# 3-D Seismic and Geosteering Analysis Reveals the Structural Style of the Appalachian Plateau*

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## Introduction

The prolific Marcellus Shale occurs within the Appalachian Plateau detachment sheet that overlies a Silurian salt décollement (Frey, 1973; Wiltschko and Chapple, 1977). The internal structures of the detachment sheet have been variously described as folds, reverse faults, and thrust-cored anticlines. Using 3-D seismic data and geosteering analysis, we show that the dominant internal structures are large, open, sinusoidal folds and reverse kink bands.

During the Mississippian to Permian, Gondwana collided obliquely with Laurentia, resulting in the Alleghanian Orogeny. The external sedimentary parts of this mountain belt include the Valley and Ridge Province and the Appalachian Plateau. The Valley and Ridge Province is characterized by a foreland-verging imbricate stack, with a detachment that ramps up from the Lower Paleozoic. The deformed Appalachian Basin is within the Appalachian Plateau, which in Pennsylvania is underlain by a décollement provided by the Silurian Salina Group (Figure 1). The Salina Group includes anhydrite and salt, and the salt is thickest in NE Pennsylvania, being up to 3000 ft. thick, although this is in anticlinal cores and does not represent primary depositional thickness.

The surface geological features of the Appalachian Plateau are broad folds with a wavelength of about 10 miles developed in rocks of Devonian to Pennsylvanian age. The folds axes have an oroclinal expression in map view as they curve around the salient of the Valley and Ridge.

The viscous décollement provided by the salt has a fundamental effect on the overriding deformation. The Appalachian Plateau detachment sheet thins very gradually towards the foreland: the taper angle is estimated to be 0.73° (Chapple, 1978), a very low taper angle that is consistent with the very weak décollement formed by the Salina Salt.

## General Structural Style

The exact nature of the deformation within the detachment sheet has been debated. Gwinn (1964), using available well data from fields in the region, deduced that the flanks of the anticlines at Devonian level were cut by syncline-ward-dipping reverse faults. Wiltschko and Chapple (1977) argued that the anticlines were developed by buckling of the detachment sheet over the salt; however, this fails to explain the pronounced hinterland-ward asymmetry of the folds. Scalin and Engleder (1973), using 2-D seismic lines, reported that, although the sequence is detached on salt, faults in the sub-salt have had an influence on the nucleation of the folds and that there is significant imbrication of the Salina Group and Lower Devonian within the cores of the anticlines.

## Detailed Structure

A detailed analysis of the structural geology is given here in order to aid seismic interpretation and well placement. The data used are principally 3-D seismic reflection data, with additional information from geosteering analysis, borehole images, and core logging.

Structural logging of the core in the Hamilton Group reveals abundant evidence of bedding parallel to slip and small-scale thrusts in the organic-rich shale, often concentrated beneath limestone units. Both small-scale and large-scale kink bands occur in the shale.

Available 3-D seismic reflection data show that deformation is characterized by large asymmetric salt pillows and by structures with a reverse sense of offset. The reverse structures have a bimodal population of dips, with modal values of 60° and 20°.

### Geosteering Analysis

Geosteering analysis provides further structural definition (Figure 2). Marcellus development begins with a single vertical pilot followed by a number of nearby laterals; geosteering analysis correlates the gamma ray log recorded in the pilot hole with the gamma ray recorded in the laterals allowing construction of detailed cross sections through the wells. Using this technique, shallowly dipping structures imaged on seismic are identified as thrusts, whereas steep reverse structures correspond to monoclines with no break in structural continuity. We, therefore, identify the steep reverse structures as reverse kink bands. This observation is supported by depth-migrated seismic data which tends to make the definition of the kink bands more clear. A very simple rule of thumb emerges: *reverse structures seen on seismic with dips of less than 45° are thrust faults, whereas reverse structures with dips of more than 45° are kink bands*. Thrusts are typically foreland-verging, occurring at various levels in the stratigraphy, and form simple planar ramps that occasionally pass downwards into kink bands.

