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FIELD AND LABORATORY PROJECT: VOLCANOLOGY AND PETROLOGY OF INTERBEDDED ANDESITIC LAVA FLOWS AND VOLCANICLASTIC ROCKS FROM WASHBURN VOLCANO, YELLOWSTONE NATIONAL PARK

Note to Field Trip Participants: What follows is an example of a three part exercise for undergraduate petrology students involving volcanic and shallow intrusive rocks in the Washburn Range, Yellowstone National Park. We will loosely follow Part 1, although Parts 2 (petrology) and 3 (geochemistry) are also included. The exercise is largely based on a recent study by Feeley et al. (2002), although on this trip we will only examine stratigrahpically high rocks on Mount Washburn proper; stratigraphically lower rocks to the southwest beneath Dunraven and Hedges Peaks are off-road and off-trail (see Figs. 4 and 5).

Because of National Park regulations, no sample collection is allowed. Bear in mind that the Washburn trail is the most heavily used backcountry trail in Yellowstone, and rock picks are quite disturbing for some guests. It is therefore probably best to leave these in the vans. The hike to the summit is not particularly physically demanding, although it is at altitude: participants should thus consider their physical condition. At the very least, bring water, snacks, sun screen, and rain gear.

We anticipate that hikers will start from Dunraven Pass at 8:00 AM. Hikers should return to the vans at 12:00 PM, from there we will go to a picnic area for lunch. All hikers must therefore turn around and head for the vans no later than 10:45. Because of these strict time limitations, there will probably not be sufficient time to examine the rocks in as much detail as one would hope. The trip is thus largely a self guided tour. It will, nevertheless, give you an opportunity to examine several rock types associated with calc-alkaline composite cones and provide a spectacular view of the Yellowstone Caldera, weather permitting.

Location: Yellowstone National Park, Mount Washburn, Lamar River Formation. We will examine outcrops exposed along the Mt. Washburn Trail, which begins at Dunraven Pass (8850') along the Grand Loop Road, north of Canyon Junction. The trail climbs 1,393 feet slightly over 3 miles to the summit of Mt. Washburn (10243').

Objectives: (1) To study intraflow characteristics of andesite lava flows and flow breccias; (2) to study sedimentological characteristics of volcanic debris flows and related sedimentary deposits; (3) to distinguish lava flows from dikes and sills; (4) to interpret the volcanic feature represented by Mount Washburn; and (5) to interpret the petrology and geochemistry of calc-alkaline volcanic rocks in order to discover their origins.

Final Products:
1. Sketches, descriptions, and interpretations (e.g., lava flow, dike, sill, debris flow, stream flow, flow breccia) of features of rock units at stations listed below and illustrated on the accompanying map (Fig. 1). The descriptions should include thickness of individual units. In addition, for dense, nonfragmental units (e.g., lava flows and tabular intrusions), include features such as chilled zones, distributions of vesicles, and a hand specimen petrographic description. For volcaniclastic units include clast sizes and composition, matrix texture, depositional structures. Answers to specific questions for stations.
2. Petrographic descriptions of rock units (note: we will complete this back in laboratory on thin sections cut from previously collected Washburn samples).
3. Interpretation of geochemical data for lava flows from Washburn volcano (note: we will complete this as a class project back at the university).

What to bring in the field:

1. Field notebook and pencil, compass, hand lens, map board or clipboard (please do not bring rock hammers - **no** sample collecting is allowed in Yellowstone National Park).
2. Sketch sheets (provided)

Using the Sketch Sheets:

You are to complete Part 1 in the field on the sheets provided. Do your work neatly in the field and do not plan on recopying. For the descriptions: use as many sheets as desired for the scale at which you wish to illustrate features. Break the section into units at distinct textural and/or compositional breaks. Draw a horizontal line across the sheet at the unit boundary. Indicate the approximate thickness in the left hand column; sketch the key features in the second column; list descriptive characteristics in the third column; provide an interpretation of deposit origin in the right column (you may also give reasons to support your interpretation in this column).

Background: The Absaroka Volcanic Province

The Absaroka Volcanic Province (AVP) of northwest Wyoming and southwest Montana is a vast northwest trending belt of volcanic and plutonic rocks with a cumulative volume of ~30,000 km^3 distributed over an area exceeding 23,000 km^2 (Smedes and Prostka, 1972; Fig. 2). As such, the province constitutes the largest Eocene volcanic field in the Northern Rocky Mountains (Sundell, 1993). Rocks of the Absaroka Volcanic Province occupy the Absaroka basin, a shallow Laramide foreland basin that formed concurrently with surrounding basement-cored uplifts exposed in the Washakie, Gallatin-Madison, and Beartooth mountain ranges (Sundell, 1993). The majority of these uplifts experienced episodic contractional deformation from late Cretaceous through middle Eocene time (Schmidt and Garihan, 1983; Winterfield and Conrad, 1983). The AVP rests unconformably on deformed Paleozoic to Mesozoic carbonate and clastic sedimentary strata and on high-grade metamorphic and igneous rocks of the Wyoming Province, an Archean granite-gneiss craton that underlies much of Wyoming, Montana, and southeastern Idaho (Fig. 2 *inset*). Seismic refraction studies indicate that the continental crust beneath the AVP is ~45-50 km thick (Prodehl and Lipman, 1989). Lithospheric thickness is estimated to be at least 170 km based on the presence of a weak low-velocity zone at 170-225 km depth (Iyer and Hitchcock, 1989). Although the composition of the deep crust beneath the AVP is poorly known, an amphibolitic to granulitic lower-crust is inferred through geochemical evidence (Meen and Eggler, 1989) and xenolith geothermobarometry (Joswiak, 1992).

Eocene rocks associated with the AVP form a northwest-trending, approximately 90 km wide zone of now deeply eroded, large stratovolcanoes, shield volcanoes, and dike swarms flanked by coalescing alluvial aprons (Sundell, 1993). Although a large part of the field is located in Yellowstone National Park, it is much older and completely unrelated to the Pliocene and Quaternary Yellowstone Plateau volcanic field (Christiansen, 2001). Previous regional studies indicate that the bulk of the AVP volcanic rocks erupted between 55 and 45 Ma from thirteen major volcanic centers situated along two subparallel northwest trending belts (Chadwick, 1970; Smedes and Prostka, 1972; Harlan et al., 1996; Feeley et al., 2002; Feeley and Cosca, 2003). Although overlap exists, compositions of the majority of igneous rocks in the two belts are distinct, with calc-alkaline series predominating in the western "low-K" belt and shoshonitic series predominating in the eastern "high-K" belt (Chadwick, 1970). Volcaniclastic rocks are volumetrically dominant in the field and include volcaniclastic sandstone, siltstone, claystone, conglomerate, and lahric breccia. Intercalated primary volcanic rocks increase in abundance near inferred eruptive centers and include effusive lava flows, flow breccias, and domes as well as pyroclastic flow and fall deposits. Hypabyssal intrusions are also common at the eruptive centers and include dikes, sills, ring dikes, cone sheets, plugs, stocks, and laccoliths (Parsons, 1939).

Smedes and Prostka (1972) defined the Absaroka Volcanic Supergroup to include all volcanic rocks within the AVP as well as associated outliers erupted or deposited during the Eocene. Based mainly on field relationships they defined three stratigraphic divisions: the Washburn, Sunlight, and Thorofare Creek Groups (Fig. 2). Rocks exposed in the Washburn Range represent the type stratigraphic section for the Lamar River Formation, the eastern member of the Washburn Group (Smedes and Prostka, 1972).

Washburn Volcano

Washburn volcano is a major calc-alkaline eruptive center in the AVP and is the largest Eocene volcanic center exposed in Yellowstone National Park. It is one of the primary source areas for the Lamar River Formation (formerly the "early basic breccia" of Hague et al., 1899); the eastern member of the Washburn Group of Smedes & Prostka (1972). The Lamar River Formation is particularly well known to visitors of Yellowstone National Park because in it are preserved the famous upright fossil forests (Dorf, 1964). Washburn volcano has been previously mapped by Schultz (1962; 1:30,000) and Prostka *et al.* (1975; 1:62,500; Fig. 3). $^{40}Ar/^{39}Ar$ age determinations indicate that magmatism at the volcano commenced around 55 Ma and continued until at least 52 Ma (Feeley et al., 2002).

