Appalachian Shales Are Not Just Unconventional, They Are Downright Kinky*

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Please refer to closely related, full article on the subject by the author and colleagues, AAPG Bulletin, 2015, v. 99, p. 51-76.

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Introduction

The organic-rich shales of the Appalachian Basin of northeastern U.S.A., such as the Marcellus, are well known as unconventional reservoirs. However, their style of deformation is almost as unusual and enigmatic as their reservoir characteristics. The Appalachian Basin has been penetrated by thousands of wells and since the pioneering work of Willis (1891), has been the subject of many structural studies, so one might think that the style of deformation was well understood by now. However, there is still controversy around the subsurface structure. We have used recent 3-D seismic and borehole data to put together a consistent conceptual model that helps to explain several perplexing aspects of the deformation.

The largely marine and fine-grained Devonian sequence of the Appalachians was deposited in a foreland basin developed during the Acadian Orogeny. In the later Alleghanian Orogeny (broadly equivalent to the Hercynian of Europe), the basin was mildly deformed by a series of contractional structures. The basin now occurs in the Appalachian Plateau, which covers vast swathes of Pennsylvania, New York, West Virginia and Maryland (Figure 1). Deep wells indicated that the deformed basin is underlain by the Silurian Syracuse salt (Figure 2) and dip logs showed that it forms a decollement under most of the region (Rogers, 1963; Gwinn, 1964; Wiltschko and Chapple, 1977). We can, therefore, call the whole sequence above the salt, the Appalachian Plateau decollement sheet.

The surface deformation is dominated by a series of broad open folds that parallel the thrust front, with wavelength of about 11 km. On closer examination the folds are often not symmetrical but have abrupt steep limbs on the mountain-ward side, i.e. they seem to be verging the wrong way (Sherrill, 1941). Apart from these steep limbs, the deformation is generally mild at the present day surface. In the 1930s and 1940s many wells were drilled to explore and produce gas from the Oriskany Sandstone, which occurs below the Marcellus shale (Figure 2). Surprisingly, it was found that at deeper levels of the decollement sheet, there are common zones of steep dips (Gwinn, 1964). The interpretation was that deformation took place on a series of steep reverse faults that accommodated inner arc contraction of the large buckle folds. Already it was clear that the structure of the Appalachian Plateau is unusual. The established model of a thin-skinned thrust belt, with foreland verging linked thrusts and associated folds in their hanging walls, that had been so successful in areas such as the Rocky Mountains and in the strongly deformed parts of the Appalachians (e.g., Rich, 1934; Boyer, 1986) could not explain the relationship between folds and reverse faults that had been described in the Appalachian Plateau.

New Observations

The shale gas boom of the last few years has led to the acquisition of vast amounts of new subsurface data. In producing these unconventional reservoirs, the normal procedure is to drill a vertical pilot well and 6 laterals. Wireline logs are acquired in all wells, and the laterals are geosteered by comparing the log signature of the pilot with that of the laterals; in this way information can be gleaned about the dips of the beds in the laterals, and faults can be identified. In addition, borehole image logs are available in selected wells; these provide a wealth of structural information. 3-D seismic surveys were also acquired which provide crucial information about the subsurface structure. In a recent article in the Bulletin we presented an integrated structural interpretation of this new information (Gillespie et al., 2015).

So what do the new data show? Firstly, we can differentiate areas underlain by thick salt from areas that are underlain by thin salt. Where the salt is thick, large open decollement folds develop, that are the folds expressed at the surface: the presence of thick salt allows these decollement folds to develop. However, where the salt is thin, towards the margin of the evaporite basin, the structure is very different. At shallow levels, the rocks look largely undeformed, except for a few gently dipping thrust faults. At deeper levels (below the Tully Limestone) there appear to be a whole series of steep reverse faults which run down to the salt and which dip both towards and away from the mountain belt; the typical dip of these structures is about 60°. These observations are consistent with the observations of steep reverse faults by Gwinn (1964). However, the dips are puzzling, as from rock mechanical considerations we would expect faults in contractional setting to be gently dipping thrusts, and it should not be possible to generate faults with dips of more than 45°. Also, these reverse structures occur not only within the cores of the anticlines, but also in areas that have no large=scale folds.

