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GEOLOGIC INFLUENCES ON APACHE TROUT HABITAT IN THE WHITE MOUNTAINS OF ARIZONA

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ABSTRACT

Geologic variation has important influences on habitat quality for species of concern, but it can be difficult to evaluate due to subtle variations, complex terminology, and inadequate maps. To better understand habitat of the Apache trout (*Onchorhynchus apache* or *O. gilae apache* Miller), a threatened endemic species of the White Mountains of east-central Arizona, we reviewed existing geologic research to prepare composite geologic maps of the region at intermediate and fine scales. We projected these maps onto digital elevation models to visualize combinations of lithology and topography, or lithotopo types, in three-dimensions. Then we examined habitat studies of the Apache trout to evaluate how intermediate-scale geologic variation could influence habitat quality for the species. Analysis of data from six stream gages in the White Mountains indicates that base flows are sustained better in streams draining Mount Baldy. Felsic parent material and extensive epiclastic deposits account for greater abundance of gravels and boulders in Mount Baldy streams relative to those on adjacent mafic plateaus. Other important factors that are likely to differ between these lithotopo types include temperature, large woody debris, and water chemistry. Habitat analyses and conservation plans that do not account for geologic variation could mislead conservation efforts for the Apache trout by failing to recognize inherent differences in habitat quality and potential.

INTRODUCTION

Analyses of habitat quality need to group landscapes into units that capture the fundamental influence of geologic processes (Omernik and Bailey 1997). Studies of land-use impacts have stratified habitats using large-scale units such as ecoregions (Robinson and Minshall 1998), landtype associations (Modde et al. 1991, Nelson et al. 1992), and basin parent material (Hicks and Hall 2003). However, Fausch et al. (2002) argued that conservation analyses need to focus attention on the interactions between aquatic populations and their habitat that occur at an intermediate scale of river segments (approximately 1 to 100 km). Montgomery (1999) championed the use of "lithotopo types," representing areas of similar lithology (rock type) and topography, and finer "process domains" for analyzing aquatic habitat at this intermediate scale. These units focus attention on formative processes such as soil formation, erosion, infiltration, and runoff, and they are particularly important for regions with high relief, variable climate, and complex geology (Montgomery 1999). Stream ecologists have made limited use of Montgomery's framework (Walters et al. 2003). One reason may be that the intermediate scale can be particularly difficult to appreciate, sample, and visualize (Fausch et al. 2002).

The Apache trout (*Oncorhynchus apache* or *O. gilae apache* Miller) is a species listed as threatened under the Endangered Species Act that is endemic to the White Mountains of east-central Arizona. Analyses of Apache trout habitat have historically focused on a few small stream reaches (Harper 1976, Wada 1991, Kitcheyan 1999), reflecting the fact that individual drainages have served as primary conservation and management units for the species. Only one study (Clarkson and Wilson 1995) evaluated trout-habitat relationships across the White Mountains region, but it did not consider geologic variation. Long-standing geologic research has revealed the region's complex geology, yet the results of that research have not been integrated into fisheries science in the region. We reviewed available geologic research in the White Mountains and habitat studies of the Apache trout to evaluate how geologic variation may influence habitat for the Apache trout. The resulting synthesis is useful for guiding conservation efforts for the Apache trout and for other species that inhabit geologically heterogeneous landscapes.

METHODS

We reviewed all major studies on the geology of the White Mountains, including both agency publications and academic dissertations. Based on the maps and descriptions in those studies, we compiled composite geologic maps at both an intermediate scale of approximately 10-100 km and a finer scale. We obtained a digital elevation model (DEM) with 10-m resolution from the US Geological Survey (http://seamless.usgs.gov/). Using the 3D Analyst extension in the ArcMap computer program (Envir-

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onmental Systems Research Institute, Redlands, CA), we projected the composite geology maps onto the DEMs to create three-dimensional views depicting lithology and topography across the region.

We reviewed all published studies of trout habitat in the White Mountains region, as well as the three master's theses on Apache trout habitat (Harper 1976, Wada 1991, Kitcheyan 1999). We then considered how geologic variation influences those variables that the studies suggested to be important predictors of trout production (often measured as standing crop or biomass at a specific time). Based on that review, we considered whether certain litho-topo types could be stratified to identify more productive trout habitats. To facilitate visualization of these differences, we compiled photographs of Apache trout stream reaches that were located in different geologic settings but in comparably sized watersheds within an 11 km radius in the White Mountains.

