BIG SKY CARBON SEQUESTRATION PARTNERSHIP

National Mafic Rock Atlas Topical Report

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Executive Summary

Regionally extensive mafic rock formations, or flood basalts, are a distinguishing feature of the geology of the Pacific Northwest and the Big Sky Carbon Sequestration Partnership. The region's Columbia River Basalt Group (CRBG) covers approximately 164,000 km^2 and is probably the most well studied igneous province in the world. The Snake River Plain basalts stretching across Idaho and High Lava Plains of Oregon add to the potential storage resource area. There are over 300 lava flows that comprise CRBG alone and each flow is from a few tens of meters to 100 meters thick. All combined, the BSCSP basalt formations offer significant long-term storage potential, with conservative estimates of CO_2 storage capacity in the range of 50 - 100 billion metric tons. Basaltic provinces, however, are not limited to the Pacific Northwest. They are found throughout North America and may provide local carbon storage sites for areas lacking more traditional storage opportunities in saline formations or oil and gas fields.

In the Big Sky Region, the Columbia River Basalt formations were formed millions of years ago as lava flows cooled on the earth's surface. As successive flows cooled over time, layers of basalt were formed, each tens to hundreds of feet thick. The exterior portions of each layer cooled quickly forming cracks and bubbles, while the slow-cooling interiors cooled slowly creating dense and impermeable layers. The dense interior sections serve as cap rocks while the porous exterior sections serve as potential injection zones for CO_2 storage.

Laboratory tests have shown that basalts are very geochemically reactive and have the ability to chemically trap CO_2 in a short period of time by forming solid minerals. When basalts have been exposed to supercritical CO_2 and water in the lab setting, minerals in the basalt react with the CO_2 and water to form limestone or calcium carbonate. This geochemical process traps the CO_2 in a solid form and permanently isolates it from the atmosphere. Similar mineralization processes happen in other rock types but at much slower rates.

BSCSP is working with local partners and Battelle Pacific Northwest National Lab to conduct a small scale geologic storage test in southeast Washington State. This project is one of the first in the world to examine both the viability and capacity of deep basalt formations and will expand laboratory findings to in-situ environments. By assessing the technical issues associated with injection, fate and transport of CO_2, scientists aim to verify that these basalts are a safe and practical site for large-scale storage activities.

To support the Washington pilot project and expand the knowledge gained to the assessment of basalt provinces nationally, the BSCSP National Mafic Rock Atlas was developed. This report documents data collected and/or created for the Mafic Database and methodologies used to build the web-based, interactive Atlas. Resulting geospatial data layers, publications, and well logs were incorporated into BSCSP's geospatial database and provide national mafic rock coverage. BSCSP used the compiled data to quantify volumetric properties of large mafic rock formations and their associated hydrochemistry. Data sources used for this effort include available literature and state and national geological survey information. The data layers are made available to research teams through a versioned Microsoft SQL Server database and the public through a user-friendly, online interactive mapping application.

The interactive National Mafic Rock Atlas mapping application can be found online at http://www.bigskyco2.org/atlas/mafic.

1. Introduction

Regionally extensive mafic rock formations, flood basalts, are a distinguishing feature of the geology of the Pacific Northwest. The CRBG, which is part of the larger Columbia Plateau Province, is probably the most well studied igneous province in the world and has over 300 individual lava flows. The basalt formations in the CRBG have a number of characteristics favorable for the storage of CO_2 including: (1) mineralogy and chemical makeup conducive for rapid *in situ* mineralization of CO_2, (2) multiple very low permeability flow interior sections that can act as cap rock seals, and (3) high porosity and permeability in interflow zones suitable for CO_2 injection.

The principal goal of Task 3.0 within BSCSP Phase II was to incorporate all referenced knowledge of mafic rocks in the United States into a geospatial database for the purpose of delineating potential reservoirs for carbon sequestration. Specifically, team members worked to quantify the volumetric properties of large mafic rock formations and their associated hydrochemistry from available maps, publications, and state and national geological survey information. The Big Sky Carbon Atlas and National Mafic Rock Atlas share similar attributes, especially accessibility and interactive structures. The Task 3.0 working group merged the two systems such that reference materials remain uniquely defined for each atlas and continue to be dynamic for updates and additions as new data becomes available. Information for the National Mafic Rock Atlas was converted into Geographic Information System (GIS)-compatible files linked to references, detailed maps, geochemical data, and hydrological data to deliver a public-facing, interactive application developed in conjunction with the Carbon Atlas. Part of this process involved detailed assessments of key target areas to demonstrate the viability of building appropriate databases, as well as to fill in regions where data was not readily available in published form.

