Mapping the Earth's structural framework

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Folded Early Eocene distal turbidites at Broto, central Pyrenes

As geologists, we all 'know' what a structural map is – the map representation of the geometry and kinematics of folds and faults. Nothing could be simpler. So, when John Jacques and I established the Petroleum Systems Evaluation Group (PSEG) at Getech back in 2004, building the structural framework for each of our new regional studies seemed the least of our worries. But, to our surprise, we were wrong. It turned out that not every structural geologist sees structural mapping in the same way. And as for the geophysicist view of structures… well, that is a story for another day. This was to cost us much time and monies. The question is why?

Faults and folds are amongst the clearest expressions of past tectonics that we can observe directly.

The graphical representation of these features depends on application and scale.

On geological maps, structural elements are usually shown by lines. These mark the trace of the intersection of each structural feature with the Earth's surface. Kinematics are represented graphically by a commonly applied symbology (Figure 1). In many structural maps, sub-surface features are also represented by extending their top trace vertically until it intersects the current land surface (in our databases, we use an attribute to distinguish between features exposed at the surface and those in the sub-surface). This combination of line features is what John and I had in mind, given our focus on New Ventures exploration and how we would use the framework: to define the crustal architecture, build tectonic models and then develop paleogeographies.

When we get to prospect scale (Figure 2), it becomes essential to consider the 3D geometry to calculate volumetrics, investigate fault closure, trapping mechanisms, migration pathways, etc. To this end, we build structural contour maps and show our faults at the surface as polygons representing the dip and throw of each fault plane with depth.

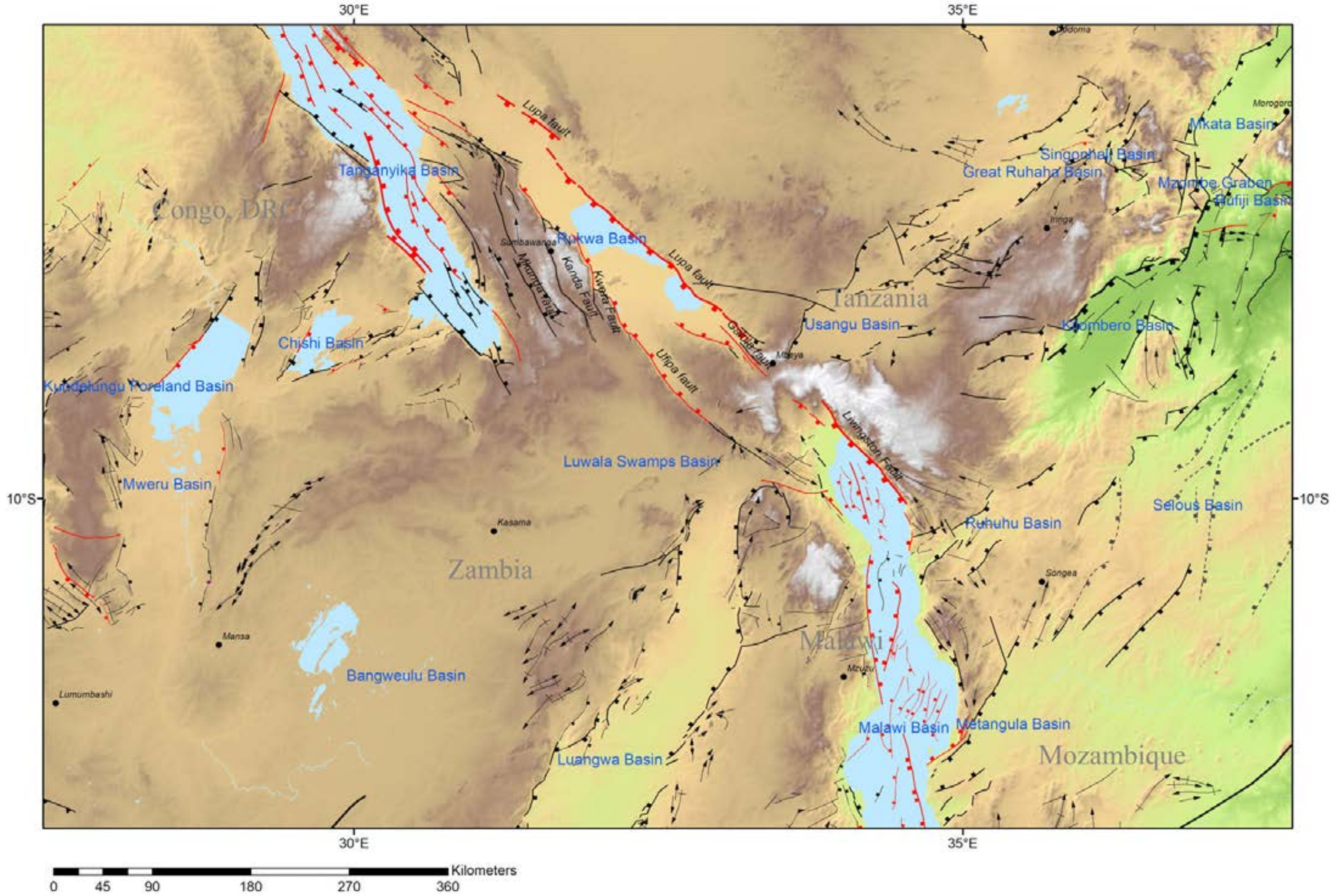

Figure 1. An example of the data in our Structural Elements database for the area around Rukwa and northern Malawi. Features are represented by lines that mark the trace of faults at the surface (or projected up from their highest expression for subsurface faults) and axes of folds. When I think of a structural map in New Ventures exploration or most of my academic work, this is what I think of.

This difference due to application and scale is nothing new. It was also not the cause of the problems that John and I faced.

I have been thinking about this recently. Primarily because I am once again building a global crustal architecture geospatial database, this time armed with 30 years of experience, much older and hopefully a little wiser. But also, because I am writing a new paper on the history of geological representation.

Much has changed since 2004. For example, our understanding of the complexity of crustal architecture has developed substantially in the last decade due to the increased availability of ultra-deep, 2D seismic data along many of the world's continental margins (Manatschal, Sutra and Péron-Pinvidic, 2010; Péron-Pinvidic and Manatschal, 2009). Databases and map representations need to take account of these advances.

The new databases I am working on are more systematic, more integrated, more detailed, and based on more data. The workflow begins with the Structural Elements database, forming the framework around which all the other elements are built. Hence the reference to a structural 'framework'. So, getting this database right, or as correct as possible, is critical because everything else hangs from this. Everything from the crustal facies and geodynamics databases to how we define our sedimentary basins and their depositional fill, and ultimately to plate reconstructions, paleogeography, and paleolandscapes.

In revisiting this whole process and detailing the mapping workflow, I realized that some questions need to be explicitly addressed from the outset if we are to get others, not least our staff, to know what we want. These questions include the following:

1. Should the maps be based on map interpretations published by other people (secondary data) or interpreted from primary data?
2. Should we assume that existing interpretations are correct?
3. What density of structures should be mapped?
4. Should only features with a direct link to petroleum be recorded?
5. Should the maps only show the present-day geometry of features or show the past geometry at a time of the compilers' choosing/interest?
6. Should the maps be schematic with segments linked into a continuous form (general pattern of faults and folds) or only what is 'observed' (actual or as close to reality as possible)?

The answers to these are relatively straightforward once stated (answers at the end of the article) – operationally, these are now addressed in the extensive documentation created for each database.

In this blog, I want to look at the history of structural mapping as a way to try and explain the problems that John and I encountered. Because by looking at this history, we can hopefully get closer to answering the fundamental question: **What is a structural map?**

The ‘architecture’ of the Earth

In this, Hunt was likely influenced by his experience as an exploration geologist and how structure often dictated the distribution of oil – Hunt was one of the first to recognize the link between anticlinal structures and oil fields (Hunt, 1862).

Crustal ‘architecture’ is much more than mapping the structural ‘framework’ as a structural elements database. It encompasses all the crust. In reading back through the early 19th century literature, it is clear that when geologists referred to ‘structure’, they were using it in the same way as Hunt used [crustal] “architecture”. Indeed mapping faults and fold axes as lines developed relatively late in geology.

> **“The structure and arrangement of the materials of the earth’s crust, its architecture, as it were…”**
> **Hunt 1873**

Folding and faulting showed how dynamic the Earth was. You only have to read Humboldt, Hutton, or Lyell to get a sense of this. But when these geologists came to map this deformation, the resulting ‘structure’ was defined by outcrop geometry in map view or bed orientation in sections, rather than by discrete fault lines and planes. The maps of Smith, for example, show outcrop geometries that define folds and faulted boundaries but do not show the fold axes or faults themselves. Similarly, his cross-sections.

So in this 19th-century view of a ‘structural map,’ we are not just representing the trace of fold axes or faults but the entire 3-dimensional crustal form. In terms of the databases I am building today, this would require three separate but related databases: (1) structural elements, which define the three-dimensional geometry of the rock volume, including folds and faults as a framework of line traces; (2) ‘crustal’ facies describing the geometry and composition/rheology of the lithosphere; and (3) bedrock geology, comprising the surface outcrop. We might add (4) igneous features; and (5) geodynamics, representing the dominant thermo-mechanical processes acting on the lithosphere. Both of these give additional information on the dynamic processes that generate the form.