When we examined the geosteering data and the borehole image data, it became clear that the bedding is continuous through the reverse structures; so they are not faults at all, but rather they are folds. In ordinary time-migrated seismic data, these structures do resemble faults, but with prestack depth migration, the reflectors fall more into place, and it becomes evident that the reflectors are continuous and that the structures are indeed folds. As these folds form steeply dipping panels with sharp hinges they are termed kink bands. Kink bands are typical of mechanically anisotropic rocks deformed in contraction under high confining pressure; fluid inclusion analysis indicates that burial at the time of deformation was around 5 km (Evans, 1995). The internal rotation within the kink band is accommodated by bedding parallel shear. Roger Faill (1969, 1973) gave a detailed description of kink bands that crop out in the Valley and Ridge province, but the significance of his work for the Appalachian Plateau was not fully realised at the time.

The geometry of the interpreted kink bands in the Appalachian decollement sheet is very distinctive (Figure 3). The lower termination of the kink bands is almost invariably at the top of the Syracuse Salt, and there is no indication that the kink bands form as the result of underlying thrusts. The kink bands typically converge upwards and terminate where they meet. These paired kink bands form box synclines that press material downwards into the underlying salt – a kind of structure termed a pop-down (Figure 4). The positions at which the kink bands meet align along the two prominent organic-rich shales in the sequence: the Marcellus and the Geneseo. It appears that an individual kink band propagates upwards until it meets an organic-rich shale and then reflects off it, changing direction and sense of displacement. Furthermore, examination of core shows abundant evidence of deformation in the organic-rich shales including layer parallel shear, indicating that the shales functioned as detachments.

The phenomenon of kink band reflection was observed long ago in laboratory experiments by layer parallel shortening of layers of plasticene lubricated by graphite and placed under a longitudinal load (Cobbold et al., 1971; Cobbold, 1976). Similar experiments have also been carried out using a stack of paper as the deforming material (Figure 5). In the experiments, the upper and lower boundaries are confined by rigid blocks and the interfaces between the rigid blocks and the deforming material act as detachments. The kinks propagate until they meet the detachment and then abruptly change direction and shear sense. At the place where the kink band changes direction, a small chevron fold is developed.

Kink band reflection is not a well-known phenomenon in rocks. However, kink bands are a commonly observed phenomenon within certain minerals. Graphite is a highly mechanically anisotropic mineral, built out of parallel sheets of graphene that are loosely connected by van der Waals bonds. When graphite is compressed parallel to the layering, it easily develops deformation twins, which are effectively kink bands on a microscopic scale. A micrograph (Figure 6) of a graphite crystal shows very symmetrical kink band reflection, although the levels at which the kink bands reflect is quite irregular in this case, and the kink bands reflect both upwards and downwards in the field of view.

In the Appalachian Plateau, it is remarkable that the kink bands meet at, or close to the organic rich shales. Where a weak shale lies directly beneath a stiff limestone unit, an upwards propagating kink band is unable to propagate beyond the interface between the shale and limestone, and the chevron syncline develops that is accommodated by thickening of the shale. The organic-rich shales may be the favoured sites simply because they have remarkably low strength. However, another possibility is that the organic-rich shales were subjected to overpressure due to hydrocarbon maturation at the time of deformation. The abundance of bedding parallel veins in these units also supports this idea.

The kink bands in the Appalachian Plateau occur on a great variety of scales. We can see kink bands with less than a centimeter of vertical offset in the core from the Marcellus Shale. The seismically imaged kink bands reflecting off the Marcellus Shale have vertical offsets of 30 – 60 m, whereas those that reflect off the Geneseo Shale/Tully Limestone have vertical offsets of 60 – 180 m. The large folds in the area have giant kink bands on their mountain-ward limb, with throws of as much as 1 km and which reach the present-day surface. It is these giant kink bands that lend the folds their characteristic asymmetry.

Discussion

The more that we understand of the structure of the Appalachian Plateau, the more clearly we see how distinctive the deformation style is. The style does not fit into conventional models of folding and thrusting at all, as the kink band folds occur beneath the thrusts, rather than above them. As far as we know, this style of deformation has not yet been identified in other basins. However, we might expect to see similar kink bands in other mildly deformed basins that are dominated by shale and which had several kilometers of overburden at the time of deformation.

