Use all resources at your disposal to prepare for this trip.

Required sources include your Geology 125 textbooks, lecture notes, and
http://wrgis.wr.usgs.gov/docs/parks/noca/noca1.html or (mirror site)
http://www2.nature.nps.gov/geology/usgsnps/noca/noca1.html
(Good site map (contents). Most of our trip will be along the route shown by "Map 1".)

Recommended sources include http://scidiv.bcc.ctc.edu/rv/208/links.html
and other websites, books, etc that you find.

On today's field trip we will be looking at igneous and metamorphic rocks that range in age from 220 to 36 million years. Mt. Baker aside, these rocks are part of a different, older mountain range than the volcanic Cascades Range of Mt. Rainier, Mt. St. Helens etc.

I. ROCKS AND TERRANES OF THE NORTH CASCADES (from east to west)

The North Cascades mountain range is bounded on the east by the Intermontane Superterrane and on the west by Wrangellia (Vancouver Island), which was part of the Insular Superterrane. The North Cascades mountain range is divided into different parts because there are many strike-slip faults that formed after the collision, and which affect the way the geology is viewed today. Although each "part" of the orogen contains very different rocks from the other parts, geologists now think that all the parts are related.

The Methow Valley (or Methow Basin or Methow Domain or Eastern Domain), which we will not see today, consists of Jurassic and Cretaceous sedimentary and volcanic rocks that have been deformed into a series of folds and thrust faults. Although these rocks are deformed, most are not metamorphosed. Structures in the sedimentary rocks indicate that the older sediments were derived from sources to east of the basin, but that the younger sediments were derived from both the east and west. What does the presence of a western source mean?

The Skagit Crystalline Core (or Metamorphic Core Domain) is separated from the Methow Basin by the Ross Lake Fault, a steep strike-slip fault. The Skagit Gneiss, a major component of the crystalline core, consists of highly metamorphosed rocks that started out as sediments and intrusive igneous rocks. During the collision of Wrangellia, sediments were buried to a depth of 30 kilometers and heated up to such high temperatures that they began to melt. Metamorphic rocks that start to melt are called migmatites. Remember: sediments form at the surface of the Earth, so these rocks have been on a very long roundtrip - down 30 km and then back up to the surface. (Major units: Cascade River Schist, Skagit Gneiss, Marblemount Meta-Quartz Diorite, and the Eldorado Orthogneiss.)

The Skagit Crystalline Core is bounded on the west by the Straight Creek Fault - another steep strike-slip fault like the Ross Lake Fault. The movement on the Straight Creek Fault occurred 35-50 Myr ago.

To the west of the Straight Creek Fault is the Northwest Cascades-San Juan Islands Thrust System (or Western Domain). The Northwest Cascades consists of two very large thrust sheets (a large package of rocks bounded by thrust faults): the Church Mountain and Shuksan thrust sheets. The Church Mountain Thrust Sheet consists of greenstones (metamorphosed basalt), slate (metamorphosed shale), and marble (metamorphosed limestone). This rock sequence, collectively called the Chilliwack Group, probably formed in a marine environment, and is believed to be Devonian to Permian in age (250-400 Myr [million years] old).

The Entiat Fault branches southeastward off the Straight Creek Fault. In a little "wedge" between those two faults lies the Chelan Mountains Terrane, including the Cascade River Formation of schists, metamorphosed sandstones, and metaconglomerates, as well as metamorphosed ultramafic rocks and gneisses derived from volcanic arc plutons. Eldorado Peak and Hidden Lake Peaks are carved from orthogneisses (metamorphosed granites). The Cascade River takes a bend as it meets the Entiat Fault.
The Shuksan Thrust Sheet of the Western Domain contains rocks from the late Jurassic Shuksan Group: graphitic phyllites (carbon-rich metamorphosed shales), and greenschists and blueschists (both are metamorphosed basalts). Blueschists are very interesting, and somewhat rare rocks, that contain the blue mineral glaucophane. This mineral forms only in low temperature, high pressure metamorphic environments. This is an uncommon situation - if the rocks had simply been buried to attain the high pressures, then one would expect that the rocks would have experienced high pressures as well. How do you get high pressures accompanied by low temperatures? In the trench of a subduction zone. The basalts of the Shuksan Group may have been thrust rapidly down a trench, inducing high pressures, then rapidly uplifted before temperatures became too high. The protoliths formed 160 Myr ago; metamorphism occurred 120 Myr ago; much of the thrusting probably took place later (100-80 Myr ago).

