Concentrate on Section 3.1

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Structural style of the Appalachian Plateau fold belt, north-central Pennsylvania

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A R T I C L E I N F O

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A B S T R A C T

New seismic and well data from hydrocarbon exploration and development activity associated with the Marcellus Formation shale gas play in north-central Pennsylvania provide insight to the structural style of the Appalachian Plateau fold belt in the region north and northwest of the Allegheny structural front in Potter, Tioga, Bradford, Sullivan, Lycoming, Clinton and Centre counties. The Plateau fold belt in this area developed over a detachment in Upper Silurian Salina Group evaporites during the Permian Alleghanian Orogeny in response to north-northwest directed shortening. At the Allegheny structural front, a deep detachment in Cambrian shales that underlies the Valley and Ridge province to the south-southeast, ramps up-section through Cambro-Ordovician carbonates and Lower-Middle Silurian clastics to a shallow detachment in Upper Silurian evaporites. At the northeastern plunge of the Nittany Anticline (south and east of Williamsport, PA), only a small amount of slip is interpreted to have been transmitted into the foreland on the shallow Upper Silurian detachment. Instead most slip was consumed in fault-propagation folds immediately north of the Allegheny structural front. The Plateau fold belt, developed above the Upper Silurian evaporites, can be divided into structural domains based on fold characteristics. Domain 1 folds have short wavelengths and low amplitudes. Domain 2 salt-cored anticlines have long wavelengths and large amplitudes. Domain 3 comprises large synclines, located between Domain 2 anticlines. Halite originally beneath Domain 3 synclines is interpreted to have been mobilized, or evacuated, into the cores of adjacent Domain 2 anticlines during folding. Seismic data indicate that the base of the salt detachment underlying Plateau folds is a non-planar, stepped surface. Possible scenarios for the development of the non-planar detachment include: 1) mobilization of halite from an evaporite sequence that contained an originally non-uniform distribution of halite, 2) it is an erosion surface that existed prior to deposition of the evaporite sequence, or 3) it developed *in response* to buckle folding of the stratigraphic layer overlying the evaporite sequence.

1. Introduction

The Allegheny structural front in north-central Pennsylvania is the structurally-defined boundary between the Valley and Ridge fold belt to the southeast and the Appalachian Plateau fold belt to the northwest, and approximately coincides with the Allegheny front, an area of subdued topography between the Valley and Ridge and Plateau physiographic provinces (Rodgers, 1970; Faill, 1998) (Figs. 1–3). The structural style of the Allegheny structural front, the Valley and Ridge fold belt, and the Appalachian Plateau fold belt have been studied for over a century (Chamberlain, 1910; Willis and Willis, 1929; Sherrill, 1934; Wedel, 1932). Over the past 50 years, deep oil and gas exploration wells drilled on the Appalachian Plateau and 2D seismic reflection data have documented that the broad, subtle, long-wavelength folds in Devonian, Mississippian and Pennsylvanian age strata at the surface are detached from deeper strata along an evaporite interval within the Upper Silurian Salina Group (Gwinn, 1964; Prucha, 1968; Frey, 1973; Wiltschko and Chapple, 1977; Davis and Engelder, 1985; Shumaker, 2002). Recent industry activity in north-central Pennsylvania associated with exploration and development of hydrocarbons within the Middle Devonian Marcellus Formation shale, has included acquisition of high-quality seismic data (both long offset, regional 2D lines and 3D surveys covering large areas) and the drilling of horizontal wells with long lateral reaches – typically over 1 mi (1.6 km). These new data clarify the structural style of the Appalachian Plateau folds above the Upper Silurian evaporites, and allow the Plateau fold belt to be partitioned into structural domains based on fold characteristics. The results of this study based on new industry data are

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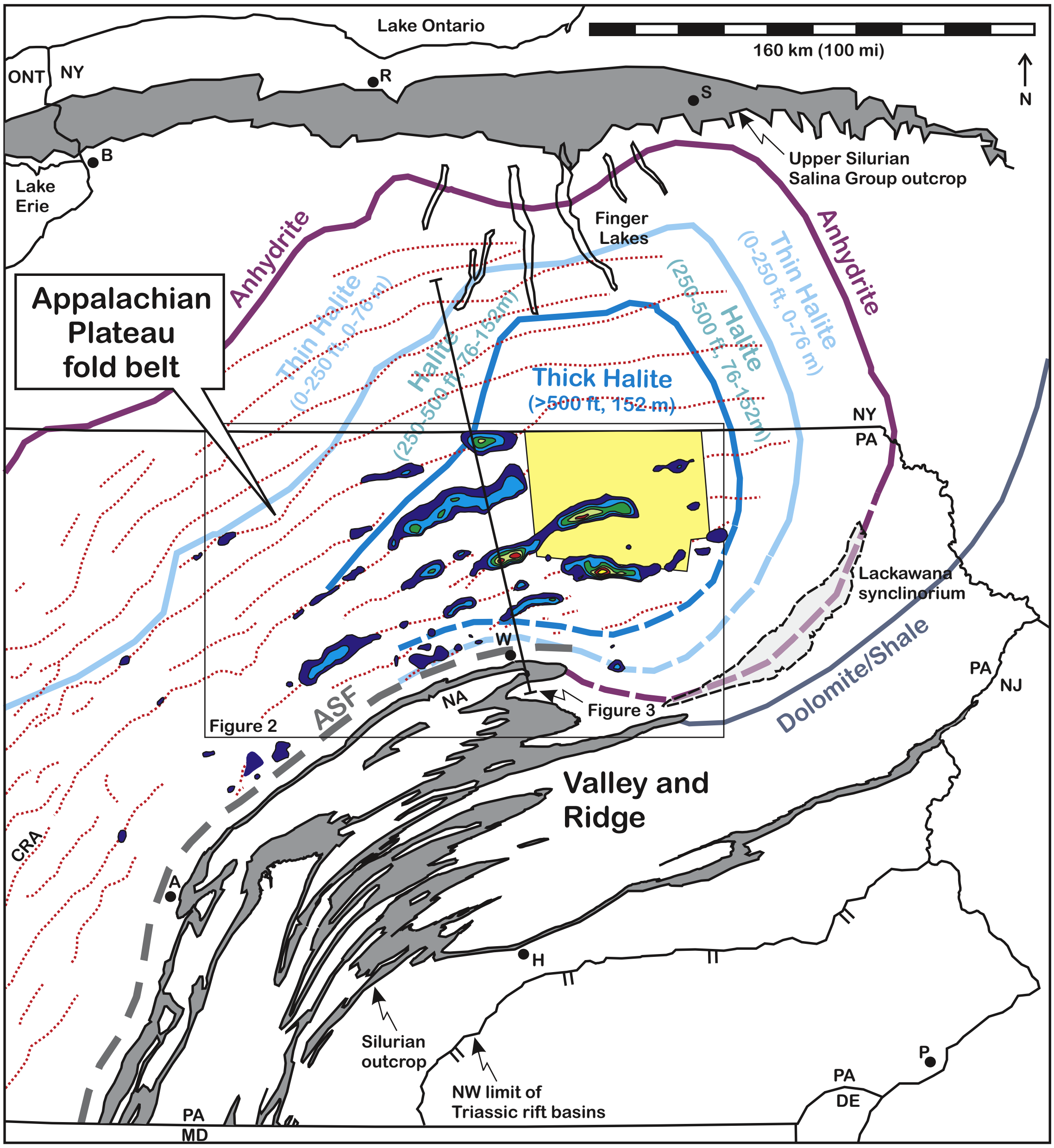

Fig. 1. Appalachian Plateau fold belt location map. Dark gray shaded areas are outcrops of Silurian age rocks (from Rickard, 1969 in New York; and Berg et al., 1980 in Pennsylvania). Red dashed lines represent axial traces of surface anticlines (from Engelder and Geiser, 1980 in New York; and Berg et al., 1980 in Pennsylvania). ASF: Allegheny structural front; NA: Nittany Anticlinorium, CRA: Chestnut Ridge Anticline. Cities in Pennsylvania: W: Williamsport; A: Altoona; H: Harrisburg; P: Philadelphia. Cities in New York: B: Buffalo, R: Rochester, S: Syracuse. Bradford County, Pennsylvania is highlighted in yellow. The extent and facies distribution of the main halite bearing unit within the Upper Silurian salt basin is constrained by hundreds of well penetrations (Salina Group "F" facies map from Rickard, 1969). The southeast portion of Rickard's (1969) map is not tightly constrained by well data and has been modified based on interpretation of seismic data. Notice areal extent of the Plateau fold belt coincides with limit of the halite facies within the underlying Salina Group. A salt isopach map is superimposed on the fold axial trace map in north-central Pennsylvania. The isopach map shows present-day salt thickness greater than 1600 ft (487 m) and illustrates the geometry of the salt cores of the anticlines (key to isopach map shown in Fig. 2). The surface trace of Mississippian strata associated with the Lackawana synclinorium are indicated by black dashed lines.

consistent with and expand on earlier interpretations regarding fold geometry and mechanics of folding within the Plateau fold belt by Wiltschko and Chapple (1977).

2. Geologic setting

2.1. Stratigraphy

The stratigraphic section underlying the Appalachian Plateau in north-central Pennsylvania consists of a wedge of Paleozoic sediments overlying Precambrian basement that thicken toward the south-southeast (Nickelsen, 1988; Childs, 1985). The basement surface dips gently (<1–$2°$) to the south-southeast, from a depth of approximately 6000 ft ($\sim$1.8 km) below sea level in the Finger Lakes region of New York, to a depth of approximately 20,000 ft ($\sim$6 km) below sea level at the Allegheny structural front in the vicinity of Williamsport in south-central Lycoming County, Pennsylvania (Figs. 1 and 3) (Patchen et al., 2004; Alexander et al., 2005).

Overlying basement is a thick (approximately 20,000 ft, $\sim$6 km) sequence of Cambrian through Middle Silurian age strata

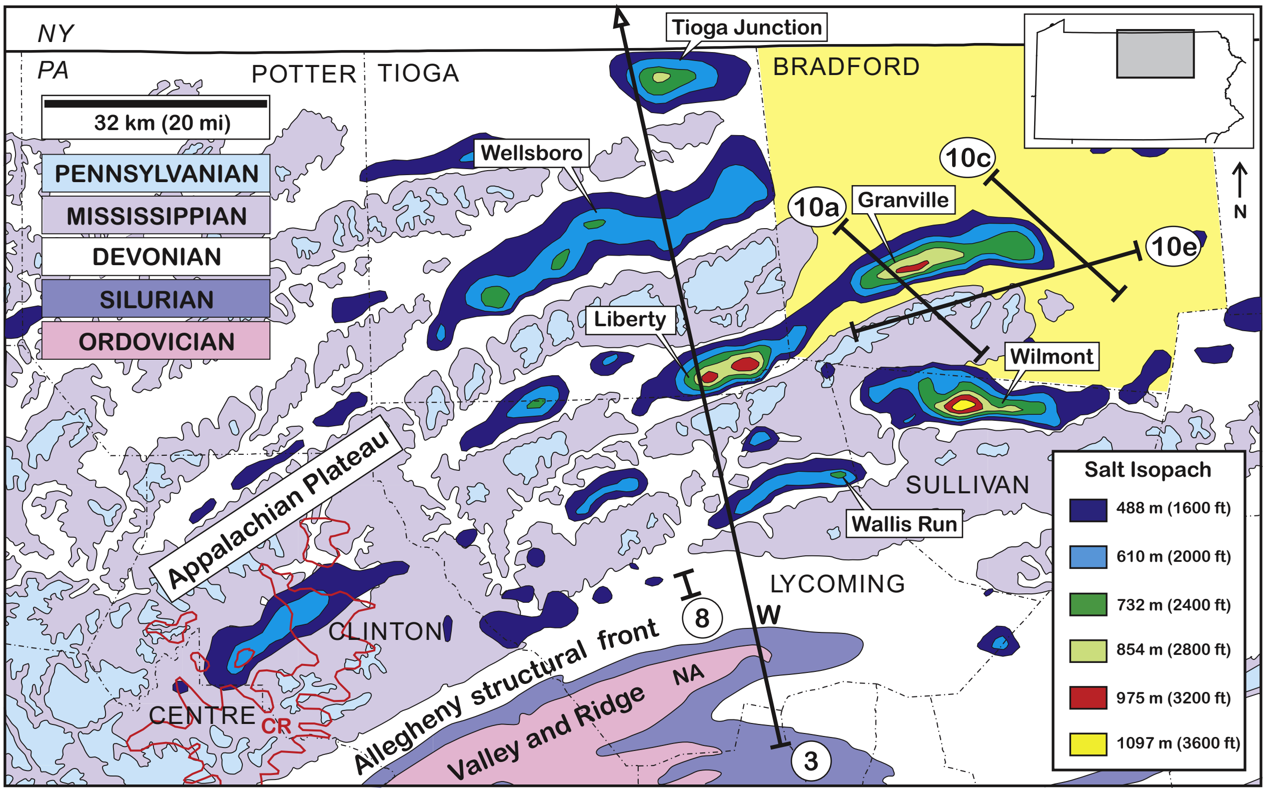

Fig. 2. Geologic map of north-central Appalachian Plateau (modified from Pennsylvania Department of Conservation and Natural Resources map 2200-MP-DCNR0498, www.dcnr.state.pa.us/topogeo/maps/map7.pdf) with superimposed isopach map of underlying Upper Silurian Salina Group salt (where salt thickness is greater than 1600 ft [487 m]). Thick areas of salt represent cores of large anticlines (yellow areas represent salt thicknesses of up to 3600 ft [1097 m]). Surface outcrop of Mississippian and Pennsylvanian strata define intervening synclines. Red polygon labeled "CR" is Council Run Gas Field in Centre and Clinton counties. "W" indicates the city of Williamsport in south-central Lycoming County. Wellsboro anticline originally identified by Wiltschko and Chapple (1977). Granville (Towanda) and Wilmont anticlines originally identified by Frey (1973). Location of transects in Figs. 3, 8 and 10 are shown.

comprising Cambro-Ordovician carbonates and Upper Ordovician/Middle Silurian shales, siltstones and sandstones (Fig. 4). The Middle Silurian clastic sequence transitions into an Upper Silurian section that includes rocks deposited in an evaporite basin. The Upper Silurian evaporite basin underlies the Plateau fold belt and controls its areal extent – detachment folding is limited to regions above relatively thick halite. The extent and facies distribution of Upper Silurian evaporites in north-central Pennsylvania and western New York are summarized in Fig. 1 (for the sequence within the Salina Group that contains the majority of halite – Facies "F" of Rickard, 1969). The thickest halite in the basin is centered near Bradford County, Pennsylvania, and thins towards the basin margins. The margin of the salt basin is defined by a facies change to anhydrite in northwestern New York, eastern Pennsylvania, and the Valley and Ridge province to the south (Fig. 1).