### Kink Bands

The kink bands dip both towards the hinterland and the foreland and invariably extend down to the salt décollement (Figure 3). Thrusts that underlie the kink bands are seldom observed, and consequently, a fault-related fold model is not generally applicable in the area where data are available to us. A series of different strata provide detachment surfaces that limit upward kink band growth and appear to reflect the kink bands so that they form conjugate pairs with a "Λ" shape¨, defining a box syncline (Figure 4). Similar kink-band reflection has been demonstrated in analog materials by Cobbold (1976) and Wadee et al. (2003). Organic-rich- shales are favored as detachment surfaces; kink-band-reflecting detachment surfaces exist at the Geneseo Shale, the Marcellus Shale and possibly at the base Oriskany Sandstone. The detachment in the upper Marcellus is best developed where the overlying Stafford Limestone is present: the limestone forms a rigid unit that is thought to help reflect the kink bands. The largest kink bands extend up to the present-day surface level where they are observed as zones with internal dips of up to 70°; borehole image data from a lateral well drilled into one such structure shows an abrupt change from sub-horizontal dips to dips of 60°. The vertical displacement (throw) of the kink bands is limited by the thickness of the underlying salt, and, in limiting cases, the base of the sedimentary pile is welded to the base of the salt.

Where conjugate kink bands meet upwards at a detachment surface, a chevron syncline is developed in which there is a significant space problem. In some cases geometric coherency is maintained by out-of-syncline thrusts that extend above the detachment.

It is often observed on seismic that there is shortening by conjugate kink bands below the upper detachment but that there is little or no shortening above it (Figure 3); the sections, therefore, appear not to balance. Some of the shortening above the detachment is taken up by planar, foreland-verging thrust ramps, however, it must be deduced that the rest of the shortening above the detachment occurs by pure shear.

The large, open folds that are mappable at the surface are underlain by salt pillows. The folds are strongly asymmetric, with a kink band marking their southern definition, and they taper gradually to the north. North of the pillows are large areas of salt weld, over which there is little or no deformation. A characteristic of many of the asymmetric anticlines is that about halfway between the kink band and the northerly pinch-out, there is an east-west-striking zone of deformation in the interval between Top Salt and Tully, typically with the development of pop-down structures (Figure 5). This band of deformation does not occur at the present structural crest, which occurs close to the kink band.

## Interpretation

A possible explanation for this geometry is that the structures first formed as symmetric anticlines, but later became increasingly asymmetric, developing a kink band on the southern flank. During the formation of the symmetric anticline, the entire sedimentary sequence above the salt behaved as a buckling competent unit, and developed inner arc compression at the crest, forming pop-downs. The asymmetry was developed as salt withdrew from the northern flank, forming a weld, and flowed towards the southern flank.

This model is supported by Gradmann et al. (2009), who developed numerical models for salt-detached folding. They found that folds developed first sinusoidally and later developed kinks, in what they termed kink-banded folds.

The structural style within the Appalachian Plateau detachment sheet varies laterally from areas of salt pillows separated by broad salt welds to areas that are dominated by smaller scale kink bands. It is inferred that the salt pillows were developed in regions of high primary salt thickness, whereas where the salt was thinner, smaller scale kink bands were developed. Within the regions dominated by kink bands, variations in the scale of the kink bands was controlled by the presence or absence of detachment zones at different levels of the stratigraphy, as well as by the total strain.

Large-scale kink bands have not often been documented in the literature, although kink bands have already been described in outcrops of the Valley and Ridge by Faill (1969, 1973). Good examples also occur in the Perdido Fold belt, that is underlain by the Louann Salt (Camerlo and Benson, 2006) and in the Ougarta of Algeria (Collomb and Donzeau, 1974). The conditions for kink band development are thought to include the presence of highly anisotropic rocks, such as shale, mild shortening, and moderately deep burial.

Although it is difficult to distinguish the exact style of deformation from seismic interpretation alone, combining seismic interpretation with well data allows the true nature of the deformation to be determined. Routine integration of depth-converted or depth-migrated seismic and geosteering analysis, together with improved structural understanding, can significantly improve placement of laterals, which in turn reduces costs and improves well performance. Availability of borehole image logs in lateral wells and improved seismic imaging can further constrain deformation.