The unraveling of the structure of this important basin should be of substantial help in steering of the lateral wells and their correct placement. We could also speculate that the abundance of kink bands, rather than thrusts is good news for the safety of fracking, as the strata are largely continuous through the kink bands and the kink bands would therefore not form conduits for fluids to penetrate vertically upwards through the stratigraphy.

Acknowledgements

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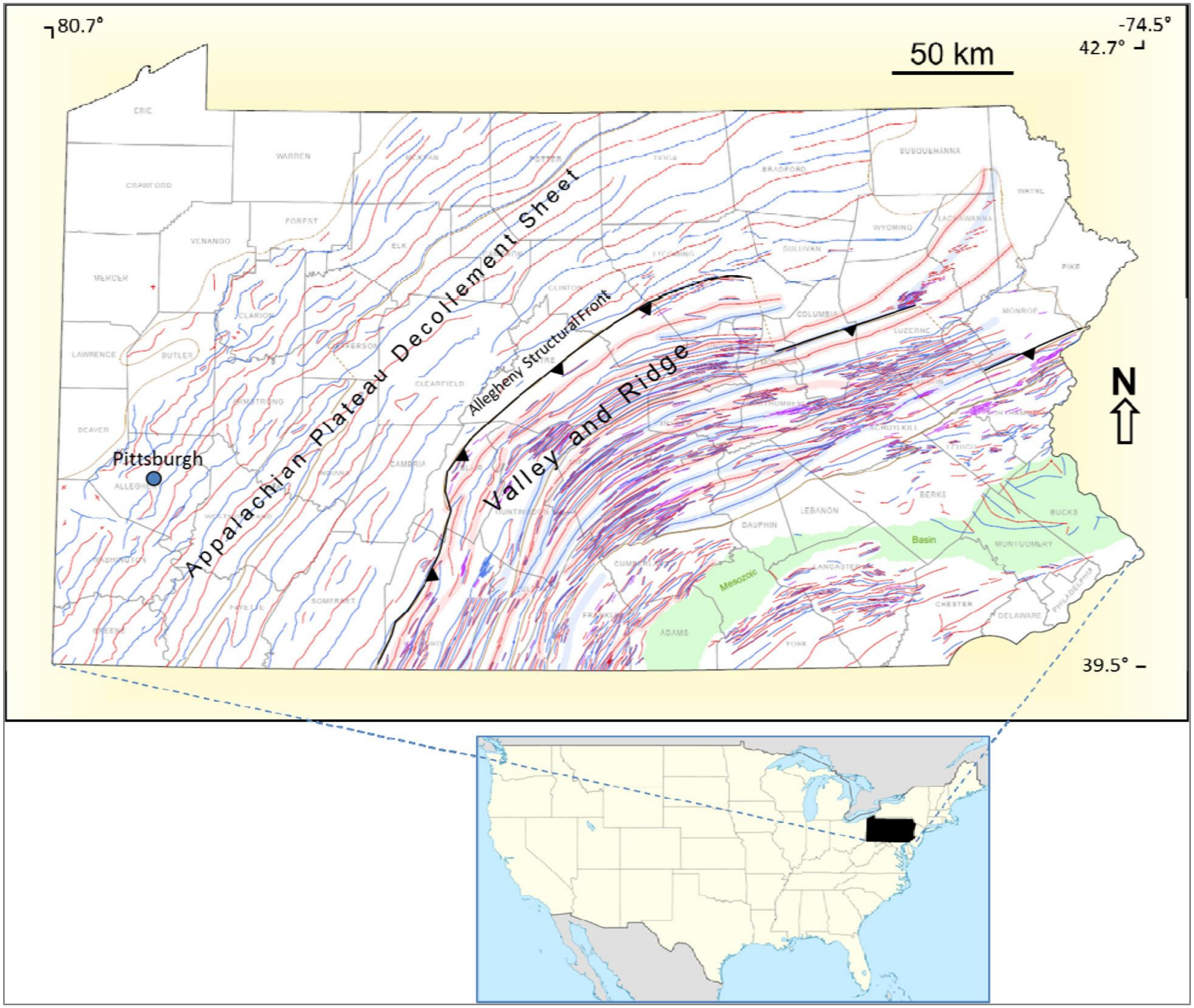

Figure 1. Structure of the Appalachian Plateau and Valley and Ridge province in Pennsylvania, U.S.A. Modified from "Folds Map of Pennsylvania" by Faill (2011). Anticline axes in red, syncline axes in blue.