The Upper Silurian interval comprises the Salina Group evaporites in the central portion of the northern Appalachian Plateau subsurface which are correlated with Tonoloway Formation shallow-water limestones exposed in surface outcrops around the basin margins (Rickard, 1969; Smosna et al., 1976; Smosna and Patchen, 1978). The Tonoloway Formation is composed of laminated, fine-grained, sparsely fossiliferous, shallow-water limestones, interpreted as sahbkha/tidal flat facies (Smosna et al., 1976). The Salina Group evaporite section does not outcrop and is constrained by well data in north-central Pennsylvania, western New York, Ohio, and West Virginia (Rickard, 1969; Smosna et al., 1976; Smosna and Patchen, 1978). Salina Group lithologies include interbedded halite, anhydrite, dolomite, and minor shale. In contrast, the Tonoloway Formation outcrops in the Valley and Ridge fold belt in Pennsylvania and West Virginia, defining the southeastern margin of the Silurian evaporite basin (Fig. 1). The Tonoloway Formation is also encountered in wells in the southern part of the basin, near the Allegheny structural front. Shales and dolomites of the Syracuse and Bertie formations, facies equivalents to the Tonoloway Formation crop out along the Mohawk River valley and northern Finger Lakes region in western New York and define the northern margin of the Silurian evaporite basin (Fig. 1).

Overlying the Salina Group and Tonoloway Formation is a thick sequence of Upper Silurian through Pennsylvanian layered carbonates, sandstones, siltstones, and shales – including the Middle Devonian Marcellus Formation shale (Fig. 4). The Upper Silurian through Pennsylvanian sequence is thicker than 10,000 ft (~3 km) in the basin immediately north and northwest of the Allegheny structural front, and thins to the north and west.

Outcrop and seismic data (regional 2D and large "county-scale" 3D seismic surveys) indicate that the entire sedimentary package – from Pennsylvanian age strata exposed in synclines at the present-day surface to Upper Silurian units immediately overlying the evaporite section at depth – are conformably folded (Fig. 3). The absence of syn-tectonic growth packages within the observed stratigraphic interval on the limbs of the Plateau folds suggests they are the result of contraction associated with post-Pennsylvanian age deformation – most likely the Permian Alleghanian orogeny.

Estimates of the amount of Upper Devonian-Permian strata eroded since the Alleghanian orogeny in the Appalachian Plateau region range from approximately 6500 ft (~2 km) in western

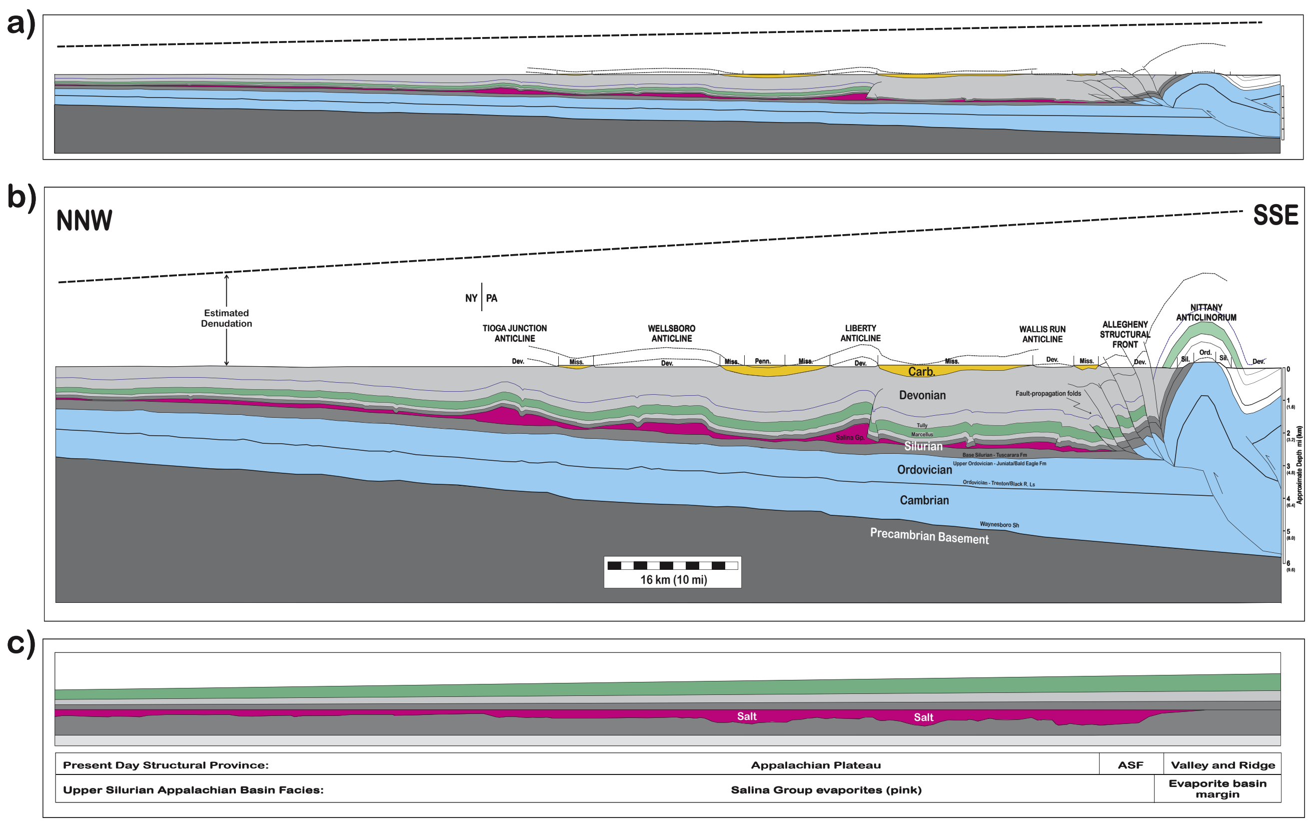

Fig. 3. Regional transect across the north-central Appalachian Plateau fold belt based on 2D and 3D seismic data, surface geology, and well data. Approximate line location shown on Fig. 1 and 2 a) Transect at approximate 1:1 scale (vertical scale = horizontal scale). b) Transect at approximate 3:1 scale (vertical scale = 3 × horizontal scale). A deep detachment in Cambrian Waynesboro Formation shale at south end of line steps up to a shallow detachment in Upper Silurian Salina Group evaporites at the Allegheny structural front. Slip above the south-dipping fault ramp between the deep and shallow detachment levels generated a fault-bend fold (the Nittany Anticlinorium south of Williamsport, Pennsylvania). A portion of the slip on the upper detachment is consumed in a series of fault-propagation folds immediately north of the fault-bend fold, and a portion of the slip is transmitted to the north, contributing to the development of the salt-cored detachment folds underlying the Appalachian Plateau. Dashed line at top of section is estimated denudation since the Alleghany orogeny based on Schultz, 1999. c) Restoration of the transect to Middle Devonian time (before the Alleghanian orogeny). The vertical scale has been exaggerated to illustrate the non-planar base of salt detachment, which is subtle and difficult to observe in the regional sections. The rugose base of salt is observed on regional 2D seismic data and detailed examples shown in 3D seismic data (Fig. 10) are discussed in the text. Notice southern margin of the Upper Silurian evaporate basin underlies the area of the present-day Allegheny structural front, and that the base of the evaporate detachment is not planar.

Pennsylvania and New York, to in excess of 20,000 ft (~6 km) near the Allegheny structural front in north-central Pennsylvania (Schultz, 1999; Rowan, 2006) (Fig. 3). Unfortunately for attempting to constrain the timing of deformation, it is within this eroded stratigraphic interval that syn-tectonic growth strata would be expected for Permian deformation (such as thinning of stratigraphic sequences deposited over the limbs of growing anticlines). The large post-Permian denudation throughout the Appalachian mountain chain is attributed to regional uplift related to Mesozoic rifting and initiation of Atlantic Ocean seafloor spreading (Blackmer et al., 1994).

2.2. Surface geology

The surface expression of the Appalachian Plateau fold belt extends from the Allegheny structural front in the south and east, to the New York State Finger Lakes region and the Ohio/West Virginia border in the north and west (Fig. 1). As described above and proposed by previous workers, the areal extent of the fold belt coincides with the extent of halite in the underlying Upper Silurian Salina Group evaporites (Fig. 1) (Rickard, 1969; Engelder and Geiser, 1980; Davis and Engelder, 1985).

The surface geology of the Appalachian Plateau in northern Pennsylvania (Potter, Tioga, Bradford, Sullivan, northern Lycoming, Clinton and Centre counties) is dominated by gentle folds defined by outcropping Devonian, Mississippian, and Pennsylvanian strata (Berg et al., 1980) (Figs. 2 and 3). Surface axial traces of the Plateau folds tend to be arcuate and generally parallel to northeast-southwest fold trends within the Valley and Ridge province to the southeast, long (10 mi to 100 mi, 16 km–160 km), with wavelengths ranging from 5 mi to 20 mi (8 km–32 km) (Figs. 1 and 2) (Berg et al., 1980). Sherrill (1934) recognized that although fold limb dips at the surface are gentle, dipping only a couple of degrees – the larger anticlines have steeper limb dips on the southeast side (typically 1.2–1.3 times steeper). The surface observation of steeper fold limbs on the southeast and south side of large Plateau anticlines is consistent with the isopach map of the salt interval coring these structures. The salt isopach map indicates that the salt cores are asymmetric, with the thickest part of the salt core on the southeast side of the structure (Figs. 1 and 2) (Frey, 1973). Amplitudes of these southeast-verging folds, which range from 100 ft (30 m) to greater than 3000 ft (900 m), tend to decrease to the northwest (Schultz, 1999) and are greatest in a series of anticlinal structures 20–50 mi (32–80 km) north of the Allegheny structural front in Bradford, Tioga, Lycoming, and Sullivan counties (Fig. 2). Recessive weathering of Upper and Middle Devonian shales in the cores of anticlines at the surface results in the crestal regions of the folds being present-day topographic lows. In contrast, the intervening

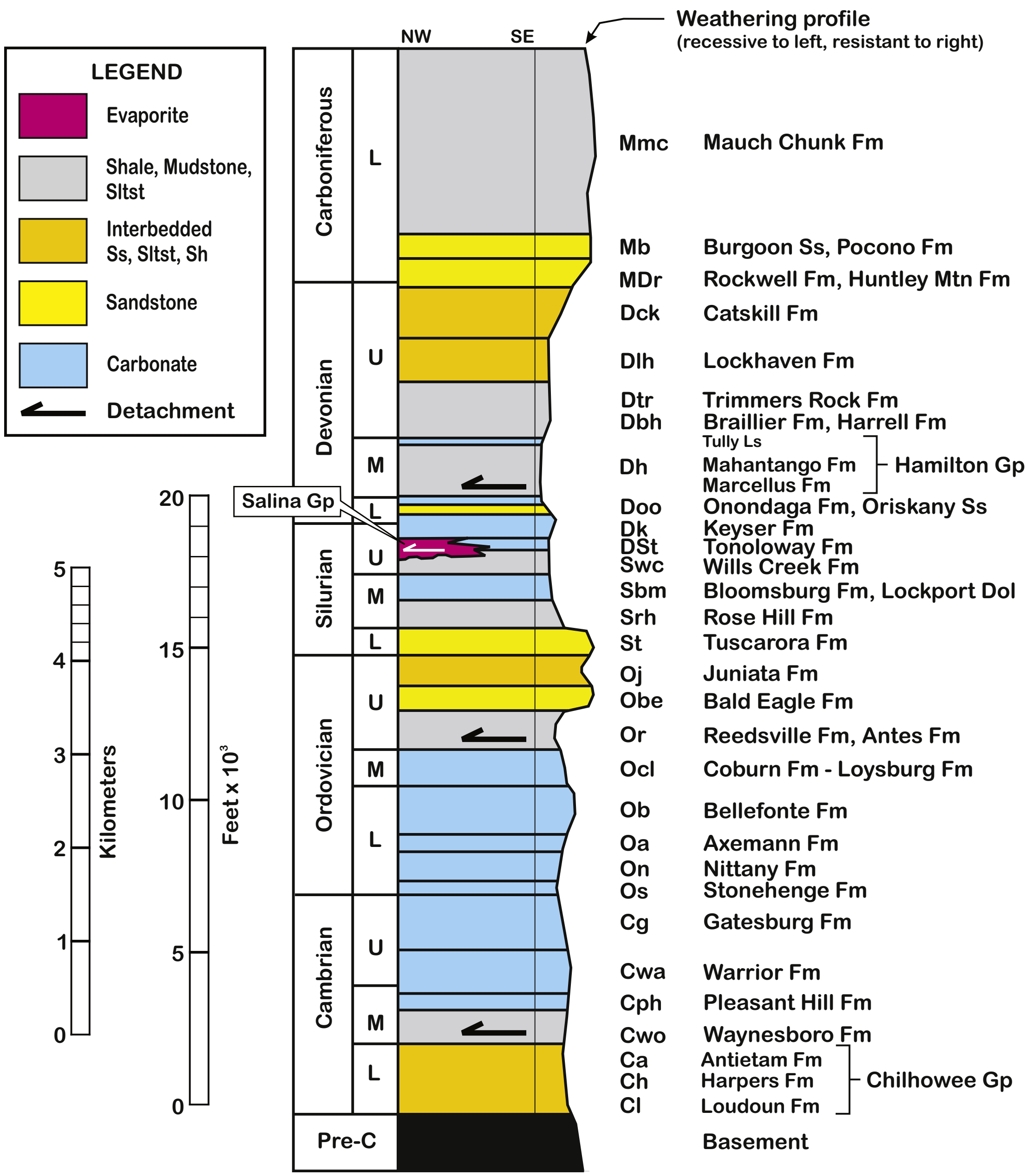

Fig. 4. Generalized stratigraphic column for north-central Pennsylvania (modified from Nickelsen, 1988; Patchen et al., 1985).

synclines are comprised of resistant weathering Upper Devonian, Mississippian and Pennsylvanian strata and are topographically high (see weathering profile in Fig. 4).