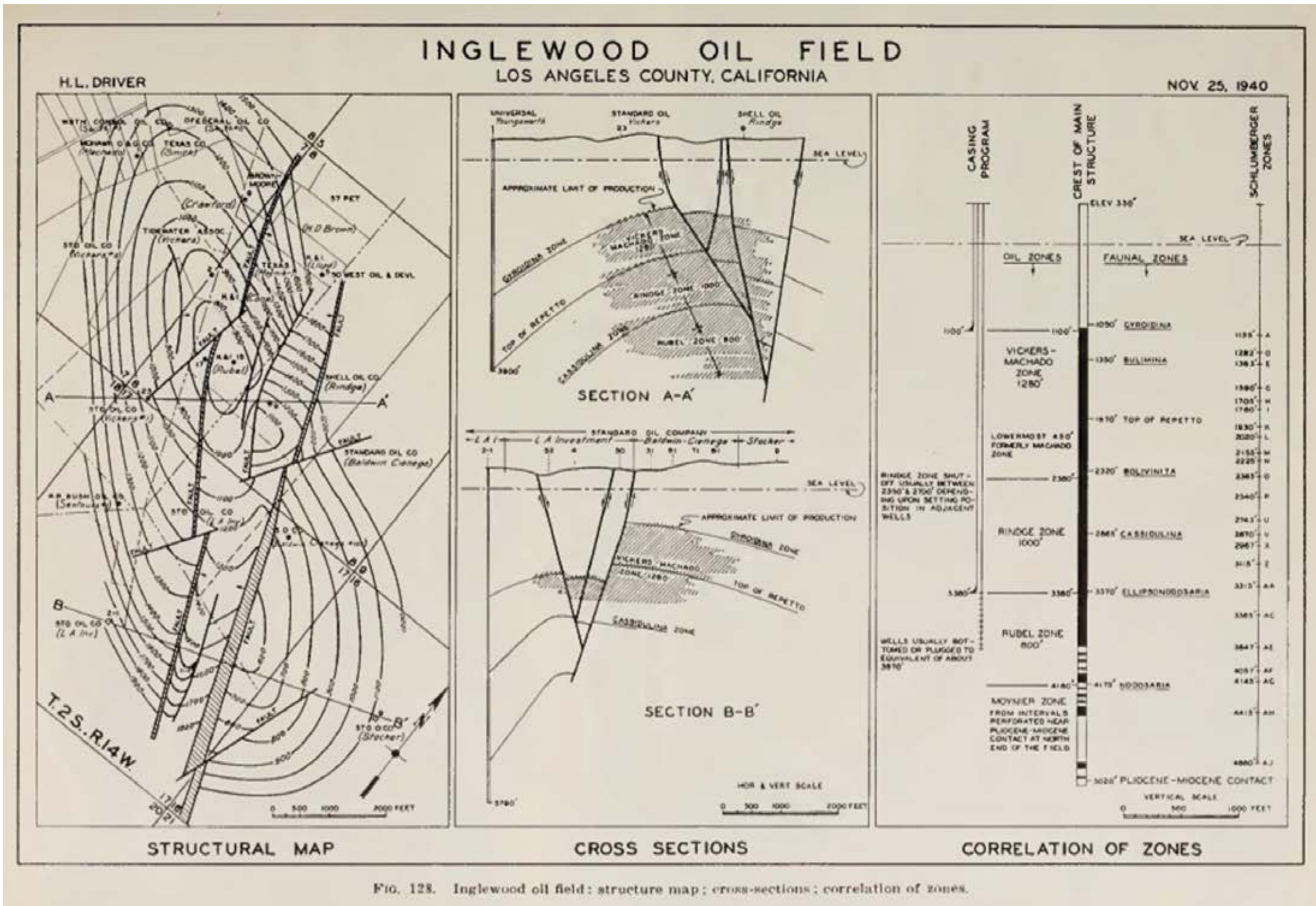

Figure 2. An example of a prospect-scale map, in this case, a vintage map of the Inglewood oil field in California. The structural map (left) includes structural contours and faults as polygons to show the geometry of dip and throw (Jenkins, 1943)

De La Beche and Faults as Lines

It was Henry De La Beche who explicitly showed faults as lines in his sections (De la Beche, 1830). These thick black lines in sections (Fig. 3) were replaced in map view by thick white lines. This symbology continued to be used on British maps throughout the 19th century (Fig. 4). There was no differentiation between different types of faults.

But a search of 19th century maps suggests that the inclusion of fault traces was not universal. Even Élisee Reclus in his seminal work on global geography, did not show maps of major fault lines, although he did provide maps of the East African rift, showing the topographic fault scarps ("Line of Volcanic Fault" (Fig.104 in (Reclus, 1876).

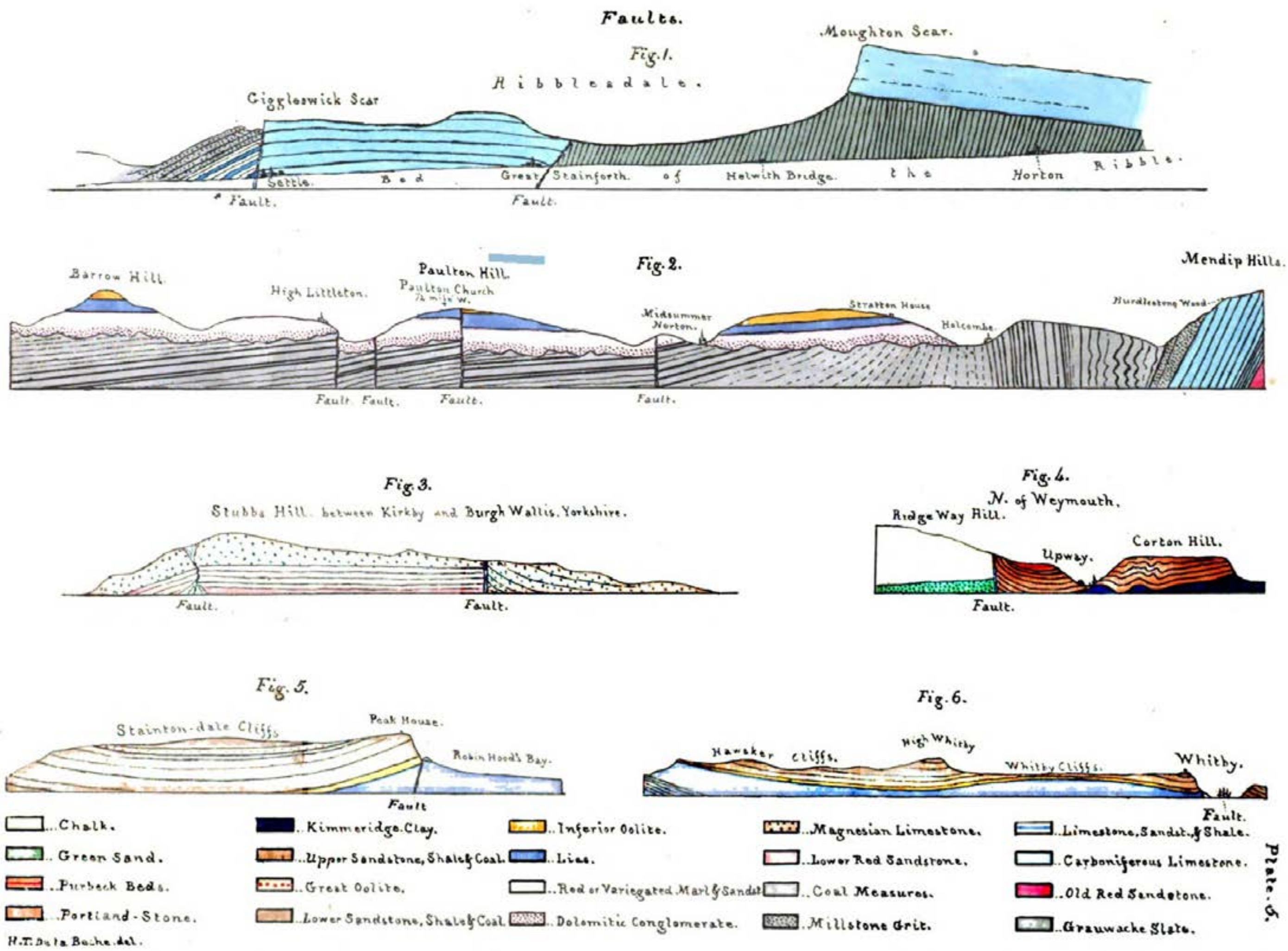

Figure 3. Examples of faults shown in De la Beche cross-sections from various locations in the United Kingdom (De la Beche, 1830)

Figure 4. An example of mapped faults represented by white lines on this map of the Mendips by De la Beche (1845). British Geological Survey materials © UKRI (1845) http://www.largeimages.bgs.ac.uk/iip/mapsportal.html?id=1000027

John Wesley Powell and the Standardization of Geological Maps

The most significant change in structural mapping occurred in the 1880s, when John Wesley Powell, the second director of the newly formed USGS, started a drive to standardize map symbology and colors. In these maps, Powell explicitly showed structural elements (Powell, 1882), but like De la Beche, these were heavy black lines without associated markers. Powell also used dashed