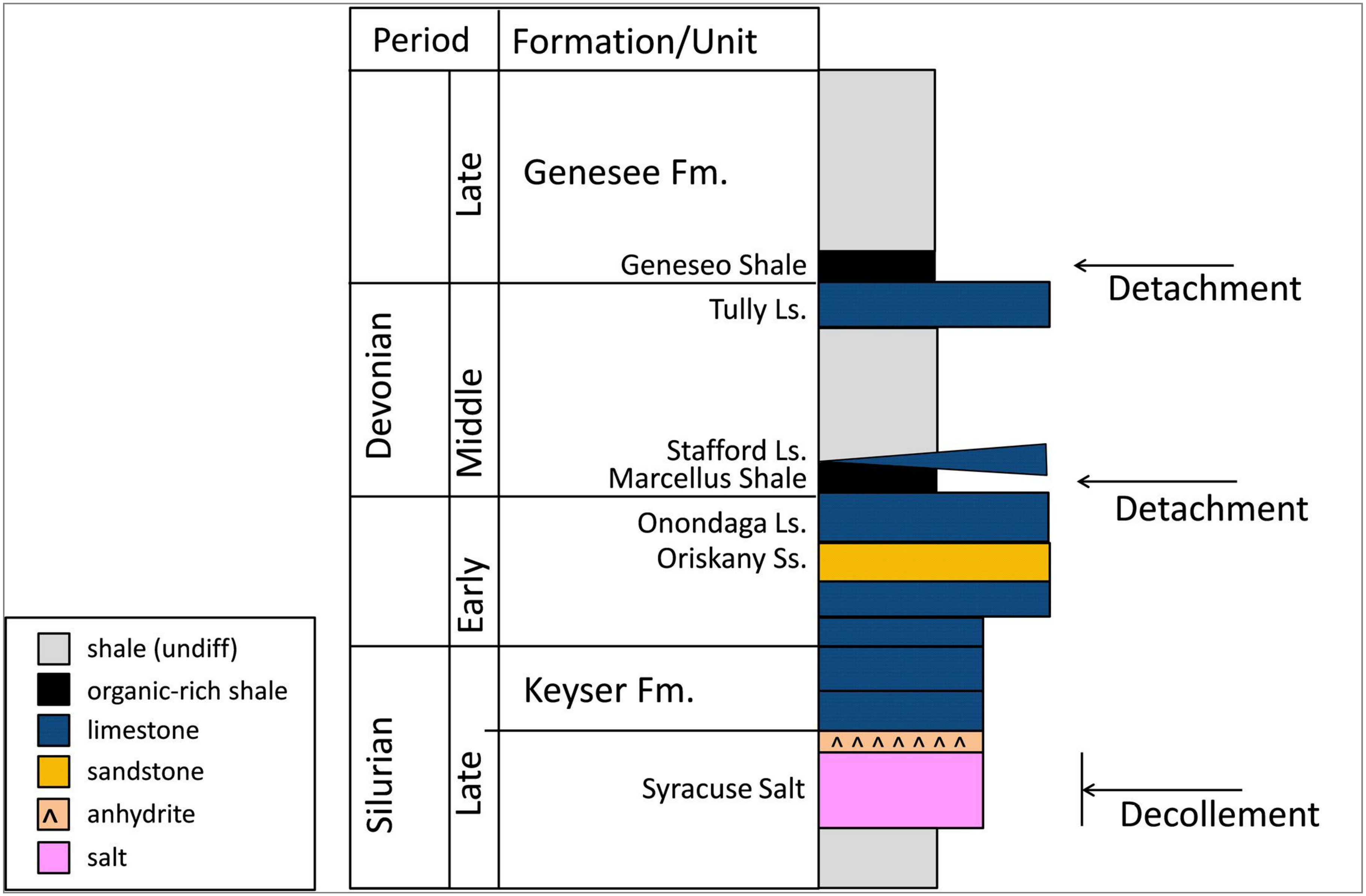

Figure 2. Silurian and Devonian stratigraphy of the Appalachian Plateau, Pennsylvania. The Syracuse Salt represents the decollement of the Appalachian Plateau decollement sheet. Organic-rich shales (black) provide detachment horizons at higher levels. Fm. = Formation; Ls. = limestone; Ss. = sandstone.