The Allegheny structural front is the structurally-defined boundary between the Valley and Ridge fold belt to the southeast and the Appalachian Plateau fold belt to the northwest (Figs. 1 and 2). Folded Devonian, Silurian, Ordovician, and Cambrian strata of the northwestern Valley and Ridge crop out in the southern portions of Lycoming, Clinton and Centre counties. Interpretation of 2D and 3D seismic data indicates that the Allegheny structural front in north-central Pennsylvania is underlain by a southeast-dipping thrust ramp (Fig. 3). The ramp steps up from a deep décollement in Cambrian shale (Waynesboro Formation) to a shallow décollement in Upper Silurian evaporites (Salina Group), similar to interpretations by earlier workers (Faill et al., 1977; Herman, 1984; Herman and Geiser, 1985; Davis and Engelder, 1985; Scanlin and Engelder, 2003; Wiltschko and Groshong, 2012). North-northwest directed shortening of strata above the ramp during the Alleghany Orogeny generated the Nittany Anticline/Bald Eagle Mountain fault-bend fold structure, with slip on the upper detachment being transmitted to the north/northwest beneath the Appalachian Plateau along the Upper Silurian evaporite detachment. Notice that a portion of the slip transmitted to the upper detachment level at the Allegheny structural front is consumed in fault-propagation folds immediately north of the front (Fig. 3a, b). The remaining slip is interpreted to have been transmitted to the north-northwest, contributing to shortening of strata above the Upper Silurian décollement.

2.3. Detachment horizons

A number of major detachment horizons within the Paleozoic stratigraphic section have been recognized for the Late Paleozoic shortening in north-central Pennsylvania – including the Cambrian

Waynesboro Formation shale, the Middle Ordovician Antes-Coburn shale, Upper Silurian Salina Group evaporites, and the Middle Devonian Marcellus shale (Rodgers, 1963; Gwinn, 1964; Herman, 1984; Davis and Engelder, 1985; Nickelsen, 1986; Scanlin and Engelder, 2003; Faill, 1998) (Fig. 4).

In the Valley and Ridge province, a large amount of slip associated with duplex development within the Cambro-Ordovician section has been distributed within Upper Silurian through Pennsylvanian age strata at shallower depths (Mitra, 1986; Dunne, 1996). In outcrops south and east of the Allegheny structural front, incompetent intervals – such as the Marcellus Formation shale – are recognized as shear zones, interpreted to have accommodated significant displacement (Rodgers, 1963; Gwinn, 1964; Nickelsen, 1986).

North and west of the Allegheny structural front, Upper Salina Group evaporites form a detachment horizon beneath the Appalachian Plateau in north-central Pennsylvania and western New York (Figs. 1 and 3) (Davis and Engelder, 1985; Faill, 1998). Much of the region underlain by Silurian evaporites (including northern Lycoming, Sullivan, Tioga, and Bradford counties) lies north of the eastern termination of plunging Valley and Ridge folds. In this area, only a small amount of slip is interpreted to have been transmitted from the deep Waynesboro Formation shale detachment to the shallow Upper Silurian Salina Group evaporite detachment at the Allegheny structural front.

3. Subsurface nature of Appalachian Plateau folds

3.1. Detachment folds – geometry and kinematics

Detachment folds are one of three main types of fold structures recognized in fold-and-thrust belts, the others being fault-bend folds and fault-propagation folds (Suppe, 1985). Detachment folds are characterized by the downward termination of a parallel fold at a basal detachment and commonly form in stratigraphic sequences with significant contrasts in thickness, competency, and ductility (Jamison, 1987; Dahlstrom, 1990; Homza and Wallace, 1995; Poblet and McClay, 1996; Mitra, 2002a,b, Mitra, 2003). The detachment for folding is typically a soft basal layer such as shale, or evaporites, overlain by a stiff section comprising layered sandstones, siltstones, and/or carbonates. Early models describing the geometry of detachment folds (Jamison, 1987) specified that there was no thinning of the basal layer beneath the synclines flanking the folds, resulting in an increase in structural relief up-section within the fold. More recent kinematic models (Mitra, 2003), developed in conjunction with material balance considerations, suggest that for long wavelength, low amplitude detachment folds the flanking synclines sink into the ductile detachment interval, and material flows from beneath the flanking synclinal regions into the anticlinal core regions. The later kinematic models are similar to previous interpretations of large Plateau folds in which Wiltschko and Chapple (1977) recognized the need for salt to flow from beneath synclinal regions into anticlinal cores in order for the structures to materially balance.

Flexural slip is the dominant deformation mechanism accommodating the formation of the overlying detachment fold. Intervals of bedding-plane slip in Middle and Lower Devonian shale cores are common in wells located on detachment folds, consistent with flexural-slip (Wilkins et al., submitted for publication). Secondary faulting occurs as folds tighten, promoting development of breakthrough faults, or fold-accommodation structures, such as out-of-syncline faults (Mitra, 2002a,b).

Anticlines and synclines in Devonian, Mississippian, and Pennsylvanian age strata at the surface of the north-central Appalachian Plateau extend downward to a detachment in incompetent evaporites of the Upper Silurian Salina Group (Fig. 3). Strata beneath the Salina Group are less deformed, generally dipping gently ($<1-2°$) to the southeast, with occasional flexures and faults within the Lower Silurian to Precambrian basement section. A Salina Group salt isopach map is superimposed onto the surface geologic map in Fig. 2 (the isopach map is based on top and base of salt interval interpreted on regional 2D seismic data). The map indicates that the surface anticlines (defined by recessively weathering Devonian strata) are underlain by salt cores within Upper Silurian Salina Group strata at depth. Salt attains thicknesses of greater than 3600 ft (1100 m) in the cores of the largest structures. A number of these large-scale salt-cored Appalachian Plateau folds have been previously described and documented (Prucha, 1968; Frey, 1973; Wiltschko and Chapple, 1977).

Gwinn (1964) recognized that the structural complexity of the Appalachian Plateau folds increased with depth. Drilling for Upper Silurian Oriskany reservoirs in the 1950's and 1960's led to the interpretation that folds developed in Upper Silurian to Lower/Middle Devonian strata above the Salina Group evaporite section were bound by high-angle reverse faults along the flanks of the folds (as in the Chestnut Ridge anticline, see Fig. 1 for location). Later work based on detailed well-based interpretations utilizing deviation surveys and dipmeter data for the Chestnut Ridge anticline (Shumaker, 1993) indicate that at least some of the folds in Upper Silurian to Lower/Middle Devonian strata above the Salina evaporite section are, in fact, detachment folds. The detachment folds, as interpreted by Shumaker (1993) comprise dip panels, some steep-to-overturned, that in places have been broken-through by secondary compensation deformation, such as out-of-syncline reverse faults when the detachment fold became too tight to deform by flexural slip (Mitra, 2002a,b).

Recent acquisition of long-offset 2D seismic lines and 3D reflection seismic data covering large "county-scale" areas, and drilling results from wells (both vertical and horizontal wells with long lateral reaches targeting the Middle Devonian Marcellus Formation shale) indicate that detachment fold geometries, similar to Shumaker's (1993) interpretation of the Chestnut Ridge anticline, are representative of folds underlying the Appalachian Plateau.

The kinematics of a detachment fold is illustrated in a 3000 ft (915 m) sedimentary package scaled to Upper Silurian through Upper Devonian stratigraphic thicknesses in wells from north-central Pennsylvania (Fig. 5). In the kinematic forward model, all shortening occurs above the undeformed Wills Creek/Bloomsburg Formations. The units above the Salina Group evaporites deform by flexural-slip folding, maintaining constant thickness and length, which requires variable shear that decreases up-section. The 200 ft (61 m) original thickness of the Salina Group evaporites deforms to accommodate folding. Salt flows from areas beneath the syncline into the cores of the adjacent anticlines, as in earlier models (Prucha, 1968; Frey, 1973; Wiltschko and Chapple, 1977; Davis and Engelder, 1985; Mitra, 2003). In this model, the cross-sectional area of the salt is constant (deformed area = un-deformed area). However, this is not required to form these structures in nature, where salt is expected to flow in both dip *and* strike directions from beneath the synclinal regions. As a result the area of salt could change in any given dip profile restoration.

In order to track the uplift and subsidence at various locations along the model profile, it is useful to define a "base level" at the top of the undeformed evaporite sequence in the undeformed model (Fig. 5a). Notice that in the deformed model (Fig. 5b), the syncline subsided below base level, and the adjoining anticlines rose above base level. These vertical movements created a structure that has a large structural relief (450 ft [137 m] at the top of the evaporites) despite a relatively small amount of shortening (300 ft, 91 m). However, the structural relief at the top of the model (Harrell Fm

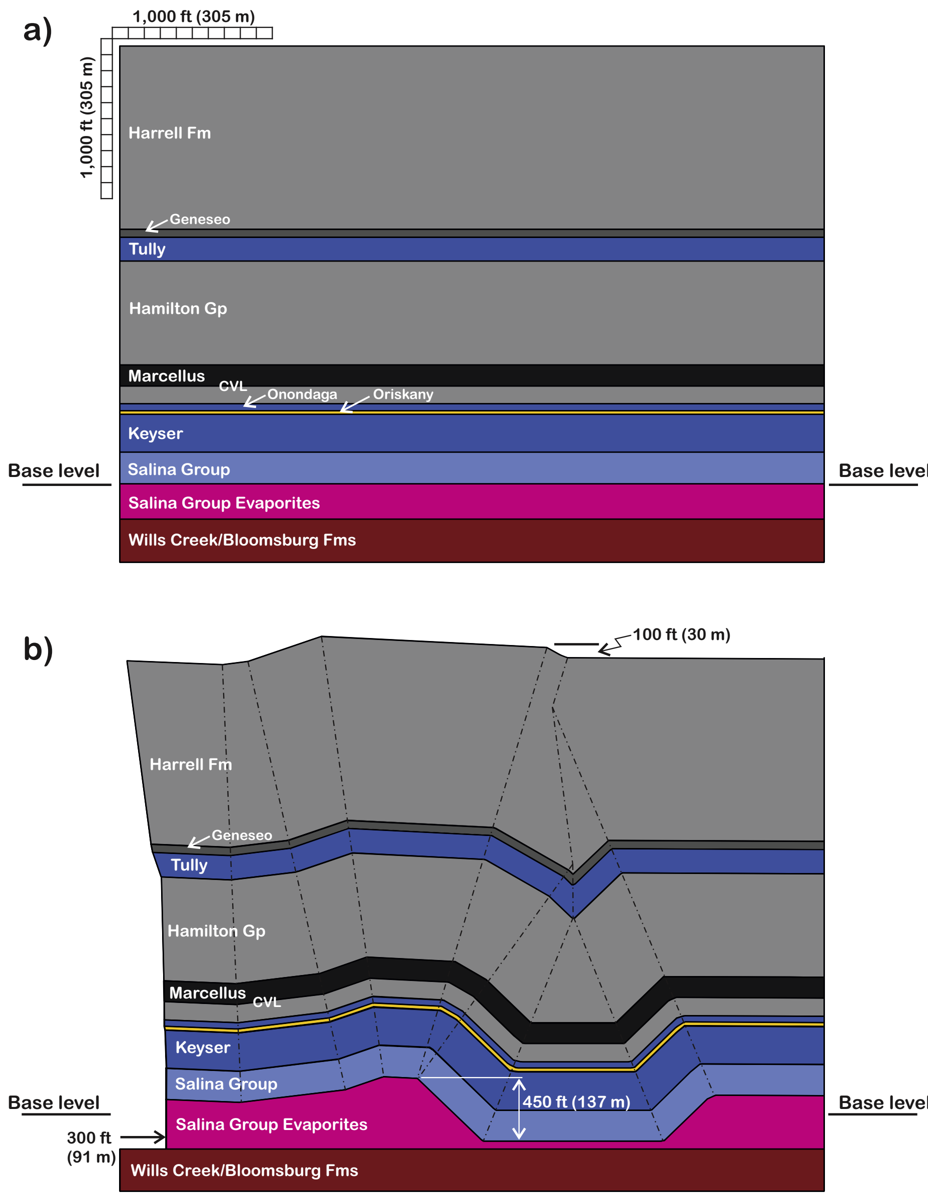

Fig. 5. Forward kinematic model of a detachment fold. a) undeformed model, b) deformed model. Stratigraphic thicknesses in model are based on well data from northeast Clinton County. Stratigraphic units above the Upper Silurian Salina Group evaporite section deform by flexural slip folding. The evaporite section deforms ductilely, flowing from beneath the syncline into the core of the adjacent detachment fold anticlines. Large structural relief (450 ft [137 m] at the top of the evaporite section) is generated in response to only a small amount of shortening (300 ft, 91 m). The large structural relief is due to subsidence of strata into the evaporite section below a pre-deformation base level in the synclinal region, and elevation of strata above a pre-deformation base level in the anticlinal region. When opposing dip panels intersect upwards, the structural relief is diminished at shallow stratigraphic levels to only 100 ft (30 m).

structural relief = 100 ft [30 m]) is less than the structural relief at depth – such as 450 ft (137 m) at the top of the evaporites. Diminishing structural relief, and less complicated structure, at shallower stratigraphic levels has been noted by previous workers describing Appalachian Plateau folds (Wiltschko and Chapple, 1977). This is a result in part of intersecting dip panels in the fold structures (Fig. 5b). The syncline is defined by three dip panels: two panels that dip in opposite directions, and a horizontal panel between them. When the dip panels that dip in opposite directions intersect (just beneath the Tully carbonate in Fig. 5b), the intervening horizontal panel between them does not extend to a shallower stratigraphic level, which decreases the magnitude of structural relief up-section. After initial development of an open detachment fold and progressive tightening of the fold structure, the next phase of deformation involves faulting. This faulting is because the tight fold can no longer accommodate strain by flexural-slip folding, resulting in out-of-syncline and break-through faults (as described by Mitra, 2002a; 2003).