2. Contributors

Work during Phase II was initiated by Dr. Scott Hughes and Dr. Daniel Ames of Idaho State University. Several ISU students contributed to the planning, compilation of data, and website development. In 2010, the geospatial data and webpage text was transferred to Stacey Fairweather, GIS Lead for BSCSP at Montana State University, for continued maintenance and development in tandem with the Big Sky Carbon Atlas. Contributors to the National Mafic Rock Atlas include:

Technical Leads:

Scott Hughes, Idaho State University – Mafic Rock Atlas Project Leader

Daniel Ames, Idaho State University – Mafic Rock Atlas Project Leader

Stacey Fairweather, BSCSP Montana State University – GIS Technical Lead

Project Contributors:

Elizabeth Helmke, BSCSP Montana State University – former GIS Technical Lead

Susan Norman Hunter, Idaho State University – Graduate Student, GeoSciences Department

Christopher Forsgren, Idaho State University – Graduate Student, Environmental Science and Management

Desiree Staires, Idaho State University – Graduate Student, GeoSciences Department

Aaron Jones, BSCSP Montana State University – GIS Analyst

Kristen Straub, Idaho State University – undergraduate research student

3. Literature Review

The initial efforts for Task 3.0 focused on a literature review to identify information sources relating to mafic rocks in the United States. In 2007, an EndNote database was created to compile publications useful for the National Mafic Rock Atlas. The EndNote database was used to organize references relating to mafic rocks and the Pacific Northwest. In order to access the EndNote file, the user must have access to the software. In EndNote, the user can search by specific authors, titles, reference types, publication date, and key word. Some references have abstracts included. GeoScienceWorld was used as the primary search engine to obtain the information listed in the database. There are currently 1824 references included in this database, many of which were used to create the geospatial data layers in the Atlas. To make the bibliography available to partners without the Endnote software, all records were exported to text format documents. A list of key references used for creation of the National Mafic Atlas database is provided in Section 8.

4. Geospatial Database Compilation

4.1 *Geospatial Database Framework*

The National Mafic Rock Atlas framework involves a three-tiered system that requires regular maintenance. The first component is termed the client or local machine. This component is the base level of the three-tiered system and is the machine in which the database administrator manipulates data, manages the other two components of the system, and develops web services to be published on the internet. The second component of this system is the GIS Server. This machine is a server that houses map documents and toolsets and hosts web services. The GIS Server also acts as the spatial database engine, which communicates between the client machine and the relational database server. The relational database server, the third and final component of the management system, holds the National Mafic Rock Atlas database. The database administrator can manage the database from the client machine once preliminary steps are completed within the relational database server. This management system allows efficient sourcing of GIS layers to map documents published online, creates a multi-editor environment, and ensures automatic backup of several different data schemas (or multiple database owner versions) within the database.

Data management within the cyberinfrastructure design occurs through three steps: 1) staging, 2) storage, and 3) delivery. Staging is the task of collecting or accepting data from outside sources, qualifying that information, and ensuring proper documentation exists. Next, information is placed in the geodatabase, where it is stored and maintained through iterative backup procedures. Finally, the delivery portion of the process entails providing access to end users through various tools that currently exist (e.g., the Interactive Mafic Atlas or Representational state transfer [REST] endpoint).

BSCSP currently utilizes ArcGIS Server 10 Enterprise for Windows for the Microsoft .NET Framework as well as the 10 version of ArcSDE (ESRI's spatial database engine) for Microsoft SQL Server to manage the mafic rock datasets. Mafic data layers included in the database are described in the following sections.

4.2 *National and Regional-Scale Datasets*

National Mafic Rocks: Shows the distribution of large mafic provinces of the U.S. Literature reviews highlighted nineteen large provinces across the country, covering approximately 270,000 square miles (Figure 1).