The eroded northern flank of Washburn volcano in the vicinity of Mt. Washburn, Hedges Peak and Dunraven Peak consists of ~1300 m of volcanic vent facies strata, mainly of the Lamar River Formation, that include dikes, lava flows, flow breccias, and debris flow deposits that dip up to 30° away from the primary vent region (Fig. 3; Prostka *et al.*, 1975). The lava flows and dikes are largely pyroxene basaltic andesites and andesites, although numerous amphibole-bearing dacitic lava flows are present near the base of the sequence beneath Dunraven and Hedges Peaks (Fig. 3). With increasing distance from Mt. Washburn and Hedges and Dunraven Peaks the vent facies rocks grade into alluvial facies lithologies consisting of epiclastic volcanic conglomerate and breccia, volcanic sandstone and siltstone, and ashfall tuff deposits. The southern flank of Washburn volcano is truncated by the northern segment of Yellowstone Caldera fault, exposing the interior of the volcano (Fig. 3). Here, fine-grained biotite tonalite of the Sulphur Creek stock intrudes stratigraphically low Lamar River Formation volcanic rocks. This stock is similar in composition and age to the Eocene volcanic rocks and represents a shallow intrusion related to Washburn volcano (Feeley et al., 2002).

The samples we will examine in laboratory and in our class project come from lava flows and tabular intrusions in well-exposed sections dominated by vent-facies rocks on Mt Washburn, Dunraven Peak, and Hedges Peak. Very few rocks were sampled directly adjacent to the trail we will walk today due to National Park Service sampling regulations. Temporal and spatial variations in bulk chemistry for lava flows we will examine are shown schematically in Figure 4. Note that on Figure 4 (and subsequent figures) samples from Mt. Washburn are designated with different symbols from those in the SW Washburn Range to the west of the Grand Loop Road because these have different compositional ranges. Lava flows and dikes in the SW Washburn Range consist of a crudely bimodal package of olivine + pyroxene basaltic andesites and amphibole-bearing dacites, whereas dikes, stratigraphically higher lava flows, and the Sulphur Creek stock to the east and northeast on Mt. Washburn are predominately olivine + pyroxene basaltic andesites and pyroxene ± amphibole andesites. Included in this latter sequence are the stratigraphically highest exposed lava flows on Mt. Washburn that Prostka *et al.* (1975) designated as part of the Langford Formation of the Thorofare Creek Group of Smedes & Prostka (1972; Figs. 3 and 4). Although these flows were originally interpreted as younger (middle to upper Eocene) and erupted from vents much more distal than other units at the volcano, geochronologic work shows that they are comparable in age and composition to other flows on Mt. Washburn (Feeley et al. 2002). All exposed units are therefore considered to be derived from the same or very similar magmatic systems.

EXERCISES

PART 1: FIELD DESCRIPTION AND INTERPRETATION OF VOLCANIC ROCKS ON MOUNT WASHBURN

Although there are only seven stations you should not waste time because the outcrop descriptions should be detailed and we must be heading down from the mountain by 10:45 am and be at the vans by noon

(**Important note: these times are for this 'mock' assignment; I would, of course, allow more time for the real thing). Record these descriptions and answer any questions **on the sheets provided**.

Station 1 (~0.5 mi from trailhead; outcrop on north side of trail): Using the sheets provided, illustrate, sketch, and interpret the origin of the rocks exposed in outcrop.

Station 2 (~0.6 mi; outcrop on west side of trail): Using the sheets provided, illustrate, sketch, and interpret the origin of the rocks exposed in outcrop. Note that the two dense units exposed along this outcrop have different orientations. One of these units is probably a lava flow and one is a dike; which is which? How can you tell? Now, turn and look toward the northeast at the south spur of Mt. Washburn across the small stream valley. Note that bedding within the rock units is apparent when viewed from this distance, but as you have probably noticed at an outcrop it is very difficult to determine in most cases. In what direction do the beds dip on the south spur? What does this imply about the location of the source region for lava flows and volcaniclastic rocks on Mt. Washburn? If you have a pair of binoculars, scan the steep slopes below and to the southwest of the 'nose' of the ridge. If you look closely, you can locate a few dikes. In what direction do these trend? If we consider a simple model wherein dikes extend radially away from the vent region of a volcano, when was the ancestral vent region for Mt. Washburn located?

Station 3 (~1.4 mi; outcrop on east side of trail): Using the sheets provided, illustrate, sketch, and interpret the origin of the rocks exposed in outcrop.

Station 4 (~1.5 mi; outcrop on northeast side of trail): Using the sheets provided, illustrate, sketch, and interpret the origin of the rocks exposed in outcrop.

Station 5 (~2.3 mi; outcrop on northeast side of trail): Using the sheets provided, illustrate, sketch, and interpret the origin of the rocks exposed in outcrop.

Station 6 (~2.6 mi; outcrop on northeast side of trail): Using the sheets provided, illustrate, sketch, and interpret the origin of the rocks exposed in outcrop.

Station 7 (~2.6 mi): Look toward the northeast across the stream valley and note the relatively thick lava flows on the first and second peaks east of Mt. Washburn summit on the east spur. Now, follow these flows with your eyes to the west and note that they truncate against other volcanic units. These features have been previously interpreted in two different ways. On the one hand, Schultz (1962) interpreted the 'contact' as an erosional surface related to channalization of older, eastern flows. On the other hand, Prostka *et al.* (1975) interpreted the feature as a fault. What do you think and why? What criteria would you use to distinguish between these two hypotheses?

Station 9 (~2.9 mi; outcrop on west side of trail): Using the sheets provided, illustrate, sketch, and interpret the origin of the rocks exposed in outcrop.

To the summit and enjoy the view!!! If you have time, walk about 100 m or so to the west from the summit to examine a N-NW striking composite dike with two intrusive phases. This is the largest dike observed at the Washburn volcano. The border phase of the dike is andesitic and the interior phase is an amphibole andesite or dacite.

Based on your knowledge of volcanology, what type of volcanic landform is Mt. Washburn? One of the intriguing aspects of Mt. Washburn and the surrounding peaks is that all the volcanic units slope toward the northwest, north, and northeast (see Figure 3). If Mt. Washburn is indeed a volcano (which it most certainly is, based on the rocks present), shouldn't some slope southward? Didn't lava flows and debris flows flow down the south slopes of this volcano also? How can you reconcile these problems?

