The Fold Analysis Challenge:

A Virtual Globe-Based Educational Resource

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1 **Abstract**—We present an undergraduate structural geology laboratory exercise using
2 the Google Earth virtual globe with COLLADA models, optionally including an interactive
3 stereographic projection and JavaScript controls. The learning resource challenges stu-
4 dents to identify bedding traces and estimate bedding orientation at several locations on
5 a fold, to fit the fold axis and axial plane to stereographic projection data, and to fit a
6 doubly-plunging fold model to the large-scale structure.

7
8 The chosen fold is the Sheep Mountain Anticline, a Laramide uplift in the Big Horn Ba-
9 sin of Wyoming. We take an education research-based approach, guiding students
10 through three levels of difficulty. The exercise aims to counter common student miscon-
11 ceptions and stumbling blocks regarding penetrative structures. It can be used in prepa-
12 ration for an in-person field trip, for post-trip reinforcement, or as a virtual field experi-
13 ence in an online-only course. Our KML scripts can be easily transferred to other fold
14 structures around the globe.

1. Introduction

Students of structural geology must master challenging spatial skills including map-making, map interpretation, cross-section construction, and stereographic projection. Several previous workers have tackled these challenges using the Google Earth virtual globe. See, for example, Jonathan Dyess and Vicki Hansen [web site A], and Barb Tewksbury [web site B]. We here add an interactive exercise to help students understand and visualize plunging and doubly-plunging (periclinal) folds.

What instructors think students see	What students see
Traces of strata intersecting the surface	Paint stripes
North and south	Up and down
Horizontal and vertical	East-west and north-south
Eroded bodies of rock	Unchanging bodies of rock
Sloping topography	Dipping contacts
Curved traces of planar structures	Folds
Down-stream direction	Down-dip direction
Apparent dip	Strike

Table 1: Common student misconceptions.

The Fold Analysis Challenge takes an education research-based approach (e.g., McKenzie, 1999) and helps students overcome geospatial learning difficulties and misconceptions (Table 1. See also Supplementary Documents). The exercise challenges students in three stages:

Stage 1: Recognize inclined strata near midway along the anticline's exposure, where the axis is approximately horizontal and estimate dips on the two limbs;

1 Stage 2: Fit bedding planes around the northwest plunging nose of the fold by
2 orienting model planes on the surface and corresponding great circles on the
3 stereographic net, and;

4 Stage 3: Fit a periclinal fold model to surface traces formed by the intersection of
5 bedding and topography in three dimensions.
6

7 As pointed out by Kali and Orion (1996) and Tewksbury and Tewksbury (2009), many
8 students have poor penetrative visualization abilities and make non-penetrative interpre-
9 tations of surface features, seeing differently colored strata on a map or a topographic
10 surface as two-dimensional paint stripes rather than the traces of three-dimensional sur-
11 faces that expert professionals envisage extending into the subsurface. Tewksbury and
12 Tewksbury (2009) recommend introducing students to dip first, and then strike, using
13 inclined strata before horizontal or vertical ones, which is the approach taken here in
14 Stage 1. Lisle (2004) reported a common misconception that limbs must have equal
15 dips in opposite directions, a misconception that Stage 1 helps to dispel.

16 Stage 2 is confined to an inclined and plunging, but approximately cylindrical, portion of
17 the structure at its northwest end. It includes a standard structural geology laboratory
18 exercise which involves measuring the dips and strikes of cylindrically folded strata,
19 plotting poles to bedding on a stereographic projection, and determining fold axis and
20 axial plane orientations.

21
22 Textbooks and laboratory manuals commonly use simplistic block diagrams to present
 folds as cylindrical and constant in plunge along their length. To counter this misrepre-
 sentation, Stage 3 presents students with the dilemma that a constantly plunging cylin-
 drical model doesn't fit the data along the length of the anticline's exposure.