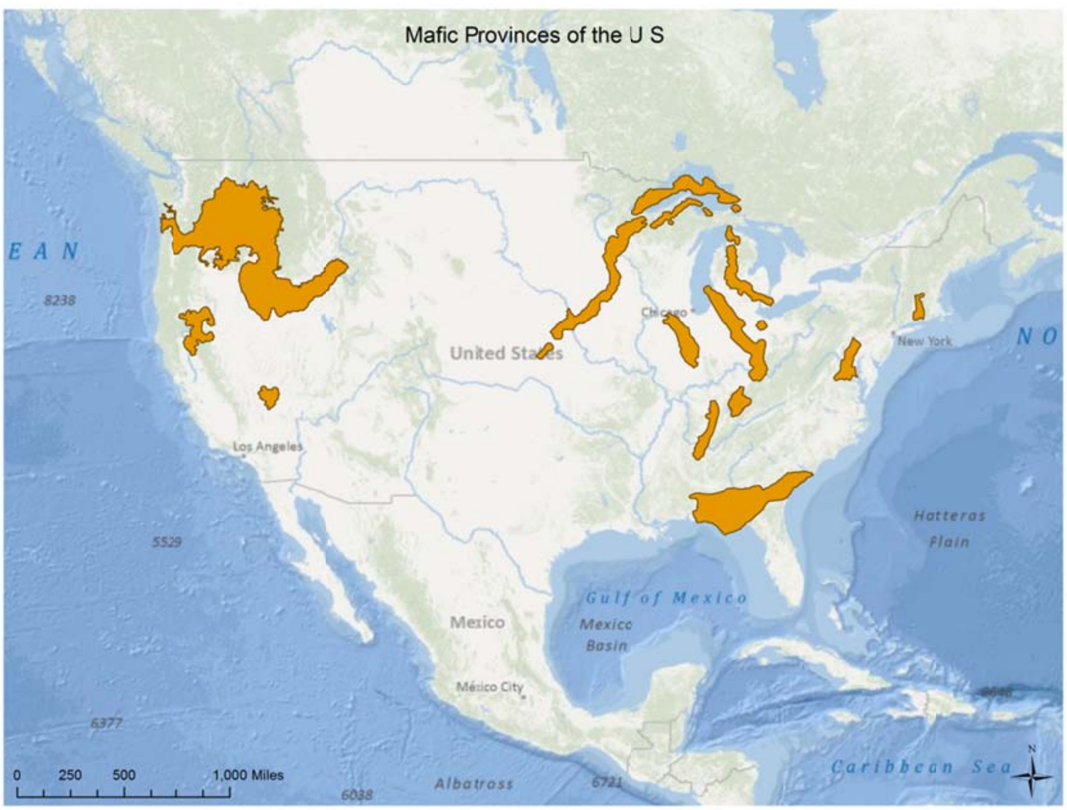

Figure 1. Map of large mafic rock provinces (in orange) throughout the United States.

BSCSP Basaltic Provinces: This dataset shows the spatial extent of the major basaltic provinces of the Pacific Northwest and within the BSCSP's area of interest. It includes the extensive Columbia River Basalt Plateau as well as the Snake River Plain basalts and the High Lava Plains of Oregon. This dataset was created as a geologic framework data layer to compare the location and proximity of large basaltic bodies to the locations of industrial greenhouse gas-emitting facilities within the Big Sky partnership region (Figure 2).

BSCSP Basalt Capacity: Rough estimates for CO_2 storage capacity in regional basalt formations have been calculated based the assumption that 3% of the mapped Columbia River Basalt Group has appropriate porosity and permeability for injection. This estimate considers only basalt formations deeper than 800 meters and with water chemistry that does not meet federal drinking water standards. The vesicular flow tops, into which CO_2 could be injected at rates reasonable for sequestration (exceeding a few hundred kilotons per year per well) are typically 15 to 30% of the flow volume. Assuming an interflow thickness of 10 m with an average porosity of 15%, the storage potential may be greater than 100 Gt CO_2. However, given the heterogeneity of flow thickness and continuity and complexities of scaling core-scale properties to regional systems, the BSCSP provides a conservative estimate of 50-100 Gt CO_2 storage potential for the CRBG (McGrail et al., 2006).