An example of a typical Appalachian Plateau detachment fold imaged in 3D seismic data is shown in Fig. 6. The vertical scale on the profile is two-way travel time, which has been stretched to present the profile at an approximate true scale (vertical scale = horizontal scale; approximate time-depth function is 100 ms = 700 ft [213 m]). An artifact of the profile (Fig. 6) being a time section stretched to approximate depth is that velocity "push-downs" exist beneath areas of thick halite, due to the seismic velocity of the halite being slower than the velocity of laterally adjacent Paleozoic rocks. The "push-down" effect must be considered when interpreting time seismic data beneath the Upper Silurian evaporite interval, so that features created by overlying lateral velocity variations are recognized as velocity-induced, and not interpreted as real structures. The seismic profile is from southeast Bradford County, oriented perpendicular to the trend of the folds in the profile, and is tied to a well (Charles Blemle-1) drilled in the 1960s to test a deep Ordovician target, beneath the Upper Silurian evaporites. Upper Silurian strata in the Charles Blemle-1 well, based on electric log and cuttings, are described in Rickard (1969) (Fig. 6c). The Salina Group in the Charles Blemle-1 well comprises 300 ft (91 m) of interbedded anhydrite, dolomite and shale; 1100 ft (335 m) of halite with some interbedded dolomite and shale; and a basal unit of dolomite and shale with thin interbedded halite. The seismic data indicates that the 1100 ft (335 m) thick halite interval encountered in the well is very thin beneath the syncline south of the well. It is inferred that the halite interval was originally constant thickness across the transect – estimated to be about 500 ft (152 m) thick based on restoration and the regional salt facies map by Rickard (1969) (Fig. 1). In response to shortening, halite from beneath the syncline flowed into the cores of the adjacent anticlines. Similar to the detachment fold model (Fig. 5), synclinal areas are below base level and anticlinal areas are above base level. The syncline in the center of Fig. 6 (a and b) comprises opposing dip panels that intersect up-section, where the horizontal dip panel between them at depth is eliminated – again similar to the detachment fold model (Fig. 5). The structural relief of this syncline is ~700 ft (213 m) at the base of the syncline, and decreases to ~150 ft (46 m) at the Tully level (in response to intersecting dip panels of opposite dip). The south limb of the syncline is interpreted to consist of two dip panels, with the interior panel dipping steeply to the north, and consisting of thinned, possibly faulted, strata. Reverse faults in the limbs of detachment folds are common in the Plateau fold belt and are interpreted to be late-stage breakthrough faults, which can extend up-section into Upper Devonian strata. It is envisioned that the thin, steep dip panel (Fig. 6) is an incipient fault zone – that with continued contraction could develop into a through-going reverse fault. Small-displacement reverse faults, offsetting the limbs of detachment folds are observed in 3D seismic data throughout the Plateau fold belt. The reverse faults are typically associated with opposing kink panels bounding detachment folds developed in Upper Silurian-through-Middle Devonian strata at depth. Notice that two low-angle reverse faults offset the Tully Limestone. These faults are envisioned to accommodate shortening of the thin competent limestone unit. In places these reverse faults at shallow levels are related to the underlying detachment fold structures, as will be discussed in the next section.

Late stage break-through faults that extend into the shallow section above two opposing detachment anticlines are shown in Fig. 7a. The time section (Fig. 7a), is from a 3D volume located in northwest Lycoming County, and is oriented perpendicular to the trend of the imaged folds and faults. A depth stretched version of the seismic interpretation (Fig. 7b) shows reverse faults in the center of the transect (labeled 1 through 4 in Fig. 7a) overlying the deep folds and extending up-section into Middle and Upper Devonian strata. The reverse faults that emanate from dip panels of the underlying tight anticlines can be mapped in the 3D seismic data along strike – parallel to, and clearly linked to, the deep structure. Detailed mapping of the shallow faults reveals fault geometries and cross-cutting relationships that record the relative timing of the breakthrough faults. Slip on the faults is restored sequentially from youngest (fault #4) to oldest (fault #1) (Fig. 7c, restoration stages a–d). The restoration indicates approximately 400 ft (122 m) of shortening for the combined breakthrough

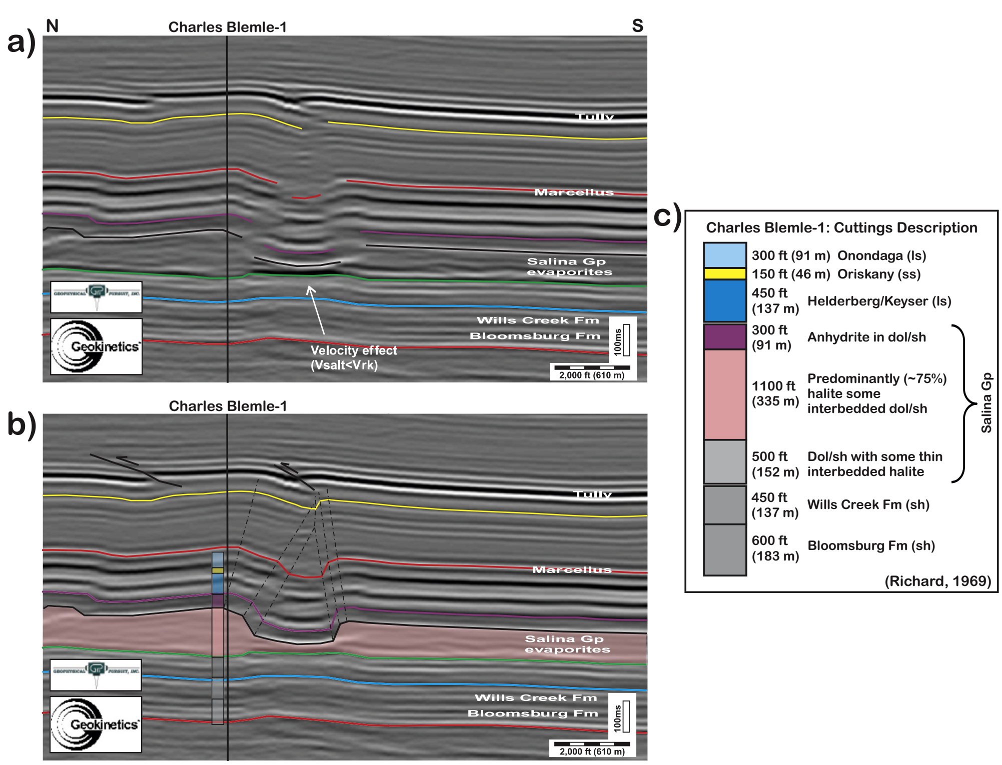

Fig. 6. Seismic profile from a 3D volume (courtesy of Geophysical Pursuit and Geokinetics™) from southeast Bradford County. a) Time section stretched to approximate depth with partial interpretation. The section is oriented perpendicular to the trend of the folds. b) Interpreted time section. The structure comprises opposing dip panels that intersect up-section, similar to the model described in Fig. 5 c) Summary of Charles Blemle-1 well (drilled pre-1969 to test a deep Ordovician target) results in Upper Silurian and Lower Devonian strata from Rickard, 1969.

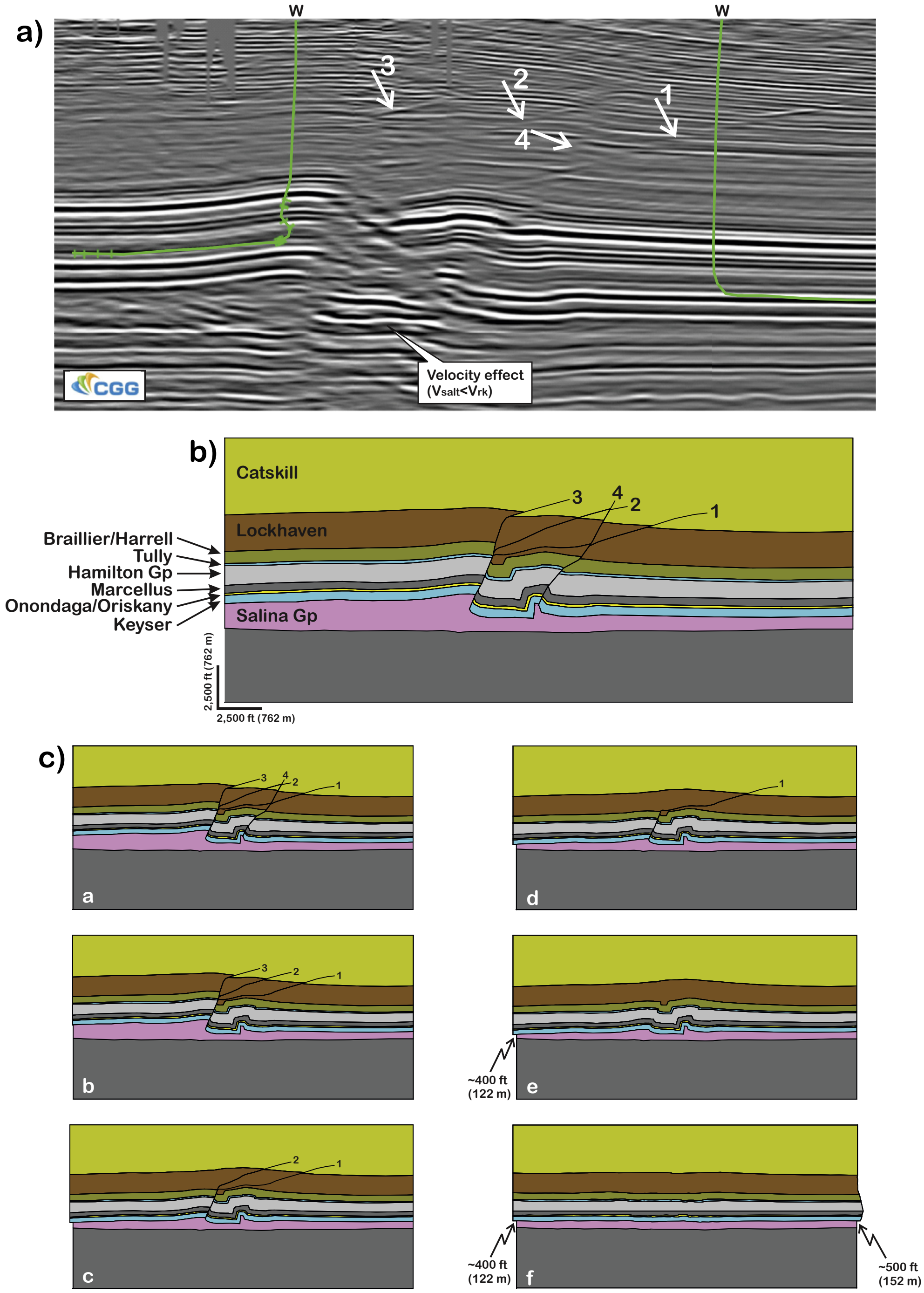

Fig. 7. a) Time profile from a Lycoming County, Pennsylvania 3D seismic volume (courtesy of CGGVeritas Land, (U.S.) Inc., Houston, Texas) showing fold accommodation breakthrough faults that extend into the shallow section above two opposing detachment anticlines. Arrows point to faults (arrows are oriented perpendicular to fault traces). The section is oriented perpendicular to the strike of the imaged folds and faults. Wells targeting the Marcellus Formation are indicated by "W" at top of transect (short lines perpendicular to wellbores are stratigraphic picks). The high in the base of salt near the center of the transect is a velocity artifact caused by the salt velocity being slower than the velocity of adjacent Paleozoic sedimentary rocks. b) Approximate depth conversion of the time profile. c) Sequential restoration of the fault system. Restoration of slip on faults in order from youngest to oldest faults (Stages a–e) results in un-faulted detachment fold structure in Stage e. Approximately 400 ft (122 m) of total slip is associated with breakthrough faults (indicated on left side of Stage e). Detachment folds are restored using flexural-slip in Stage f. Approximately 500 ft (152 m) of shortening required to generate detachments folds (indicated on right side of Stage f).

faulting (shown in stage e, along left edge of the restoration). After the breakthrough faults are restored, the structure consists of a syncline between two detachment anticlines (Fig. 7c, stage e). The final restoration uses flexural slip to unfold, or restore, the detachment fold structure (Fig. 7c, stage f). The restoration indicates approximately 500 ft (152 m) of shortening required to generate the detachment fold (before breakthrough faulting). Thus a total of only 900 ft (274 m) of shortening is required to generate the complete structure. The gentle dip of the breakthrough faults is common and possibly related to the mechanical stratigraphy of the deformed package. The faults are localized at depth by steeply-dipping kink panels in more competent strata. The dips of the faults tend to decrease in the less competent, layered clastics of the overlying Lockhaven and Catskill Formations. Similar systems of reverse faults at shallow depths related to deep, tight detachment folds are common in the Plateau fold belt of north-central Pennsylvania. In cases, the shallow faults emanating from structures similar to those in Fig. 7 dip in opposite directions forming conjugate systems overlying the deep fold structures. These shallow fault systems may have been migration pathways for gas generated from deeper source rock intervals (i.e. Marcellus Formation) or leak points for gas reservoired in deeper traps (i.e. Marcellus Formation). It is interesting to note that the shallow Council Run gas field in Centre and Clinton counties (Fig. 2) is a stratigraphic trap comprised of deltaic and nearshore sandstone reservoirs within the Upper Devonian Lockhaven and Catskill Formations (Laughrey et al., 1994) and overlies a system of faults emanating from kink bands very similar to that shown in Fig. 7b.