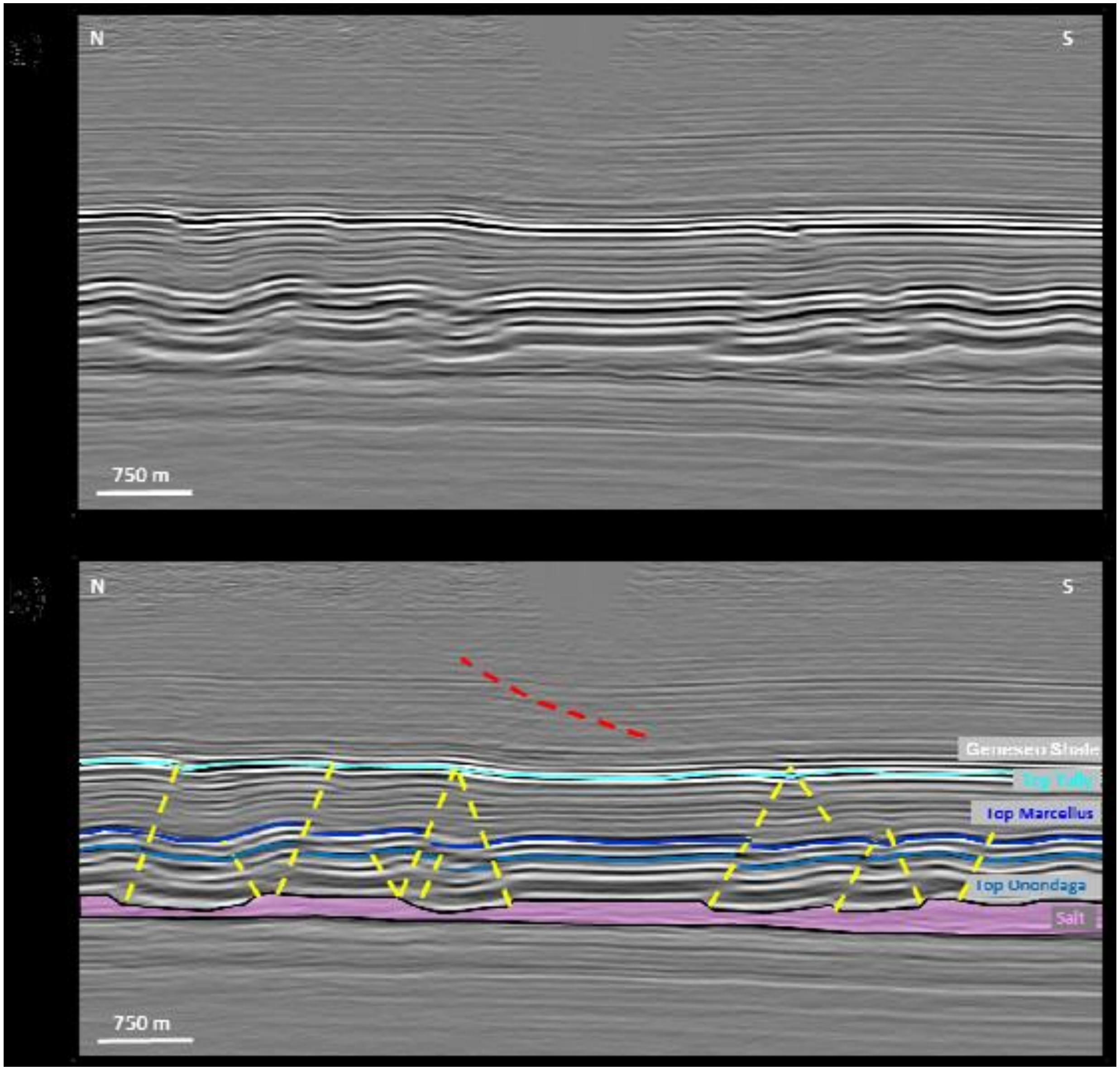

Figure 3. (a) Uninterpreted and (b) interpreted seismic section showing kink bands (yellow dashed lines) developed beneath the Geneseo Shale (above the cyan top Tully Limestone horizon) and the Marcellus shale (dark blue). A thrust is interpreted in the strata above the Geneseo Shale (red dashed line). Prestack time-migrated data scaled so that vertical and horizontal