountains (from NMGS Circular 163, p. 185). The bold numbers not in circles are field trip stops from NMGS Circ. 163. We will refer to these same stop numbers in the text. The circled numbers are NM Highway numbers.

The JVC is built on the east-dipping flank of the Nacimiento Uplift (Fig. 15). Extrusive rocks from the JVC lie on top of Precambrian, Paleozoic, and Mesozoic rocks along the eastern margin of the uplift and the western margin of the Rio Grande Rift. The JVC vents were controlled by the Pajarito Fault, in this area the western rift-bounding normal fault of the Rio Grande rift (Fig. 13). Volcanism began about 13 Ma, but the caldera-forming phase that built the Toledo/Valles caldera complex began at 1.5 Ma. As a perusal of the Smith, Ross, and Bailey map will have shown, the detailed stratigraphy of a large caldera center can be exceedingly complex. To simplify things a bit, refer to the Valles area stratigraphy (Fig. 24).

The most important unit in the JVC, the Bandelier Tuff, includes extrusive rocks produced by the two caldera-collapse eruptions. The Bandelier Tuff is a pumice-bearing, vitric, white to pale-yellow, rhyolite tuff with a characteristic swiss cheese weathering pattern.

The Bandelier Tuff is subdivided as follows (Fig. 24).

Bandelier Tuff Unit	Associated Caldera	Age
Tshirege member	Valles	1.1 Ma
Cerro Toledo Rhyolite	post-Toledo, pre-Valles	
Otowi member	Toledo	1.4 Ma

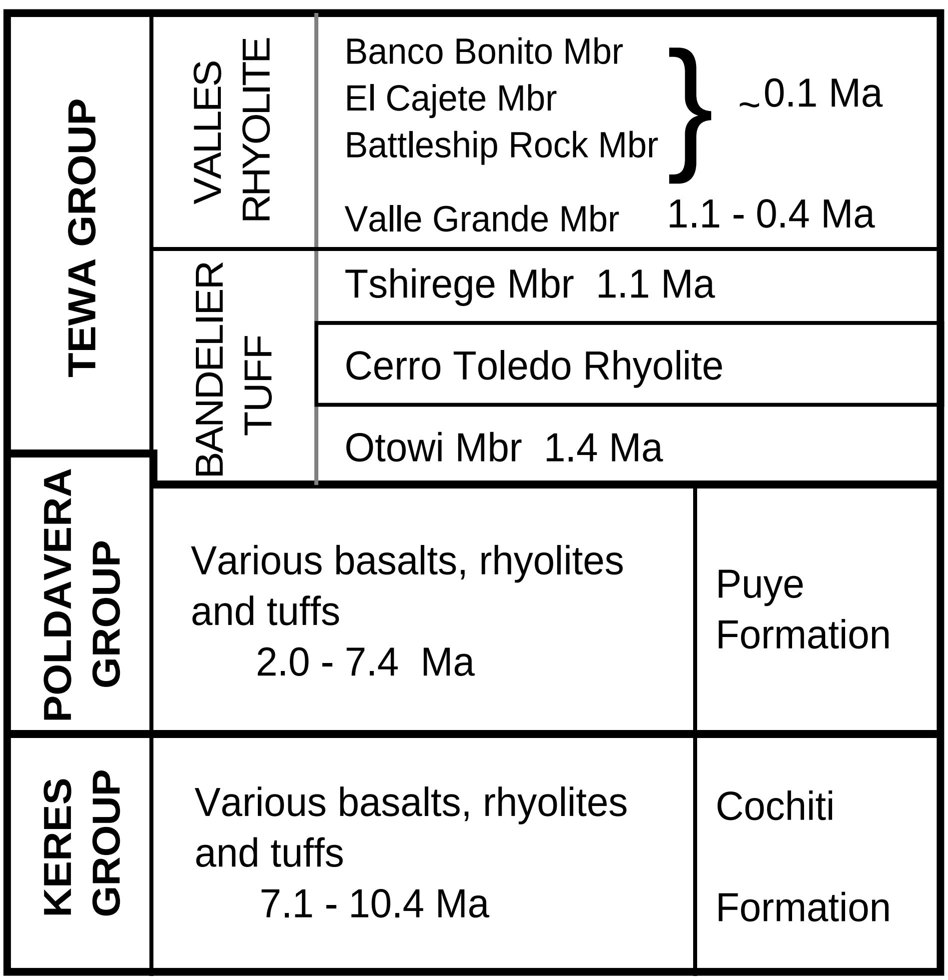


Figure 24: Stratigraphic nomenclature and K-Ar ages in the Jemez Volcanic Field

The Valles caldera-forming eruption was catastrophic. About 50 km3 of ash and pumice were erupted over a short period of time (a few days to maybe a week or two). For reference, the 1980 eruption of Mt. St. Helens produced 1 km^3 of ejecta.

The JVC is a young volcanic center. To envision its 3-dimensional morphology, use the present-day topographic relief to imagine what the terrain was like at the time of the eruptions. The distributions and thicknesses of pyroclastic deposits vary greatly. Ashfall and pumice falls, as contrasted to lava flows and ashflow tuffs, cover all but the steepest slopes with uniformly thick blankets. Rhyolite lava flows usually form domes and mounds near to their eruptive vents; ashflow tuffs may spread over vast areas surrounding the source caldera; the deposits are thickest in pre-eruption valleys and thin to nonexistent on hills and topographic divides. Pyroclastic-flow deposits are unsorted and not bedded. Ashfall deposits are typically well bedded and they may be well sorted; clast size decreases with distance from the vent. Think, too, how quickly unconsolidated ashfall or pyroclastic-flow deposits will erode away.

In places the two members of the Bandelier Tuff are separated by the Cerro Toledo Rhyolite. Strong relief and deep valleys characterized the land surface when the Tshirege member was erupted. Thus in some places, the Tshirege member fills valleys cut into the Otowi tuff and older rocks, or it caps old hills on the pre-Bandelier erosion surface.

Following about 100,000 years after collapse of the Valles caldera, a resurgent dome (called Redondo Peak), rose in the center of the collapse structure (Fig. 23). This spectacular mountain, elevation 11,250', is the highest point in the JVC and can be seen from as far away as Bernalillo (the pre-caldera collapse top of the volcano was much higher). The core of the resurgent dome is undoubtedly a near-surface, intrusive rhyolite. However, one can presently see only Bandelier tuff and moat, lake sediment passively carried upwards on the rising dome. If you've seen video footage of the lava dome at Mt. St. Helens, Redondo Peak formed in a similar way, but of course, the volumes of dome-forming magma were orders of magnitude larger.

Moat-fill sediments, moat-related volcanic rocks, and a ring of twelve, isolated, post-caldera lava domes (0.49 to 1.14 Ma) surround the resurgent dome. The lava domes mark the ring fracture zone of the caldera; the oldest domes are south and east of the center of the caldera and they become successively younger in a counterclockwise sense. Volcanic rocks that postdate the Bandelier Tuff are lumped as Valles Rhyolite (a potentially misleading designation since they are younger than the caldera). There's lots to see on our Jemez caldera trip. The sequence and number of stops will vary depending on time, weather. The sequence of stops below assumes one first heads east from La Cueva.

The El Cajete roadcut (stop #7, Fig. 23): This exposure contains different types of volcanic ejecta and is a good place to see a variety of pyroclastic materials and lavas. The topmost unit is the Banco Bonito member of the Valles Rhyolite (Fig. 24). It's the basal, blocky, vitrophyric (glassy) portion of a rhyolite lava flow. The Banco Bonito overlies the El Cajete member of the Valles Rhyolite, a well-bedded pumice and ashfall deposit C-14 dated at 42,000 years. The basal El Cajete contains some pinkish ashflow tuffs that fill small, roadcut-scale swales on the underlying South Mountain flow of the Valle Grande member, Valles Rhyolite. The Valle Grande is a rhyolite lava dated at 0.49 Ma (K-Ar). Thus, these rocks postdate caldera collapse and resurgence. However, they are spatially related to the various ring-fracture domes.

The Valle Grande overlook (stop #8, Fig. 23): We can see the resurgent dome, Redondo Peak, and many of the ring-fracture domes from this location. The flat, grassy, pasture lands that stretches from here to Redondo are an old lake bottom. The eruption that formed the caldera was not dissimilar to the one that destroyed Mt. Mazama and formed Crater Lake in Oregon, although the Valles event was a good deal larger. The caldera lake was emptied after the Jemez River breached the south wall of the caldera. This also happens to be an especially nice settings for a cattle ranch. You might want to get out a pair of binoculars here and scan the valley — the little dots are mainly cattle and maybe a few deer or elk (sorry, no dinosaurs!).

The Pajarito Plateau: We will descend, precipitously, the Pajarito Fault scarp that marks the east flank of the Valles caldera. On a clear day, the Sandia Mountains near Albuquerque can be viewed through the trees to the right (south). The Pajarito Plateau is a broad, flat, apron of Bandelier tuff that extends out into the Rio Grande Rift (Fig. 23). Deeply incised rivers and streams produce spectacular canyons and gorges. In one such canyon, Frijoles Canyon to the south, early Pueblo Indians built cliff-houses and freestanding structures now preserved at Bandelier National Monument. We will likely not stop there since we will see the Trump Towers of cliff-dwellings at Mesa Verde later in the summer. Along the highway, you will see bunkers and buildings with U.S. Government codes (part of the Los Alamos National Lab.) tucked into cliffs and crannies of Bandelier Tuff. We can only imagine what Strangelovian-type materials and devices lurk within.

Most of the Bandelier Tuff on the Pajarito Plateau is the younger, Tshirege member; it is typically 250 m thick in this area while the older Otowi member is only about 75-90 m thick. The Bandelier Tuff exhibits a characteristic, swiss-cheese weathering pattern. The larger, highly porous pumice lumps disintegrate more rapidly than the matrix of the rock, resulting in numerous small holes and openings that enlarge by further weathering.

White Rock Canyon Overlook (stop #10, Fig. 23): From the municipal park in White Rock, a bedroom community for Los Alamos, we look down into White Rock Canyon, cut by the Rio Grande after eruption of the Bandelier Tuff. The tuff caps the high plateaus and makes comprises most of the rocks exposed in the canyon walls. La Mesita, a basaltic volcanic center, is the large, dark-colored hill to the north directly across the canyon. Black Mesa is the prominent basalt-capped mesa to the north-northwest. It was eroded from rocks of the Española Basin, part of the northern Rio Grande Rift (Fig. 13). Black Mesa was sacred ground to the Indians of the San Ildefonso Pueblo, nestled at its base. In 1680, the northern New Mexico Indians rebelled against 150-years of tyrannical Spanish; many colonists and missionaries were killed, and the Spanish retreated to El Paso. Reinforced, well-armed, and bent on vengeance, they returned in 1692 and forced the pueblos into submission. The Indians of San Ildefonso refused and retreated to Black Mesa. The Spanish laid siege and eventually captured the mesa; the people of San Ildefonso leaped to their deaths in defiance, were killed, or forced into slavery.

On a typical, clear, early summer, New Mexico day, you can see the snow-capped peaks of the Sangre de Cristo on the opposite side of the Rio Grande Rift. The southernmost peak is Santa Fe Baldy. It's just east of Santa Fe and marks the southern end of the Sangre de Cristo range.

After crossing the Valle Grande to La Cueva, our route heads south through San Diego Canyon toward Jemez and San Ysidro on NM-4. The canyon was cut by the Jemez River along a high-angle normal fault that cuts the margin of the Valles caldera (Fig. 23). The lake that filled the caldera depression apparently overflowed to the south across a plain underlain by Bandelier Tuff. This proto-Jemez River downcut along the Jemez Fault through the tuff and into the underlying Paleozoic rocks. The lake was eventually drained about a million years ago.

Battleship Rock (stop #5, Fig. 23): Battleship rock is a convenient lunch stop. You can visit with cronies, swap war stories, and compare notes on faculty, TAs, and drivers, but not the camp manager!

Battleship Rock is a 250 ft-thick outlier of columnar jointed, vitric, welded tuff that exhibits spectacular eutaxitic textures. The rock represents one of the youngest pyroclastic flows erupted from the JVC (0.1 Ma). The source vent was 3-4 miles to the east near El Cajete Crater.

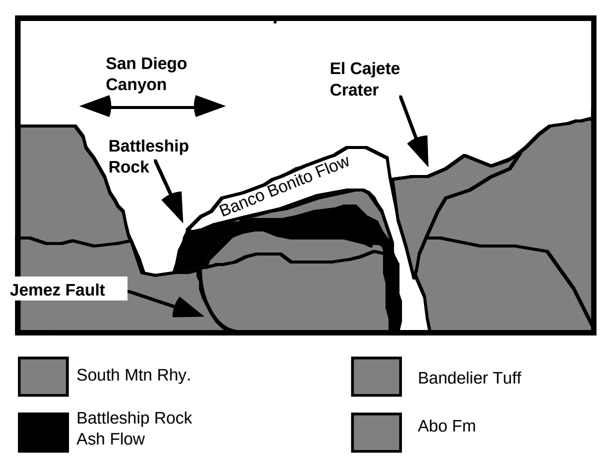


Figure 25: Schematic cross-section of Battleship Rock (not to scale)

The Rock is an example of inverted topography (Fig. 25). The pyroclastic flow moved down the proto-Jemez River channel, filled the valley, welded, and cooled to the resistant welded tuff we see today. When the Jemez River renewed downcutting, it eroded out softer rocks of the old valley slopes avoiding the more resistant welded tuff. Thus the old river valley now stands as a ridge composed of welded tuff — inverted topography.

You can climb Battleship rock along a well worn trail lust north of the picnic area — but **once at the top be careful of dislodging rocks**. Many an eager geologist looking at the fiammé have had to withstand a rain of rocks dislodged by careless climbers above. There are actually two separate flow units here, but being erupted very close in time, they cooled as one unit. Try finding the 12" zone of flattened pumice lumps near the top of the lower flow unit. It is about 115' above the base, but may be difficult to find.

As we continue south, we follow San Diego Canyon and the trace of the Jemez Fault. Offset is evident in several places; compare outcrop elevations on both sides of the canyon. Pennsylvanian carbonate rocks (Madera Formation) in the west canyon wall are at the same elevation as Permian redbeds in the east wall. Therefore, the east side of the Jemez Fault must be down (younger rocks) relative to the west side (older rocks).

Soda Dam (stop #4, Fig. 23): At Soda Dam, splays of the Jemez Fault cross the canyon and act as conduits for rising hydrothermal fluids. Exposed rocks are badly altered, Precambrian granites uplifted as a horst between two splays of the fault. The heated waters are apparently dissolving carbonate rocks at depth, probably Madera limestones. Note that Permian redbeds make up most of the southern and eastern valley floor. The hot spring waters cool and precipitate calcium carbonate, building up the massive travertine "dam" that we see. The dam has a layered or exfoliate structure typical of travertine, hot spring deposits. Early reports, about 1900, indicated that 22 springs issued from the dam. Almost a hundred years later, a single, present-day hot spring issues from the base of the roadcut and flows to a pond just east of the road.

You can see other, higher, travertine deposits perched on the valley walls. Some are as high as 300 m above the present valley floor and incorporated Pleistocene stream deposits. This indicates that the Jemez River has downcut appreciably in the last few hundred thousand years. A mile or so south of Soda Dam, you will pass through the little town of Jemez Springs. It houses several spas and religious retreats; the hot spring waters are reputed to redirect lost souls and cure what ails ya! For those who read road signs, the word **paracleet** may present anything from a trivial-pursuit riddle to a mid-life crisis. Relax? A paracleet is not a small green parrot, but a person who lends comfort or succor. It comes from an old Greek word meaning to intercede on someone's behalf.

Several miles south of Jemez Springs, San Diego Canyon widens considerably, offering excellent views of Bandelier tuff overlying Permian redbeds (a profound unconformity!). The welded, columnar-jointed, lower Bandelier Tuff (Otowi Member) forms spectacular cliffs up to several hundred feet high. The younger Tshirege Member is less welded, softer, and less of a cliff former. With careful observation, one can see the pre-Bandelier surface and paleovalleys filled by ashflow tuff. You may recognize the erosion surface representing the 300,000 year gap between the Otowi and Tshirege Members and mesas eroded from Otowi later buried by Tshirege tuffs.

NM-4 will pass through the Jemez Pueblo, one of the larger and more prosperous pueblos in this area; about six or seven miles farther south, NM-4 intersects NM-44 at San Ysidro. From here, we turn right and head north (about 30 miles) to Cuba.

The Colorado Plateau Revisited

This is a good time to review Colorado Plateau geology (Fig. 26). As we have noted, the Plateau is a high tableland underlain by flat-lying to shallowly dipping sedimentary rocks. These sediments were deposited on a relatively flat erosion surface of Precambrian continental basement rocks. The Phanerozoic sedimentary rocks are platformal, ranging in age from Cambrian to Recent. There are, as one might expect in a platform sequence, many gaps. In addition, only portions of the stratigraphic column can be seen in any one place (Fig. 27). For much of the Paleozoic, the Colorado Plateau region was periodically inundated by shallow seas. Most of the clastic sediments deposited on this cratonic platform were shed off of the Ancestral Mogollon Highlands in southern Arizona and the Uncompahgre Highlands in southwestern Colorado and northern New Mexico (Fig. 18). Minor uplifts like the Zuni and basins like the Paradox resulted in local modifications of

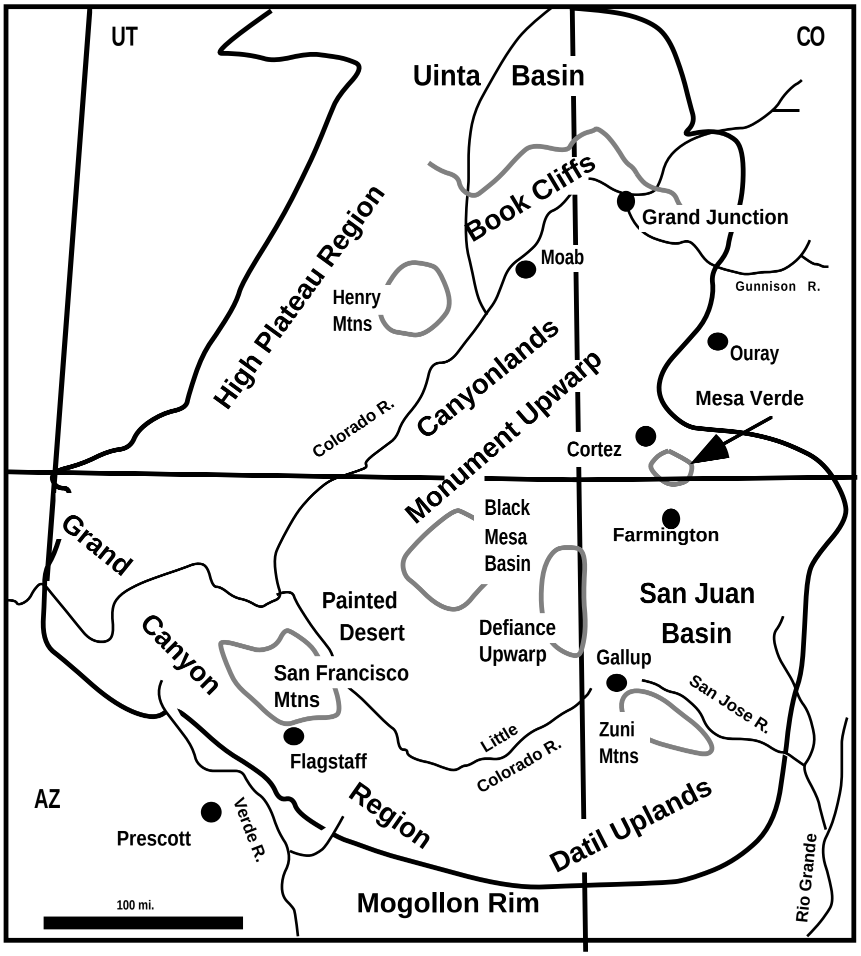


Figure 26: Major physiographic regions of the Colorado Plateau

this depositional sequence. By early to mid-Mesozoic, episodic sea level rise and fall and the general wearing away of the highland source regions for the Permian and early Triassic clastic sediments produced the complex pattern of marine-deltaic-fluvial deposition that we saw in Cuba.

Tectonic subsidence can be measured by the thickness of the sedimentary cover. During the 500 million years from the Cambrian to the end of the Cretaceous, net subsidence of about three kilometers is recorded. In some places, entire sections are missing, e.g., the pre-Permian along the eastern edge of the San Juan Basin where the Uncompahgre Uplift either prevented deposition of late Paleozoic sediments or allowed them to be eroded away. In the past 70 million years, since the end of the Cretaceous, the area as a whole has been dominated by uplift and has "recovered" about 2 km of the Phanerozoic subsidence.