Large detachment folds in the Plateau fold belt are first-order structures. The small-scale, break-through faults are interpreted as second-order features formed primarily in response to tightening of detachment folds to the point where flexural slip is no longer efficient, with break-through faulting, often associated with the steep limbs of the detachment folds, accommodating subsequent deformation. Data from horizontal wells support this interpretation: typically lateral wells that are oriented perpendicular to the trend of detachment folds encounter large uniform dip panels with thousands of feet of relief separated by tight fold hinge zones, with only minor widely spaced faults encountered (faults have stratigraphic offsets typically on the order of only 50–200 feet). Whereas in areas of very steep dip panels, the intensity of faulting increases, but the faults typically have small offset.

Wells targeting the Middle Devonian Marcellus Formation shale can also constrain the detailed geometry of detachment folds in the Plateau fold belt. Formation tops are interpreted from electric and mud logs in both vertical wells and laterals to obtain a true scale (vertical = horizontal) transect oriented perpendicular to the fold trend, and constrained by 5 numbered wells (Fig. 8). The lateral wells (#1, #3, and #4) extend approximately 4000 ft (1200 m) in directions to both the northwest and southeast of vertical well #2 and are projected distances of less than 1000 ft (300 m) onto the line of section. Bed dips interpreted from image log data in the vertical well (#2) indicate northwest dips that steepen with depth, dipping greater than 80°NW in the Geneseo Formation-to-Hamilton Group interval. The dips then change abruptly to nearly horizontal in the lower portion of the Hamilton Group, and then gently to the south in the Marcellus Formation at a depth of 7500 ft (2286 m) (bsl). Formation top picks in the vertical well do not identify any large-offset faults. Similarly, only small-offset faults are encountered in the horizontal wells. The anticline on the southeast side of the transect is interpreted as a detachment fold, with a south-dipping reverse fault cutting the northwest limb. Given its location immediately north of the Allegheny structural front, the structure is likely similar to the fault-propagation folds interpreted along the north side of the Allegheny structural front (Fig. 3). The interpretation of the oppositely verging anticlines (Fig. 8) is similar to Shumaker's (2002) interpretation of the Chestnut Ridge anticline in the southern part of the Appalachian Plateau, also tightly constrained by well data.

3.2. Appalachian Plateau fold belt – structural domains

The Plateau fold belt in north-central Pennsylvania (Potter, Tioga, Bradford, Sullivan, and northern Lycoming, Clinton and Centre counties) and southwestern New York can be divided into three structural domains based on the style of detachment folds developed in Upper Silurian and Lower-Middle Devonian strata overlying the Upper Silurian evaporite detachment. The structural domains have been delineated using surface geology, seismic data, and well data. Domain 1 is dominated by systems of short-wavelength folds with small amplitudes. Domain 2 consists of long-wavelength, large-amplitude, halite-cored anticlines. Domain 3 comprises large, relatively undeformed synclines. A conceptual model illustrating the geometry, evolution and kinematics of

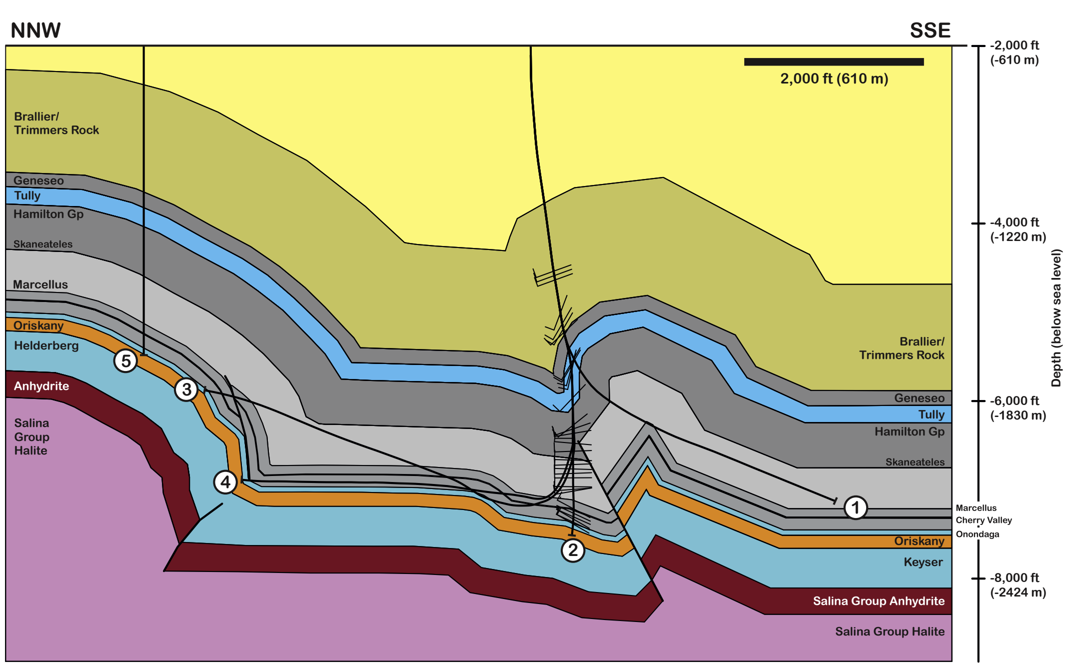

Fig. 8. a) A true-scale (vertical scale = horizontal scale) interpretation of an Appalachian Plateau fold based on well data. The approximate transect location is shown in Fig. 2. The transect is oriented perpendicular to the trend of the fold and constrained by 5 numbered wells: a vertical well at the northwest end of the section (#5), a vertical well with bed dips interpreted from image log data (#2), and three lateral wells (#1, #3, and #4).

Domain 1, 2, and 3 structures is shown in Fig. 9. An important aspect of the model is the depression of synclinal regions into underlying salt, likely in response to buckling of the post-evaporite section, caused by north-northwest directed shortening during the Alleghanian orogeny. Therefore, the depositional thickness of salt within the Upper Silurian evaporite basin (Fig. 1) is proposed to have been a controlling factor in determining the style of the overlying deformation. Following is a description of each of the three structural domains, with examples based on seismic data.

3.2.1. Domain 1

Regions dominated by short-wavelength (1–2 mi, 1.6–3.2 km), low-amplitude (100–500 ft, 30–150 m), folds detached over originally thin halite (Fig. 9d). The thin salt layer results in short wavelength, low amplitude folds because welds (areas where the salt is completely evacuated) develop beneath the synclines prior to the development of large anticlines. Pop-up and push-down (Cotton and Koyi, 2000) structures are common within Domain 1 detachment fold trains.

3.2.2. Domain 2

This domain comprises large (8–10 mi, 12.8–16 km across) halite-cored anticlines, with amplitudes of over 3000 ft (915 m) (Fig. 9d). These large anticlines extend to the present-day surface (Berg et al., 1980). Some have been recognized in previous studies; for example Frey (1973) described the Granville (Towanda) and Wilmont anticlines based on early 2D seismic data, and Wiltschko and Chapple (1977) mapped the Wellsboro anticline (Fig. 2). The Wallis Run, Liberty, and Tioga Junction anticlines are Domain 2 anticlines recognized in this study (Fig. 2). The large fold amplitudes are related to the presence of thick halite cores. Four of the large salt-cored Domain 2 anticlines are observed on the regional transect in Fig. 3. A salt-isopach map in the cores of Domain 2 anticlines illustrates the along-strike extent, and asymmetric geometry of these structures (Fig. 2). Notice that the large Domain 2 anticlines (Fig. 1) are located within the area of thickest halite deposition as delineated by Rickard (1969). Salt that was deposited in a relatively uniform layer on the order of 500 ft (152 m) thick (or greater) in this region (Rickard, 1969) has been mobilized to attain thicknesses of greater than 3000 ft (915 m) in the cores of some

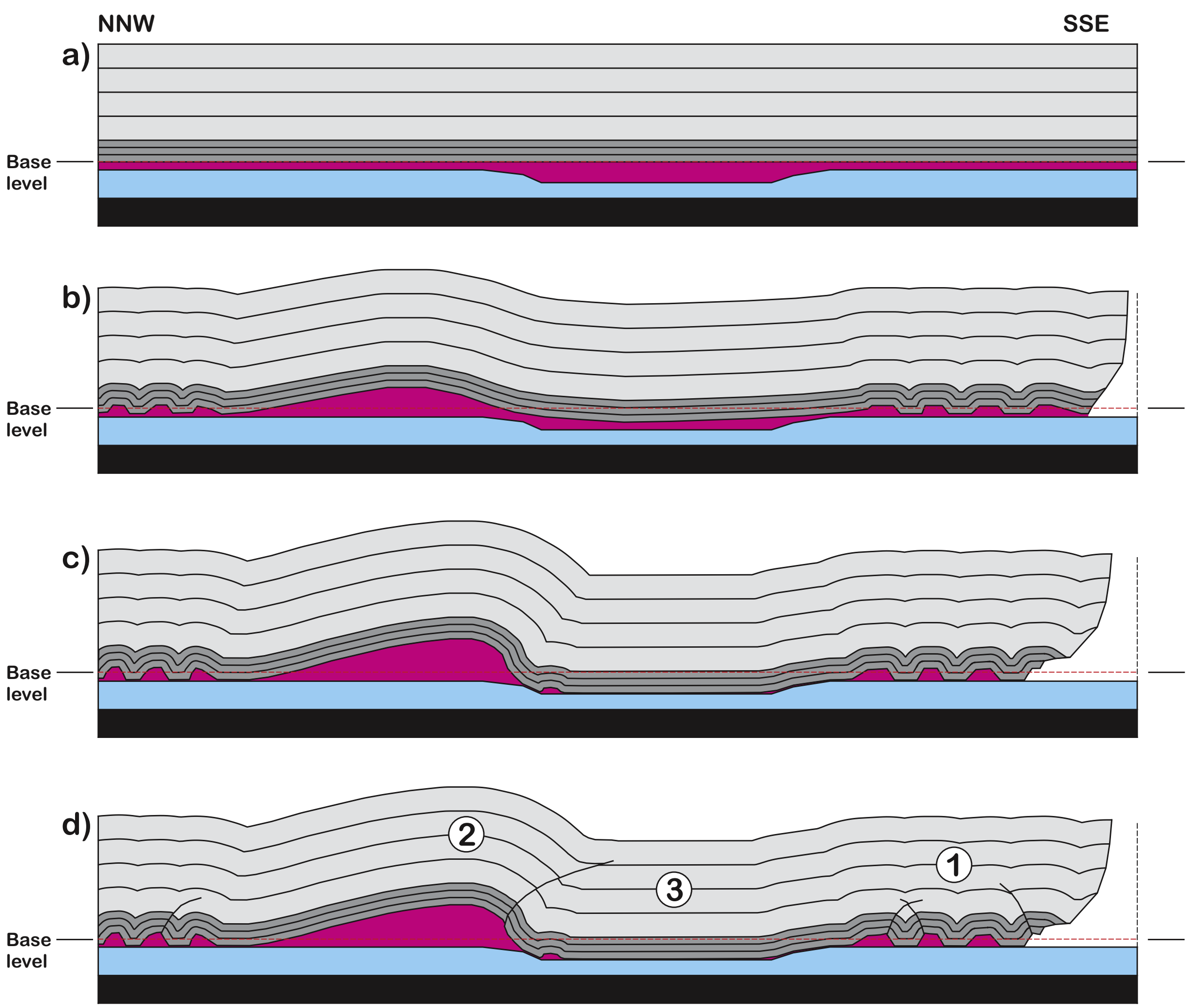

Fig. 9. Conceptual model illustrating the structural geometry and evolution of Appalachian Plateau detachment fold Domains 1, 2, and 3. See text for a description and examples from seismic data of the structural domains and a discussion regarding the genesis of the observed non-planar basal detachment. a) Pre-contraction configuration. b) Early-contraction stage. A small amount of shortening forms Domain 1 short-wavelength folds and causes initial subsidence below base level of Domain 3 syncline into halite. Base level in this model is the elevation of the top of the undeformed salt layer. c) With continued contraction, Domain 3 syncline subsides, or is depressed, further below the base level elevation in response to folding and halite moving from beneath syncline to fill salt core of adjacent Domain 2 anticline. d) Breakthrough faulting in response to tightening of detachment folds and cessation of flexural-slip.