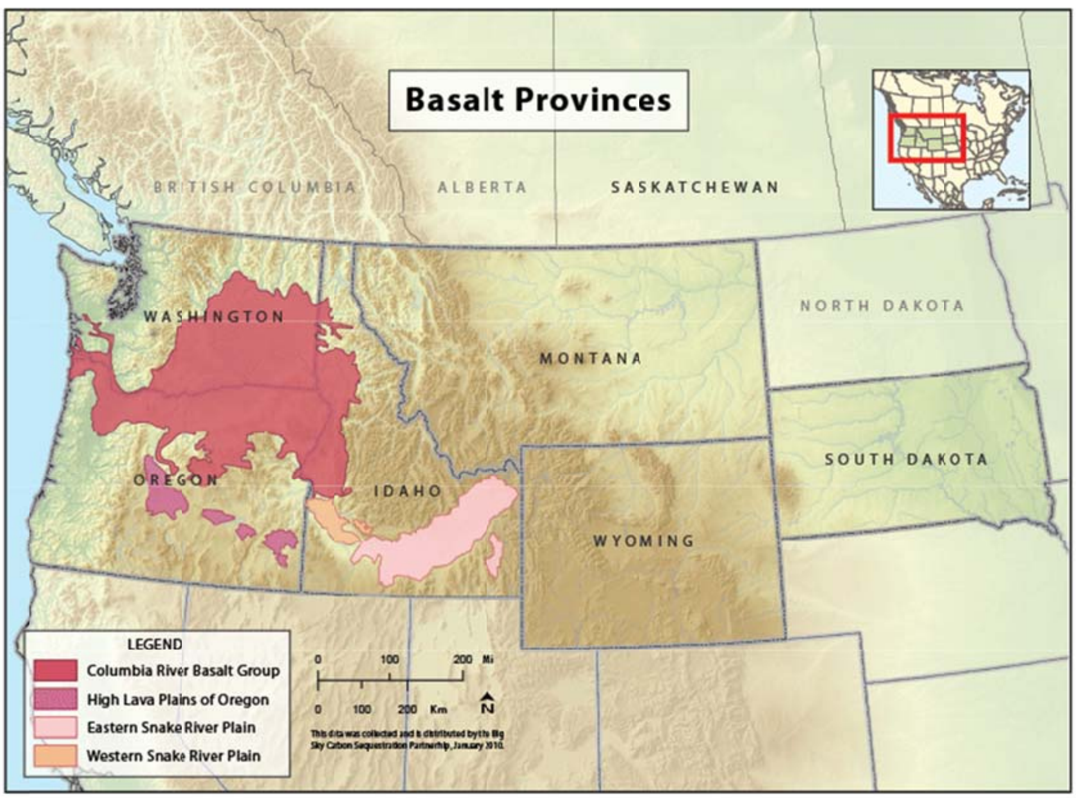

Figure 2. Four large basalt provinces exist in the Big Sky Region. The largest, the Columbia River Basalt Group, spans Washington, Oregon, and Idaho.

4.3 *Snake River Plain*

The Snake River Group basalt formations are Pliocene to Holocene in age. They consist of interbedded sediments and span over 24,000 square kilometers. Stacked basalt layers are as thick as 1,500 meters and form layered aquifers, which at depth have high total dissolved solids that make them unsuitable for drinking water.

Snake River Plain Isopach: This polygon data layer shows the thickness of basalt formations in the Snake River Plain (SRP) of Idaho. In general, SRP basalts thicken to the east (Figure 3). Volumetric information derived from geologic maps and well data has been used to generate rough estimates of carbon storage potential. Capacity estimates for the eastern SRP are estimated between 0.5 to 2 Gt CO_2 (Table 1). Large CO_2 emission sources in this area include cement production plants, electric utilities, sugar and potato processing facilities, and a chemical plant.

Table 1. Estimated capacity of Snake River Plain basalts. Efficiency factors used for these calculations are derived from methodologies for saline aquifers (NETL, 2008) and therefore only provide a coarse estimate of storage capacity.

Depth (meters)	Volume (km^3)	Capacity (Gt CO_2) 1% Efficiency Factor	Capacity (Gt CO_2) 4% Efficiency Factor
800-900	458	0.130	0.521
900-1000	335	0.125	0.500
1000-1100	229	0.110	0.440
1100-1200	140	0.078	0.312
1200-1300	66	0.040	0.158
>1300	8.9	0.006	0.022

SRP Thickness Contours: A polyline data layer showing thickness contours for Snake River Plain basalts was derived from Geological Survey maps (Whitehead, 1992). Thickness layers and depth are a primary input to carbon storage assessments as storage sites must be deeper than 800 meters.

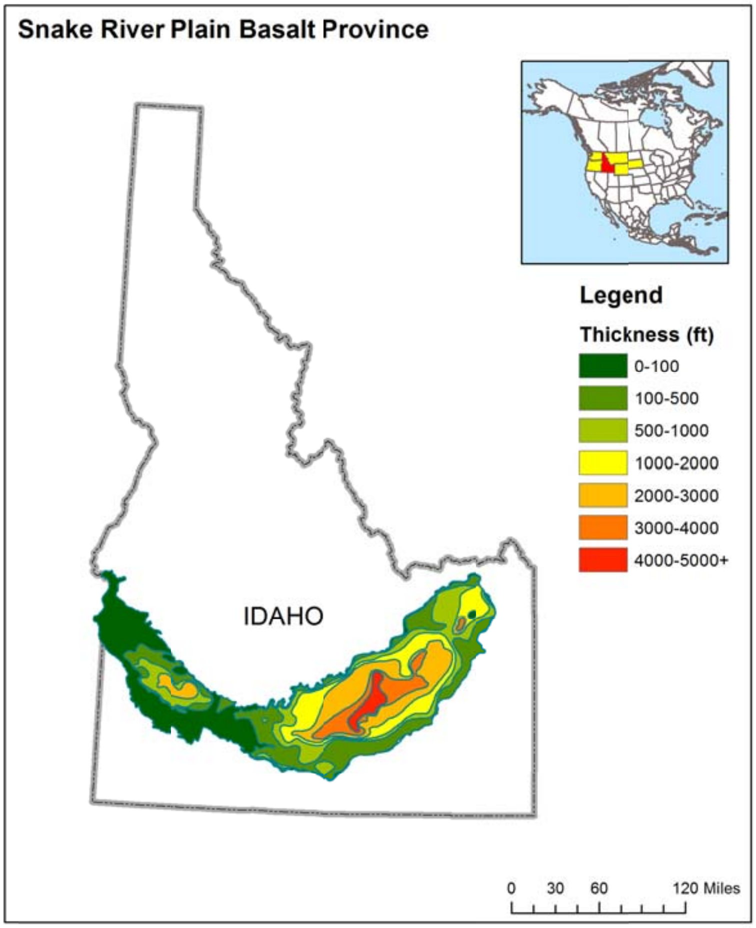

Figure 3. Map showing data layers (thickness contours and isopachs) for the Snake River Plain in Idaho.