To demonstrate how stream hydrographs relate to lithology and topography within the region, we obtained stream gage data for six watersheds with comparable watershed areas (75-150 km^2). Data on the North Fork of the White River, the East Fork of the White River, the North Fork of the East Fork of the Black River, and the Little Colorado River were obtained from the U.S. Geological Survey (USGS 2005), while data on Beaver Creek and the West Fork of the Black River were obtained from the Apache-Sitgreaves National Forest. To compare the hydrographs, we charted the daily discharge per unit watershed area averaged over the period of record for each gage.

RESULTS AND DISCUSSION

Geologic Heterogeneity in the White Mountains

In 1875, a geologist with the Wheeler Expedition described Mount Baldy, the central massif of the White Mountains, as “massive eruptions of trachyte – a variety of trachyte affiliated with, and passing into, sanidin-dolerite – and comprises a cluster of rugged knobs. From it, there stretch, in every direction, long slopes of sanidin-dolerite” (Gilbert 1875). That statement described two rock types that can be readily distinguished: light-colored felsic rocks (trachyte) and dark-colored mafic rocks (“sanidin-dolerite” is an archaic term for basalt, which is one of the most common varieties of mafic rock), the complex mixing of the two types, and differences in topography associated with the rock types.

Geologic research in the 1960s, 1970s, and 1980s elaborated upon that accurate but brief description by identifying numerous glacial and other sedimentary valley-fill deposits and by detailing subtler distinctions in the volcanic rocks (Melton 1961, Wrucke 1961, Merrill 1974, Berry 1976, Wrucke and Hibpshman 1981, Nealey 1989, Potochnik 1989, Condit et al. 1999). Drawing upon these sources, we compiled an intermediate-scale composite map (Fig. 1), which uses colors to indicate clear differences in lithology and topography. The lithologic differences are associated with topographic differences because felsic magmas tend to form steep lobes while mafic magmas tend to form flatter flows. The upper flanks of Mount Baldy are composed of felsic volcanic rocks that Merrill (1974) dubbed the “Mount Baldy Formation.” He also identified five large valleys on the north and east slopes of Mount Baldy that contained glacial deposits. Many of the valleys along the lower slopes of Mount Baldy are filled with the Sheep Crossing Formation, deposits of poorly sorted sand, gravel, and boulders shed from the upper mountain (Merrill 1974). On the south and west slopes of Mount Baldy, drainages flow from

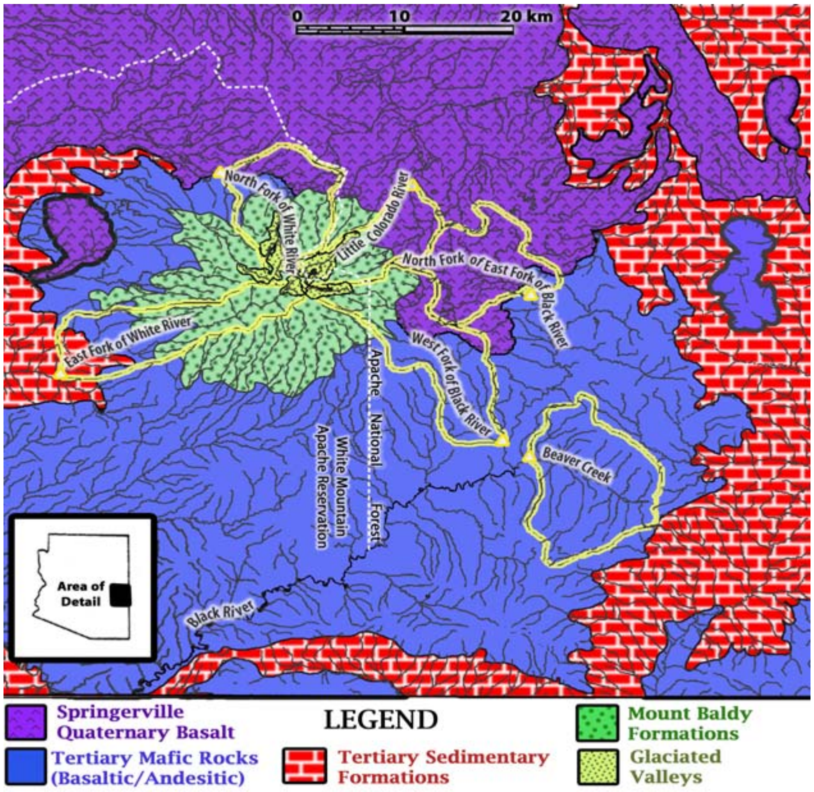

***Figure 1**. Geology of the White Mountains region in east-central Arizona, with six gaged watersheds outlined.*

the felsic summit into canyons that have incised deeply into older mafic rocks mixed with volcaniclastic deposits (Berry 1976, Nealey 1989). Drainages on the southeastern slope of Mount Baldy flow into an expansive region of plateaus and canyons also formed from Tertiary mafic flows (Berry 1976). The area north and east of Mount Baldy is composed of cinder cones and flat basalt flows of the relatively young Springerville volcanic field (Nealey 1989, Condit et al. 1999). On the eastern edge of the White Mountains, Escudilla Mountain also harbors Apache trout. The species was introduced to two small, formerly fishless streams, Coyote and Mamie Creeks, which flow northeast from the mafic summit of the mountain through slopes composed of volcaniclastic sandstones, mudstones, and conglomerates of the Spears Group (Wrucke 1961, Cather et al. 1994).