How did the Colorado Plateau form? The Colorado Plateau is part of the North American craton — the stable nucleus of North America. This, then, makes the Plateau a bit odd. It is separated from the rest of the craton by Cenozoic tectonism: the Rio Grande Rift and Laramide uplifts on the north and east and neotectonic extension in the Basin and

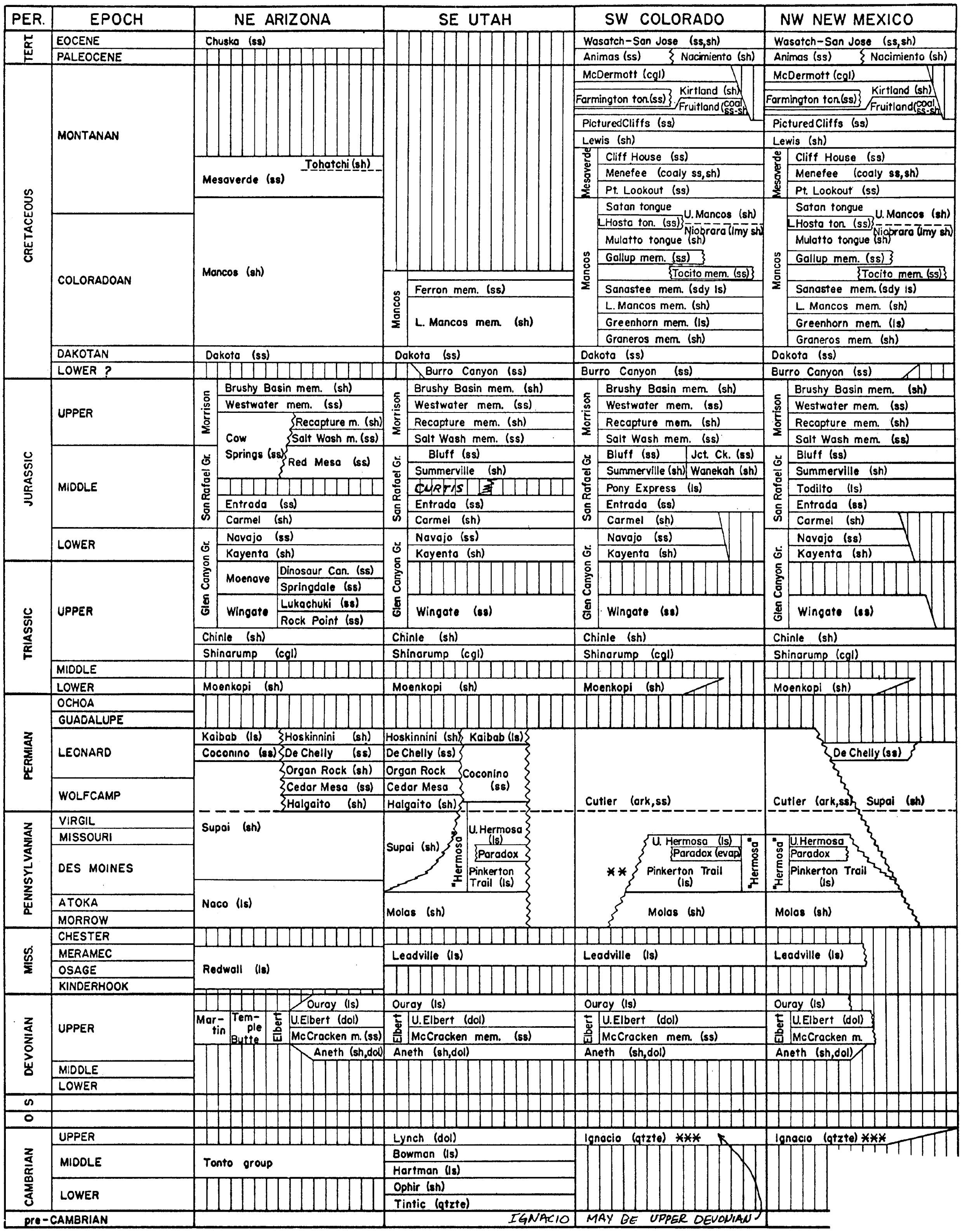


Figure 27: Stratigraphic columns from the Four Corners Region (Elias, 1968)

Range Province to the west and south. Geophysically, there is nothing especially unusual about this area. It appears to be in isostatic equilibrium, unlike the surrounding tectonically active areas. The continental crust is thicker than usual, 45-50 km, whereas the crust beneath the surrounding Basin and Range and the Rio Grande rift are only 30 km thick. Heat flow, though higher than typical cratonic areas (Fig. 22), is on the low side for such a thick crust. The regional magnetic high is thought to reflect this lower heat flow (i.e., low heat flow means a depressed Curie point isotherm and thus a thick, magnetic crust). The heat flow is <u>much</u> lower than that in the surrounding tectonically active areas.

One explanation for the thicker that normal continental crust and resulting isostatic uplift is an off-scraping of the continental lower crust and upper mantle to the west beneath the Basin and Range followed by underthrusting or underplating of this material beneath the Plateau. Others have suggested that the Colorado Plateau sits astride the East Pacific Rise which has been overridden by the North American Plate. It should be pointed out that much of the Cenozoic uplift can be seen as simply a reflection of the overall regional uplift of the western U.S. (which still requires an explanation).

The real conundrum is why the Plateau has remained as a single, intact, undeformed piece of crust, surrounded on all sides by areas of compressive and extensional deformation.

When did the Plateau form? As an entity, the Plateau was essentially defined by the end of the Laramide orogeny, Late Cretaceous to early Tertiary (40-80 Ma). This is well before rifting began in the Rio Grande Rift (20 Ma) — these are not contemporary events. Furthermore, all was not quiet on the Plateau during the Cenozoic. Any number of volcanic fields have been and still are active including the Oligocene (Navajo volcanic field), Miocene-Pliocene (San Francisco and Mt. Taylor volcanic fields), and Holocene (Sunset Crater; formed about 1180 A.D.).

<u>Energy Resources of the San Juan Basin</u>: Oil and gas were first discovered in the San Juan Basin in 1910. The basin is a giant oil and natural gas field (i.e., one with >500 million barrels of oil or gas equivalent), having once had recoverable reserves of about 900 million barrels of oil and 5.75 trillion cuft of gas. As of 1977, about 550 million barrels of oil and 0.66 trillion ft3 of gas had been produced. The vast majority of this production was from Cretaceous stratigraphic traps at depths of 5000-6000 ft. While there is limited oil production today, stable, domestic, natural gas prices have stimulated gas exploration in the basin over the last fifteen years.

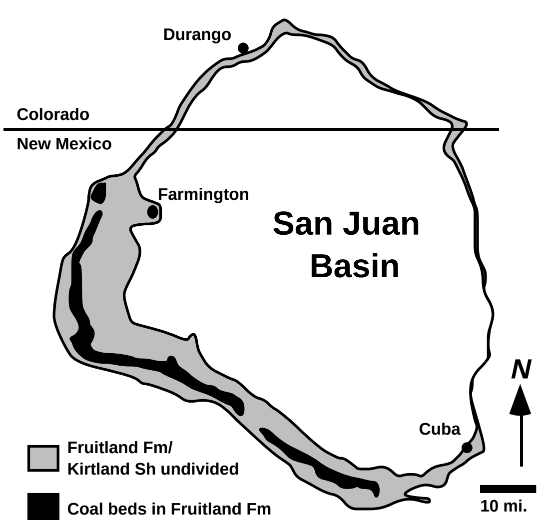


Figure 28: Outcrop pattern of the Cretaceous coal beds of the San Juan Basin

The southwestern rim of the San Juan Basin (Fig. 28) is a highly productive coal provinces. Subbituminous coals are mined from the Menefee Formation (Mesaverde Group; remember Cuba) and the Fruitland formation, especially where exposed along the north flank of the Zuni-Defiance Uplift. Utah International's Navajo mine and the Four Corners generating station opened in 1963 near Farmington, NM, is one of the largest continuous coal mining and power generating facilities in the world. Power lines stretch to LA, Phoenix, Tucson, and El Paso. Over a billion tons of reserves are contained in the Fruitland Formation on lands of the Navajo Nation.

Finally, uranium production exceeds 100,000 tons of uranium oxide, making the San

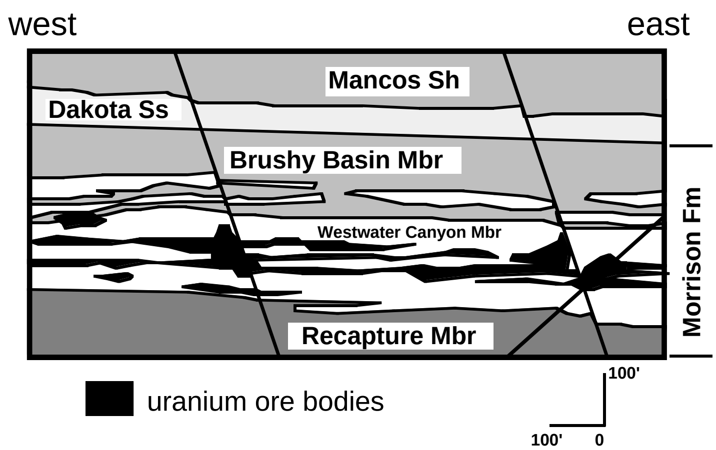


Figure 29: Generalized cross-section through ore bodies, Ambrosia Lake district, San Juan Basin

Juan Basin the principal uranium district in the U.S. The major producing area is the Grants district, stretching from Gallup east along the southern edge of the basin to Laguna, about 40 miles west of Albuquerque.

Vanadium was mined as early as 1942, but the big boom began in 1948 when the U.S. Atomic Energy Commission issued ore-buying schedules and other incentives to stimulate prospecting. By 1950, the area was alive with prospectors and the uranium boom had begun. The uranium deposits consist of stratabound, sediment-hosted accumulations of uranium- and vanadium-rich oxides, hydroxides, and carbonate minerals (e.g., coffinite, carnotite, uraninite) primarily from fluvial and lacustrine facies of the Morrison Formation. The principle ore controls are host rock permeability and porosity, (e.g., point bars are often selectively mineralized), and the presence of organic debris and certain clay minerals. Figure 29 is a cross-section of several ore bodies in the Ambrosia Lake district just east of the I-40 exit at Thoreau. The ore-grade mineralization is limited to specific facies within the Morrison, although district-wide there has been production from all three members, i.e., the Recapture, the Westwater Canyon, and the Brushy Basin. There has been lesser production from the Todilto Limestone, the Dakota Sandstone, and the Fruitland Formation. Uranium shows are evident in almost the entire Cretaceous section and in the Paleocene and Eocene Ojo Alamo and San Jose Formations. Significant reserves remain in the district.

Geologic History of the northern Colorado Plateau

Before we get too involved in what we will be seeing today, we need to review and elaborate upon the Phanerozoic history of the region. Figure 30 shows six paleogeographic reconstructions of Utah and western Colorado. Each time-slice is highlighted below:

Early to Mid-Paleozoic: The late Cambrian through Devonian is the classic geosynclinal phase of development of the Cordillera to the west. The rocks of this age in the Grand Canyon region are thin, platform deposits deposited on the western continental margin of North America.

Late Paleozoic to early Mesozoic: As in northwestern New Mexico, the late Paleozoic is dominated by the Uncompahgre Uplift.

In southeastern Utah and southwestern Colorado, the Paradox Basin was a restricted marine basin with thick sequences of evaporites. Clastic sediments shed into the basin from uplifts to the east.

Mid- to Late Mesozoic (Sevier Orogeny): In the latest Triassic and into the Jurassic, the marine influence on deposition waned and fluvial/eolian conditions prevailed — likely as a result of the wind-shadow effect of the Sevier highlands to the west. Desert sands like the Navajo and Entrada and fluvial/lacustrine sequences like the Chinle and Morrison chronicle the dry lands setting. Then, in the Cretaceous, things change.

By late Jurassic and early Cretaceous, east-verging thrust sheets of Paleozoic miogeosynclinal strata piled up and loaded the crust, producing subsiding, foreland, marine basins which merged to the east with the Cretaceous seaway of interior North America. The transgression was marked on the Colorado Plateau by deposition of the Dakota Sandstone and the overlying, marine Mancos Shale. North and west of the Plateau in central Utah, large deltas were built out from the Sevier highlands, producing thick sequences of clastic sediments that interfinger with the deeper-water deposits of southeastern Utah and Colorado.

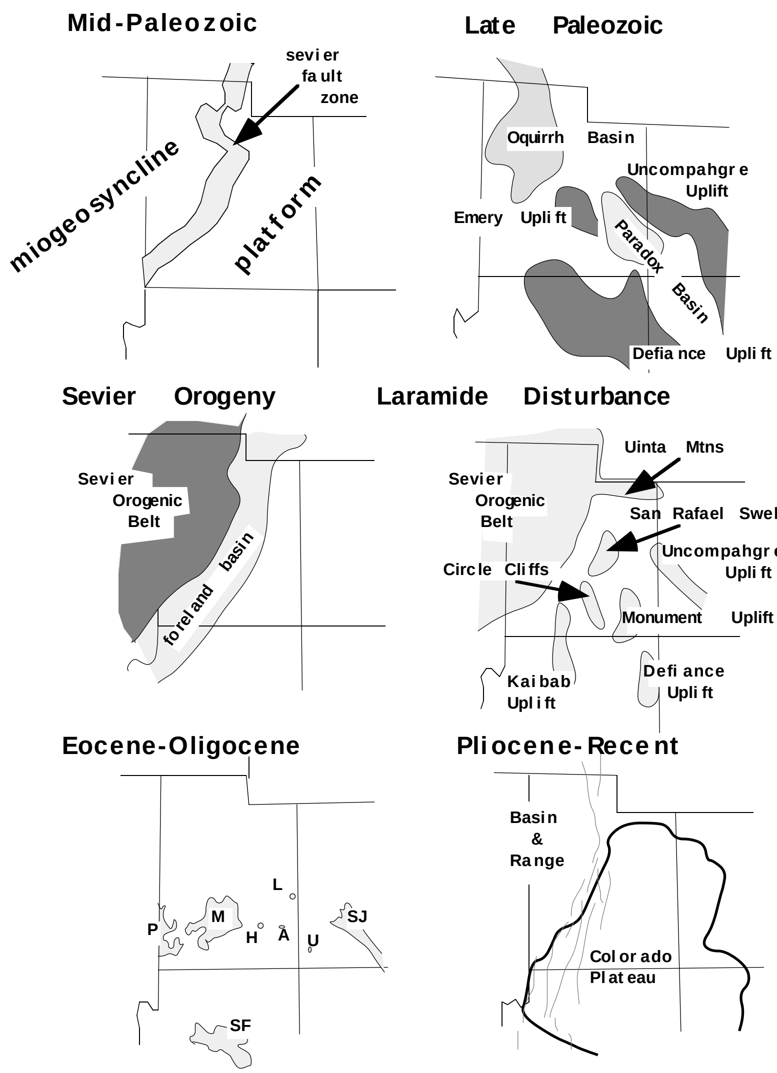


Figure 30: Structural evolution of Utah

<u>Late Cretaceous to Eocene (Laramide Disturbance)</u>: The Laramide Orogeny which produced the front ranges of the Rockies in central New Mexico and Colorado resulted in a broad regional upwarp and a series of isolated ranges in Utah and western Colorado. The

individual, asymmetrical uplifts are surrounded by deep basins, some of which received more than 10,000 feet of early Tertiary, nonmarine sediments. Most of the Laramide Basins of the Colorado Plateau area were not that deep, e.g. the Black Mesa and Defiance Basins, but did contain extensive lakes and swamps. Coals of the Mesaverde Group and Eocene units were deposited at this time.

Eocene to Oligocene: This time period was dominated by terrestrial deposition and volcanism on the Plateau and surrounding areas. In addition to the San Francisco Volcanic Field (SF in Fig. 43), the San Juan Volcanic Field (SJ; southern Colorado), the Marysvale Field (M; central Utah) and the Pine Valley Field (P; southwestern Utah) were active; laccolith intrusions characterized smaller centers like the Henry (H), La Sal (L), Ute (U), and Abajo (A) Mountains in southeastern Utah and southwestern Colorado.

Pliocene to Recent: Major epeirogenic uplift of the Plateau dominates late Cenozoic tectonic movements on the Colorado Plateau. Along the margins, basin and range and rift-style faulting occur. With the exception of localized volcanic centers, deposition is dominantly fluvial, eolian, and lacustrine. During the Pleistocene, Lake Bonneville in western Utah covered over 20,000 square miles and extensive alpine glaciers carved U-shaped canyons and deep cirques in the Uinta Mountains, northeastern Utah and in the San Juan Mountains, southwestern Colorado.

Mesa Verde National Park

Mesa Verde rises about 600 m above the Great Sage Plains, as the Mancos surface is locally called. The first cliffs that we see are the Point Lookout Sandstone. The highway climbs the Point Lookout and at various points one can see spectacular views of the San Juan Mountains to the northeast, the San Juan Basin including Shiprock to the south, and the Great Sage Plains west into Utah. The Point Lookout Sandstone forms a gentle cuesta capped by carbonaceous shales, siltstones, fine sandstones and coals of the Menefee Formation. This flat surface is also capped by Dove Creek Loess and thus provides a fertile foothold for juniper and piñon forests; thus, the "green mesa" or Mesa Verde. The spectacular dwellings of Mesa Verde are at the contact of the Menefee Formation with the overlying Cliffhouse Sandstone. The easily eroded shales and siltstones beneath the massive cliff-forming sandstones erode into deep alcoves where the dwellings were built.

In spite (or because?) of our being proto-geologists, spend a morning enjoying the remarkable Native American dwellings on Mesa Verde. The ruins were discovered by the white man in the 1880's and the area became a national park in 1906. Archeological work has identified over 4000 habitation sites. The dwellings at Mesa Verde represent the peak of the Anasazi (Navajo for "old ones") culture from about 1100 to 1300 AD; during this period, the large communal dwellings were built and continuously occupied.

While suggestive of fortresses, there is no real evidence that these were built for defensive purposes. In all likelihood, the were built here for convenience and comfort (the cliffs provide a stable foundation and back wall as well as shade and some shelter from torrential rains), for proximity to water running in the creek valleys and as seeps and springs at the base of the Cliffhouse Sandstone, and because they did not use up any arable or grazing lands. The Anasazi farmed on the mesa and had relatively elaborate dams, diversion channels, and irrigation systems.

The dwellings were abandoned relatively quickly in the thirteenth century. It was once thought that the Anasazi were driven out by the arrival of Navajo-Apache peoples from the north, but the oldest Navajo-Apache sites date at about 1540, 250 years after the last Mesa Verde dwellings were built (1273 AD). A quarter-century-long drought (1276-1299 AD) probably doomed the Mesa Verde settlements, but there is some evidence that Mesa Verde peoples were already moving south into the Chaco Canyon area near Farmington, NM by the late 1100's. While it may seem mysterious to us that the Anasazi built these magnificent structures and abandoned them a few hundred years later, we should remember that 200 years was six or seven generations and that these people were strongly dependent on spring and summer rainfall for farming. The mesa could only support a limited population which may well have been exceeded long before the thirteenth century drought finally forced the last Anasazi to abandon their homes.

Mesa Verde National Park to Montrose, CO Via US 160 and US 550

From the Mesa Verde NP turnoff to Mancos and Durango, US 160 mainly rests on Mancos Shale. It is relatively soft and easily eroded; outcrop areas are characterized by broad, open valleys and highly dissected, sparsely vegetated slopes. Badlands are common at lower elevations (< 6000 ft). Mesaverde Group sandstones are locally exposed along the highway between the La Plata River crossing and Durango. The Mesaverde Group, the familiar sequence of sandstones, coals, and dark, nonmarine shales, represents beach sands, fluvial sands, and swamp sediments deposited along the western margin of the North American Cretaceous seaway. The La Plata Mountains, north of the highway, are mainly Cretaceous strata (Dakota and Mancos) intruded by Paleocene stocks and laccoliths.

Durango is the commercial and recreational hub of southwestern Colorado and the "Gateway" to the San Juan Mountains. The city, nestled in the valley of the Animas River, rests on Cretaceous strata along the northwestern margin of the San Juan Basin. Remember, Cuba is situated on the southeastern margin of the same basin. In Durango, we turn north on US 550, widely known as the Million Dollar Highway. Built at a time when a million dollars represented a noteworthy expenditure of public funds, the original two-lane road was widely acclaimed as an engineering marvel. Recently, in keeping with the increasing emphasis on tourism and recreational land use, it was incorporated into the San Juan Skyway, a State of Colorado and National Forest Scenic Byway.

The highway cuts directly through the West Needle Range and the western San Juan Mountains. Between Durango (6500 ft.) and Ouray (8000 ft.), it crosses Coal Bank (10, 640 ft.) and Molas Lake (10, 901 ft.) passes, descends to Silverton (9300 ft.), and climbs again to Red Mountain Pass (11, 800 ft.) before descending to Ouray. This is the "million dollar" stretch of the highway; it ends in a series of steep, hairpin curves cut into the cliffs just above Ouray. Observation points provide scenic views of the Uncompahgre River gorge and of the city and its numerous hot-spring pools; drivers are allowed only a single, quick glance!

Northward from Durango, the highway climbs gradually along the valley of the Animas River. The red and pink strata visible between Durango and Hermosa are the Dolores (Triassic) and Cutler (Permian) Formations, dipping gently southward away from the San Juan Mountains structural dome and toward the San Juan Basin. The Cutler is roughly equivalent to the Maroon Formation in the Gunnison area. North of Hermosa, the highway crosses the narrow-gauge, Durango & Silverton railroad, a popular tourist attraction known for its wood-burning locomotives and 1890's decor.

From the railroad bridge to Molas Lake summit, the highway route lies mainly in drab, relatively nonresistant, clastic, marine strata (Rico and Hermosa Formations, Pennsylvanian) that overly resistant, cliff-forming, Leadville Limestone (Mississippian) and older Paleozoic strata. Most roadcuts expose slope rubble and mass wastage deposits. East of the highway, Precambrian, crystalline rocks (gneiss, schist, and intrusive granite) comprise the steep slopes and sharp peaks of the West Needle Range. However, between the hairpin curves at Cascade and Lime Creeks, the highway cuts down into Paleozoic carbonates below the Rico, and in an upraised fault block (horst) near Coal Bank summit, nearly-vertical, Proterozoic quartzites and argillites of the Uncompahgre Formation are unconformably overlain by subhorizontal, lower Paleozoic beds. Another 90° angular unconformity between the same units is well-exposed in Box Canyon near Ouray.