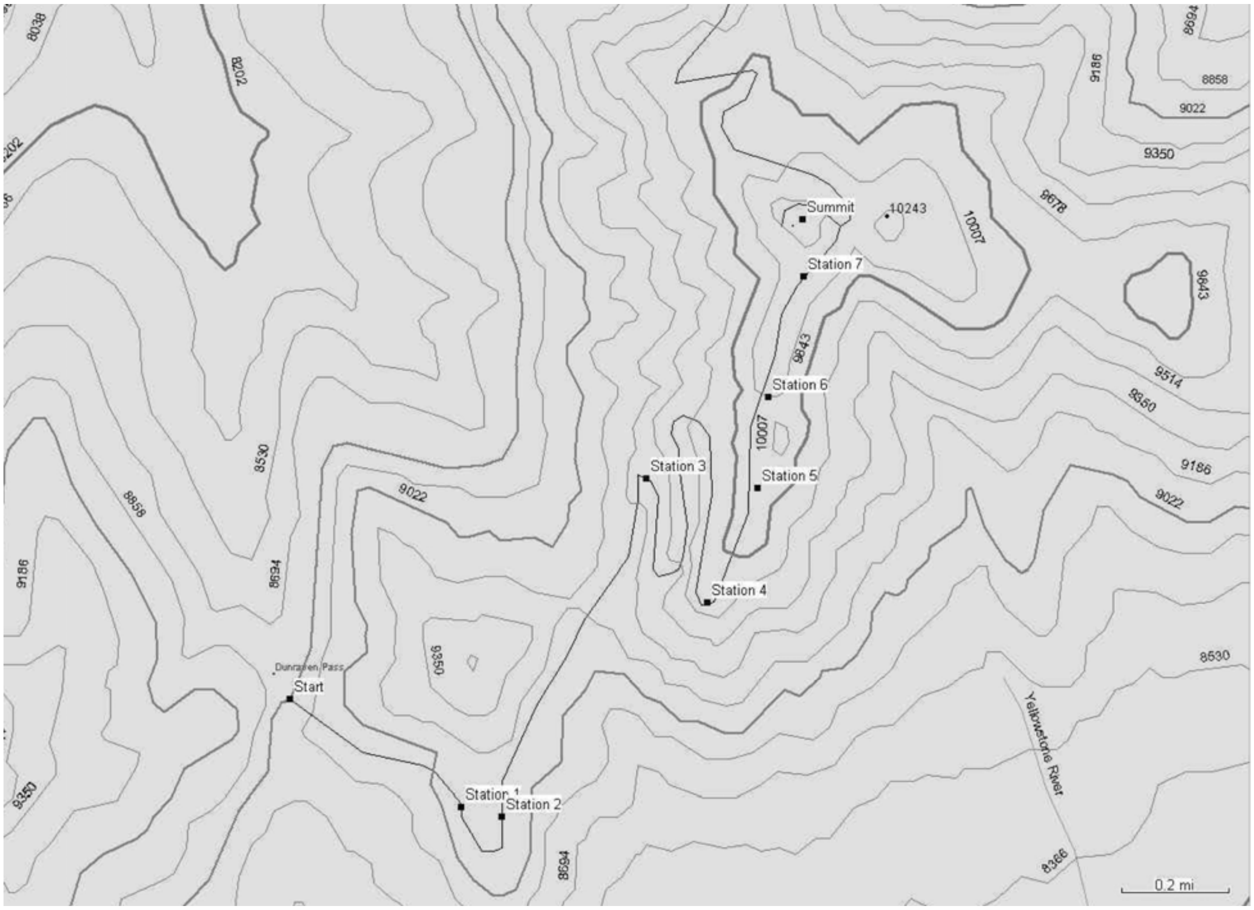

Figure 1: Location map of stations for this exercise. North is to the top of the page.

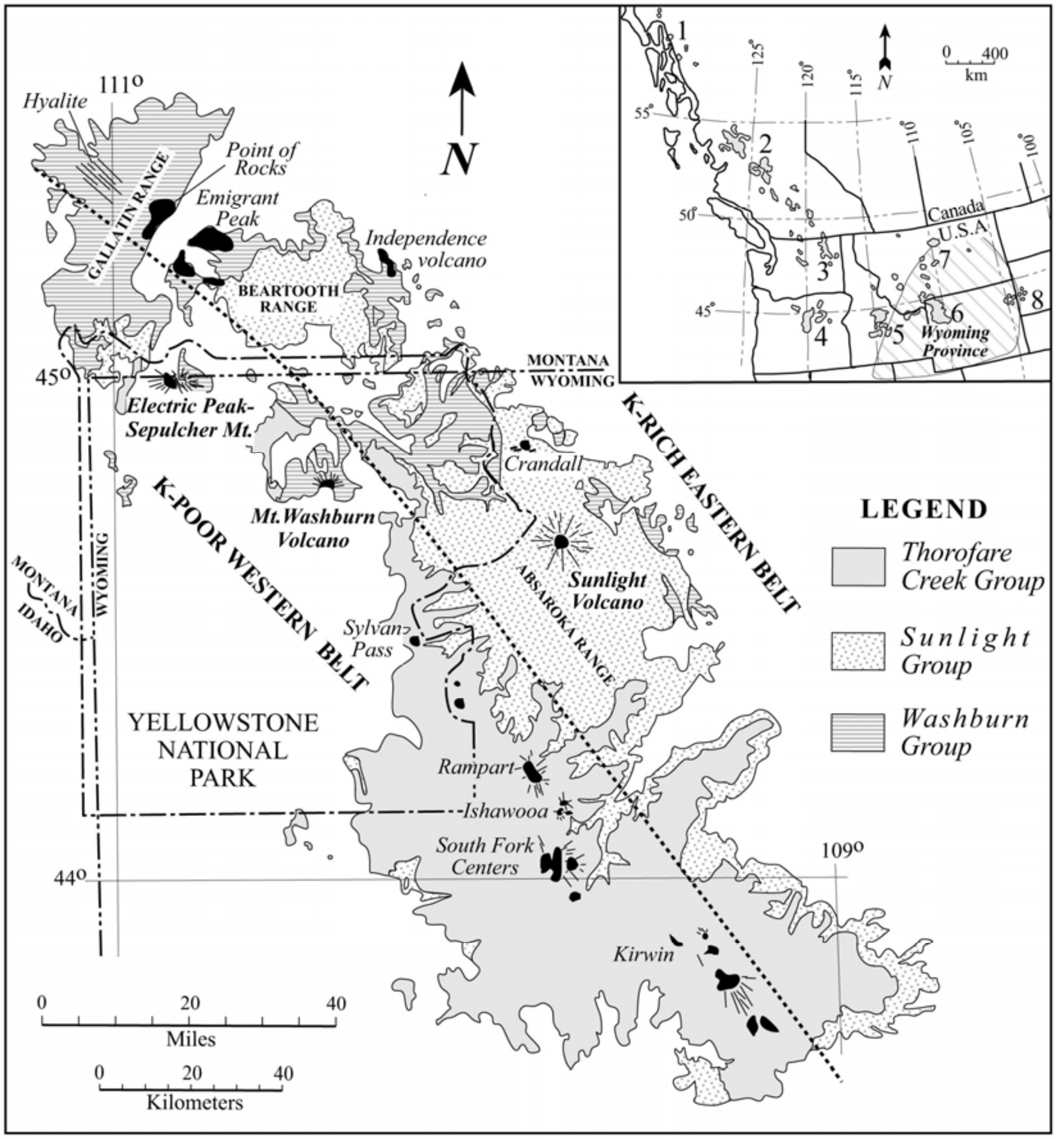

Figure 2: Map of the Absaroka volcanic province showing the stratigraphic units of Smedes & Prostka (1972). Black areas represent locations of principal vent complexes and intrusive centers discussed by Chadwick (1970). Thick dashed line shows the approximate division between western K-poor (calc-alkaline) and eastern K-rich (shoshonitic) belts (after Chadwick, 1970). Single dot dashed line is the boundary of Yellowstone National Park. Inset shows the locations of early-to-middle Eocene magmatic fields (after Chadwick, 1985; Holder & Holder, 1988; Dudas, 1991; Norman & Mertzman, 1991; Wheeler *et al*., 1991; Luedke, 1994). Numbers refer to : 1. Sloko volcanic province; 2. Francois Lake igneous complex; 3. Colville igneous complex; 4. Clarno volcanics; 5. Challis volcanic province; 6. Absaroka volcanic province; 7. Montana alkalic province; and 8. Black Hills. Diagonally ruled field shows inferred extent of Archean cratonic Wyoming Province (Dutch and Nielsen, 1990).