Slivers of olivine-rich ultramafic rock from the mantle occur throughout the North Cascades. One of the largest and most famous such examples in the world is the Twin Sisters Dunite, near Mt. Baker. East of Mt. Baker (remember: Mt. Baker wasn't there when the North Cascades were forming), rivers have eroded deep valleys through the Chilliwack and Shuksan Groups, exposing younger rocks underneath - Jurassic andesites and greywacke sandstones (Nooksack Formation and Wells Creek Volcanics), and Triassic sandstones (Cultus Formation). Underneath, drilling uncovers Chilliwack and Shuksan Group rocks in their normal (unthrusted) stratigraphic order.

The San Juan Islands consist of a series of stacked thrust faults and several terranes, similar to those found in the North Cascades.

An added complication: after the North Cascades were constructed, a transform fault zone developed at the edge of the new continental margin. The Straight Creek Fault extends from near Mt. Rainier to Alaska. It is a right-lateral fault, just like most of the other transform faults along western North America. Apparent displacement along the Straight Creek Fault may exceed 200 km. How do geologists determine the amount of displacement? Other complications are the post-collision intrusions (like the 35 Myr old Chilliwack Batholith, which intrudes the Straight Creek Fault) and volcanic rocks (like the Mt. Baker Andesites) that now cover many areas of the North Cascades. Most igneous rocks were intruded along fault lines (zones of weakness in the crust), masking many structures.

After the Wrangellian collision, a trench developed to the west of Vancouver Island, producing subduction zone plutons and volcanoes. Sediments eroding off these volcanoes are found in the Nanaimo Group and Chuckanut Formation, north of the thrust zone of the San Juan Islands. The upper part of the Nanaimo Group contains conglomerates, sandstones, and shales - both marine and non-marine - as well as some pieces of metamorphic rock from the Northwest Cascades. The lack of thrust faults or metamorphism and the presence of Northwest Cascades rocks indicates post-collision deposition of these sediments.

In the Cenozoic, deposition continued in the Nanaimo and Chuckanut basins. To the southeast, the Chiwaukum Graben (a fault-bounded basin) near Leavenworth contains coal and sandstones, indicating a swamplike coastal plain and tropical climate. These coal seams are also present in the Chuckanut basin, along with large palm fossils and fossils of other tropical plants.

The Chuckanut Formation is not very extensive, but consists of sediments that filled a 6000 meter thick basin in 5 million years (58-54 Myr ago). This would correspond to a sedimentation rate exceeding 6 mm/10 years, one of the most rapid rates ever recorded.

Mt. Baker is a relatively young (late Quaternary) stratovolcano and the second most active volcano in the Cascades. We know that it is older than the last period of glaciation (20,000-10,000 years ago) because geologic evidence points to extensive glacial erosion and lavas that were erupted under the ice. However, it is much less eroded than many other Cascade volcanoes, so it is probably younger than Mt. Rainier, Mt. Adams, and Mt. Hood.

II. THE CONCEPT OF METAMORPHIC FACIES:

Look at the pressure-temperature (P-T) diagram below. It has been divided into regions representing different metamorphic facies. As you can see, greenschist facies rocks are metamorphosed at medium temperatures and fairly low pressures. Amphibolite facies rocks are metamorphosed at high temperatures and low to medium pressures - and so on.
Now the confusing part: not all greenschist facies rocks are actually called greenschists; not all amphibolite facies rocks are called amphibolites etc. The facies were named after the various types of metamorphosed basalt protoliths (some of which are described above), but any rock metamorphosed at point X on the diagram is a greenschist facies rock. If the protolith was a basalt, then it would be a true greenschist. If the protolith was a shale, the metamorphic rock would be called a schist.