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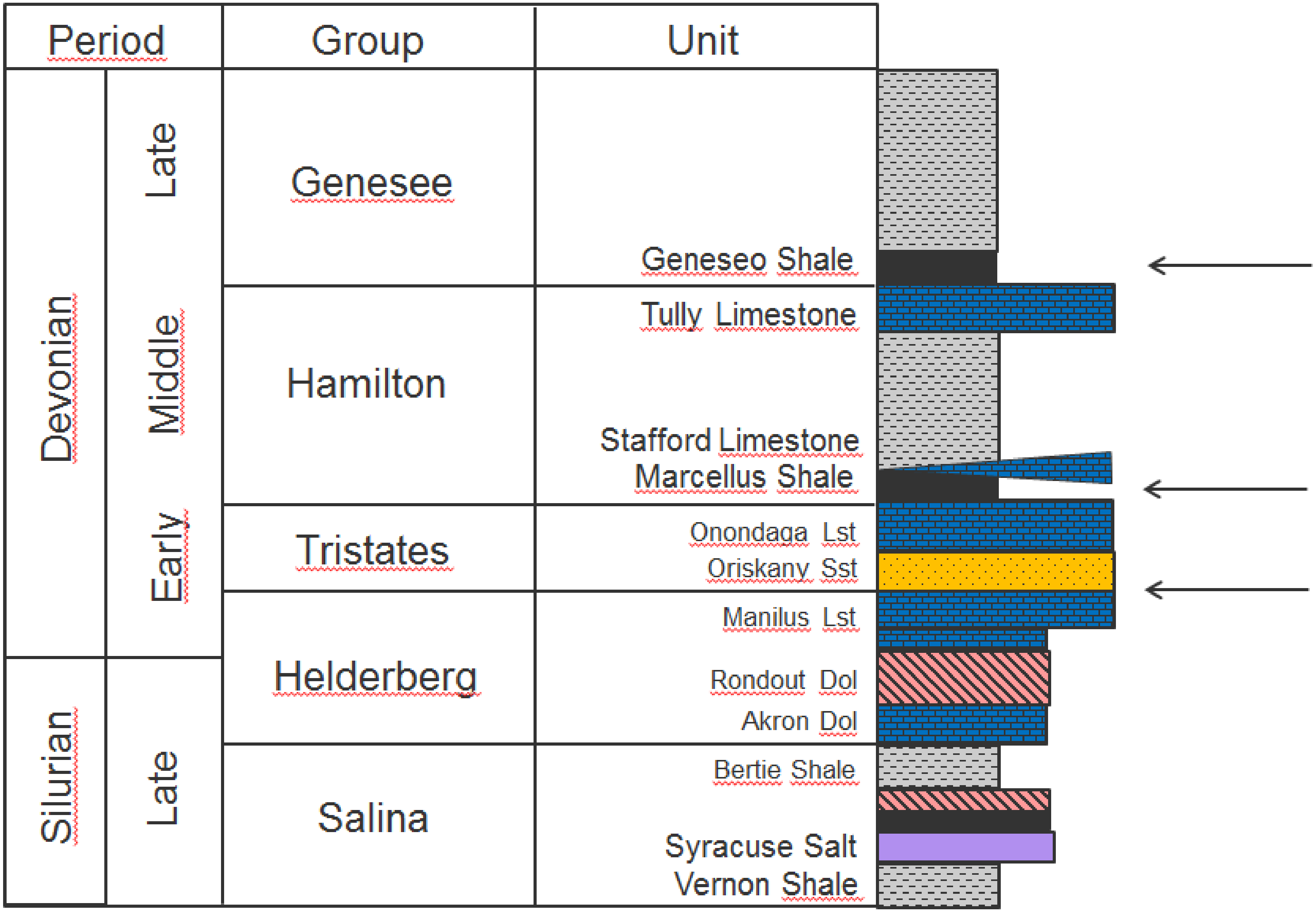


Figure 1. Silurian-Devonian stratigraphy for the Appalachian Plateau detachment sheet. The Syracuse Salt forms the major regional décollement. Arrows mark the positions of kink-band-reflecting detachments.