4.4 *Columbia River Basalt Group*

The CRBG extends across parts of Oregon, Washington, and Idaho, covering approximately 164,000 km^2. These basalt formations offer significant long-term storage potential for the Pacific Northwest, an area with few traditional storage resources such as the deep saline aquifers found across the central and southern US.

<u>CRBG Formations:</u> This layer is a digital representation of the five major formations in the Columbia River Basalt Group with data documenting the volume and age of each unit (Figure 4).

<u>CRBG Members:</u> Consists of a polygon data layer of the major members of the Columbia River Basalt Group formations.

<u>CRBG Structures:</u> A shapefile containing line elements representing the major geologic structures of the Columbia River Basalt Group (Figure 4). Geologic structures in the data layer include regional faults, craton boundaries, anticlines, and magnetic anomalies.

CRBG Thickness: Generalized thickness of Columbia River basalts. The center of the basalt province is over 15,000 feet thick.

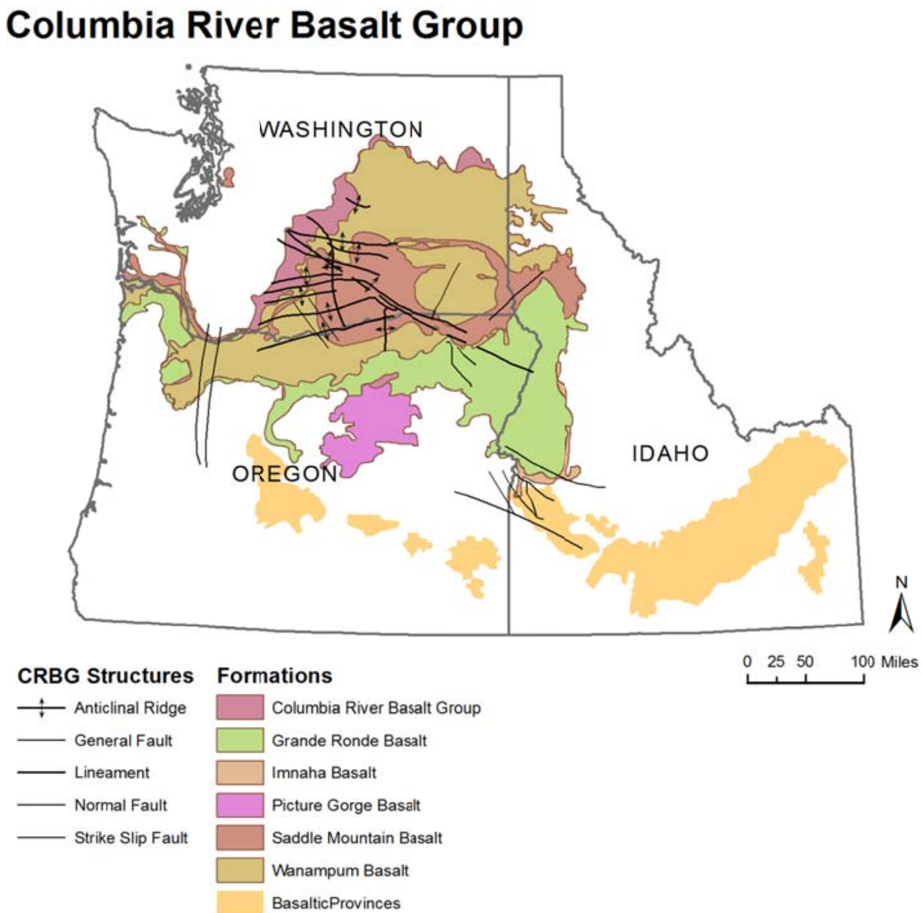

Figure 4. Geospatial data layers created for the CRBG include individual formations and large-scale geologic structures.

CRBG Wells: The US Geological Survey and Oregon Water Resources Department compiled data from borewell cuttings represented in this data layer to construct the stratigraphy and geochemistry of Columbia River basalts. The well log coordinates were used to create a point shapefile that links to more detailed geochemistry data hosted online and well log stratigraphy documents (Figure 5). A critical consideration when evaluating storage potential is water quality, specifically determining formations with water chemistry that does not meet federal drinking water standards. This data layer contains 85 well records with associated documentation.