scales are approximately equal. The interpretation of kink bands is supported by geosteering data.

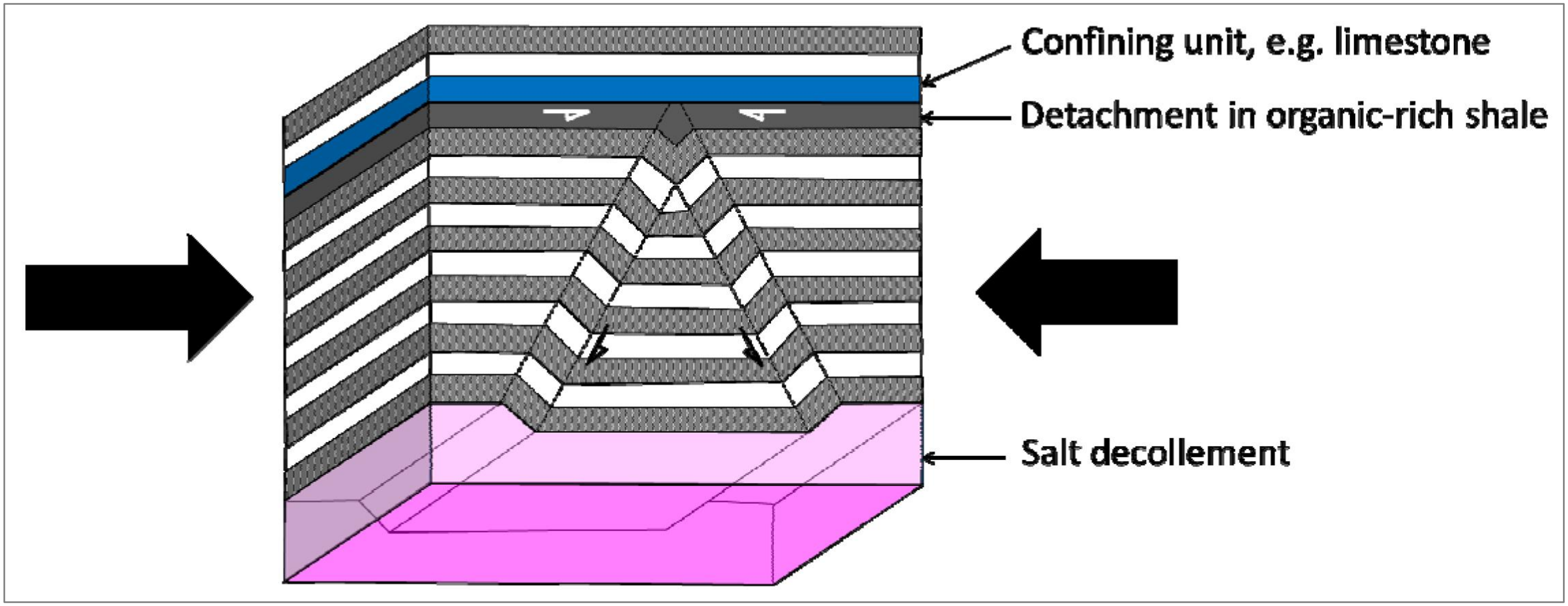

Figure 4. Conceptual model of kink band style in the Appalachian Plateau decollement sheet. Kink bands form conjugate pairs that meet at a detachment level, commonly with a rigid confining unit above. As a result of kink band formation, a pop-down is developed.