Light-colored, Tertiary intrusive rocks, emplaced along the edges of the San Juan and Silverton calderas, are evident in outcrops and rubble along the Lime Creek hairpin and along the section between Molas Lake summit and the junction with Colorado Highway 110 at Silverton. About at the Silverton turnoff, the highway crosses the bounding, ring-fracture zone and passes into the Silverton caldera.

The Silverton and Lake City calderas (both about 20 km in diameter) are nested inside the older, much larger (nearly 60 km in its maximum dimension), Uncompahgre caldera. Immense thicknesses of ashflow tuff accumulated inside the calderas and numerous, mid to late Oligocene, ashflow tuff sheets spread over large portions of southwestern Colorado; some reached the Gunnison area. Outflow tuff sheets from the older San Juan calderas form the steep, resistant ledges visible above Blue Mesa Reservoir and in other parts of the Curecanti National Recreational Area west of Gunnison. Explosive, ashflow volcanism and caldera collapse represent the later stages of the mid-Tertiary volcanic episode in the San Juan region. Large stratovolcanoes and stratovolcanic complexes, comprised mainly of andesitic lavas, fragmental units, and mudflow deposits interbedded with lesser quantities of rhyolite and basaltic andesite, were built during the earlier stage. Batholithic emplacement at depth accompanied volcanism.

Between Silverton and Red Mountain summit, the lower course of Mineral Creek closely follows the western, ring-fracture zone; thus the highway lies just inside the Silverton caldera. At Red Mountain summit, the highway crosses the western boundary of the San Juan-Uncompahgre caldera complex and remains in pre-caldera rocks the rest of the way to Ouray. Intracaldera rocks (those inside the caldera) are rhyolitic, ashflow tuffs and intrusives; those outside are mainly the andesitic rocks formed during the earlier, stratovolcano-building episode. The bright, rock colors (yellow, red, and brown) attest to strong, primary hydrothermal alteration and secondary leaching associated with oxidation of pyrite; mineralizing fluids circulated along the ring-fracture zones and spread into caldera-margin rocks on both sides of the caldera boundary.

Between Red Mountain summit and Ouray, the highway descends through the heart of the western San Juan Mineral belt, an area roughly enclosed by the towns of Telluride, Ouray, Lake City, and Silverton. Abandoned dumps and adits, idle headframes, and weather-beaten buildings litter the mountainsides, barely hinting of the immense mineral wealth once extracted from this region. Mining on a substantial scale began during the 1880s when small, near-surface, bonanza-grade gold and silver deposits were discovered. In later years, unoxidized Pb-Zn-Cu sulfide ores with lower contents of precious metals were mined at deeper levels. Most of the mineralization occurs in steeply-dipping veins; veins with intermediate dips (45°), vertical, pipelike masses (chimneys), and subhorizontal, tabular masses occur less commonly. Veins are especially numerous and extensive west of the Silverton caldera between Red Mountain and Telluride and in the highly-fractured, Precambrian rocks between the Lake City and Silverton calderas.

The typical vein has thick, outer zones consisting of massive, intergrown galena, sphalerite, chalcopyrite, pyrite, and quartz with smaller amounts of silver-bearing tetrahedrite/tennantite. Central parts of veins are commonly rich in manganese minerals including alabandite, a manganese sulfide. Some veins contained very-rich, interior concentrations (ore shoots) of silver-bismuth sulfides; in others, rich gold values occurred in thin, central zones characterized by abundant adularia, a low-temperature, hydrothermal potassium feldspar. Despite the regional prominence of Telluride as a place name, gold and silver telluride minerals are quite rare

By the 1970s, exploration, mainly deep drilling, had penetrated porphyry copper-molybdenum mineralization associated with the tops of the batholithic complex four to five thousand feet below the surface. However, a plunge in metal prices, reduced demand, and less expensive supplies available elsewhere snuffed out further interest in the deep mineralization.

Ouray, CO, lies in a glacial cirque ringed by steep cliffs of subhorizontal, Devonian and Mississippian limestones and underlying, near-vertical, Proterozoic strata. The city stands on the north flank of the San Juan structural dome and between Ouray and Montrose, the Paleozoic and Mesozoic strata dip gently to the north The Ouray area was structurally high during the middle Paleozoic; in Box Canyon, upper Devonian marine strata rest directly on Proterozoic rocks. Late Paleozoic tectonism produced the Uncompahgre Uplift, extending from the San Juan region northward to Grand Junction. It was regionally prominent in late Paleozoic time and may well have been uplifted again during the "Laramide" (late-Cretaceous-Tertiary) episode of compression and uplift.

South of Ouray, the impressive cliffs lining the narrow, upper gorge of the Uncompahgre River consist of drab-colored, Pennsylvanian Rico-Hermosa Formations overlain by bright-red, Permian Cutler strata. Farther north near Ridgeway, the valley walls are cut into Morrison (Jurassic) and Dakota (Cretaceous) Formations and the valley widens considerably. Between Ridgeway and Colona, the valley again narrows; very gently-dipping Morrison and Dakota beds comprise the valley walls. Just south of Colona, the Morrison and Dakota beds dip beneath the valley floor, exposing Mancos shale in the valley walls. From Uncompahgre to Montrose, the valley progressively widens to a very broad, open valley so typical of Mancos-underlain areas in western Colorado. To the west, Dakota sandstones cap the broad, gently-sloping Uncompahgre Plateau; east of the highway, Mancos shale forms the lower valley slopes, but in the more distant, higher areas, the Mancos is mantled by gravel and colluvium shed southward from the San Juan Mountains. Cimarron Ridge, comprised of rocks of the stratovolcano-building stage, may be visible in the distance.

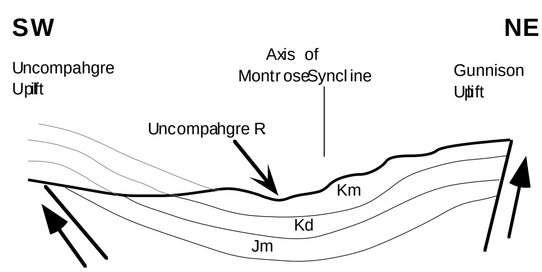


Figure 31: Schematic cross-section of the Montrose Syncline at Montrose, CO

At Montrose, we turn east on US 50, cross the east limb of the Montrose syncline (Fig. 31) and head toward the southern margin of the Gunnison Uplift. Two en echelon, high-angle normal faults mark its boundaries. The northernmost of the faults, the Red Rocks Fault can be traced for over 30 km. The southernmost is the Cimarron Fault; it can be traced for over 60 km and has a vertical displacement of over 1500 m. Just as you leave the east side of Montrose, you can see monoclinal folds in the reddish Entrada Sandstone where it sits in unconformity on the Precambrian rocks of the uplift. The highest snow-capped peak to the south is Mt. Sneffels in the San Juans with an elevation of 14,150' above sea level. For some of you this might be the first 14,000' mountain you have ever seen.

Still driving on Mancos Shale along the axis of the Montrose Syncline, we reach the intersection of CO 347 about 8 miles east of Montrose. Again, time permitting, we may make a side trip to the Black Canyon of the Gunnison. If not, you may have another chance to return here in the next two weeks; Gunnison is only 50 miles farther east.

THE GUNNISON COUNTRY

Gunnison Country generally refers to the lands of the Gunnison River basin more-or-less to the mouth of Black Canyon, northeast of Montrose, CO. It is bordered by the high peaks of the San Juan Mountains south and west of Lake City, by the high country of the Sawatch Range to the east, and by the Elk and West Elk Mountains to the northeast, north, and northwest.

Much of the area is federally owned. A chunk of the northern San Juans and a large percentage of the drier lands at lower elevations are administered by the Bureau of Land Management (BLM). Most forested and high mountainous areas are included in the Gunnison National Forest administered by the USDA Forest Service. Both agencies have district offices in the town of Gunnison. The Curecanti National Recreation Area, administered by the National Park Service, includes the Gunnison River canyonlands clustered about Crystal, Blue Mesa, and Morrow Point Reservoirs. Only well-watered floodplains, stream valleys, and remote mining areas were originally homesteaded or claimed, and these lands largely remain in private hands.

The Gunnison Country passed through the same stages of development and attempted development as other western public lands; first trappers came, then miners, ranchers, and the railroad men. The legendary “sodbusters” never even tried the Gunnison Country. The summer nights are too cool and the growing season too short; one can only hope for a single crop of hay! Beaver, once decimated by fur trappers, are staging a strong comeback; but the mines are closed and the last railroad tracks were ripped up many years ago. An orphaned steam locomotive displayed on US 50 at the east end of town is the one remaining relic from Gunnison’s railroading past.

Ranching is the main commercial activity to survive from the early days. In recent years, fishing, hunting, skiing, fat-tire mountain bikes, hiking, and wildflower watching have fueled a rapid growth in family-oriented, outdoor, recreational activities. LA and Raleigh have instant radio reports of fog, smog, multicar pileups, and gridlocked traffic; the Gunnison Country has the fishing, hunting, and ski reports interspersed with country music. Take your pick!!

Geologic History of the Gunnison Country

Gunnison Country geology is as diverse and interesting as the region’s recreational activities. The area lies on the northwestern flank of the broad, northwest-trending Uncompahgre Uplift (Fig. 31). Rocks range from Precambrian to Tertiary. Pleistocene-to-Holocene unconsolidated deposits are common. Figure 32 shows several stratigraphic columns for the Gunnison Country. As you will see below, we will use basically the version referred to in this figure as the Treasure Mountain section.

Precambrian: Precambrian rocks include intrusive plutonic rocks, gneisses, metavol-

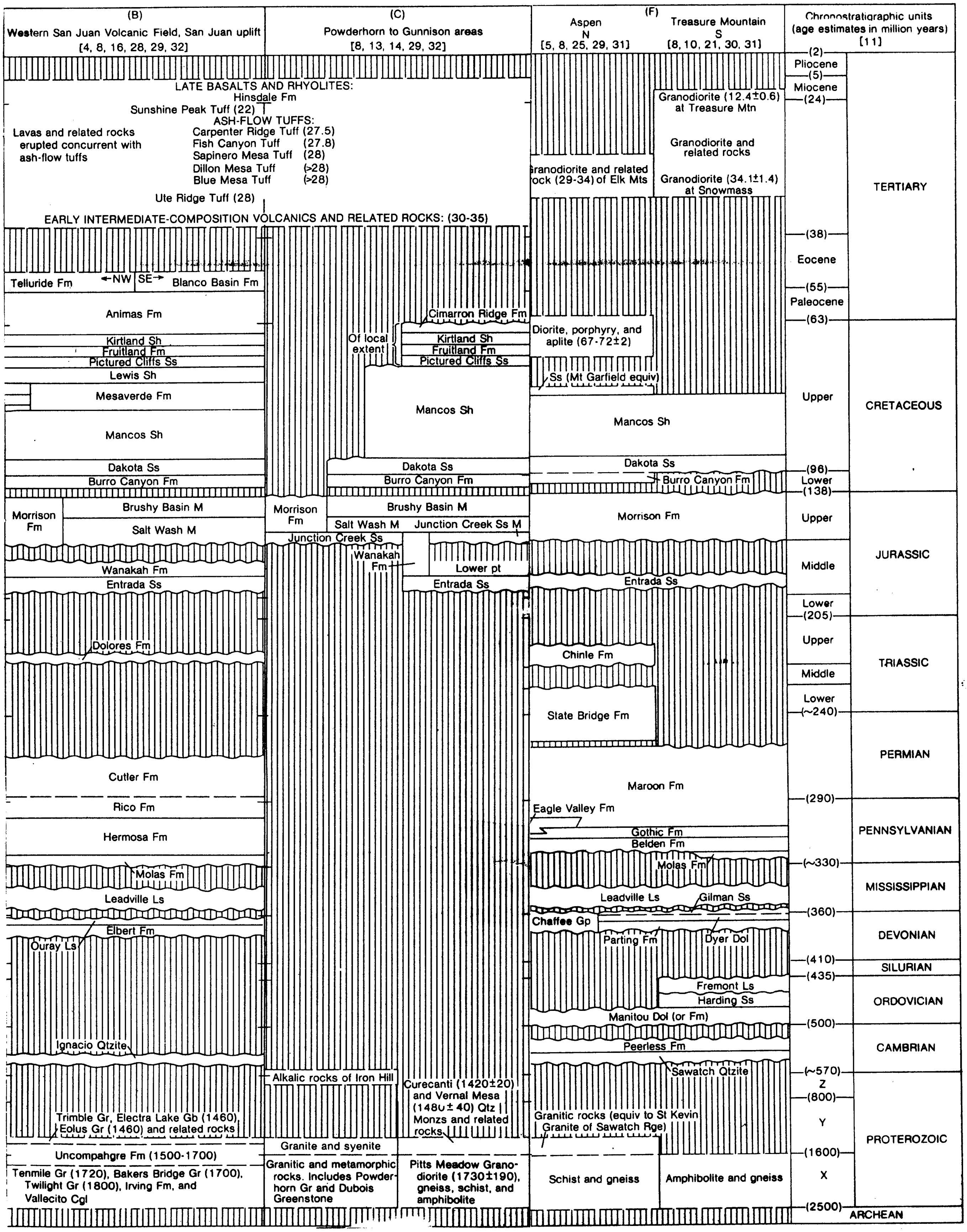


Figure 45: Stratigraphic columns for the Gunnison Country (from MacLachlan, 1981)

canic units and metasedimentary schists and phyllites. Granite quarried near Gunnison was used in construction of the Colorado state capitol building in Denver.

Paleozoic: In Colorado, as in other parts of the interior craton of North America, a Cambrian beach sand, called the Sawatch Sandstone (equivalent to the Tapeats Sandstone in the Grand Canyon), was deposited on deeply eroded Precambrian crystalline rocks as the sea advanced onto the continent. Above the Sawatch, limestones and dolomites of Ordovician to Mississippian age dominate the section. The Devonian strata include distinctive shale and sandstone members in addition to the carbonates. Silurian strata are missing. The Mississippian Leadville limestone is one of many, thick, age-correlative limestones, such as the familiar Redwall in the Grand Canyon region and the Madison in Wyoming and Montana, that are recognized in the Rocky Mountain region. In places, the Leadville was deeply weathered before the overlying strata were deposited; ancient sinks, caves, collapse breccias and bright-red, clayey deposits (terra rosa) locally characterize the upper part of the formation. These early to mid Paleozoic strata represent shallow-water marine sediments deposited in a continental shelf and continental platform environment.

After acting as a single intact terrane from the beginning of the Cambrian Period, the old stable craton was fragmented into very large, fault-bounded, tectonic blocks during Pennsylvanian time (Fig. 43). This very important tectonic and depositional event "built" the "Ancestral Rockies". They extended north from northern New Mexico and southeastern Utah to northern Colorado and eastward to the front ranges of the modern Rocky Mountains. Some blocks rose to become "basement uplifts"; adjacent blocks sank to become "depositional basins". The tectonic activity was driven by North and South America colliding along the southern margin of North America, far to the south of central Colorado. Fault displacements must have been quite large, given known sediment thicknesses.

In the Gunnison area, the Ancestral Rocky Mountains event began with submergence of the weathered Leadville and older strata. As the seas deepened, black shales and dark limestones rich in organic matter (the Belden Formation) were deposited. Preservation of organic matter implies oxygen-poor water, so the Belden is interpreted to have accumulated in a rapidly subsiding basin with little mixing between surface and bottom waters. The Gothic Formation, a very thick accumulation of shallow water, marine, arkose, feldspathic sandstone, conglomerate, and limestone units, overlies the Belden. Gothic conglomerates include pebbles from older Paleozoic and Precambrian source rocks; some are limestone conglomerates, consisting of detrital limestone pebbles set in a crystalline matrix of lithified, chemically-deposited carbonate mud. Gothic beds are generally light tan to light gray; occasional redbeds occur high in the section. Evaporites (mainly gypsum) are common in Gothic-age strata from the Eagle Basin, about 50 miles north of Gunnison. The evaporites and occasional redbeds suggest a transition from shallow marine to continental conditions of deposition.

The Ancestral Rocky Mountain event culminated with deposition of the Pennsylvanian-Permian Maroon Formation, a very thick, alluvial fan and continental basin sequence of red to maroon, pebble and boulder conglomerates, sandstones, siltstones, and minor shales. When the tectonic activity ceased, the region was deeply eroded and only low remnants of the basement-rock uplifts remained.

Mesozoic: Triassic continental strata were deposited in the Aspen and Grand Junction areas, but they thin and disappear toward the Gunnison area. In Jurassic time, interior parts of the Ancestral Rockies were finally buried as the Entrada, Wanakah, and Morrison

Formations transgressed into the Gunnison region. The Entrada here represents coastal dunes that accumulated along the eastern shore of the Sundance Seaway in central and eastern Utah, and the Wanakah includes marine or closed-basin limestones, evaporites, and clastic beds. In the Black Canyon downstream from Blue Mesa Reservoir, the Wanakah includes a prominent eolian sandstone called the Junction Creek member. For our Gunnison area field exercises, we define the Entrada as the first prominent sandstone (Jurassic) above the Paleozoic or Precambrian rocks. Thus, we may be incorrectly using Entrada for the slightly younger Junction Creek. For now, the name Entrada is acceptable, but a good thesis study (senior, M.S., or Ph.D..) might force a change of heart!

Our old-friend the Morrison Formation, overlies the Entrada and Wanakah Formations. It was deposited across much, if not all, of the Gunnison Country. One of the most distinctive and easily recognized formations on the Colorado Plateau, the Morrison was deposited in a very large, dry, interior basin. High mountain ranges, extending from southern Arizona to south-central California, shut off direct precipitation; but, streams flowing northward and eastward from the mountains carried large quantities of sand, gravel, mud, and dissolved salts into the basin and volcanoes in the mountains contributed detrital and airfall ash. The streams were probably subjected to seasonal flooding; they fed into marshes, ephemeral lakes, and saline lakes.

Regionally extensive and very complex groundwater circulation patterns developed in the basin. Fresh groundwaters from the mountains and upper alluvial fan areas overrode more dense saline groundwaters in the basin interior, forming springs and marshes at the toes of alluvial fans and along stream courses. Chemical interactions between the sediments and groundwaters were extensive. Glassy volcanic ash was decomposed and converted to clays, zeolites or alkali feldspar, depending on groundwater salinity. Clays mark the largely fresh water zones and zeolites (clinoptilolite) and feldspars (orthoclase and/or albite) formed in zones of increasing groundwater salinity. Many of the colorful greenish and deep-maroon "mudstones" in the Morrison are actually altered ash and chemical sediments with minor detrital components. Sandstones in the Morrison are stream channel deposits; sparse freshwater limestones represent chemical sediments precipitated in spring-fed ponds and saline lakes.

In the Gunnison area, the Morrison sandstones are thinner and less extensive than in areas to the south (New Mexico) and west (Utah) that were closer to the mountain source areas. A few, very rare dinosaur fossils have been found in the Gunnison area. Chert pebble conglomerate beds like those exposed on the Radio Tower side of the Jacks Cabin project area are high in the Morrison section or may actually belong to the early Cretaceous Burro Canyon Formation. The Morrison is well-exposed in roadcuts on US 50 and Colorado 135 near Gunnison, and it is an important unit in your field mapping projects.

Early in Cretaceous time, the Dakota Sandstone (a beach sand) was laid down by a Cretaceous seaway transgressing over eroded Morrison and older rocks. The unit includes black shale interbeds and abundant plant remains, showing that beach, shallow-water marine, and coastal swamp environments oscillated back and forth during Dakota deposition.

Eventually the region and most of the western US was inundated. The seaway extended from Arizona and Utah to eastern Kansas and Montana and was the depositional basin for the thick, dark-colored to black, marine shales that so typify Cretaceous strata in the western plains and Rocky Mountain region. In the Gunnison Country, western Colorado, and the four-corners region, this is the Mancos Shale. It erodes quickly, slopes fail easily, especially when wet, and its soils provide poor nutrition to growing plants. At lower elevations, the Mancos typically forms "badlands"; at intermediate elevations, sagebrush and grasses cover the weathered shale. Evidence for slope failures and mass movements is especially common at higher elevations. Being very thick and easily eroded, the Mancos underlies most wide river and stream valleys in the Gunnison Country.

The Mesaverde Group lies above the Mancos. It includes deltaic sediments, beach sands, and coastal swamp sediments deposited when the great Cretaceous seaway was shrinking and retreating eastward. In the Gunnison region as in other parts of the Colorado Plateau, the Mesaverde contains abundant and thick coal beds. Coals from the eastern flanks of the West Elk Mountains near Crested Butte have very good coking qualities, and early in the 20th century, coal mining and coke-making were important industries. The coke was shipped by rail to the now-defunct steel mills of Colorado Fuel and Iron Company in Pueblo, CO.

Late Cretaceous-Early Cenozoic: The gradual, oscillatory, withdrawal of the Cretaceous seaway signals the Late Cretaceous-early Tertiary Laramide orogeny and of the uplift, continental sedimentation, and volcanism that were to dominate the Cenozoic geological history of the region (Fig. 43).

In the Grand Canyon region and south-central Utah, Laramide-age offsets on steeply-dipping reverse faults in the crystalline basement rocks were accommodated by bending in the late Paleozoic and Mesozoic strata, giving the now-familiar Colorado Plateau monoclines. In northern Utah, Wyoming, and western Montana, the crust was broken into large rising blocks and basins, bounded by reverse faults. Vertical displacements exceeded 10,000 feet in some areas, such as along the Wind River fault system. Gravitational collapse increased the tendency for the uplifted Precambrian crystalline rocks to be thrust laterally. This was the Laramide orogeny, a late Cretaceous-early Tertiary compressive tectonic event.

