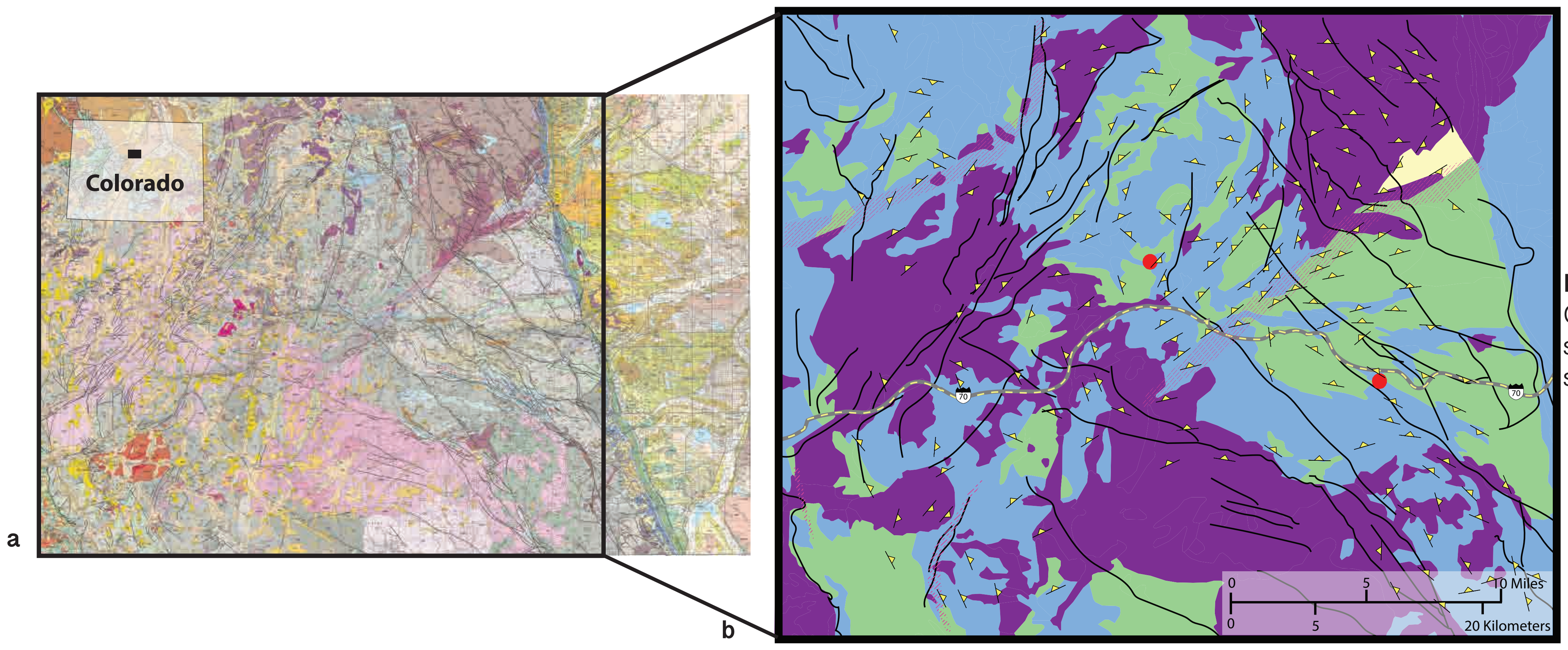
A Voyage into the Continental Crust of Central Colorado: Linking Seismic Anisotropy and Surface Geology

Jordan Wachholtz [1], Vera Schulte-Pelkum [2], Kevin Mahan [2], Omero Orlandini [2], Jonathan S. Caine[3]

1. Dept of Geoscience, University of Nevada Las Vegas
2. Dept of Geological Science, University of Colorado, Boulder
3. United States Geological Survey

Abstract

Exposed igneous and metamorphic rocks contain faults, folds, and ductile fabrics that result from lithospheric deformation, but characterizing the geometry of these structures below the surface is challenging. Analysis of crustal seismic anisotropy is highly promising but still presents challenges for interpretation, particularly in regions where multiple tectonics events have likely left their imprint in the crustal structure. One difficulty in the successful use of these data is resolving the scale difference between km-size seismic waves and the sub-mm scale microstructures that influence how seismic waves move through rock. Here, we use an interdisciplinary approach that utilizes a combination of regional geologic map data, a worldwide compilation of crustal rock elastic tensors and their properties, and a variety of seismic techniques including receiver function and surface wave analyses. We use the 1:100,000 Denver West quadrangle in Colorado's Front Range as a first test of this methodology. Using a simplified lithologic map and applying best-fit elastic tensors selected from the compilation, we homogenized the seismic properties across the whole study area. Results show 2.4% Vp anisotropy with NE-SW striking slow plane and NE dipping fast axis. We compare the modelled anisotropy with receiver function seismic data from two stations in the study area and with published regional surface wave anisotropy. Further analyses will be aimed at determining what fabric orientations dominantly influence anisotropy in the subsurface and the relationship between fabric orientations and anisotropy as a function of depth. The successful scaling between microstructures and seismic waves allows the methodology to be applied to structurally complex crust anywhere there is recorded seismic and regionally available structural geologic data, with the ultimate goal of characterizing crustal structure at the scale of the entire continent.