The photographs in Figures 2 through 6 portray typical variation in Apache trout habitats within a small area in the White Mountains between mid-June and mid-July in 2003. Because all reaches but the first one have a watershed area of approximately 6 km, this series helps to visualize variation associated with geology, rather than watershed area or stream order. Distinguishing characteristics such as gradient, base flow, vegetation, and woody debris reflect whether the reaches originate from near the summit of Mount Baldy (Figs. 2 and 3), whether they were scoured by glaciers (Fig. 2), whether they formed in deposits of the Sheep Crossing Formation (Figs. 3 and 4), and whether they formed from felsic formations (Figs. 2, 3, and 4) or mafic formations (Figs. 5 and 6). As the reaches decrease in elevation, lithology shifts from felsic to mafic formations and upland vegetation shifts from spruce (*Picea* spp.) and fir (*Abies* spp.) to ponderosa pine (*Pinus ponderosa*). Base flow appears generally more abundant at higher elevations (Figs. 2 and 3) than at lower elevations (Figs. 4 and 5), although unusual groundwater features create notable exceptions to this pattern, such as Soldier Spring (Fig. 6).

Hydrologic Regimes

Since water is the *sine qua non* of trout habitat, base flow and stream depth are key variables explaining variation in trout biomass in small Southwestern streams (Rinne 1978, Rinne and Medina 1988). Studies of Apache trout streams have indicated that pool size and depth are limiting factors for adult trout (Wada 1991, Kitcheyan 1999). Because stream discharge has great influence on pool depth (Lisle 1987), it is important to account for differences in flow when comparing aquatic habitats. Many reaches in the White Mountains have tended to run dry, causing declines in trout populations (Rinne 1985b, Medina and Steed 2002, Robinson et al. 2004). Differences in lithology and topography can induce differences in runoff and groundwater storage that explain the vulnerability of some streams to flashy flows and desiccation (Kelson and Wells 1989).

To demonstrate how stream hydrographs relate to lithology and topography within the region, we compared six gaged watersheds with comparable watershed areas (75-150 km^2) (Fig. 1). The standardized hydrographs (discharge per unit area) for

Figure 2. *The headwaters of the West Fork of the Black River flow through Mount Baldy formations that have been repeatedly scoured by glaciers. This reach is located at an elevation of nearly 3000 m with a watershed area of approximately 3.23 km^2.*

Figure 3. *Thompson Creek heads on Mount Baldy, then flows through meadows formed in deposits of the Sheep Crossing Formation. This reach is located at an elevation of nearly 2750 m with a watershed area of approximately 5.67 km*^{2}.

Figure 4. *Stinky Creek heads on the lower flank of Mount Baldy in deposits of the Sheep Crossing Formation. This reach is located at 2660 m elevation with a watershed area of approximately 6.34 km*^{2}.

Figure 5. *Boggy Creek flows intermittently through purely basaltic formations. This reach, lined with thinleaf alder* (Alnus incana *ssp*. tenuifolia*), is located at 2490 m elevation with a watershed area of approximately 6.16 km*^{2}.

Figure 6. *Soldier Creek emerges from a large spring near a transition between mafic flows. This reach is located in a ponderosa pine forest at 2287 m elevation with a watershed area of approximately 5.45 km*^{2}.

those six watersheds (Fig. 7) show that streams originating from Mount Baldy, including the Little Colorado River and the East and North Forks of the White River, tend to peak later in the season and maintain higher base flows than streams draining basaltic areas, such as Beaver Creek and the North Fork of the East Fork of the Black River. The latter watershed is dominated by Quaternary basaltic formations overlain by montane grassland, where spring runoff occurs more rapidly than in forested areas (Leven and Stender 1967). The West Fork of the Black River flows from the east side of Mount Baldy, but it crosses into the mafic plateaus as it turns south (Fig. 1). The fact that a smaller portion of its watershed is composed of high-elevation Mount Baldy terrain may explain why its hydrograph is intermediate between the basaltic streams and the other Mount Baldy streams.