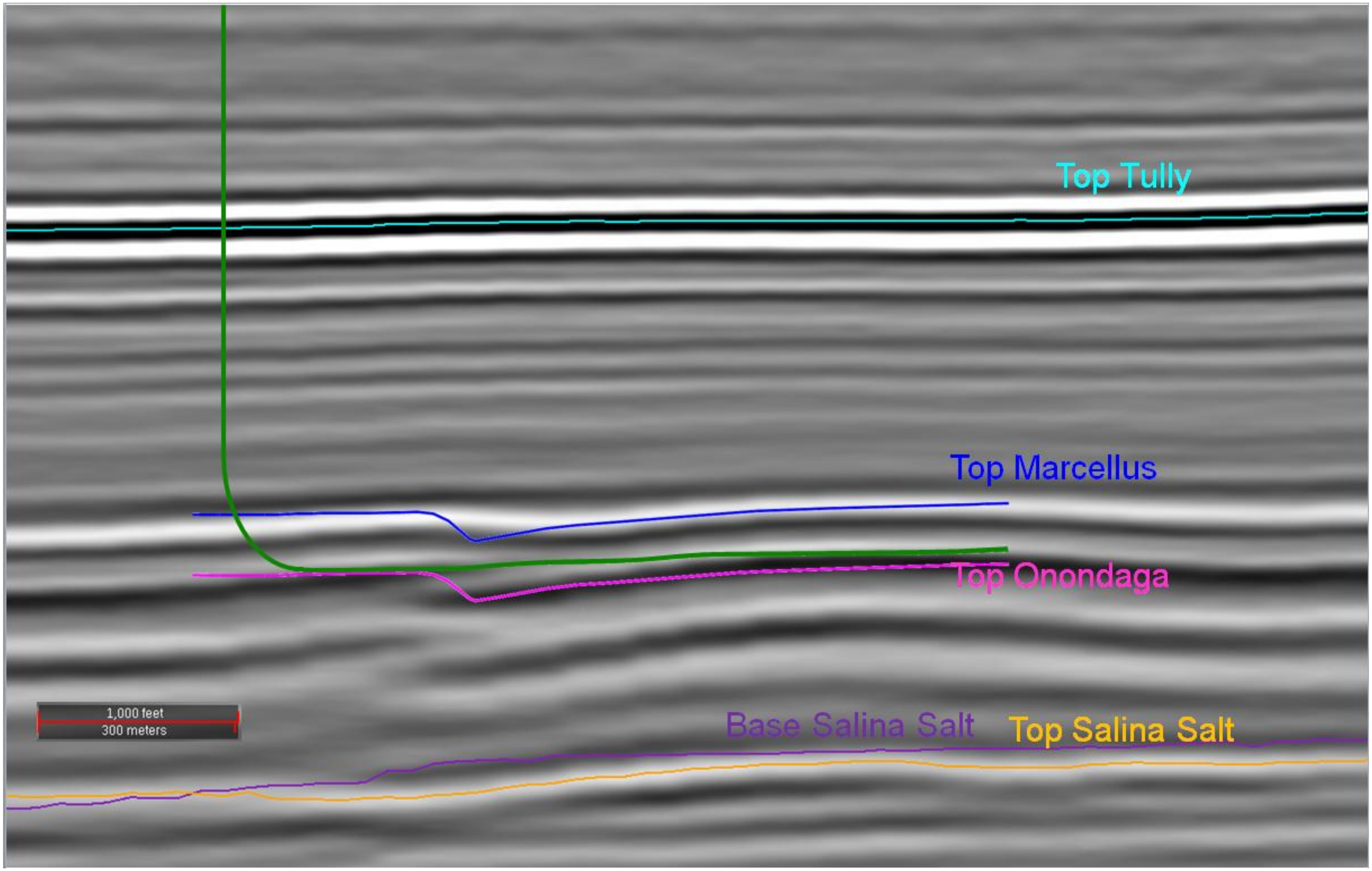


Figure 2. Section through the depth converted seismic volume, showing well path (green) and interpretation of Top Marcellus and Top Onondaga taken from geosteering analysis. The steep reverse structure is proved by geosteering to be a fold (kink band) rather than a reverse fault. The Salina Gp Salt is thin in this area, and consequently, Top and Base Salt are not easily distinguished. Scale bar = 1000 ft. Horizontal scale = vertical scale; seismic data courtesy of GPI/GeoKinetics.