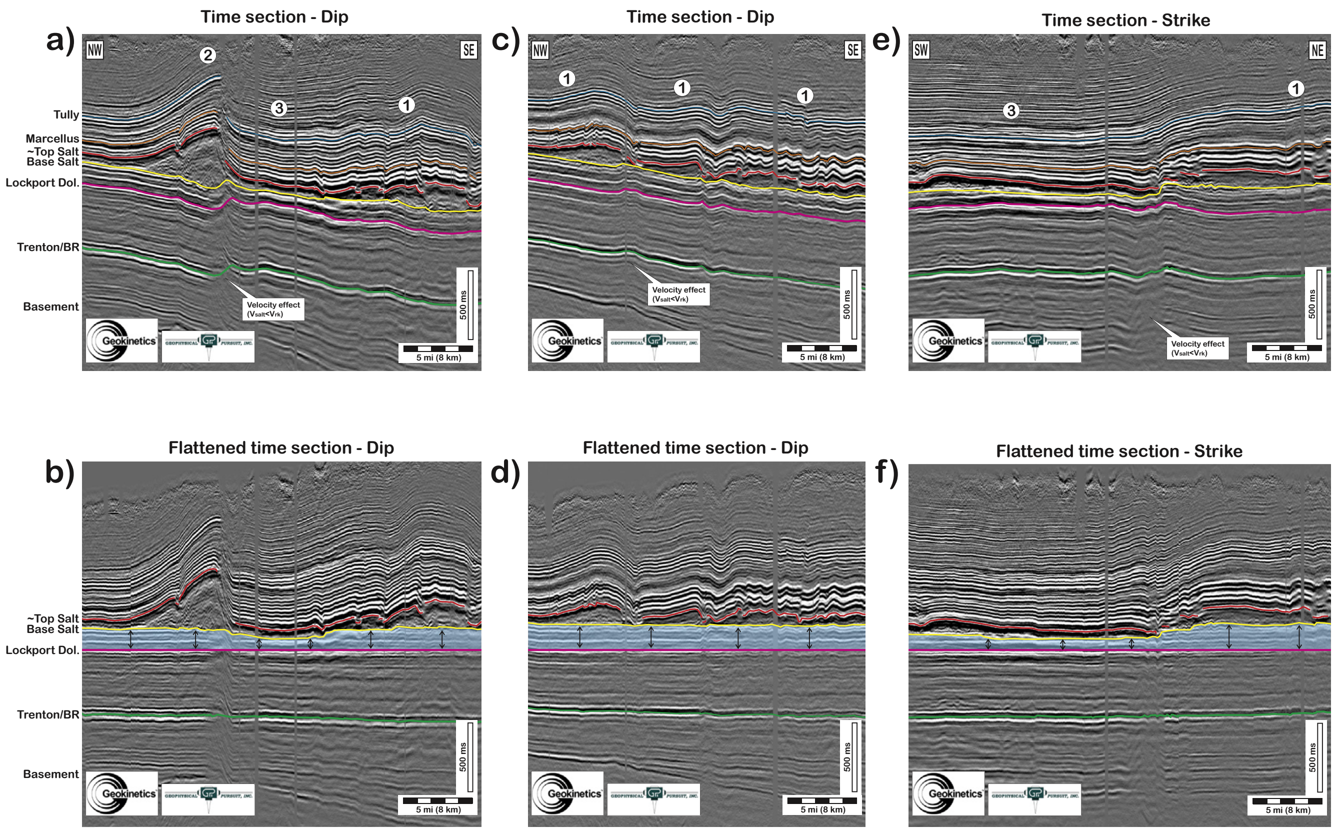

Fig. 10. Seismic profiles (time sections) from a large 3D survey that illustrate characteristic features of Structural Domains 1, 2, and 3 in central Bradford County (seismic data courtesy of Geokinetics™). See Fig. 2 for approximate line locations. Profiles in Fig. 10a, b, c, and d are oriented perpendicular to the strike of the folds, and profiles in Fig. 10e and f are oriented parallel to the strike of the folds. Profiles 10b, 10d, and 10f are flattened on a horizon beneath the base of the evaporite section (the Lockport Dolomite Formation) in order to remove some of the effects of lateral velocity variations in the overlying strata and provide a clearer structural view of the detachment surface, which is stepped (see text for details). 10a-b) Section across a Domain 2, large, salt-cored anticline on the northwest end of the profile; a large, relatively undeformed, Domain 3 syncline in the center of the profile; and a series of short wavelength, Domain 1 folds at the southeast end of the profile. 10c-d) Section across a sequence of Domain 1 short-wavelength folds. 10e-f) Section across large Domain 3 syncline on southwest side of profile, and Domain 1 short-wavelength folds on the northeast side of profile.

Domain 2 anticlines. Halite within the fold cores is interpreted to have flowed from beneath adjoining synclinal areas – similar to detachment fold models proposed by earlier workers (Frey, 1973; Wiltschko and Chapple, 1977; Davis and Engelder, 1985; Mitra, 2002b, 2003). As recognized previously from surface dip measurements and vintage 2D seismic data (Sherrill, 1934; Frey, 1973; respectively), Domain 2 folds typically have limbs that dip more steeply on the southeast side of the folds than on the northwest side of the structure. The asymmetry of the folds is apparent in the salt isopach map of the salt cores in Fig. 2 – the thickest portion of the salt core is preferentially located on the southeast side of the Wilmont, Granville, Liberty, and Wellsboro anticlines. In places, Domain 1 folds are developed on the long northwest limbs of the large Domain 2 folds. It is proposed that the small Domain 1 structures formed early and became incorporated into the Domain 2 structure as the larger structure grew.

3.2.3. Domain 3

Large (8–10 mi, 12.8–16 km across), relatively undeformed synclines comprise Domain 3 (Fig. 9d). These synclinal structures are interpreted to have developed over areas that were depressed into the underlying Salina Group evaporites. Flow of halite from beneath the large synclinal regions into the cores of the large Domain 2 anticlines resulted in subsidence of the Domain 3 synclines below base level (the elevation of the top of the undeformed salt layer in Fig. 9a). Few Domain 1 structures are observed within Domain 3 synclines – the synclines tend to be relatively flat-bottomed and undeformed.

3.3. Plateau fold belt structural domains: seismic examples

Seismic profiles from a large 3D time volume that illustrate characteristic features of Structural Domains 1, 2, and 3 in central Bradford County are shown in Fig. 10 (see Fig. 2 for approximate transect locations). The seismic lines, as displayed, would be approximately 7× vertically exaggerated if converted to depth (vertical scale = 7 × horizontal scale).

A seismic profile that images structures representative of all three Domains is shown in Fig. 10a. The section crosses a large, Domain 2, salt-cored anticline on the northwest end of the section; a large, relatively undeformed, Domain 3, syncline in the center of the section; and a series of short wavelength, Domain 1, detachment folds at the southeast end of the section. The section is oriented perpendicular to the strike of the imaged folds. The Domain 2 salt-cored anticline is the Granville anticline (Fig. 2). The structure is approximately 8 mi (12.8 km) across with a salt core that is approximately 3000 ft (915 m) thick at its maximum. Similar to other Domain 2 salt-cored folds, the structure is asymmetric with a steeper dipping, shorter limb on the southeast side of the structure, and a longer, gently-dipping limb on the northwest side of the structure. In plan view, the Granville anticline is approximately 20 mi (32 km) long and has an arcuate trend (as defined by the salt isopach map in Fig. 2). A small Domain 1 fold is present on the long, gently dipping, northwest limb of the Granville anticline. In the center of the section, the large Domain 3 syncline is approximately 7 mi (11.2 km) across and relatively undeformed. The geometry of the syncline is defined at the surface (Fig. 2) by the outcrop pattern of Mississippian and Pennsylvanian age units, which are resistant to weathering and topographically high. In contrast, the recessive-weathering Devonian age strata that define anticlines at the surface are topographically low. Across the entire section, relatively uniform stratigraphic thicknesses are observed in the deep section beneath the base of Upper Silurian evaporites, as well as in the Upper Silurian through Pennsylvanian age strata overlying the evaporites (Fig. 10a). Large changes in unit thickness occur only in the interval between the top and base of the salt. As discussed previously, in a time seismic section lateral variations in the velocity of the strata above the salt interval cause velocity-induced structures beneath this interval (due to areas of salt having slower velocities than the adjacent Paleozoic rocks). A method to remove some of the velocity effects of the Salina Group evaporite section (for interpretation of the interval beneath the evaporites) is to flatten the section on a horizon that has been picked beneath the Salina Group. This was done in order to interpret the detailed geometry of the base of the Salina Group evaporite section – in effect, the velocity perturbations generated by nonuniform thicknesses of the Salina Group salt are removed for the section below the Salina Group in the section flattened on the Lockport dolomite (Fig. 10b). Analysis of the flattened section indicates that the base of the evaporite detachment is not planar. The base of salt, or base of the detachment interval, comprises a deep segment below the Domain 3 syncline and shallower segments below the Domain 1 short-wavelength folds and the Domain 2 salt-cored fold at opposite ends of the transect.

Fig. 10c is a dip-oriented seismic time section located about 12 mi (19.2 km) northeast of Fig. 10a (see Fig. 2 for location), that images only Domain 1 structures. Notice the short wavelength, low-amplitude detachment folds imaged on the southeast end of the section. When this section is flattened on the Lockport dolomite (Fig. 10d), this portion of the base of the Salina Group detachment is planar, unlike the non-planar, stepped detachment in Fig. 10a and b.

Fig. 10e is a strike-oriented seismic time section that ties the dip-oriented sections in Fig. 10a and c (see Fig. 2 for location). The southwestern end of the section is located within the Domain 3 syncline, and the northeastern end of the section is within Domain 1 short wavelength folds (because the section is oriented parallel to the strike of the short wavelength folds, few folds are imaged). Fig. 10f is a version of this section flattened on the Lockport dolomite. At the southwest end of the section beneath the Domain 3 syncline, the detachment horizon is deep (ties its low structural position in the center of Fig. 10b), rising to a shallower depth to the northeast to tie its structural position in Fig. 10d.

In summary, the seismic data indicate that the basal detachment beneath the Plateau fold belt is not planar. Depressions in the detachment surface underlie large Domain 3 synclines. In areas beneath Domain 1 fold systems and Domain 2 large salt-cored anticlines, the detachment surface is at a shallower depth. The relationships illustrated in the three seismic profiles in Fig. 10, and the transect in Fig. 3c, are representative of structural relationships and the detachment surface geometry associated with Domain 1, 2, and 3 structures mapped in the study area of Potter, Tioga, Bradford, Sullivan, and northern Lycoming, Clinton and Centre counties. On a regional scale, based on well penetrations, the thickness of Silurian salt increases from the salt basin margins to a maximum thickness in the vicinity of Bradford county (Rickard, 1969) (Fig. 1). Seismic data allows a more detailed depiction of the base of salt detachment and indicates that it is not planar, but consists of a series of depressions immediately south of each large Domain 2 salt-cored anticline (Figs. 3c and 10). The irregular base of salt is an important issue which will be discussed in the following section.

4. Discussion

4.1. Genesis of non-planar detachment surface

Interpretation of recent 2D and 3D seismic data indicate that the present-day geometry of the base of the Silurian salt detachment underlying the Appalachian Plateau is a non-planar, stepped surface. As described above, the surface is observed to be somewhat deeper beneath Domain 3 synclines, and shallower beneath Domain 1 and 2 anticlines. It is important to note that seismic data indicate that strata directly beneath the base of the detachment in areas underlying Domain 1 and 2 anticlines is horizontally bedded (Fig. 10). Therefore, if these strata contain halite within the evaporite section, it would appear that it has not been mobilized. Explanations for the development of the non-planar detachment include the following possibilities:

1) Variations in the amount of halite within the evaporite sequence

Variations in halite thickness within the original Upper Silurian Salina Group evaporite sequence could have led to the development of the stepped, non-planar detachment surface. Deep portions of the detachment surface, under Domain 3 synclines, would develop over areas where preferentially thick halite was deposited and later evacuated and moved into anticlinal cores in response to folding (Fig. 11a). In this scenario, shallow portions of the detachment surface represent areas where the original thickness of the halite was thin, and horizontal bedding underlying the detachment beneath anticlines are non-halite bearing evaporites (or an evaporite sequence with a small percentage of halite).

2) Evaporite deposition on a rugose surface

The non-planar detachment could be a relict erosion surface developed prior to evaporite deposition (Fig. 11b). Similar to the model in which halite thickness varies due to facies changes within the evaporite sequence, here evaporite deposition over a preexisting rugose surface results in deposition of variable thicknesses of halite. A thick evaporite sequence would be deposited over deeply eroded areas, and a thin evaporite sequence deposited over areas subjected to less erosion. In this scenario, the erosion surface is the base of salt detachment, and horizontal bedding underlying the detachment beneath anticlines are sediments deposited prior to evaporites.