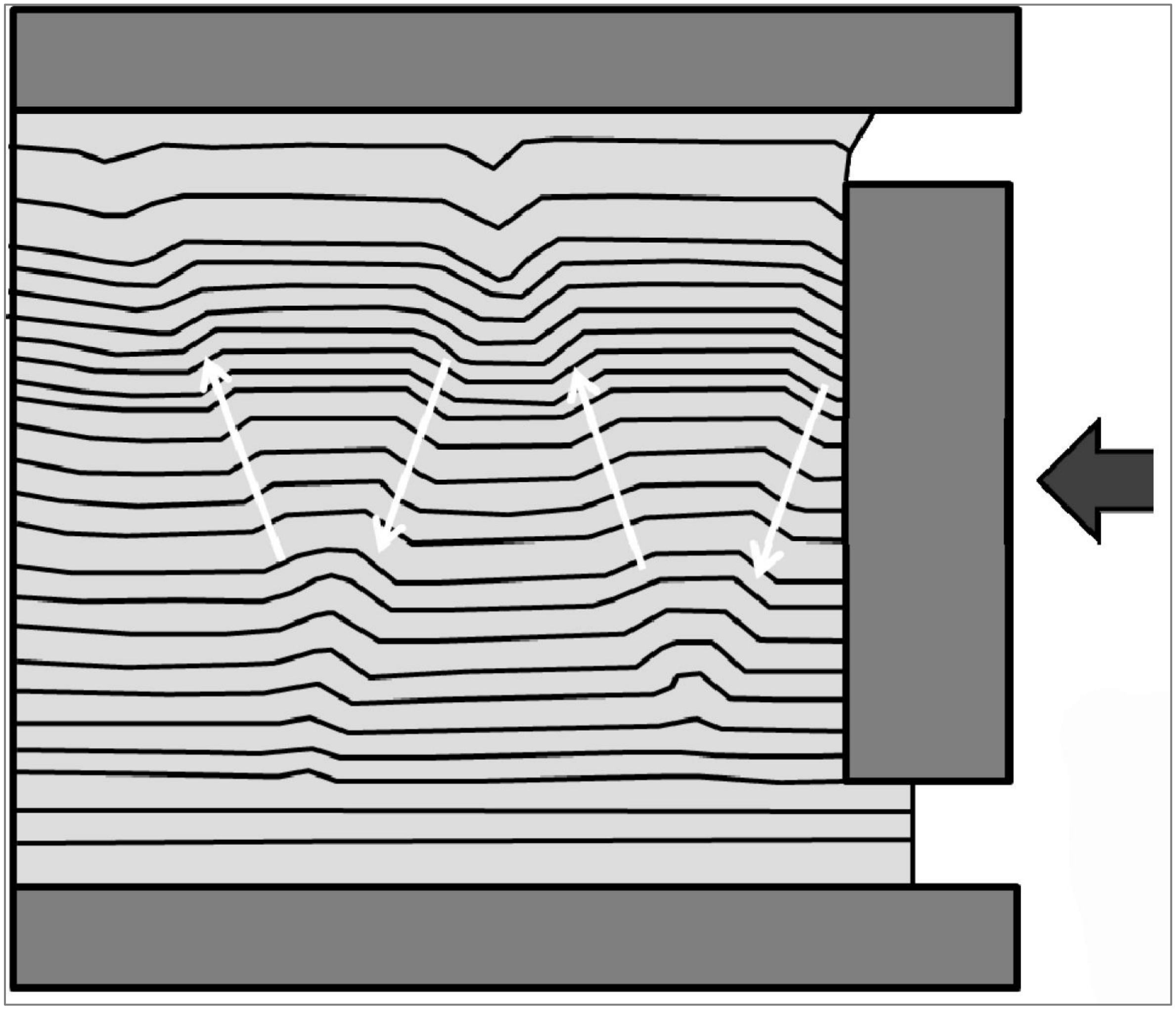

Figure 5. Kink bands developed in a stack of paper under axial shortening between two rigid confining units; the kink bands propagate sequentially in the direction of the arrows, reflecting symmetrically on detachment levels near the top and bottom of the stack of paper. In the case of the Appalachians, only the upper boundary is rigid and so the kink bands only reflect downwards.

