Developing Improved Geologic Maps and Associated Geologic Spatial Databases Using GIS: Candy Mountain and Badger Mountain, WA

by

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To my Father.

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List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
BFZ	Brecciated fault zone
CLEW	Cle-Elum-Wallula deformed zone
DEM	Digital elevation model
DNR	Department of Natural Resources
Esri	Environmental Systems Research Institute
FGDC	Federal Geographic Data Committee
GIS	Geographic information system
JPEG	Joint Photographic Experts Group
Ka	Thousand years ago
Ma	Million years ago
NGMDB	National Geologic Map Database
OWL	Olympic-Wallowa Lineament
PDF	Portable Document Format
PLSS	Public Land Survey System
USC	University of Southern California
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WA DNR	Washington State Department of Natural Resources

Abstract

With the possibility of mass movements such as landslides in the mountains near Richland, WA, understanding the detailed surface and subsurface geology is critical. These mountains, including Candy Mountain, Badger Mountain, and Little Badger Mountain, provide year-round public access to hiking trails offering stunning views of the Columbia River Basin located below. However, these views have also drawn housing developments onto the mountains. The new construction and increase in the water supply can contribute to landslide potential. Unfortunately, existing geologic maps of Candy Mountain, Badger Mountain, and Little Badger Mountain severely lack both quality and detail. This study establishes a greater understanding of the surface and subsurface geology of these mountains by developing updated professional-grade geologic maps, associated spatial database information, geologic cross-sections, and a surface geology 3D scene. Most notably, the identification of previously unmapped faults and folds provides users with a greater awareness of the geologic structures and landforms present in the project area. Improved geologic maps provide essential information necessary for engineers, geologists, and housing developers to explore potential landslide-prone areas and assess other information, such as hydrogeological conditions and surface/subsurface interactions.

Chapter 1 Introduction

Washington State is no stranger to landslides. The Oso landslide in 2014 devastated an area of approximately 320 acres, resulting in the loss of life and destruction of over 40 homes and structures. The landslide occurred in an area with evidence of prior landslide activity. However, the landslide occurred at a magnitude much larger than any previous slide (USGS 2015). More recently, an advancing fault on Rattlesnake Ridge just outside Yakima has raised concern and gathered media attention (Figure 1). The slide has slowly been advancing at a rate of up to 1.5 feet per week (DNR 2019). However, in the event of a sudden mobilization, the landslide could impact nearby homes, an interstate highway, and the Yakima River. These recent events have raised awareness of landslides and associated geologic hazards.

Figure 1. Rattlesnake Ridge Fault (Geo Engineer 2018)

This increased awareness of the dangers associated with landslides has prompted geologic studies of hills and ridges near residential areas. Geologic studies, including detailed geologic maps, cross sections, and associated information, are crucial tools for understanding landslide potential, as well as other geologic hazards, such as earthquakes and floods. It is important to identify where these geologic hazards have more potential to occur in order to make informed decisions on areas to build and areas to avoid or monitor.

This study focuses on the mountains just outside the city of Richland, Washington, a crucial residential and recreational site. These mountains include the popular and publicly-accessible Candy Mountain, Badger Mountain, and Little Badger Mountain (Figure 2). All three of these mountains contain hiking trails, frequented by locals every day, which provide stunning views of the Columbia River Basin located below. While these mountains provide recreation for local residents, they also contain a geologic history of prior landslides.

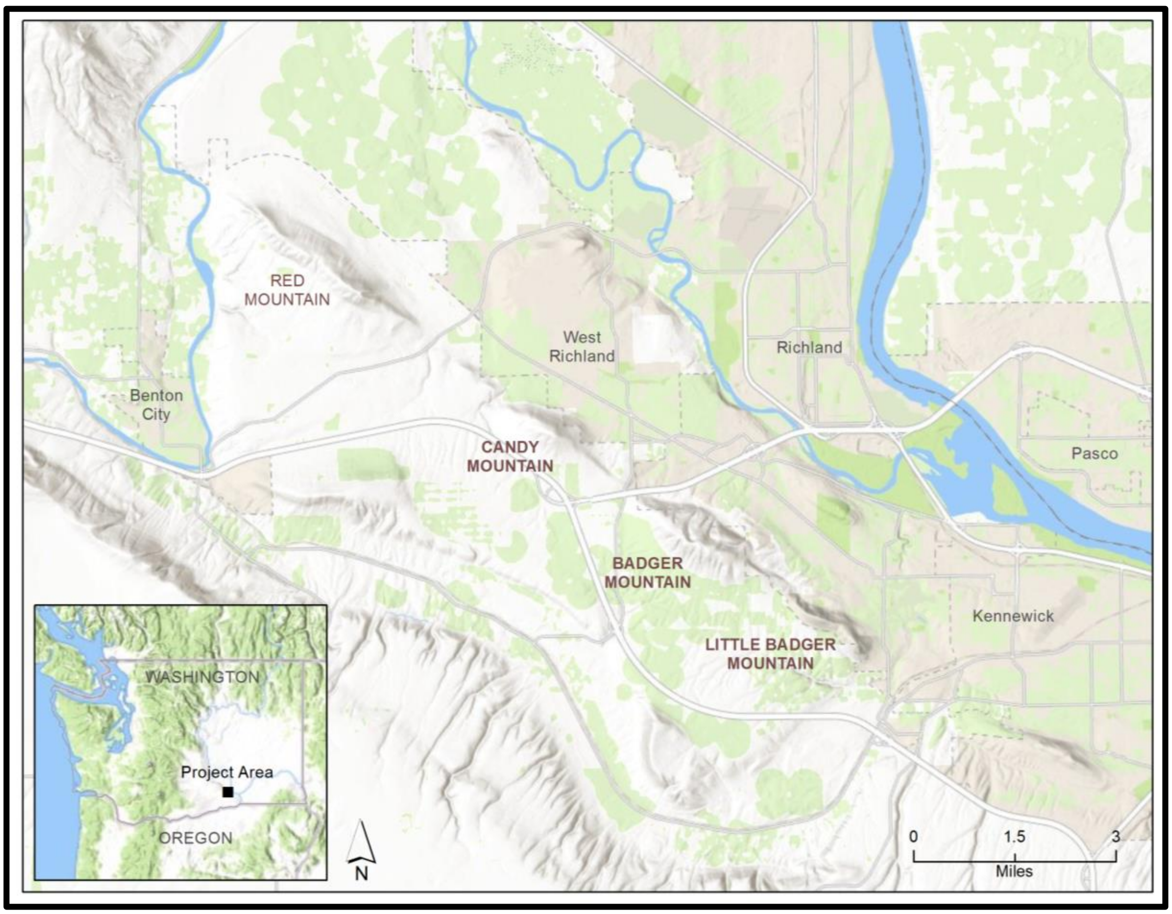

Figure 2. Location Map

Additionally, urban sprawl over the past thirty years has resulted in several new residential developments adjacent to the mountains, and in some instances, housing has been developed on the mountains themselves. The new construction on the mountains involves removing material from the slope, exposing previously unmapped faults. An increase in irrigation and water infiltration can result in increased pore pressure in the fault zones. The increase of pore pressure and water supply can attribute to slope failure. As a result, these new developments increase the potential risk of catastrophic geologic events, such as landslides and mudslides.

With the ever-increasing popularity of the mountains for recreation and residential development, it is important to gain a better understanding of their geology in order to identify potentially hazardous areas. The following sections in this chapter incorporate a discussion on the study's research objectives and motivation. This chapter also provides an overview of the local, regional, and historical geology of the study area.

1.1. Research Objectives

The objectives of this thesis project are to develop modernized geologic maps and associated detailed geologic spatial databases of Candy Mountain, Badger Mountain, and Little Badger Mountain, using newly collected and as yet unmapped data. The final product consists of a geologic map of Candy Mountain, a geologic map of Badger Mountain (including Little Badger), and a larger geologic map including both Candy and Badger Mountains. Structural geology (e.g., faults and folds), locations of glacial erratics and locations of geologic cross section transects will also be displayed on each respective map. Simply put, a glacial erratic is a large rock or boulder carried a far distance by glaciers and deposited as the glacier receded. Typically, they differ from the surrounding rocks. The development of geologic cross sections, displayed on the information panel supporting the map(s), will aid in the understanding of the subsurface geology and underlying geologic structures.

The geologic maps will accompany an associated geologic report currently in development by local expert geologists (Fecht and Chamness, pers. comm). Once completed, applicable local government entities (e.g., Benton County, City of Richland) could post the detailed geologic maps and accompanying report on their website(s), as well as at the Candy Mountain and Badger Mountain trailheads to inform the interested public of the updated information. Due to the fact that existing surficial geologic maps of the area lack detail, the resulting geologic maps and cross sections developed during this project will provide a much greater level of detail and understanding of the local surface and subsurface geology.

In addition to the 2D geologic maps, a simple 3D scene of the surface geology of Candy Mountain and Badger Mountain was developed and published as part of an ArcGIS Online Story Map. This interactive Story Map provides users with the ability to view the mountains surface geology, locations of faults and folds, location of glacial erratics, and locations of cross section lines in a 3D setting. The Story Map also provides users with the ability to view the cross sections of the subsurface geology through the mountain, view the 2D geologic maps, and provides the user with information on the local and regional geology.

1.2. Motivation

The motivation for this project came when two local retired geologists, Karl Fecht and Mickie Chamness, approached the author at her current employer, Freestone Environmental Services, Inc. Fecht and Chamness have worked on mapping the mountains in detail since the 1970s, but have only created hand-drawn paper maps and cross sections. Thus, the development of updated and detailed digital maps of Candy Mountain, Badger Mountain, and Little Badger

Mountain is an exciting and significant project for the geologists. The geologists requested assistance in digitizing the hand-drawn maps, which required GIS expertise and capabilities to create professional-grade geologic maps and cross sections. This exercise represents a thrilling opportunity to work with this detailed data in GIS for the first time and share it with the public.

This work will greatly contribute to the understanding of the local geology, as existing maps of the area lack detail. By gaining a greater understanding of the surface and subsurface geologic features on the mountains, one could infer potential landslide-prone areas, seismic hazards, hydrogeological conditions, and more detailed knowledge of surface and subsurface interactions, to name a few. The development of detailed geologic maps and associated information as part of this research project will provide valuable, quality data which will aid future research in a variety of topical areas.

The updated geologic maps and information provide crucial details required to better identify areas at higher-risk for geologic hazards such as landslides and seismic activity. For instance, these maps identify new, previously unmapped faults. These maps and accompanying information can be utilized in numerous fields of study and professions. For example, geologists, engineers, housing developers, and local professionals can use these maps and information to assist in determining areas to build and areas to avoid. The maps can also be used by hydrogeologists and engineers to identify areas prone to flash-floods. Above all, the completed maps and associated data will benefit policymakers and other stakeholders by providing an accurate, updated representation of the local geology in order to make better-informed decisions and reduce potential risk.

With the scope of this project in mind, although it is specific to a small mountain range in Washington State, the methodology and process utilized can be applied to a variety of geologic mapping projects of varying scopes and scales. This applicability is particularly important, as geologic hazards occur globally and can have devastating effects on communities worldwide. Additionally, due to persistent geological change, the need for accurate and detailed geologic maps remains all the more important.

Moreover, geologic studies allow for a greater understanding of the past and help to forecast potential future occurrences with a direct impact on society (USGS 2006). This concept resonates in the well-known quote, “the present is the key to the past” by Charles Lyell (1830). The information provided on geologic maps can also help to mitigate the damage and deaths associated with catastrophic geologic events, such as earthquakes and floods. Geologic maps also assist in locating valuable resources such as minerals, oil, and water. Furthermore, geologic data provide crucial information for the agricultural, construction, and environmental fields (USGS 2006)

1.3. Background

Candy Mountain, Badger Mountain, and Little Badger Mountain fall within the Columbia Basin region of Washington State (Figure 3). The Columbia Basin lies between the Cascade Range and the Rocky Mountains and consists of the Columbia River Basalt Group (CRBG) volcanic rocks. The CRBG consists of several basalt flows that erupted over an eleven-million-year period, from seventeen million years ago (Ma) to six Ma. These volcanic rocks are overlain by fluvial and glaciofluvial deposits (Martin, Petcovic, and Reidel 2005).

The glaciofluvial deposits are the product of repeated catastrophic flood outbursts from Glacial Lake Missoula. As the glacier which dammed Lake Missoula periodically retreated due to climatic oscillations, floodwaters broke through and formed the Channeled Scablands of the Columbia Basin (Bretz 1969). These mega-floods carved through basalt rock, created giant ripple-marks, and deposited large boulders and gravel bars (Bretz 1959). Thus, the geologic history of the Columbia Basin makes the region undeniably unique in many aspects.

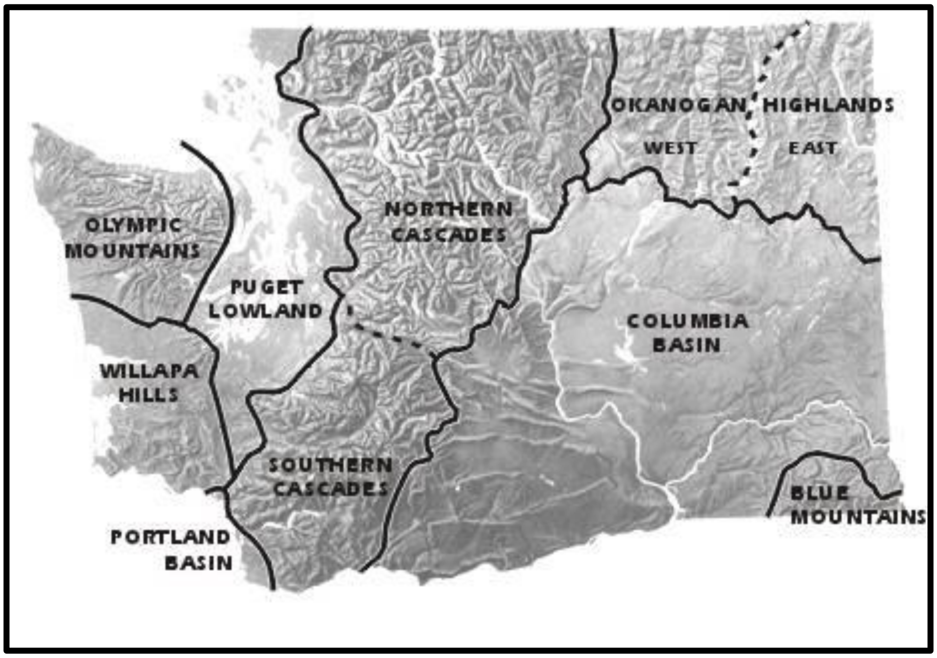

Figure 3. Washington Regions (WA DNR)

Moreover, Candy Mountain, Badger Mountain, and Little Badger Mountain are all part of the Olympic-Wallowa Lineament (OWL), which spans from the Blue Mountains in Northeast Oregon to the Olympic Mountains in Northwest Washington. The OWL is a major topographic feature which crosscuts the Columbia Basin (Martin, Petcovic, and Reidel 2005). Figure 4 shows the extent of the OWL, depicted by the thick black line. The Cle Elum-Wallula deformed zone (CLEW) is the portion of the OWL which crosses central Washington and contains Candy and Badger Mountains.

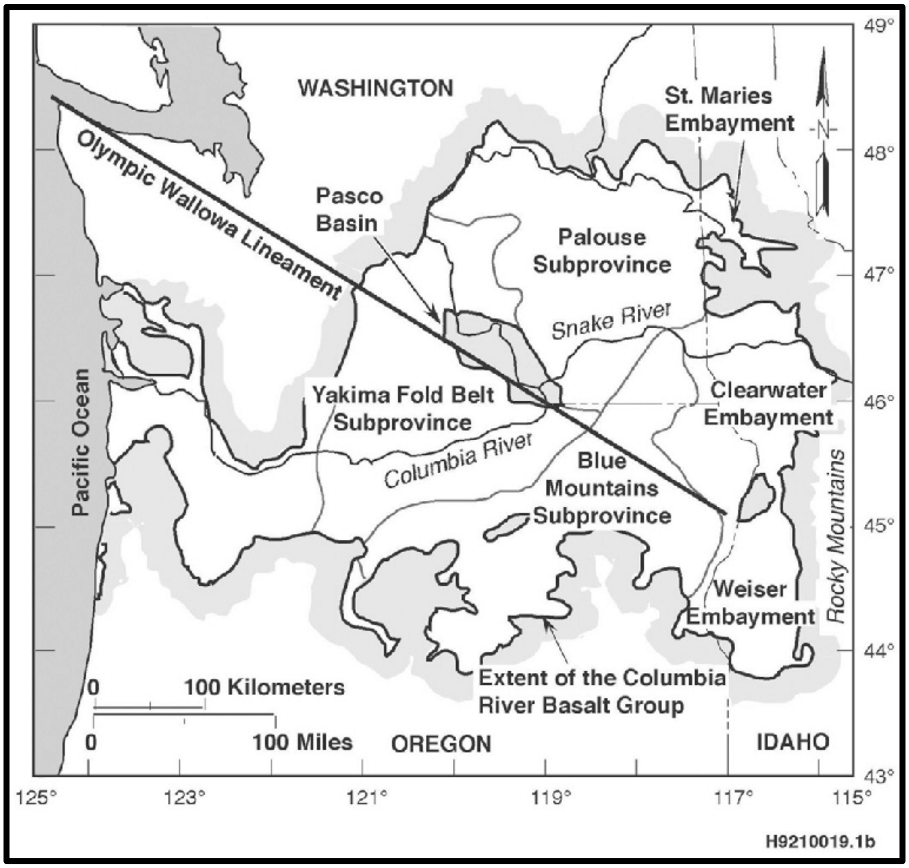

Figure 4. Olympic-Wallowa Lineament Extent (Reidel et al. 2013)

The OWL has previously been mapped as a strike-slip fault. However, the information presented in this study shows evidence of thrust faulting. Specifically, Candy Mountain, Badger Mountain, and Little Badger Mountain all show evidence of thrust faults. These mountains are plunging anticlinal structures (Martin, Petcovic, and Reidel 2005). This structure is apparent in the geologic cross-sections included in this study, which show the underlying geology through the mountains. Understanding the detailed structure of the mountains is crucial for conducting accurate geological studies.

The following chapters of this report cover the related work, data and methodology, results, and discussion and conclusions. The related work chapter includes discussions for related geologic mapping efforts, related spatial data manipulation, geodatabase creation standards, and related ArcGIS Online Story Map and geologic 3D model development. The data and methodology chapter covers the georeferencing and digitizing of the geologic map data, geodatabase development, field verification work, data manipulation, surface geology 3D scene development, and Story Map development. The results chapter contains the geologic map, the ArcGIS Online Story Map, and the geodatabase results. Lastly, the discussion and conclusions chapter includes discussions on the applicability and limitations of this project, as well as potential opportunities for related future research projects.

Chapter 2 Related Work

This chapter examines related geologic mapping efforts and existing maps of the study area. It also contains an investigation of related work in the fields of georeferencing and digitizing historic and hand-drawn maps, and the benefits of visualizing a geological scene in 3D, as opposed to 2D representations. Additionally, the chapter incorporates a discussion of spatial database, herein referred to as geodatabase, standards for geologic data.

2.1. Related Geologic Mapping

Expert geologists in the area have conducted geologic mapping efforts of the region surrounding Candy Mountain and Badger Mountain on several occasions. Reidel and Fecht (1993) created the first geologic map of the Richland quadrangle, which includes the study area, at a scale of 1:100,000 or smaller. This geologic map incorporated both bedrock and surficial geology on a map of the region. However, these maps are quite difficult to view and interpret due to many factors such as the hand-drawn, black-and-white depiction of the maps (Figure 5). In addition, the maps contain multiple, crowded areas of overlapping topographic contour lines, geologic units, and their corresponding labels. Geologic units are specific, distinguishable rock types such as basalt, granite, or sandstone.

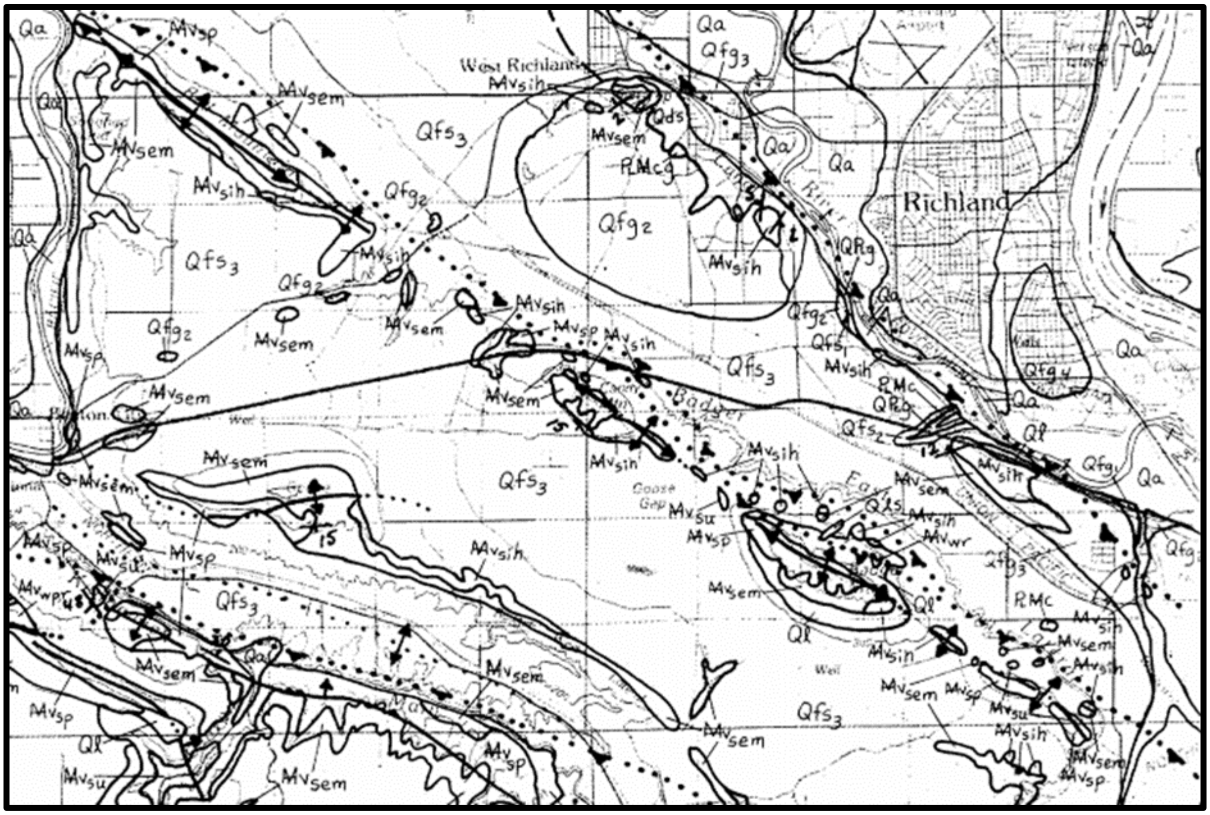

Figure 5. Portion of the Richland 1:100,000 Quadrangle Geologic Map (Reidel and Fecht 1993)

Moreover, Reidel and Fecht (1993) mention that geologic maps of the area created prior to 1979 lack detail. Specifically, these maps did not contain any valuable Columbia River Basalt Group information and were primarily used for identifying younger geologic units. An example of these maps includes the United States Geological Survey 1:24,000-scale maps of the Badger Mountain and Richland area created in 1978. These early maps, utilized by Reidel and Fecht, remain slightly more detailed than the 1:100,000-scale maps; however, the resulting overall map quality suffers considerably in legibility (Figure 6). The unclear and crowded areas of geologic units, contour lines, and labels make the maps hard to interpret. Also, the lack of color symbology contributes to the difficulty in interpreting the maps.