3) Developed *in response* to large wavelength buckle folding

In this case, large wavelength buckle folding over an evaporite section of relatively uniform thickness results in the syncline being depressed into the evaporite layer – causing mobilization of the underlying halite and resulting in a non-planar detachment surface (Fig. 11c). Low areas of the detachment surface are developed in response to the downward deflection of the stratigraphic layer overlying the evaporite sequence. Note that the base of the depositional evaporite section in the model is planar (Fig. 11c). The surface that represents the base of salt detachment is actually the top of the original evaporite sequence beneath anticlines, and the depressed top of the evaporite sequence beneath synclines. Implicit in this model, and supported by seismic data, is that halite within

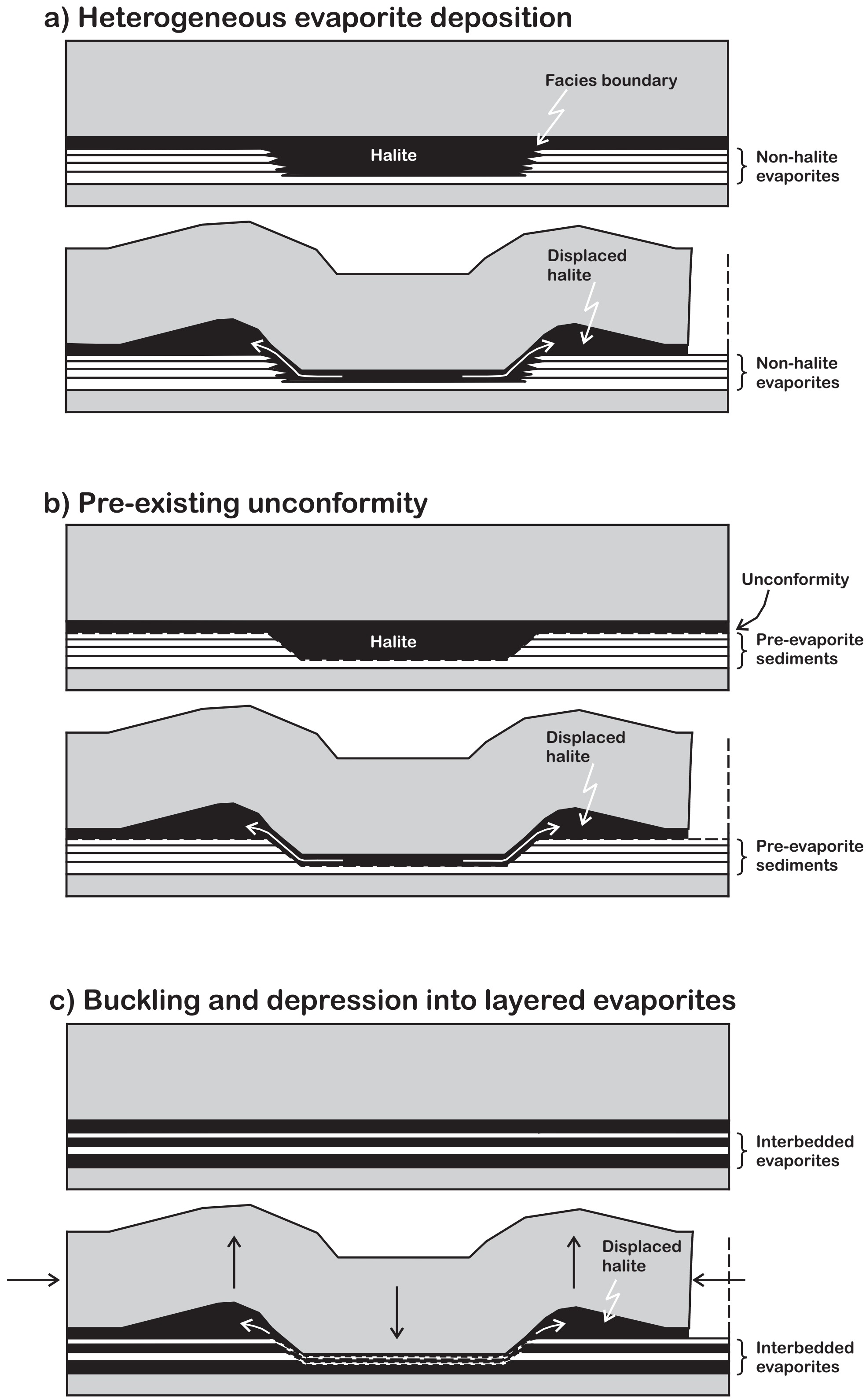

Fig. 11. Proposed scenarios for genesis of the observed stepped base of salt detachment surface underlying the Appalachian Plateau fold belt in north-central Pennsylvania. a) Variation in the depositional thickness of halite within the evaporite sequence. b) Evaporites are deposited over a pre-existing, rugose erosional surface. c) Buckling of stratigraphic interval overlying evaporites results in downward deflection of synclines and flow of halite into cores of adjacent anticlines.

the interbedded evaporites beneath the synclines flows into the cores of the anticlines, but the halite within the interbedded evaporites beneath the anticlines remains in place and is essentially undeformed. The halite that flows from the synclinal regions fills the cores of anticlines *above* the top of the original depositional evaporite sequence. In this scenario, large Domain 2 anticlines and Domain 3 synclines develop over portions of the evaporite basin where halite was thick, and Domain 1 anticlines develop over areas

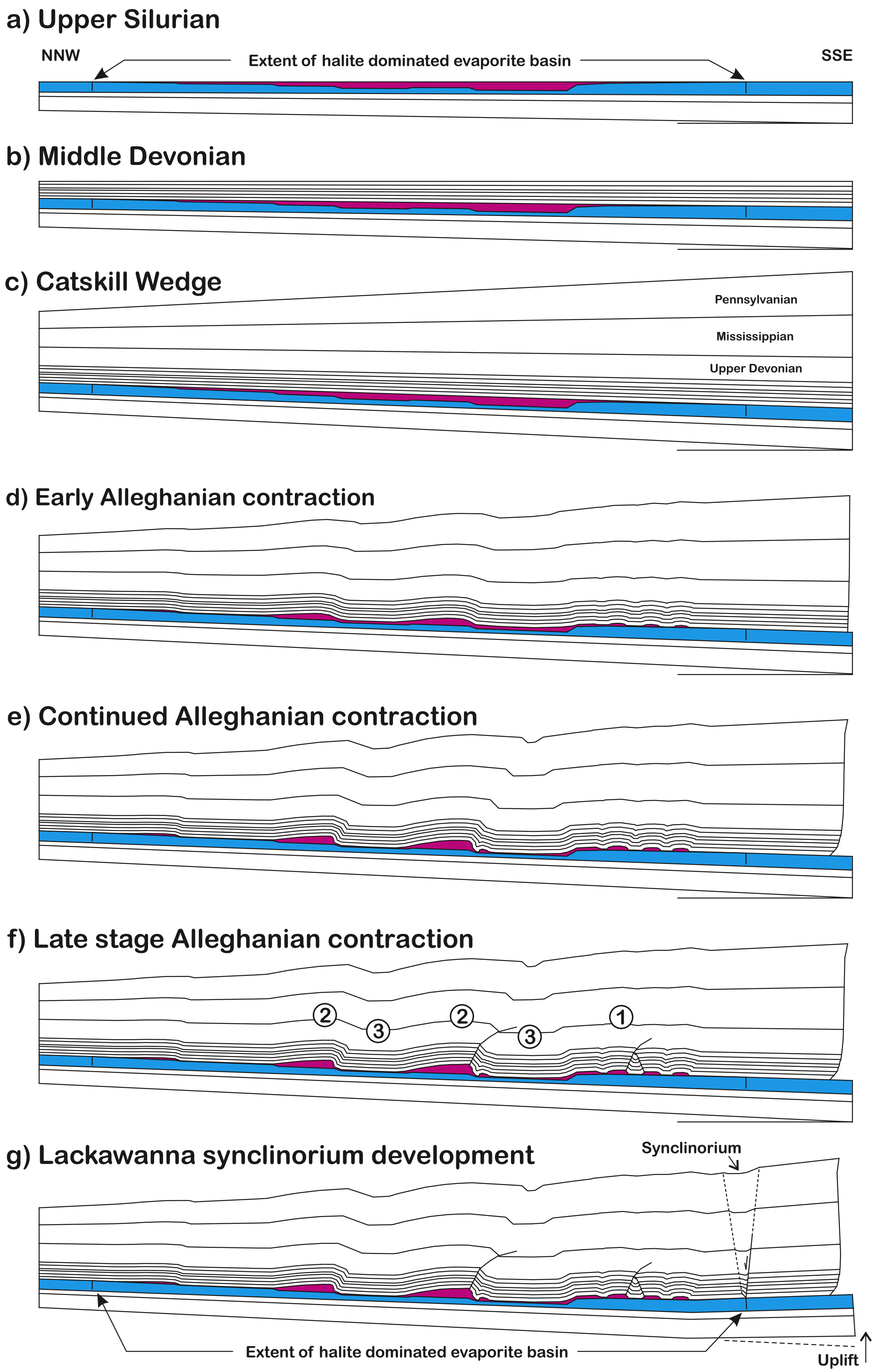

Fig. 12. Regional model summarizing the structural evolution of the Plateau fold belt. a) Depiction of Upper Silurian Salina Group evaporite basin. Halite facies pinches out at both the NNW and SSE ends of the transect. b) Deposition of uppermost Silurian, Lower and Middle Devonian age strata (including the Marcellus Formation). Note that there is no indication of halokinetic deformation occurring during deposition of these strata. c) Deposition of wedges of Upper Devonian and Carboniferous age strata. Again there is no large scale halokinetic deformation observed at this stage. d) Early contraction in the foreland of the Alleghany orogeny. e) Continuation of Alleghanian deformation – detachment folding associated with minor shortening, synclines subside into areas originally underlain by halite. Halite flows from beneath synclines into cores of adjacent anticlines. f) Accentuation of detachment folding – with breakthrough faulting of steep dip panels comprising detachment fold limbs. g) Development of extensional fault system localized at halite pinch-out and regional uplift on south side of basin – results in geometry similar to Lackawanna synclinorium (see text for details).

where halite was thin. A correlation exists between the area of the evaporite basin with the thickest halite (Rickard, 1969) and the location of the large Domain 2 salt-cored anticline structures as delineated by the salt isopach map in Fig. 1.

4.2. Regional development

Fig. 12 shows a schematic model for the regional evolution of the Plateau detachment fold structural domains that assumes that in the pre-deformation stages (Fig. 12a–c) there are variations in the thickness of halite in the Salina Group–Tonoloway stratigraphic interval – as would be the case if there were differences in the amount of halite within the evaporite sequence, or if the evaporites were deposited on a pre-existing erosional surface, as discussed above. If the non-planar detachment surface results from buckle folding above a uniform evaporite sequence, the entire halite interval, and the unit directly underlying it, would be envisioned as an initially uniform evaporite package.

As observed in Fig. 3 and depicted in the model (Fig. 12a–c), there are no large thickness variations in the Upper Silurian-through-Carboniferous strata overlying the Upper Silurian evaporite section. There is a regional depositional taper, or thickening to the south-southeast, but it appears that the underlying evaporites had little, if any, effect on the deposition of overlying Upper Silurian and Devonian strata, at least at a seismic scale. There is no indication of halokinetic deformation prior to Late Paleozoic Alleghanian contraction. Fig. 12c shows a sedimentary wedge (the Catskill "delta", or wedge) deposited in response to Acadian deformation to the east-southeast, which shed sediments to the west (Schultz, 1999; Rowan, 2006). In addition, tectonic loading of the crust during Acadian deformation (and possibly early Alleghanian deformation) to the east-southeast caused the southeast dip of the basement underlying the plateau to increase (Fig. 12c–f). With onset of contraction (Fig. 12d), strata begin to subside below base level (the elevation of the top of the undeformed salt) into the salt layer (Domain 3), or buckling of the layer overlying the evaporites causes deflection of the developing syncline into the evaporite layer. Where evaporites are thick in the center of the basin, large, long wavelength Domain 2 and 3 detachment folds develop. Whereas on the basin periphery where the evaporite layer is thinner, Domain 1 short wavelength fold trains develop. With continued shortening (Fig. 12e), the Domain 3 synclines subside further into the salt, with salt being mobilized from the area beneath the syncline into the cores of adjacent Domain 2 anticlines. After detachment folds tighten and can no longer deform by flexural slip, late stage contraction is accommodated by break-through reverse faults that developed on the steeply dipping limbs of some anticlines (Fig. 12f). Overall, the shortening required to generate the observed structures is only about1–2% the length of the section. The large structural relief, especially of the Domain 2 salt-cored anticlines, is a combined result of the anticlinal core being elevated and the adjacent syncline being depressed into the salt.

4.3. Plateau deformation link to Allegheny structural front

Transects across the northeastern Valley and Ridge province and the Appalachian Plateau typically feature displacement from a detachment in Cambrian Waynesboro Formation shale ramping up to a detachment in Upper Silurian evaporites (Fig. 3). The north-northwest directed displacement at the evaporite level is interpreted to generate the Plateau detachment fold structures. However, as has been described, only a small amount of shortening is required to generate the observed Plateau fold belt structures. Therefore, it is possible that the folds developed in response to regional, layer-parallel, north-northwest directed bulk shortening that affected the entire Paleozoic section (both above and below the Silurian evaporites) in the foreland of the north-central Appalachians. Bulk shortening was accommodated by large wavelength folding (Domain 2 and 3 structures) above regions of thick halite, short wavelength folding (Domain 1 structures) above regions of thin halite, flow of halite, small-scale folding and faulting, pressure solution producing stylolites, and cleavage development. In this scenario, the slip being supplied to the Upper Silurian detachment at the Allegheny structural front is not required to generate the Plateau deformation in north-central Pennsylvania and western New York, but may have enhanced it (i.e. tightened the detachment folds, and generated break-through faults). Note that the largest amplitude Plateau fold belt structures (Granville, Liberty, and Wilmont anticlines) (Fig. 13) actually occur north and east of Williamsport, PA and the eastward plunge of Valley and Ridge structures. Seismic data indicate that displacement on the fault system underlying the Allegheny structural front decreases from the Willamsport area to the east, with no slip being transmitted to the Upper Silurian evaporite detachment in the vicinity of southeastern Lycoming County (Fig. 13).