Although the cause or causes of the Laramide will undoubtedly be controversial for decades, one current idea is that flat to low-angle subduction of the Farallon Plate (the Mesozoic and early Tertiary floor and lithosphere of the Pacific Ocean east of the East Pacific Rise) may have resulted in a powerful shearing stress being applied to the base of the continental lithosphere, causing it to shorten (mainly in an east-west direction) and thicken. Responding to these accumulating strains at depth, the crust was uplifted and broken into giant fault blocks that either rose as mountains or subsided to form basins.

West of the fault-block uplifts in areas like the western Wyoming thrust belt, Paleozoic and Mesozoic strata from farther west were being carried eastward along horizontal or very gently-dipping, regionally-extensive thrust faults, causing older strata to pile up and override younger strata. Laramide block uplifts and similar-style thrust faults have long been thought to be important in the Gunnison Country. Laramide-age uplifts are identified along the western margin of the Gunnison block in Black Canyon of the Gunnison National Monument and along the western front of the Sawatch Range where unbroken, middle Tertiary ashflow tuffs, erupted from the calderas of the San Juan volcanic province, overlie Mesozoic strata faulted against Precambrian crystalline rocks. Elsewhere, the ashflow tuffs are missing and the Laramide structural movements are not so well constrained.

In addition, reactivation of older faults was evidently common; some faults may have moved only once. Others may have first moved during the Laramide or Pennsylvanian; in the Black Canyon area, a Proterozoic ancestry can be demonstrated for some faults that show later movements. Once broken, major faults tend to exhibit recurrent movements during later tectonic events. Except for the early Tertiary Ohio Creek Formation and the Wasatch Formation in the Ruby Range west of Crested Butte, erosion removed the early Tertiary basin sediments. Tertiary igneous rocks were intruded into Laramide block boundary zones and along zones proposed to be regionally-extensive Laramide thrust faults, complicating the problem of "isolating" Laramide structures from those associated with emplacement of the later intrusions.

In the Sawatch Mountain block, Precambrian rocks were elevated at least 6000 feet above the level of the Morrison-Precambrian contact just to the west of the boundary fault zone exposed on US 50 about 25 miles east of Gunnison. South and west of Black Canyon of the Gunnison National Monument, Precambrian rocks are in fault contact with Mancos Shale. Structural complications are concentrated along the block-boundary fault zones; gentle dips and small-displacement faults characterized interior areas away from the major faults.

A few late Cretaceous-early Tertiary plutonic rocks have been recognized in the Gunnison region, but many such plutons were intruded along the Colorado Mineral Belt from southwest of Durango, CO to the Central City area near Denver. In contrast, Middle Tertiary and younger volcanic and intrusive rocks are common.

Cenozoic: The Oligocene West Elk Mountains volcanic center includes a line of laccoliths injected into the Mancos Shale on the north flank and a massive, stratovolcanic complex that forms the south flank of the West Elk Mountains northwest of Gunnison. Complex volcanic breccias of diverse origins comprise much of the exposed central vent zone; mudflow breccias and minor lava flows exposed in the prominent cliffs along lower Ohio Creek near Gunnison were deposited on the lower flanks of the volcanic center. Thick sections of West Elk volcanic breccias are visible in the high country south of the Ohio Creek road and volcaniclastic rocks, pyroclastic units, and breccias crop out in the higher portions of the steep canyons draining toward the upper reaches of the Black Canyon west of Gunnison.

Distal, rhyolitic, ashflow tuffs from caldera-related source areas in the San Juan Mountains overlie the West Elk volcanics in the lower reaches of these same canyons north of Blue Mesa Reservoir. Elsewhere, a few fairly thin late Tertiary ashflow tuffs underlie Pliocene or late Miocene basaltic lavas that cap Red and Flat Top Mountains west of Colorado 135 between Gunnison and Crested Butte. These were probably erupted from one or more of the nearby late Tertiary stocks or laccoliths.

The West Elk volcanic center, granitic laccolithic intrusions in the Crested Butte-Gothic area, and the Whiterock granitic stock (Elk Mountains) form a major middle Tertiary igneous zone aligned along the Colorado Mineral Belt. Some other, roughly aligned middle to late Tertiary, granitic stocks extend southward from Italian Mountain to Tomichi Dome, a laccolith easily visible from US 50 about 20 miles east of Gunnison. A well-defined gravity low coincident with this latter zone suggests that the separate stocks merge into a much larger granitic batholith at depth. Other late Tertiary stocks and laccoliths include the Mount Emmons stock near Crested Butte and the much smaller Round Mountain laccolith halfway between Gunnison and Crested Butte, visible from the Jacks Cabin project area.

The Cenozoic was a time of volcanism, continental sedimentation, and uplift throughout the Colorado Plateau and Rocky Mountain region. Regional uplift also elevated the "High Plains", east of the Rockies. In the Black Mesa Basin (northeastern Arizona), late Cretaceous, marine shoreline, Mesaverde units are 7000 feet above sea level; in the Gunnison region, the same Mesaverde units are from 9000 to 10,000 feet above sea level in many areas. Strongly influenced by regional uplift, Eocene warm-temperate to subtropical flora in the Yellowstone region (northwestern Wyoming) were gradually replaced by the cool-temperate to boreal forests of today. Meanders, left from the early Cenozoic landscape of low elevations and low stream gradients, were entrenched in deep canyons as the major streams responded to uplift by downcutting. Major changes in regional drainage patterns, such as diversion of the ancestral lower Colorado River through the newly eroded Grand Canyon segment about 5 Ma, accompanied regional uplift.

Middle Tertiary volcanism, Laramide-age structures, and late Cenozoic uplift controlled formation of the Black Canyon of the Gunnison. After volcanism ceased in early Miocene time, the ancestral Gunnison River was "trapped" in a broad valley between the huge volcanic piles of the San Juan and West Elk Mountains. This valley lay above thin Mesozoic strata and hard, crystalline, Proterozoic rocks of the Gunnison block, uplifted in Laramide time. Only a few miles southwest of the valley lay soft, thick Mancos Shale on the other side of the Cimarron Fault, the southwestern boundary of the block.

As regional uplift continued, the river quickly cut through the Mesozoic strata and down into the Proterozoic rocks. In late Pliocene or early Pleistocene time, the downstream Unaweep Canyon segment of the Colorado and Gunnison Rivers across the Uncompahgre Plateau was abandoned, leading to rapid downcutting through the Mancos Shale west of the Black Canyon and steepening of gradients across the Gunnison block. This "sealed the fate" of the Gunnison River and forced it to continue downcutting the Black Canyon into the Proterozoic rocks. Had the river been diverted through the Mancos Shale south of the Cimarron fault, downcutting and valley widening would have been quick and easy. Instead of another predictable, broad, open valley in the soft shales of the Mancos, we see an anomalous, narrow, steep-sided canyon cut in hard, crystalline Proterozoic igneous and metamorphic rocks. Such are the wonders of geologic history.

Quaternary: Quaternary fluvial, glacial, and slope-failure deposits are common in the Gunnison region. Glacial activity and intense frost action affected many areas above 9000 feet; landslide and mass wasting deposits commonly mantle Mancos Shale slopes, particularly those above 8000 feet. In many areas, larger slides carried slope debris to lower elevations, so make sure that you can tell outcrops and "local float" from transported mass wasting deposits and glacial debris.

Field Hydrogeology
Cuba, New Mexico and Vicinity

Description of the Area

Located 70 miles north-northwest of Albuquerque, New Mexico, the town of Cuba lies on a high plain at the foot of the Nacimiento Mountains (Figure 46). The western flank of the Nacimento Mountians is fault bounded and the escarpment forms a rugged wall that extends for more than 45 miles in a north-to-south direction. A highly fractured, pink, Precambrian granite forms much of the core of the Nacimiento Mountains. West of the mountains, extensive pediments and alluvial fans extend outward from the mountains onto the plain, their upper surfaces often capped by pink gravel, cobbles, and boulders of granite. The town of Cuba is at an altitude of about 6,910 feet; the Nacimiento Mountains rise to altitudes greater than 10,000 feet west of town. The Circle A Ranch, the base camp for this exercise, is located approximately 5 miles north-northeast of Cuba on a pediment surface. The altitude at the ranch house is about 7550 feet.

The Circle A Ranch is located at the western edge of the Santa Fe National Forest. Vegetation at the ranch is typical of the mountains to the east, consisting of ponderosa, firs, and a variety of deciduous trees, including cottonwood, aspen, and oaks. As altitude increases east of the ranch, aspen increase in abundance. The tree line in the area occurs at about 7,000 feet. Below this altitude, the vegetation is more typical of a semi-arid to arid climate. Typical vegetation includes grasses, sage, juniper, and cactus.

Hydrogeology

Much of the western flank of the Nacimiento Mountains is drained by the Rio Puerco and its tributaries. From its headwaters in the mountains east of Cuba, the Rio Puerco flows southwest to Cuba where is is joined by the Rito Leche, Arroyo San Jose, and other streams. From Cuba, the Rio Puerco flows in a southerly direction, passes west of Albuquerque, and eventually joins the Rio Grande 115 miles south of Cuba. Immediately south of Cuba, the Rio Puerco flows across and is incised into relatively flat-lying sediments of the San Juan Basin. Thirty two miles south of Cuba the Rio Puerco begins to pass through a landscape dotted with volcanic vents and necks, some of which rise more than 1,000 feet above the surrounding desert. At the northern edge of this volcanic field is the abandoned town of Cabezon and the prominent volcanic neck for which it was named (Figure 47). Cabezon Peak rises more than 1,500 feet above the surrounding desert. Near Cabezon Peak is a gaging station operated by the U.S. Geological Survey that measures flow in the Rio Puerco. The drainage area upstream from the station is approximately 440 square miles. In the interval since 1951, annual average flow past this station has been only 14.0 cubic feet per second, equivalent to about 0.45 inches annually. There is no flow at the station many days most years. Annual average precipitation ranges between 10 and 20 inches.

Erosion plays a prominent role in shaping the landscape of the Rio Puerco watershed. The volcanic necks near Cabezon, the arroyos dissecting the pediment along the mountain front, mass wasting, including toreva blocks, spring sapping, badlands and hoodoos, are all evidence of the role of water and differential erosion in this arid region.

The orographic effect of the Nacimiento Mountains is also apparent. Violent thunderstorms occur over the mountains in summer and mountain snows occur in winter. The effect of the higher precipitation amounts is also apparent, as evidenced by the dense forests, grassy meadows, and perennial streams in the mountains. Streams flow out of the mountains, and on the lower mountain slopes and pediments, springs can be found. Some springs appear to be associated with faults. Others occur at changes in slope, and still others appear to occur at the contacts with low permeability strata. A number of springs

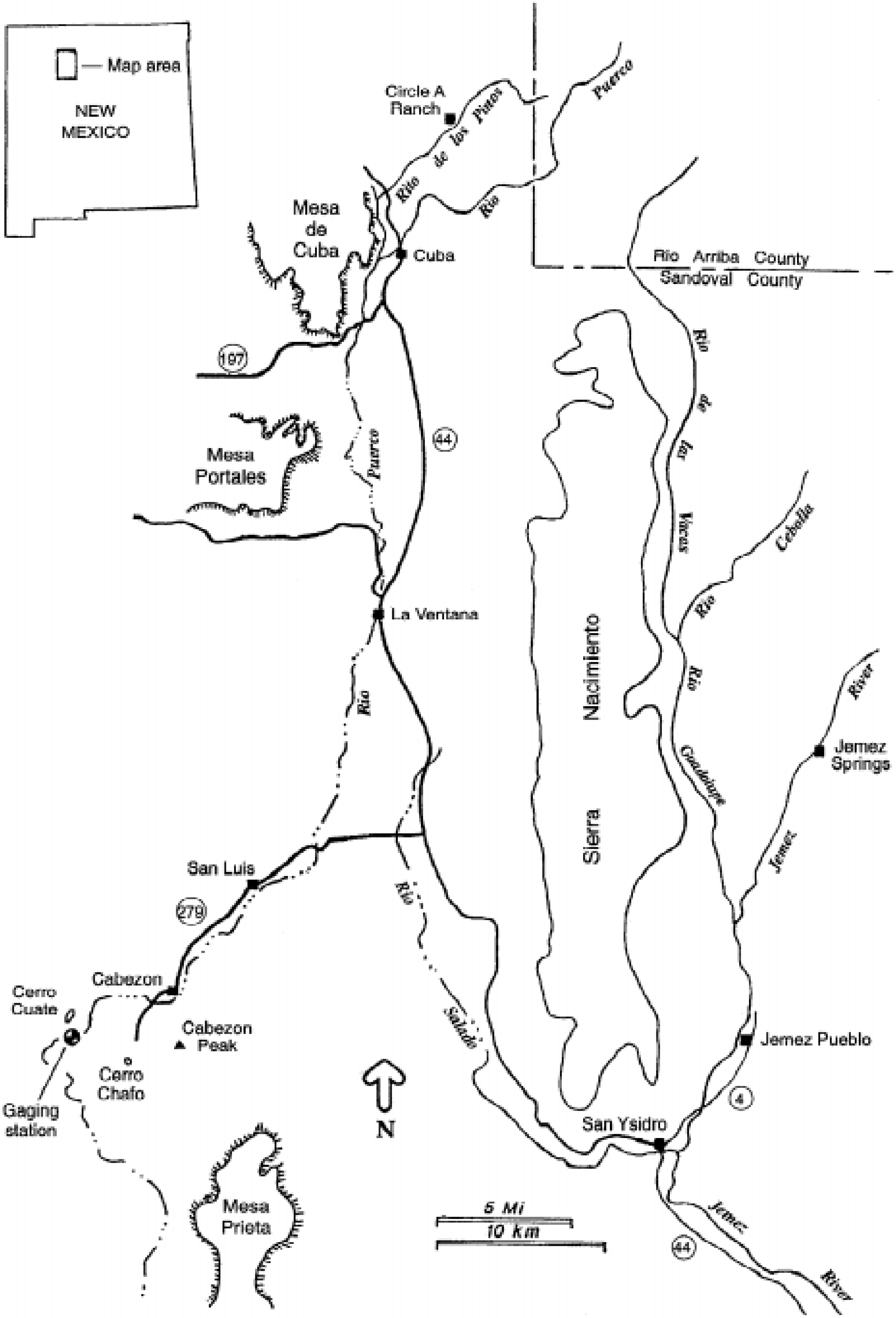


Figure 46: Hydrogeology exercise field area, Cuba, New Mexico and vicinity.

can be found on the pediment near the Circle A Ranch; the water supply at the Circle A Ranch is spring derived.

The Rito de los Pinos, a tributary to the Arroyo San Jose, flows through the Circle A Ranch. As the Rito de los Pinos flows out of the Nacimiento Mountains, its course, like other streams in the region, has been modified so that the water can be used to irrigate pastures and farmland.

Instruction

In order to have the necessary skills to complete the hydrogeology field exercise, attendees will be instructed in methods of making discharge measurements in streams. Methods to be discussed include use of Price meters, weirs, and Parshall flumes. Methods of discharge computation based on these instruments will be presented. Techniques for comparing streamflow from contributing areas of different size also will be discussed.

The water quality within the Rio Puerco basin will be evaluated. Attendees will learn to measure specific conductance in water with a conductivity meter and, using these measurements, a method to estimate the mass transport of total dissolved solids in streamflow.

Short lectures will be given about the hydrogeology and climate of the area. Fundamentals of watershed hydrology and terminology will be presented. Water budgets of arid and humid regions will be described and compared. Surface processes such as erosion, mass movement, and spring sapping will be described. The role of man and the effects of his interaction with the hydrogeology of an arid region will be discussed.

Objectives

1. To learn fundamental principles regarding hydrogeology in an arid environment, including climate, streamflow, ground water, and surface processes;
2. To learn basic concepts regarding watershed hydrology;
3. To learn about selected instruments and techniques for evaluating hydrogeologic conditions; and
4. To evaluate hydrogeologic conditions within a watershed. Hydrogeologic conditions will be evaluated by conducting a synoptic survey of streamflow and water quality conditions, mapping of springs and other surface features, and a site visit to a stream-gaging station.

Scope

The hydrogeology field exercise with take four days. Once instruction on techniques for making discharge measurements is complete, the class will be divided into teams. Approximately four teams consisting of five or six members each will be expected to make discharge measurments at a number of predetermined sites for which the drainage areas are known. Responsibility for making discharge measurements is to be rotated among team members so that everyone has the opportunity to make one or more discharge measurements. At any given site, other team members will assist with site preparation, note taking, and other activities. Samples of water will be collected at the time that the discharge measurements are made. The samples will be brought back to camp where specific conductance will be measured.

The area to be studied during the exercise will extend from the headwaters of the Rio Puerco, specifically the headwaters of the Rito de los Pinos, downstream to the U.S. Geological Survey gaging station near Cabezon. A site visit will be made to the gaging station where techniques of gaging-station operation will be described and discharge past the station will be determined from stage readings recorded by instruments at the station. The gaging station is equipped with satellite telemetry for the collection of real-time flow data.

The station is also equipped with an automatic suspended-sediment sampler (in operation since August 1981). Suspended-sediment concentrations measured at this station are among the highest in the country (Jerry Larson, USGS, personal communication); between 1981 and 1992, the maximum daily mean concentration was 214,000 mg/L, and the maximum daily load was 730,000 tons.

On the return trip from the gaging station, visits to Box Canyon on the Rio Guadalupe and Soda Dam on the Jemez River are planned. Although in an adjacent watershed, Soda Dam and the hot springs that produced it are an excellent example of fault-controlled ground-water circulation. The return trip will continue to follow the Jemez River up Canyon de San Diego to the rim of the Valles Caldera, with stops to look at volcanic features associated with the caldera, postcaldera rhyolite ring domes, Valle Grande (suspected site of a once vast caldera lake), and the site of the U.S. Department of Energy's "hot, dry rock" geothermal energy experiments.

One day will be spent in the vicinity of the Circle A Ranch mapping springs, surficial features, and related geology. The synoptic survey of streamflow and water quality conditions will require two days. One day will be spent on the site visit to the gaging station near Cabezon, Soda Dam near Jemez Springs and, the Valles Caldera.

Equipment and Clothing

Equipment for making discharge and water-quality measurements will be supplied. **Participants should bring a pocket calculator and boots or old shoes for wading in streams.** An old pair of tennis shoes is recommended. Because most stream discharge measurements will be made near bridges, no barefoot wading will be allowed. Optional equipment that will help relieve the strain on camp supplies includes stop watches, folding rulers, and tape measures up to 50 feet in length. Participants who have available these pieces of optional equipment are encouraged to bring them to camp.

Products

Stream discharge and water quality measuments are to be compiled by each team so that each team member has a complete compilation of measurements. These data are to be summarized in a table. At the end of the four-day field hydrogeology exercise, **individuals will be expected to write a brief, two page, "extended abstract" describing the hydrogeology of the Rio Puerco watershed** that is supported by mapping, observation, and field measurements. Two maps detailing hydrogeologic conditions along the Rito de los Pinos will be prepared. Included in the area to be mapped are modifications to the natural drainage system and a geologic hazard that has been induced or exacerbated by human activity. A hydrogeologic section will be prepared that illustrates hydrogeologic conditions associated with the hazard.

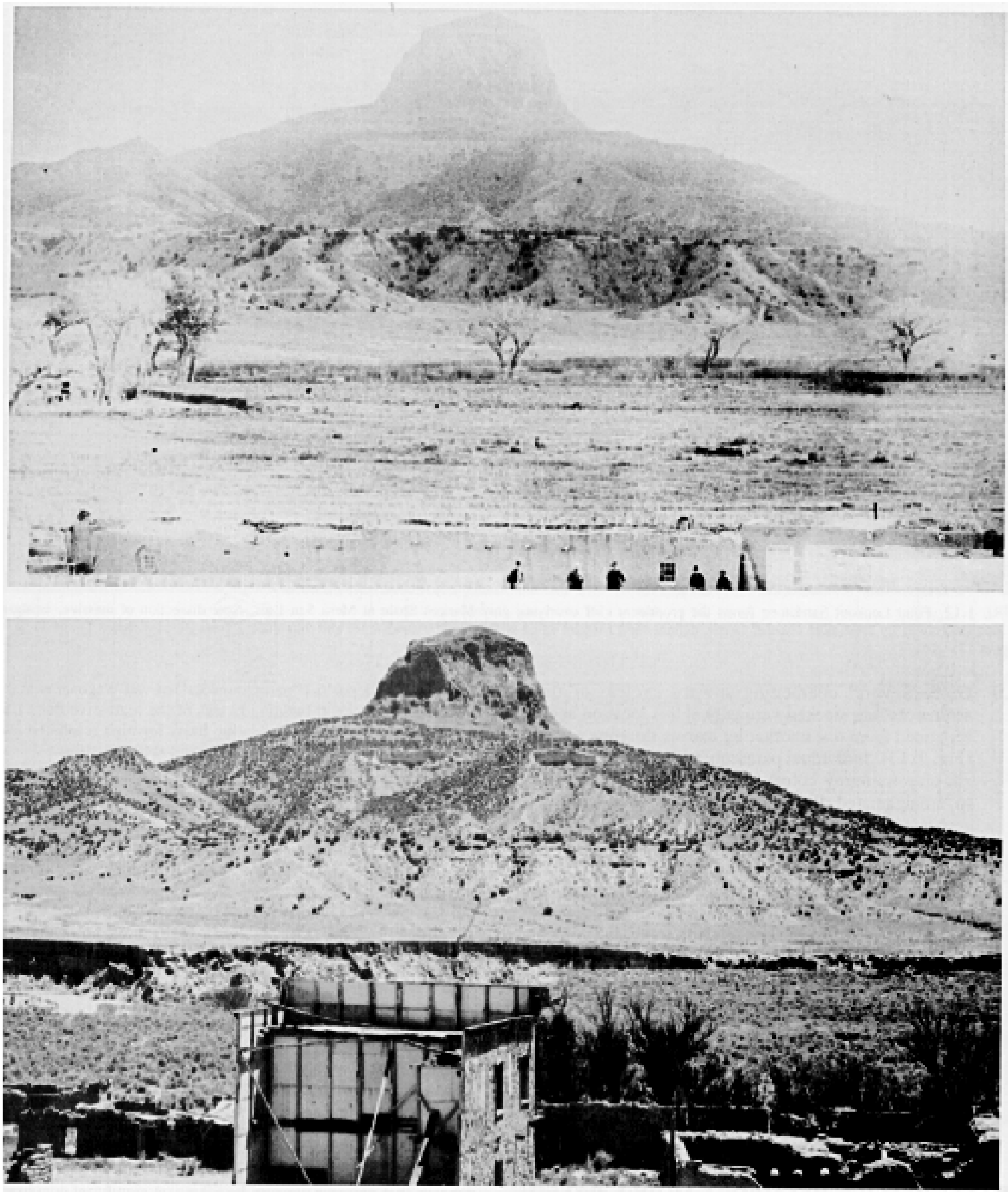


Figure 47: The Rio Puerco and Cabezon Peak as seen from the town of Cabezon, New Mexico. Top picture was taken in 1884; bottom picture in 1977. In 1884 the Rio Puerco flowed in a shallow channel. Today the Rio Puerco flows in an arroyo 15 m deep.