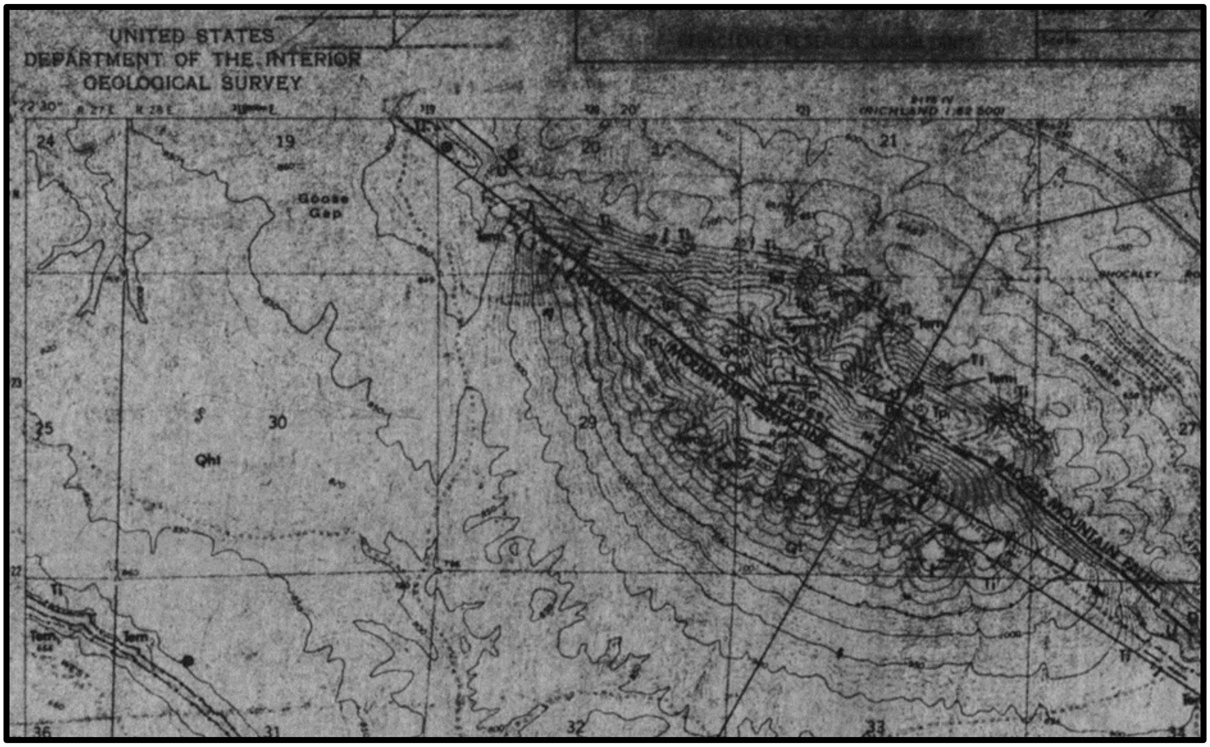

Figure 6. Portion of the Badger Mountain 1:24,000 Quadrangle Geologic Map (USGS 1978)

Additionally, Reidel and Fecht's 1:100,000-scale geologic map was used as a resource in the development of the 1:250,000-scale Southeastern Washington quadrant geologic map created in 1997 and subsequently the 1:500,000-scale Washington State Geologic Map developed in 2005 (Schuster et al.). While these maps prove beneficial due to currency, ease of interpretation, color symbology, and utilization of GIS, the extremely small scale of the maps results in a lack of detail provided for the Candy and Badger Mountain area.

In summary, all previous mapping efforts relative to the Candy Mountain, Badger Mountain, and Little Badger Mountain regions remain inadequate in terms of present-day standards of map quality and detail. The prior mapping efforts also lack a specific emphasis on the area immediately surrounding the mountains and the underlying geologic details, such as minor faults and folds.

2.2. Related Spatial Data Manipulation

The process of georeferencing and digitizing a hand-drawn or historical geologic map is a tedious one. In his article on georeferencing, digitizing, and analyzing historical maps, Pearson demonstrates the fundamental benefits of converting historical maps into a digital format (2006). Although Pearson's study mainly concerned historical maps pertaining to the development and improvements of the agricultural landscape in England and Wales, the underlying methodology used can still apply to this study. For example, when georeferencing, it is important to keep the map coordinate system in mind and to ensure the basemap (or target data) contains distinct boundaries or recognizable features. As a result, the connection between the georeferenced raster dataset and the target data will yield a stronger registration (Pearson 2006).

Pearson does not elaborate in great detail regarding the specific methodology used for digitizing. Rather, Pearson simply stated that he approached his digitizing effort by tracing the georeferenced maps with line data and subsequently converted the line data into polygons using topological rules (2006). He does, however, mention the topological rules include no overlapping polygons, dangling lines, or pseudo lines. This study incorporated several of these topological rules during the digitization process as well. While Pearson digitized distinct agricultural administrative boundaries, the digitization of geologic features which are inherently 3D in nature can present additional challenges.

For example, it is often difficult to interpret or comprehend the true nature of a geographic feature when referencing a 2D map. This is partly due to the fact that geological structures are innately 3D in nature (Jones et al. 2007). Thus, the ability to view a topographic feature in a 3D scene greatly improves one's overall understanding of that feature. As Jones et al. states, the digitalization of geologic mapping has facilitated major improvements in the limited dimensionality of traditional 2D methods (2007). Jones et al.'s study focused on visualizing multi-scale geological models, including 2D maps and cross sections into a 3D model (2007). Although this study does not include a complex 3D model displaying the mountains' subsurface geology, the benefits of developing such a model remain apparent. This exclusion also provides the opportunity for future work by visualizing the data presented in this report in a complex 3D geologic environment.

Nonetheless, this study does incorporate a simple 3D scene of the mountains surface geology in order for the viewers to acquire a greater understanding of the area and overall topography. The 3D scene displays the surficial geology and terrain, represented as a digital elevation model (DEM) with shaded relief. This simple, surface geology 3D scene is often considered the first step in presenting geological data in the third dimension (Malolepszy 2005). The 2D cross sections developed as part of this study also provide a 3D aspect and a better understanding of the subsurface geology.

2.3. Geodatabase Creation Standards

The spatial databases, or geodatabases, developed during this study comply with the United States Geological Survey (USGS) National Geologic Map Database (NGMDB) mapping standards and guidelines. These standards and guidelines exist in order to maintain consistency among digital earth-science information created and managed by multiple organizations. Although the standards are still under development, they remain useful as a guideline when developing geologic spatial databases. The NGMDB also contributes to advancements in database design and digital mapping techniques (Soller and Berg 2005). The National Geologic Mapping Act of 1992 and the Federal Geographic Data Committee (FGDC) promote these widely-accepted standards and guidelines (USGS 2019).

Establishing and utilizing these standards results in improved map clarity and reduces discrepancies between maps developed by different agencies. This consistency is important since discrepancies between geologic maps require additional effort and time to research and solve (Asch 2005). Examples of these discrepancies include geological unit classification, mapped units, topographic base, scale, level of detail, color, symbols, and data structure. In her paper on the importance of consistency and standardization of geologic maps, Asch (2005) mentions how these inconsistencies can lead to misunderstandings between geologists and may contribute to future risk when applied to geohazard or mineral maps. Additionally, computers, including GIS and database systems, do not have the ability to easily resolve these discrepancies (Asch 2005). Therefore, consistency and standards remain crucial for producing quality work and safety reasons.

Similarly, the NGMDB Geologic Map Feature Class Model was developed to assist in streamlining the process for creating digital geologic map databases and producing final cartographic outputs (Priest 2010). This model is also available as the Esri geology data model, developed by Richard et al. (2005). It provides information for geologic entities of interest, such as geologic units, faults, and folds. The model also provides information on the feature class descriptions, attributes, and symbology for various geologic data (Richard et al. 2005). Though the Esri geology data model currently exists as a prototype design, the information provided will assist in the development of the geologic datasets and cartographic outputs for this study.

Furthermore, NGMDB mapping standards are implemented by agencies in the United States and internationally. For example, Soller and Garrity (2010) apply these standards during the process and design of a surficial materials map and database. Specifically, Soller and Garrity (2010) address the geodatabase design by listing the map unit attributes and metadata.

Additionally, they created and applied geodatabase topology and generated topological error logs. Soller and Garrity (2010) mention that common topological problems included overlapping polygons, gaps between polygons, overlying line features, and self-overlapping line features. They concluded that execution of topology rules in ArcMap removed these errors. This geologic mapping study also applied topology rules in order to attain a clean and error-free surface geology layer.

Spatial data quality is a central concept present in all of the previously mentioned standards and guidelines. Ensuring that the datasets developed have a degree of consistency, completeness, and accuracy is crucial before publishing for use publicly or privately. In his article titled "Spatial Data Quality: An Introduction," Ravi Srivastava (2008) states that spatial data quality is the degree in which the data satisfies a given objective. The geologic mapping objectives for this thesis project are certainly met by following the USGS NGMDB standards and guidelines ensuring spatial data quality.

Moreover, Srivastava (2008) discusses how spatial data quality can be grouped into four categories. These categories include data consistency, data completeness, data accuracy, and data precision (Srivastava 2008). Of course, all of these categories can be satisfied at varying levels due to the individual mapping project objectives. For example, this geologic mapping project focused more on data consistency, data completeness, and data accuracy, and less on data precision, as it was not necessary at the utilized map scale.

In this geologic mapping project, certain geologic unit polygon contacts have been smoothed out or exaggerated for clarity. Some of the smaller geologic units depicted on the maps have a slight exaggeration, however this minor level of exaggeration is common practice among geologic mapping professionals. Typically, the smaller the map scale, the more generalization and smoothing out boundaries of geologic unit contacts occurs. This exaggeration occurs in order to increase the legibility of these features at smaller scales.

In the USGS article on geologic mapping, Soller (2004) describes geologic mapping as a highly interpretive and scientific process that can result in a variety of map products for several different uses, including evaluating landslide hazards and land-use planning. Geologic mapping is an interpretive process as it typically involves field work where geologists record their observations in field notebooks. However, the use of GPS devices and GIS software have greatly improved the overall accuracy of geologic maps. GPS devices are used in the field to record locations of the geologic unit contacts and other map features. These locations are then imported into GIS where more accurate geologic maps can be developed.

Soller (2004) also states that advancements in GIS technology have transformed the way that geologic data can be stored. The geometry and attributes of geologic units and other geologic features can now be electronically stored, displayed, queried, and analyzed. An example Soller (2004) describes is how GIS can be used to identify areas with unstable slopes in determining areas for a potential roadcut. The main goal in geologic mapping projects nowadays is not the geologic map itself, but the geologic database associated with it (Soller 2004). The geologic database can be shared and used by engineers and geologists to create many different types of maps. The database can also be easily managed and updated as new information becomes available. This improved methodology provides much greater value than the 2D maps alone.

2.4. Related Story Map Development & 3D Modeling

The rise of web-based mapping applications has made presenting and sharing maps and associated information much easier. In his article titled "Understanding Our Changing World through Web-Mapping Based Investigations," Joseph Kerski discusses the benefits of the multimedia-rich tools included in today's web-maps (2013). Unlike former static maps, web maps are dynamic, customizable, and shareable. Due to the increase in new capabilities, educators and students are attracted to applying web maps in their curriculum and research (Kerski 2013).

Story Maps have become a powerful media for telling stories (Kerski 2013). The Story Map developed as part of this thesis project showcases the geologic mapping effort results, including the 2D geologic maps, 3D geologic scene, geologic cross sections, and informative text. Compiling this information through a Story Map helps to better display the material and invites users to explore the pages. Additionally, the format can easily be shared among interested users.

Another powerful visualization used for clearly communicating geologic investigations includes 3D mapping and complex models displaying the subsurface geology. These models are typically used by geologists and engineers to better understand the subsurface geologic units and structures and identify areas with natural resource deposits. Subsurface geologic 3D models are especially useful for mining investigations, oil & gas exploration, and groundwater studies.

3D maps and subsurface geologic models provide users with a perspective not available through traditional 2D mapping approaches. The British Geological Survey (BGS 2011) use a 3D geologic model to illustrate the how the underlying geology can be displayed and analyzed in various ways. Geologic 3D models can be utilized in studies related to identifying floodplains, geothermal resources, and mining deposits. It is apparent that 3D geologic models are the future of geology as they illustrate information and issues much clearer than a 2D map can.

In addition, fence and block diagrams can be created using the Xacto cross section tool and ArcScene. DeMerritt (2012) describes this process of visualizing the subsurface terrain in a dynamic 3D environment. Perhaps the most important data source in viewing the subsurface geology are wells and boreholes. A borehole is similar to a well, as it is a vertical hole in the ground, however boreholes do not have casing, screens, or any construction applied. The 3D borehole tools in ArcScene can interpolate surfaces between the well and borehole data, creating a conceptual model of the subsurface geologic units (DeMerritt 2012).

This geologic mapping project has a lack of wells in the immediate project area due to the fact that the mountains are also nature preserves. However, the lack of extensive subsurface geology information provides the opportunity for future research. For example, seismic instruments could be used to gather geophysical information on the subsurface geologic units, providing a better understanding of their extent and thicknesses.

Chapter 3 Data and Methodology

This chapter discusses the data and methodology utilized in the development of professional-grade digital geologic maps and spatial geologic databases of Candy Mountain and Badger Mountain. Specifically, it details the spatial data digitization and manipulation and geodatabase development. This chapter also describes the field verification work performed to assess a certain level of accuracy in the previously hand-drawn map data. Finally, it discusses the development of a simple surface geology 3D scene and the compilation of the geologic maps and information into an ArcGIS Online Story Map.

In order to achieve the objective, this project aimed to develop professional-grade geologic maps, cross-sections, geodatabase, and a surface geology 3D scene of Candy Mountain and Badger Mountain. An ArcGIS Online Story Map containing all of the geologic maps, cross-sections, and information was then developed. The diagram below depicts the high-level workflow process for this study (Figure 7).

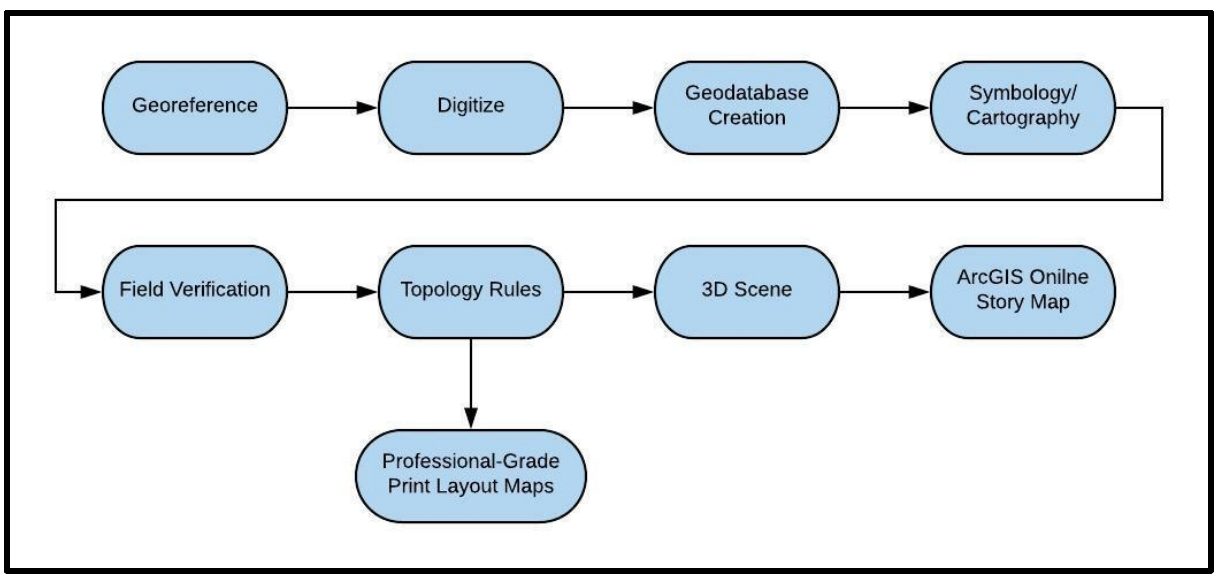

Figure 7. Project Workflow Diagram

The updated geologic maps and information provide crucial details required to better identify areas at higher-risk for geologic hazards, such as landslides and seismic activity. These maps and accompanying information will be available to be utilized by geologists, engineers, housing developers, and local professionals in order to determine areas to build new residential or commercial developments, as well as areas to avoid. In order to develop the geologic maps and geodatabase, local expert geologists Karl Fecht and Mickie Chamness provided hand-drawn geologic maps and cross sections, as well as geologic descriptions (Fecht and Chamness, pers. comm).

3.1. Georeferencing and Digitizing Data

The primary data required to complete this mapping effort includes hand-drawn geologic maps, on 11”x17” paper, of Candy Mountain and Badger Mountain (including adjacent Little Badger Mountain). The paper maps were scanned into digital copies and converted to JPGs, also known as raster data. The scanned maps were then georeferenced in ArcMap version 10.7 using key landmarks identified on both the raster maps and in GIS. Georeferencing is a necessary first step in the digitizing process, as it aligns and transforms the raster data to the map coordinate system. In order to georeference the raster map image in GIS, control points were identified on both the raster maps and the topographic basemap in ArcMap. Fortunately, the scanned geologic maps were drawn on top of the topographic basemap used in ArcMap. This consistency ensured that there were several common areas on the raster map and the GIS basemap to assign control points to.

Control points were identified at distinct locations such as road intersections, corners, and landmarks. Figure 8 shows the locations of control points used to georeference the Candy Mountain geologic map. Control points must be assigned to the raster map (the *from* point) and the basemap or target data (the *to* point). The connection between the *from* points and *to* points are called links. The number of links utilized is not as important as distributing the links throughout the map. Typically, identifying at least one link near each corner of the raster map generates ideal results (Pearson, 2006). Due to the complete overlap between the raster data and target data, the alignment results were deemed quite accurate, with first-order polynomial transformations applied to both the Badger and Candy Mountain maps. A total root mean square (RMS) error of 9.5 existed in the Candy Mountain georeferenced map, and a total RMS error of 31 existed in the Badger Mountain georeferenced map.

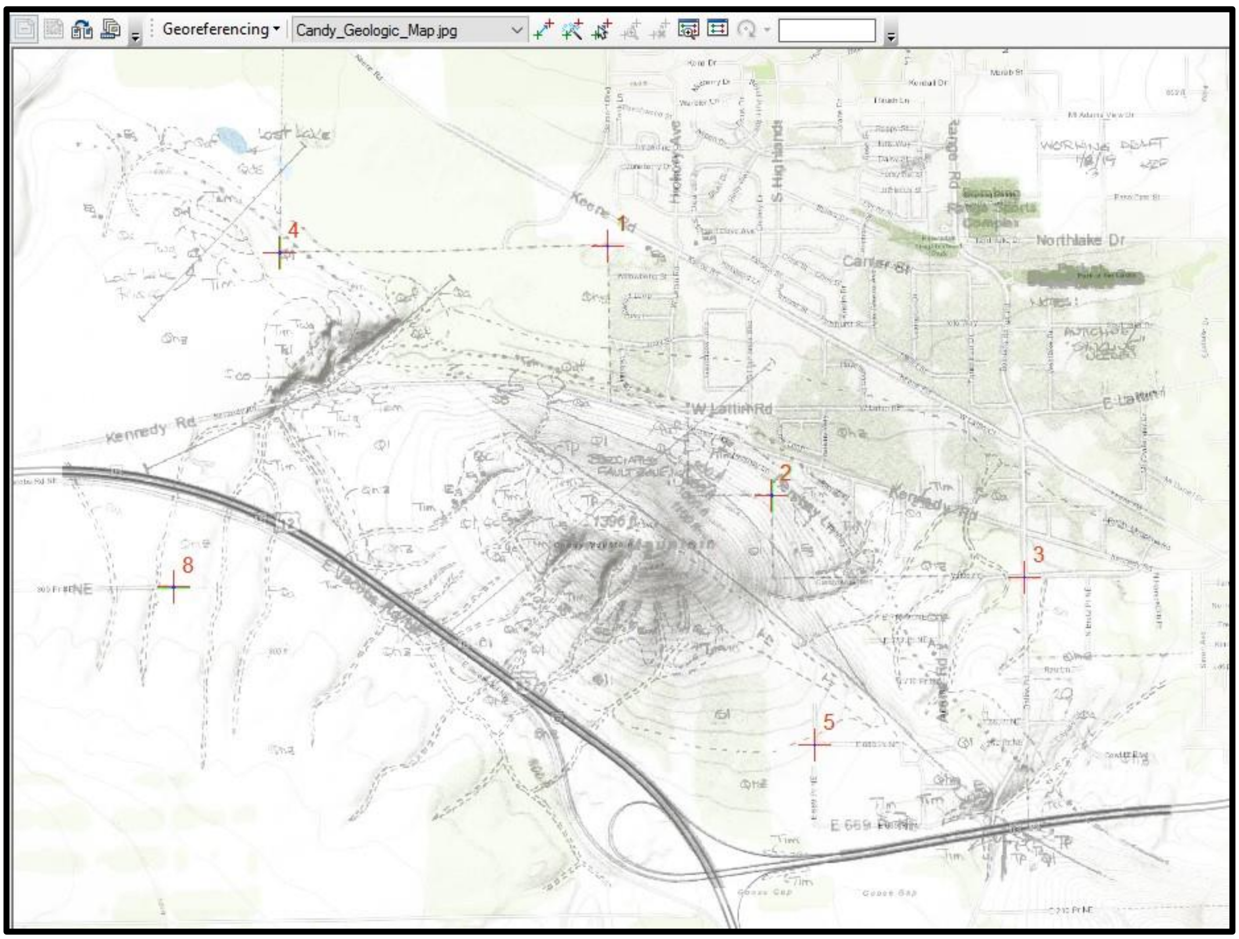

Figure 8. Georeferencing the Candy Mountain Geologic Map

Once georeferenced, the digitization of the geologic unit polygons, fault and fold lines, and glacial erratic and other point data could begin. The digitizing approach for each layer remained the same, only with slight variations between the polygon, line, and point datasets. The geologic unit polygons were digitized using the create features construction tools by carefully tracing the geologic units on the georeferenced raster map. Figure 9 shows the beginning stages of the digitization of geologic units on the Candy Mountain geologic map. Due to the nature of the geologic unit polygons, specifically, how some polygons fall within other polygons, tools such as auto-complete polygon and cut were utilized.