To guard against gender-based differences in performance, we present this exercise as a personal challenge rather than a competitive game. Research shows that girls enjoy puzzles and collaborative challenges but are put off by combative interfaces involving student-student competition (e.g., Johnson et al., 1985). Giorgis (2015) found that female structural geology students had lower spatial visualization scores than males in pre-tests, but that exercises using Google Earth closed the gender gap, as females made larger learning gains than males in post-tests. Thus the efficacy of the virtual globe approach has been tested and established.

2. Big Horn Basin and Sheep Mountain

The exercise is based around Sheep Mountain¹ (Fig. 1), an iconic American field location in the Big Horn Basin of Wyoming [web site C]. Both the Big Horn Basin in general and the Sheep Mountain structure in particular have been extensively studied (Stephens, 1938; Johnson et al., 1965; Livaccari et al., 1981; Hennier and Spang, 1983; Johnson et al., 1985; Rioux, 1994; Banerjee and Mitra, 2004; Stanton and Erslev, 2004; Bellahsen et al., 2006; Fiore Allwardt et al., 2007; Sanz et al., 2008; Amrouch et al., 2010 a,b; Lovely et al., 2010; McAttee, 2011; Barbier et al., 2012 a,b; Daniel et al., 2012; Malinconico, 2012; Brown, 2014). Sheep Mountain is the destination for many annual field excursions, [e.g., web sites D, E]. It has featured in the Earth Science Picture of the Day, [web site F], the Earth Science World Image Bank, [web site G], and Pinterest, [web site H], and is the most common result of a google image search for “plunging fold.” Three dimensional printed models of the structure have been constructed [web site I].

¹ Note that there are a number of locations in Wyoming by this name and a search in Google Earth defaults to the wrong place. The correct field area is most easily found by searching for the town of Greybull WY and exploring 10 to 20 km to the north-northwest, just east of Route 26. If you reach the town of Lowell, you’ve gone too far!

1
2 The anticline is almost entirely within public lands and is accessible to four-wheel drive
3 vehicles via a dirt road or by moderately strenuous hiking. Nevertheless, only a small
4 number of students get to visit it in person, consequently a virtual field exercise is war-
5 ranted. This exercise can be used in preparation for an in-person field trip, for post-trip
6 reinforcement, or as a virtual field experience for students who are not able to visit in
7 person, such as students in online-only courses or students who use wheelchairs.

8 The Big Horn Basin is a Phanerozoic sedimentary basin containing strata of Paleozoic
9 through Cenozoic age resting on Precambrian basement. These rocks were deformed
10 in basement-cored folds during the Paleocene Laramide Orogeny (Livaccari et al.,
11 1981). One such fold, the Sheep Mountain Anticline (Fig. 2), exposes rocks from the
12 Madison Formation (Mississippian karstic limestones) through the Fort Union Formation
13 (Paleocene sandstones, shales, and coals) (Rioux, 1994). Hennier and Spang (1983)
14 and Stanton and Erslev (2004) interpret the anticline to be cored by a pair of oppositely
15 dipping basement thrusts (Fig. 2 inset).

16 The surface traces of strata on the limbs of Sheep Mountain Anticline make magnificent
17 flat irons and hogbacks (Fig. 3). By using a virtual globe interface, students can view
18 surface traces from different camera angles and discover their three-dimensional form
19 when viewed in a certain direction such as along the strike of a bedding plane or down
20 the plunge of a fold.

21 **3. Design and Student Experience**

22 The Fold Analysis Challenge is available at: <http://geode.net/fac>. We created two ver-
23 sions, a KMZ archive that can be downloaded and opened with the Google Earth desk-
24 top application, and an online version that uses the Google Earth web browser plugin

1 and application program interface (API). The API version benefits from a stereographic
2 net in an interactive screen overlay, following the method of Dordevic (2012). However,
3 the plugin has been deprecated owing to security issues with plugins in general. It still
4 works in selected browsers (Safari and Firefox but not Chrome or any Windows 8
5 browser) but will not be further supported. A non-plugin API is under development by
6 Google and we will adopt that if and when it is released. If Google does not deliver a
7 non-plugin API, we will port the API version to the Cesium virtual globe, which does not
8 require a plugin [web sites J, K]).