Stream classifications based on surface attributes have long struggled in how to account for groundwater influences (Kuehne 1962). Coarse-scale geology maps often lack the detail that is needed to specify the locations of gaining reaches (Malard et al. 2002). Fractures within and boundaries between volcanic flows store and transport water through underground networks (Leven and Stender 1967). Consequently, groundwater-fed reaches also occur may be difficult to delineate from surface geology maps of volcanic terrain. However, glacial deposits often serve as natural reservoirs that attenuate hydrographs in mountain valleys (Kelson and Wells 1989). Smith Cienega on Ord Creek is a large meadow formed in one of the most extensive glacial deposits in the White Mountains. An observation of base flow doubling from the middle to the bottom of this meadow without significant input from tributaries testifies to the storage capacity of the glacial deposit (Rinne et al. 1981). Deposits of the Sheep Crossing Formation, which are more extensive on Mount Baldy than glacial deposits but are similar in texture, also serve as groundwater aquifers, feeding springs that emerge at the contacts with less permeable volcanic formations (Merrill 1974). Consequently, lithology and topography serve to highlight features of unusual hydrologic significance in the Mount Baldy area.

The influence of groundwater is important in understanding relationships of aquatic biota to landscapes (Poole 2002). Physiographic features that enhance groundwater storage and discharge are

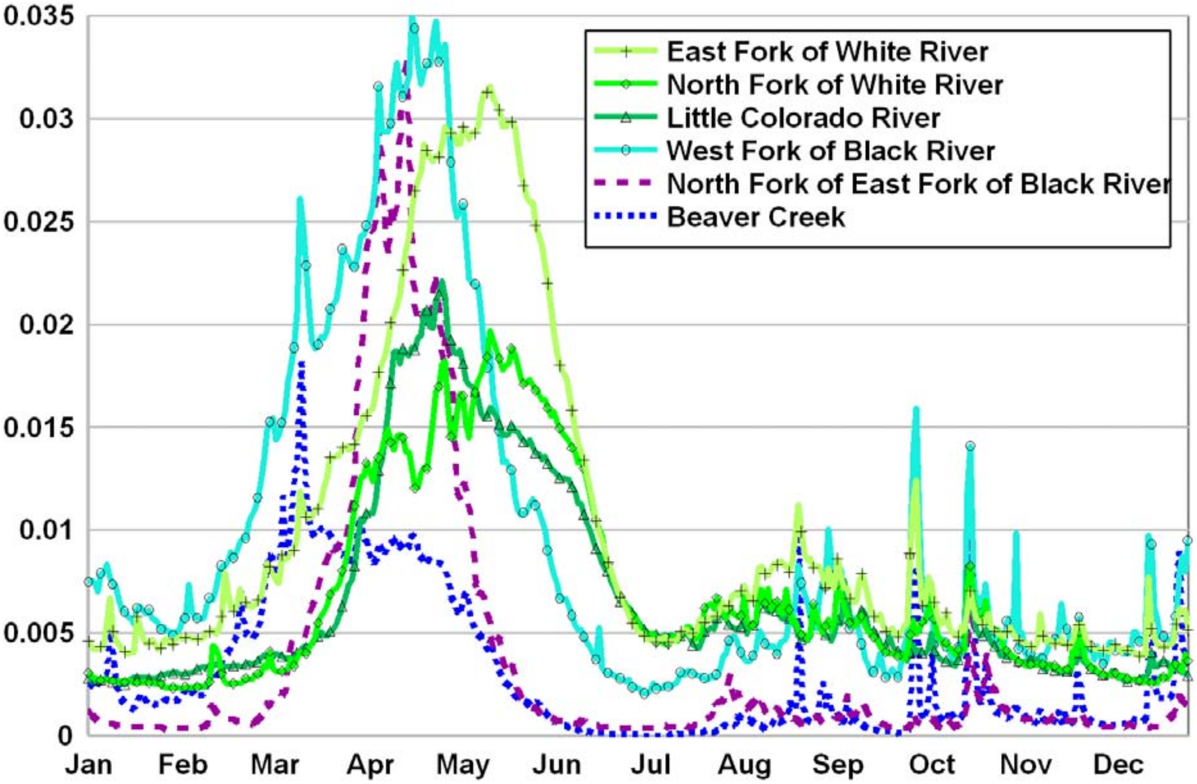

Figure 7. *Mean daily discharge per unit area at six stream gages in the White Mountains of Arizona with drainage areas 75 and 150 km^2. Streams draining Mount Baldy (green lines with symbols) peak later and maintain higher base flow than streams draining adjacent basaltic areas (dark solid lines).*

important when evaluating habitat potential for trout (Imhof et al. 1996). Influxes of groundwater help stream reaches to avoid high summer temperatures, low winter temperatures, and rapid changes in daily temperature, all of which negatively impact trout (Lee and Rinne 1980, Cunjak 1996). Alluvial valley segments with upwelling groundwater provide spawning habitat for bull trout (*Salvelinus confluentus*) in steep mountains of Montana because they maintain favorable temperature and oxygen levels for eggs (Baxter and Hauer 2000). By providing similarly favorable hydrologic conditions, the valley fill deposits on Mount Baldy may be important features for trout in the White Mountains.