What are the different types of TERRANES? – List types of rocks you may find with each:

1. **Microcontinents** = Continental crust (like Japan, S California)
   - Miscellaneous ages and composition

2. **Islands and Seamounts** = Hot spots (like Hawaii)
   - Basalt, limestone, sediments

3. **Oceanic Lithosphere Formed at Mid-Ocean Ridges** = Like Juan de Fuca
   - Basalt (different REE chemistry), sediments = ophiolite sequence

4. **Island Arcs** = Like Aleutians
   - Intermediate/felsic volcanics, limestone, trench sediments

How do we know where they originally formed?
- **Paleobotany** - fossils reflect climate
- **Paleomagnetism** - field reversals and declination
- **Sediment Provenance** - where do the sediments on the terrane come from?

How do we know when they were accreted or amalgamated?
Using radiometric dating - date the age of:
- Overlap sequences
- Stitching plutons
- Age of metamorphism
- Age of terrane rocks
<table>
<thead>
<tr>
<th>ERA</th>
<th>SYSTEM</th>
<th>EPOCH</th>
<th>Millions of years ago</th>
<th>Some important events in the life of North Cascades rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROTEROZOIC</td>
<td>ARCHEAN</td>
<td>Precambrian</td>
<td>570</td>
<td>Possible deposition of rocks of the Yellow Aster Complex.</td>
</tr>
<tr>
<td>PALEOZOIC</td>
<td>Permian</td>
<td>Carboniferous</td>
<td>210-375</td>
<td>Deposition of rocks of the Chilliwack Valley terrane.</td>
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<td></td>
<td>Devonian</td>
<td>Silurian</td>
<td>120-170</td>
<td>Deposition of rocks of the Nooksack terrane.</td>
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<tr>
<td></td>
<td></td>
<td>Ordovician</td>
<td>92-135</td>
<td>Deposition of rocks of the Methow ocean</td>
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<td></td>
<td></td>
<td>Cambrian</td>
<td>65</td>
<td>Metamorphism in Core Domain, stitching plutons, and thrusts of Western Domain.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>45</td>
<td>Extension, continued metamorphism in Core Domain, and deposition of extensional deposits.</td>
</tr>
<tr>
<td></td>
<td>Jurassic</td>
<td>Triassic</td>
<td>35</td>
<td>Beginning of Cascade Volcanic Arc.</td>
</tr>
<tr>
<td>CENOZOIC</td>
<td>Quaternary</td>
<td>Holocene</td>
<td>0.01</td>
<td>Extensive glacial ice in the North Cascades and in Puget Sound.</td>
</tr>
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<td></td>
<td>Tertiary</td>
<td>Pliocene</td>
<td>1.6</td>
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<td>Miocene</td>
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<td>Paleocene</td>
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</tbody>
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NORTH CASCADES WORKSHEET

You should describe the rocks at each outcrop in your field notebook. Also describe the outcrop itself and make any necessary sketches. After making your observations answer the following questions on this worksheet. And remember to turn in your answers to the pre-trip questions, too.

Take I-5 North to Exit 230 and, following signs, turn east onto the North Cascades Highway (Rt. 20). Continue on Rt. 20 to Sedro-Woolley. (We may make a grocery stop in Sedro-Woolley at Food Pavilion.) Take a right onto Rt. 9 South. Immediately after crossing the Skagit River (about 2 miles from intersection of Rt. 20 & Rt. 9), turn right onto South Skagit Highway. Set your odometer to 0.0.

STOP 0: While Driving...

Keep an eye out on your surroundings as we drive. After ~8 miles, look for Sand & Rock Quarry on the left side of the road. Where might the "sand and rock" come from?