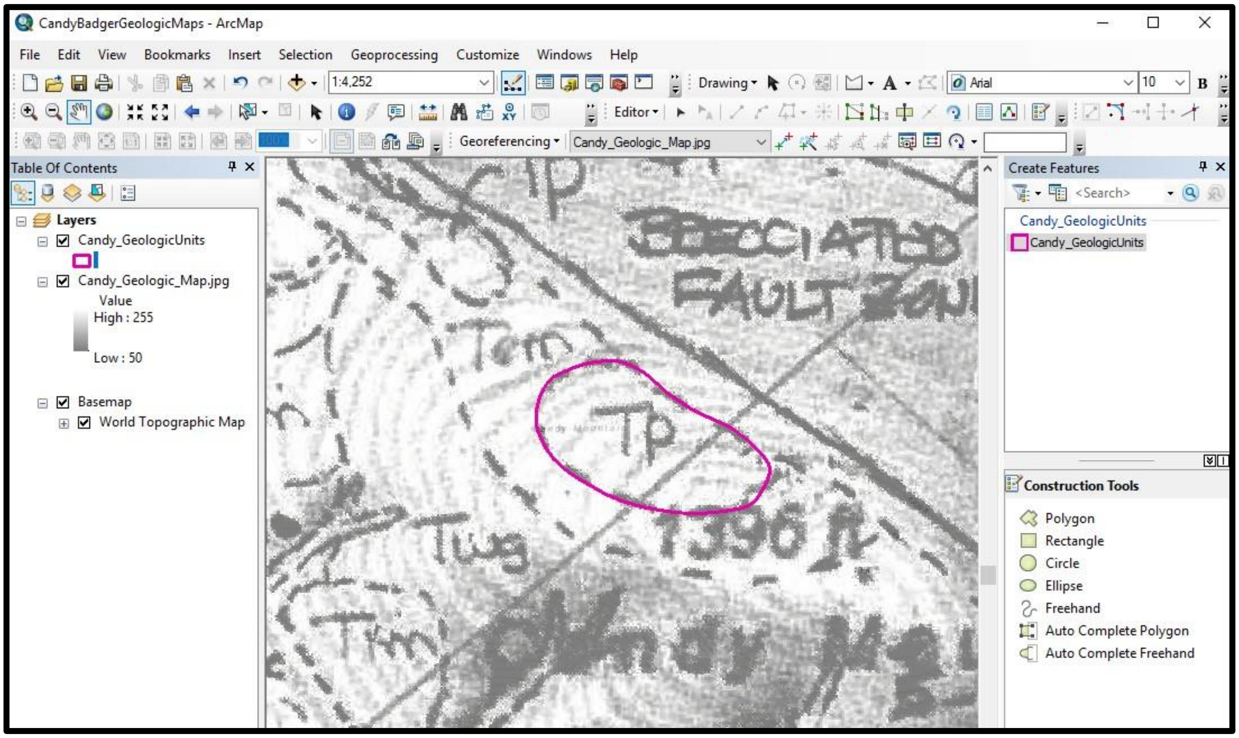

Figure 9. Digitizing the Candy Mountain Geologic Map

Some larger polygon features were created in segments. These segments were then selected for each cohesive geologic unit and exported to a separate feature class. The dissolve tool was then used to turn the feature into one polygon. Next, the selected segments were deleted from the main polygon feature class. Lastly, the append tool was used to combine all the dissolved units and the remaining geologic units.

The geologic unit polygons were also modified using the ‘cut’ and ‘edit vertices’ tools. The cut tool was used to cut segments out of polygons, including segments within existing polygons. The ‘edit vertices’ tool was used to reshape adjacent polygons. The gullies of Quaternary alluvium (Qa) were reshaped using the ‘edit vertices’ tool and by comparing the gullies against aerial imagery and topography in GIS.

The fault and fold line features were digitized using the ‘create features’ construction tools by tracing the fault and fold lines on the georeferenced raster map. Similarly, the glacial erratic and other point features were digitized using the ‘create features’ construction tools by placing a marker at each point on the georeferenced raster map. The fault/fold line and point feature datasets were easier to digitize than the geologic unit polygons because of their smaller size and lack of complexity.

The geologic unit polygons were digitized from the georeferenced hand-drawn map first, followed by the line features, and then the point features. Figure 10 shows the step-by-step sequence of layer construction and then a compilation of all three layers for the northwest area on the Badger Mountain map. The layers displayed do not have any standardized geologic symbology applied, as they were initially created using a simple and generic symbology. For example, the geologic unit polygons were digitized using a bright pink line with no fill color in order to better see the labels and lines on the underlying georeferenced hand-drawn map.

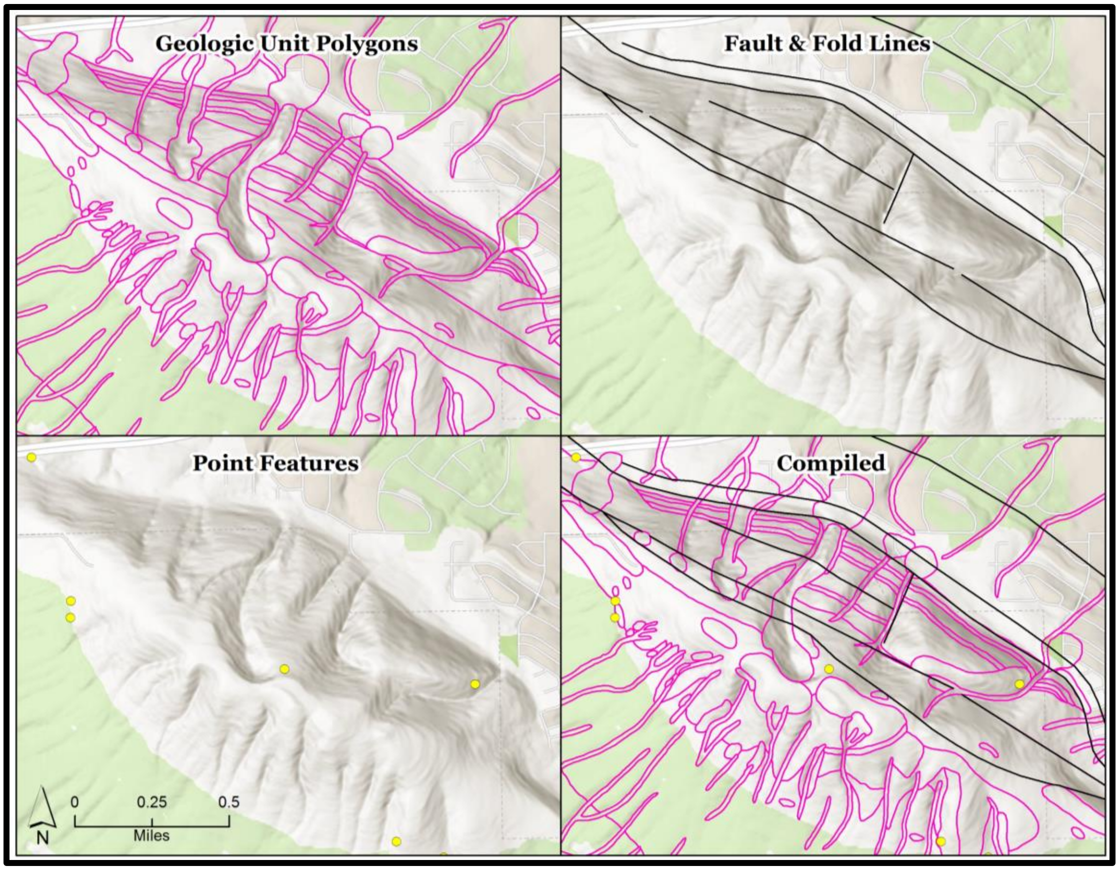

Figure 10. Digitizing Sequence and Compilation

Several rounds of map edits were made after the initial geologic polygon, line, and point feature digitization. These edits included modifying the geologic unit polygons shape, size, and/or placement, modifying the fault and fold line placement, and adding in point features not present on the hand-drawn geologic maps. Meetings were frequently held with Fecht and Chamness to review each draft of the maps and discuss edits (Fecht and Chamness, pers. comm).

Lastly, after the final round of map edits, the geologic unit contacts were created by exporting the finalized geologic unit polygon feature class to a new layer and then converting that layer from polygons to a line feature class. The geologic formation contacts layer was then edited to show dashed or dotted lines where contacts are approximate or inferred. The default outline symbology on the geologic unit polygon layer was then removed as well. Furthermore, the NAD 1983 HARN State Plane Washington South (US Feet) coordinate system was used for all of the digitized feature classes.

Additionally, the existing hand-drawn geologic cross sections were digitized and modified to appear more professional-grade, meaning adhering to published government and industry (i.e. private consulting) mapping formats and standards rather than a purely academic approach. The digitizing and professional-grade modifications included tracing lines and adding color to the geologic units. These cross sections display valuable information on the sub-surface geology and structures underlying the mountains. Due to the fact that the cross sections are represented as vertical planes in 2D, they were digitized in Adobe Illustrator version 15.3 instead of ArcGIS. A complex subsurface geology 3D model developed from these cross sections and nearby geologic well logs was considered beyond the scope of this project and not necessary to meet the primary objectives of this thesis project. A significant amount of time and effort would be required to create such a model. The lack of such a complex subsurface geology 3D model provides an opportunity for future work, and is discussed in detail in the future work section of this thesis.

Similar to the geologic maps, the geologic cross sections were scanned, traced, and modified using the various drawing tools in Adobe Illustrator. The cross sections were hand-drawn by Karl Fecht, then digitized in Adobe Illustrator by Steve Reidel and modified further by Frances Krutsky. Fecht initially developed the geologic cross sections using the currently available subsurface data. However, with the lack of wells and other subsurface data directly in the mapped area, the geologic cross sections were interpreted based on knowledge of the regional geology (Fecht, pers. comm.). The x and y-axis of the cross sections display horizontal distance and vertical height, respectively. The vertical height is displayed in both feet and meters, while the horizontal distance is displayed in both kilometers and miles. In addition, the cross sections contain notes on vertical exaggeration.

Figure 11 displays an example of one of the eight geologic cross sections developed as part of this geologic mapping project. All eight of the geologic cross sections are included in Appendix B. The example cross section of Little Badger Mountain below shows the subsurface geology underlying the H – H’ cross section line depicted on the Badger Mountain geologic map. This example cross section depicts several geologic units and faults, including the brecciated fault zone (BFZ) present in several of the cross sections and on the maps. The faults are represented as dashed until approximately halfway down where they change to dotted. This change represents the transition from inferred to concealed/unknown.

In the final map layouts, the geologic cross sections are included as a component either directly below the geologic map or on the supporting information panel. Draft geologic cross sections were developed by Steve Reidel in Adobe Illustrator (Reidel, pers. comm.). These Adobe Illustrator files, along with scanned drawings of the cross sections with editorial notes were obtained and sent to Frances Krutsky, a professional graphic designer (Krustky, pers. comm). Krutsky made several rounds of aesthetic edits to all of the cross sections in this thesis, but made no changes of contributions to the geologic and spatial science inherent within the drawings. This editorial contribution to these map layout components was requested in an effort to expedite the associated workload and obtain the most professional final products possible.

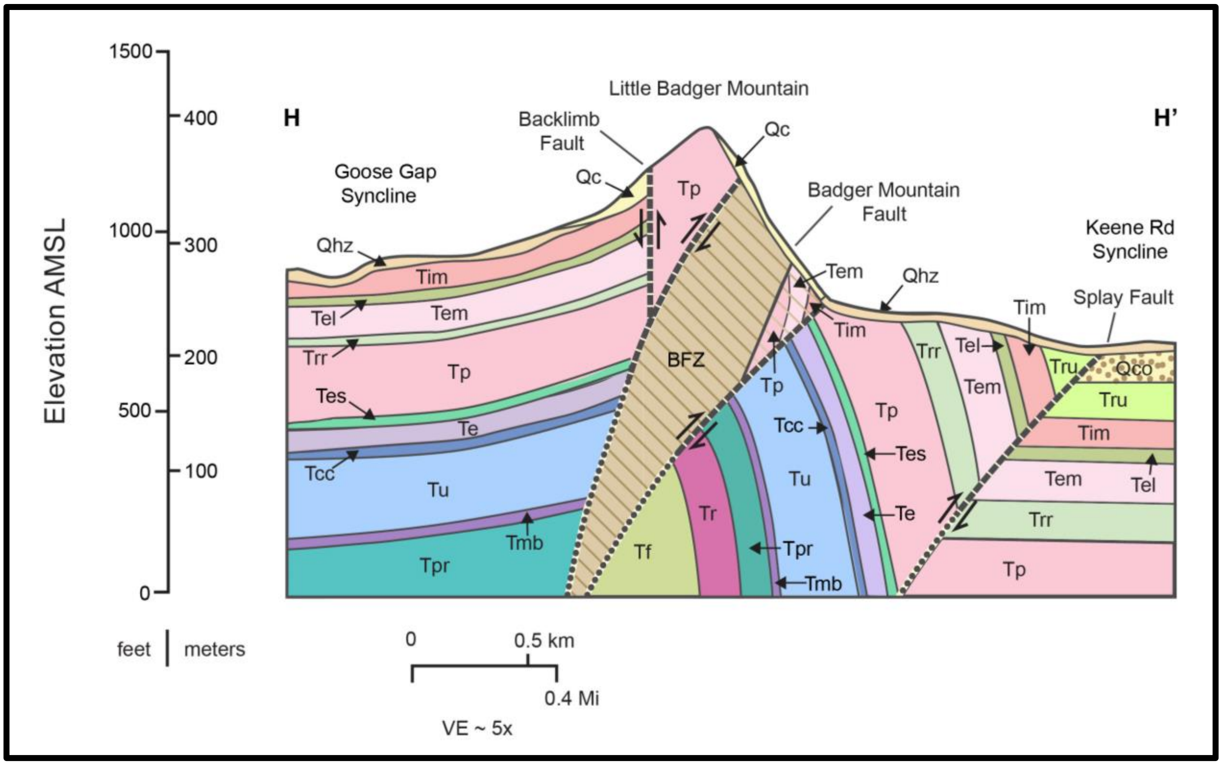

Figure 11. Little Badger Geologic Cross Section

The colors of the geologic units in the cross sections match the colors of the geologic units in the geologic maps. However, the cross sections contain some geologic units which are not present on the geologic maps, as they do not outcrop anywhere along the surface. These units were interpreted by Fecht, Reidel, and Chamness based on knowledge of the regional geology and nearby well log information, including unit thicknesses (Fecht and Chamness, pers. comm.). It is also important to note that the colors in the digital cross sections can appear slightly different from the maps until added to a map layout in GIS, exported as a PDF, and printed. This color deviation has to do with computer screen resolution and printer calibration.

3.2. Geodatabase Development

Development of the geodatabase containing associated geologic information followed the digitization of the Candy and Badger Mountain geologic maps. This geologic information is important in order to give context to the point, line, and polygon datasets. The various geologic information enables users with the ability to classify, identify, and perform queries. The different geologic datasets were compiled into a geodatabase in order to keep them all in one place and save defined symbology layers.

Each geologic layer provides various attribute information. Figure 12 displays the geologic unit, fault, and fold, and map point attribute information. The geologic unit feature class contains the attributes geologic unit label, name, geologic unit description, lithology, and geologic age. The faults and folds feature class contains the attributes name and description. The map points feature class contains the attributes label, name, and description. These attributes provide important information on the geologic features, whereby enabling users to perform various queries on the data and better understand the individual features.

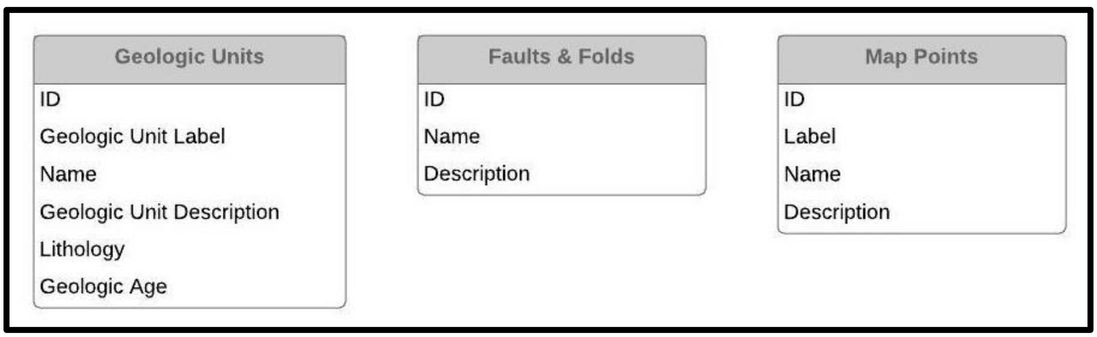

Figure 12. Geologic Feature Attributes

In addition to the map point feature attribute information included above, the strike and dip point data contain fields for dip direction value and estimated strike value. Strike and dip values represent the orientation of geologic unit bedding planes. Strike is depicted as the compass direction of a horizontal line on a planar surface of a bedding plane. Dip is the angle at which the bedding plane tilts down from the horizontal (Dawes 2011). These values were included in the attribute information so the strike and dip symbols could be labeled with the dip value and rotated based on the strike value. Metadata for the feature classes includes notes on when the dataset was created, who created it, and the associated report(s) it is described in.

Upon creation of the geodatabase and inclusion of the attribute information, the symbology was modified to reflect the appropriate colors and styles of the various geologic units and features. The symbology of geologic units, faults, folds, and point features comply with the USGS NGMDB mapping standards as well as the Washington State geologic map standards and guidelines (USGS 2019). However, certain geologic units present in the mapped area do not have a standard symbology. For example, the brecciated fault zone and several sub-units of basalt flows in the area do not have a standardized geologic unit symbology. In fact, most maps do not contain so many sub-flows of basalt units. For these units, the geologic maps included as part of a well-known report titled "Geologic Studies of the Columbia Plateau: A Status Report: RHO-BWI-ST-4" (Meyers et al. 1979) were referenced.

The geologic unit polygon symbology was modified to represent the various geologic units present on the map. The geologic units are generally represented by different colors. For example, soils tend to be represented by shades of yellow, tan, and brown, while volcanic rocks are represented by shades of purple and pink. Patterns are included in some geologic unit representations as well, such as diagonal lines in the brecciated fault zone, and speckling in certain sand units.

Similarly, several different symbology representations exist for various faults, including thrust faults, tear faults, and extensional faults. Various types of folds, such as anticlines and synclines, are also represented with different symbology. A solid line represents certainty in the fault or fold location, a dashed line represents uncertainty in the fault or fold location, and a dotted line represents a concealed fault of fold location. Line symbols also help to distinguish between the different types of faults or folds, the direction of the thrust, and the uncertainty of the fault or fold extent. For example, a query or question mark symbol is placed at the end of a fault line where its extent is unknown.

Map feature points include strike and dip measurements and locations of glacial erratics, overturned beds, shatter breccia, and ash outcrops. The strike and dips were previously measured in the field by Karl Fecht (Fecht and Chamness, pers. comm.). The dips values were recorded; however, the strike direction was estimated on the hand-drawn maps. To rotate the strike and dip symbols in GIS, the angle of the strikes was visually estimated from the hand-drawn maps, and those values were recorded in a new field in the attribute table. Then, those values were used to automate the symbol rotation using the advanced rotation settings in the symbology properties window. The lack of actual strike values provides the opportunity for future work, specifically, to verify the strike and dips of the geologic unit bedding planes.

The map layouts were developed following the USGS NGMDB and Washington State map standards and guidelines. The layouts include areas for the geologic map(s), geologic unit descriptions, cross sections, correlation of map units, geologic summary, references, credits, and additional key map content. The resulting maps and information included in the layout were compiled on poster-sized paper (31” x 41”). The final product consisted of three separate maps: a map of Candy Mountain, a map of Badger Mountain, and a larger map containing both Candy Mountain and Badger Mountain. Figure 13 below displays an example geologic map layout with several common geologic map elements.

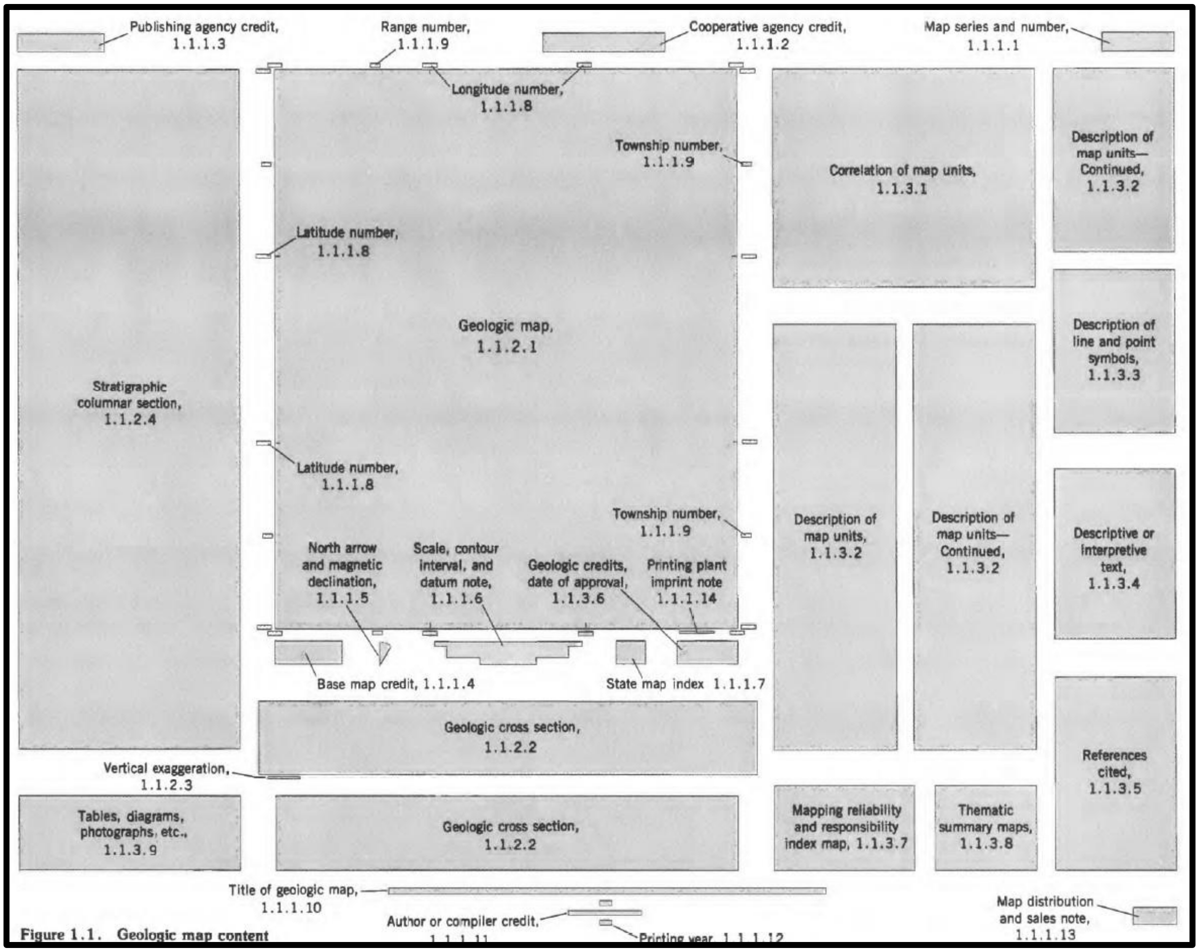

Figure 1.1. Geologic map content

Figure 13. Example Geologic Map Layout (USGS 1995)

In addition, secondary versions of the geologic maps were created at a more manageable size. As opposed to the large poster-sized maps with all layout elements included, the map and layout elements were split into two separate pages using a standard A2 paper size (16” x 23”). This smaller size was desired for ease of posting the maps and supporting information at the Badger Mountain and Candy Mountain trailheads.