9 **4. Desktop Version**

1 Before starting the challenge, students are invited to seek help with basic Google Earth
0 navigation. Although Google Earth is renowned for its user friendliness, previous studies
1 by the GEODE² research group have shown that students' lack of familiarity, or discom-
1 fort with, navigation details—such as changing the camera view angle or moving with a
1 combination of mouse and keyboard controls—presents a significant hindrance to learn-
2 ing in the virtual globe environment (Coba et al., 2015). This is especially true in the
1 desktop version which does not permit custom buttons and sliders to be coded in.

3 *4.1 Stage 1*

1 In the first stage of the challenge, students are presented with two sites on either limb of
4 the periclinal fold near its crest, thus minimizing the topographic effect of plunge (Fig.
1 4a). An interactive COLLADA model (De Paor, 2007) of a semi-transparent red plane
5 intersects the terrain at both sites. It is pre-set to the correct strike so that students need
1 only adjust the dip. They can do this by selecting a value from a folder of radio-buttons
6 that load models with incrementally increasing dip until the model plane coincides with

1 ²NSF DUE 1323419: Google Earth for Onsite and Distance Education (GEODE).
7

1 the surface trace of a stratum in the flat irons. The interactive plane helps students to
2 distinguish strata from other planar structures such as joints, faults, and planar erosional
3 surfaces, by highlighting the fit to stratigraphic color variations. When students are satis-
4 fied with their bedding planes, they find the trend of the fold axis by aligning the stereo-
5 graphic net with the near-horizontal intersection of the two great circles (Fig. 4b).

6 4.2 Stage 2

7 Students must next fit the strike of strata at seven sites distributed about the northwest-
8 plunging nose of the anticline (Fig. 5a). The dips are preset and visible on the net. Site 1
9 is much like Stage 1's first site, so the fitting of strike starts simply and becomes pro-
1 gressively more challenging around the fold nose. As they fit bedding planes on the
0 map, students may notice a clustering of great circle intersections on the net (Fig. 5b).

1 Their next task is to fit a plunging fold axis (green arrow) by selecting from a limited
1 range of preset plunge and trend radio buttons. Students then fit the fold's axial plane
1 which is represented by a semi-transparent blue COLLADA model (Fig. 5c). This plane
2 is constrained to contain the fold axis and therefore has only one degree of freedom,
1 namely rotation about that axis. This rotation angle was termed *lean* by De Paor (2001).
3 It can be described either in the range -180° to $+180^\circ$ as viewed in the down plunge di-
1 rection, with zero vertical, or as an hour-angle (9 o'clock, 10 o'clock, etc.). As seen in
4 Figure 5, the Sheep Mountain Anticline leans to about 1 o'clock and this adjustment
1 causes the axial plane to align well with successive hinge exposures. The angle of lean
5 completes the triad of Euler-related angles—plunge, trend, lean—for a linear structure
1 with an associated plane (e.g. a fold), as opposed to strike, dip, rake, which describe a
6 plane with an associated lineation.

4.3 Stage 3

The third Stage of the challenge presents students with three-dimensional COLLADA models of bedding to fit to strata. The cylindrical fold that fits surface data at the northwestern end is clearly incompatible with the horizontal axis in Stage 1 and with the oppositely plunging cylindrical model at the southeast end (Fig. 6a). A simple oval surface can be displayed (brown surface in Fig. 6b) but it is only an approximate fit to the data. COLLADA models for the northern, central, and southern regions were adjusted to fit the actual geometry of the fold. The gorges separating the COLLADA models provide two natural cross sectional exposures that students can examine up-close (Fig. 6c). The central part is well served by a simple inclined cylindrical surface, but the plunging ends require conical surfaces. The sections are slightly different in width due to the shape of the outcrop and each is fitted to the stratum that best displays the flat irons locally. Students select the altitudes of the best-fit surfaces to maximize the fit to bedding traces. They can now make sense of the tooth-like exposure patterns on the Rioux (1994) map (Fig. 2) where erosion has incised the surface of the fold. Students can also observe that opposite limbs of the anticline have very different dip values.