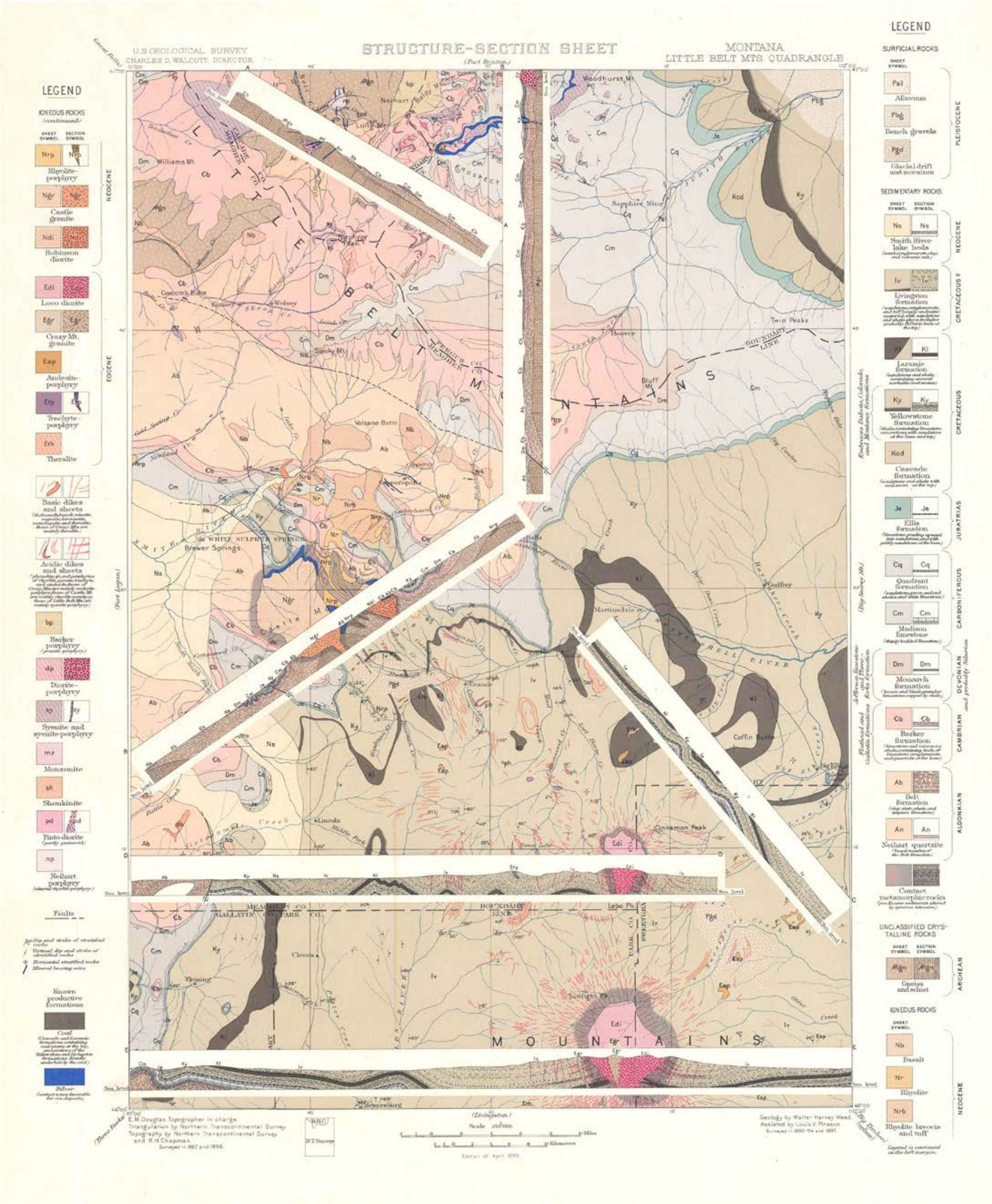

Figure 5. An example map from the Folios of the Geological Atlas of the United States. In this example from 1899, faults are represented by solid and dashed black lines following the guidelines laid down by Powell in the 1880s. The inclusion of sections on the map is unusual but emphasizes an increasing focus on geological maps for resource exploration. Note that the map title now includes the term "Structure".

lines to show fault extents where the trace could not be discerned but was assumed to continue. Forty years earlier, De la Beche had also shown dashed fault lines on some of his maps, but had not explained what these meant in the legend; one assumes to show uncertainty like Powell:

> *"Fault lines (particularly when they are formation boundaries) shall be indicated when actually traced by somewhat heavy full lines in black; and when not actually traced, by similar broken lines, toward which the formation devices may blend or fade as circumstances seem to require."*
>
> (Powell, 1890)

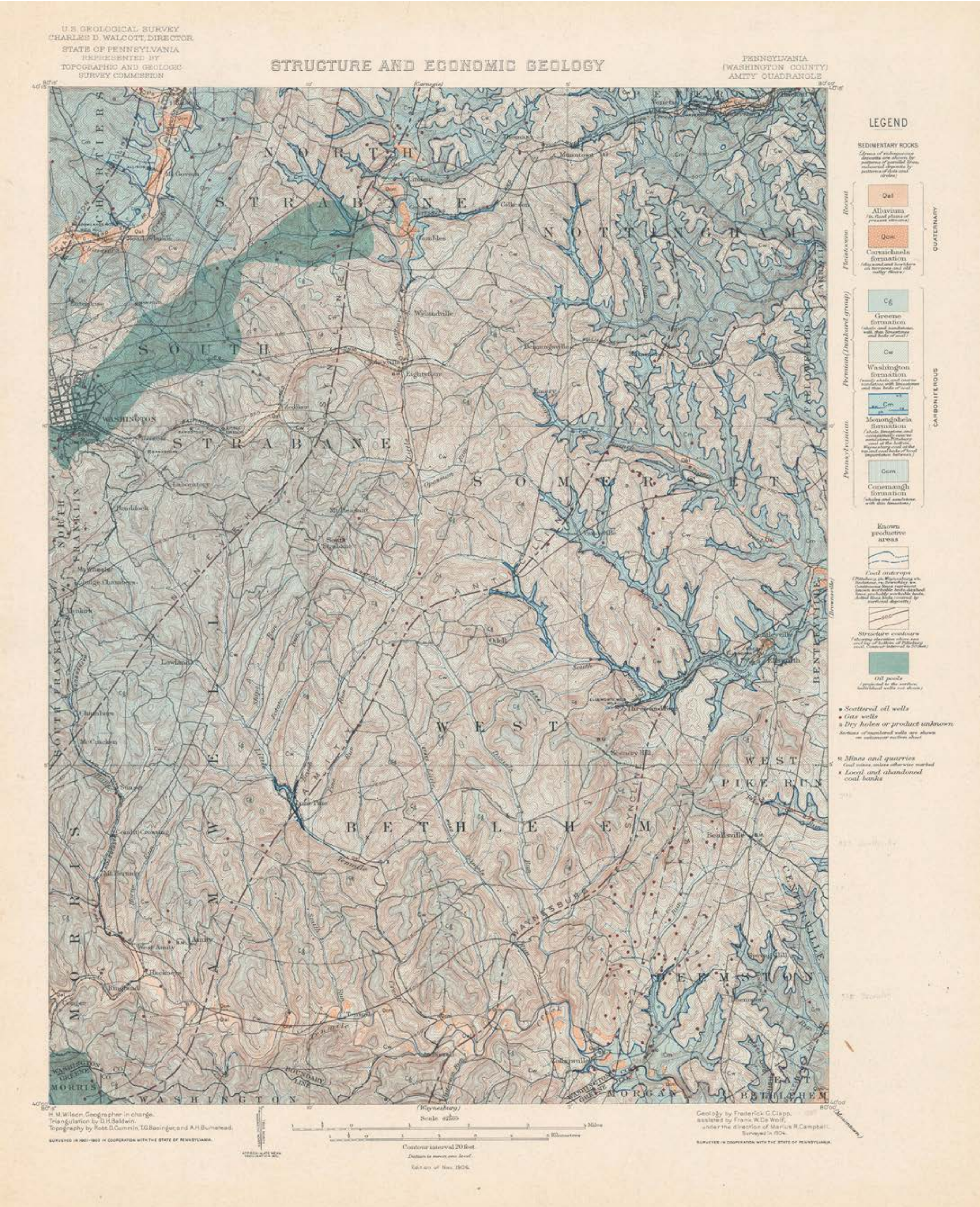

Figure 6. In this map from the "Folios of the Geological Atlas of the United States" series, the geologists have included structural contours in addition to stratigraphy, lithology, and structure (Clapp, 1907)

This standardized approach to mapping was implemented under the auspices of the next USGS Director, Charles Doolittle Walcott. The results can be seen in the USGS "Folios of the Geologic Atlas of the United States", a series published between 1894 and 1945, which included maps of topography and geology with an emphasis on structure and economic geology (see Figure 5 for an example from the Little Belt Mountains in Montana; Weed, 1899)). Some of these folios also included structural contours on the maps (see Figure 6 from Clapp, 1907).

The folios of Walcott during at the turn of the 19th-20th centuries look remarkable modern. But this 'standard' symbology does not seem to have been systematically adopted more widely outside of the U.S.. The British Geological Survey continued to mostly use white lines to represent faults until around 1912, after which they were changed to darker colors such as dark browns (Fowler et al., 1926) or dark blue lines (Ussher and De la Beche, 1953) (Figure 7). Although Strahan's geological map of Ingleborough in 1910 (Strahan, 1910) users black lines and is more similar to Powell's scheme and the USGS folios.

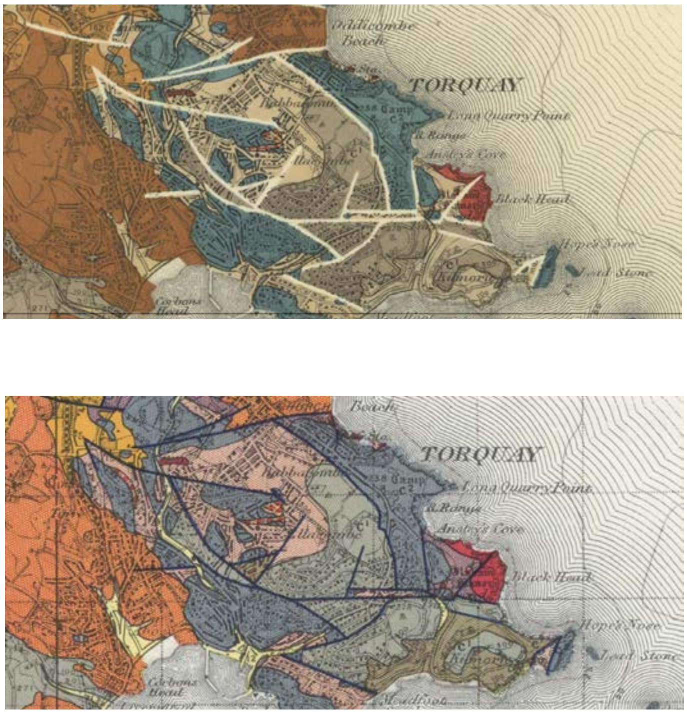

Figure 7. White solid lines continued to be used by the British Geological Survey until at least 1912 (top)(Ussher and De la Beche, 1912). Subsequent editions such as this reprint from 1953 (Ussher and De la Beche, 1953) show faults in dark blue (bottom image). This was not universal with Strahan's map of Ingleborough in 1910 representing faults with black solid lines (Strahan, 1910). British Geological Survey materials © UKRI (1912) British Geological Survey (BGS) | large image viewer | IIPMooViewer 2.0 and (1953) British Geological Survey (BGS) | large image viewer | IIPMooViewer 2.0 (this is actually the 1962 reprint of the 1953 map)

The nomenclature of Powell was expanded in 1920, when the USGS published formal guidance to its geologists on how to prepare illustrations and maps (Ridgway, 1920). Faults on maps were now represented by lines with associated marker symbols to indicate the footwall and hanging wall sides of normal faults, and overthrust (upper plate) side of thrusts. Anticlines and synclines were represented by a line along the fold axis, differentiated by arrows perpendicular to the line - a symbology that has changed little since (Figure 8).