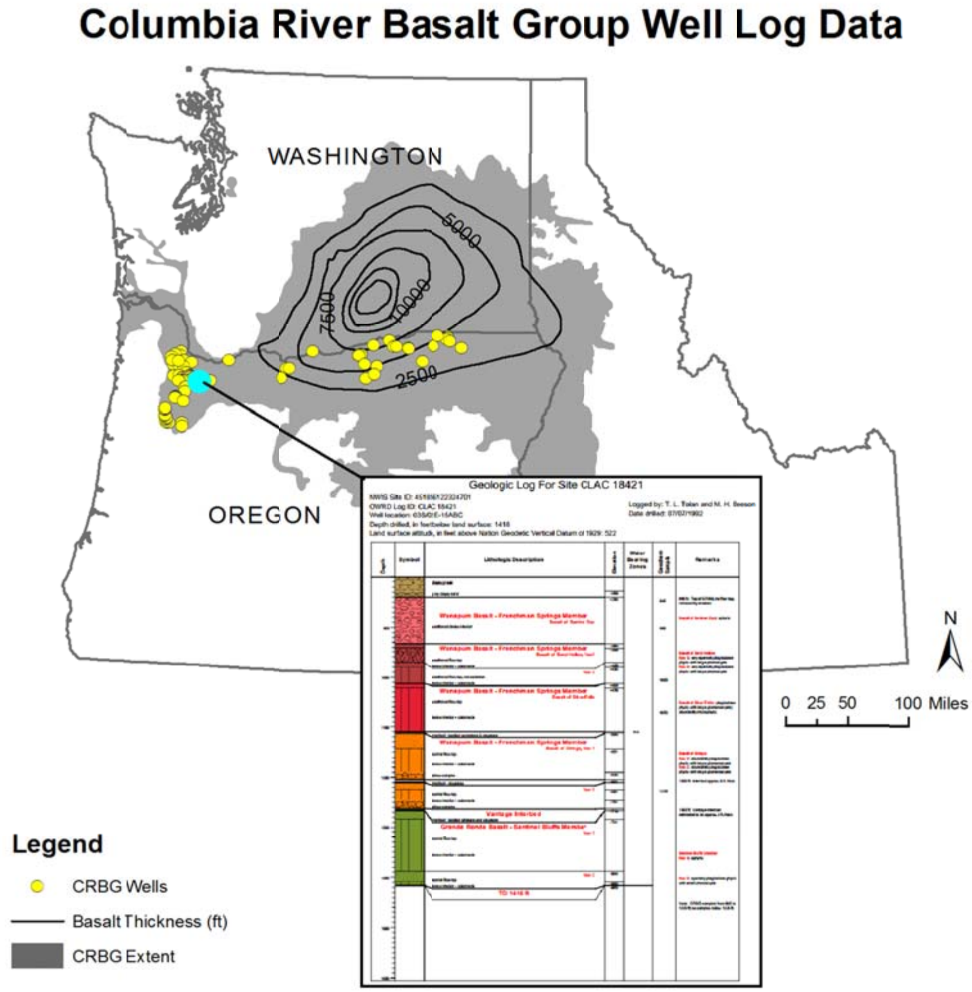

Figure 5. Point data for CRBG well locations are linked to individual well logs and geochemistry analyses. The well logs provide information on individual formations and members as well as information about basalt thickness.

5. Website Development

5.1 *Interactive National Mafic Rock Atlas*

Significant research was conducted to determine the most effective options for development of the interactive map. After comparing both server and client-side software, the Adobe Flex software development kit was selected for the final version of the online National Mafic Rock Atlas. With ESRI's Flex application programming interface and highly configurable Flex Viewer client application, BSCSP was able to develop a solution that integrated base maps hosted through third parties (including ESRI's web portal for topographic maps and Microsoft BING satellite imagery) with the National Mafic Rock Atlas geodatabase (Figure 6).

The online base imagery proved to be a significant improvement for both loading time and smooth map rendering. Originally the base layers were housed and cached within the BSCSP geodatabase. This was taxing the server and slowing the map service. Web hosted base maps are tiled and cached to allow for the most efficient use of client resources, and because the application is a mash-up of several available web services, the partnership is not responsible for housing and maintaining all the data locally.

Smaller sized point and polygon layers in the Mafic Rock geodatabase are displayed above the base layers and are accessed through the ArcServer REST endpoint. The endpoint is publically available, allowing third parties to access the shapes and metadata for their own analysis and mapping; however visibility scales and symbology are not configurable. This allows for some control by BSCSP over the scales at which the data is reasonable and accurately portrayed.