(The road will take a 90° right turn.) Stop in the pullout at the right side of the road along the South Skagit Highway - Odometer 13.6 miles, just past official road mile marker 13. There's a large outcrop on the right, and another good exposure a short walk back along the road at the curve (be careful of traffic!).

STOP 1: Shuksan _________________________ (Fill in the rock name)

What was the protolith of this rock?

What is the metamorphic facies of this rock?

Under what temperatures and pressures do rocks that belong to this facies form? Describe the tectonic setting in which these rocks were metamorphosed.

Continue on South Skagit Highway to pullout on the right at the turnoff toward Concrete - at the intersection with Concrete-Sauk Valley Road (at odometer 24.4 miles, ~mile marker 24).

STOP 2: Darrington _________________________ (Fill in the rock name)

This is a metamorphic rock. How can you tell by looking at it?

Before this rock was metamorphosed, it was a layer of mud in the deep ocean (the protolith was shale.) Has this rock been highly metamorphosed? That is, does it still look a lot like mud, or has it changed a lot?

The mineral graphite gives this rock a shiny, silvery appearance. What does the graphite tell you about the protolith of this rock?
Note the present-day relation between the Shuksan and Darrington rocks. Describe how the protoliths of these rocks might have been related before metamorphism. (Think ocean crust.)

**Turn left onto Concrete-Sauk Valley Road. Cross Dalles Bridge and turn right onto Rt. 20 at odometer 25.4 miles (Rt. 20 mile marker 84.3). We will head eastward on Rt. 20 to our remaining stops. At the town of Concrete (odometer 26.3), take a left onto "E" Avenue, then an immediate right onto Main Street. We will stop at the public restrooms on the left (odometer 26.4), which are in front of an old (concrete) school.**

**STOP 3A: Chilliwack Formation Boulders of _________________________ (Fill in the rock name)**

Surrounding the restrooms are a number of large dark boulders with white veins. What mineral are these boulders (and also their veins) made of? Be sure to test and describe your hypothesis (cleavage planes in veins; acid reaction; etc.)

What was the protolith of this rock?

What is the name of this metamorphic rock?

Why might the town have been named Concrete? (Think about your answers to the preceding questions.)

There may be a few O-shaped fossils in the boulders. If so, describe and sketch them in your fieldbook. What kind of fossils are they? What do these rocks, and the fossils in them, tell us about the depositional environment of the protolith?

**Turn around and retrace your path to Rt. 20 eastbound (left onto "E" Avenue, left onto Rt. 20; odometer 26.5). You will soon turn left onto North Everett Avenue (odometer 27.0). Bear left toward Lake Shannon. Bear right at odometer 27.5, up Baker River Road ("primitive road"), not over bridge back to Concrete. Pass Lower Baker Dam. Bear left. Bear left at the branch at odometer 28.0. Bear right at odometer 28.4. Drive to the gate, park, and walk uphill past the old shed to the quarry in the big opening on the right.**

**STOP 3B: Chilliwack Formation Quarry of _________________________ (Fill in the rock name)**

(Optional stop, assuming your fearless leader can find it!)

On a clear day, there's a view of Mt. Baker from the center of the quarry. How old is Mt. Baker? How did it form?

What kind of rock do you find here in the quarry?

In your fieldbook, describe and sketch the fossils you find at the quarry (indicate scale). What do the rocks and fossils tell you about the depositional environment of the protolith of these rocks?)
In your fieldbook, describe and sketch the rock "structure" (folds and faults) of these rocks (indicate scale). What does this information tell you about what has happened to these rocks after deposition and lithification?

Return to the vehicle and retrace your path downhill. There are a couple tricky turns; for example, be sure to bear right at the "load limit 15 tons" sign. Return to Rt. 20 eastbound. There are restrooms at Rockport State Park (if need be; odometer 37.3).