This map nomenclature was quickly adopted and most clearly exemplified in the detailed local USGS maps of the time, for example, the excellent 1929 geological map of the Tyrone quadrangle in Pennsylvania (Figure 9) in which thrust faults, normal faults, synclines, and anticlines were differentiated (Butts, 1929). In Britain, the 1:63,360 map of Norham used a tick mark to denote the downthrown side of faults (Fowler et al., 1926). But we can also see its use in exploration maps during the following decades (Figure 10). And it was the oil Industry that then started to drive the need for more significant differentiation in the structural elements symbol set.

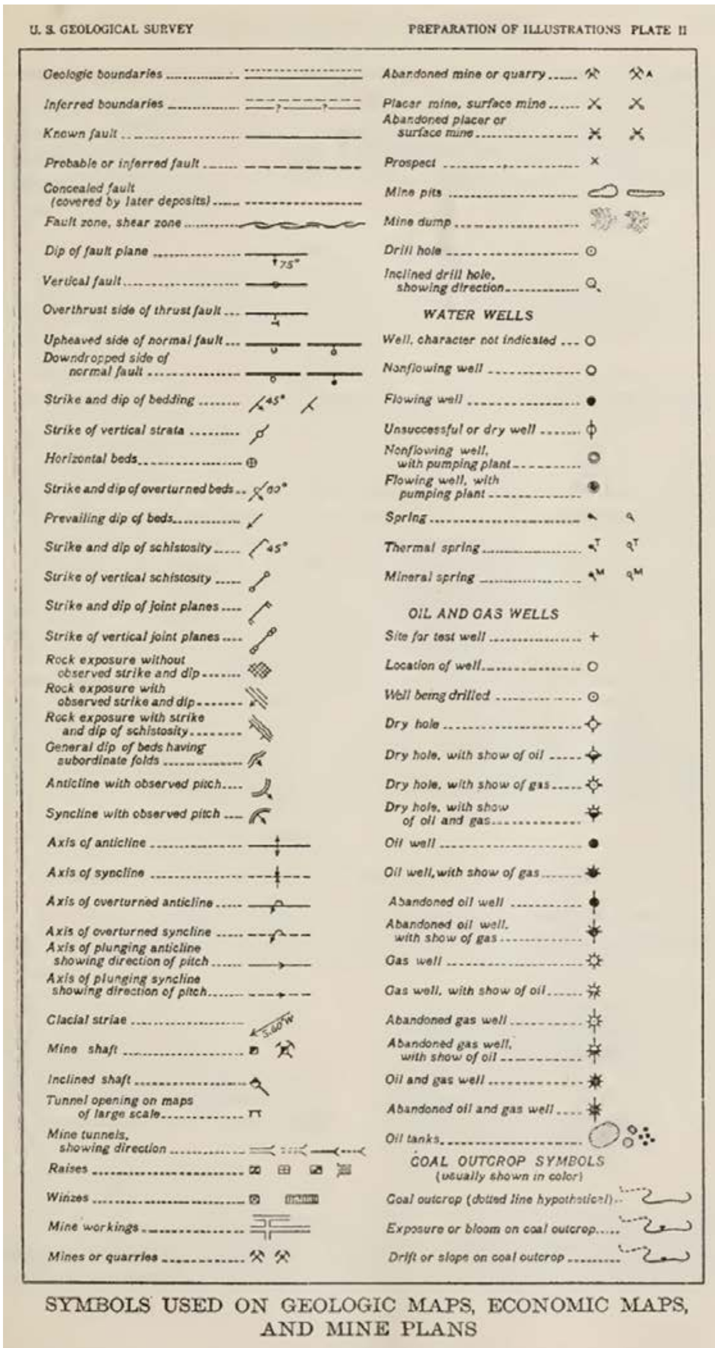

Figure 8. The map symbol set presented by the USGS in 1920 (Ridgway, 1920)

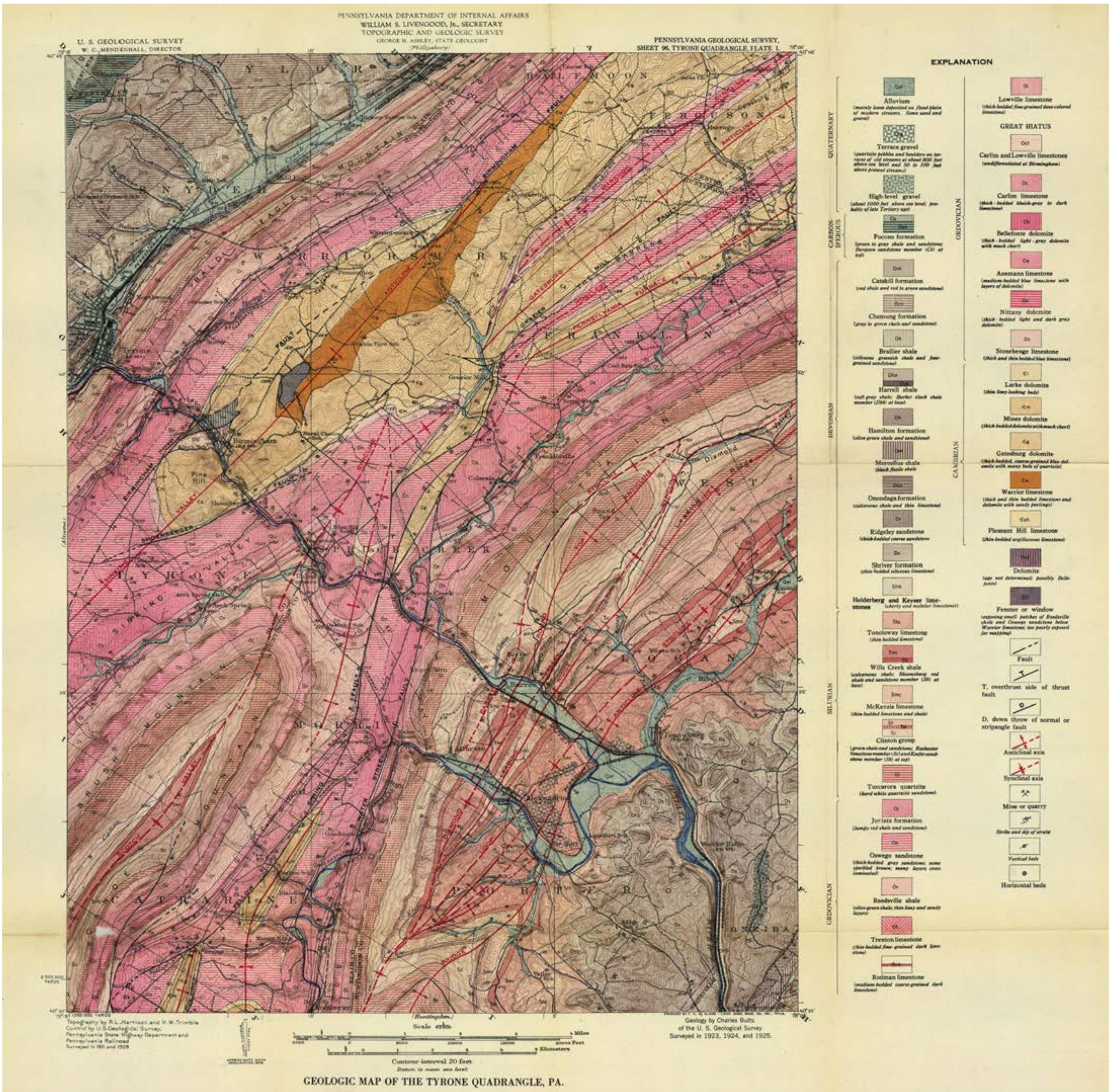

Figure 9. The 1929 geological map of the Tyrone quadrangle in Pennsylvania (Butts, 1929). Note the use of different symbols for anticlines, synclines, normal and thrust faults. Many of the fold axes are named. Image made available online courtesy of the Pennsylvania State University.

The need for more symbols

But it was becoming clear that there was a much greater diversity of structural models – different fold and fault types - that needed to be represented graphically (Boyer and Muehlberger, 1960; Crowell, 1959; Davis, 1913; Hill, 1947; Hubbert, 1927; Reid et al., 1913; Sopwith, 1875; Straley III, 1934).

In 1950 the USGS expanded the range of recommended fold and fault symbols (Cloos et al., 1950), including many that we still use today. But it still lacked the diversity of symbols that we use today. It also restricted some symbols to specific types of maps (Figure 11).