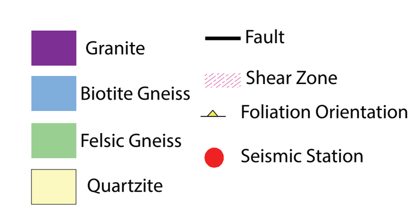


Figure 1. a) The 1:100,000 Denver West Quadrangle by Kellogg et.al. (2008). **b)** The simplified lithologic map used to model the seismic properties across the region.

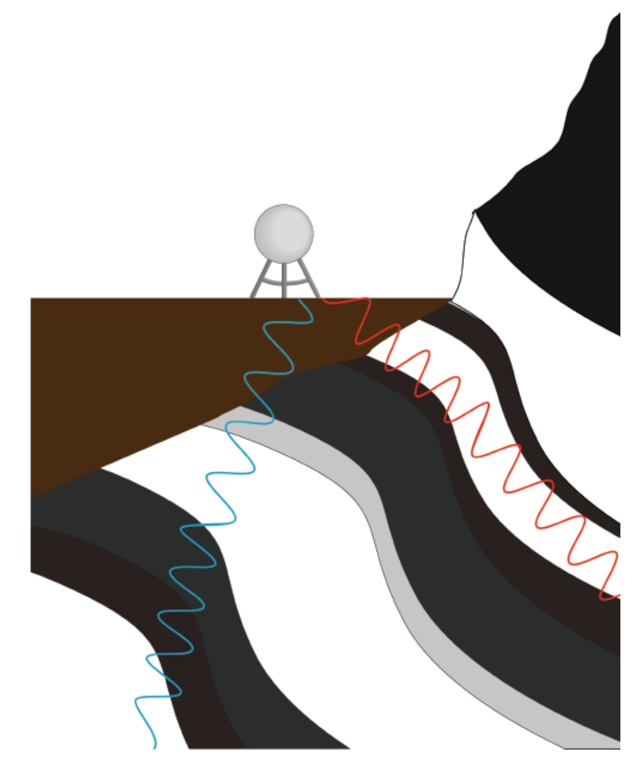


Figure 3. Illustration explaining seismic anisotropy. The red wave moves along one layer at a faster rate than the blue wave navigating multiple layers.

Methods

Simplified Lithology

We focused on crystalline basement rocks, ignoring overlying, phanerozoic units. Units were simplified further by grouping units that behave similarly:

Biotite Gneiss, Felsic Gneiss, Granite, Quartzite

Synthetic Thin Section in ArcGIS

- **Fishnet Tool** - create a grid over study area
- **Thiessen Polygon** - smooths structural data
- **Spatial Join** - Applied the lithology and orientation to each cell in the grid by joining them to the lithology and orientation layers.

In this project, we treat the simplified map like a thin section to determine seismic properties.

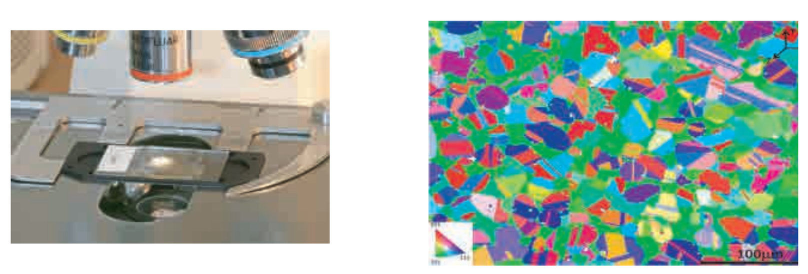


Figure 3. Example of a thin section (far left), and mineral assemblage "map" (left). Seismic properties are determined from thin slices of rock samples that are then analysed to determine their orientation.