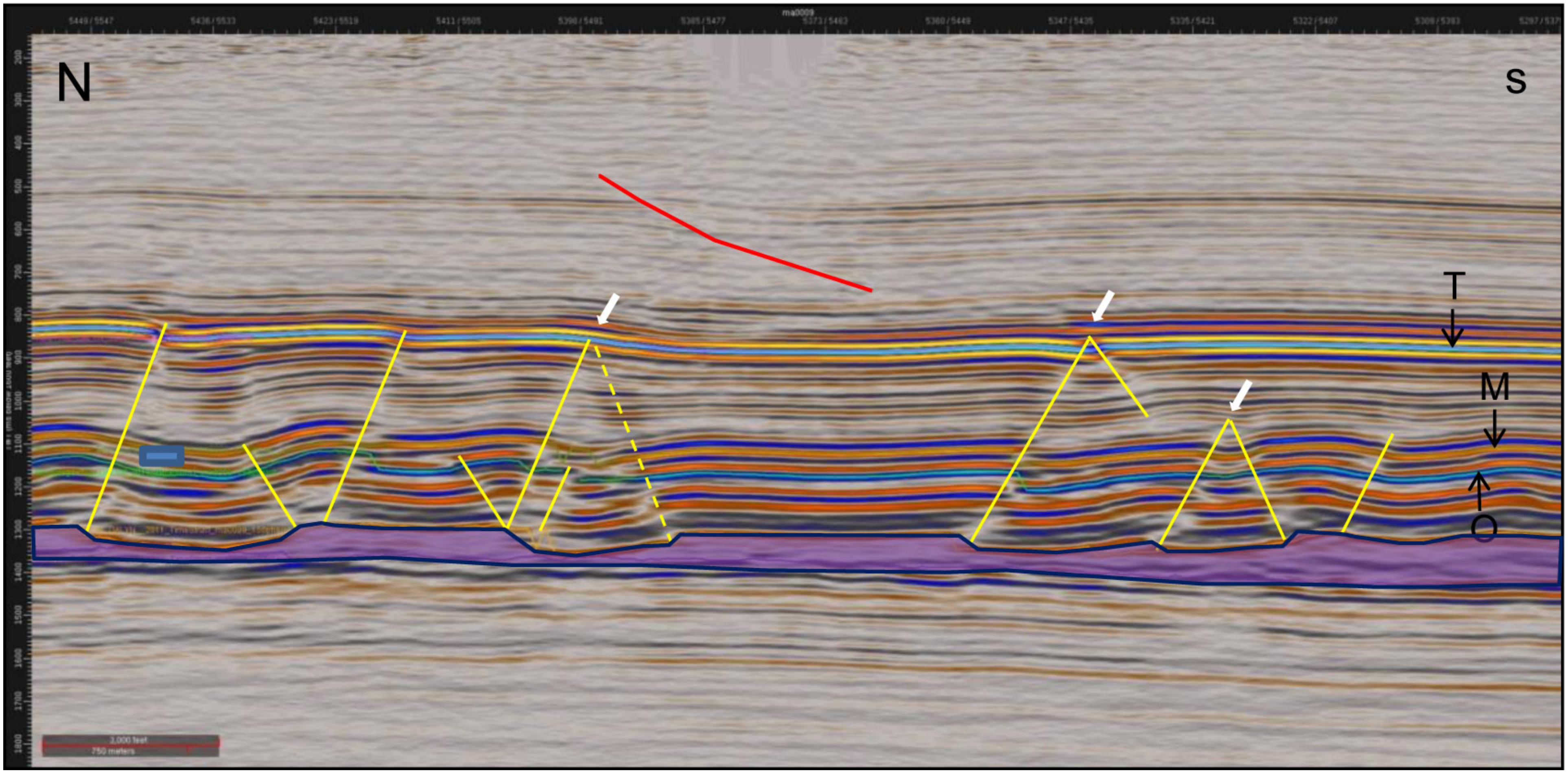


Figure 3. Section through the depth converted seismic volume, showing the tops of Tully (T), Marcellus (M), and Onondaga (O). The kink bands (yellow) run down to the Salina Salt (purple). White arrows show points of kink-band convergence; the points are inferred to be at detachment horizons at the Geneseo Shale, above the Tully Limestone and near the top Marcellus. A small thrust (red) occurs above the Tully. Scale bar = 2000ft. Horizontal scale = vertical scale; seismic data courtesy of GPI/GeoKinetics.