From 1989 to 1995 the USGS built a more extensive cartographic standard map symbol (Reynolds, Queen and Taylor, 1995; Soller, 1996). In this version, all thrust faults were represented using the saw-tooth marker pattern, which is now the most widely used visualization. Normal faults were still represented by a tick mark to indicate the downthrown side. This was further expanded with the 2006 update to the USGS symbol set (Federal Geographic Data Committee, 2006). However, confusingly here, the USGS chose to represent normal faults with half-circles indicating the downthrown side and rectangles to represent the upthrown block of reverse faults. Unfortunately, by this time, other structural

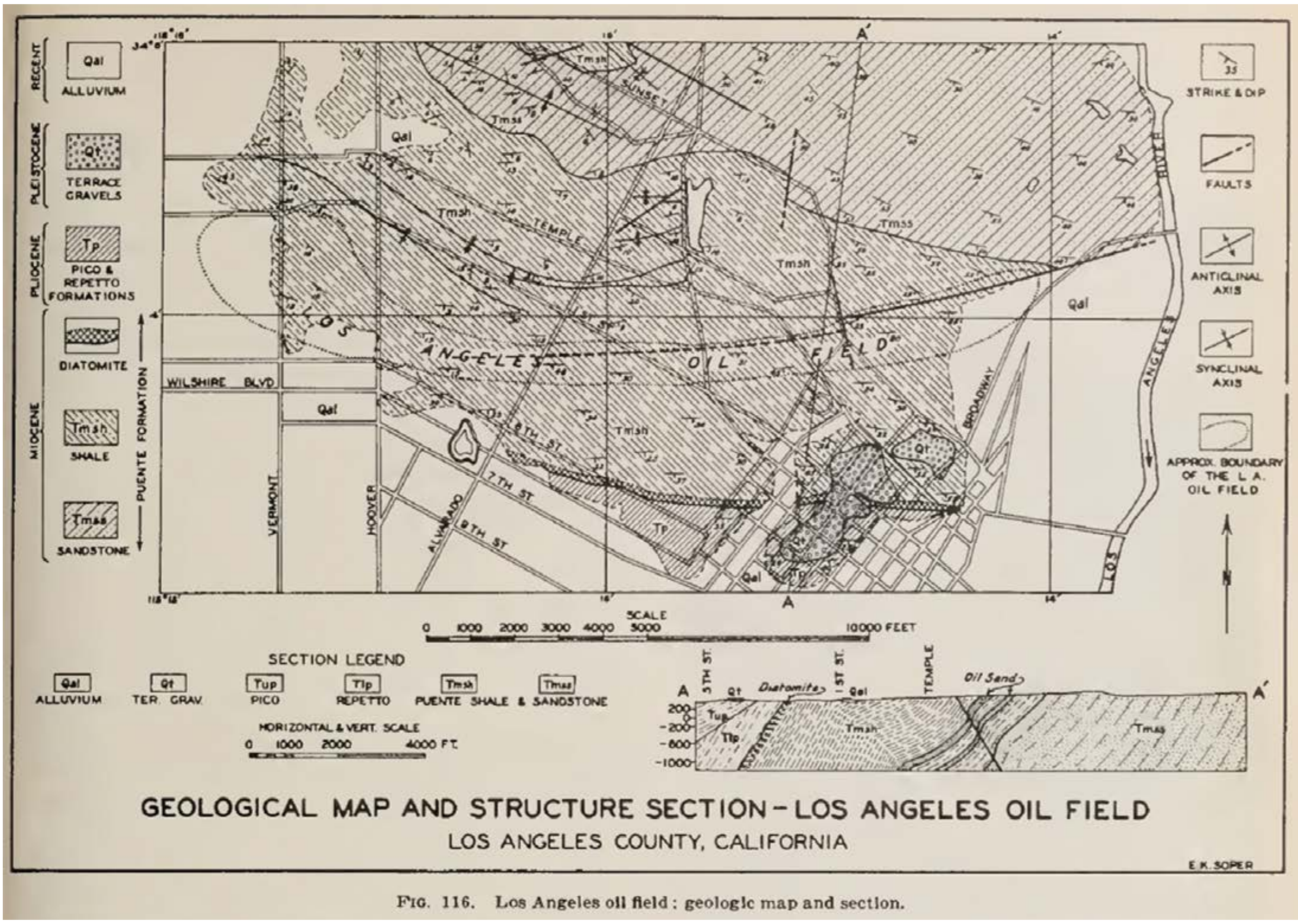

Figure 10. The Los Angeles City Oil field showing fold axes and faults in the 1940s (Jenkins, 1943)

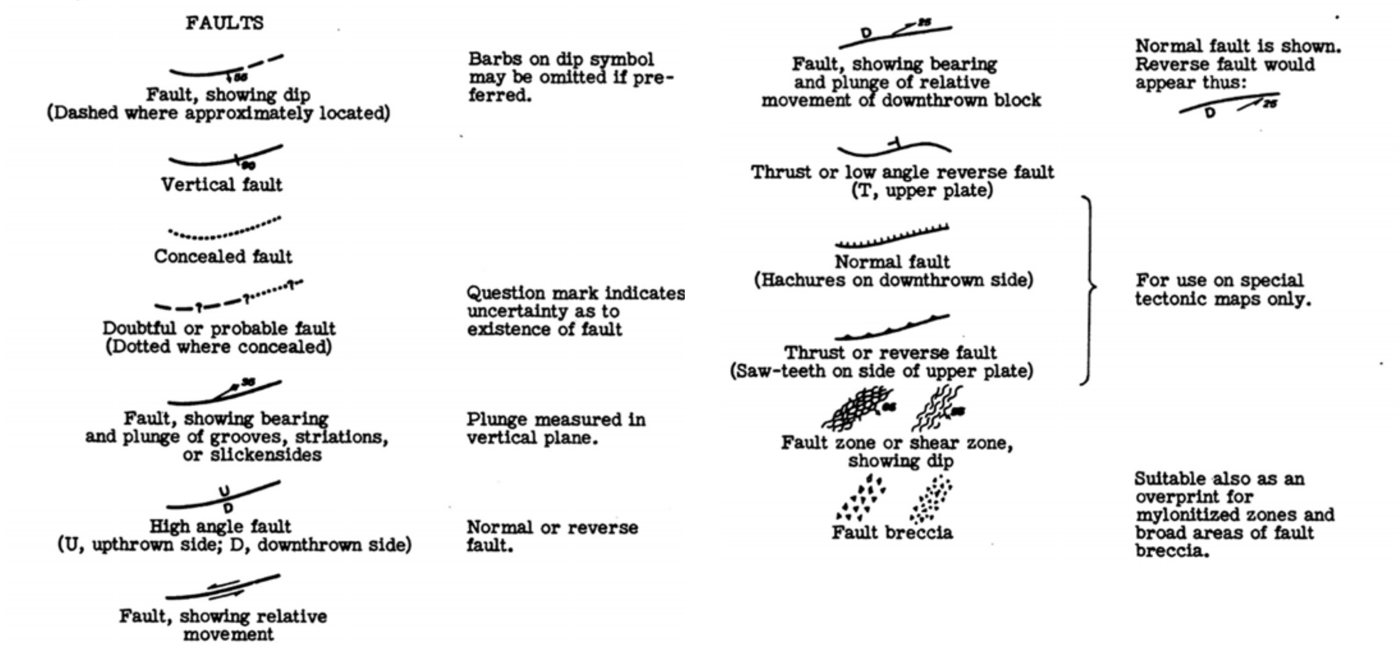

Figure 11. The additional fault symbols suggested by Cloos et al. (1950) for the USGS. It is interesting to note that although the saw-tooth marker symbol for thrust and reverse faults is illustrated, it is only "for use on special tectonic maps".

geologists and many companies had already appropriated the idea of using rectangle markers but to replace the tick marks on normal faults (Hulshof, 2012; Markwick, 2019); this included Robertson Research in the late 1990s, which is where I got into the habit. Other organizations, such as the BGS continue to use tick marks (Mawer, 2002).

With this diversity of map symbols, we can create a more detailed map of the 'structural framework' built of structural elements. These are the map representations of the structure rather than the whole structural form: a fold axis, not the entire fold form, a fault trace at the surface (or top sub-surface fault trace), not the whole fault plane. It is these elements that are recorded in our **Structural Elements database.**

This distinction may seem like semantics. But it is important and as we stressed at the beginning of this article, it is a function of the application. In New Ventures exploration or plate modeling or paleogeography, we need to understand the overall structural context and what it tells us about geodynamic evolution, whether for basins or basin hinterland. But at the prospect scale, we need to understand the form.

This explains why we distinguish between the "structural framework" and the "crustal architecture" of which the framework is an integral part in our paleogeographic workflow.

A further complication here is that when we talk about 'crustal' architecture, we are, of course, referring to the whole lithosphere - **nothing is ever simple!**

...the structural framework...[is]...the map representation of structure rather than the whole structural form: a fold axis, not the entire fold form...

We all know what a structural map is.

So, what was the cause of the problems that John and I had?

In truth, even with 15 years of hindsight, I still do not fully understand the causes. But I think I have more of an idea than I did then.

What is a structural map? When looking at the example in figure 1, everything seems obvious. John and I had assumed that all structural geologists saw a structural map, in the same way, especially the most experienced structural geologists, those with the most years. But what they 'knew' and we 'knew' turned out not to be the same.

In our defense, I should point out that we ultimately hired a brilliant Polish structural geologist, whose tectonic model of SE Asia is, I still think, one of the best solutions I have seen for that area. And then a series of excellent MSc graduates who all immediately understood what we meant. So perhaps it was also partly the individuals concerned after all? Perhaps…

Structural mapping is fundamental to solving geological problems, especially in resource exploration. Getting the structural framework right impacts everything else, which we then build upon it.

As geologists, we all 'know' what a structural map is. But what we 'know' has changed through time, depends on the application, and, as it turns out, it may also depend on the geologist you ask.

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Answers to the questions

Q1. Should the maps be based on published maps (secondary data) or interpreted from primary data?

Answer. The intention is that all structural features in the database should be identified in primary data. This data includes gravity and magnetic data, seismic, radar, bathymetry, topography, Landsat, and observations. Features from secondary (published) data are only included if the feature is considered important but cannot be seen with primary data available (remember that the primary data are all publicly available). In these cases, the feature will carry by default a low mapping confidence and will have attribution reflecting its source. We have kept such 'secondary' interpretations to a minimum (<<1% of the entire database).

Q2. Should we assume that existing interpretations are correct?

Answer. Assume nothing. Generally, the location of a feature would have been placed using primary data and information from published, secondary sources will refer to the age assignments or kinematic histories. Attribution is used in the database to explain the source of this information – i.e., what it is based on if quoted in a paper.

Q3. What density of structures should be mapped?

Answer. This will depend on the data grain and structural complexity. Map what you can see, but consider a set resolution limit and keep to that. This becomes the "minimum resolvable feature" in the database. In operation, there is a clear density difference between features mapped on land using Landsat or SRTM3 radar data and features in the oceans constrained only by satellite-derived gravity anomalies.