Field Hydrogeology
Schedule of Activities

Day 1: Circle A Ranch and vicinity—

Lecture—Introduction to the hydrogeology of arid regions. Discussion will focus on watersheds, water budgets, gaining versus losing streams, springs, erosion and mass wasting. The climate in New Mexico will be described and compared to the mid-Atlantic states of the eastern United States. Terms, processes and concepts to be discussed include: hydrology, the hydrologic cycle, watersheds, water budgets, precipitation, evapotranspiration, potential evapotranspiration, orographic effect, rain shadow, streamflow, gaining streams, losing streams, ground water, water table, aquifers, confining beds, ground-water recharge, ground-water discharge, springs, spring sapping, mass wasting (slow versus rapid), toreva blocks, listric faults, erosion, and flood irrigation (use of acequia madre, acequia, laterals, and field ditches to divert and channel flow into fields). Methods of expressing the volume of water in watersheds—for example, equivalent uniform depth (EUD), and unit area discharge (UAD)—will be defined.

Polls of past students have shown that most do not have course work or job experience in the field of hydrology prior to attending field camp. **Therefore, it is strongly urged that attendees prepare for this exercise by locating and studying relevant reference materials prior to attending camp**. Attendees will be expected to have a basic understanding of hydrologic concepts and terminology. The references listed at the end of this section can be used to study the terms, processes and concepts listed above, as well as other topics related to this exercise. If the references listed are not available, students are encouraged to locate other source materials.

Although many hydrology texts begin by defining the science of hydrology and introducing the concept of the hydrologic cycle, the introduction to these topics by Meinzer (1942), and Chow (1964) are classics. Chow (1964) also presents an excellent discussion of the history of hydrology as a science (up to the time of publication). A comparison of ground-water regions in New Mexico and North Carolina can be found in Heath (1984). A summary of climatic conditions in North Carolina is given by Kopec and Clay (1975). The orographic effect is described by Fetter (1988, p. 24-26) and Dingman (1994, p. 95-97). Evapotranspiration and potential evapotranspiration are discussed by Chow (1964), Schulz (1973), and others. Aquifers, confining units, ground-water recharge, ground-water discharge, the water table, and other ground-water related topics are described by Freeze and Cherry (1979), Heath (1983), and Fetter (1988). Good discussions of gaining and losing streams are presented by Heath (1983, p. 21-24), Fetter (1988, p. 45-48), and Dingman (1994, p. 318). Functions of ground-water systems and the relation between ground-water movement and topography are discussed by Heath (1983). Springs are discussed by Fetter (1988, p. 231-233). Mass wasting, landslides, creep, listric faults, and erosion are discussed in physical geology texts. The American Geological Institute's (1974, and later editions) Glossary of Geology is an excellent source for definitions of terms.

Field exercise—Mapping along the Rito de los Pinos and in the "Little Grand Canyon."

Mapping is to be performed individually. However, for safety, students will work in small teams of two or three and team members should stay within sight or calling distance at all times. Teams will be assigned for mapping. The mapping teams will be combined into larger teams of four to six people for making discharge measurments during the second and third days of the exercise. The discharge measurement teams should select team leaders who will be responsible for the field equipment and related materials.

Mapping will be at two scales. One base map will be at a scale of 1:18,000 and the other will be at a scale of 1:6,000. Base maps and graph paper for a hydrogeologic section will be furnished.

A. On the 1:18,000 base:

Map drainage, including modifications to drainage, along the Rito de los Pinos. Locate any diversions that may affect the reliability of discharge measurements for hydrologic analysis. Locate control structures used to regulate flow. Map reaches of the Rito de los Pinos where flow is or is not occurring.

Locate and map springs. Attempt to identify structural, stratigraphic, or topographic controls on locations of springs.

Evaluate sites for stream-discharge measurements along the Rito de los Pinos (sites 1-3 in Table 1). Identify straight reaches of stream channel with non-turbulent flow suitable for making discharge measurements.

B. On the 1:6,000 base:

Map mass wasting in the "Little Grand Canyon." Identify toreva blocks and attempt to decipher cause(s) of slumping. Identify hydrogeologic features and processes, such as springs, spring sapping, seeps, drainage diversions, channel deepening or meandering, that may have contributed to slope failure. Map hydrogeologic features. Note badlands topography. Note the relative abundance of vegetation and variation in vegetation communities. Vegetation is an important indicator of hydrologic conditions; therefore, knowledge of the relation between different plant species, vegetation abundance, and the availability of water can be used to support hydrogeologic interpretations. As an aid to interpretation of the hydrogeology of this area, construct a hydrogeologic section along line A-A′ on the 1:6,000 scale map. The base of the hydrogeologic section will be at an altitude of 7,100 feet. The vertical scale is 1 inch equals 100 feet (each vertical division equals 5 feet). When constructing the hydrogeologic section, note that the vertical and horizontal scales are not equal; therefore, the dip of bedding and formation contacts to be shown on the section will need to be corrected for vertical exaggeration. To find the dip to be shown on the section, use the formula:

$$\text{exaggerated dip} = \arctan\ [\text{vertical exaggeration} \times \tan\ (\text{measured dip})].$$

C. Completion of mapping:

If field parties complete their discharge measurements early on days 2 or 3, they should return to the Circle A Ranch and continue mapping hydrogeologic features of the Rito de los Pinos and "Little Grand Canyon." Maps, a hydrogeologic section, a table summarizing discharge and water-quality data, and an "extended abstract" summarizing findings and interpretations will be required for completion of the exercise. By the end of day 2, attendees should have sufficient information to begin organizing a written description of the hydrogeology of the watershed.

Days 2 and 3: The watershed of the Rio Puerco between the headwaters of the Rito de los Pinos and the Rio Puerco near San Luis—

Lecture—Discussion will focus on methods for measuring stream discharge, including use of Price meters (to make partial section discharge measurements), Parshall flumes, and v-notch weirs. These methods are described by various authors, including Schulz (1973), Buchanan and Somers (1969), and Dingman (1994, Appendix F). A technique for estimating the mass transport of total dissovled solids also will be discussed. At the end of the lecture, team leaders will meet with the instructors for assignment of field equipment, sample bottles, and packets containing location maps, discharge computation forms, manuals, and instrument rating tables.

Field exercise—Discharge measurements will be made at eight locations; seven of the discharge measurements will be made on days 2 and 3, one measurement will be made on day 4. On day 2, discharge measurements will be made at four locations along the Rito de los Pinos (Figure 46). These locations are (1) about 1.9 miles northeast of the Circle A ranch house near the Los Pinos trailhead, (2) about 0.7 miles northeast of the ranch house, or 0.25 miles north-northeast of the upper (swimming) pond, (3) about 0.2 miles southwest of the ranch house on the north side of the road to the ranch house, and (4) about 1.25 miles north of Cuba where Highway 44 crosses the Rito de los Pinos. On day three, discharge measurements will be made at three locations along the Rio Puerco between Cuba and San Luis (Figure 46). These locations are (1) about 1 mile southwest of Cuba where Highway 197 crosses the Rio Puerco, (2) about 12.5 miles south of Cuba on the west side of Highway 44 near La Ventana, and (3) about 5.0 miles west of Highway 44 where the road to San Luis (Highway 279) crosses the Rio Puerco. The eighth, and final, discharge measurement will be made on day 4 during the site visit to the gaging station on the Rio Puerco near Cabezon Peak (Figure 46). Drainage areas at each of the eight sites are given in Table 1.

Table 1.—Drainage areas at sites on the Rito de los Pinos and the Rio Puerco

	Drainage areas at sites on the Rito de los Pinos	
Site No.	Name	Drainage Area (mi^2)
1	Rito de los Pinos at Los Pinos trail head	2.21
2	Irrigation ditch at diversion structure NNE of pond	2.32
3	Irrigation ditch at road to Circle A Ranch	2.51
4	Rito de los Pinos at Highway 44 near Cuba	9.58
	Drainage areas at sites on the Rio Puerco	
Site No.	Name	Drainage Area (mi^2)
5	Rio Puerco at Highway 197 near Cuba	113
6	Rio Puerco near La Ventana	307
7	Rio Puerco at Highway 279 near San Luis	375
8	Rio Puerco above Arroyo Chico near Guadalupe (at gaging station located 4.0 miles west of Cabezon Peak)	436

Discharge values are to be recomputed as unit area discharges (UADs) for (1) the total area of watershed upstream from each of the eight sites, and for (2) the intervening watershed between each of the eight sites. The UADs are to be compared to determine gaining and losing reaches within the watershed.

Samples of water are to be collected at each site where discharge is measured. These samples are to be taken back to camp where the specific conductance will be determined and total dissolved solids estimated. Total dissolved solids (TDS), in mg/L, can be estimated from specific conductance (SC), in us/cm, using the following equations:

$$TDS = 0.0 + 0.6292\,(SC) \qquad (1)$$
$$TDS = -128.34 + 0.8114\,(SC) \qquad (2)$$

Equation 1 is to be used when specific conductance is less than 705 us/cm; equation 2 is to be used when specific conductance is greater than 705 us/cm. Equation 1 was derived from a linear regression of data shown in Figure 48A, and equation 2 was derived from a

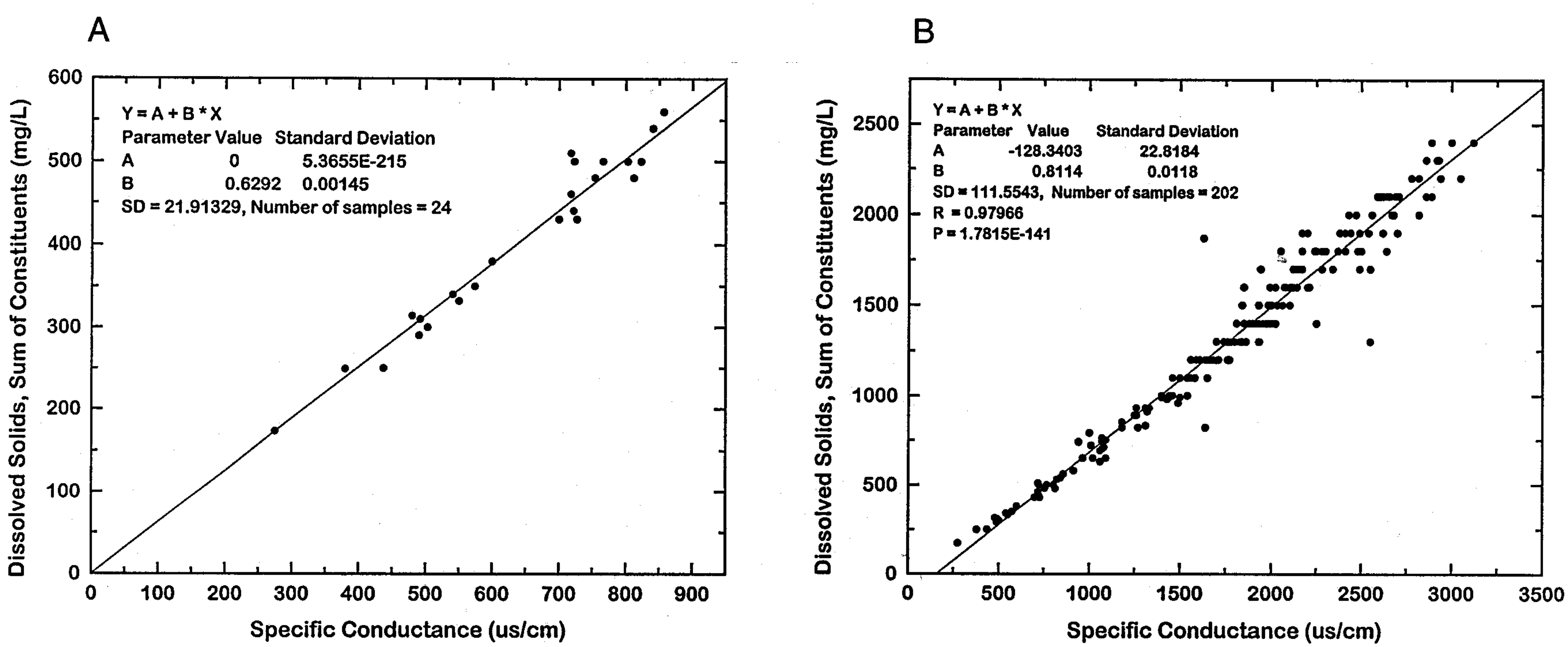


Figure 48: Relation between total dissolved solids and specific conductance in water from the Rio Puerco when (A) specific conductance is less than 705 us/cm, and (B) specific conductance is greater than 705 us/cm. The total dissolved solids concentrations are the computed sums of dissolved constituent concentrations determined from complete chemical analyses of water samples.

linear regression of data shown in Figure 48B. The total dissolved solids concentrations in Figure 48 are the computed sums of dissolved constituent contrations from complete chemical analyses of water samples.

The estimates of total dissolved solids, in combination with the discharge measurements, are to be converted to estimates of total dissolved solids load (TDSL). The estimates of total dissolved solids load, or mass transport, from the eight sites are to be converted to unit area loads and compared. Because the measurements of stream discharge and estimates of TDS are considered to be instaneous values, the estimates of TDSL are also considered instantaneous values. However, estimates of mass transport are often expressed in units of mass per day. The TDSL, in tons per day, can be computed from discharge (Q), in ft^3/s, and TDS, in mg/L, using the following equation:

$$TDSL = 0.002697 (Q) (TDS) \qquad (3)$$

Remember, if field parties complete their discharge measurements early on days 2 or 3, they should return to the Circle A Ranch and continue mapping of springs, mass wasting, and other hydrogeologic features. Maps, a hydrogeologic section, and a written description of the features will be required for completion of the exercise. By the end of day 2, attendees should have sufficient information to begin organizing a written description of the hydrogeology of the watershed.

This description should utilize information from field observation and mapping, measurements of discharge, comparisons of runoff within the watershed based on UADs, chemical data and estimates of TDSL. The description should focus on the sources, movement, and distribution of water within the watershed. The description should also include possible explanations for any differences in runoff within the watershed.

Day 4: Site visits to U.S. Geological Survey gaging station near Cabezon Peak, Guadalupe Box Canyon, Soda Dam near Jemez Springs, and the Valles Caldera—

All field parties will caravan to several sites on day 4. The first site will be the U.S. Geological Survey gaging station on the Rio Puerco near Cabezon Peak (Figure 47). Discussion will focus on gaging station operation, computation of continuous records of streamflow (Kennedy, 1983; 1984), and automatic water samplers. The last of the eight discharge measurements will be made by reading the stage of the river on water-level recorders at the gaging station, and converting the stage to discharge by means of a rating table. The rating table was developed by the New Mexico District of the USGS from many discharge measurements at the gaging station and is specific for this gaging station. A water sample will be collected and specific conductance measured.

The caravan will return to the abandoned town of Cabezon at the foot of Cabezon Peak. Discussion will focus on erosion in the watershed of the Rio Puerco, its history and possible causes.

> "San Luis is the northernmost of four abandoned or nearly deserted towns that occupied the middle Rio Puerco valley; the others being Cabezon, Guadalupe, and Casa Salazar. Several villages had appeared in the mid-1700s as the Rio Puerco was being parceled into nine large land grants (1753-1769), but all were abandoned by 1740 because of constant raids by the Navajos. Early American exploring parties crossed and recrossed the Rio Puerco in the late 1840s and 1850s but found no permanent inhabitants. By the 1860s the Navajos had been confined to reservations, and people began to settle again in the Rio Puerco valley. The four middle Rio Puerco towns all date from 1870 to 1872. Typically, they were built on the floodplains of the river, on or close to the locations of the 18th century villages. The settlers constructed irrigation ditches, dug by hand or with scoops pulled by draft animals, and built rudimentary dams to divert the flood waters. Agricultural fields

were planted between the diversion channels and the river so irrigation water would flow by gravity across the fields and drain into the river (a practice known as flood-irrigation agriculture). Crops were grown along the river between the towns for a distance of more than 25 miles and for a time the Cabezon area was known as the breadbasket of New Mexico. Cattle, sheep, goats, and horses were grazed in the surrounding areas farther from the river.

"Cabezon is one of the best preserved ghost towns in New Mexico. It consists of numerous low adobe buildings and ruins, including an old store and an intact church. Indeed, except for the deteriorating effects of solitude and the elements, the town seems little changed from the early part of the century. Cabezon (originally the settlement of La Posta) developed and served as an important station on the stage coach route between Santa Fe and Fort Wingate. This area was also an important stop for the Great Navajo Trail. For this reason, Cabezon grew into a major trading center for the Navajos. The town's name was changed to Cabezon in 1891 when a post office was granted, and by 1915 it contained saloons, dance halls, and general stores on both sides of the Rio Puerco serving a population of several hundred. Richard Heller, a prosperous store owner and leading citizen of Cabezon for more than 50 years, was reputed to have owned at one time as many as 10,000 sheep and 2,000 cattle, and that it took as many as 40 wagons to transport his wool to market in Albuquerque.

"The middle Rio Puerco towns were reasonably successful into the early 20th century. However, beginning in the 1880s, overgrazing and depletion of plant cover, and the accelerated erosion and arroyo entrenchment that resulted, began to alter the landscape and the productivity of the farmland. Lowering of the water table, deepening of the river and arroyo channels and silting of the irrigation channels became increasingly severe. Devastating flash floods, alternating with periods of drought, contributed to the problems. Most buildings at Cabezon were moved beyond the banks of the Rio Puerco to escape flooding. Gradually the towns' prosperity waned. The Santa Fe railroad decided against a branch through Cabezon, and the towns were bypassed by the main highways in the 1920s and 1930s. To the south, in the lower valley, the channel width of the Rio Puerco increased from 75 feet in 1880 to 790 feet in 1939. At La Ventana, to the north, the channel was only 8 feet deep in the 1870s, but was more than 50 feet deep in the 1950s. Deepening of the Rio Puerco channel made it more difficult to build and maintain diversion dams. The last dam to be built in 1931 was washed out in 1951 by a large flood.

"By that time, decades of decreasing productivity and crop yields too small to provide a living had caused nearly every family in the valley to drift away, and most of the towns had been abandoned Only two families remained in San Luis by the end of the 1950s. Here and there along the Rio Puerco the remains of the irrigation ditches and dams may still be seen, together with the ruins of the towns—testimony to the difficulty of farming in a deteriorating environment, along a mostly dry, but unpredictible river" (Lucas, and others, 1992).

The caravan will return to Highway 44. Turn south (right turn) and proceed to San Ysidro; turn north (left turn) onto Highway 4 and proceed north along the Jemez River, past the Jemez Pueblo, and into Canyon de San Diego. At Highway 485 turn left; follow Highway 485 along the Rio Guadalupe to the Guadalupe Box Canyon, site of two former railroad tunnels known as the Gilman tunnels. At the entrance to Box Canyon, you will see a gaging station on the Rio Guadalupe; look down to the right. Go through the tunnels and stop for lunch. Return to Highway 4. Turn north (left turn) and proceed to Soda Dam about 1.0 mile north of Jemez Springs. Jemez Springs is noted for its hot springs and bath houses. Soda Dam and the hot springs that produced it are an excellent example of fault-controlled ground-water circulation. Discussion at this stop will focus on ground-water circulation, fault-control of springs, and sources of dissolved minerals in the spring discharge.

> "This unusual travertine spring deposit has been built by carbonated waters issuing from a segment of the Jemez fault that crosses the canyon here and brings a structural horst of Precambrian granite up against Abo Formation (Permian) on the east and Madera Limestone (Pennsylvanian) on the west. Remmnants of older travertine dams enclosing Pleistocene stream deposits occur as much as 975 feet (300 m) high on the canyon walls, indicating that the springs have been active for a long time during down-cutting of the canyon. According to S.A. Northrop (1961), 22 springs were issuing from the crest of the dam in 1902, but by 1912 only 11 were active. During the 1950's spring waters were issuing from only three points near the east end of the dam, but highway reconstruction in the late 1960's cut off the water flow entirely, and the dam is no longer renewing itself. Up Canyon de San Diego, 3.2 miles from Soda Dam, the highway passes a small solfatara (a strong hydrogen sulfide odor may be detected) to the right below the highway. Like Soda Dam, this solfatara is on the Jemez fault and is one of the few solfataras outside the Valles Caldera" (Bailey and Smith, 1978).