The Flex mapping application was built with navigation tools that would be familiar to anyone who has used Google Earth or Yahoo Maps, such as a zoom bar, coordinate display, mouse navigation, and a click-able compass. Adobe Flash deployment eliminates cross-browser compatibility issues and allows for a simplified version of the interactive map to be embedded in several web pages in addition to the stand-alone page.

The interactive map is integrated with the Carbon Atlas on the BSCSP website and allows users to explore well logs, geochemical data, mafic rock distributions, CO_2 emission sources, and more. A Web Feature Service (WFS) was created to supply point data for the map. The advantage of a WFS (as opposed to a Web Mapping Service, or WMS) is that individual records can be accessed, exported, and edited versus the WMS, which can only be queried. A WMS serves up the polygon data layers.

ESRI Flex code was modified to customize the interface styling and build new toolboxes. Features of the online National Mafic Rock Atlas consist of:

Streamlined header and tool bar – Along the top header there are icons for several user tools Clicking these will bring up various moveable pop-up windows with the associated functionality, including:

- Location bookmarks where the user can access preset bookmarks to quickly zoom to relevant scales or set their own
- An address finder to look up an address and zoom to that point
- Information access, where users can search by text or graphically for data layer attributes then zoom to selected features by double-clicking the result
- Live GeoRSS feeds provide near real-time information about earthquakes or carbon sequestration related news
- The drawing tool allows users to annotate the map with text, points, or polygons. Within the drawing tool there is a measure feature that can be used to find the length of a line or area of a polygon in units selected by the user.
- A print tool with preset disclaimers allows the user to title their map for printing or export.
- The legend pop-up shows all active layers selected by the client, and
- The elevation profile tool lets users draw a line across the map then extract an elevation profile based on topographic data along that line.

Layers and Controls – There are three base layer options toggled by buttons including a street map, satellite imagery, and topographic map. National mafic rocks, regional basalt provinces, and well location features are loaded initially. Using the “Data Layers…” button users can load additional layers such as capacity estimates, geologic structures, and CRBG members from the geodatabase. Once the initial load is complete, the service allows local caching so that panning and zooming around the map once layers are loaded is quick and relatively seamless.

Overview map – In the lower right corner is an overview map that expands from a click-able arrow. There is a scale bar in the lower left, and coordinates that display the location of the user’s cursor.

Splash page – As the interactive atlas first loads, a splash page is presented, which provides information about the partnership and program as well as disclaimers about data usage. A similarly formatted “About” link brings forward a pop-up with links to more detailed information for the data layers.

Help page – The functionality of all tools and features are described in the “Help” page. As end-users have questions, this page is updated with Frequently Asked Questions.

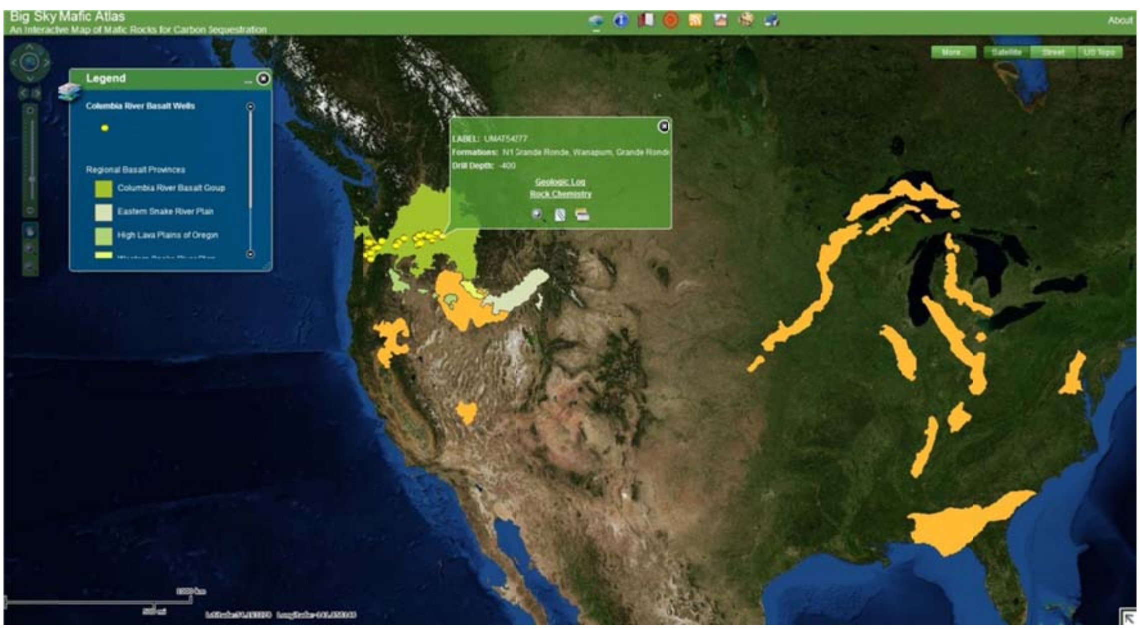

Figure 6. The BSCSP Mafic Atlas interactive mapping application.