Q4. Should only features with a direct link to petroleum be recorded?

Answer. No. This database is about understanding the Earth so not restricted to any single application.

Q5. Should the maps only show the present-day geometry of features or show the past geometry at a time of the compilers' choosing/interest?

Answer. The default database is the present-day geometry. Separate databases are used for each geological timeslice starting with features extracted from the present-day database and rotated. Changes in kinematics are stored in a related "Activation" table. Also, be aware that there will be cases where features will need to be spatially adjusted after rotation to reflect deformation (palinspastic reconstruction), especially in compressional settings. In the oceans, there may also be features that no longer exist (subducted).

Q6. Should the maps be schematic with segments linked into a continuous form (general pattern of faults and folds) or only what is 'observed' (actual or as close to reality as possible)?

Answer. Observed takes precedence, but connections may sometimes be useful. If so, connections will have the lowest confidence and be dashed. This is why attribution is so crucial.

Knowing Earth Structural Elements Mapping Legend (2018)

Tectonic elements

Tectonic elements comprise crustal-scale features that define either plate boundaries and intra-plate, crustal-scale folds, which are commonly referred to in the literature as 'arches'. All features that represent plate boundaries will cut the crust through to the Moho and are therefore class 1 features by definition.

SYMBOL ACTIVE Defined	SYMBOL ACTIVE Inferred	SYMBOL INACTIVE Defined	SYMBOL INACTIVE Inferred	CLASS	DESCRIPTION
S100A	S100Ai	S100I	S100Ii	1	Spreading Ridge
S102A	S102Ai			1	Transform Fault
		S104I	S104Ii	1	Fracture Zone (Major)
		S106I	S106Ii	1	Fracture Zone (Minor)
S108A	S108Ai	S108I	S108Ii	1	Subduction Zone
S109A	S109Ai	S109I	S109Ii	1	Basement Arch
S209A	S209Ai	S209I	S209Ii	2	Basement Arch

Normal and reverse faults

The symbology for normal, reverse, thrust, and undifferentiated faults are shown in Figure 23. All four fault types can be of any scale, from major basin bounding faults that may cut the crust down to the Moho and therefore be considered as Class 1 to smaller faults in the overburden or even features within surficial deposits. Whilst the larger features can be identified using seismic data, satellite imagery (Landsat), and even potential fields data, the finer-scale features are mostly only resolvable through careful field mapping. Whilst surface and sub-surface geometries may be readily mappable, the depth significance of most features is often difficult to assess without good seismic data.

The symbology of both normal and reverse faults comprises two components in ArcGIS:

1. a solid (defined) or dash (inferred) line, that defines the geometry of the feature (this will be at the present-day surface unless otherwise specified) – the line weight will vary by class;

2. a marker line symbol that denotes the type of fault (square for normal faults, triangle for thrusts and reverse faults) and dip-slip direction (square on the down-thrown side for normal faults; triangles point towards the upper plate for thrust and reverse faults).

SYMBOL				CLASS	DESCRIPTION
ACTIVE		INACTIVE			
Defined	Inferred	Defined	Inferred		
S110A	S110Ai	S110I	S110Ii	1	Normal fault
S210A	S210Ai	S210I	S210Ii	2	Normal fault
S310A	S310Ai	S310I	S310Ii	3	Normal fault
S410A	S410Ai	S410I	S410Ii	4	Normal fault
S120A	S120Ai	S120I	S120Ii	1	Reverse fault
S220A	S220Ai	S220I	S220Ii	2	Reverse fault
S320A	S320Ai	S320I	S320Ii	3	Reverse fault
S420A	S420Ai	S420I	S420Ii	4	Reverse fault
S125A	S125Ai	S125I	S125Ii	1	Thrust fault
S225A	S225Ai	S225I	S225Ii	2	Thrust fault
S325A	S325Ai	S325I	S325Ii	3	Thrust fault
S425A	S425Ai	S425I	S425Ii	4	Thrust fault
S199A	S199Ai	S199I	S199Ii	1	Fault undifferentiated
S299A	S299Ai	S299I	S299Ii	2	Fault undifferentiated
S399A	S399Ai	S399I	S399Ii	3	Fault undifferentiated
S499A	S499Ai	S499I	S499Ii	4	Fault undifferentiated

Strike-slip faults

Strike-slip faults like most of the other structural elements in this legend, follow the traditional symbolization used by the USGS [Federal Geographic Data Committee, 2006] with the addition of variants for defined, inferred, active and inactiv. Arrows indicate the sense-of-shear where this is documented. An undifferentiated strike-slip fault symbol has been included here where the sense-of-shear is equivocal or there is disagreement in the literature. This is the same symbol used for undifferentiated faults. As part of the mapping workflow, bedding and foliation are mapped to provide indications of sense-of-shear.

SYMBOL: ACTIVE		SYMBOL: INACTIVE		CLASS	DESCRIPTION
Defined	Inferred	Defined	Inferred		
S130A	S130Ai	S130I	S130Ii	1	Strike-slip fault, undiff.
S230A	S230Ai	S230I	S230Ii	2	Strike-slip fault, undiff.
S330A	S330Ai	S330I	S330Ii	3	Strike-slip fault, undiff.
S430A	S430Ai	S430I	S430Ii	4	Strike-slip fault, undiff.
S140A	S140Ai	S140I	S140Ii	1	Dextral strike-slip fault
S240A	S240Ai	S240I	S240Ii	2	Dextral strike-slip fault
S340A	S340Ai	S340I	S340Ii	3	Dextral strike-slip fault
S440A	S440Ai	S440I	S440Ii	4	Dextral strike-slip fault
S145A	S145Ai	S145I	S145Ii	1	Sinistral strike-slip fault
S245A	S245Ai	S245I	S245Ii	2	Sinistral strike-slip fault
S345A	S345Ai	S345I	S345Ii	3	Sinistral strike-slip fault
S445A	S445Ai	S445I	S445Ii	4	Sinistral strike-slip fault

Transpressional and transtensional faults

The symbology for transpressional and transtensional faults is shown. These are used where evidence of translation and dip-slip are clearly defined. In many cases, this may reflect multiple phases of activity.

SYMBOL				CLASS	DESCRIPTION
ACTIVE		INACTIVE			
Defined	Inferred	Defined	Inferred		
S150A	S150Ai	S150I	S150Ii	1	Dextral transtensional fault
S250A	S250Ai	S250I	S250Ii	2	Dextral transtensional fault
S350A	S350Ai	S350I	S350Ii	3	Dextral transtensional fault
S450A	S450Ai	S450I	S450Ii	4	Dextral transtensional fault
S155A	S155Ai	S155I	S155Ii	1	Sinistral transtensional fault
S255A	S255Ai	S255I	S255Ii	2	Sinistral transtensional fault
S355A	S355Ai	S355I	S355Ii	3	Sinistral transtensional fault
S455A	S455Ai	S455I	S455Ii	4	Sinistral transtensional fault
S160A	S160Ai	S160I	S160Ii	1	Dextral transpressional fault
S260A	S260Ai	S260I	S260Ii	2	Dextral transpressional fault
S360A	S360Ai	S360I	S360Ii	3	Dextral transpressional fault
S460A	S460Ai	S460I	S460Ii	4	Dextral transpressional fault
S165A	S165Ai	S165I	S165Ii	1	Sinistral transpressional fault
S265A	S265Ai	S265I	S265Ii	2	Sinistral transpressional fault
S365A	S365Ai	S365I	S365Ii	3	Sinistral transpressional fault
S465A	S465Ai	S465I	S465Ii	4	Sinistral transpressional fault