Streamflow in the Jemez River watershed is measured at several gaging stations. One is located on the Jemez River 3.5 miles north of the village of Jemez. Another is located on the Rio Guadalupe, a tributary to the Jemez River, at Box Canyon. The drainage area of the watershed upstream from the gage Jemez River near Jemez is 470 mi2. The drainage area upstream from the gage Rio Guadalupe at Box Canyon near Jemez is 235 mi2. Between 1937 and 1993 (water years), the average annual runoff past the gage at Jemez was 2.23 inches (maximum 5.45 inches, minimum 1.01 inches). Between 1959 and 1993, the average annual runoff past the gage on the Rio Guadalupe was 2.53 inches (maximum 5.80 inches, minimum 0.84 inches). Unlike the gage on the Rio Puerco near Cabezon (average annual runoff, 1951-1993, 0.45 inches), there have been no recorded days of zero flow at these two gages.

Using a technique called hydrograph separation, the ground-water contribution to total streamflow can be estimated from records of streamflow (Pettyjohn and Henning, 1979; Fetter, 1988, p. 41-45; Rutledge, 1993; Rutledge and Daniel, 1994). Several methods have been developed to perform hydrograph separations. Two methods (Pettyjohn-Henning local minimum method and the Rorabaugh-Daniel method) were used to analyze the streamflow record from the Jemez River watershed. Results for the Jemez River near Jemez suggest that, on average, the annual ground-water contribution to streamflow is in the range of 1.58 to 1.79 inches, or 71 to 80 percent of total streamflow. Results for the Rio Guadalupe at Box Canyon suggest that, on average, the annual ground-water contribution to streamflow is in the range of 1.98 to 2.22 inches, or 78 to 88 percent of total streamflow.

After leaving Soda Dam, the caravan will continue north on Highway 4 past Battleship Rock. Between Soda Dam and Battleship Rock are several hot springs and a small solfatara; when weather conditions are favorable, you will notice the strong odor of sulfurous gases as you drive up the canyon. Just before reaching Battleship rock, we will pass a gaging station (to our right) equipped with a suspension cable for measuring discharge at high flows. This is the gaging station, Jemez River near Jemez, discussed previously.

Continue up Canyon de San Diego to the rim of the Valles Caldera. The rim of the caldera is breached by the Jemez River and its headwater streams, San Antonio Creek and East Fork Jemez River. The interior of the caldera to the west and north is drained by San Antonio Creek; the southeastern part of the caldera, including Valles Grande, is drained by the East Fork Jemez River. The confluence of these two streams at Battleship Rock forms the Jemez River.

At the intersection of Highways 4 and 126 (at La Cueva), turn right to continue on Highway 4 and proceed about 10 miles to Valle Grande on the southeast side of the caldera. Along this segment of the route, Highway 4 generally follows the rim of the caldera. There will be stops to look at volcanic features associated with the caldera, postcaldera rhyolite ring domes, and Valle Grande (suspected site of a once vast caldera lake). From the Valle Grande overlook, return to La Cueva and continue on Highway 126 to the site of the Department of Energy's "hot, dry rock" geothermal energy experiments.

At this point the trip is complete and the caravan will return to camp. Continue along Highway 126 back to Cuba. This is a scenic route through the Santa Fe National Forest that will provide excellent views of Redondo Peak, spires and other features produced by differential erosion of the Bandelier Tuff, and high-country forests and meadows. Some of the route will be at altitudes of 8,000 ft and above.

Note: If attendees have not completed their summary of the hydrogeology exercise, about two hours is to be dedicated at the end of day four to the completion of the written part of the exercise. Remember, the "extended abstract" is to be no longer than two pages and is to be written in a good, scientific format. Thus, it will have a definitive title; it will contain a statement of purpose, and scope, to be followed by a description of findings, discussion (interpretations), and conclusions; separate headings for these topics are not necessary in an extended abstract. Orderly presentation of the material will suffice. The two maps, hydrogeologic section, and data table are to be attached and used as figures and a table for the abstract. Figures and tables should have captions, explanations, and footnotes where necesscary.

CHARACTERISTICS AND CLASSIFICATION OF SLOPE MOVEMENTS

Stephen B. Harper, Visiting Assistant Professor, East Carolina University

Morphology and Geometry of Slope Movements

A large body of descriptive terminology has evolved relating to the size, shape, and morphology of slope movements and their deposits. A close association often exists between the morphology of a slope movement and its dominant genetic process. Therefore, descriptive terms for slope movement features and geometry have been suggested (Varnes, 1978; Cruden and Varnes, 1996). The most common terms used to describe the features and geometry of slope movements are shown in Figure 1**.**

The term landslide encompasses all moderately rapid falls, slides, slumps, flows, and avalanches that have well-defined boundaries and that move downward and outward from a natural or artificial slope (Crozier, 1986). Therefore, the term landslide is often used interchangeably for the term mass movement. However, the term, landslide, has been considered unsuitable as a broad collective term because the active part of the word denotes sliding, which does not describe the type of motion for all types of mass movements, such as falls, flows, and avalanches (Crozier, 1973; Varnes, 1978). For this reason Varnes (1978) has advocated the term, slope movements, instead of landslides for mass movements restricted to slopes. Henceforth, in this overview the term, **slope movement**, will be used in lieu of the terms, mass movement and landslide.

Classification of Slope Movements

Slope movements, like most geologic features, can be classified into types or categories based on the primary mechanism or process by which they form or based on their morphology and material properties. Because most rapid slope movements are not observed as they occur, the fundamental properties of motion must be interpreted after the slope movement has occurred. Interpretations are based on the morphology of the slope movement scar and the geometry and sedimentology of their deposits (Ritter et al, 1995). Therefore, clearcut distinctions between the primary methods of transport are difficult to assess. Several slope movement classifications have evolved, which incorporate some combination of the morphology of the slope movement scar and the type of material transported. In this study Varnes' (1978) and the Cruden and Varnes' (1996) classification of slope movements will be used because it easily applied in the field. For the Varnes' (1978) and Cruden and Varnes' (1996) classification the **primary classification criterion is**, **'type of movement,'** which establishes the principal categories of slope movements, such as falls, slides, and flows. The **secondary classification criterion**, used in the Varnes' (1978) and Cruden and Varnes' (1996) **classification, is based on the 'type of material moved'** (Table 1). The approach of using material subgroups, based on characteristics of the source material, as opposed to the displaced material, is a useful and important distinction because the displaced material in some cases may derive its characteristics as a result of the slope movement (Crozier, 1986).

In the Varnes' (1978) and Cruden and Varnes' (1996) classification, slope movements are divided into five main categories: falls, topples, slides, spreads, and flows (Table 1). A sixth category, composite slope movements, includes combinations of two or more of the other five types (Table 1). Furthermore, in the Varnes' (1978) and Cruden and Varnes' (1996) classification a debris avalanche is considered to be a very rapid to extremely rapid hillside debris flow. Thus, avalanches are not included as a type of slope movement in this classification. **For the secondary level of Varnes' (1978) classification, the type of material is broken down into two sub-categories,**

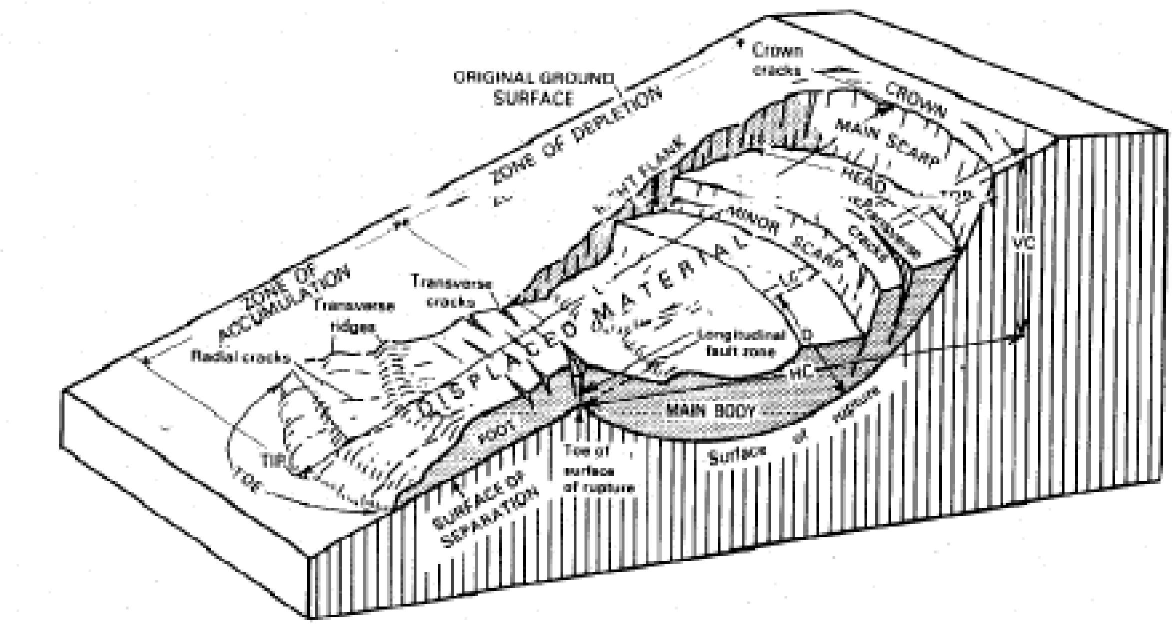


Figure 1 - Block diagram of idealized composite rotational earth slide-earth flow with definitions of features shown (after Varnes, 1978; Cruden and Varnes, 1996).

Crown - Practically undisplaced material adjacent to the highest parts of the main scarp.
Flank - Undisplaced material adjacent to the sides of the surface of rupture.
Foot - Portion of a landslide that has moved beyond the toe of the surface of rupture and overlies the original ground surface.
Head - Upper parts of a landslide along the contact between the displaced material and the main scarp.
Left and Right - Compass directions are preferable in describing a landslide, but if right and left are used, they refer
to the flanks of a landslide as viewed from the crown.
Longitudinal Fault Zone - Elongate fractures or faults in a landslide approximately parallel to the direction of landslide movement.
Main Scarp - Steep surface on the undisturbed ground at the upper edge of a landslide, caused by movement of displaced material away from undisturbed ground. It is the visible part of a surface of rupture.
Minor Scarp - Steep surface on the displaced material of a landslide produced by differential movements within the displaced material.
Original Ground Surface - Slope that existed before the movement, which is being considered, took place. If this is the surface of an older landslide, that fact should be stated.
Radial Cracks - Fractures in a landslide that radiate outward.
Slope Reversed - Sloping surface at the top of a slump block that dips gently into a hillside and in the opposite direction of the original hillslope.
Surface of Rupture - Surface below the original ground surface along which a slump block is detached from the original in-place material and subsequent movement occurs.

<u>bedrock</u> and <u>engineering soils</u>, which are further divided into two classes, <u>debris</u> (predominantly coarse) and <u>earth</u> (predominantly fine) (Table 1).

Table 1 - Classification of slope movements (landslides) (after Varnes, 1978; Cruden and Varnes, 1996).

TYPE OF MOVEMENT	**TYPE OF MATERIAL**		
	Bedrock	**Engineering Soils**	
		Predominantly Coarse	**Predominantly Fine**
Falls	Rock Fall	Debris Fall	Earth Fall
Topples	Rock Topple	Debris Topple	Earth Topple
Rotational Slides	Rotational Rock Slide	Rotational Debris Slide	Rotational Earth Slide
Translational	Translational Rock Slide	Translational Debris Slide	Translational Earth Slide
Lateral Spreads	Rock Spread	Debris Spread	Earth Spread
Flows	Rock Flow (deep creep)	Debris Flow	Earth Flow
Composite (Combination of 2 or more principal types of slope movements)			

In the section below slope movements and materials, as defined by Varnes (1978) and Cruden and Varnes (1996), will be discussed in more detail. Slope movements such as, topples, lateral spreads, flows in bedrock, and solifluction, which are not pertinent to the geology field course exercise, will not be discussed.

Material and Water Content in Slope Movements

The division of materials involved in slope movements is completely gradational but is intended to enable one to assign a name to these materials based on a limited amount of information (Varnes, 1978).

1. Bedrock designates hard or firm rock that was intact and in place before the initiation of a slope movement.

Engineering soil includes any loose, unconsolidated, or poorly cemented aggregate of solid particles, generally of natural mineral, rock or inorganic composition and either transported or residual, together with any interstitial gas or liquid. Based on texture, engineering soil is then divided into two types, debris and earth.

a. Debris refers to an engineering soil, generally surficial, that contains a significant proportion of coarse material. Debris is used to specify material in which 20 to 80 percent of the fragments are greater than 2 mm (sand-sized) and the remainder of the fragments less than 2 mm (sand-sized or less) (Shroder, 1971).

b. Earth refers to material in which about 80 percent or more of the fragments are smaller than 2 mm. These materials range from nonplastic sand to highly plastic clay (Shroder, 1971).

The following terms are used to describe water content: (a) dry - contains no visible moisture; (b) moist - contains some water but no free water and may behave as a plastic solid but not as a liquid; (c) wet - contains enough water to behave in part as a liquid, has water flowing from it, or supports significant bodies of standing water; and (d) very wet - contains enough water to flow as a liquid under low gradients (Varnes, 1978).

Types of Slope Movements

Falls

Falls occur when a single mass of any size is detached from a steep slope or cliff along a surface on which little or no shear displacement occurs (Table 1). The detached material descends mostly through the air by free fall, leaping, bounding, or rolling (Figure 2a). Falls are very rapid to extremely rapid and may or may not be preceded by minor movements leading to a progressive separation of mass from its source (Varnes, 1978).

Rock falls are most common in areas in which the bedrock is well jointed and has a steeply sloping rock face. The joints may enlarge progressively by heaving until the gravitational force exceeds the internal resistance. In temperate regions heaving is caused primarily by freeze-thaw cycles. The removal of subjacent support at the base of a slope by undercutting of the rock or soil by erosive agents tends to increase tension in the overhang and thus helps to create and expand incipient cracks (Ritter et al, 1995).

Slides

Slides are slope failures that are initiated by slippage along a well-defined failure surface and are subdivided into two classes, **rotational** and **translational** (Table 1). Rotational slides, formerly referred to as slumps, usually consist of only one unit or a few units that move along a curved, concave-upward surface (Figure 1; Figure 2c). In addition, the displaced material in rotational slides is not greatly deformed. On the other hand, translational slides, sometimes simply referred to as slides, consist of many semi-independent units that move along a flat planar surface (Figure 2d-e). Furthermore, the displaced material that has undergone translational sliding is greatly deformed (Varnes, 1978; Ritter et al, 1995).

Rotational slides occur most frequently in fairly homogeneous materials. However, geologic materials are seldom uniform in composition and physical properties so rotational slides tend to be complex or at least significantly controlled in the nature of their movement by internal inhomogeneities and discontinuities in the geologic materials in which they occur. Therefore, the concave upward rupture surfaces on rotational slides are rarely uniform in curvature. Often the shape of the rupture surface is significantly influenced by faults, joints, bedding planes, or other pre-existing discontinuities in the material. Upward thrusting and slickensides can also occur along the lateral margins of the toe of rotational slides (Varnes, 1978).

Movement in rotational slides occurs only along internal slip surfaces. Thus, in terms of recognition in the field or on aerial photographs, rotational slide failure surfaces are concentric in plan view and concave toward the direction of movement. In many rotational slides the underlying surface of rupture along with the exposed scarps is spoon-shaped (Figure 1; Figure 2c)**.** If the rotational slide extends for a considerable distance along the slope perpendicular to the direction of movement, much of the rupture surface may approach the shape of a cylinder, which is oriented with its axis parallel to the slope**.** Therefore, movement in rotational slides is more or less rotational about an axis, which is parallel to the slope. Movement in rotational slides may almost be totally downward in the head area and thus have little apparent rotation (Figure 2c) (Varnes, 1978)

Morphologically, the scarp at the heads of rotational slides may be almost vertical. If the main mass of the rotational slide moves down very far, a steep scarp is left unsupported and the stage is set for new failure (similar to the original failure) at the crown of a rotational slide (Figure 1). Occasionally, the scarps along the lateral margins of the upper part of a rotational slide may also be so high and steep that rotational slide-blocks break off along the sides and move downward and inward toward the middle of the main rotational slide. The top surface of each unit in rotational slides commonly tilts backward toward the slope (Figure 2b). Hence, water that drains into the head of a rotational slide may be ponded by backward tilting of the unit blocks or by other irregularities in topography so that a rotational slide is kept wet constantly. Thus, by the successive creation of steep scarps and trapping of water, rotational slides often become self-perpetuating areas of instability and may continue to move and enlarge intermittently until a stable slope of very low gradient has evolved (Varnes, 1978).

Translational slides are the most common of sliding-type slope movements. In a translational slide the slide mass progresses outward, or down and outward, along a more or less planar surface (Figure 2d-e). Thus, the moving mass commonly slides out onto the original ground surface of areas below the origin of the slide. Furthermore, a translational slide may progress indefinitely if the surface on which it rests is sufficiently inclined and the shear resistance along the failure surface remains lower than the constant driving force of gravity. A translational slide may consist of a single unit, which has not been greatly deformed, or of a few closely related units (Varnes, 1978).

Movement in translational slides is commonly controlled structurally by surfaces of weakness, such as faults, joints, bedding planes, or foliation surfaces, by variations in shear strength between layers of bedded deposits, or by the contact between firm bedrock and overlying sediment or residual soil. In many translational slides the slide mass is greatly deformed or breaks up into many independent units (Figure 2e). As deformation and disintegration continue, and as water content or velocity or both increase, disrupted slide material may change into a flow, an example of a composite type of slope movement (Varnes, 1978; Cruden and Varnes, 1996).

Flows in Engineering Soils

Flows occur in both **coarse-grained (debris)** and **fine-grained (earth) soil and regolith**

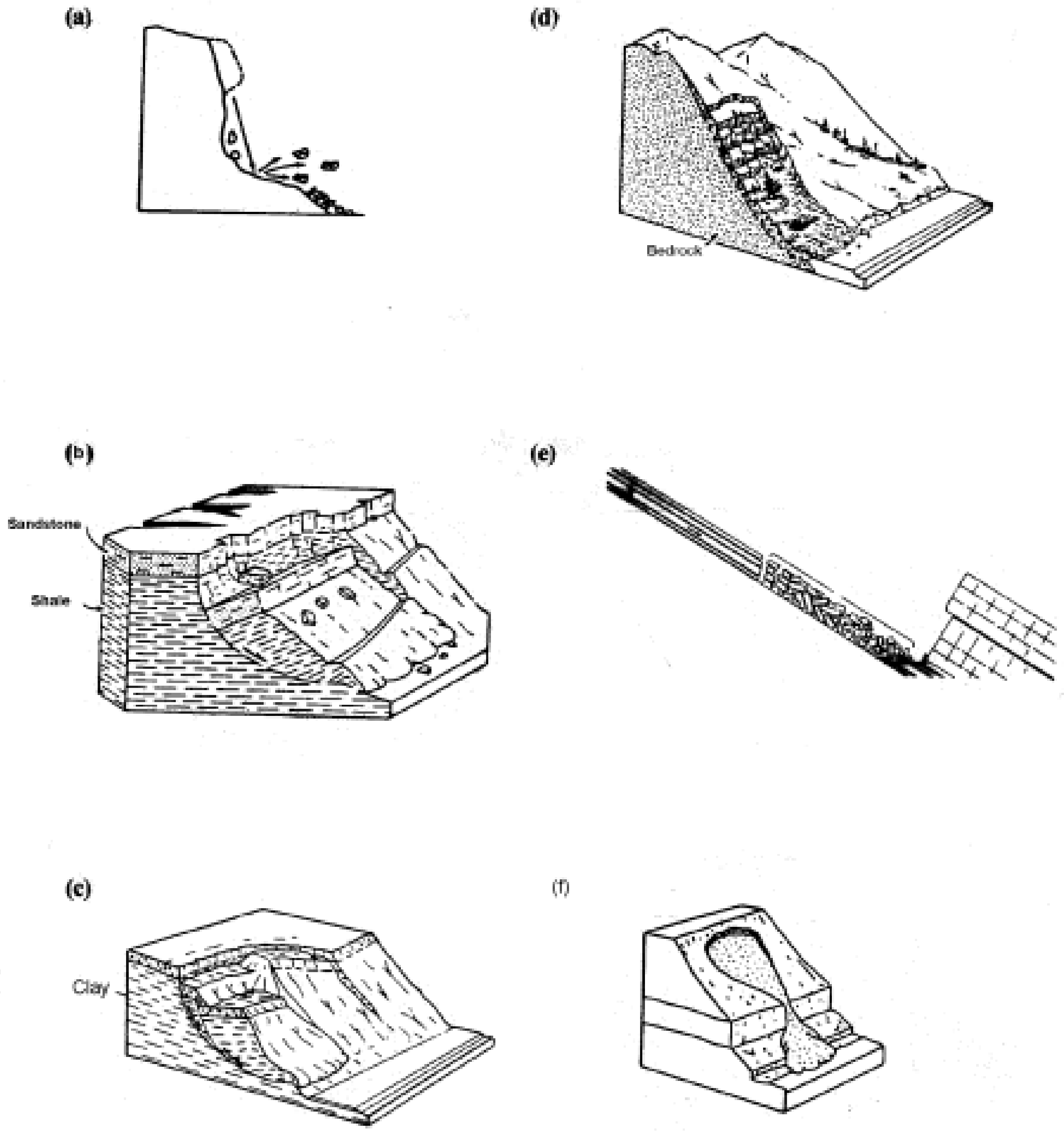


Figure 2 - Types of Slope Movements: (a) Fall; (b) Rotational Rock Slide; (c) Rotational Earth Slide; (d) Translational Debris Slide; (e) Translational Rock slide; and (f) Flow (from Cruden and Varnes, 1996).

materials when these materials are liquefied (Table 1; Figure 2f). In flows the movement within the displaced mass closely resembles that of a viscous fluid in which velocity is greatest at the surface and decreases downward in the flowing mass (Ritter et al, 1995). Thus, flows involve the movement of unconsolidated earth materials in a plastic or semifluid state (Pipkin, 1994). In many cases flows are the final event in a slope movement begun as a slide (i.e., a composite slope movement). The transporting power of a flow is disproportionate to its size. Moreover, as more material is added to a flow by bank caving or other incoming flows, its size and power increase. Flows commonly follow pre-existing drainage courses, and they are often of high density, 60 to 70 percent solids by weight, so that very large boulders may be transported. Usually, some of the coarser material will be heaped along the margins of the flow to form a natural levee while the more fluid phase of the flow moves down the channel. Flows may extend many kilometers until they drop their loads in a valley of lower gradient or on an alluvial fan at the base of a mountain front (Varnes, 1978).