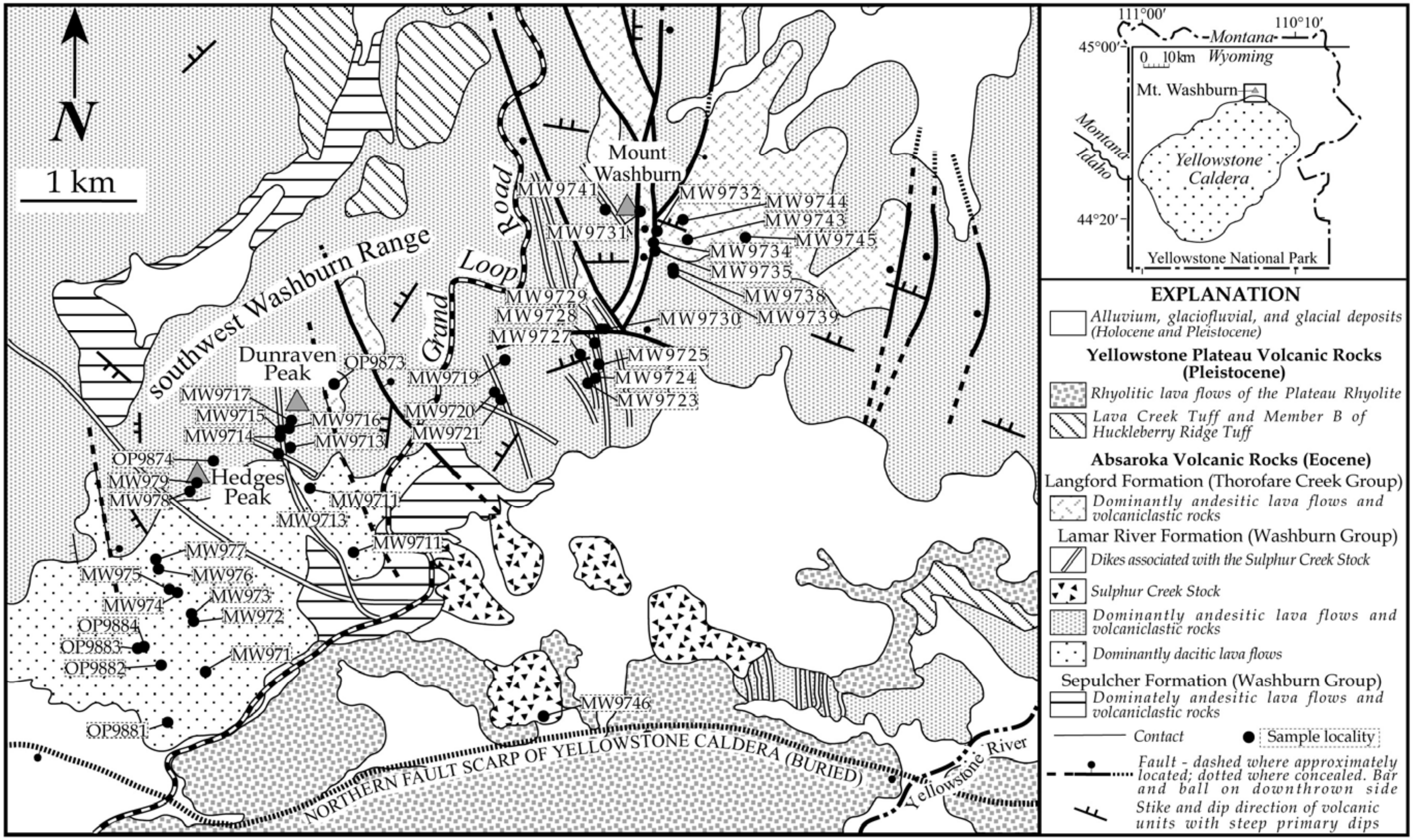

Figure 3: Simplified geologic map of Washburn volcano and surrounding area (modified from Prostka *et al.*, 1975). Filled circles show the locations of samples analyzed in Feeley et al. (2002). Inset shows the location of Washburn volcano in Yellowstone National Park.

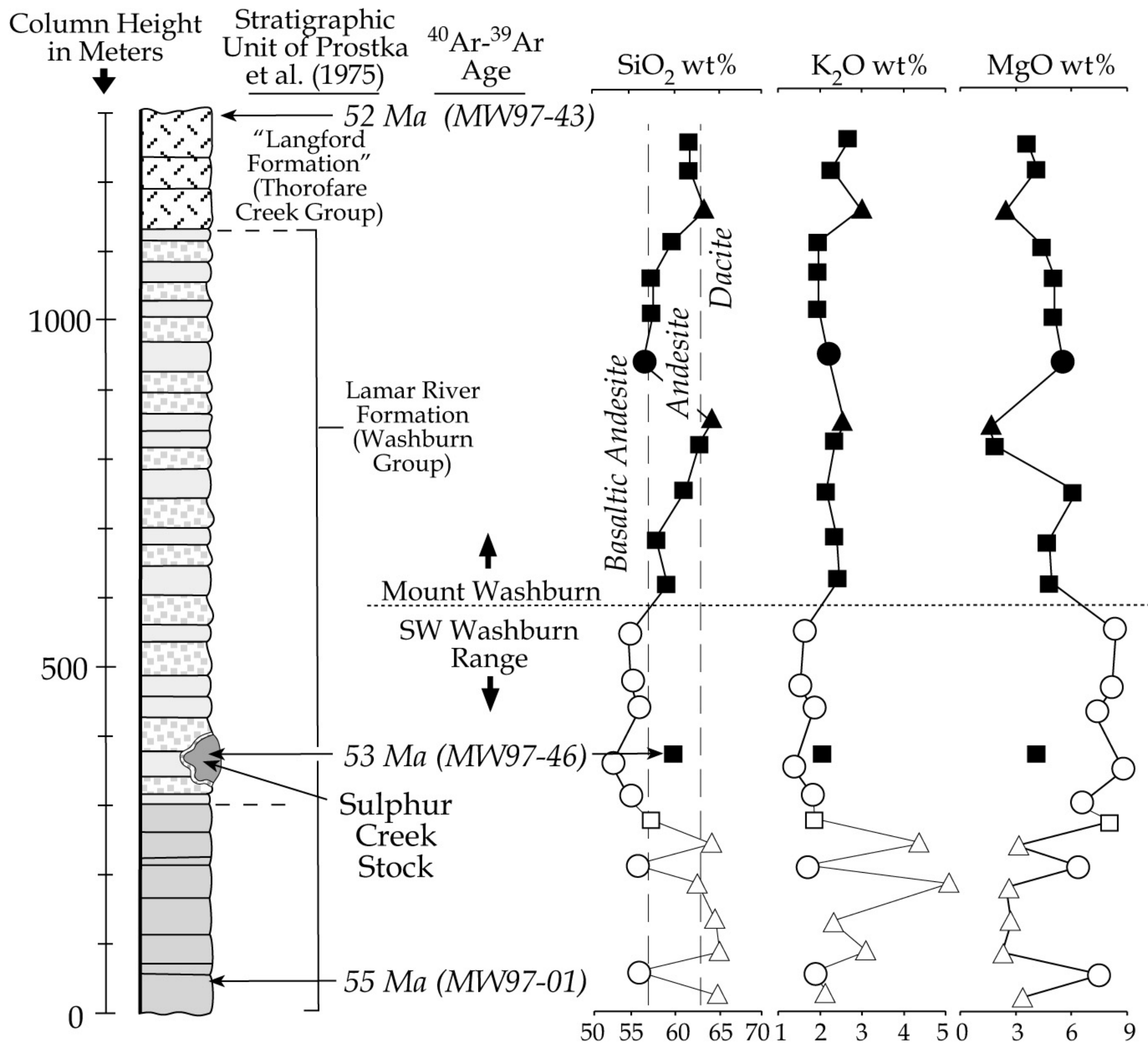

Figure 4: Schematic composite stratigraphic column for Washburn volcano combining total thicknesses of strata from the SW Washburn Range and Mt. Washburn areas. Lava flows are indicated by solid patterns; clastic units are indicated by stipple patterns (excluding brecciated autoclastic lava flow tops and bases). Geochemical data panels show the compositional variations of magmas with stratigraphic position. Open symbols are for samples from the SW Washburn Range and filled symbols are for samples from Mt. Washburn. Circles, squares, and triangles are for basaltic andesitic, andesitic, and dacitic composition rocks, respectively. Note: (1) reinterpretation of "Langford Formation" flows on Mt. Washburn as late Washburn volcano units (e.g., Fig. 2) based on data presented in Feeley et al. (2002); (2) bimodal assemblage of dacitic and basaltic andesitic lavas in lower part of section from SW Washburn Range and (3) dominantly andesitic lavas in upper part of section from Mt. Washburn.