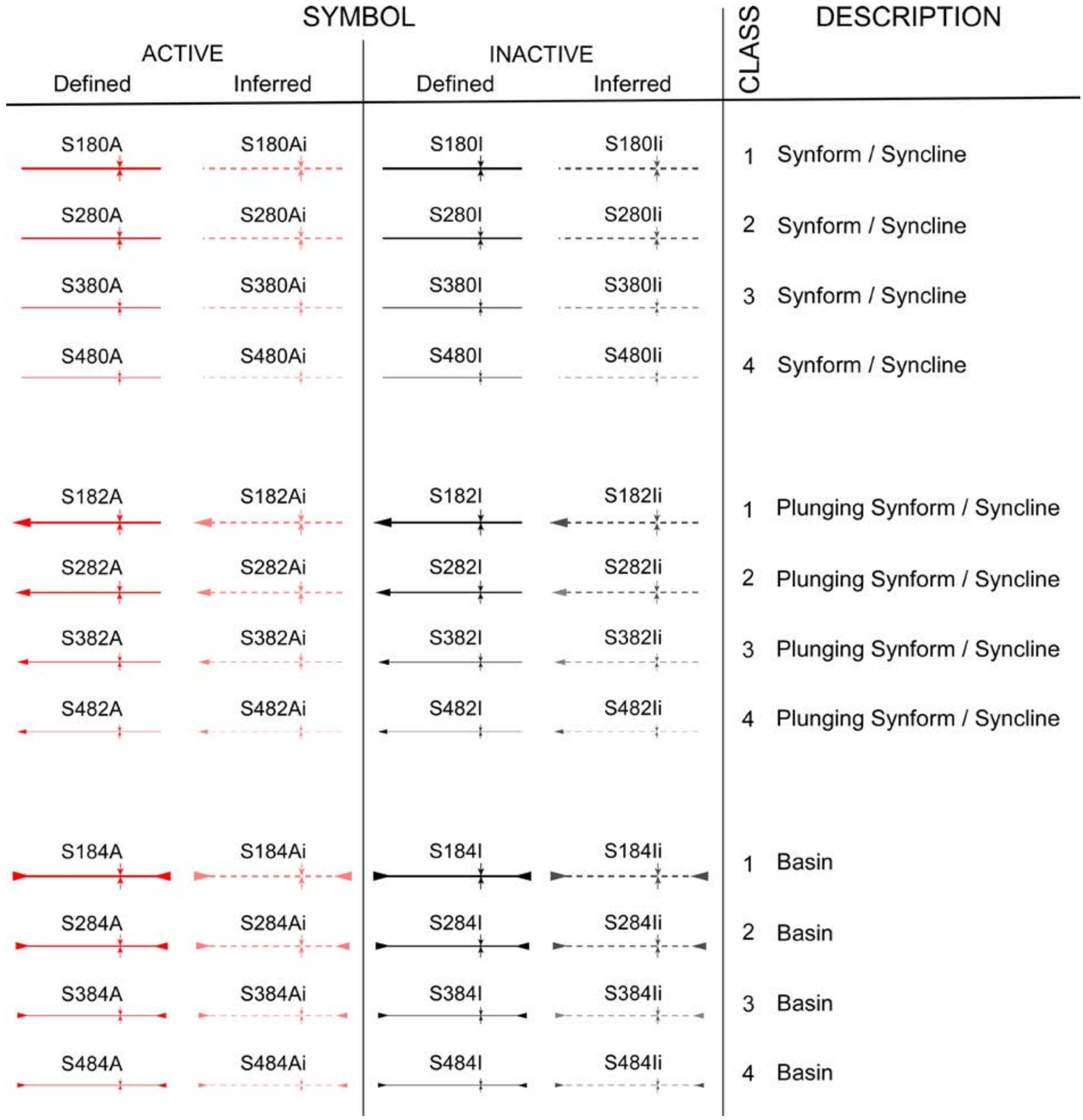
Undifferentiated folds

Undifferentiated folds have been symbolized to account for folds identified (especially) from Landsat imagery where bedding is clear, but dip and age relationships are not. This allows for fold trends to be quickly captured which may be checked later against detailed geological maps if these are available. This is not a traditional standard symbol.

SYMBOL					
ACTIVE		INACTIVE			
Defined	Inferred	Defined	Inferred	CLASS	DESCRIPTION
S177A	S177Ai	S177I	S177Ii	1	Fold undiff.
S277A	S277Ai	S277I	S277Ii	2	Fold undiff.
S377A	S377Ai	S377I	S377Ii	3	Fold undiff.
S477A	S477Ai	S477I	S477Ii	4	Fold undiff.
S175A	S175Ai	S175I	S175Ii	1	Plunging fold undiff.
S275A	S275Ai	S275I	S275Ii	2	Plunging fold undiff.
S375A	S375Ai	S375I	S375Ii	3	Plunging fold undiff.
S475A	S475Ai	S475I	S475Ii	4	Plunging fold undiff.
S179A	S179Ai	S179I	S179Ii	1	Double plunging fold undiff.
S279A	S279Ai	S279I	S279Ii	2	Double plunging fold undiff.
S379A	S379Ai	S379I	S379Ii	3	Double plunging fold undiff.
S479A	S479Ai	S479I	S479Ii	4	Double plunging fold undiff.

Synclines and synforms

Syncline and synform symbology, like that for anticlines and antiforms, follows the traditional use of arrows to indicate dip direction either side of an axis. The arrow marker symbol used is that provided with ArcGIS [ESRI, 2017] as the "ESRI Geology USGS 95-525" character marker symbol set. These are the symbols presented in the USGS Open-File Report 95-525 [Reynolds et al., 1995]. There appears to be some confusion in the literature about the correct geometry of arrows indicating the plunge direction for closed, double-plunging ("basin") fold features, with some mappers showing plunge direction away from a basin feature. In the scheme presented here, we show the arrows dipping into the feature, which in our view is the only correct geometry since this follows the bedding dip direction.



Inverted and over-turned folds

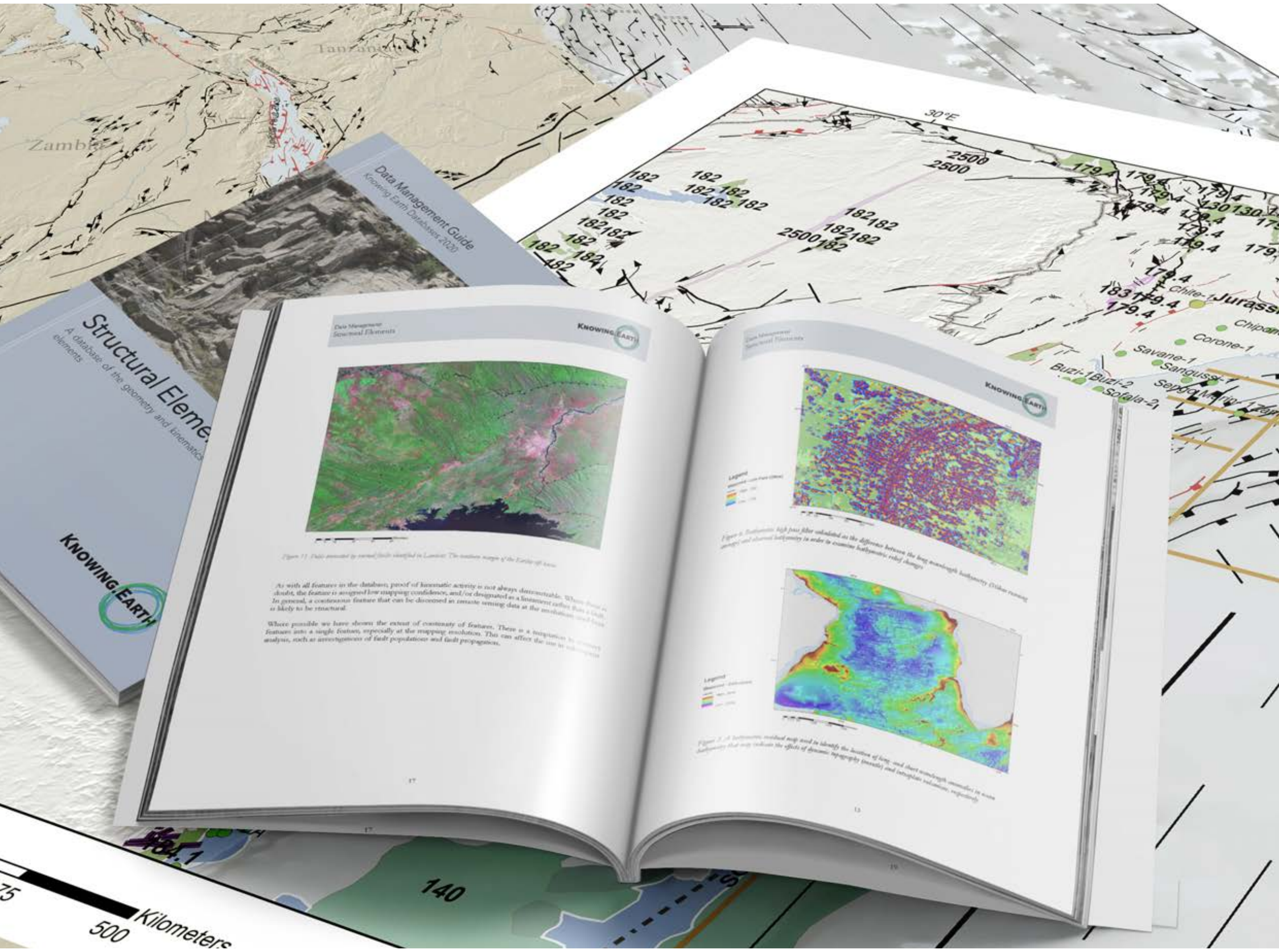
Inverted and over-turned folds reflect, by definition, a complex deformational history and care must be taken to ensure that the sense of fold inversion or over-turning is correctly recorded when lines are captured digitally (in ArcGIS this will depend on the direction in which the line is digitized, which can be easily managed using the "Flip" command). The marker symbols are those used by the USGS [Federal Geographic Data Committee, 2006; Reynolds et al., 1995] and which are provided with ArcGIS [ESRI, 2017] as the "ESRI Geology USGS 95-525" character marker symbol set.

SYMBOL				CLASS	DESCRIPTION
ACTIVE		INACTIVE			
Defined	Inferred	Defined	Inferred		
S176A	S176Ai	S176I	S176Ii	1	Inverted anticline
S276A	S276Ai	S276I	S276Ii	2	Inverted anticline
S376A	S376Ai	S376I	S376Ii	3	Inverted anticline
S476A	S476Ai	S476I	S476Ii	4	Inverted anticline
S186A	S186Ai	S186I	S186Ii	1	Inverted syncline
S286A	S286Ai	S286I	S286Ii	2	Inverted syncline
S386A	S386Ai	S386I	S386Ii	3	Inverted syncline
S486A	S486Ai	S486I	S486Ii	4	Inverted syncline
S178A	S178Ai	S178I	S178Ii	1	Overturned anticline
S278A	S278Ai	S278I	S278Ii	2	Overturned anticline
S378A	S378Ai	S378I	S378Ii	3	Overturned anticline
S478A	S478Ai	S478I	S478Ii	4	Overturned anticline
S188A	S188Ai	S188I	S188Ii	1	Overturned syncline
S288A	S288Ai	S288I	S288Ii	2	Overturned syncline
S388A	S388Ai	S388I	S388Ii	3	Overturned syncline
S488A	S488Ai	S488I	S488Ii	4	Overturned syncline