Because Mount Baldy formations are higher than the surrounding mafic plateaus, their elevation tends to reinforce lithology in maintaining favorable conditions for trout. While summer drought and high temperatures pose a threat to trout, winter habitat conditions might also be limiting populations. Harper (1976) and Kitcheyan (1999) noted that the Apache trout streams they studied at elevations between 2500 and 2750 m experienced harsh winter conditions including formation of anchor ice and ice bridges. Anchor and surface ice have been linked to trout mortality (Maciolek and Needham 1952, Bjornn and Reiser 1991). A study of trout streams in Wyoming reported that anchor ice was more common at mid-elevation sites (2550-2700 m) than at high-elevation sites where snow cover was more complete (Chisholm et al. 1987). A similar pattern may hold for the White Mountains, as streams nearer to the summit of Mount Baldy are more likely to experience insulating snow cover.

Substrates

After flow volume, one of the most important ingredients for productive trout habitat is suitable substrate quality (Platts 1976, Rinne and Medina 1988). Rinne (2000) found that 3 Mount Baldy streams had significantly higher amounts of fine gravels (4-32 mm) than did 11 streams on adjacent mafic plateaus. He also found that greater trout biomass in Mount Baldy streams was significantly correlated to the relative abundance of fine gravels. While numerous other factors could mediate these associations, the fine gravels hypothesis is supported by observations that Apache trout prefer that particle size for spawning (Harper 1976, Wada 1991). Felsic rocks of Mount Baldy are relatively rich in silica (53-70% by weight) and often contain large crystals (10 to 25 mm); mafic rocks, in contrast, have less silica and rarely contain large crystals (Nealey 1989) (Fig. 8). As a result, felsic volcanic rocks behave like granite (a felsic plutonic rock) in producing sandy soils, while mafic rocks produce soils rich in silt and clay (Long et al. 2003); however, these textural relationships may not necessarily apply to other volcanic regions due to variations in mineralogy and weathering. Steep topography reinforces this lithologic difference in giving Mount Baldy greater capacity to deliver coarse sediments to streams compared to the flat-lying basaltic plateaus. Extensive erosion of Mount Baldy has produced substantial deposits of coarse-textured Sheep Crossing Formation, glacial till, and alluvium in its valleys (Merrill 1974). Consequently, the combination of lithology and topography can explain why Mount Baldy streams have greater abundance of favorable substrates for spawning.

These differences in lithology and topography also suggest that fine sediments would be relatively more abundant in basaltic streams. A laboratory study by Rinne (2000) suggested that fry emergence was significantly reduced at 25% fine sediments (<2 mm, measured by weight), leading him to hypothesize that inputs of fine sediments in basaltic streams could be limiting trout production. However, Rinne (2000) did not find a significant difference in the relative abundance of subsurface fine (<2 mm) particles between streams draining felsic and basaltic areas, nor did he find a significant relationship between the relative abundance of fines and trout biomass. Similarly, Harper (1976) reported high biomass (0.13 g/m^2) of Apache trout in Big Bonito Creek, despite measuring 25% and 38% fine (<4 mm) particles (by volume) in the bed substrates of redds and riffles, respectively. These observations did not lend support to the hypothesis that fine sediments are a major factor inhibiting trout productivity in the region. However, geologic heterogeneity itself complicates efforts to sample fine particles accurately. Basaltic streams are particularly problematic for sampling fines using methods such as pebble counts and McNeil corers (Bunte and Abt 2001), embeddedness estimates (Sylte and Fischenich 2002), and measurements of filled residual pool volume (Lisle and Hilton 1999). Difficulty in sampling arises because clay and silt particles are more easily suspended in water and because they tend to accumulate in the spaces between larger particles rather than as discrete deposits in pools.

Streambank Cover

Cover in the form of large woody debris, boulders, overhanging vegetation, and undercut banks are often regarded as important for trout production (Covington and Hubert 2000), and three habitat use studies in the White Mountains have reported the Apache trout prefer such features (Wada 1991, Kitcheyan 1999, Cantrell et al. 2005). The high-elevation, coarse-textured slopes of Mount Baldy support spruce, fir, and aspen (*Populus tremuloides*) forests, while the basaltic areas are dominated by more drought-tolerant ponderosa pine and Douglas-fir (*Pseudotsuga menziesii*; USDA-SCS and USDI-BIA 1981). Because the higher elevation trees grow more densely, they provide more abundant sources of large woody debris (e.g., Fig. 2). Streams in the lower-elevation mafic areas tend to have greater abundance of thinleaf alder (Medina and Steed 2002), a shrubby species whose limbs are generally too weak and small to form effective large woody debris (see Fig. 5). Another potentially important source of streambank cover is large boulders, which are particularly abundant in younger glacial deposits and in the Sheep Crossing Formation (Merrill 1974).