When choosing the Flex platform, consideration was also paid to platform longevity and scalability. Future development of the Flex atlas will include partner-only functionality where users can log in and download excel files from data layers, edit data, add notes or photos, and more. This framework and ArcServer 10 also support time-series data rendering.

5.2 *Supporting Web Pages*

A simplified version of the interactive map is embedded within the BSCSP Mafic Atlas webpage. On this page, an overview and description of basalts in our partnership region provides context for the maps. The page also includes links to more information including the BSCSP basalt injection page and factsheet. Links to the interactive map user guide and frequently asked questions pages give end-users tips to customize their data exploration. Also on the Mafic Atlas webpage there are links to the Carbon Atlas Map Gallery, which houses pre-made maps for basalts as well as other geospatial data related to project research. The Data Resources page with metadata for GIS layers guides users to more detailed information. Finally, a discussion of software tools used to create the interactive maps with links to ESRI products is provided.

6. Educational Opportunities

This task offered several educational research experiences for students at Idaho State University. For a graduate degree in GIScience one student developed and assessed a set of laboratory exercises for an Advanced GIS course at ISU that teaches undergraduate students how to create, modify, and use models in ArcGIS 10 ModelBuilder. The research and lab exercises placed special emphasis on raster analysis, earth science issues, and real world problems. Each of the laboratory exercises contains background information on a hypothetical problem, written instruction on how to complete the exercise, and electronic input data related to national mafic rocks.

ISU students performed the majority of literature reviews and data collection, as well as digitization of maps. Work products derived from Task 3.0 research include:

Ames, D.P. and Michael, C. (2007). Evaluation of the OGC Web Processing Service for Use in a Client-Side GIS. *OSGeo Journal* (1), 50-56.

Norman, S.H. (2011) Development and Assessment of Eight Advanced GIS Laboratory Exercises using ArcGIS ModelBuilder (Master’s Thesis). Idaho State University, Boise, Idaho.

7. Conclusion

Completion of BSCSP Phase II, Task 3.0 National Mafic Rock Atlas has resulted in a comprehensive geospatial database utilized in several ways throughout the partnership, such as research, outreach, contribution to the National Carbon Sequestration Atlas, and CO_2 storage capacity estimates at the regional scale. Researchers and students at Idaho State University transferred all derived geospatial data, literature sources, and web service configuration files to the GIS Technical Lead at Montana State University. The layers were merged with the BSCSP database architecture and are currently hosted alongside the Big Sky Carbon Atlas. To complete the transfer process, mafic data layers were revised and updated to be compatible with existing software, and metadata was revised for consistency with BSCSP standards. The National Mafic Rock Atlas web mapping service and web feature service host thirteen data layers that feed the online mapping application. The BSCSP interactive Mafic Atlas provides a user-friendly framework for public access and exploration of information relevant to carbon storage in basalt formations. The final Mafic Atlas can be found online at http://www.bigskyco2.org/atlas/mafic.

8. Key References

This section highlight primary references used to compile geospatial data for regional basalt provinces. Geospatial data was also obtained directly from the Idaho Geologic Survey (http://www.idahogeology.org/data/idgml.asp), the U.S. Geological Survey Water Resources NSDI Node (http://water.usgs.gov/lookup/getgislist), and the Oregon Department of Geology and Mineral Industries (http://www.oregongeology.org/sub/ogdc/background.htm).

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Reidel SP and PR Hooper, eds., 1989, Volcanism and tectonism in the Columbia River flood-basalt province. Geological Society of America Special Paper 239, 386 p.

Reidel SP, PR Hooper, GD Webster, and VE Camp, 1992, Geologic Map of Southeast Asotin County, Washington. Washington Division of Geology and Earth Resources Geologic Map GM-40, scale 1:48,000

Reidel SP, TL Tolan, PR Hooper, MH Beeson, KR Fecht, RD Bentley, and JL Anderson, 1989, The Grande Ronde Basalt, Columbia River Basalt Group: Stratigraphic descriptions and correlations in Washington, Oregon, and Idaho *in* SP Reidel and PR Hooper, eds., Volcanism and tectonism in the Columbia River flood-basalt province. Geological Society of America Special Paper 239, p. 21-53.

Swanson DA, TL Wright, VE Camp, JN Gardner, RT Helz, SM Price, SP Reidel, and ME Ross, 1980, Reconnaissance geologic map of the Columbia River Basalt Group, Pullman and Walla Walla Quadrangles,southeast Washington and adjacent Idaho: U.S. Geological Survey Miscellaneous Investigations Series Map I-1139, scale 1:250,000.

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