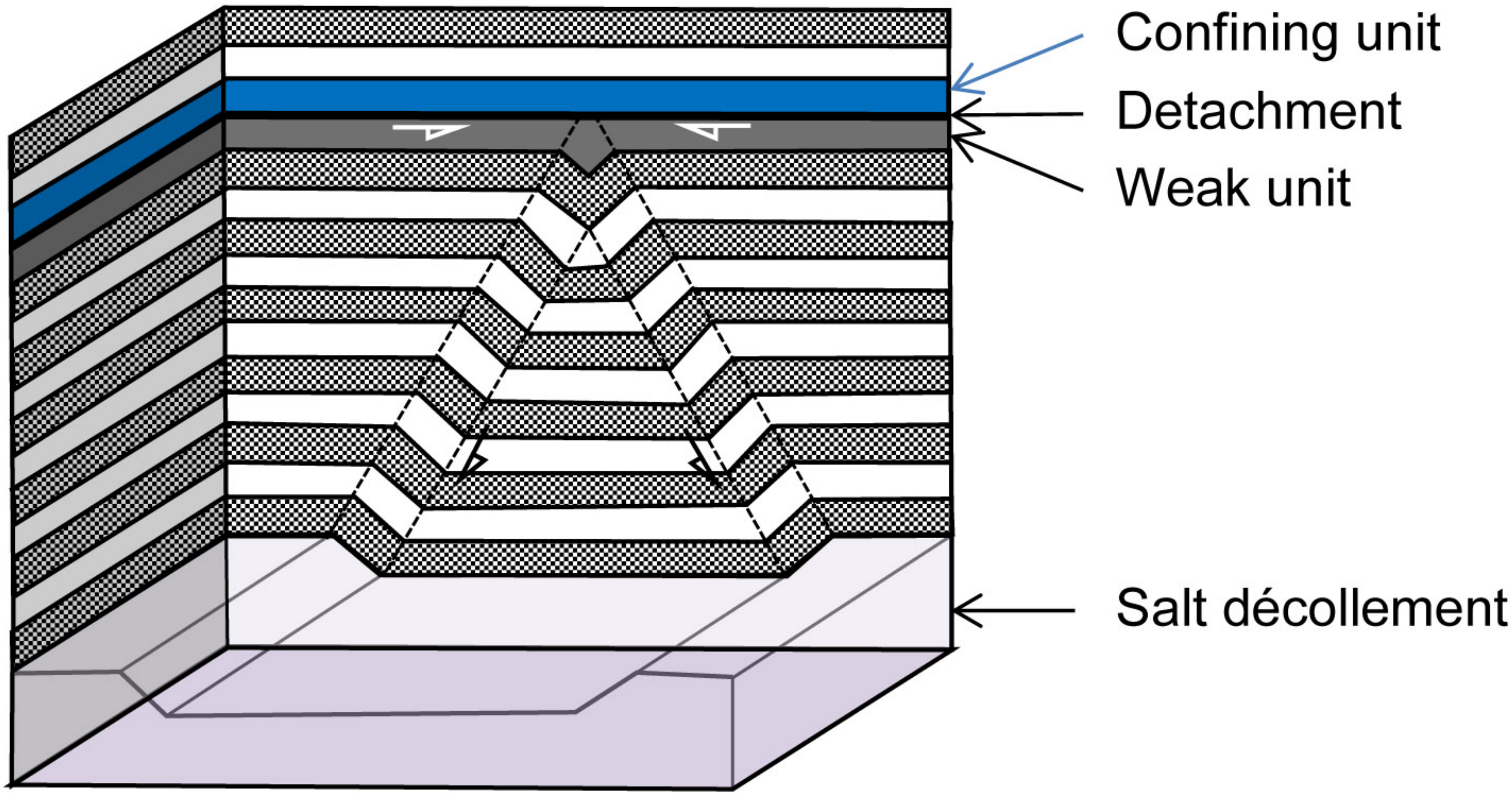


Figure 4. Conceptual model for the development of conjugate kink bands over a salt décollement. The kink bands are reflected at a detachment unit, typically an organic rich shale and define a box syncline that moves downwards into the underlying salt décollement. The point where the kink bands converge marks the position of the detachment.