Land Use

Not only is geology intrinsically related to many natural factors that influence trout habitat quality, but also areas of different geology have historically received different kinds and intensities of management due to physical and political constraints. For example, high-elevation spruce-fir forest in the White Mountains has historically been less intensively managed, with timber harvest largely limited to small clearcuts on ridges and relatively little livestock grazing other than summer sheep use in the early 1900s (Gomez and Tiller 1990). By contrast, ponderosa pine forests have been more intensively managed, beginning with railroad logging and widespread sheep and cattle grazing in the early 20th century (Gomez and Tiller 1990). Since that period, the road networks in the lower-elevation areas have grown to accommodate multiple land uses including recreational fishing, while the higher-elevation areas have been protected by wilderness designations and land-use restrictions established to conserve Apache trout (Rinne 1985b, Gomez and Tiller 1990). Furthermore, populations of elk (*Cervis elaphus nelsonii*, introduced in place of the extinct *merriami* subspecies) have burgeoned in the White Mountains in recent decades, and feral horses have been common in the region (Medina and Steed 2002). Less snow cover and warmer temperatures allow those wild ungulates to graze lower-elevation riparian habitats throughout the year (Medina and Steed 2002).

Synthesis

For the reasons given above, there are important differences between areas of different lithology and topography that influence trout habitat. Trying to quantify how these different mechanisms affect trout habitat is challenging due to the confounding of variables (Platts 1976, Isaac and Hubert 2000). However, key attributes such as high base flows, more stable temperatures, greater availability of coarse substrates, and greater abundance of cover in the form of large woody debris and boulders all suggest that Mount Baldy streams should provide better trout habitat than streams on the mafic plateaus.

Only three main mechanisms have been suggested for the opposite relationship to hold. First, lower elevation could increase productivity by lengthening the growing season (Harper 1976). Supporting this argument, Harig and Fausch (2002) concluded that streams at lower elevations produced larger pools and warmer summer temperatures that aided survival of cutthroat trout in the Rocky Mountains. Second, a study showed that downstream reaches of streams in the White Mountains yielded higher phosphorus than high-elevation reaches draining felsic terrain; that nutrient enrichment was linked to higher in-stream plant cover and potential productivity (Rampé 1982). Streams draining glacial deposits or granitic bedrock are often phosphorus-limited (Hicks et al. 1991). Because of that geochemical relationship, Lloyd (1986) suggested using a lower reference for standing crop of trout streams in granitic areas of Montana. Third, because of differences in upland vegetation and geologic substrate, lower-elevations reaches tend to have greater alkalinity, which can be positively correlated with fish production (Rinne 1988). Therefore, these water quality variables might diminish the postulated positive associations of Mount Baldy streams with trout production.

Overall, a review of trout-habitat relationships in the White Mountains suggests that intermediate-scale landscape variation could account for significant variation in trout habitat quality. Many studies have demonstrated that in addition to such landscape variation, smaller-scale patch characteristics are also important for predicting species abundance (Mazerolle and Villard 1999). Gaining and losing reaches represent an example of a patch-scale dynamic that adds another layer of complexity to understanding trout-habitat relationships.

Overcoming Barriers to Understanding Geologic Influences

We noted several examples of misinterpretations of geologic variation in biological studies of White Mountain streams. Harper (1976) described his study stream, Big Bonito Creek, as flowing through basaltic soils, despite the fact that its headwaters originate in Mount Baldy Formation rocks (Merrill 1974). Clarkson and Wilson (1995) dismissed geologic heterogeneity in arguing that reaches of three Mount Baldy streams on the Reservation had higher trout biomass than mafic streams on the National Forest due to differences in livestock grazing. More recently, Rinne (2000) noted the significance of alluvial and glacial deposits in Mount Baldy drainages, but the geologic differences do not coincide with the political boundary between the Reservation and the National Forest as neatly as he suggested.