The final geologic maps included additional data layers to comprise a basemap and landmark or reference information. These layers include Topography (20-foot contour intervals), Roads, Park Boundary, and Township/Range/Section. Descriptions of these data layers and their sources are included in Table 1.

Table 1. GIS Data Table

Data Layer	Format	Description	Use	Source
WA State Boundary	Polygon Shapefile	Washington State boundary	Inset & Location Map	WA DNR GIS Open Data https://www.dnr.wa.gov/GIS
County Boundary	Polygon Shapefile	Benton County boundary	Inset & Location Map	Benton County WA GIS https://www.co.benton.wa.us/pview.aspx?id=690&catid=45
Roads	Line Shapefile	Benton County roads	Basemap element	Benton County WA GIS https://www.co.benton.wa.us/pview.aspx?id=690&catid=45
Parks	Polygon Shapefile	Benton County parks (including candy and badger mountain preserve)	Basemap element	Benton County WA GIS https://www.co.benton.wa.us/pview.aspx?id=690&catid=45
DEM	Raster file	10 meter DEM of Benton County	To create topography layer	USDA Open Source GIS Data Website https://datagateway.nrcs.usda.gov/
Topography	Line Feature Class	20-foot interval contours	Basemap element	Developed from the DEM
Township	Polygon Shapefile	Benton County townships	Basemap element	Benton County WA GIS https://www.co.benton.wa.us/pview.aspx?id=690&catid=45
Section	Polygon Shapefile	Benton County sections	Basemap element	Benton County WA GIS https://www.co.benton.wa.us/pview.aspx?id=690&catid=45

The majority of the additional map layers, including roads, parks, and PLSS were obtained from the Benton County, Washington GIS website. The Washington State boundary was obtained from the Washington State Department of Natural Resource GIS Open Data website. The DEM used to develop the topography was obtained from the United States Department of Agriculture (USDA) Geospatial Data Gateway website. This DEM has a resolution of 10 meters, which was the highest resolution available for the area immediately containing the mountains.

3.3. Field Verification

Following the completion of the geologic maps and cross sections, field work was performed to collect GPS data points to verify the locations of select faults, folds, geologic contacts, glacial erratics, and other key map features. This field verification work was performed alongside expert geologists Karl Fecht and Mickie Chamness, the authors of the original hand-drawn geologic maps. The GPS data was subsequently uploaded into ArcGIS and added to the map. Where any major offsets existed between the two datasets, necessary edits were made to the digitized geologic maps to reflect the location verification data points.

These GPS spot-checks were performed to ensure the location accuracy of the map features. This is particularly important for the fault and fold locations, as these features have the greatest potential for geologically hazardous events. Given the nature of geologic unit contacts, and how changes between the overlying and underlying sediments tend to be gradual and can shift over time, pinpointing the precise locations of the contacts was not crucial. The accuracy of a handheld Garmin GPS device of approximately 5 to 10 meters was satisfactory for this mapping effort. Nevertheless, verifying these locations was necessary in order to gain a better understanding of the relative amount of offset apparent in the dataset.

Field work to collect GPS verification points of faults, brecciated zones, ash, glacial erratics, contacts, and other locations was performed over a four-day period. On the first day, the field verification work was performed on Little Badger Mountain using four different GPS devices. A Garmin CSx, Garmin eTrex Vista (2003), Garmin eTrex Vista (2009), and the GAIA GPS iPhone app were all tested in the field to compare accuracy. Figure 14 shows the numbered locations for each device. A description of each location is included in Table 2. Once it was determined that all four GPS devices were reading approximately the same, only two devices (the Garmin CSx and GAIA GPS iPhone app) were used during the subsequent three days of field data collection.

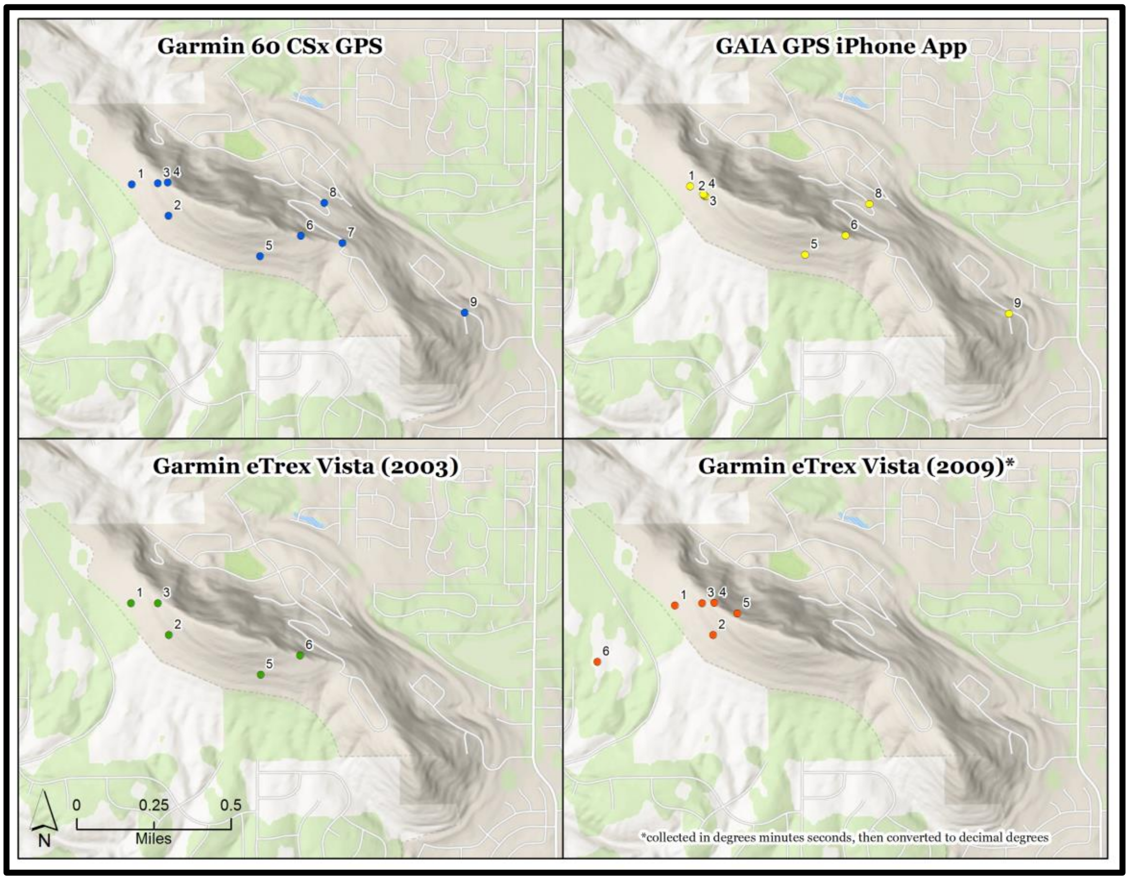

Figure 14. Little Badger Mountain GPS Point Comparison

As Figure 14 shows, a few of the initial GAIA GPS points on Little Badger Mountain were off due to user-error. Specifically, points 2, 3, and 4 were off. While gaining familiarity with the GAIA GPS iPhone app, the “Add Waypoint” option was selected, instead of the “Add Waypoint (My Location).” This error was realized in the field after the first four measurements. The Garmin eTrex Vista (2009) points also contain a couple of instances of user error (points 5 and 6). For these initial measurements, the Garmin CSx GPS points remained accurate and were used for verification.

The second day of field work was performed on Candy Mountain. The third and fourth days of field work were performed on Badger Mountain. On the third day, special access was granted by a private land owner to drive along the orchard road along the backside (south-side) of Badger Mountain in order to assist in data collection. On the fourth day, GPS verification work was conducted by hiking along a small area on the southwest-side of Badger Mountain to investigate basalt outcrops. This day, just the GAIA GPS iPhone App was used to mark locations. Figures 15 and 16 display the GPS verification locations on Candy Mountain and Badger Mountain, and a description of each location is included in Table 2.

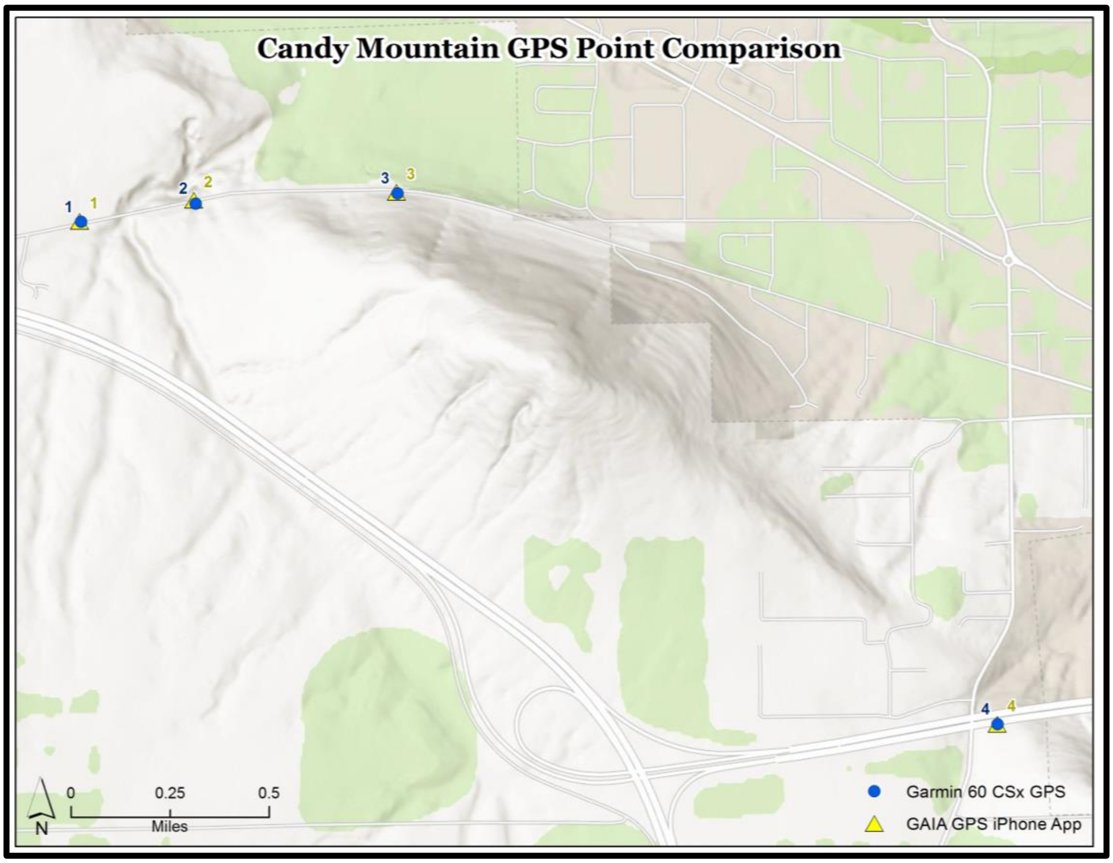

Figure 15. Candy Mountain GPS Point Comparison

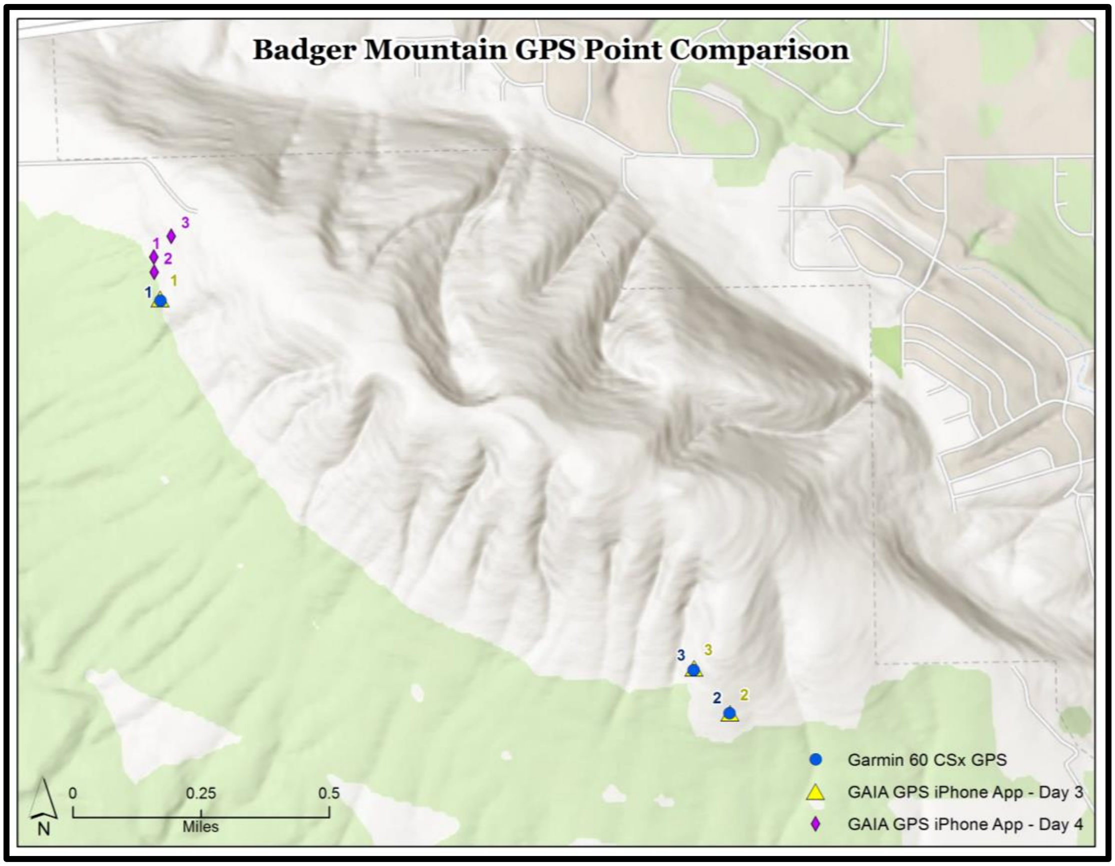

Figure 16. Badger Mountain GPS Point Comparison

After plotting the GPS points in GIS, it was apparent that some minor adjustments needed to be made to the digital geologic formation feature locations. The primary area in need of digital feature adjustments was along the southwest-side of Badger Mountain. In this area, several geologic unit polygons of various basalt rock outcrops needed to be shifted to the northeast, along the road and trail where they actually outcrop. Areal imagery, along with the GPS points, were utilized as a visual aid in adjusting the basalt polygon placement. In other areas, on Candy Mountain and Little Badger Mountain, the GPS points were perfectly aligned with the existing map features.

Table 2. GPS Point Location Descriptions

Day	Location	Point Number	Description
1	Little Badger	1	Levey Interbed
1	Little Badger	2	Teme-Qco Fault
1	Little Badger	3	Tem-Tp Fault
1	Little Badger	4	High Dike
1	Little Badger	5	Big Rock
1	Little Badger	6	Little Shears
1	Little Badger	7	Light Pole
1	Little Badger	8	Big Wall CaCO3
1	Little Badger	9	Central Shears
2	Candy	1	Mt. St. Helens Ash
2	Candy	2	Temw-Teme Contact
2	Candy	3	Brecciated Zone on Kennedy
2	Candy	4	Goose Gap
3	Badger	1	Shatter Breccia
3	Badger	2	Tp Outcrop - Orchard
3	Badger	3	Tim Outcrop - Orchard
4	Badger	1	Tp Outcrop - Road
4	Badger	2	Am - Road
4	Badger	3	Tp - Trail

3.4. Data Manipulation

Following the geodatabase creation, symbology modifications, and several rounds of map edits, and once the geologic unit polygon and fault/fold line feature classes were finalized, topology rules were implemented to remove any errors in the datasets. Critical errors in the geologic unit polygon layer could include instances of overlapping polygons and gaps between polygons. Topology rules define how points, lines, and polygons share geometry. When implemented in GIS, the topology rules check and validate the spatial relationships between neighboring and adjacent features. If any errors exist within the target feature class, these areas will be highlighted in red in the resulting topology error dataset.

The topology rules were implemented as one of the final steps of the methodology workflow as an overall check of the feature classes. Numerous rounds of edits to the geologic unit polygon and fault and fold line features occurred before and after the field verification work. Due to these numerous edits, the topology check was saved till the end.

The topology rules utilized in this study comply with the Washington State Geological Survey standards (Reidel and Schuster, pers. comm.). These topology rules were included as a zipped rule (.RUL) file within the Washington State standards. The polygon topology rules include ‘must not overlap’ and ‘must not have gaps.’ Line topology rules include ‘must not overlap,’ ‘must not self-overlap,’ ‘must not have dangles,’ and ‘must not intersect’ within the same feature class.

In order to implement the topology rules, the geologic unit polygon datasets were added to a feature data set, and topology rules were created and added. Once the topology rules were created, they were validated and the error report was generated. The topology rules resulted in the discovery of 36 total errors. A total of 20 errors in the Badger Mountain geologic unit polygon dataset and 16 errors in the Candy Mountain geologic unit polygon dataset were discovered. These errors included 13 instances of gaps between polygons and 23 instances of overlapping polygons.

The fault and fold line datasets were investigated using the same approach as the geologic unit polygon datasets. The topology rules resulted in the discovery of 34 total errors. There were 31 instances of dangles, one instance of overlapping lines, and two instances of intersecting lines. All 31 instances of dangles were deemed okay to leave as is, as they occurred where a fault or fold line ended, or where the map frame ended.

In order to correct any inconsistencies, the resulting topology errors were added to the map, inspected, and resolved. The errors were inspected and resolved one-by-one using the “error inspector” report on the topology toolbar. The majority of the geologic polygon errors were resolved manually by aligning the vertices of adjacent polygons. The fault and fold line errors were resolved manually as well, by adjusting the line vertices. Implementing these rules ensures there are no errors in the dataset, resulting in the high-quality geologic unit, fault, and fold GIS layers.

3.5. Surface Geology 3D Scene

A simple 3D scene was then developed of the surface geology of Candy Mountain and Badger Mountain. This 3D scene displays the surface geology overlaying a hill-shade digital elevation model (DEM) of the area (USDA 2019). The 3D scene was developed using ArcGIS Pro’s local scene creator. A local scene was used, as opposed to a global scene because the project area is comprised of a relatively small extent. Therefore, the curvature of the earth is not an important factor.

The 3D scene includes layers for the geologic units, faults and folds, park boundaries, and 20-foot contours, in addition to the default ArcGIS 3D scene elevation. In order to create this scene in a single viewer, the geologic unit polygons for Badger Mountain and Candy Mountain were merged. The combined geologic unit polygon was then edited to fill in some of the gaps between the Badger and Candy mapped area. The gaps were intentionally filled in with the genuine geology of the area based on prior mapping efforts performed by Karl Fecht (Fecht, pers. comm.). This process was also followed for the faults and folds. Figure 17 shows a screenshot of the completed 3D scene at Badger Mountain.

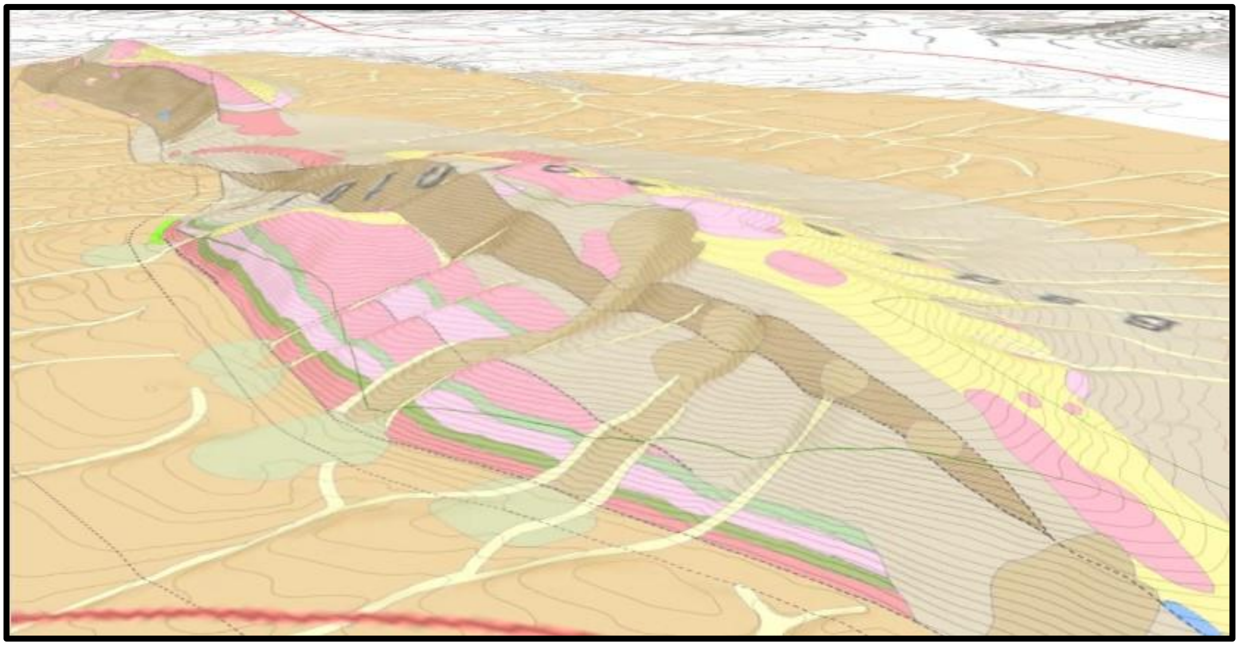

Figure 17. Surface Geology 3D Scene

The 3D scene was created in ArcGIS Pro as a local scene. Then, the layers were shared as web layers to ArcGIS Online. The 20-foot contours, park boundaries, and faults and folds were shared as individual feature layers. The geologic units were shared as a tile layer in order to preserve the symbology. In ArcGIS Online, a new local scene was created using the shared layers and navigating to a visually intriguing opening bookmark.