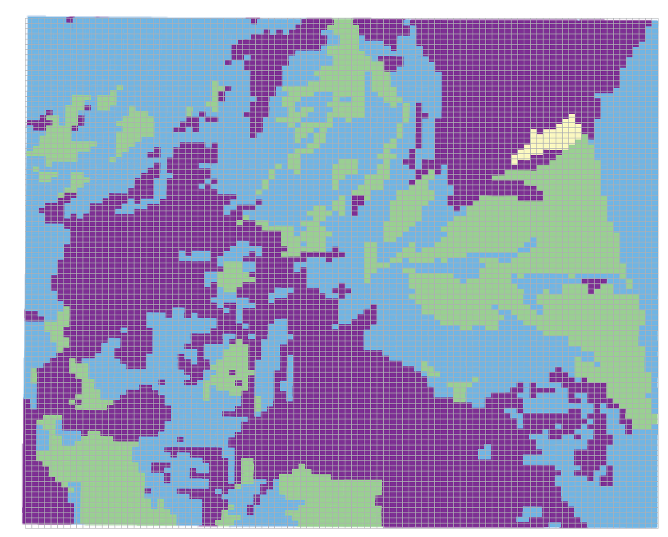


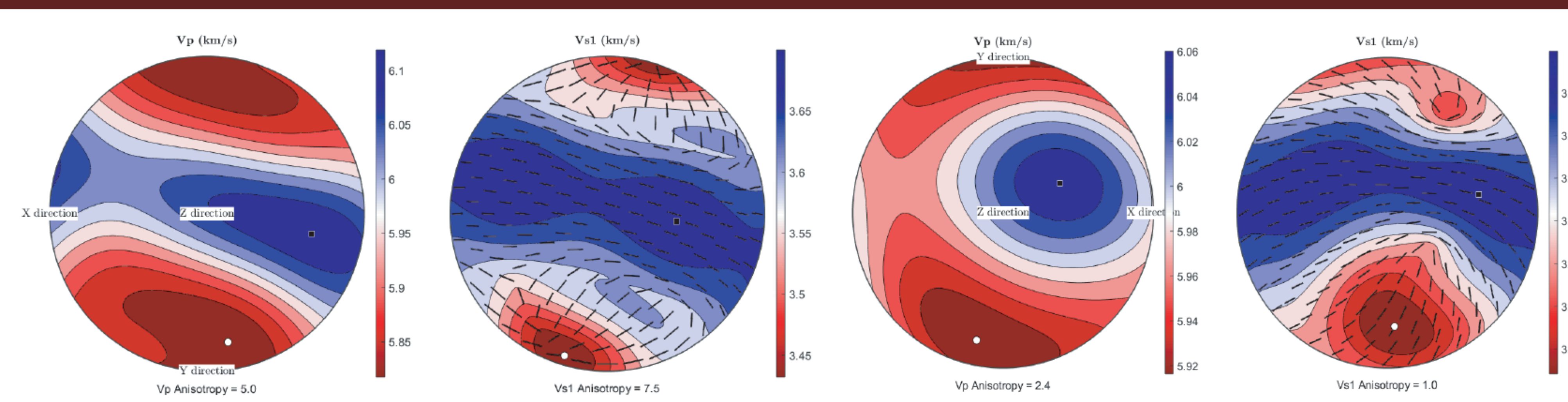
Figure 4. Resulting map of the study area with 100x100 cell grid. Each grid has strike, dip, lithology, and (x,y) coordinate attributes that can be exported as a text file.

Modelling

The Elastic and Seismic Properties Toolbox (Cook et.al., 2018) allows us to model the seismic behavior of the whole region as if it were a thin section.
For this project, the we took 4 tensors from the database compired by Brownlee et. al. (2017) including:

> Biotite Gneiss (Tensor 41)
> Quartzofeldspathic Gneiss (Tensor 55)
> Quartzite (Tensor 12)
> Plutonic tonalite (tensor 83)

Results



Assuming Vertical Orientation

Velocity of the P and fast S wave show an anisotropy of 5-7.5%.

It has a clear fast plane going W-NW, and dipping slightly E-SE.

Considering structural Orientation

Applying orientations across the map area, the velocity of the P wave shows 2.4% anisotropy.

The P wave velocity shows a weak, N-S slow plane dipping west, with a east plunging fast axis.