Mount Washburn Exercise - Field Sheet for Description and Interpretation of Stations

Name ______________________________

Station # ____________________

Approx. Thick.	Sketch	Description	Interpreted Deposit Origin

Mount Washburn Exercise - Field Sheet for Description and Interpretation of Stations

Name ______________________________

Station # ____________________

Approx. Thick.	Sketch	Description	Interpreted Deposit Origin

Mount Washburn Exercise - Field Sheet for Description and Interpretation of Stations

Name ______________________________

Station # ____________________

Approx. Thick.	Sketch	Description	Interpreted Deposit Origin

Mount Washburn Exercise - Field Sheet for Description and Interpretation of Stations

Name ____________________

Station # ____________________

Approx. Thick.	Sketch	Description	Interpreted Deposit Origin

Mount Washburn Exercise - Field Sheet for Description and Interpretation of Stations

Name ______________________________

Station # ________________

Approx. Thick.	Sketch	Description	Interpreted Deposit Origin

PART 2: PETROGRAPHIC DESCRIPTION AND INTERPRETATION OF VOLCANIC ROCKS AT WASHBURN VOLCANO

In this section we will examine rocks from Washburn volcano under the petrographic microscope in order to determine the crystallization history of the rocks. Although you are only required to turn in one thin section report, you should not waste time during class because the report should be detailed. Record these descriptions and answer any questions **in your laboratory notebook**. An outline for the petrographic descriptions is given below and **examples of detailed reports follow this exercise**. **This format must be followed for "detailed" thin section reports in this and all subsequent laboratories.** If you are unclear about anything that you are observing in the thin sections or are asked about in the questions, do not hesitate to ask. Also, in order to correctly interpret what the physical or chemical significance of what you are looking at, you may want to consult your text book.

Note that there rock compositions in this exercise we did not examine on the field trip last weekend. Specifically, our collection includes basaltic andesitic and dacitic rocks collected from beneath Hedges and Dunraven Peaks that are generally not exposed along the Mt. Washburn trail.

<u>OUTLINE FOR DETAILED THIN SECTION REPORTS</u>

I. **Sample number**

II. **Drawing**: draw a representative area of the thin section as seen through the microscope at low power with the polars crossed or partially crossed. Use colored pencils to illustrate colors observed. Give a scale bar in mm at the base of the illustration. Note the principal phases (e.g., minerals, glass, vesicles). At the top of the illustration, cite the magnification and state the configuration of the polars.

III. **Mineralogy:** Identify and estimate percentages of:

- A. **Phenocrysts** (phyric phases; pyrogenetic; **by definition phenocrysts are grains > 0.3 mm)**.
- B. **Groundmass phases** (pyrogenetic), including glass, minerals, and vesicles;
- C. **Secondary**: what alteration, if any, has occurred to which minerals for both plutonic and volcanic rocks.

IV. **Megascopic Description**: be brief.

V. **Microscopic Textural Description**: from the lists given and in the text, use as many applicable terms as possible and give a complete textural description of the rock, including shapes, size range, and occurrences of each mineral phase), groundmass and whole-rock textures, etc. **This section is extremely important because the information contained within constitutes the DATA that you will use to formulate your interpretation in Section VII.**

VI. **Rock Name**: based on all of the above and the IUGS classification schemes. In this course we will use the following protocol for naming rocks (this must be strictly adhered to):

For **volcanic rocks**: Accessory **phenocrysts**-bearing (excluding trace minerals), varietal **phenocrysts**, base rock name. Note that for volcanic rocks only phenocryst phases are included in the rock name. Minerals smaller than phenocrysts (< 0.3 mm) are not considered in the naming process.

VII. **Origin and History**: based on all of the above. The origin and history should describe your **interpretation** on the order and conditions of crystallization of minerals in the rock and **the *evidence* that you *observed*** to derive this sequence. In addition, any evidence that you observe that bears on aspects such as cooling rate, gas content, deformation processes, and alteration should also be included.

VIII. **Schematic illustration of crystallization sequence.** Include essential and varietal minerals for plutonic rocks and phenocrysts and groundmass phases (including glass) for volcanic rocks.

Questions

1. Examine and give a detailed thin section report of one of the samples in our Washburn collection.

2. Examine very carefully the thin sections for Washburn volcano rocks. Is there textural evidence for magmatic disequilibrium in any of the samples? If so, what is this evidence?

3. Estimate phenocryst modes for the Washburn volcano rocks. Describe how phenocryst abundances change with changing compositions of the rocks?

PART 3: NORMATIVE CALCULATIONS, CLASSIFICATION, AND COMPUTER MODELING OF MAJOR ELEMENT GEOCHEMICAL DATA

The goal of this part of the laboratory is to give you the opportunity to carry out a series of simple calculations using commercially available geochemical modeling software. Specifically, using major element data for rocks from Washburn volcano you will classify the rocks and test various models for differentiation of the magmas that formed them. In the final question you will address the question of whether your preferred differentiation model is consistent with petrographic features of the rocks that you observed during the past two weeks.

This assignment assumes a basic level of familiarity with the Windows operating system. None of the operations using the software IGPET are particularly complex; it's more a matter of following instructions and thinking about the petrologic significance of the results.

1. **Norm Calculations.** In your readings about igneous rock nomenclature, you undoubtedly came across the terms *normative mineralogy* or *mineral norm*. Norms permit all rocks to be defined on the basis of a calculated (theoretical) mineral assemblage, independent of any differences in observed mineralogy (the mineral mode) that may reflect differing conditions of crystallization and/or equilibration. Norms also carry key information about rock chemistry not always evident in the observed mineralogy. Of paramount importance are norm calculations for mafic rocks, because different minerals in the norm appear to be associated with magmas from specific tectonic environments. So, for example, basalts with hypersthene (orthopyroxene) in the norm are referred to as "tholeiites" and are typically associated with plate boundaries, particularly divergent plate margins (e.g., MORB). In contrast, those with nepheline in the norm are referred to as "alkaline basalts" and are frequently erupted at volcanic centers located within plate interiors. The reasons for this will be explored later in lecture.

   Normative calculations begin with a chemical analysis of a rock (in weight percent oxide), from which a series of ideal (perfect) minerals are then calculated, based on a proscribed recipe. There are two principal methods for calculating a norm. The first, which was devised early in the 20th century by the American petrologists Cross, Iddings, Pirsson, and Washington, reports results as weight percentages of minerals. This is referred to as the **CIPW weight norm**. The second, which was developed several decades later by the European petrologists Tomas Barth and Paul Niggli, is based on cation percentages of minerals (the **Barth-Niggli cation or molecular norm**). In this exercise we will calculate CIPW norms.

   OK, so let's calculate the CIPW normative compositions for the Washburn rocks. Typically, this is a rather involved calculation to do by hand (see the Appendix of your text). Fortunately, computer software exists to make the procedure much easier. To use the IGPET software, follow these steps: (Note: I have omitted this from this 'mock' exercise for brevity).

2. **Major element modeling of Washburn rocks**. As you probably noticed during petrographic analysis, some of the Washburn rocks differ from one another in terms of sizes and proportions of the various phenocryst phases in the rocks. Furthermore, as pointed out above, the rocks also have differing chemical compositions. One of the major goals of igneous petrologists is to explain these differences by developing geochemical "models". In effect, **a geochemical model is a well-defined description of geochemical behavior during magma or rock formation**. The best models are those that are constrained by more than one type of observation or data. So, for example, a model that accounts for petrographic and geochemical features of a rock suite is more desirable than a model based solely on geochemical data or petrographic observations alone. In this final section you will attempt to reconcile your petrologic observations of Washburn rocks with the given geochemical data.