The completed 3D scene provides users with the ability to explore the mountains and their geology in a 3D setting and obtain a better understanding of the mountains' terrain and overall topography. This scene was shared with users as part of an ArcGIS Online Story Map so that those without GIS on their computers could view and explore the 3D geologic scene. Users can change the basemap, apply different daylight options, zoom and pan, measure, and toggle layers on and off.

3.6. Story Map Development

The completed geologic maps, cross sections, 3D scene, and supporting information and figures were subsequently compiled into an Esri ArcGIS Online Story Map for interactive viewing. Story Maps are a useful tool that allows for the combination of maps, figures, and text to engage the audience. Due to the fact that Story Maps are published online, they allow users without GIS software on their computer the ability to view and interact with 2D and 3D maps simply using a standard Internet-enabled browser. The Story Map developed in this study contains tabs for the 2D geologic maps, 3D surface geology scene, geologic cross sections, correlation of map units, and short paragraphs explaining the local and regional geology.

Esri's Story Map Journal template was utilized, as it allows for information to be organized into sections and contains simple navigation tools. The maps, 3D scene, and images were displayed in the content area, and informative narrative text was displayed in the side panel. This format was utilized because it provides the users with informative text alongside the geologic maps and figures. The Journal template is also arguably the most straightforward and easiest to navigate for end users. A screenshot of the Story Map Journal template is displayed in Figure 18 below.

The Story Map was created in ArcGIS Online by adding figures to the content page. The figures and 3D scene were then added to the Story Map as individual pages. The Story Map cover-photo, displayed in Figure 18, was taken by the author on one of many hikes along the mountains. The Story Map also contains links to a Github archive created specifically for this project, where full-size PDFs of the geologic maps are stored for viewing and downloading.

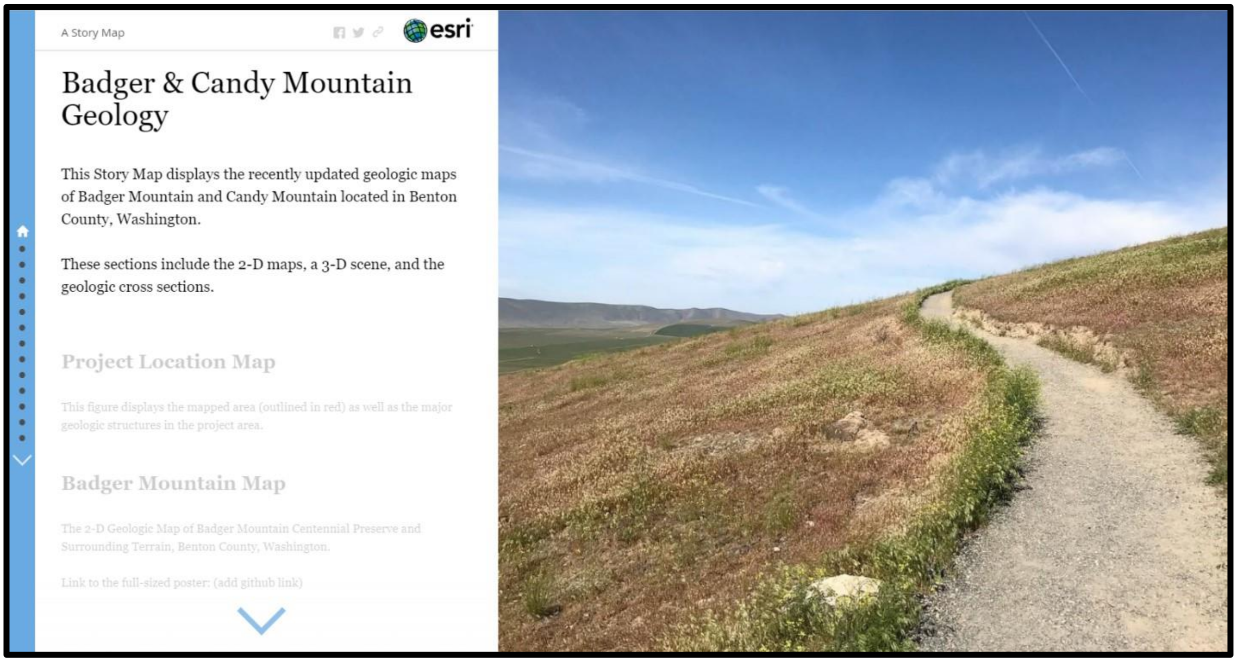

Figure 18. ArcGIS Online Story Map Template

The overall purpose of the Story Map is to showcase all of the work completed in updating the geologic maps and information for Badger Mountain and Candy Mountain. Although the digital 2D maps will be used by Benton County, and paper versions will be posted at trailheads to inform the public of the updated geologic mapping efforts, the online interactive 3D scene is more captivating and invites users to explore the mapped area. Compiling all of the geologic information in a Story Map and Github repository provides easy to use, valuable, and engaging platforms for sharing and communicating the information to interested users.

Chapter 4 Results

The results of this project include three poster-sized geologic maps with included informational panels for Candy Mountain, Badger Mountain (including Little Badger Mountain), and a combined Candy Mountain and Badger Mountain geologic map. In addition, separate, smaller versions of the Candy Mountain and Badger Mountain geologic maps were also created for posting at the trailheads. The digitized geospatial layers also include detailed geodatabases and metadata information. Additionally, an ArcGIS Online Story Map consisting of the 2D geologic maps, geologic cross sections, 3D surface geology scene, and informational text resulted in a user-friendly interface for viewing all components developed as part of this thesis project.

Revisiting the thesis objectives, the goals of this project were to develop updated, professional-grade digital geologic maps, geologic cross sections, an Esri geodatabase, and a digital surface geology 3D scene of Badger Mountain and Candy Mountain. In addition, an ArcGIS Online Story Map containing all of the geologic maps, cross-sections, 3D scene, and information was developed. These goals were certainly accomplished, and the results are discussed in the following sections.

4.1. Geologic Maps

The Badger Mountain and Candy Mountain geologic maps developed for this thesis project incorporate newly collected information not present on the older geologic maps. This update resulted in improved clarity of the geologic maps of the mountains. The revised geologic maps provide viewers with a deeper knowledge of the geology of the mountains and surrounding terrain. Moreover, the maps also provide the user with a better understanding of the local geology via the visual representation of newly identified (previously unmapped) faults and folds.

Two versions of geologic maps were created for both Badger Mountain and Candy Mountain. The first version was a poster-sized, 31” x 41” layout containing the geologic map and all map layout elements. The second version was a standard A2 paper sized, 16” x 23”, layout with one page containing the geologic map, and the second page containing all the supporting information. The second version of the geologic maps was created as a more manageable size to post at the Badger Mountain and Candy Mountain trailheads. In addition, all of the maps use the NAD 1983 HARN State Plane Washington South (US Feet) coordinate system and have the Lambert Conformal Conic projection.

All of the maps use a scale of 1:12,000, where one-inch equals 1,000 feet. Due to the somewhat small scale of the geologic maps, some of the smaller geologic unit outcrops were exaggerated slightly so they would be visible at the utilized scale. This exaggeration was deemed acceptable for this mapping project to simply identify the general locations of various basalt rock outcrops. However, this presents a limitation and opportunity for future research if one were to create a larger-scale map or if a specific area is in question.

The Badger Mountain geologic map poster-sized layout contains areas for the title, geologic map, scale information, declination diagram, credits, five geologic cross sections, location map, description of map units, explanation of map symbols, correlation of map units, informational text, references, acknowledgements, and disclaimer. Figure 19 displays a thumbnail of the poster-sized Badger Mountain geologic map. The full-sized Badger Mountain geologic map is available through this project’s Github URL provided in Appendix A.

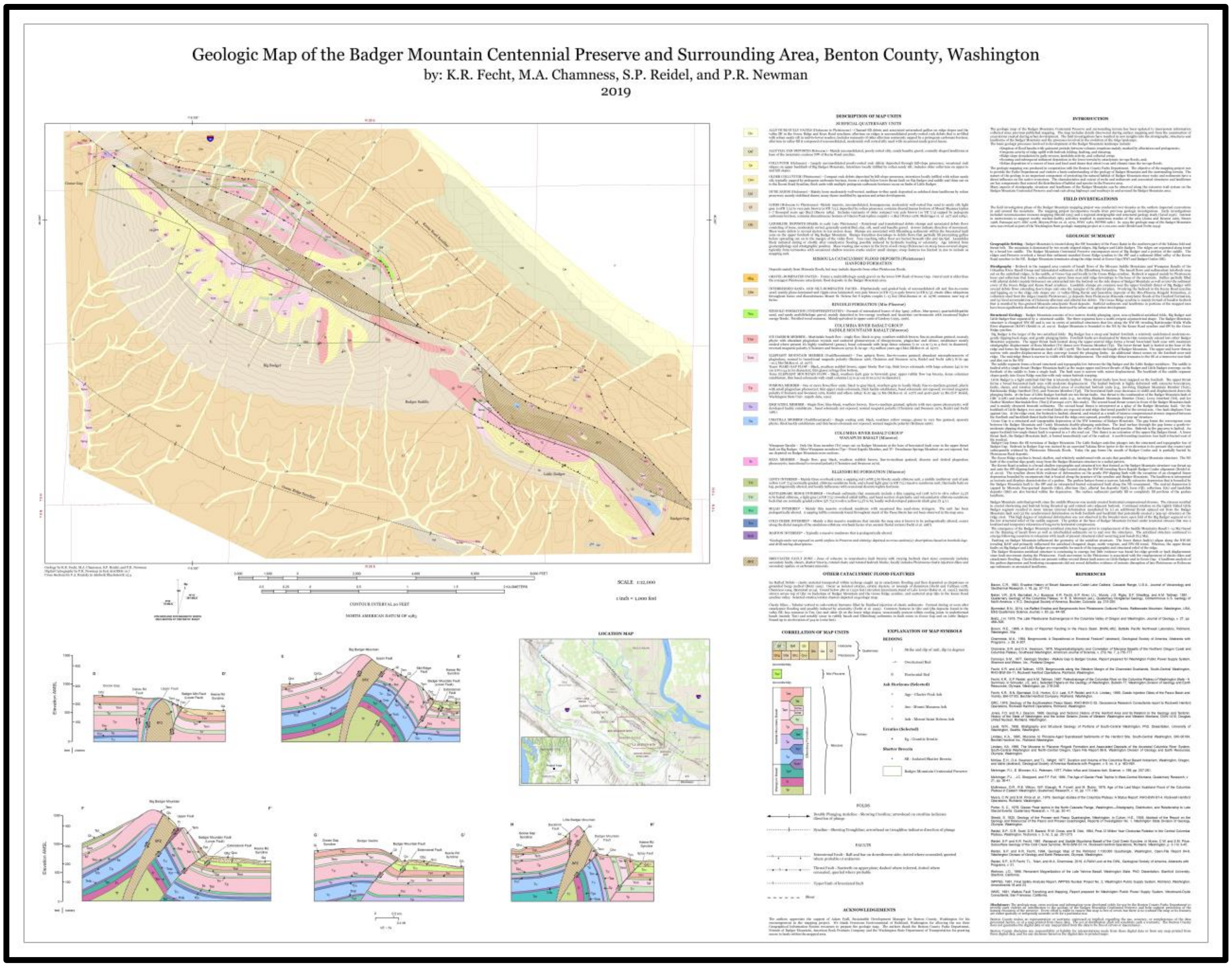

Figure 19. Geologic Map of Badger Mountain (Poster-Sized)

Similar to the Badger Mountain geologic map, the Candy Mountain geologic map poster-sized layout contains areas for the title, geologic map, scale information, declination diagram, credits, four geologic cross sections, location map, description of map units, explanation of map symbols, correlation of map units, informational text, references, acknowledgements, and disclaimer. The Candy Mountain map differs from the Badger Mountain map, as it only contains four geologic cross sections. The Candy Mountain map also contains less informational text and fewer map symbols. These differences result in the addition of white space in the map layout. Figure 20 displays a thumbnail of the poster-sized Candy Mountain geologic map. The full-sized Candy Mountain geologic map is available through this project’s Github URL in Appendix A.

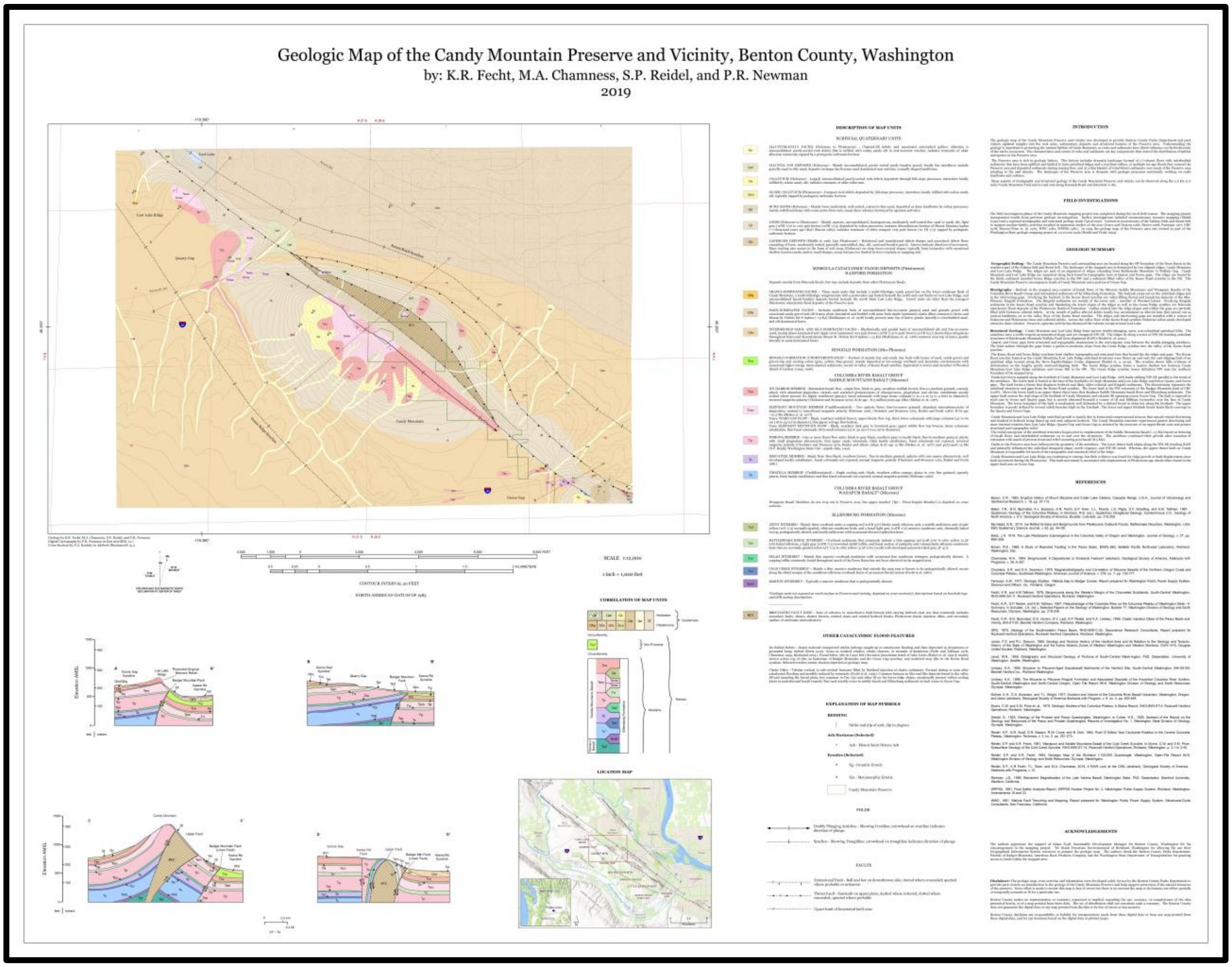

Figure 20. Geologic Map of Candy Mountain (Poster-Sized)

The A2 paper sized geologic maps of Badger Mountain, and Candy Mountain contain all the same information as their poster-sized counterparts. However, the map is split between two separate pages. One page contains the title, geologic map, scale information, declination diagram, and credits, while the second page contains the geologic cross sections, location map, description of map units, explanation of map symbols, correlation of map units, informational text, references, acknowledgments, and disclaimer. The split nature of the maps provides an easier method of posting within the existing hiking trailhead informational kiosks.

The Badger Mountain and Candy Mountain A2 paper sized geologic maps and supporting information panels are displayed in Figures 21, 22, 23, and 24 below. Although the text on the thumbnail figures is difficult to interpret at the size provided in this thesis, these figures provide a sense of the overall figure layout. The full-sized geologic maps and supporting information pages are available through this project's Github URL in Appendix A.

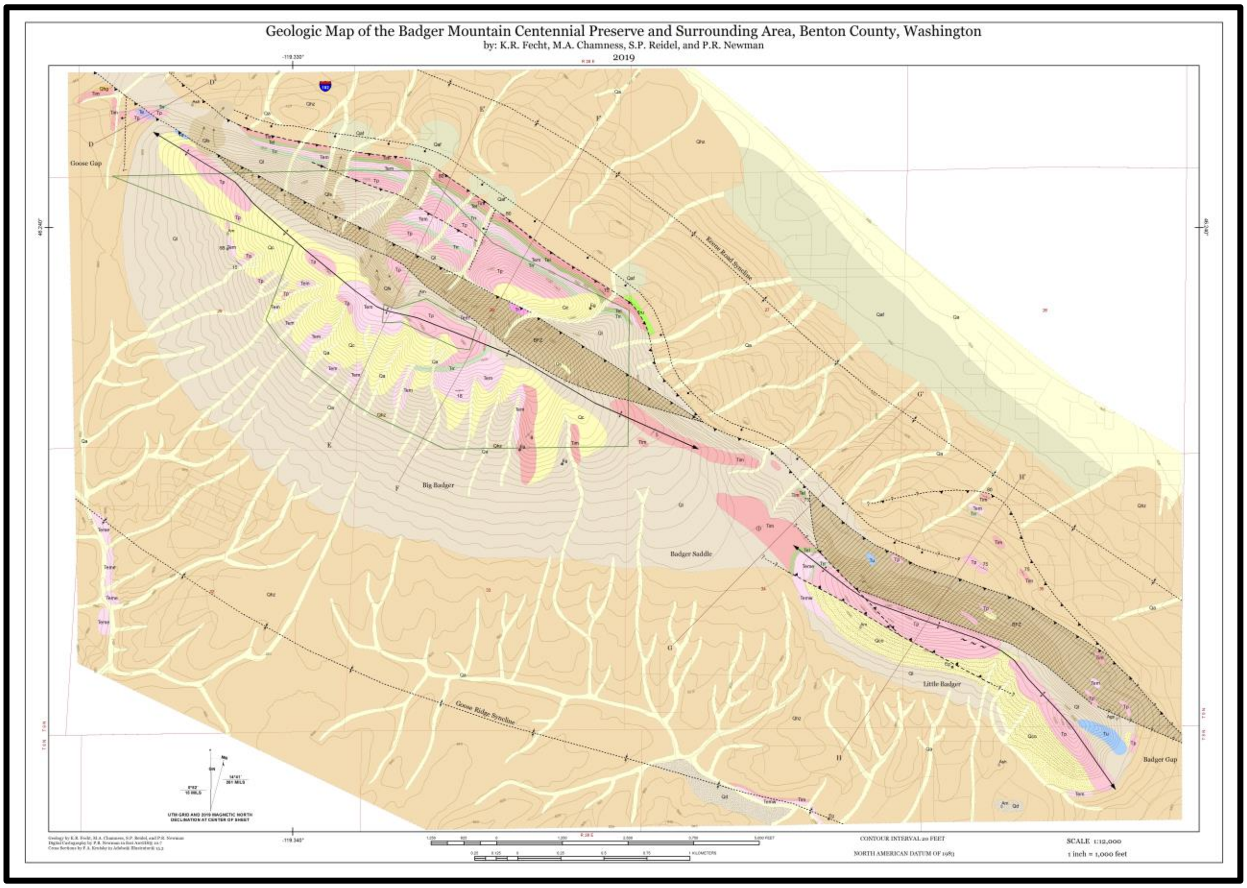

Figure 21. Geologic Map of Badger Mountain (A2 Paper-Sized)

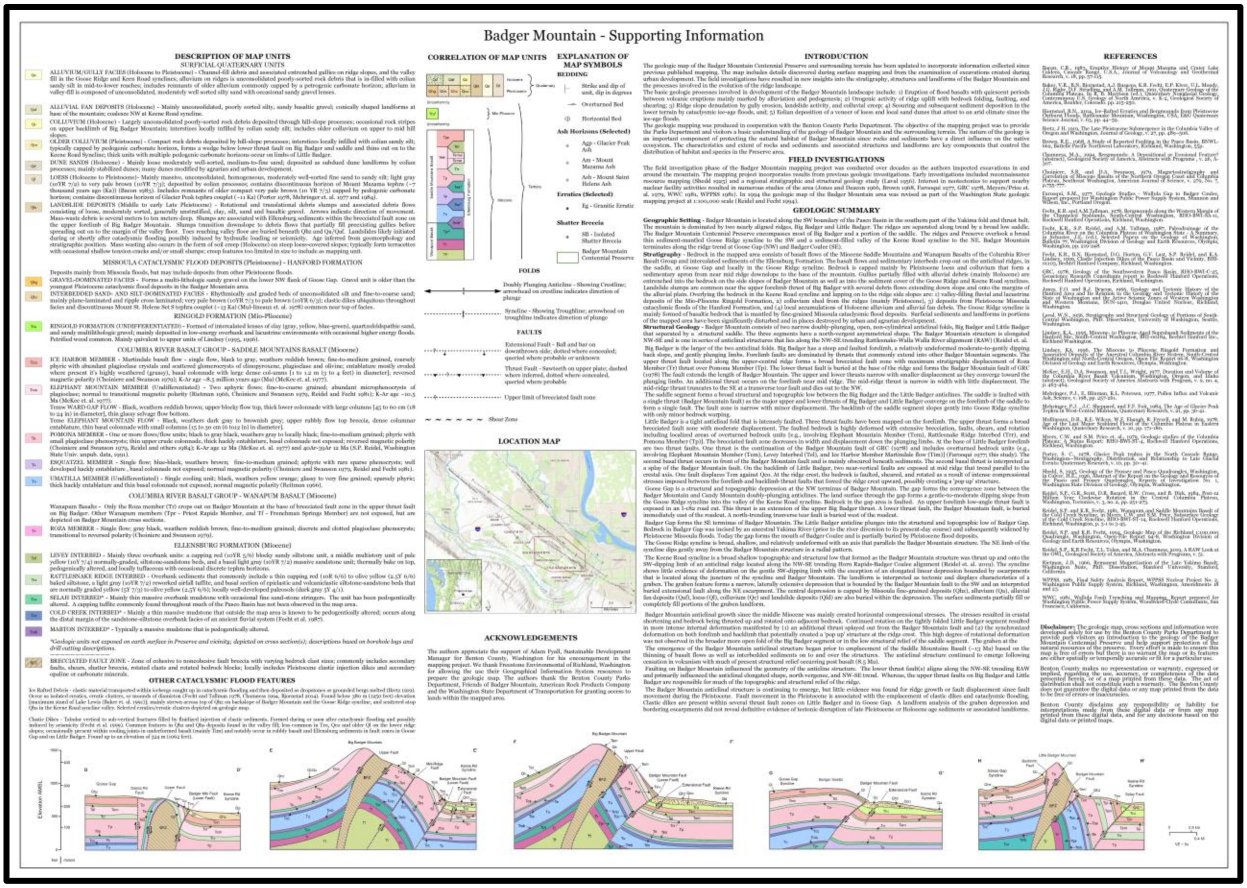

Figure 22. Badger Mountain Supporting Information (A2 Paper-Sized)