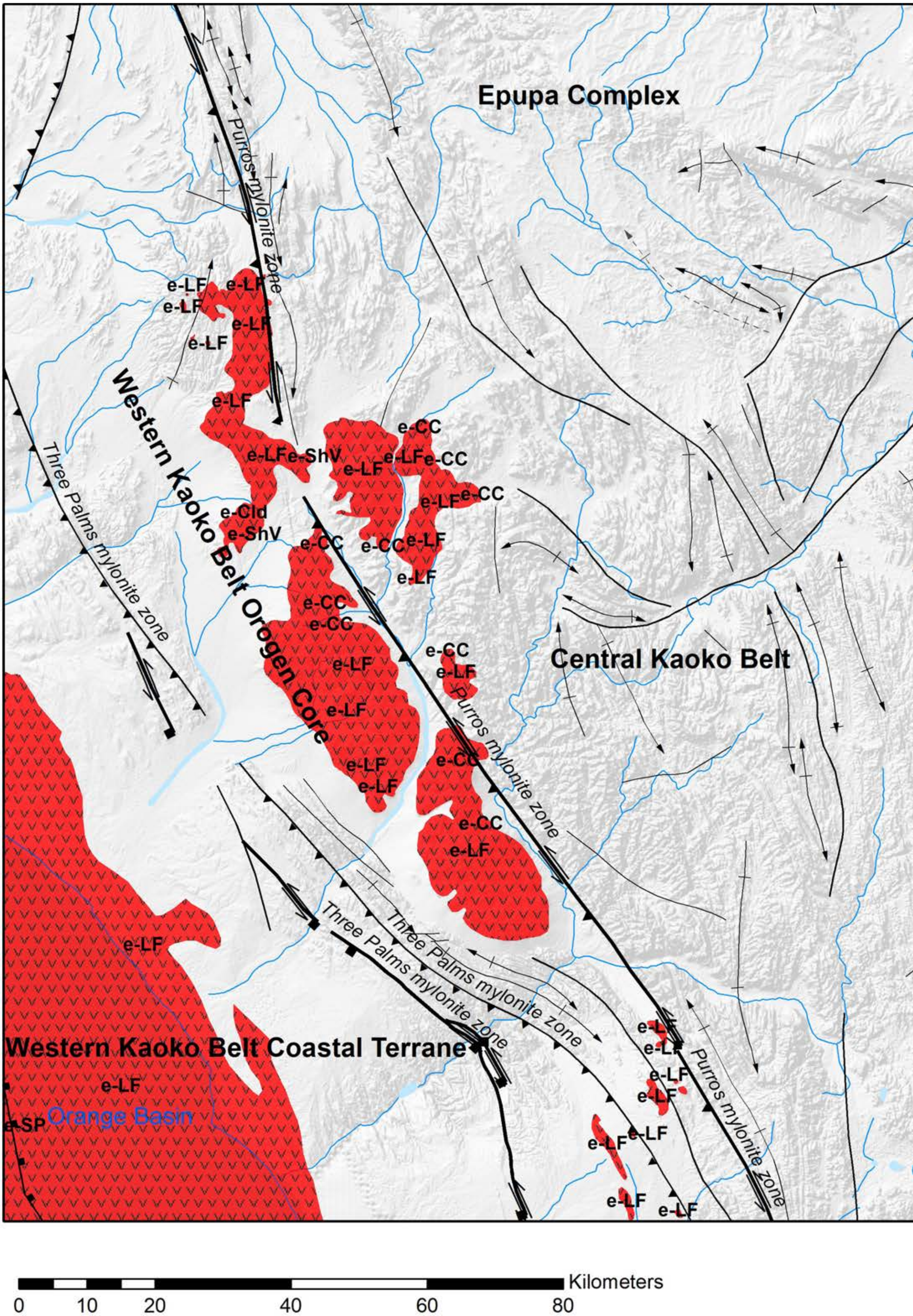
4.12. Lineaments, bedding, and foliation

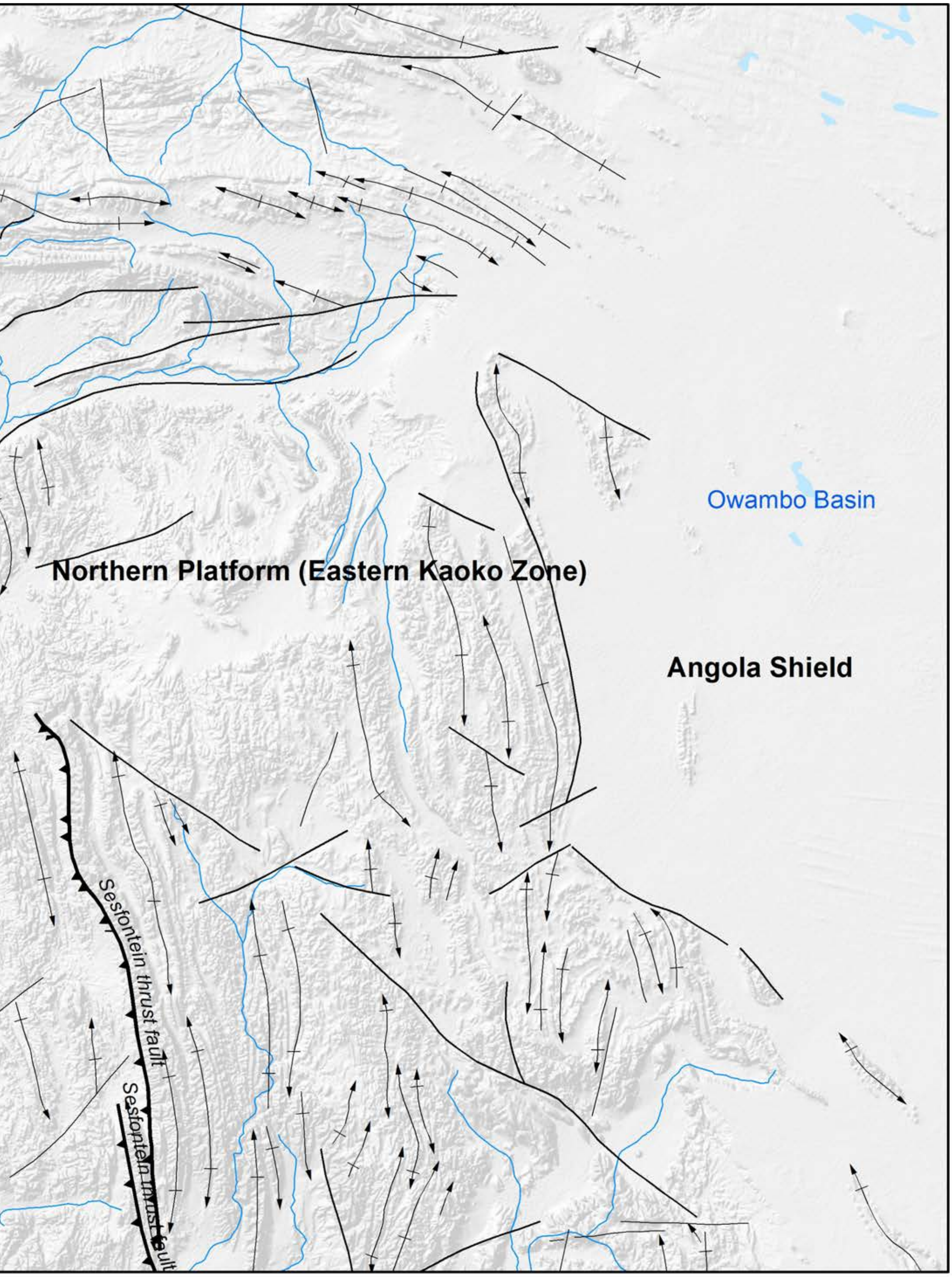
Lineaments are linear features expressed in either the surface or sub-surface that lack any information about kinematics or geological cause. These may be revised as more data are added or removed where they are found to be artifacts of specific source data. Bedding and foliation are extremely useful to record to pick out the large-scale sense of shear around translational features, or folds. Both can be identified in Landsat imagery depending on the vegetation cover and degree of weathering.

SYMBOL	DESCRIPTION
S9000	Lineament undifferentiated
S9100	Bedding
S9200	Foliation



Each database includes a comprehensive documentation


Epupa Complex
Purros mylonite zone
Western Kaoko Belt Orogen Core
Three Palms mylonite zone
Central Kaoko Belt
Western Kaoko Belt Coastal Terrane
Orange Basin
e-LF
e-CC
e-ShV
e-Cld
e-SP
Kilometers
0
10
20
40
60
80



An example of the Structural Elements and Igneous Features databases for northern Namibia , West African Atlas

Further Information

If you would like to learn more about the Knowing Earth suite of structural and crustal architecture databases or any of our other Knowing Earth databases, please contact me at paul.markwick@knowing.earth.

We have several manuscripts currently in review, which will provide additional examples and enable us to get as much of our work into the public domain for community use. More on this soon.

The first version of the cartographic symbol set used by Knowing Earth was published as part of Markwick (2019) and is available through the Geological Magazine website https://www.cambridge.org/core/journals/geological-magazine/article/abs/palaeogeography-in-exploration/444CC2544340A699A01539A2D4C6E92A

The associated ArcGIS style file can be downloaded from my research website: www.palaeogeography.net

We will be publishing our new 2021 version shortly.

Others symbol sets

USGS: https://ngmdb.usgs.gov/fgdc_gds/geolsymstd/download.php

BGS: http://nora.nerc.ac.uk/id/eprint/3221/1/RR01001.pdf

Shell: https://www.arcgis.com/home/item.html?id=8a89e7ffe4154efa94c65090c4dab485

Knowing Earth: http://www.palaeogeography.net/publications.html

About the author

Paul is CEO of Knowing Earth Limited, as well as a Visiting Lecturer at the University of Leeds and Visiting Research Fellow at the University of Bristol. He graduated from St. Edmund Hall, Oxford University in 1987 and received his Ph.D. from The University of Chicago in 1996.

He worked for two years at BP's Research Centre in Sunbury-on-Thames before moving to Chicago, where Paul studied with Professor Fred Zeigler's oil industry-sponsored Paleogeographic Atlas Project. This was followed by a post-doctorate at the University of Reading researching the exploration significance of the paleoclimatic and drainage evolution of southern Africa using computer-based climate models with Professor Paul Valdes. He then moved to Robertson Research International Limited, now part of CGG, as a Staff Petroleum Geologist, where he developed global predictive models of source and reservoir facies. In 2004 Paul moved to Getech Group plc, to set-up the Petroleum Systems Evaluation Group with Dr. John Jacques. From 2006 to 2017 Paul served on the Getech board overseeing the strategic technical direction, which saw the business transition and grow from an academic research group to a multi-million-pound company with four offices, 120 staff and an international client base.

His active research interests include global tectonics, palaeogeography, palaeoclimatology, the history of geology and depositional modelling. Paul is the author of over 100 published scientific papers and articles.

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