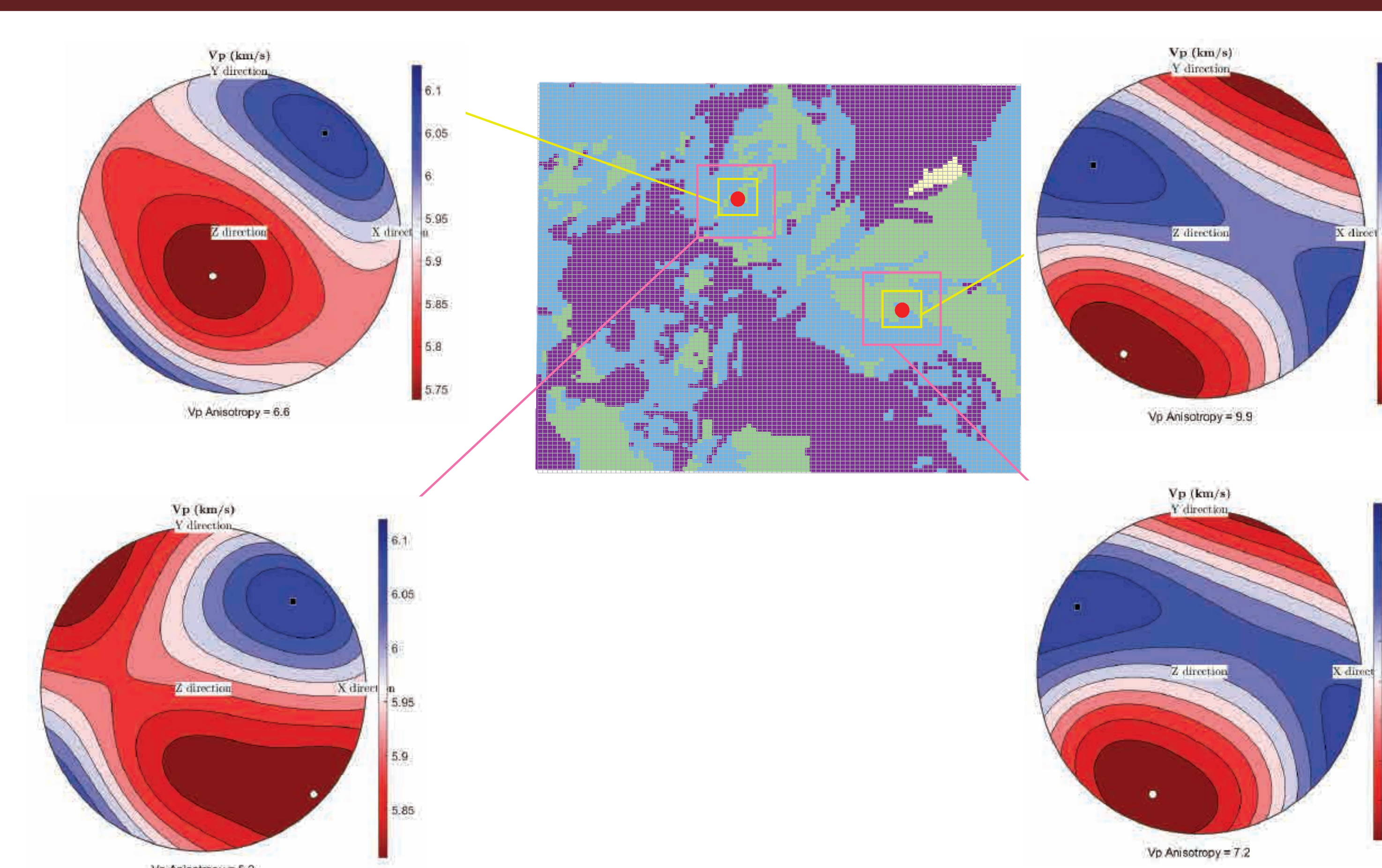


Figure 7. Modelled seismic properties for smaller subset of the study area centered around the seismic stations. Yellow boxes represent a 25km² area and pink, 100 km² area.

Discussion

From the model, we can see that orientation plays a significant role in the amount of observed anisotropy as applying rotations to the same set of properties resulted in the anisotropy of the P wave velocity being halved.

The resulting plots of modelled anisotropy do not conclusively correlated to the measured anisotropy from recorded at the two seismic stations in the area.

The orientation of the model does appear to coincide with the orientation of the foliations measured in the quadrangle. One possible explanation of the modelled orientation is that multiple orientations with a fast plane and slow axis

Future Areas of Research

>> Testing the area with different set of seismic properties to see how the overall area if changed.

>> Analysing the seismic data from the stations at different depths to determine how far into the subsurface these fabrics go.

> Investigating the role of the Idaho springs Shear Zone in the region.

Conclusion

The Earth's crust preserves deformational structures and fabrics at depth that inform the evolution of the continental crust. By understanding these processes, we can better estimate seismic hazards in on low-activity faults, as well as characterize crustal dynamics. Here we present a quantitative approach that combines the seismic properties of rocks and structural data to model the seismic behavior of formations in the Front Range of Central Colorado. The successful application of this method to a small area will help achieve the ultimate aim of applying this approach at the continental scale.

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