   The IGPET software makes petrologic mixing calculations using **least squares regression** of the major elements. Many researchers use this technique to test the plausibility of models of crystal fractionation or magma mixing. What criteria to use to judge whether a model is permissible is debatable and can vary with the problem being addressed. In general, the residuals (the difference between the observed and calculated model composition) should be within analytical error. However, the high degree of covariation of major elements really means that there are few degrees of freedom and it allows successful appearing fits of some nonsense models. The best one can say of a model with low residuals is that it has not been rejected, but it certainly can not be proved with this technique. The good news is that a great many models fail and can be rejected, so this is a valuable technique within limits.

   To perform these calculations for the Washburn rocks perform the following (omitted for this workshop):

<u>**Questions**</u>

(2.A) A frequently invoked mechanism to explain the presence of diverse composition magmas in geologic settings such as Washburn volcano is crystallization differentiation (e.g., crystallization and separation of solid phases from one magma to produce a magma of a different composition). Using the IGPET Mixing program, try fractionation of different combinations of phenocryst phases. Is crystal fractionation of **modal phenocrysts** a viable hypothesis to explain the compositional diversity of Washburn rocks? If no, explain why not. If yes, briefly explain why and list the F, r^2, and percentages of minerals that must be fractionated from the basaltic andesite to account for the composition of the andesite, and so on for more silicic rocks.

(2.B) Is mixing between basaltic andesite and dacitic magmas a viable hypothesis to explain the origin of andesitic magmas at Washburn volcano? Explain your answer. If you propose that mixing is viable, what are the relative proportions of basaltic andesite and dacitic magmas that must be mixed to form our andesitic sample?

(2.C) Is your preferred geochemical model consistent with the petrography and field relationships of the rocks? Explain your answer.

Background: Petrography and Geochemistry of Washburn Volcano Rocks

The following is summarized from Feeley et al., (2002).

Petrography of Washburn Lava Flows and Intrusions

Igneous rocks exposed on Mount Washburn and Dunraven and Hedges Peaks are generally non- to slightly vesicular (< 3 vol% vesicles), porphyritic to partially glomeroporphyritic lavas and dikes. In thin section these rocks are hypocrystalline with intersertal to pilotaxitic groundmass textures. Phenocryst contents range from 44 to 5% (by volume) with the total decreasing with increasing SiO_2 contents until about 63 wt% SiO_2. Dacitic rocks have widely varying phenocryst contents (~2-25 vol%) relative to andesitic and basaltic andesitic rocks. Changes in mode with bulk composition are regular throughout the suite. Basaltic-andesitic rocks contain plag ≥ cpx > ol ± opx; andesitic rocks contain plag > cpx > opx ± amph ± ol; and dacitic rocks contain amph + plag ± cpx ± opx ± bio. All rocks also contain Fe-Ti oxide microphenocrysts. Glomerocrysts are common of cpx ± Fe-Ti oxides, ol + cpx ± Fe-Ti oxides ± plagioclase ± opx, and plag + amph ± Fe-Ti oxides.

Mineral inclusion patterns and the occurrence of minerals in the glomerocrysts, together with textural features and compositions of the phenocrysts described below, suggest the following generalized crystallization sequences. Basaltic andesitic magmas crystallized olivine followed by Fe-Ti oxides, clinopyroxene + plagioclase, and orthopyroxene. Andesitic magmas crystallized plagioclase followed by clinopyroxene + orthopyroxene, Fe-Ti oxides and then amphibole in some cases. Dacitic magmas, in which pyroxenes are rare or absent, precipitated plagioclase followed by Fe-Ti oxides, amphibole, and then biotite when present. Groundmass assemblages include glass (partially to pervasively devitrified), plagioclase, clinopyroxene, and orthopyroxene. Zircon and apatite are common accessory phases in the intermediate and silicic lavas.

Xenocrysts, identified by non-equilibrium compositions or magmatic reaction textures, are present but rare. Furthermore, no clear petrographic evidence for mixing or mingling between compositionally disparate magmas, such as the presence of undercooled blobs of mafic magma that are frequently found in many andesitic to dacitic rocks, was identified.

The Sulphur Creek stock is tonalitic to quartz dioritic with plag > qtz > bio > opx = opx > Fe-Ti oxide > amph. Texturally, the stock is fine-grained, phaneritic, and subophitic in that late-crystallizing anhedral quartz partially encloses elongate plagioclase and biotite grains.

Chemical Compositions of Washburn Igneous Rocks

Variations in major element compositions of Washburn rocks are illustrated with respect to SiO_2 on Figure 4. According to the classification schemes of Peacock (1931), Peccerillo & Taylor (1976), and Le Maitre (1989) Washburn igneous rocks form a medium- to high-K, calc-alkaline suite (alkali-lime index ≈ 60) ranging in composition from basaltic andesitic through dacitic. In these respects the compositions of Washburn rocks share broad overall similarities to other Eocene calc-alkaline igneous rocks in the Absaroka Volcanic Province and elsewhere in the "Challis arc" (e.g., Norman & Mertzman, 1991; Hooper *et al.*, 1995; Dostal *et al.*, 1998; Lindsay & Feeley, 2003; Morris *et al.*, 2000). As is typical of calc-alkaline suites, MgO, Fe_2O_3, CaO, TiO_2, and MnO decrease with increasing SiO_2, whereas Na_2O and K_2O increase. Trends for Al_2O_3 and P_2O_5 are diffuse and show no obvious correlation with SiO_2.

With respect to identification of magmatic sources, differentiation processes, and compositional evolution of the Washburn magmatic system, the important major element features are: (1) samples from the SW Washburn Range consist mainly of a bimodal package of basaltic andesitic and dacitic rocks, whereas stratigraphically higher units on Mt. Washburn range continuously from basaltic andesitic through dacitic rocks, but are dominated by andesitic compositions; (2) trends with respect to SiO_2 for many elements are linear, except for MgO, Al_2O_3, and P_2O_5 which have more diffuse distributions of data; and (3) at a given SiO_2 content, rocks from Mt. Washburn tend to have lower MgO and higher Al_2O_3, respectively, than rocks from the SW Washburn Range.

Many trace elements (e.g., Ba, Rb, Y, Zr, Sc) display overall linear, but diffuse variations with respect to SiO_2, although highly compatible trace elements such as Cr and Ni scatter widely so that some intermediate composition rocks have relatively high concentrations of these elements (Fig. 5). It is noteworthy that, analogous to variations in MgO, rocks from Mt. Washburn generally have lower Ni and Cr contents than most equivalent bulk composition rocks from the SW Washburn Range.

Initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios corrected for 53 m.y. of *in situ* growth of radiogenic Sr and Nd for nine Washburn rocks are illustrated in Figure 6. Relative to "bulk Earth" all rocks have high Sr and low Nd isotopic ratios and thus plot within the "enriched" quadrant on Figure 6. The data define a negatively correlated array extending from a field defined by ultramafic xenoliths brought up in Eocene alkalic magmas in the Crazy Mountains, ~150 km north of Washburn volcano, to fields defined by Wyoming Province Archean granulite-facies rocks brought up as xenoliths in Cenozoic magmas (Fig. 6; Leeman *et al.*, 1985; Dudas *et al.*, 1987) and Archean supracrustal amphibolites and granitoids that dominate the exposed basement near Washburn volcano (Meen, 1987a; Wooden & Mueller, 1988). Although the Washburn rocks have MORB-normalized trace element patterns characterized by depletions in Ta and Nb (Fig. 13), they plot well below the field defined by modern subduction-related basalts due to their low Nd isotopic ratios. This feature is characteristic of many early- to late-Cenozoic magmatic rocks in the Wyoming Province and is considered to reflect derivation from or interaction with ancient subcontinental lithospheric mantle (e.g., O'Brien *et al.*, 1995; Scambos, 1991; Fraser *et al.*, 1985; Dudas *et al.*, 1987; MacDonald *et al.*, 1992; Meen & Eggler, 1987).