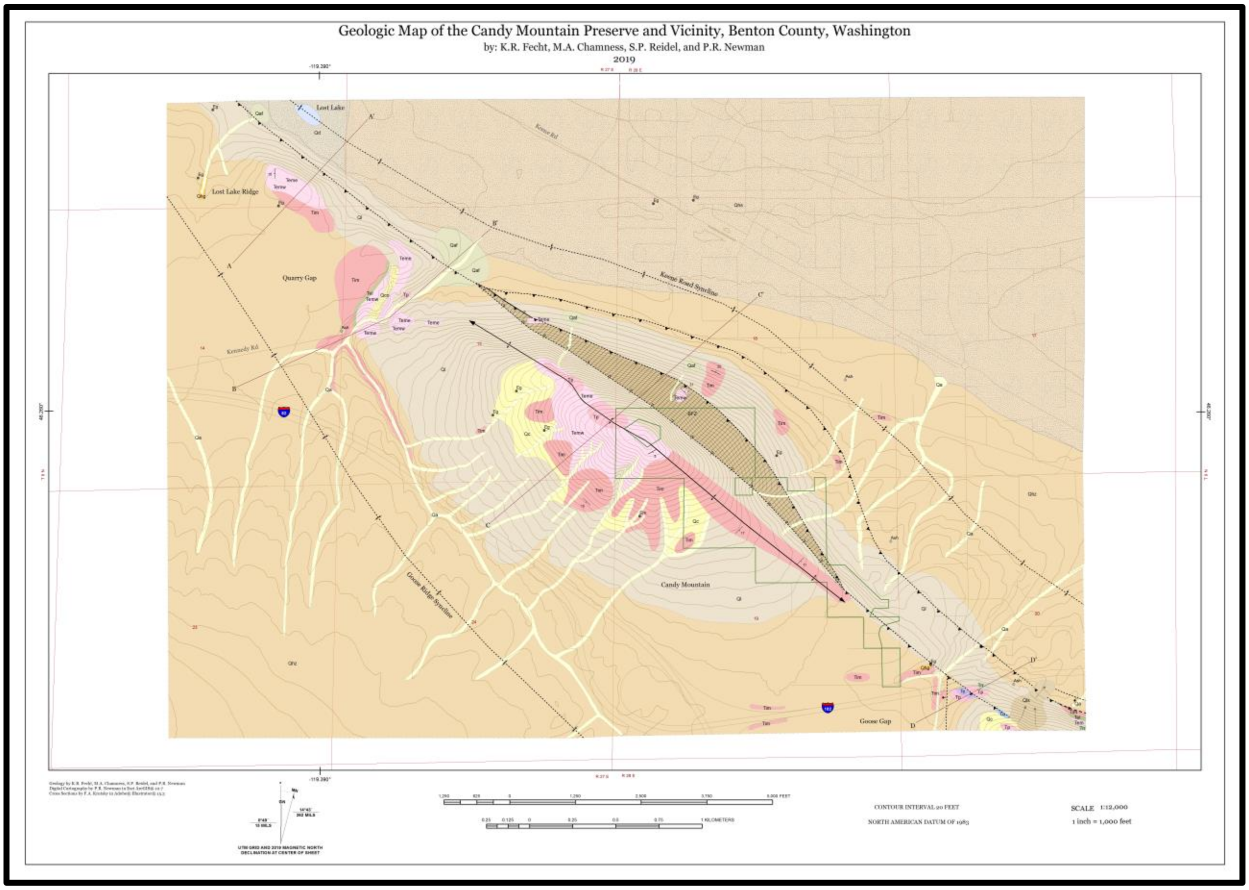

Figure 23. Geologic Map of Candy Mountain (A2 Paper-Sized)

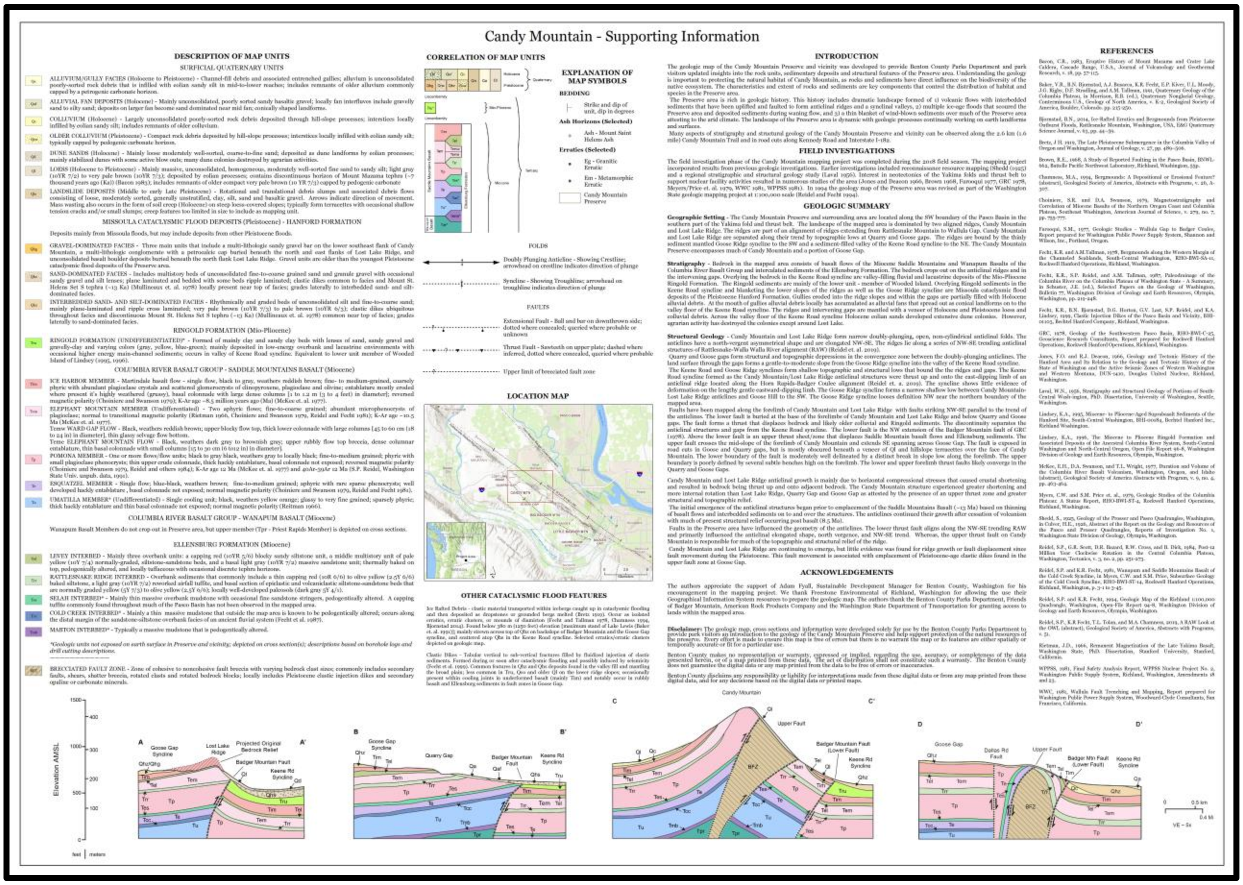

Figure 24. Candy Mountain Supporting Information (A2 Paper-Sized)

Both the Badger Mountain and Candy Mountain geologic maps are at a scale of 1:12,000, in which one-inch equals 1,000 feet. Both the poster-sized and A2 paper sized maps utilize this scale for consistency. The Candy Mountain geologic map covers a smaller total area than the Badger Mountain geologic map, resulting in some additional white space in the map frame margins.

Additionally, a combined Badger Mountain and Candy Mountain geologic map was developed by merging the two datasets together and filling in some of the gaps between the Badger Mountain and Candy Mountain mapped areas. These merged datasets were subsequently used to create the 3D scene. This geologic map was developed as a 31” x 41” poster-sized map. The combined map includes areas for the title, geologic map, scale information, declination diagram, credits, location map, description of map units, explanation of map symbols, and geologic cross sections. The correlation of map units, acknowledgments, and disclaimer are included in a separate informational panel. A thumbnail of the map is displayed in Figure 25. The full-sized geologic map is available through this project's Github URL in Appendix A.

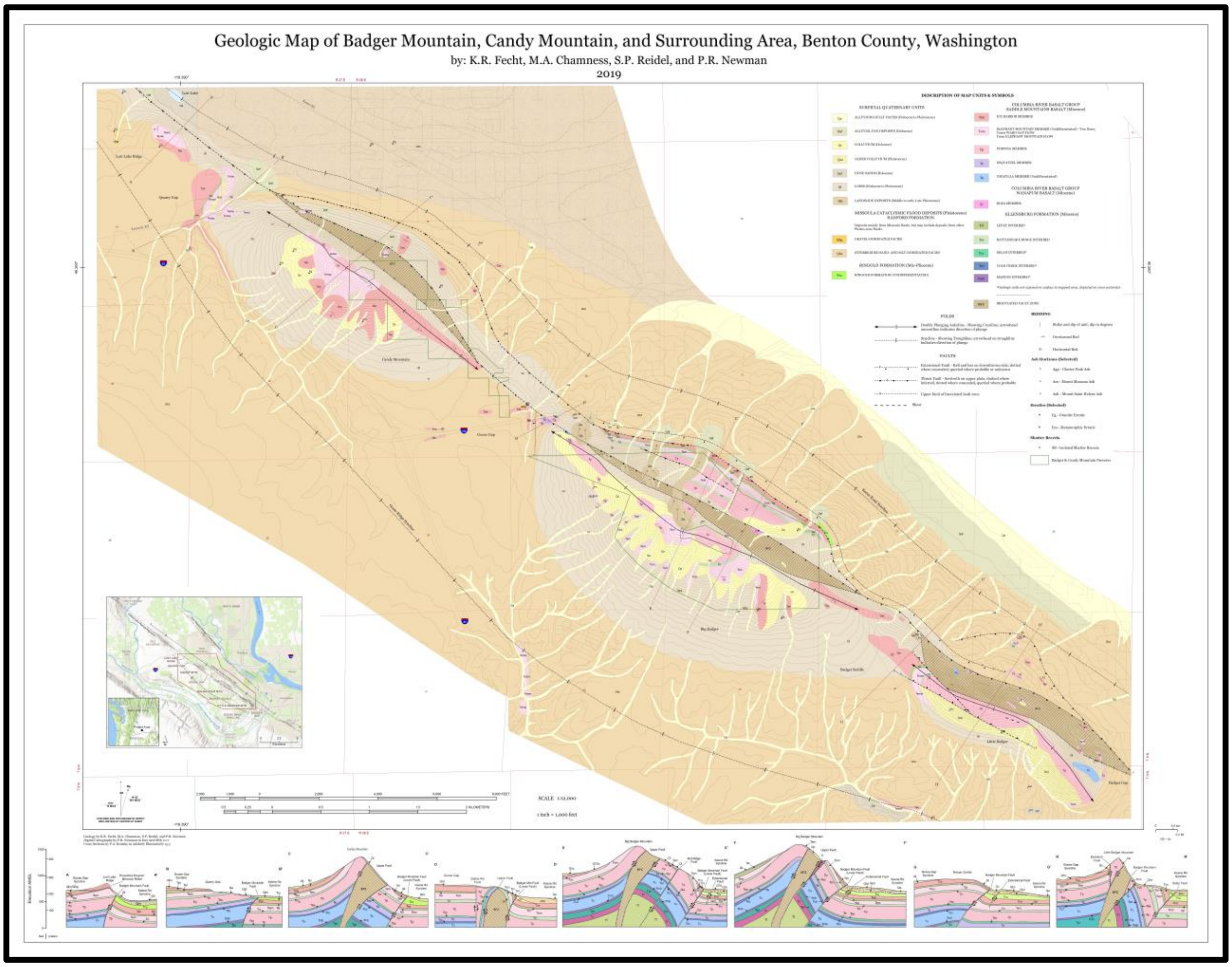

Figure 25. Combined Badger and Candy Mountain Geologic Map

The geodatabase and metadata information added to the geologic map layers provides users with a greater understanding of the individual features as well as how the features were created. The geodatabase information includes several attributes for the geologic unit polygons, fault and fold lines, and map point features. The geologic unit polygon features contain the attributes of Label, Name, Description, Lithology, and Geologic Age. The fault and fold line features contain the attributes of Name and Description. The map point features contain the attributes of Label, Name, and Description. Additionally, the Strike and Dip points contain fields for dip direction value and estimated strike value. The metadata includes notes on when the dataset was created, who created it, and the associated report(s) it is described in. Figure 26 displays the metadata associated with the Badger Mountain geologic unit polygon feature class.

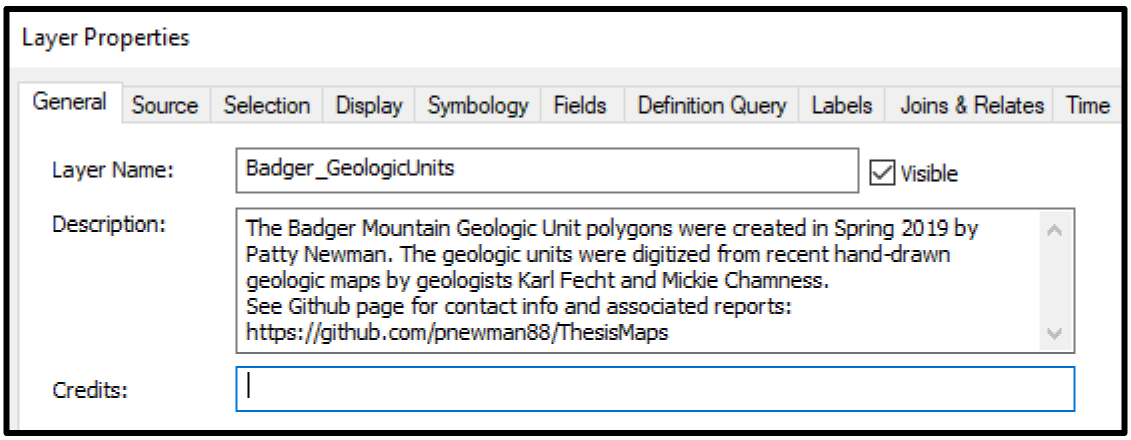

Figure 26. Metadata Example

The geologic cross sections developed as part of this thesis project provide the user with a greater understanding of the subsurface geology underlying the mountains. Geologic cross sections offer insights into the stratigraphy and geologic structure of the mountains. The colors of the geologic units depicted in the cross sections match the colors of the geologic units depicted on the maps. However, some subsurface geologic units depicted on the cross sections do not appear on the corresponding maps, as the units do not outcrop anywhere along the surface in the mapped area. Interpretation of the subsurface geologic units was generated from nearby geologic well log information and knowledge of the regional stratigraphy (Fecht and Chamness, pers. comm.).

In instances where a geologic unit is present in a cross section, but not on the geologic map, an asterisk is placed next to its name or label in the description of map units and correlation of map units. Subsequently, near the bottom of the description of map units, a note explains the asterisk's meaning. Different geologic units outcrop along the surface between the Badger Mountain and Candy Mountain geologic maps. The correlation of map units and description of map units were modified to reflect this difference between the two maps.

The eight geologic cross sections are depicted as lines A-A', B-B', C-C', D-D', E-E', F-F', G-G' and H-H' on the geologic maps. Cross sections A-A' through D-D' are present on the Candy Mountain geologic map, while cross sections D-D' through H-H' are present on the Badger Mountain geologic map. The maps overlap in the area covered by D-D', leading to its inclusion on both the Badger and Candy Mountain geologic maps. All eight geologic cross sections are available in Appendix B, as well as in the ArcGIS Online Story Map.

4.2. ArcGIS Online Story Map

The resulting ArcGIS Online Story Map consists of a compilation of all the elements developed in this thesis project. It contains the 2D geologic maps, project location map, geologic cross sections, 3D surface geology scene, and informational text all compiled into a user-friendly web interface. Users can gain a better understanding of the geology and geologic structure of Badger Mountain and Candy Mountain by scrolling through the Story Map tabs, reading the informational text, and exploring the interactive 3D scene.

The overall purpose of the Story Map is to showcase the revised geologic maps and 3D surface geology scene and encourage users to expand their knowledge of the mountains' geology. The interactive 3D scene invites users to explore the mountains and gain a unique perspective not available with the traditional 2D map format. Figure 27 shows a screenshot of the 3D scene in the Story Map format. The Story Map is available through the URL provided in Appendix A.

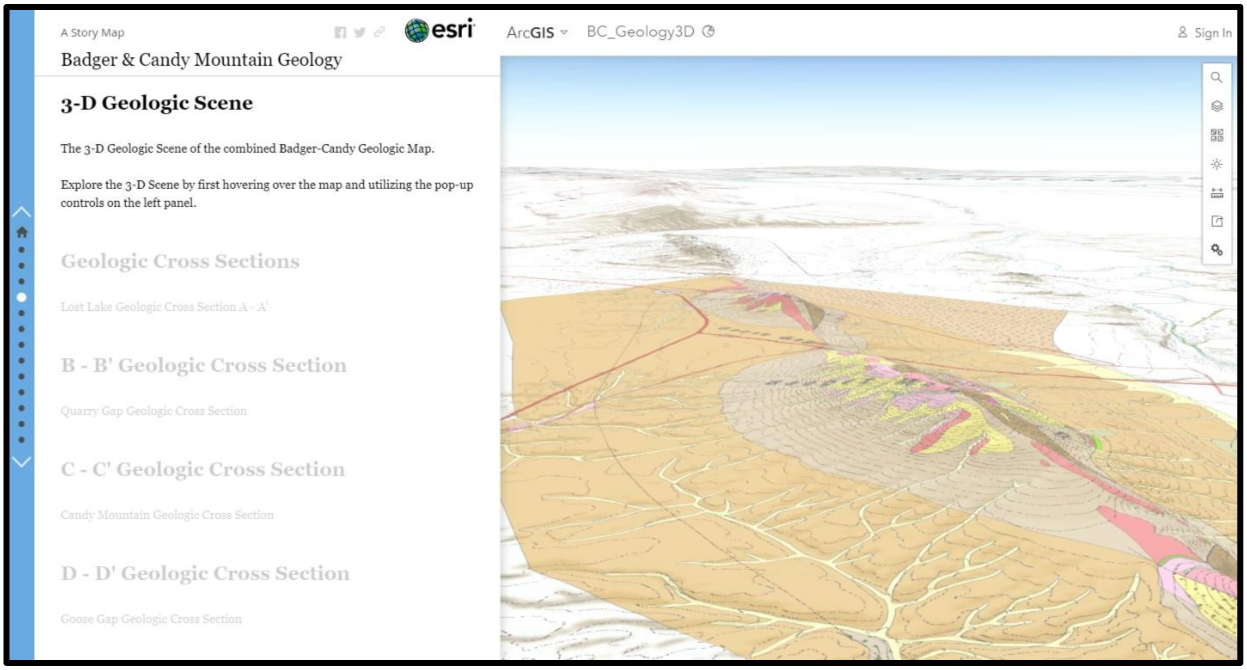

Figure 27. Story Map Surface Geology 3D Scene

The Story Map includes an explanation of the geologic mapping project, as well as the purpose and objectives of the project. The geologic map pages also include links to the Github page where the full-sized geologic maps can be viewed and downloaded. Additionally, the Story Map includes pages containing future work, map references, and contacts.

4.3. Geodatabase Results

The resulting geodatabase and metadata information developed in this thesis project contains valuable information to assist the user in better understanding the data. Each feature class in the geodatabase includes populated attribute tables with information about the geologic unit polygons, fault and fold lines, and map feature points, to name a few. The geodatabase for the final maps also contains annotation features, as several of the map feature labels were converted to annotation for final modifications.

The final geodatabase contained 28 individual feature classes. These feature classes include the Badger Mountain geologic unit polygons, Candy Mountain geologic unit polygons, Badger Mountain faults and folds, Candy Mountain faults and folds, Badger Mountain geologic cross section lines, Candy Mountain geologic cross section lines, Badger Mountain map points, Candy Mountain map points, Badger Mountain strike and dip points, Candy Mountain strike and dip points, Badger Mountain horizontal bed, Badger Mountain overturned bed, Badger Mountain shear zone, Badger Mountain landslide (Qls) direction arrows, Badger Mountain geologic unit contacts, Candy Mountain geologic unit contacts, Badger Mountain park boundary, and Candy Mountain park boundary. The modified basemap layers for roads, 20-foot contours, townships, and sections were saved to the geodatabase as well. Annotation layers for the geologic unit polygons, map points, and strike and dip features were also included in the final geodatabase.

Moreover, the combined Badger & Candy Mountain map geodatabase contained nine individual feature classes. These feature classes include the combined Badger & Candy Mountain geologic unit polygons, combined Badger & Candy Mountain faults and folds, combined Badger & Candy Mountain geologic cross section lines, combined Badger & Candy Mountain map points, combined Badger & Candy Mountain strike and dip points, combined Badger & Candy Mountain geologic unit contacts, and annotation layers for the geologic unit polygons, map points, and strike and dip features. The combined Badger & Candy geodatabase was saved separately as it was developed strictly for this thesis project and there are currently no plans to further publish the map.

Additionally, the topology rules used for this project were saved to a separate geodatabase titled ‘MapTopology’, where the final geologic unit polygon and fault line map layers were examined for errors. A total of six separate topology rules were used in this project. The polygon topology rules include ‘must not overlap’ and ‘must not have gaps.’ Line topology rules include ‘must not overlap,’ ‘must not self-overlap,’ ‘must not have dangles,’ and ‘must not intersect’ within the same feature class. The topology rules used in this project are also available for download through the Github repository developed specifically for this project. The Github URL is located in Appendix A.

Chapter 5 Discussion and Conclusions

The updated geologic maps of Badger Mountain and Candy Mountain contribute to the local and regional communities by providing new information not present on older geologic maps. The improved clarity and legibility of the geologic maps, when compared to prior mapping efforts, alone adds immense value to the user. Moreover, the revised geologic maps offer the local community multiple modalities to better understand the geology of the mountains and surrounding terrain. Most notably, the identification of previously unmapped faults and folds provides users with a greater awareness of the geologic structures and landforms present in the mapped area in both 2D and interactive 3D renderings.

The original objectives of this project were to develop updated, professional-grade, geologic maps, geologic cross sections, geodatabase, and a surface geology 3D scene of Badger Mountain and Candy Mountain. In addition, an ArcGIS Online Story Map containing all of the geologic maps, cross-sections, 3D scene, and information was developed. The achieved objectives all add value to the overall understanding of the local geology and can be applied in a wide variety of professional areas.