Debris Flows

In the Varnes' (1978) classification **debris flows** are distinguished from earthflows or mudflows on the basis of particle size (Table 1). Earthflows or mudflows contain mostly fine-grained material, such as sand, silt, and clay mixed with water. In contrast, debris flows are dense, fluid mixtures of boulders, cobbles, pebbles, gravel, sand, mud, and water, which may be generated quickly during heavy rainfall or rapid snowmelt where an abundant supply of loose soil and rock material exists (Varnes, 1978). Additionally, the Varnes' (1978) classification reserves the term, debris avalanche, for an extremely rapid form of debris flow, which is generated on steep bedrock slopes with thin colluvial and soil cover, contains single or multiple head scarps, and follows a long, narrow chute/track down moderately steep slopes of 20^{o} or more.

A complete gradation exists from debris slide to debris flow depending on water content, mobility, and the rate and character of the movement as movement becomes more rapid due to lower cohesion or due to higher water content and steeper slopes. Debris slides may have rotational slide blocks at their heads. However, this morphology is much less common for debris flows. In debris flows progressive failure is rapid, and the whole mass, either because it is quite wet or because it is on a steep slope, liquefies or partially liquefies, flows, and tumbles downward usually along a pre-existing drainage path. As a result, a debris flow may advance well beyond the foot of a slope. Hillside debris flows generally have long and narrow chutes and often leave a serrated, V-shaped scar tapering uphill at their heads (Varnes, 1978).

Debris flows have a wide distribution. Although they are generally associated with semiarid regions, they commonly occur in mountainous regions with semiarid, temperate, or tropical climates and in active volcanic terrains (Varnes, 1978; Brunsden, 1979; Innes, 1983). Source area conditions for initiation of most debris flows include: (1) steep slopes; (2) an abundant supply of unconsolidated surficial materials; (3) a large supply of moisture; and (4) sparse vegetation (Costa and Williams, 1984). Debris flows move in discreet slugs or surges rather than as a steady, continuous flow. The periodicity of these surges ranges from a few seconds to several hours (Costa and Williams, 1984). Specific flow properties of debris flows usually vary with water and clay content, sediment size and sorting, and channel geometry (Costa, 1984). Debris flows contain a wide variety of grain sizes from boulders to clay mixed with varying amounts of water (Costa, 1984; 1988). The general characteristics of debris flows are that they have high fluidity during movement (from 1 to 93 m/s), contain up to 50 percent sand-sized or finer material, which is poorly sorted and lacks stratification, and have high densities, commonly 1.5 to 2.0 g/cm^3, they are capable of transporting large boulders (Brunsden, 1979).

Earthflows

Earthflows occur in a variety of forms, range in water content from above saturation to essentially dry, and range in velocity from extremely rapid to extremely slow. Varnes (1978) uses the term earthflow for all types (slow or rapid) of flow movements (wet or dry) involving predominantly fine-grained soil materials, which contain at least 50 percent sand-, silt-, and clay-sized particles (Table

1). Some earthflows have basal lobes and other features suggestive of fluid-like flow whereas others exhibit slickensides and other properties suggestive of rigid blocks moving on distinct shear surfaces (Ritter et al, 1995).

Earthflows have been observed on slopes of variable steepness. Their mobility appears to depend on a combination of the following factors: unit weight of the material, shear strength of the soil, maximum pore water pressures, and geometry of the slope mass (Keefer and Johnson, 1983). Unlike most other forms of slope movements, earthflows are commonly characterized by slow movements spread over long periods of months to years (Ritter et al, 1995). However, episodic surges in earthflows have been observed (Keefer and Johnson, 1983; Grainger and Kalaugher, 1987).

Some slope movement classifications differentiate between earthflows and mudflows. In contrast to Varnes' (1978) classification, Sharpe (1938) noted that mudflows differ from earthflows in several ways. Usually, mudflows move more rapidly than earthflows because they have higher water contents and originate on steeper slopes. Also, they usually follow former stream channels and are produced when water is suddenly supplied to an area in which an abundant supply of fine-grained soil material is readily available whereas earthflows are drier movements usually accompanied by sliding. Finally, mudflows consist of a tumbled mass of heterogeneous debris whereas earthflows consist of larger segments of regolith, which may preserve large portions of the regolith with only minor fragmenting, tilting, and deformation.

In slow earthflows the original failure of the slope usually occurs as a rotational slide (Figure 1), especially when the mass becomes saturated with groundwater (Ritter et al, 1995). However, rapid earthflows form a complete gradation with slides involving failure by lateral spreading. These rapid earthflows not only involve liquefaction of the subjacent material but also retrogressive failure and liquefaction of the entire slide mass. They usually occur in sensitive materials, whose shear strength has been greatly reduced due to remolding at a constant water content (Varnes, 1978).

Composite Slope Movements

Composite slope movements exhibit more than one type of movement (Table 1; Figure 1). A slope movement may become composite either by acquiring different characteristics over its course or by acquiring different characteristics during different stages of its development (Varnes, 1978; Cruden and Varnes, 1996). An example of a composite slope movement is a rotational earth slide, which turns into an earthflow with addition of water to the sliding mass. Varnes (1978) noted that rock slide- and rock fall-debris flows are the most common composite slope movements in mountainous regions.

Slope Stability and Geomorphic Thresholds

Rock or residual soil material on a slope will remain stable as long as the sum of the applied shear stresses does not exceed the sum of the shear strength of the slope materials. All types of slope movements are similar in that they are initiated when the shear stress (driving force) tending to displace the material exceeds the shear strength and friction (resisting forces) of the materials on the slope. The shear strength of any material is derived from three components: (1) its overall frictional characteristics, usually expressed as the angle of internal friction; (2) the effective normal stress; and (3) cohesion. These factors determine the shear strength of the material by the Coulomb equation:

$$S = c + s' \tan(f)$$

where S is shear strength in units of stress, *c* is cohesion, s' is effective normal stress, and f is the angle of internal friction (Ritter et al, 1995).

Stability represents some balance between driving forces (shear stress) and resisting forces (shear strength) and can be expressed as a safety ratio:

$$F_S = \frac{\text{resisting forces (shear strength)}}{\text{driving forces (shear stress)}}$$

F_S values greater than 1 connote slope stability, but as this safety ratio approaches unity, a critical condition evolves, and failure becomes imminent as this threshold value is approached. Thus, any factor that lowers the safety ratio can trigger or cause a slope movement. This tendency can be produced by increasing the driving force (shear stress), lowering the resisting force (shear strength), or both (Ritter et al, 1995). Therefore, the initiation process for slope movements can be viewed in the context of: (a) factors that increase shear stress on earth materials and (b) factors that decrease shear strength of earth materials. Some common factors that tend to increase shear stress on a hillslope are an increase in the slope angle, removal of lateral support at the toe of a slope, and added weight to the top of a slope. Conversely, some common factors that tend to decrease shear strength in slope materials are infiltration of water underground, weathering and breakdown of minerals and rocks, and human activities, such as overdeveloping hillslopes or deforestation (Pipkin, 1994). Hence, a complex set of causes is usually involved in the initiation of slope movements. One set may reduce the internal shear strength of the materials whereas another set may increase the shear stress on these materials (Savage, 1968).

Rio Grande - Rio Pueblo de Taos Slope Stability Project

Rick Wooten, Engineering Geologist North Carolina Geological Survey

Location

The slope stability project will be based out of the Orilla Verde campsite located near the confluence of the Rio Grande and the Rio Pueblo de Taos. These rivers have cut down through numerous lava flows of the Servilleta basalts of the Santa Fe Group creating 500 ft (150 m) walls in the Cañon Del Rio Grande and the Lower Taos Canyon. The area is between Pilar and Taos in the northwest corner of the Taos SW 7.5-minute quadrangle within the Rio Grande Depression (Rift).

Project Overview

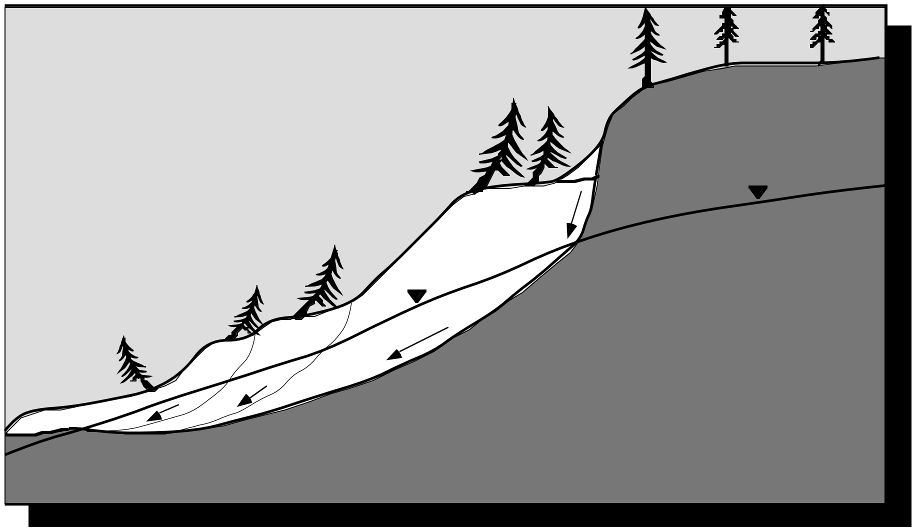
Both erosion and various types of mass wasting shaped much of the canyon wall landscape, and modified the courses of the Rio Grande and the Rio Pueblo de Taos. These processes affect, and are affected by, human activity in the canyons. The project will focus on canyon slope processes, surficial deposits, geomorphology and geology and hydrology related to slope stability. The two-day project will have two parallel parts. Field teams of 3-5 students will complete a reconnaissance slope stability study of the surrounding 13 km^2 (5.2 mi^2) area. The teams will also conduct an initial (scoping) level, site-specific investigation of a slope failure that blocks New Mexico State Route 570 (lat. N36020'30", long. W105043"19") near the campsite. On the first day one group of teams will work on the area assessment while the other teams work on the site-specific part of the exercise. The teams will switch on the second day so that each team completes both parts of the exercise.

Area Slope Stability Study.

Each team will complete reconnaissance-level slope stability mapping of the surrounding 15 km^2 (5.5 mi^2) area using the 1:24,000 scale 7.5-minute topographic map augmented by interpretations of 1:40,000 scale, stereo-pair color-infrared aerial photographs. Students will delineate and classify slope movement features using the map and aerial photographs, and confirm the interpretations with limited field checking. This part of the exercise will enable students to look at the site-specific part of the exercise in the context of the bigger picture.

Site-Specific Slope Failure.

Students will complete field-developed geologic cross section and plan view drawings of the slope failure showing the geometry and components of the slope failure (e.g. scarps, tension cracks, hydrologic features, vegetation etc.), surface and subsurface geologic materials, and their geologic and engineering classifications. This mapping will form the basis to complete questions and computations related to the site-specific exercise. For example, the students will calculate an estimated volume and mass of the slope failure



deposit, and discuss different alternatives to mitigate the slope failure.

Instruction

A short lecture on aerial photography interpretation, engineering classifications of soil and rock, slope failure terminology, nomenclature, and processes, and field methods will help prepare the students for the field exercise. Soil classification will be based on the Description and Identification of Soils (Visual-Manual Procedure) found in ASTM 2488-84. Rock mass classification will be based on the Unified Rock Classification System (Williamson, 1984) along with standard geologic classification systems. Slope failure nomenclature and classification will be based on Varnes (1978). Students are encouraged to become familiar with these references before field school if possible . Safety precautions will be emphasized throughout the exercise!

Safety

Safety precautions are **very important** when working on the slope failure and steep slopes in the canyon areas. Students and faculty should keep away from both the toe of the slide above the Rio Pueblo de Taos, and slopes immediately above and below the main scarp. Basalt boulders and loose soil deposits combined with steep slopes require careful footing. Field teams will take precautions not to work immediately up slope from other people - loose rocks can be dislodged and roll down slope. Precautions should be taken when working on the flatter slopes, some of the boulders may shift slightly when walked on. Normal precautions against snakes and scorpions apply.

Student Objectives

1. Learn organized and systematic methods for recording field measurements and observations.

2. Develop observational and interpretive skills to: a) complete a field developed geologic

cross section and a plan view map of a slope failure, b) identify, map and describe features related to the slope stability of an area at a reconnaissance level, and c) relate the site specific study to the area study. Learn about making interpretations (working hypotheses) of the subsurface from surface exposures.

3. Learn to classify materials using both geologic and engineering classification systems. Classifying soil properties (e.g., grain size, compactness, cementation and angularity) will give students experience in observing and describing properties relevant to strength, permeability, and unit weight.

4. Become familiar with slope failure nomenclature, classification and surficial processes. Learn about the origins and make-up of different surficial deposits and relationships to the underlying bedrock. Learn about slope failure processes such as rotational and translational movement, block slide, flow and granular movement.

Equipment and Clothing

Students should bring field boots and a pocket calculator, protractor, engineering scale ruler (with 20 and 40 divisions/inch) along with the supplies normally provided by the student. The field school will provide the following equipment and supplies used in the exercise: aerial photographs, stereoscopes, 7.5-minute topographic maps, Brunton compass, clinometer (for measuring slope angles), 30m/100 ft. cloth measuring tape, spring weight scale and water bucket (to determine rock unit weights), and classification charts for slope failures and soil and rock.

The Trip West on I-40

by Jim Reynolds, Western Carolina University

The first few days of the trip will be spent sitting in a vehicle watching a good portion of North America pass by. Because our main objective is to get to New Mexico, we will not make any outcrop stops en route. Even so, you will be able to see a lot of roadcuts and physiographic features from where you sit. These next few pages will provide you with a general road guide to the geology.

During the first few hours of the trip, from Chapel Hill to eastern Tennessee, we will cross metamorphic rocks associated with the orogenies that combined to construct the Appalachian Mountains. Once we leave the Blue Ridge Province, however, our trip will be focused on sedimentary strata that were deposited in foreland basins that formed adjacent to orogenic belts.

Foreland basins, also referred to as foredeeps, are isostatic depressions that result from crustal thickening derived from thrusting in the mountain belts. These basins result because the crust has flexural rigidity. This is best visualized by standing on a mattress. The mattress subsides not only below your feet but also away from your feet because the mattress also possesses a degree of flexural rigidity. As the basin fills in with sediment, the added weight from the basin-fill causes the basin to continue to prograde away from the mountain belt (Figure 49).

In the case of migrating fold-thrust belts, the oldest foreland basin-filling strata are frequently uplifted as fault migration cannibalizes the oldest part of the basin. As a result, foreland basins tend to exhibit strata with overall coarsening-upward characteristics.

Chapel Hill, NC to Morganton, NC

The Inner Piedmont Province

There are no roadcuts along this segment of the trip. The rocks beneath the surface represent a Paleozoic accreted terrane. Most exposures in this region are of deeply weathered saprolite derived from metamorphosed, immature siliciclastic and pelitic sediments. Metamorphosed basaltic lavas are present as well.

Morganton, NC to Newport, TN

The Blue Ridge Province

Starting at about Morganton, the highway begins to climb the Blue Ridge Mountains. Roadcuts finally start to appear. We will cross the Brevard Fault into the Blue Ridge Province just west of the Marion exit. The rocks that you see between Hickory and Maggie Valley are relatively high grade metamorphic rocks, predominantly Precambrian schists and gneisses.

Twenty-five miles west of Asheville, we enter the Pigeon River gorge, cut by the superposed Pigeon River. Spectacular, vertically dipping roadcuts line nearly the entire length of this segment. These rocks are Neoproterozoic to early Paleozoic metasedimentary rocks that were deposited on the continental shelf such as the lower Cambrian Chilhowee Group.

The Blue Ridge Province was thrusted over early Paleozoic shelf sediments during the continental collision with Africa in the Pennsylvanian.

Newport, TN to Harriman, TN

The Valley and Ridge Province

Before we get to Newport, the rocks suddenly change from the metasedimentary strata described above to unmetamorphosed lower Paleozoic shelf facies as we cross the Blue Ridge Thrust (not exposed). Accompanying this change, the topography suddenly falls off from the steep mountains of the Blue Ridge Province to a more subdued, linear, rolling topography typical of the Valley and Ridge Province.

High sea levels formed epicontinental seas during the Ordovician. In this particular area, most of the rocks are Ordovician carbonate platform rocks of the Knox Group. As a result, the valleys tend to be broad and the ridges occur where siliciclastic strata are exposed, typically Silurian beach sands. Directly overlying the Knox Group, however, are black Ordovician shales that were probably deposited in an anoxic basin between the continental coast and an offshore island arc associated with the Taconic Orogeny.

The Valley and Ridge Province is a westward verging, fold-thrust belt. These rocks were folded and overthrust during the Pennsylvanian while continental collision with

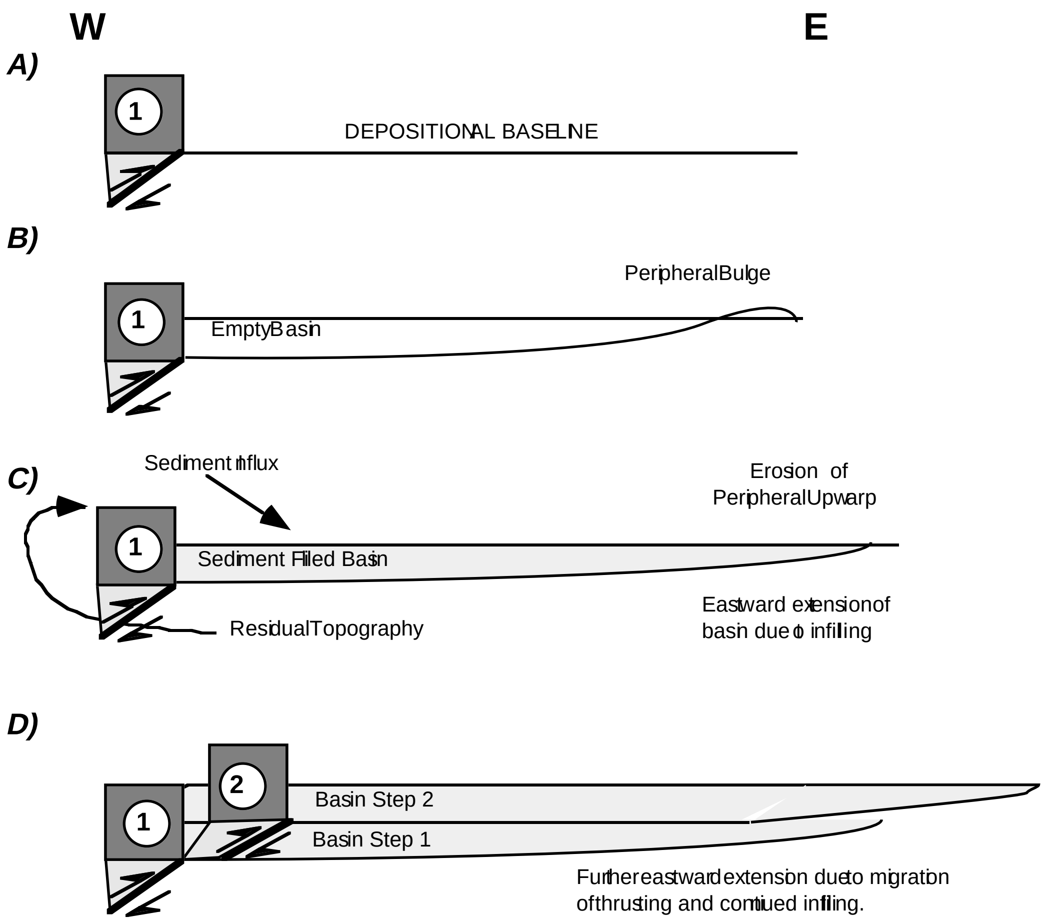


Fig. 49. Schematic representation of foreland basin development (modified from Beaumont, 1980): A) A mountain block is thrust above the depositional base level. B) The added mass induces isostatic subsidence, creating an empty foreland basin. C) Infilling of the basin causes further isostatic subsidence farther to the east. D) Eastward migration of thrusting causes the entire process to be repeated, extending the basin farther to the east. The west side of the basin is cannibalized in step D.

Africa causing the Alleghanian Orogeny took place.

Harriman, TN to Cookeville, TN

The Cumberland Plateau

Starting near Harriman we start to climb onto the Cumberland Plateau. The rocks of the plateau are a thick pile of Pennsylvanian continental and marginal marine siliciclastic rocks that were deposited as a clastic wedge in the Appalachian foredeep. These strata record a detailed record of the uplift history of the Blue Ridge Mountains.