The Nd and Sr isotopic data indicate that crustal material was important in the genesis of Washburn magmas. Specifically, although values for all rock types overlap, there are fairly well-defined positively and negatively correlated arrays between SiO_2 content and Sr and Nd isotopic compositions, respectively (Figs. 6b and c).

Petrologic Interpretations for Washburn Rocks

At Washburn volcano the geochronologic, petrologic, and geochemical data have been used to construct a model for the evolution of the system with the following components. (1) Primitive mantle-derived basaltic magmas fractionated clinopyroxene-rich mineral assemblages and assimilated partial melts of conduit walls at mid- to deep-crustal levels. (2) Contaminated mafic magmas stalled in the mid- to deep-crust where they melted rocks with compositions similar to Archean granulite facies rocks and mixed thoroughly with the resultant melts. This stage is, analogous to the MASH (mixing, assimilation, storage, homogenization) process of Hildreth & Moorbath (1988) and it produced the dominant volume of andesitic and basaltic andesitic rocks present on Mt. Washburn and explains the relative scarcity of either basaltic or dacitic rocks. (3) Ascent of hybrid magmas to shallow crustal reservoirs where they crystallized and in some cases fractionated small amounts of low-pressure mineral assemblages dominated by plagioclase. (4) Repeated injections of hybrid, intermediate composition magma into the bases of the shallow chambers caused minor oscillatory and reverse zoning in any resident phenocrysts.

The scenario for rocks in the SW Washburn Range differs from that for rocks on Mt. Washburn in that the amount of fractionation of the mafic magmas was generally less and the silicic magmas experienced small degrees of shallow level fractionation. Moreover, because the SW Washburn suite is a bimodal assemblage of basaltic andesitic and dacitic rocks it appears that the extent of homogenization was also less. At all temporal stages in the evolution of Washburn volcano the hybrid magmas stalled in shallow magma chambers prior to eruption. This episode is documented by growth of new, plagioclase-rich mineral assemblages in equilibrium with the hybrid liquids. In the case of the SW Washburn system where early batches of silicic magma were probably small and the crust relatively cold, convective velocities within the shallow chambers may have been sufficiently low to permit fractionation of resident phenocrysts.

Petrologic significance

In light of the foregoing discussion one of the more intriguing aspects of the Washburn suite is that although bulk compositions strongly suggest that the intermediate composition rocks are hybrids, compositional and modal data for phenocrysts show only limited evidence for mixing in the form of mineral-melt disequilibria or coexisting high and low temperature phenocryst assemblages. In this regard the rocks can be referred to as "cryptic hybrids." Dungan (1987) suggested that the most likely condition for generating cryptic hybrids involves blending of mineralogically similar, low viscosity tholeiitic mafic magmas, although he also proposed a more general model applicable to calc-alkaline and bimodal systems where endmember magmas differ markedly in solidus temperatures, densities, viscosities, and mineral assemblages. Important elements of the model include incremental mixing of superheated, crystal-poor magmas long before eruption. Although Dungan (1987) did not further identify specific magmatic environments where these conditions are optimized, he noted that the main requirement is that sufficient time must exist following mixing for the hybrid magmas to achieve textural and mineralogical equilibrium prior to eruption.

The petrogenetic model developed in this paper implies that generation of cryptic hybrids in compositionally diverse calc-alkaline systems may be facilitated in deep crustal zones of differentiation. At Washburn volcano juxtaposition of compositionally diverse magmas appears to have occurred in deep chambers repeatedly fluxed by high temperature, relatively primitive mafic magmas. In such environments heating of the crust may be substantial, resulting in production of partial melts that are effectively liquid due to nearly complete resorption of any entrained pre-existing crystals (Watson, 1982; Tsuchiyama, 1985; Huppert & Sparks, 1988; Koyaguchi & Kaneko, 1999). Furthermore, as proposed by Hildreth & Moorbath (1988) and suggested by the stratigraphic succession documented at Washburn volcano, mixing in deep crustal magma chambers may be incremental and involve repeated blending of fractionated mantle-derived mafic magmas, silicic crustal melts, and evolved magmas which themselves are hybrids formed during earlier injection-mixing episodes. In this manner endmember magmas progressively converge toward intermediate compositions that can readily homogenize. Subsequent ascent and crystallization of hybrid magmas in shallow chambers will overprint these earlier mixing episodes.

In contrast to the Washburn system, many calc-alkaline suites contain dramatic mineralogic and petrographic evidence for mixing, particularly where homogenization is incomplete and compositionally banded tephra or commingled mafic inclusions occur within more silicic hosts (Wilcox, 1999). In these systems magma interaction appears to have occurred rapidly during injection of basaltic magma into the bases of shallow silicic chambers (Blake *et al.*, 1965; Eichelberger, 1975; Anderson, 1976; Bacon, 1986; Coombs *et al.*, 2000). There is also abundant evidence in these systems that basaltic injection is responsible for triggering eruption, thereby arresting re-equilibration of high and low temperature phenocryst assemblages within the new hybrid magma (Pallister *et al.*, 1992; Feeley & Sharp, 1996). At Washburn volcano injections into shallow chambers may also have triggered eruptions. These injections, however, were probably hybrid intermediate magmas compositionally similar to resident magmas, thereby producing little discernable textural or mineralogical disequilibrium in the erupted lavas.

Implications for magmagenesis in the AVP

Recognition of the Washburn magmas as cryptic hybrids and crustal melts provides new insight into magmatic processes operating in the AVP. An outstanding question concerning the origin of magmatic rocks in the AVP is the extent to which the calc-alkaline magmas interacted with the continental crust. At other magmatic fields in the "Challis arc" (Fig. 2 *inset*), a magma mixing origin has been demonstrated for calc-alkaline rocks (e.g., Morris and Hooper, 1997; Morris et al., 2000). However, prior to this study a simple closed system history was assumed for AVP calc-alkaline magmas because no convincing evidence had been presented to indicate crustal involvement during differentiation. Indeed, the simple phenocryst assemblages of the rocks were cited as strong evidence for differentiation by closed-system fractional crystallization. This facet was established over a century ago in the classic work of Iddings (1891) on AVP calc-alkaline rocks exposed at the Electric Peak-Sepulchur Mountain eruptive center (Fig. 2), which produced rocks temporally, compositionally, and petrographically similar to those at the Washburn volcano. At this center Iddings (1891) utilized optical and chemical techniques available at the time to argue for textural and compositional equilibrium between phenocrysts and whole-rocks and correlated changes in phenocryst modes with differentiation nearly identical to those documented here. In his view these features suggested that: "*...the chemical differences of igneous rocks are the result of a chemical differentiation of a general magma*" (Iddings, 1891). Subsequent petrologic studies based on limited chemical data sets maintained this opinion and further argued that differentiation of AVP calc-alkaline magmas involved simple fractional crystallization of plagioclase-rich assemblages (e.g., Schultz, 1962; Peterman et al., 1970; Love et al., 1976; LaPointe, 1977), largely because the simple phenocryst assemblages and major element compositions of the rocks provided no compelling evidence to implicate crustal involvement during differentiation.