5. Browser-API version

The version that uses the Google Earth browser plugin and API works similarly to the desktop / KMZ version, but it adds HTML interface elements—sliders and text fields. It also has a more interactive stereographic net. For example, at Stage 2 in the API version, dragging a pole across the net simultaneously changes a red plane's dip and strike on the terrain. We use the right-hand-rule so students must choose between two strike values, only one of which allows them to simultaneously fit the dip. Also, in the API version students vary the fold axis plunge and trend simultaneously. They can discover that the best way to estimate the axis is to fit a fold profile plane through the poles to the seven bedding planes, which appear on the net (Fig. 7). Gold, silver, bronze, and

wooden medallions are awarded based on closeness to the stored instructor values. In the final step of Stage 2 using the API, students drag a HTML5 slider to change the lean angle, as opposed to selecting one of the preset values in the KML version. They can thus select from a continuous range of values.

In the API version, the computer auto-scores student work by comparison with stored values set by the authors and awards students with game-like medallions based on closeness of fit. It does this in Stage 1 simply by comparing dips and in Stage 2 by calculating the cross-product of the student and instructor bedding poles. This is necessary as there can be large differences in strike despite small dihedral angles when dips are low.

In Stage 3, the API version provides JavaScript controls to allow students to design their own Bézier curves (see De Paor 1996) to fit the periclinal structure. The Bézier curves are fitted to match the fold structure using two end points (red squares in Fig. 8a inset) and two tangents (green dots), just as in many drawing programs. Students are challenged to fit the Bézier curves as closely as possible to the surface cut-off points of a specific stratum. They add at least three cross sections, one at the crest near the two Stage 1 sites, one at the northwest plunging end of the fold near the seven Stage 2 sites, and a third at the southeast-plunging end. Students also create a long section to help visualize the whaleback surface in three dimensions (Fig. 8a). Finally, given the added features of the API, they explore a region to the northwest of Sheep Mountain Anticline and discover a saddle structure defined by antiformal cross sections perpendicular to the fold axis but a synformal long section parallel to the axial trace of the fold (Fig. 8b).

6. Discussion

Virtual globes are well established as powerful tools for helping students with geological map interpretation, however, the need for basic training in the user interface and navigation must be stressed. The Google Earth API and browser plug-in lower the cognitive load by hiding unwanted features of the desktop app's sidebars and toolbars, and allows one to build a rich interactive and engaging student experience by adding Javascript controls such as the stereographic net overlay, COLLADA models, and parameter value sliders.

We see potential for the Fold Analysis Challenge to help students prepare for in-person field trips and to reinforce learning and retention after they return. Additionally, for the vast majority of students who will never get to visit Sheep Mountain in person, we see this resource as a potentially valuable substitute, certainly a lot better than still imagery.

Research shows that female students learn STEM by “making and doing,” [web site L], therefore this activity may help engage them in structural analysis. To promote gender-neutrality, we recommend allowing student collaboration, for example, by making the assembly of multiple great circles a team effort.

Future plans include teacher-level access to allow instructors to create their own field areas and manage their course modules as in Dordevic et al (2015). Meanwhile, readers who are proficient in KML scripting can modify the desktop version to fit other folds across the globe. The KMZ download can be unzipped and the enclosed KML document can be opened with a code editor in order to change the locations and orientations of the COLLADA models.

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Figure Captions

Fig. 1. Sheep Mountain is located east of Route 310. between Greybull and Lovell Wyoming, at latitude and longitude: 44.611466°N, 108.137322°W. Google Earth is ©2015 Google. Image: Landsat.