As thrusting progressed during the Alleghanian Orogeny, the continental lithosphere downwarped isostatically to create the foredeep (Fig. 49). Because this was a time of high eustatic sea levels, parts of the foredeep were inundated. Sediments from the rising mountains in North Carolina spilled westward into the foredeep causing further isostatic depression. These strata were deposited in fluvial and deltaic environments that were present during the Alleghanian Orogeny. Large swamps formed on the deltas and important bituminous coal deposits formed all through the plateau provinces on the west side of the Appalachians during this time from Pennsylvania to Alabama. Stratigraphically, this is as high as we will get on our first day.

Cookeville, TN to Cedars of Lebanon State Park, TN

Nashville Dome

Continuing westward to our first night's destination, we gradually descend through Mississippian, Devonian Silurian, and Ordovician carbonate and clastic strata as we cross to the center of the Nashville Dome. Note that the carbonate topography is much more subdued than the Pennsylvanian strata.

This region experienced all of the major transgressions and regressions of the middle part of the Paleozoic. Devonian strata are much thinner in Tennessee than they are farther to the north in West Virginia, Pennsylvania, and New York. This is because the Acadian foreland basin, resulting from a primarily northeastern North American orogeny, was much deeper in the areas immediately adjacent to the rising mountains.

Cedars of Lebanon State Park is situated near the summit of the dome, so we will camp on Ordovician carbonates. If it is still light when we arrive, there is a short trail that will take you through several small sinkholes and work out the kinks in your bones. Be sure to bring a flashlight if you go!

Cedars of Lebanon State Park, TN to the Tennessee River, TN

Nashville Dome

The first leg of the second day of the trip crosses the western flank of the Nashville Dome. We gradually climb from Ordovician carbonates back into Mississippian carbonate platform rocks.

Tennessee River, TN to Little Rock, AR

Mississippi Embayment

Just west of the Tennessee River, we cross a subtle angular unconformity changing from Devonian strata with a slight eastward dip to Upper Cretaceous strata with a slight westward dip. This transition marks the eastern edge of the Mississippi Embayment. During the high sea stands of the late Cretaceous, the ocean transgressed as far north as southern Illinois. As we continue toward the Mississippi River, we pass over Paleocene and Eocene clastic strata deposited by later sea level rises. At about the Jackson exit, we cross into Holocene fluvial deposits and eolian deposits that were blown off of the continental ice sheets that encroached upon but never reached this latitude. The bluffs above the Mississippi at Memphis are Eocene clastic shallow marine strata of the Wilcox and Claiborne groups.

Once we cross the Mississippi River we travel across many miles of Holocene floodplain sediments. At Forrest City the highway climbs onto Quaternary terrace deposits. From here to Little Rock the highway crosses these strata except where it travels in the St. Charles and Arkansas river valleys where Holocene floodplain deposits are present.

Beneath the Quaternary cover are eastward dipping Cenozoic and Upper Cretaceous strata on the west side of the Mississippi Embayment. Beneath these rocks is a significant angular unconformity. Below the hiatus is a fairly complete westward dipping Paleozoic section. At about the Monroe/Prairie County Line, a westward dipping normal fault drops the section to depths > 3000 m and a thick Pennsylvanian marine sequence suddenly appears. These strata were deposited in the Arkoma foreland basin during the Ouachita Orogeny.

Little Rock, AR to intersection with OK 99, north of Seminole, OK

Arkoma Basin, Ouachita Mountains, and Boston Mountains

This segment of the trip passes through the Arkoma Basin. The Arkoma Basin is the foreland basin of the Pennsylvanian Ouachita Orogeny. High sea levels inundated the area during basin subsidence. The basin filling strata are composed of a graywacke turbidite flysch sequence. The rocks of the basin are folded and cut by northward-verging thrust faults that developed as Ouachita deformation migrated inland. Little of this is evident at the surface and few roadcuts are available for examination until we get to western Arkansas.

The Ouachita Orogeny is somewhat related to the Alleghanian Orogeny of the Appalachians. Like the Appalachians, mountain building resulted from a continental collision with Gondwana. It the case of the Ouachitas, however, it appears that the collision took place with the part of modern northern South America where Venezuela is situated.

The highlands to the south are the Ouachita Mountains while those to the north are the Boston Mountains. The Boston Mountains are along the southern flank of the Ozark Dome, a broad uplifted area centered in southern Missouri.

As we continue westward we continue climbing upsection to the western extreme of the Arkoma Basin. Near the bridge crossing the North Canadian River we cross into Permian strata. Lower Permian rocks were deposited in marine environments during high sea level stands.

OK 99, north of Seminole, OK to Red Rocks Canyon State Park, Hinton, OK

Anadarko Basin

For the first time on our trip we are crossing strata derived from western sources. Upper Permian strata all over the world tend to exhibit a characteristic red coloring of continental sedimentary rocks. This marks a final regression of the seas after the assembly of Pangaea. The sediments were derived from sources in the Ancestral Rockies, in Colorado and Utah, and from associated uplifts that were rising on the western side of the supercontinent. The Anadarko Basin is the foreland basin that resulted from these uplifts.

Although we probably won't see any roadcuts of these rocks, due to the late hour, our campground at Red Rocks Canyon is located in an arroyo that displays these strata. In the morning, take a little time to look at the rocks exposed in the canyon walls.

Red Rocks Canyon State Park, Hinton, OK to ≈15 miles west of Shamrock, TX

Continuing through western Oklahoma along I-40 we see little evidence of the geology around us. Beneath us are rocks of the Wichita Mountains, buried beneath the rocks of the Anadarko Basin. These rocks were uplifted in the Pennsylvanian and contain cores of middle Cambrian granite. The Wichita Mountains, along with the Arbuckle Mountains farther to the east, may represent an aulacogen oriented nearly perpendicular to the Ouachita-Marathon trend.

≈15 miles west of Shamrock, TX to ≈30 miles west of Vega, TX

Rocky Mountain Foreland Basin

Somewhere on the north Texas plains, about halfway between Shamrock and McLean, we cross another unconformity, passing from the Permian Anadarko Basin strata into Pliocene strata of the Ogallala Group. The younger strata are distal facies of the modern Rocky Mountain foreland basin. Beneath the Tertiary are Permian and, farther west, Triassic continental strata, derived from the Ancestral Rockies. Be sure to note the strike of the imbricate Cadillacs to the south of the highway as we pass through Amarillo.

≈30 miles west of Vega, TX to U.S. 285

In the very westernmost part of Texas, Triassic continental strata of the Dockum Group are exposed in the broad valley of the Canadian River. As we enter New Mexico, the Triassic rocks are seen exposed in the mesas on both sides of the highway. Pleistocene alluvial deposits make up the valley floor. The Jurassic Morrison Formation and Cretaceous Dakota Sandstone are exposed in a few of the mesas west of Tucumcari; both formations are noted for their dinosaur bones and trace fossils. They were deposited in a foreland basin the developed in response to thrusting and folding that took place farther to the west during the Sevier Orogeny. Both of these units will become old friends during your Nacimiento Uplift project near Cuba, NM.

For the remainder of our journey on I-40, we will pass through Triassic and Permian strata exposed along the Pedernal Uplift. In the distance we will see the Sandia Range to the west, and the snow-capped (probably) Sangre de Cristo range to the northwest. Both are basement cored uplifts that arose during the Cretaceous-Tertiary Laramide Orogeny.

U.S. 285 to Taos, NM

Río Grande Rift

From here, we will head north to Santa Fe, passing between the Sangre de Cristo and Sandia ranges into the Río Grande Rift. The rift is a broad, N-S trending graben that has developed since the Miocene. It is filled with Neogene continental sedimentary and volcanic rocks. Volcanic activity associated with the rift has continued into the Holocene. Most of the volcanism is basaltic, but explosive rhyolitic volcanism formed the Valles Caldera in the Jemez Mountains and the welded tuffs around Los Alamos. After a quick stop at the grocery store and Wal-mart in Española, we will head on to the Orilla Verde campground south of Taos and set up camp next to the Río Grande.

REFERENCES

We won't burden you with a comprehensive list of references for this course. This manual should suffice for most purposes. Our literature citations include general references, specific reports on course field areas, and useful, regional field guides. Some will be available at field camp. Others you may want to look up on your return home. Arizona, New Mexico, and Utah have useful, highway, geological maps available

If you want to buy a field guide, map, or regional report, browse through book shops and camping stores in the west. People are geologically literate in this part of the world and you can find good selections of books and maps. National park and monument book stores are well stocked with interesting books and maps. You can spend lots of money wisely at the Grand Canyon Visitor's Center and the bookstore in Gunnison — on the west side Main Street (the Crested Butte Highway). This store has one of the best selections of geological books and maps you will ever see in a commercial bookstore.

General, Regional Field Guides

Beus, S. S.., ed., 1987. Centennial Field Guide Volume 2, Rocky Mountain Section of the Geological Society of America, GSA

In general, this is excellent and useful. You will be given a copy of Beus's guide to the Kaibab Trail hike of the Grand Canyon

Keith Rigby, a geology professor from Brigham Young (Provo, UT) published several popular guides (Kendall/Hunt). Those on the Northern and Southern Colorado Plateau are useful, though skimpy on regional tectonics. The 1990 International Geological Congress (IGC) published a number of guidebooks as part of the Washington, D. C. meeting including one on the Grand Canyon. Vol. 3 includes trips through the Rio Grande Rift, the transition area from the Colorado Plateau to the Basin and Range, and an overflight of the Plateau.

Avoid the touristy guidebooks written by Halka Chronic. These are nigh-on useless at best, inaccurate and uninformed at worst.

Regional Stratigraphy

Sloss, L. L., 1988. Sedimentary Cover — North American Craton, GSA Centennial Series, The Geology of North America, vol. D-2

Regional Geography and Geomorphology

Hunt, C. B., 1967. Physiography of the United States, Freeman and Co.

Highway Maps

Many highway geologic maps available. Be selective. The AAPG series are generally very small scale, covering three or four or more states. They give little more than the age of the cover rocks and generalized tectonic features.

Most western state surveys produce highway geologic maps that are uniformly good and worth owning. New Mexico sets the standard; the map is printed on very heavy stock and includes very helpful satellite images.

San Juan Mountains and San Luis Valley

Carpenter, R. H., 1968, Geology and ore deposits of the Questa molybdenum mine area, Taos County, New Mexico: in Ridge, J. D. editor, Ore Deposits of the United States, 1933-1967, the Graton/Sales Volume, AIME, NY, NY, p. 1328-1350

Johnson, R. B., 1971, The great sand dunes of southern Colorado: in James, H. J., editor, San Luis Basin, New Mexico Geological Society Guidebook for 22nd Field Conf., New Mexico Bureau Mines and Mineral Resources, Socorro, NM, p. 123-128

Lipman, P. W., Sawyer, D. A., and Hon, K., 1989, Oligocene-Miocene San Juan volcanic field, Colorado; Central San Juan caldera cluster: in Chapin, C. E. and Zidek, J., editors, Field excursions to volcanic terranes in the western United States, Volume I: Southern Rocky Mountain region, Memoir 46, New Mexico Institute of Mining & Technology, Socorro, NM, p. 330-349

Steven, T., 1968, Ore deposits in the central San Juan Mountains, Colorado: in Ridge, J. D. editor, Ore Deposits of the United States, 1933-1967, the Graton/Sales Volume, AIME, NY, NY, p. 706-713

Northwestern New Mexico

Bauer, P. W., 1989. Stratigraphic nomenclature of Proterozoic rocks, northern New Mexico - revisions, redefinitions, and formalization. New Mexico Geology, v. 11, n. 3, p. 45-52

Bauer, P. W., Love, J. C., Schilling, J. H., and Taggart, J. E., 1991, The Enchanted Circle; Loop drives from Taos: New Mexico Bureau Mines & Mineral Resources, Socorro, NM, 137 p.

Brookins, D. G., Chakoumakos, B. C., Cook, C. W., Ewing, R. C., Landis, G. P., and Register, M. E., 1979, The Harding pegmatite; Summary of recent research: in Sante Fe County; New Mexico Geological Society Guidebook, 30th Field Conf.; New Mexico Bureau Mines and Mineral Resources, Socorro, NM, p. 127-133

Hawley, J. D., ed., 1978. Guidebook to the Rio Grande Rift in New Mexico and Colorado, NM Bureau of Mines and Mineral Resources Circular 163, 241p. Worth every penny; very good on Jemez Volcanic Field

Jahns, R. H. and Ewing, R. C., 1976, The Harding Mine, Taos County, New Mexico: in Vermejo Park; New Mexico Geological Society Guidebook, 27th Field Conf.; New Mexico Bureau Mines and Mineral Resources, Socorro, NM, p. 263-276

Mawer, C. K., Grambling, J. A., Williams, M. L., Bauer, P. W., and Robertson, J. M., 1990. The relationship of the Proterozoic Hondo Group to older rocks, southern Picuris Mountains and adjacent areas, northern New Mexico: in Bauer, P. W., et al., eds., Tectonic Development of the Southern Sangre de Cristo Mountains, New Mexico. New Mexico Geological Society Guidebook, 41st Field Conf., p. 171-177

Montgomery, A., 1953. Precambrian geology of the Picuris Range, north-central New Mexico. New Mexico Bureau of Mines and Mineral Resources Bulletin 30, 89p.

Williams, M. L., 1990. Proterozoic geology of northern New Mexico: recent advances and ongoing questions: in Bauer, P. W., et al., eds., Tectonic Development of the Southern Sangre de Cristo Mountains, New Mexico. New Mexico Geological Society Guidebook, 41st Field Conf., p. 151-159

Woodward, L. A., 1987. Geology and mineral resources of Sierra Nacimiento and vicinity, NM, NM Bureau of Mines and Mineral Resources Memoir 42

The New Mexico Geological Society (NMGS) has an annual field conference and publishes excellent guidebooks with road logs and technical articles. Although focused on New Mexico, the conferences often roam into Utah, Arizona, and Colorado. Trips have been run in the San Juan Basin (1967, 1977, 1992), the Albuquerque Basin (1982), Central-Northern New Mexico (1974), Monument Valley (1973), and western Colorado (1981)

Arizona

Beus, S. S., 1990. Grand Canyon Geology, Oxford University Press. Good book, available in paperback

Nations, J. D., Conway, C. M., and Swann, G. A., eds., 1986. Geology of Central and Northern Arizona, Field Trip Guidebook for GSA Meeting, Rocky Mountain Section, Flagstaff, AZ

Smiley, T. L., Nations, J. D., Pewe, T. L., and Schafer, J. P., eds., 1984. Landscapes of Arizona, University Press of America

Specific References, Prescott area

Karlstrom, K. E., Bowring, S. A., and Conway, C. M., 1987. Tectonic significance of an Early Proterozoic two-province boundary in central Arizona. GSA Bull., v. 99, p. 529

Krieger, M. H., 1965. Geology of the Prescott and Paulden Quadrangles, Arizona. USGS Prof. Paper 467

Utah

Weigand, D. L., 1981. Geology of the Paradox Basin, Rocky Mountain Geological Society (RMAG) 1981 Field Conference Guidebook

Doelling, H. H., 1985. Geology of Arches National Park, Utah Geological and Mineral Survey Map 74; accompanied by a brief, useful text

Gunnison , CO Region

Hansen, W. R., 1987. The Black Canyon of the Gunnison - In Depth, Southwest Parks and Monuments Association, Tucson, AZ

Prather, T., 1982. Geology of the Gunnison Country, printed in Gunnison and available at most local bookstores

many authors, 1981. Western Slope Colorado; 32nd Field Conf. Guidebook, New Mexico Geological Society (road logs and articles on the Gunnison region)

Landslide References:

American Society for Testing and Materials, 1989, Standard practice for description and identification of soils (visual-manual procedure) Designation D 2488-84$^{\Sigma 1}$ in Annual Book of ASTM Standards, v. 4.08, Soil and Rock; Building Stones; Geotextiles, 997p.

Williamson, D. A., 1984, Unified rock classification system, Bulletin of the Association of Engineering Geologists, vol. XXI, no. 3, August 1984, p. 345-354.

Varnes, David J., 1978, Slope movement types and processes, in Landslides: Analysis and Control, Transportation Research Board, National Academy of Sciences, Washington D. C., Special Report 176, Chapter 2 1978).

Hydrology References

American Geological Institute, 1974, Glossary of geology: Falls Church, Virginia, American Geological Institute, 805 p.

Bailey, R.A., and Smith, R.L., 1978, Volcanic geology of the Jemez Mountains, New Mexico, *in* Hawley, J.W., compiler, Guidebook to Rio Grande rift in New Mexico and Colorado: Socorro, N.M., New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 184-196.

Buchanan, T.J., and Somers, W.P., 1969, Discharge measurements at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chapter A8, 65 p.

Chow, V.T., 1964, Handbook of hydrology: New York, McGraw-Hill Book Company, Inc., 1418 p.

Dingman, S.L., 1994, Physical hydrology: New York, Macmillan Publishing Company, 575 p.

Fetter, C.W., 1988, Applied hydrogeology: New York, Macmillan Publishing Company, 592 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Heath, R.C., 1984, Ground-water regions of the United States: U.S. Geological Survey Water-Supply Paper 2242, 78 p.

Kennedy, E.J., 1983, Computation of continuous records of streamflow: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chapter A13, 53 p.

Kennedy, E.J., 1984, Discharge ratings at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chapter A10, 59 p.

Kopec, R.J., and Clay, J.W., 1975, Climate and air quality, in Clay, J.W., Orr, D.M., Jr., and Stuart, A.W., eds., North Carolina atlas, portrait of a changing Southern State: Chapel Hill, The University of North Carolina Press, p. 92-111.

Lucas, S.G., and others, 1992, First-day road log, from Cuba to La Ventana, San Luis, Cabezon, Mesa Portales, Mesa de Cuba, and return to Cuba, *in* Lucas, S.G., Kues B.S., Williamson, T.E., and Hunt, A.P., eds., San Juan Basin IV: New Mexico Geological Society Guidebook, 43rd Annual Field Conference, p. 1-32.

Meinzer, O.E., 1942, ed., Hydrology: New York, Dover Publications, Inc., 712 p.

Pettyjohn, W.A., and Henning, Roger, 1979, Preliminary estimate of ground-water recharge rates, related streamflow, and water quality in Ohio: Columbus, Ohio, Ohio State University Water Resources Center, Project Completion Report No. 552, 323 p.

Rutledge, A.T., 1993, Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records: U.S. Geological Survey Water-Resources Investigations Report 93-4121, 45 p.

Rutledge, A.T., and Daniel, C.C., III, 1994, Testing an automated method to estimate ground-water recharge from streamflow records: Ground Water, v. 32, no. 2, p. 180-189.

Schulz, E.F., 1973, Problems in applied hydrology (7th edition, 1989): Fort Collins, Colorado, Water Resources Publications, 501 p.

Smith, R.L., Bailey, R.A., and Ross, C.S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey Miscellaneous Investigations Series Map I-571, 1 sheet, scale 1:250,000.

References Cited for Classification of Slope Movements

Brunsden, D., 1979, Mass movements: In: *Process in Geomorphology*, edited by C. Embleton and J. Thornes, Edward Arnold, London, England, p. 130-186.

Costa, J.E., 1984, Physical geomorphology of debris flows: In: *Developments and Applications of Geomorphology*, edited by J.E. Costa and P.J. Fleisher, Springer-Verlag, Berlin and Heidelberg, p. 268-317.

Costa, J.E., 1988, Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows: In: *Flood Geomorphology*, edited by V.R. Baker, R.C. Kochel, and P.C. Patton, John Wiley & Sons, New York, p. 113-121.

Costa, J.E. and Williams, G.P., 1984, Debris flow dynamics (videotape): U.S. Geological Survey Open-File Report 84-606, 22.5 minutes.

Crozier, M.J., 1973, Techniques for the morphometric analysis of landslips: Zeitschrift fur Geomorphologie, v. 17, no. 1, p. 78-101.

Crozier, M.J., 1986, Landslides: Causes, consequences & environment: Croom Helm, London, 251 p.

Cruden, D.M. and Varnes, D.J., 1996, Landslide types and processes: In: *Landslides: Investigation and Mitigation*, edited by A.K. Turner and R.L. Schuster, Transportation Research Board Special Report No. 247, National Research Council, National Academy Press, Washington, D.C., p. 36-75.

Grainger, P. and Kalaugher, P.G., 1987, Intermittent surging movements of a coastal landslide: Earth Surface Processes and Landforms, v. 12, p. 597-603.

Innes, J.L., 1983, Debris flows: Progress in Physical Geography, v. 7, no. 4, p. 469-501.

Keefer, D.K. and Johnson, A.M., 1983, Earth flows: Morphology, mobilization, and movement: U.S. Geological Survey Professional Paper 1264, 56 p.

Pipkin, B.W., 1994, Geology and the environment: West Publishing Company, New York and San Francisco, 476 p.

Ritter, D.F., Kochel, R.C., and Miller, J.R., 1995, Process geomorphology: Third Edition, Wm. C. Brown Publishers, Dubuque, Iowa, 546 p.

Savage, C.N., 1968, Mass wasting: In: *The Encyclopedia of Geomorphology*, edited by R.W. Fairbridge, Reinhold Book Corporation, New York, Amsterdam, and London, p. 696-700.

Sharpe, C.F.S., 1938, Landslides and related phenomena: Columbia University Press, New York, 137 p.

Shroder, J.F., 1971, Landslides of Utah: Utah Geological and Mineralogical Survey Bulletin, no. 90, 51 p.

Varnes, D.J., 1978, Slope movement types and processes: In: *Landslide Analysis and Control*, edited by R.L. Schuster and R.J. Krizak, Transportation Research Board Special Report No. 176, National Academy of Sciences, Washington, D.C., p. 11-33.