**Straight Creek Fault (a drive-by viewing...) (Town of Marblemount)**

The Straight Creek Fault runs north-south through the town of Marblemount and separates the Northwest Cascades Thrust System on the west and the Skagit Crystalline Core to the east. The rocks on either side of the fault have experienced different grades of metamorphism (among other differences).

WARNING: You are now entering the Skagit Crystalline Core. Enter at your own risk. 😊

Rt. 20 takes a 90° left turn at a bridge at the east side of Marblemount (odometer 47.2). Go straight over the bridge onto Cascade River Road. Continue until just past the park boundary, at an old-fashioned wooden-guardrailled overlook on the right (odometer 54.1). Park there. There's a wonderful view of rushing water below, and Eldorado Peak and Hidden Lake Peaks in the near distance. Observe the outcrops across the road, and walk back along the road to the exposures between there and the park boundary (be careful of traffic!).

**STOP 4A: Cascade River Schist (etc) of the Chelan Mountains Terrane**

What kind(s) of rocks are exposed here?

What evidence is there as to whether the rocks are igneous, sedimentary, or metamorphic? If metamorphic, what were their protoliths?

Why might the Cascade River take a bend as it meets the Entiat Fault in the river valley below?

**Turn around. At odometer 55.9, there is a waterfall on the right. Pull off at the flat area on the left.**

**STOP 4B: Cascade River Rocks of the Chelan Mountains Terrane**

What kind(s) of rocks are exposed here?

Interpret the geologic history of these rocks. (Hint: What do the clasts and matrix consist of? What do they tell us about the protolith(s)? What has happened since the protolith(s) formed?)
We'll return to Rt. 20 at odometer 61.1. Take a right and continue eastbound on Rt. 20. At odometer 64.8 (mile marker 109-110), park in the pullover area on the right. (If we're running short on time, we'll at least pick up a couple samples from the outcrop so we can compare the rocks of the Marblemount Meta-Quartz Diorite and those of the Chilliwack Batholith at the following stop.)

STOP 5: Marblemount Meta-Quartz Diorite

This rock is 220 million years old, but it was metamorphosed 90-100 million years ago along with all the other rocks in this part of the North Cascades (i.e., in the Crystalline Core). Before this rock was metamorphosed, it was an intrusive igneous rock called a diorite. How can you tell that this is now a metamorphic rock?

As you wander around looking at the outcrop, look for dark, fine-grained basaltic dikes. Are these older or younger than the diorite? Explain your answer. (Hint: Consider the principles of relative dating we discussed in class.)

Are they younger or older than metamorphism? Explain your answer.

(Keep an eye out for a quarry at about mile marker 111.) There are at least 4 pullover areas across the highway from exposures of the Chilliwack Batholith, starting at mile marker 115. Try to stop at the 3rd one (odometer 70.9), or the 4th one (odometer 71.1; just before mile marker 116).

STOP 6: Chilliwack Batholith (This is not the same as the Chilliwack Formation we saw earlier!)

What kind of rock is it?

What is the black mineral? What is the white mineral? What is the grayish glassy mineral?

Did the Chilliwack Batholith intrude before or after the metamorphism of the Crystalline Core? Explain your answer.

Look at a geologic map that shows this unit and note that the Straight Creek Fault is truncated by it. What does this mean? - i.e., which is older and why did the Chilliwack Batholith intrude where it did?

At the western edge of the town of Newhalem, turn off Rt. 20 toward the Newhalem Visitors' Center (turn at odometer 75.2; visitors' center is at odometer 76.0).

STOP 7: Newhalem Visitors' Center (usually open 9am-5pm)

We will explore the visitors' center. Be sure to fully peruse their exhibits. Take notes in your fieldbook, and make a few brief notes here. Rangers are often available to assist.
Retrace your path to Rt. 20 (you’ll turn onto it at odometer 76.8). There are some nice picnic tables and a little shop in Newhalem itself, where we may stop if time permits.

There was an enormous landslide just east of Newhalem in autumn 2003. For safety, the public is not allowed to park and look at it. We’ll see if we can at least slow down for a glimpse as we drive by. It is at mile marker 122 (odometer 78.9).