Such errors might be explained by the fact that geologists have not made geologic knowledge consistent and accessible. Gradations between felsic and mafic rocks (Fig. 8) and the use of different naming systems complicate efforts to classify substrates based on lithology. For example, Merrill (1974) described the Mount Baldy rocks as predominantly latite and quartz latite, while Nealey (1989) referred to the same rocks as different varieties of trachyte, echoing the description used by Gilbert (1875) over a century earlier. Based on detailed petrologic analyses, Nealey (1989) demonstrated that several of Merrill's formations lumped dissimilar units and separated similar ones. However, Nealey's work is much more difficult to use because he never produced a detailed map for his dissertation; instead he published only a small-scale map of the region with incomplete labeling of the formations (Nealey and Sheridan 1989). He also noted that many of the formations were overlapping, poorly exposed, and therefore hard to group. Variations within the older mafic formations have not been well-delineated (Berry 1976, Wrucke and Hibpshman 1981), and complex variations within the younger basaltic flows (Condit et al. 1999) are difficult for laypersons to recognize.

Even when geologic variation can be recognized in hand samples and on maps, classifying it for purposes of habitat analysis is not straightforward. Classifications using categorical variables may work in well-differentiated watersheds, but downvalley relationships among geologic units can complicate the results (e.g., Nelson et al. 1992). Because streams integrate flows of water and sediment along their course, a continuous variable, such as percent of watershed area, may be a better way of representing longitudinal integration of landscape types (e.g., Richards et al. 1996). However, more complex models may be needed where transitions between landscape types are less continuous and where the spatial relationships of types within the watershed are important (Wiens 2002). Boundaries between landscape types, or ecotones, warrant special consideration because they can represent distinctive combinations of substrates, channel morphology and hydrology (Long et al. 2003).

Depicting lithotopo types in three dimensions provides a useful way to explore how geologic variation might influence habitat quality. For example, a fine-scale three-dimensional representation of

Figure 8. *Felsic rocks (left) and mafic rocks (right) are often distinguished by the presence or absence of large crystals, the color of the crystals and the matrix rock, and surface texture. Intermediate varieties (center) are particularly difficult to classify based on such attributes. A precise identification requires chemical analysis.*

Mount Baldy (Fig. 9) reveals valley-fill deposits of sands, gravels and boulders that were shed from the felsic slopes of Mount Baldy. The well-watered meadows formed in these deposits have yielded the highest trout biomass values in the White Mountains (Rinne et al. 1981, Clarkson and Wilson 1995), ranking them among the most productive trout habitats in North America (Platts and McHenry 1988). The lithotopo visualization helps to highlight these ecological hotspots and understand how they formed. Other researchers have asserted that using a perspective comparable to a low-altitude flight helps people to visualize landscape variation at a scale that is particularly relevant to fish (Fausch et al. 2002).

Using Geographic Information Systems (GIS) not only helps to construct landscape visualizations, but it can also help examine relationships between natural variation and anthropogenic impacts. Multivariate statistical analyses can process large numbers of landscape variables in an attempt to identify important influences on habitat quality, but the results may be difficult to intuitively understand and may even be spurious (Li and Wu 2004). For example, our three-dimensional GIS representation of the White Mountains (Fig. 9) distinguishes reaches that Clarkson and Wilson (1995) deemed to be "lightly grazed," but it also shows that those reaches flow through distinctive lithotopo types on the slopes of Mount Baldy. This juxtaposition reveals how an