5.1. Applicability

The updated geologic maps and associated information can be utilized by geologists, engineers, housing developers, local government, local residents, and insurance companies, to name a few example stakeholders. Geologists and engineers can use these maps and information to assist in studies related to the mountains' geomorphology, hydrogeological conditions, and surface/subsurface interactions. For example, geologists can apply the information included in the maps to identify high-risk areas prone to landslides and areas at risk for flash flooding. Local government agencies may also use the maps to recognize and delimit natural hazards zones. In turn, the latter could have a big impact on insurance company designations.

Geologic maps are also a key component in all housing development studies. Local professionals can use the maps and associated data in order to determine areas to build new residential or commercial developments, as well as potential areas to avoid. The updated geologic maps provide crucial details required to better identify areas at higher risk for geologic hazards, such as landslides and seismic activity. For instance, accurate strike and dip measurements are useful to engineers when determining potential surfaces of slope failure (Mote et al. 2005). Thus, the maps produced in this project could serve as a valuable resource in annotating areas of high risk to natural hazards such as mass movements, to be avoided or otherwise taken into consideration when planning construction of new residential, commercial, or other developments.

Moreover, the possibility of catastrophic geologic events, such as landslides and mudslides, on Badger Mountain, Little Badger Mountain, or Candy Mountain increases as a direct result of urban development adjacent to and directly on the mountains. As an example, new construction on the mountains typically involves removing material from the slope, exposing previously unmapped faults, and destabilizing the slope. Additionally, an increase in irrigation and water infiltration can result in increased pore pressure within the fault zones. The increase of pore pressure and water supply can contribute to slope failure, resulting in landslides or mudslides.

To further illustrate these concerns, Little Badger Mountain, in particular, has experienced a massive increase in urban sprawl over the past thirty years, as continued efforts to preserve the land from increased urbanization have failed. Due to the dip of the geologic unit bedding planes, there could be houses sliding down the hill if not built in the correct areas. Additionally, many of the residential homes developed on Little Badger Mountain sell for upwards of one million dollars, well above the average residential home price within Benton County, Washington. Due to the potential high insurance costs and elevated risks associated with these homes, the role of geologic studies and subsequent understanding of potential terrain and environmental hazards become all the more important.

Similarly, the geologic maps provide policymakers and other stakeholders with valuable information on how continued urban development surrounding Badger and Candy Mountains will impact the local ecosystem. As an example, man-made alterations to the existing geologic features, such as rocks, sediments, and geologic structures, greatly affect vegetation, habitat and wildlife species. Thus, the maps and associated geologic information could assist policymakers in determining whether or not certain portions of the study area should be designated as natural preserves or other protected status.

Furthermore, the geologic mapping workflow followed during this project can be modified and applied by other field mapping geologists to future mapping projects. The workflow was fairly standard for any typical geologic mapping project; however, it could be modified to include the topology rules at the beginning of the digitizing process to identify and resolve errors as they occur, rather than a final quality check at the end. Additionally, further geologic mapping efforts should reference the national and state standards and guidelines to see if they have been finalized yet. If the standards have not been finalized, they could still be useful as a general guideline for the project.

The intellectual merit contributed by this project workflow includes the value of developing a 3D surface geology scene and the use of a Github repository. Github is much more commonplace now and offers a free online space to store and share data. The Github repositories can simply be used to showcase work products, or they can be used to contribute to open-source projects with others. In addition, 3D geologic scenes and models are becoming more common and offer a deeper level of understanding of the terrain and underlying geology than can be inferred from a 2D map.

5.2. Limitations

The limitations that existed during this project include the lack of a nationally accepted geologic mapping standard, lack of geologic wells and boreholes immediately within the mapped vicinity, and precise surficial geologic unit extent. Overall, these limitations represent minor issues which were overcome using the best available information and research tactics. However, these limitations are worth mentioning so that future mapping efforts, especially those within the Badger Mountain and Candy Mountain vicinity, can seek additional solutions to mitigate known limitations.

The USGS NGMDB standards and guidelines provide helpful information, although they are still under development, and serve as a guideline more than a strict standard (USGS 2019). Similarly, the Washington State standards and guidelines are also not easy to track down and serve as more of a guideline than a documented standard. Additionally, not all of the geologic units and information included in these geologic maps have a national or Washington State standard associated with them.

The lack of geologic wells and boreholes in the mapped vicinity directly affect the accuracy associated with the subsurface geologic unit extents and thicknesses depicted in the geologic cross sections. The surface geology is readily available for investigation; however, the subsurface 3D geology is always interpreted to a degree, especially when limited subsurface information is available. The geologic cross sections developed as part of this mapping project represent the best possible interpretation based on the currently available subsurface data.

Several of the surficial geologic units were visually approximated during field investigations. These approximations were satisfactory for the overall mapping project objectives; however, an independent evaluation might be useful if a specific area is in question. Additionally, some areas are concealed by thick vegetation, resulting in limited exposures of geologic unit outcrops.

5.3. Future Research

Several opportunities for future work exist in relation to the Badger Mountain and Candy Mountain geologic mapping project. These opportunities include verifying the strike and dip of the various basalt units through additional field investigations, verifying and adjusting the locations and extent of mapped geologic units, further investigating the subsurface geology using seismic devices, and developing a complex 3D model showing the underlying stratigraphy. Additional mapping and research opportunities of surrounding terrain may present themselves in the future as well.

While the dip values were recorded during this mapping effort, the strike values were estimated in the field and hand-drawn on the paper map. The lack of definitive strike values provides the opportunity for future work, specifically, to verify the strike and dips of the exposed geologic unit bedding planes. The mapped strike and dip locations could be verified in the field and updated in GIS as necessary.

The geologic maps created for this thesis project contain a minor level of exaggeration for certain small geologic unit outcrops. This type of exaggeration is generally accepted in geologic mapping professional practice and was applied for clarity, so the geologic units would be visible on the map at the utilized scale. As stated by S.M. Mathur in the Guide to Field Geology, “a little exaggeration is inevitable” (2001). While this exaggeration was deemed acceptable for this mapping project, further mapping efforts could verify the exact locations and actual extent of the outcrops. This would also be recommended if a future geologic map focused on a smaller area, or included the current mapped extent at a larger scale.

Various seismic instruments could be utilized or installed long-term in the mapped vicinity to gather geophysical data to gain a greater understanding of the subsurface geologic units. Examples of these devices include various seismometers, seismographs, and geophones. The information obtained from such investigations could be applied to updating the extent and thicknesses of the geologic units depicted in the cross sections, providing a more detailed representation of the underlying geology (Cakir et al. 2014).

A complex subsurface geology 3D model could be created in ArcGIS Pro using the geologic cross sections developed during this thesis project, as well as nearby well log information. Well logs could be obtained from the Washington State Department of Ecology website (Ecology, 2019). A fence diagram and/or a block diagram of the subsurface geology could be created utilizing the Xacto Cross Section Tool and ArcScene. The Xacto Cross Section Tool utilizes well/borehole location and geologic information in GIS to create 2D renditions of subsurface geologic cross sections. These cross sections are composed of a collection of polyline and point shapefiles, which can be digitally edited in GIS (DeMerritt 2012). The Ecology well log information can be input into a tabular x,y,z attribute format, and then visualized as 3D tubes in ArcScene. Importing all the raw data would require substantial time and effort. Using the 3D Borehole tools in ArcScene, wells and boreholes can be symbolized as tubes, and raster surfaces can be interpolated. 3D fence and block diagrams can then be created in ArcScene, resulting in a layer cake filled with the various geologic units (DeMerritt 2012).

Lastly, as new information becomes available, the geologic maps and cross sections of Badger Mountain and Candy Mountain will be updated. Future updates to the geologic maps and cross sections will now occur with greater ease, as the newly developed digital GIS data formats provide much better tools for versioning and editing than the previous hand-drawn formats. In addition, digital formats can be readily shared and downloaded between agencies and interested users.

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Appendix A Geologic Map and Story Map URLs

Github

Github was utilized to store the full-sized geologic maps for viewing and download. It also contains the additional figures included on the map layouts; the location map, correlation of map units, and geologic cross sections.

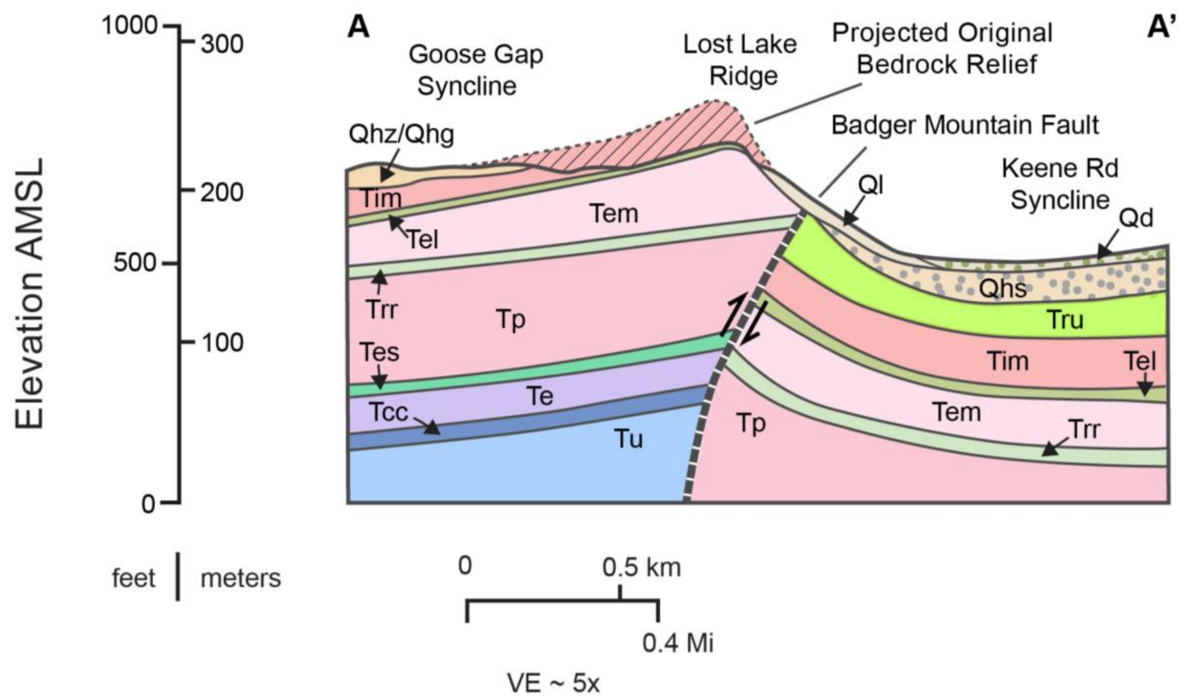
Github URL: https://github.com/pnewman88/ThesisMaps

ArcGIS Online Story Map

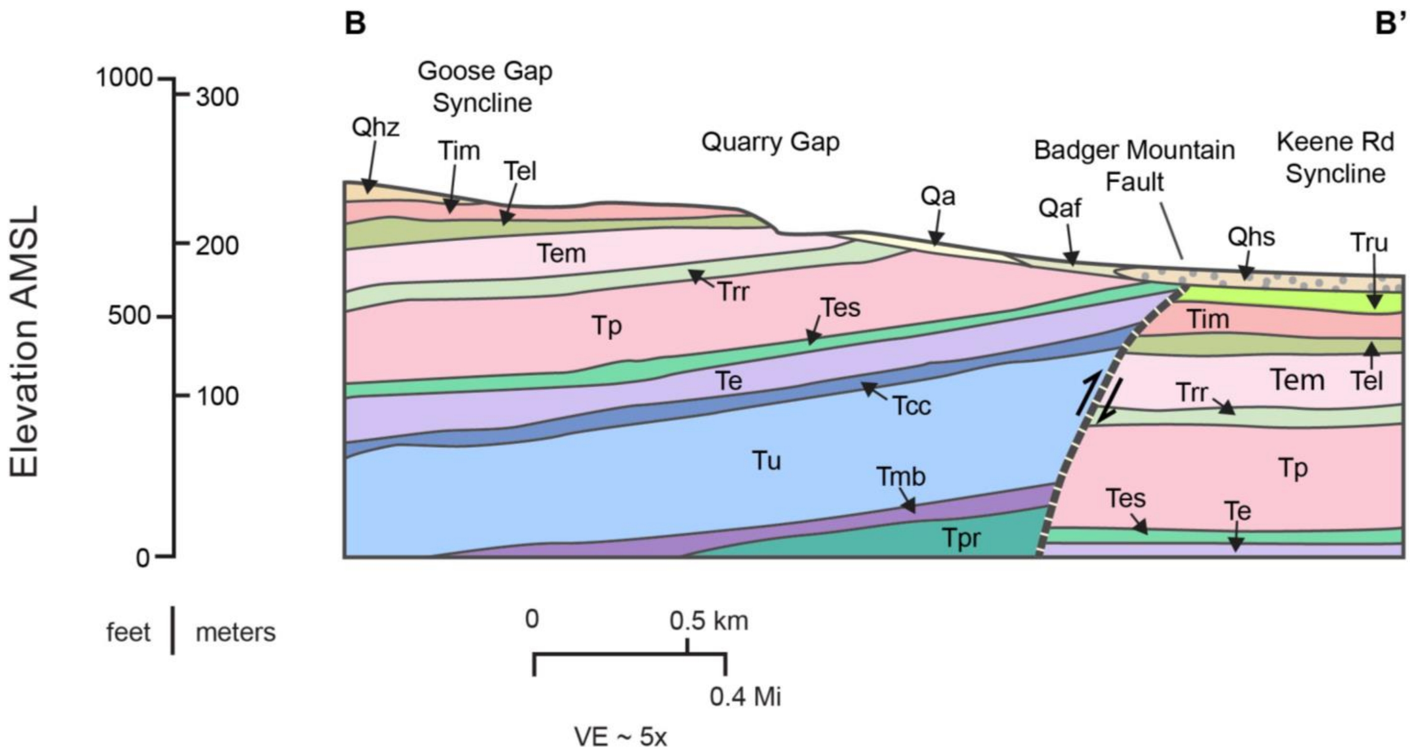
The ArcGIS Online Story Map was created to showcase the mapping results from this project, simply to facilitate sharing of the maps archived in Github. The Story Map contains the interactive 3D geologic scene, and images of the project location map, 2D geologic maps, geologic cross sections, correlation of map units, and convenient links to the Github archive throughout.

ArcGIS Online Story Map URL: https://arcg.is/1fKrDi

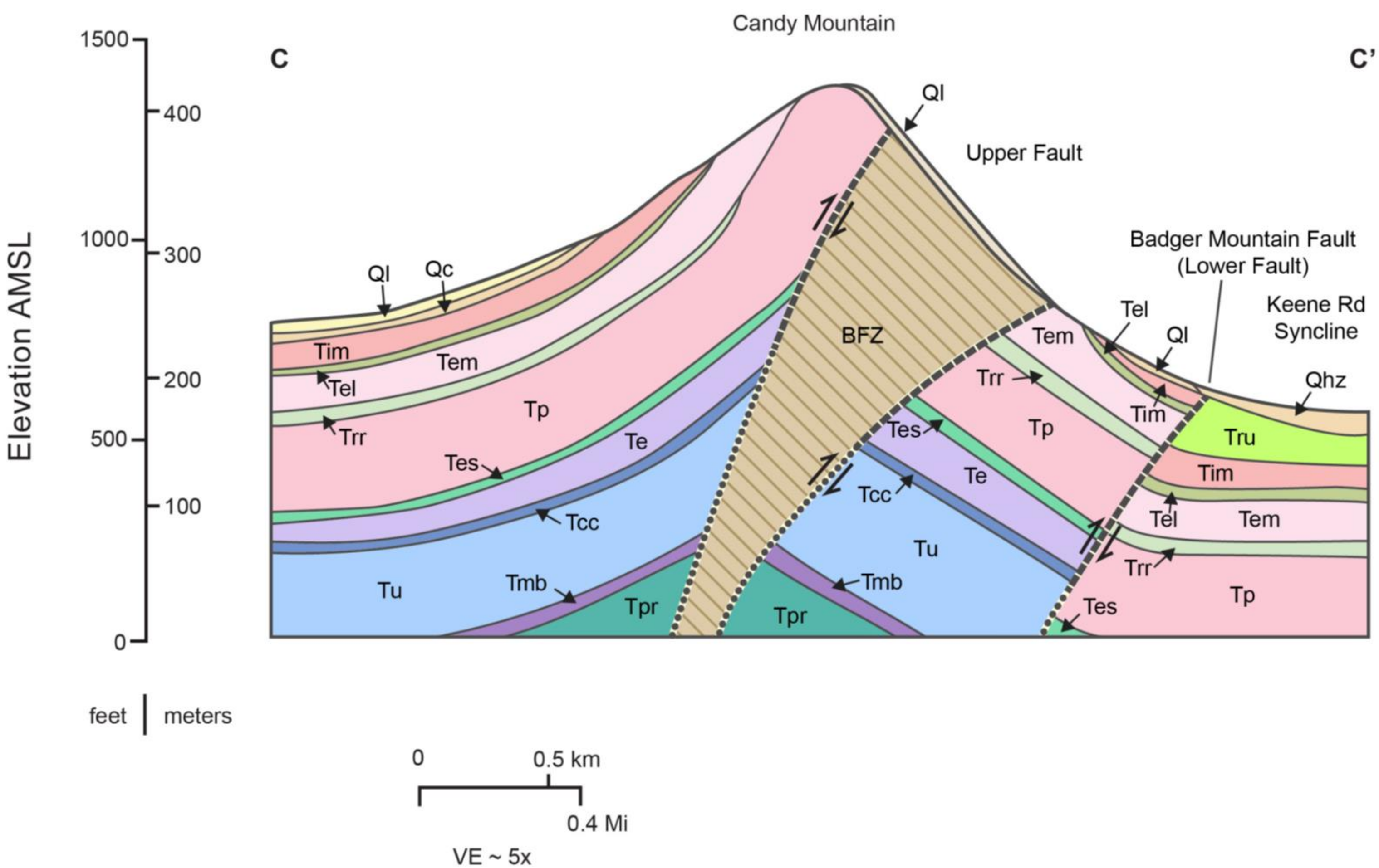
Appendix B Geologic Cross Sections



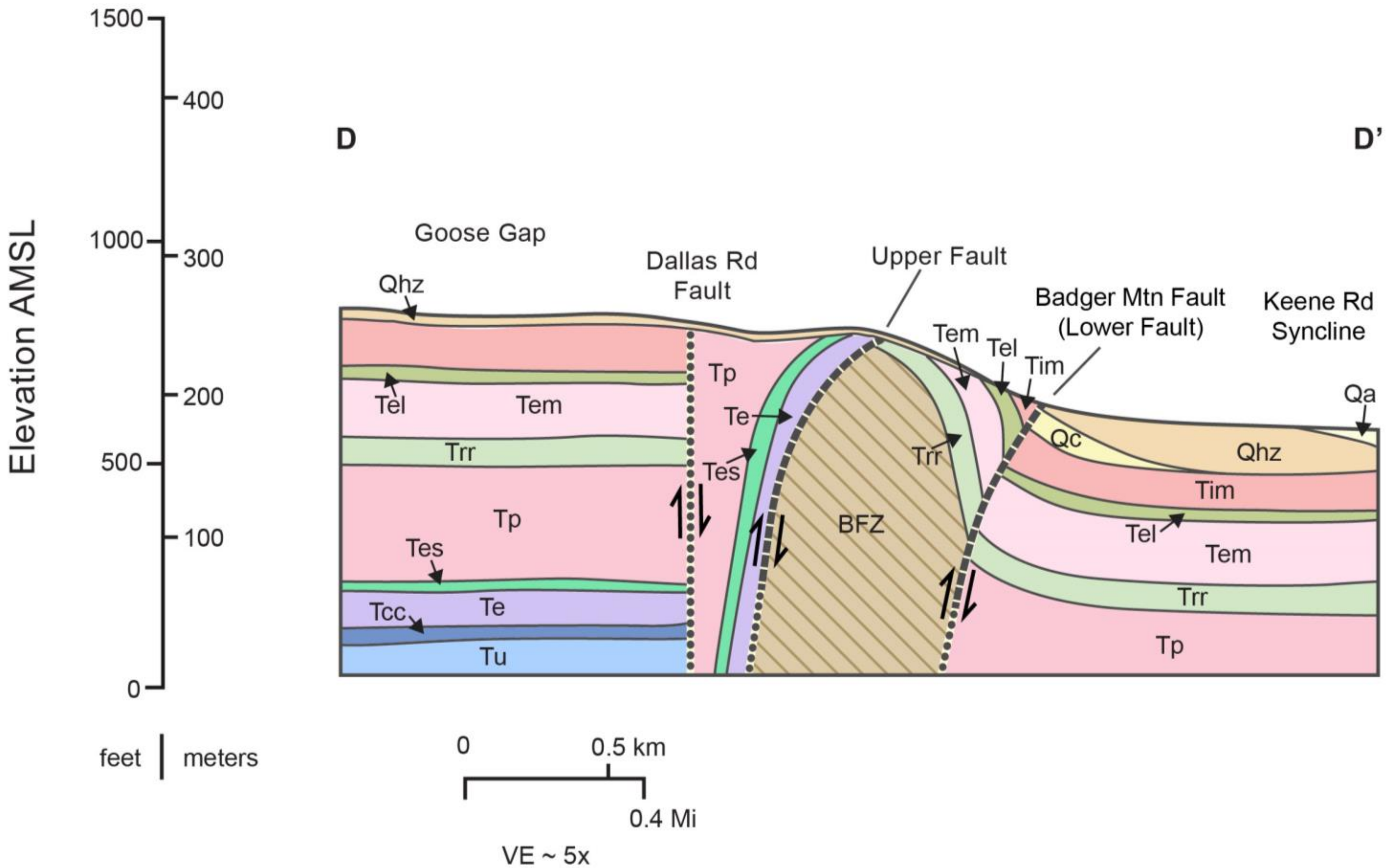
B1. Lost Lake Ridge Geologic Cross Section