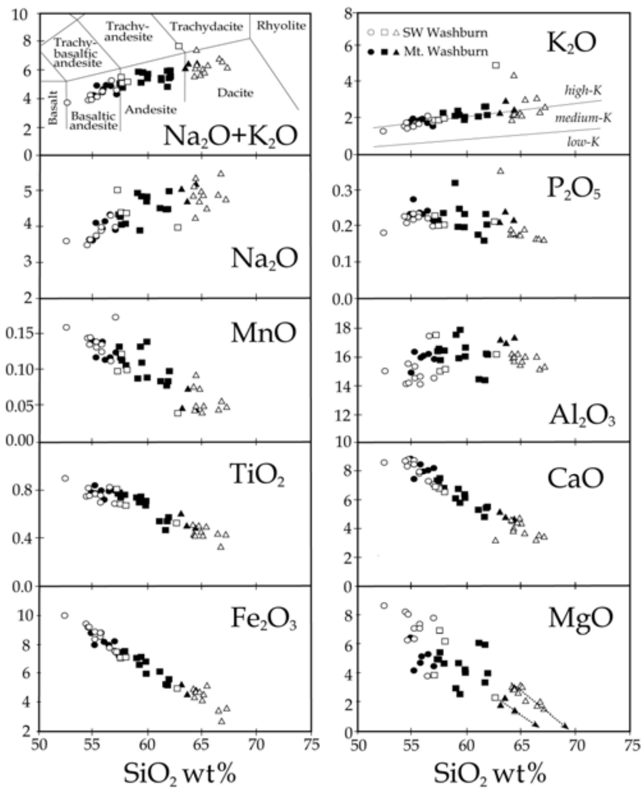

Figure 5: Major element compositions of Washburn igneous rocks versus SiO_2. K_2O classification boundaries are from Peccerillo & Taylor (1976). Total alkali diagram shows classification scheme of Le Maitre (1989). Open symbols are for samples from the SW Washburn Range and filled symbols are for samples from Mt. Washburn. Circles, squares, and triangles are for basaltic andesitic, andesitic, and dacitic composition rocks, respectively. Dashed arrows through dacitic composition rocks on MgO versus SiO_2 diagram are linear regression lines.

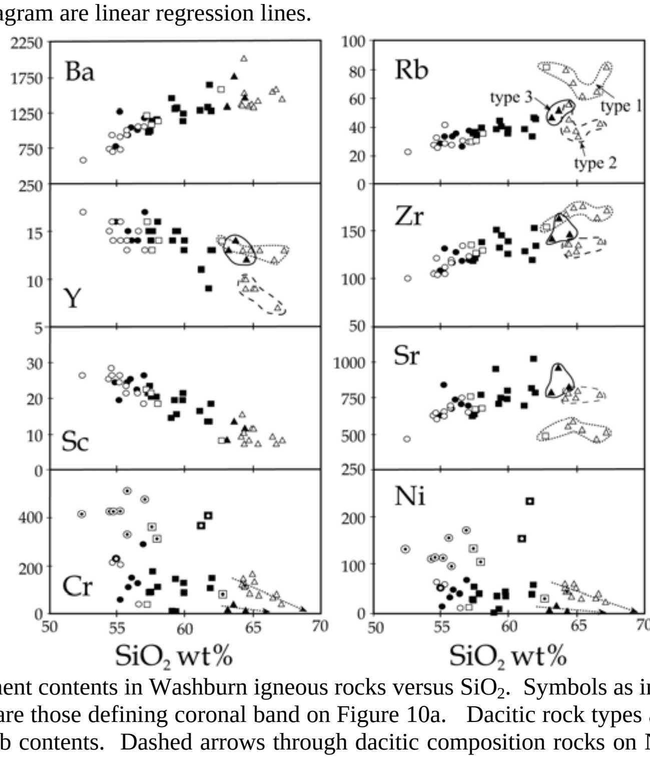

Figure 5: Selected trace element contents in Washburn igneous rocks versus SiO_2. Symbols as in Figure 9. Symbols with center point on Ni and Cr diagrams are those defining coronal band on Figure 10a. Dacitic rock types are distinguished on the basis of location and Sr, Zr, Y, and Rb contents. Dashed arrows through dacitic composition rocks on Ni and Cr versus SiO_2 diagrams are linear regression lines

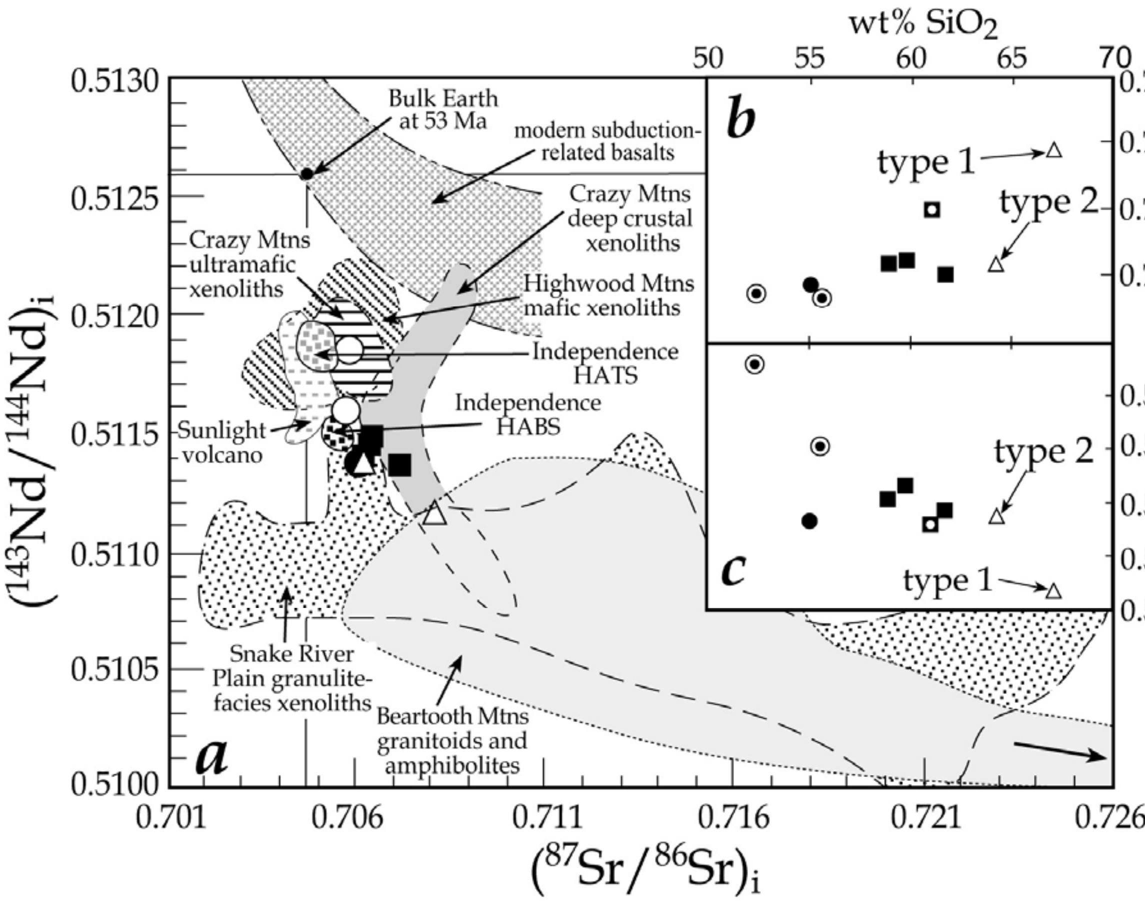

Figure 6: (*a*) Comparison of initial Sr and Nd isotopic compositions (at 53 Ma) of Washburn igneous rocks with published data for crustal rocks from the Wyoming Province and Eocene igneous rocks from the AVP. Highwood Mountains xenolith field from Joswiak (1992), Crazy Mountains xenolith fields from Dudas *et al.* (1987), Snake River Plain xenolith field from Leeman *et al.* (1985), Beartooth Mountains Archean granitoid and amphibolite field from Meen (1987) and Wooden & Mueller (1988), Independence fields from Meen & Eggler (1987), and Sunlight volcano field from Feeley (unpublished data). All data are calculated for an age of 53 Ma except for data from Independence and Sunlight centers. Data defining these fields calculated for 50 Ma for the Independence volcano (Harlan *et al.*, 1996) and 48 Ma for the Sunlight volcano (Feeley and Cosca, 2003). (*b*) $(^{87}Sr/^{86}Sr)_i$ and (*c*) $(^{143}Nd/^{144}Nd)_i$ versus SiO_2 for Washburn rocks. Symbols as in Figure 4.

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