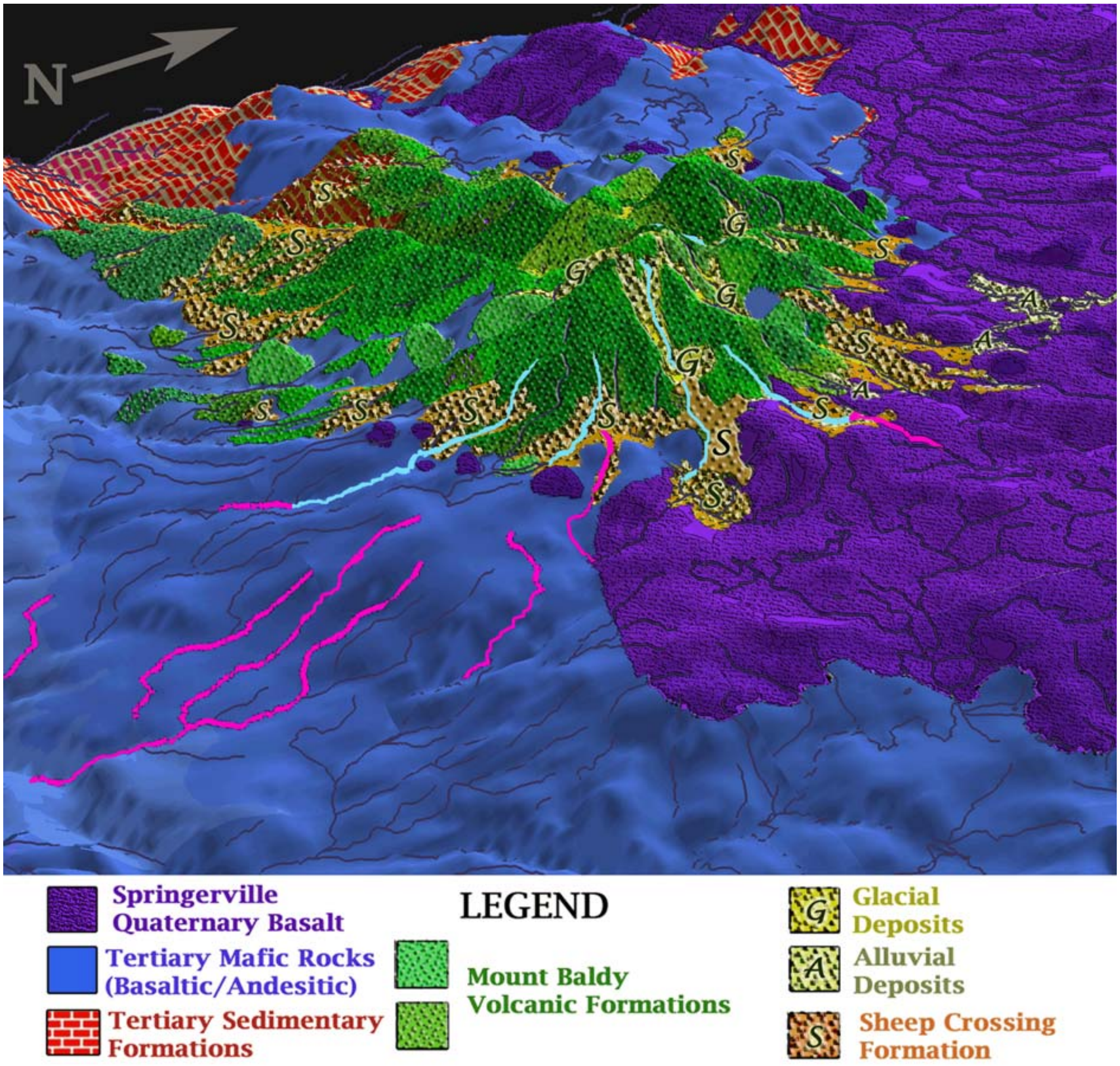

Figure 9. Stream reaches that Clarkson and Wilson (1991) identified as "lightly grazed or ungrazed" (highlighted in light blue) flow from the felsic slopes of Mount Baldy. Other stream reaches in their study (highlighted in dark pink) flow through predominantly mafic areas.

analysis could mistakenly infer that land use was responsible for differences in habitat quality that were actually induced by geologic variation.

Improving Conservation by Accounting for Geologic Influences

Failing to account for geologic variation can mislead conservation efforts not only by improperly implicating land use, but also by diverting attention and resources toward inherently marginal habitats. For three decades, studies have cited a linear estimate of 965 km as the original extent of Apache trout habitat (Harper 1976). That estimate has served as a benchmark for recovery: "when all recovery actions have been implemented, Apache trout will exist in at least 39 stream systems providing approximately 478 kilometers (km) of stream habitat (over ½ the estimated historic distribution of 965 km)" (Ruiz and Novy 2000:157). The source of estimate is not clear, although it was likely similar to the process used by Rinne (1985a), who examined topographic maps to estimate that there were 809 km of streams in the White Mountains above an elevation of 1800 m. While the simplicity of such statistics are appealing, they imply that one kilometer of habitat in the glaciated valleys of Mount Baldy is equivalent to one kilometer of habitat on the basaltic plateaus. Because a linear measurement does not distinguish among a stream's past, existing, or potential production, it creates an incentive to prioritize long stream reaches regardless of their quality. Conservation and restoration efforts commonly focus on the number of kilometers treated. Although the length of a stream reach is an important consideration for recovering a species (Harig and Fausch 2002), the viability of threatened trout populations likely depends more on the absolute numbers of spawning fish (Rieman and Allendorf 2001). By that standard, it would make sense to give greater weight to stream reaches that are capable of producing more trout. Consequently, habitat measures that account for natural variations in production across geologic types could provide a more insightful benchmark of sustainability.

To ensure that conservation and recovery efforts steer resources where they will yield the greatest return, conservation planners need to account for the influence of geologic variation on habitat quality and potential. Lithotopo visualizations are useful for such recognizing variation, but practitioners also need a good foundation in geology to interpret its significance. A recent critique of species recovery plans highlighted the need to train the next generation of conservation biologists to be more effective in translating basic ecological theory into management (Clark et al. 2002). Emphasizing geologic literacy as an essential component of such skill development could lead to more effective conservation efforts in the future.

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