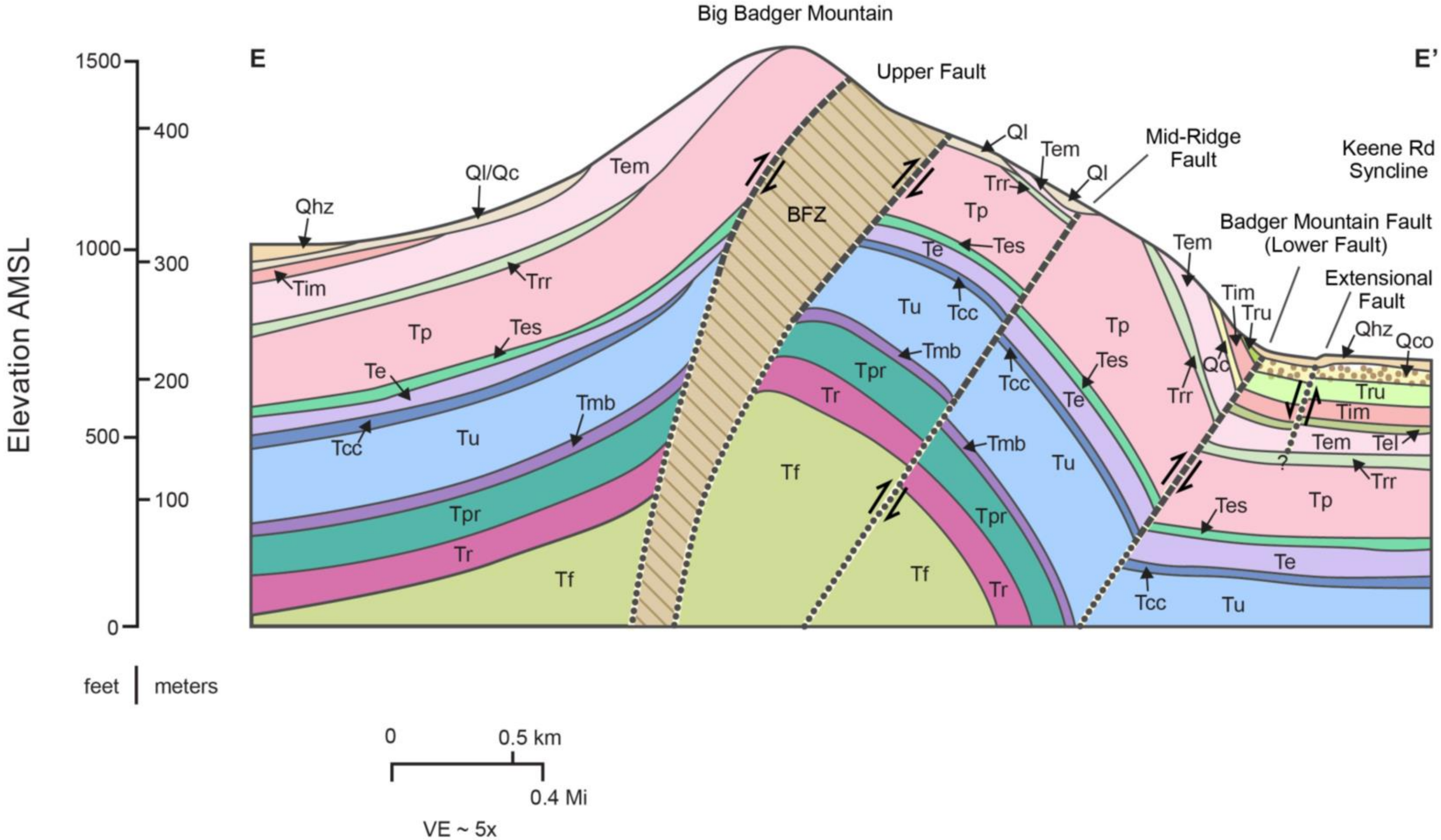
B2. Quarry Gap Geologic Cross Section



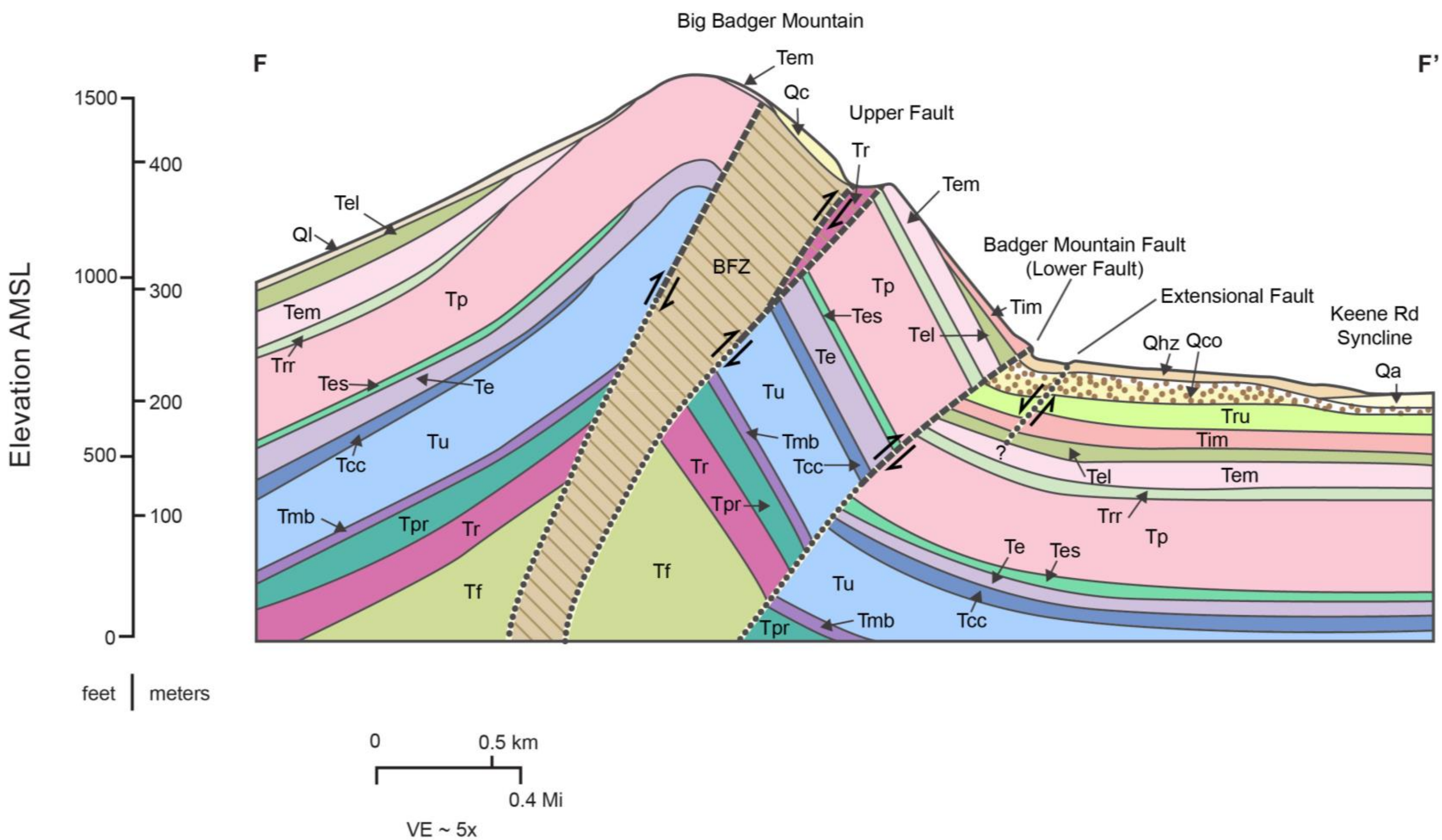
B3. Candy Mountain Geologic Cross Section



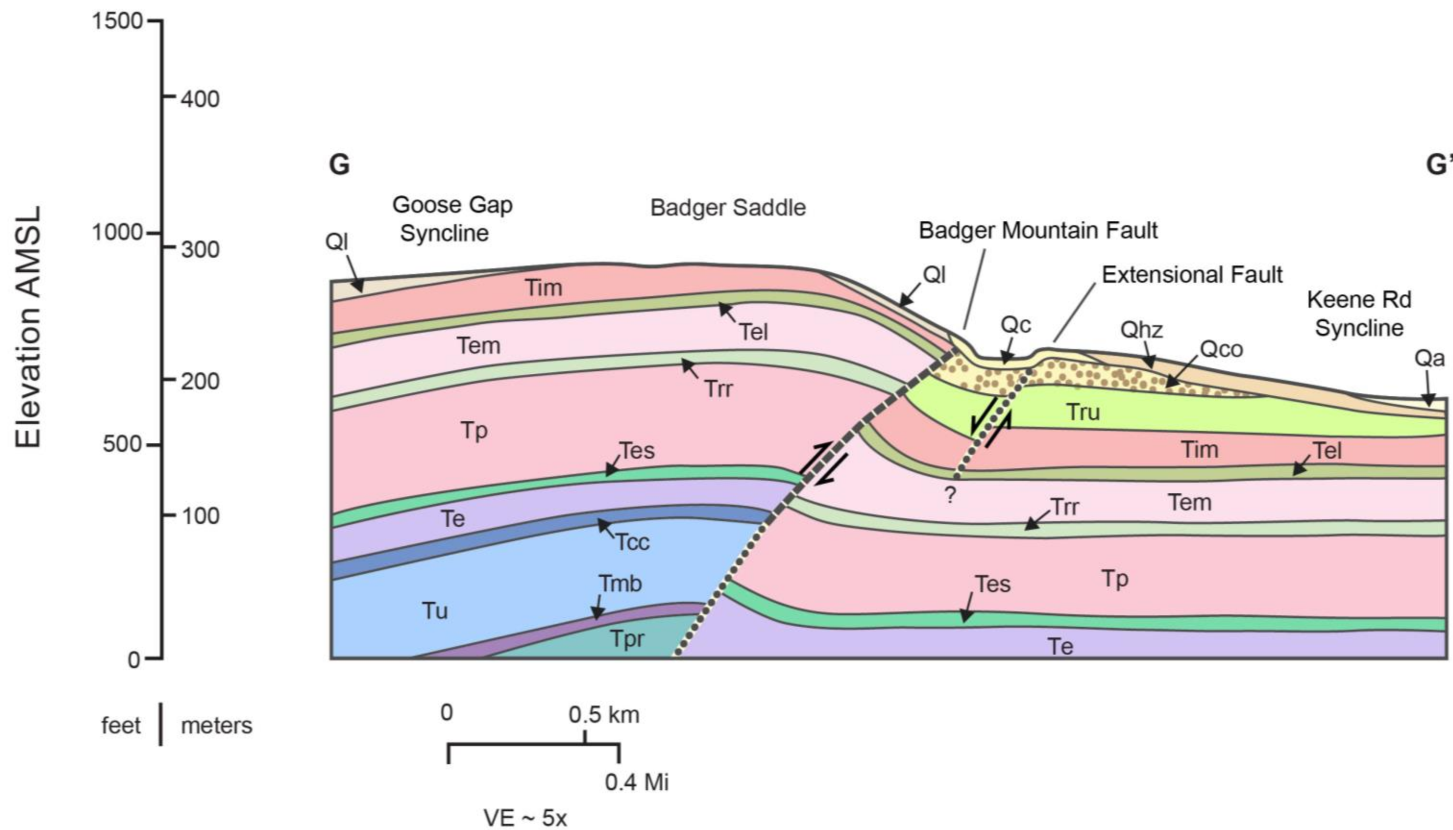
B4. Goose Gap Geologic Cross Section



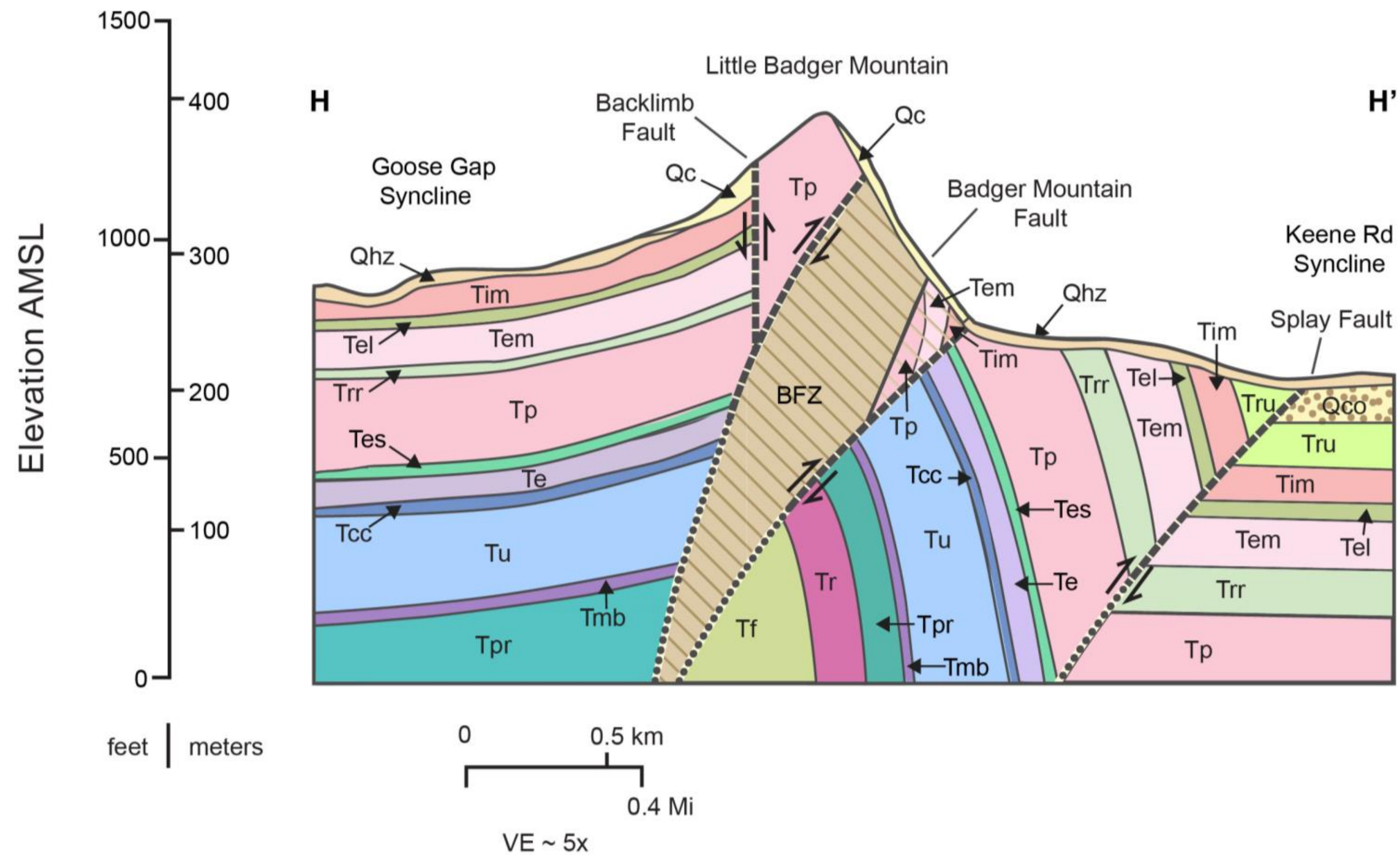
B5. Badger Mountain West Geologic Cross Section



B6. Badger Mountain East Geologic Cross Section



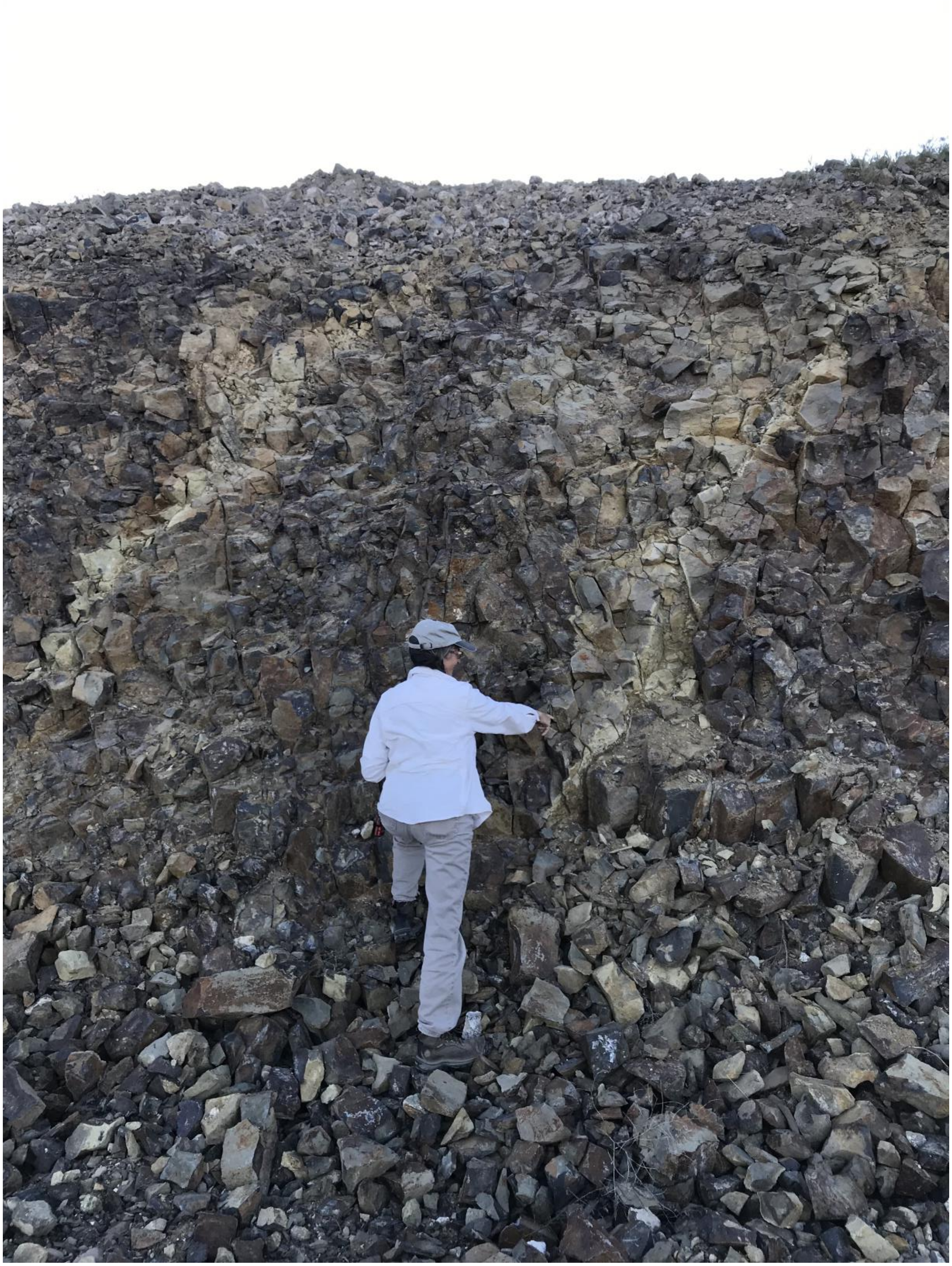
B7. Badger Saddle Geologic Cross Section



B8. Little Badger Mountain Geologic Cross Section

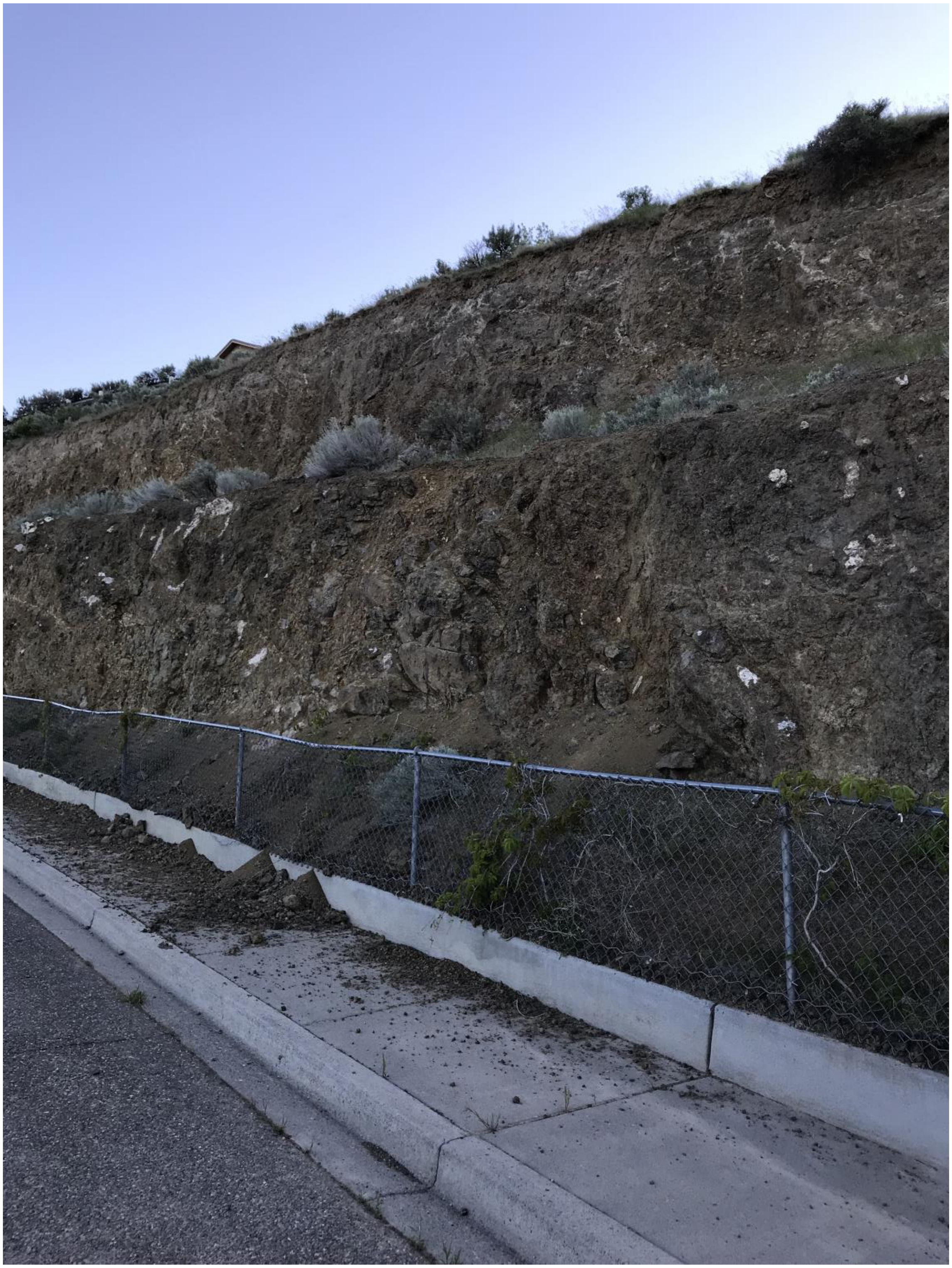
Appendix C Field Verification Photos

C1. Glacial Erratic on Little Badger Mountain



C2. Shear Zone on Little Badger Mountain (Mickie Chamness for scale)

C3. $CaCO_3$ Wall (Brecciated Fault Zone) on Little Badger Mountain



C4. CaCO3 Wall (Brecciated Fault Zone) on Little Badger Mountain (2)

C5. Mount Saint Helens Ash Layer off Kennedy Road

C6. Brecciated Fault Zone on Badger Mountain

C7. Brecciated Fault Zone on Badger Mountain (Mickie Chamness for scale)

C8. Brecciated Fault Zone and Field Map Updates on Badger Mountain

C9. Pomona Basalt Outcrop on Badger Mountain

C10. Little Badger Construction as viewed from Badger Mountain

C11. Badger Mountain Trail with Candy Mountain in the Distance

C12. Karl Fecht and Mickie Chamness in the Field on Little Badger Mountain