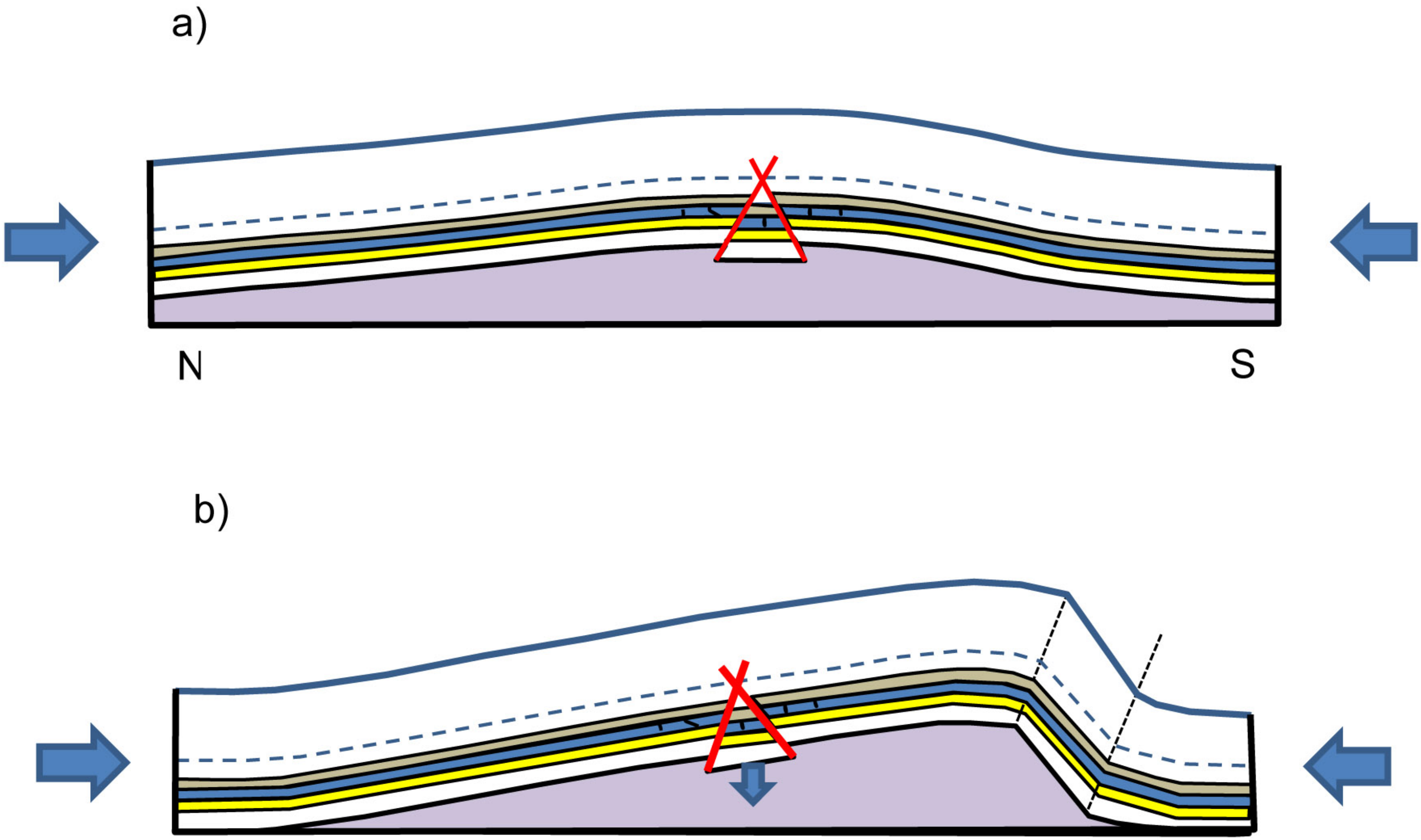


Figure 5. Development of salt pillows in the Appalachian Plateau detachment sheet showing a) the development of an early sinusoidal fold and a pop-down in the inner arc of the detachment sheet, b) the development of a single large kink band on the southern flank to form an asymmetric fold with salt welds on either side.