Fig. 2. A. Geologic map of Sheep Mountain, after Rioux 1994, shows distribution of formations from the Mississippian (purple) to the Quaternary (yellow). B. Interpretative cross section, after Amrouch et al. 2010, extending to the Precambrian basement (white).

Fig. 3. Sheep Mountain Anticline is exposed in magnificent flat-irons on either side of the crest. However, novice students may fail to visualize a ground-penetrating three-dimensional structure and see instead, ribbons of differently colored surface rocks (Tewksbury & Tewksbury 2009). Google Earth is ©2015 Google. Image: Landsat.

Fig. 4. a) The user interface for the desktop version—Stage 1. The planes have already been rotated into the correct dips by selecting from the Site 1 and Site 2 Dips folders. Note that the 3D terrain must be selected in the sidebar (or preferences). b) The fold trend is determined by rotating the stereographic net overlay using a folder of radio buttons visible in the sidebar. Google Earth is ©2015 Google. Image: Landsat.

Fig. 5. Stage 2 (desktop version). a) Students must fit strikes at seven locations around the fold nose. Dips have been preset. b) When strikes are correctly fitted, a set of great circles on the net intersect at a point corresponding to the fold axis (green arrow). Its trend is determined by rotating the net and its plunge by selecting from folders of op-

tions in the sidebar. c) After fitting the fold axis, the lean of the axial plane (blue) is selected from the choices in the sidebar. Google Earth is ©2015 Google. Image: Landsat.

Fig.6. a) Independent cylindrical models fit the northwest, central, and southeast regions but they are mutually incompatible because of the doubly-plunging nature of the fold on the regional scale. b) A simple oval model (brown) is a very rough fit to the surface data. c) A complex model surface with cut at two gorges to reveal cross sections. The middle of the model is cylindrical but the two ends are conical. When the correct elevation is selected in the sidebar, the models recreate the pattern in Rioux's (1994) map (Fig.2). Google Earth is ©2015 Google. Image: Landsat.

Fig.7. The API version has a more interactive net that displayed draggable poles to bedding. These allow simultaneous fitting of dip and strike. Google Earth is ©2015 Google. Image: Landsat.

Fig.8. a) The API version allows students to custom design bézier curves at the bottom of the purple semi-transparent planes to fit the long section and three cross sections of the structure, using standard bézier controls (inset). The red boxes mark the northwest, central, and southeast segments of the model. b) Just northwest of the Sheep Mountain Anticline students can discover a saddle structure and fit a synform to the long section and antiform to the cross section. Blue-green placemarks are draggable across the terrain for fine-tuning the positions and rotations of the sections. Google Earth is ©2015 Google. Image: Landsat.

Fold Analysis Challenge

A Digital Lab for Structural Geology

by
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Figure 1

Figure 2

Figure 3

Figure 4a

Figure 4b

Figure 5a

Figure 5b

Figure 5c

Figure 6ab

Figure 6c

- ▼ ☒ Fold Analysis Challenge
 - ▶ ☐ Stage 1
 - ▶ ☐ Stage 2
 - ▼ ☒ Stage 3
 - ▼ ☐ Cylindrical Fold Models
 - ☐ NW Surface
 - ☐ NW Axis
 - ☐ Central Surface
 - ☐ Central Axis
 - ☐ SE Surface
 - ☐ SE Axis
 - ☐ Generalized model
 - ☐ 0
 - ☐ 100
 - ☐ 200
 - ☐ 300
 - ☐ 350
 - ☐ 400
 - ☐ 425
 - ☐ 450
 - ☐ 475
 - ☒ 500
 - ☐ 525
 - ☐ 550
 - ☐ 575
 - ☐ 600
 - ☐ 700
 - ☐ 800
 - ☐ 900
 - ☐ 1000
 - ▶ ☐ Welcome

Figure 7

Figure 8a

Figure 8b