Last chance for restrooms: Gorge Creek Overlook (odometer 80.3, mile marker 125).

Continue eastward to odometer 82.3 (shortly after mile marker 125, large orangey weathered area in roadcut).

STOP 8: Skagit _________________________ (Fill in the rock name)

This is a highly metamorphosed rock. Note the layers in this rock. Sketch a section of the outcrop in your notebook; include a scale in your sketch and label the dark and light layers.

List the minerals present in the light-colored layers:

List the minerals in the dark-colored layers (including the round red mineral):

This rock contains some of the same minerals as the Chilliwack Batholith (Stop #6), yet it formed in a different environment. How does this rock differ from the rocks at Stop#6?

Bear right over the river at Diablo (not left to the town of Diablo), past Diablo Dam (unfortunately, gated since 9/11/01). Park at the large overlook off to the left at the bend at odometer 88.9 (just before mile marker 132).

STOP 9: Diablo Overlook

If it is a clear day, there is an amazing view at this stop. Wander around the overlook area for a while and look at the geology displays put up by the National Park Service. Make notes in your fieldbook, and jot a little below.

Head across the road and look at the rocks. In your fieldbook, sketch part of the outcrop showing several of the large, white dikes and any folds or faults you see. Include a scale on your sketch. These dikes intruded the North Cascades about 50 million years ago, and may be related to the Challis Volcanic Arc.

Describe the sort of swirly rock which is cut by the dikes. What would you call this rock? Did it form under high-grade or low-grade metamorphism?

Do the dikes appear to be metamorphosed? What does this tell you about the relative timing of events at this location?
Continue east on Rt. 20. Some extremely high-grade metamorphic rocks (evidence from moving vehicle?) start a couple of miles later. Pull off to the right at odometer 90.6, just past the bridge over John Pierce Falls.

STOP 10: Alpine Roots

The rocks exposed at this stop are migmatites - a rock that is a combination of igneous and metamorphic rocks. They formed under very high temperatures (720°C) and pressures (30 km deep) at the very bottom of a collisional mountain range. These rocks have made a long journey from great depths...like at the roots of the Himalayas! Explain why this rock only partially melted.

What does the light color of the dikes imply about their composition? Why did this material melt, while the remaining rock did not?

Continue east to odometer 92.4 (mile marker 135). Park on the left.

STOP 11: Ross Lake Overlook

The parking area overlooks Ross Lake (reservoir) and the surrounding mountains (Canada is in the distance, in the gap between the mountains). Look around for evidence of glacial erosion.

The Ross Lake Fault runs along the base of Jack Mountain to the northeast and divides the Skagit Crystalline Core from the Methow Domain to the east. Why is Ross Lake so long and skinny?

Continue east to odometer 102.3, and take a left into the parking lot at East Creek Trail. The outcrop is in the parking lot, just below the highway. (There are also pit toilets here.)

STOP 12: Rapakivi Granite

What is rapakivi granite? Why is it unusual?

If we were to continue eastward (for an overnight trip), we would cross Rainy Pass (elevation ~4800 ft) and Washington Pass (elevation ~5400 ft), into the heart of the Methow Domain. The splendid peaks and views at about odometer 121.2 are of the Golden Horn Batholith, subsequently carved by glaciers.

Summary Question:
Put the following events in order from oldest to youngest. (List events that are contemporaneous together.)

- Collision of the Insular Terrane (Wrangellia)
- Collision of the Intermontane Terrane
- Formation of the Straight Creek Fault
- Intrusion of the Chilliwack Batholith
- Eruption of the Mt. Baker Volcanics
- Metamorphism and uplift of the Skagit Crystalline Core
- Intrusion of the Marblemount Meta-Quartz Diorite
- Deposition of the Shuksan and Darrington protoliths
- Deposition of the Methow Basin rocks
- Deposition of the Chelan Terrane protoliths
- Metamorphism of the Chelan Terrane rocks