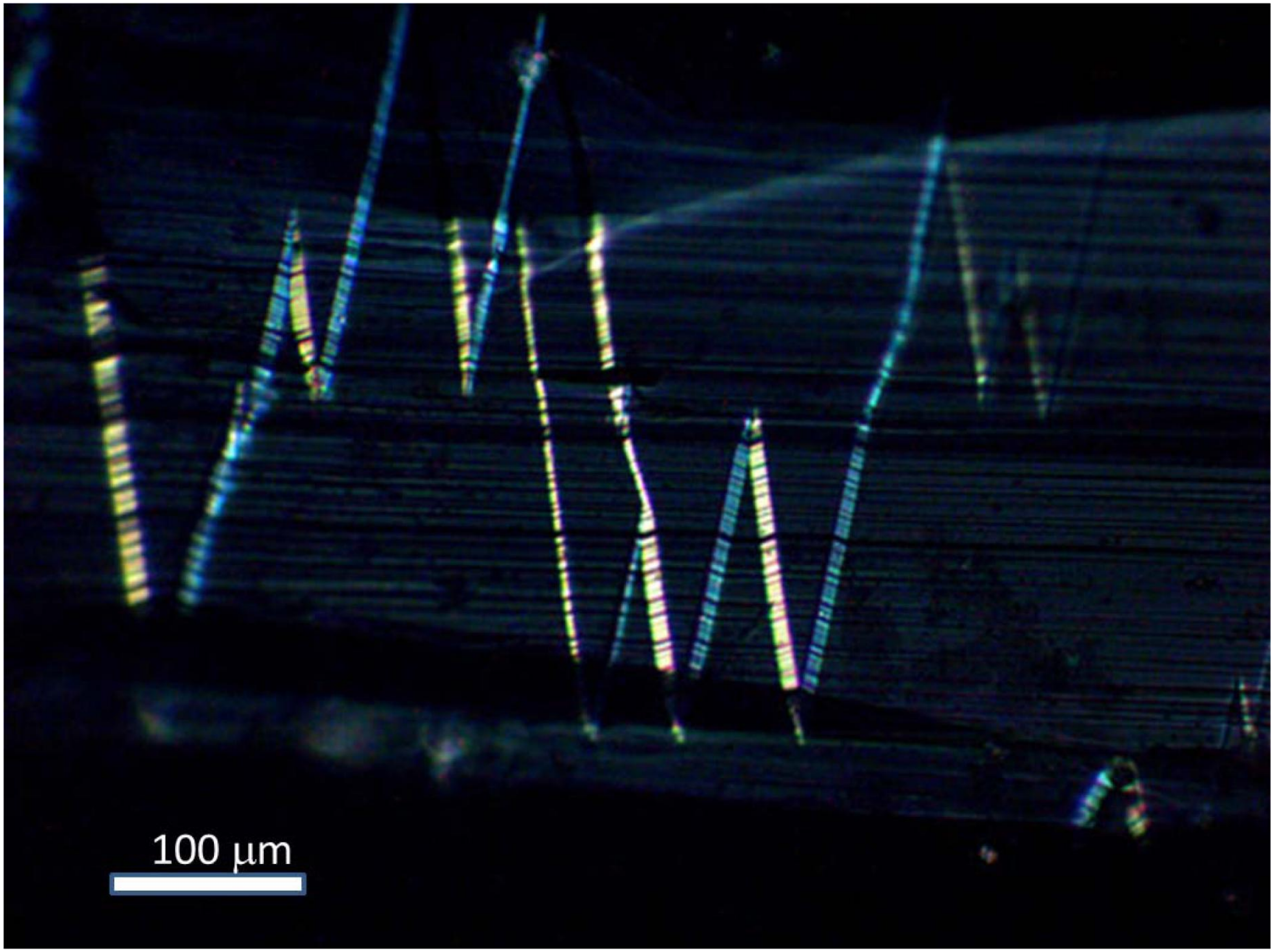

Figure 6. Micrograph of a graphite crystal viewed in crossed polars. The kink bands, which are visible as yellow and blue lines traversing the crystal, are mechanically formed twin domains reflecting both upwards and downwards in the field of view. Sample from Louis Coupal Prospect, Arundel, Argenteuil, Quebec, Canada, from Jaszczak (2015).