4.4. Fold asymmetry

As described earlier, large Domain 2 anticlines typically have long gently-dipping limbs on the north-northwest side of the fold, and relatively short and steeper dipping limbs on the south-southeast side of the fold. This fold geometry and asymmetry would indicate a vergence direction to the south-southeast (Suppe, 1985). The interpreted south-southeast vergence for folds on the Appalachian Plateau based on their geometry is opposite to the north-northwest vergence direction documented for the Valley and Ridge province to the south-southeast of the Allegheny structural front (Frey, 1973; Faill, 1998). It is not uncommon in other foreland fold belts developed over salt detachments, such as the Ebro basin in the southern Pyrenees (Sans and Verges, 1995; Sans et al., 1996) and the Salt Range in Pakistan (Cotton and Koyi, 2000), to observe hinterlandward vergence for folds in the foreland. Structures within fold belts that verge toward the hinterland have been interpreted to form in response to: (1) deformation of a low taper sedimentary wedge over a low-friction salt detachment, in which case there is not a dominant hinterland or foreland vergence direction for faults (Davis and Engelder, 1985), and (2) at locations where there is a lateral change affecting the mechanical behavior of the sedimentary sequence involved, such as a stratigraphic pinch-out of the salt detachment horizon, or a fault offsets the salt detachment horizon (Sans and Verges, 1995; Sans et al., 1996). Similar processes may have in part controlled the asymmetry and implied vergence direction of the Plateau Domain 2 detachment folds. Fig. 3c illustrates that the base of the salt underlying the Silurian Appalachian basin is not planar, but consists to a first approximation of a series of steps down to the south-southeast (with intermittent areas where the base of salt steps up). Each of the flat intervals between steps may have behaved as a salt pinch-out when the overlying strata were deformed. Once the salt beneath the synclines was welded out, these areas acted as buttresses, or stratigraphic pinch-outs of the salt – promoting asymmetric structures with hinterland vergence. A model illustrating the multiple-weld scenario as a mechanism to generate the Appalachian Plateau asymmetric Domain 2 anticlines and Domain 3 synclines is shown in Fig. 12. Unfortunately, due to the large amount of denudation after the folding (Fig. 3), no growth strata exist to constrain the kinematics and timing of the structures. An additional factor that may have contributed to both the asymmetry and the arcuate trend of the Domain 2 folds is the depression below base level, or "pop-down", of Domain 3 synclines adjacent to the

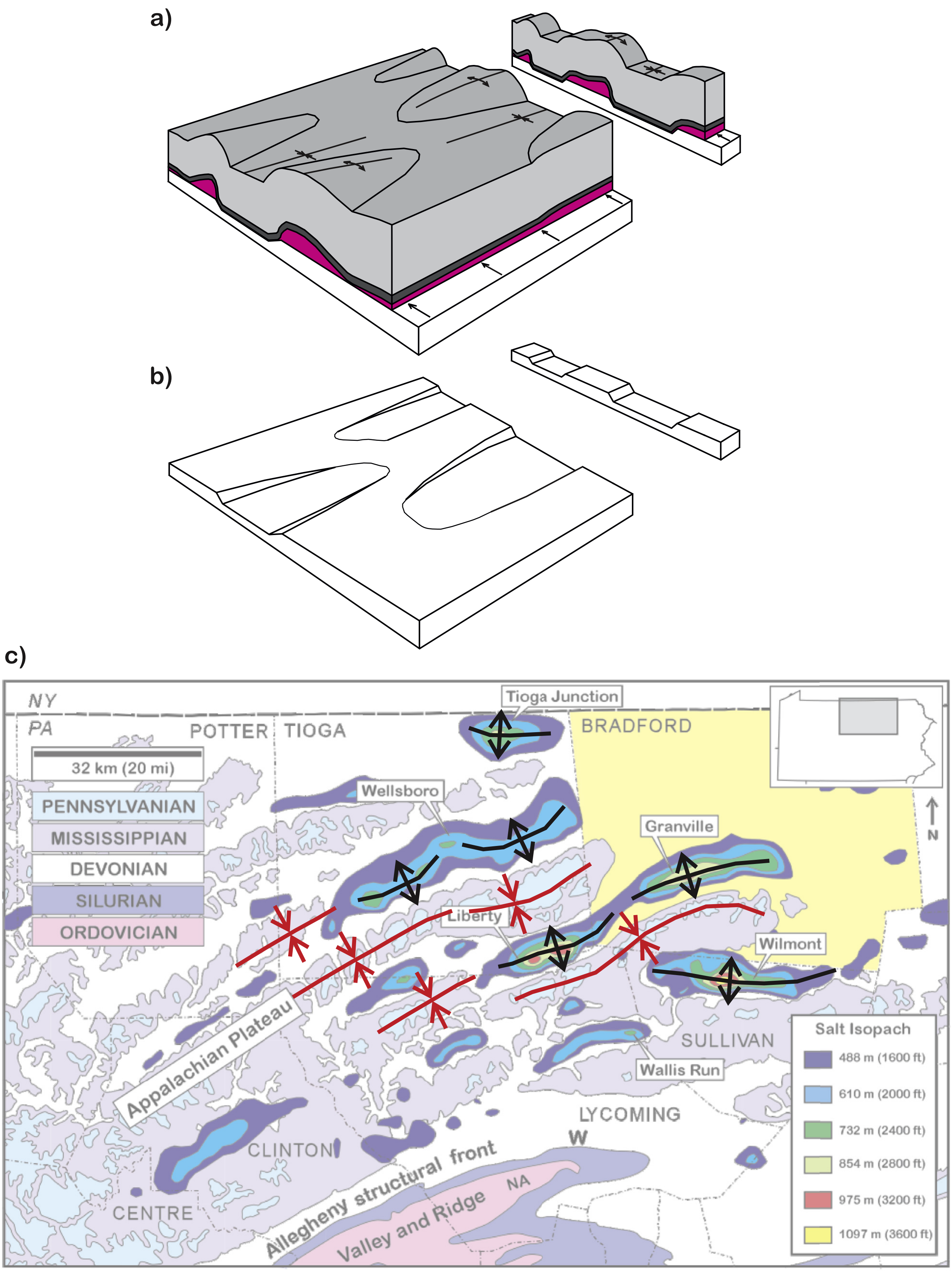

Fig. 13. a) Schematic block diagram illustrating the non-planar geometry of the base of salt detachment and along-strike changes in fold geometries – from anticlines to synclines, and vice versa, that result in response to minor shortening over the stepped detachment. In the model, the location of originally thick halite, or depression of the synclinal region into the underlying evaporite section, controls the location of synclines, and the related development of adjacent halite-cored anticlines. b) Base of salt detachment surface with overlying strata removed illustrates the geometry of the stepped detachment surface. c) Surface geologic map (modified from Berg et al., 1980) with Upper Silurian salt isopach map superimposed to illustrate geometry of salt-cored anticlines in the subsurface. Anticlinal (black) and synclinal (red) fold axial traces are highlighted to illustrate along-strike variation. For example, synclines are developed along the southwest projection of both the Liberty and Wellsboro anticlines.

Domain 2 anticlines. In this scenario: 1) with onset of shortening, the Domain 3 syncline is depressed into the salt, 2) salt is evacuated from beneath the syncline into the core of the adjacent salt-cored anticline to the north, 3) with continued shortening, the synclinal region acts as a rigid beam, or indenter, and is translated to the north-northwest, steepening the south-southeast limb of the adjacent salt-cored anticline. Such a process would serve to generate the observed asymmetry, but also explain the arcuate trend of some Domain 2 folds – which in cases are concave to the north-northwest – opposite to that expected for a south-southeast vergent fold.

4.5. Map pattern of Domain 2 and 3 folds in north-central Pennsylvania

At first glance the regional map pattern of Plateau folds indicates long fold axial traces that are sub-parallel to the Allegheny structural front (Fig. 1). However, in north-central Pennsylvania (in the area underlain by Upper Silurian salt, Fig. 1), the fold axial traces are less continuous and they are sinuous along strike. In addition, Domain 2 anticlinal axial traces commonly appear to be nearly continuous along trend with Domain 3 synclinal axial traces (e.g. the Liberty anticline and the syncline immediately to its southwest in Fig. 13). It is envisioned that flow of halite from areas beneath synclines, into the cores of adjacent anticlines, occurred in directions both perpendicular, and parallel, to the trend of the folds. Fig. 13a illustrates along-strike changes between anticlines and synclines generated by minor shortening over a non-planar detachment. In the model example, as with the north-central Pennsylvania Plateau structures, apparent offsets of fold axial traces are not interpreted to be due to through-going strike-slip faulting, but related to plunge of fold hinges along strike (Fig. 13a).

4.6. The Lackawanna synclinorium

The Lackawanna synclinorium is a crescent-shaped trough on the southeast side of the Appalachian Plateau (Fig. 1), which has a concave-to-the-northwest geometry – seemingly at odds with northwest directed shortening observed in the Valley and Ridge province to the south. The genesis of the synclinorium has been debated for many years. Harrison et al. (2004) present a nice summary of the structural geology of the feature based on field observations, well data, potential field data, and 2D seismic interpretation. Harrison et al. (2004) propose that the structure formed in response to large-scale dissolution of halite within the Upper Silurian Salina Group, followed by northward translation of the southern portion of the trough by Alleghanian thin-skinned thrusting. Although beyond the scope of this paper to discuss in detail, following are a couple comments regarding the Lackawanna synclinorium, that relate to the Plateau fold belt structural styles that have been described earlier.

First, Harrison et al.'s (2004) interpretation that the synclinorium formed by dissolution of a thick halite interval at depth and collapse of overlying strata into the void, is in some respects similar to the proposed model of halite flowing from beneath the Plateau synclines, and subsidence of the synclines below base level. However, in the case of the Plateau synclines, the flow of the halite into adjacent anticlinal cores precludes the necessity of large-scale halite dissolution. In fact, halite from beneath Domain 3 synclinal regions is required to material balance the excess halite observed in the cores of the large Domain 2 anticlines. A similar flow of halite from beneath the Lackawanna synclinorium may have been distributed in the cores of long, linear, low amplitude anticlines adjacent to the synclinorium, possibly in addition to the dissolution proposed by Harrison et al. (2004). It should be noted that occasionally halite is observed precipitated in fractures in cores from Middle Devonian strata – suggesting that at least some dissolution and re-precipitation of halite has occurred in the Plateau fold belt.

Second, an alternative interpretation for the Lackawanna synclinorium is that it is folding over a graben system that is localized by the pinch-out of halite in the Upper Silurian Salina Group evaporite sequence – shown schematically in Fig. 12g. Notice that the surface expression of the syncline coincides with the basin margin halite pinch-out (or transition from halite to anhydrite dominated facies) in the interpretation of the Salina Group evaporite facies shown in Fig. 1. In this scenario, the concave-to-the-northwest geometry is inherited from the shape of the southeast margin of the Upper Silurian salt basin. The graben system underlying the Lackawanna synclinorium would have a genesis similar to faults along the west and northwest perimeter of the East Texas salt basin (Mexio-Talco fault system) that are localized by the depositional pinch-out of the Middle Jurassic Louann salt (Jackson, 1982). An extensional fault system, localized by the pinch-out of halite, would contribute to decreasing the taper of the wedge developed by deposition of the Catskill delta sediments, where the wedge overlies a salt detachment. For the most part, the basement underlying the Plateau fold belt dips gently to the south-southeast. However, the Lackawanna synclinorium occurs above a portion of the basin where the basement dips to the northwest (Patchen et al., 2004; Alexander et al., 2005). Seismic data shows that there is no thinning of Upper Devonian strata over the region of northwest dipping basement suggesting that the basement dip to the northwest was relatively late formed. Possibly, the Lackawanna synclinorium resulted from the regional uplift of northeastern Pennsylvania, and was localized by the depositional pinch-out of halite which generated the concave to the northwest geometry of the structure. Wise (2004) suggested that the Lackawanna basin may have originated as a trailing edge graben associated with thrust-related shortening on the periphery of the Pocono autochthon. Perhaps the salt pinch-out localized and influenced the shape and trend of the Lackawanna synclinorium.

5. Conclusions

- New seismic and well data from hydrocarbon exploration and development activity associated with the Marcellus Formation shale gas play in north-central Pennsylvania provide insight to the structural style of the Appalachian Plateau fold belt in the region north and northwest of the Allegheny structural front in Potter, Tioga, Bradford, Sullivan, and northern Lycoming, Clinton and Centre counties.
- The Plateau fold belt developed over a detachment in Upper Silurian Salina Group evaporites during the Permian Alleghany Orogeny in response to north-northwest directed shortening and can be divided into three structural domains based on detachment fold characteristics. Domain 1 detachment folds have short wavelengths and low amplitudes. Domain 2 salt-cored detachment anticlines have long wavelengths and large amplitudes, and Domain 3 comprises large synclines, located between Domain 2 anticlines. Halite originally beneath Domain 3 synclines is interpreted to have been mobilized, or evacuated, into the cores of adjacent Domain 2 anticlines during folding.
- Seismic data indicate that the detachment underlying the Plateau fold belt is a non-planar, stepped surface. Possible scenarios for the development of the non-planar detachment include: 1) mobilization of halite from an evaporite sequence that contained an originally non-uniform distribution of halite, 2) it is an erosion surface that existed prior to salt deposition, or 3) it developed *in response* to folding of the stratigraphic layer

overlying the evaporite sequence (depression of Domain 3 synclines into the evaporite sequence and flow the halite from beneath the syncline into the cores of adjacent Domain 2 anticlines).

- The apparent hinterland (SSE) vergence of some large Plateau fold belt Domain 2 salt-cored anticlines is proposed to be related to shortening of strata over a salt detachment, similar to observations from other fold belts over salt detachments. In addition, the non-planar geometry of the base of salt detachment may have contributed to the apparent SSE vergence of Domain 2 folds through depression of Domain 3 synclines into the salt detachment layer, to behave as a rigid beam, or indentor, to steepen the SSE limbs of some of the large Domain 2 Plateau folds with subsequent shortening.
- An interpretation is proposed for the Lackawanna synclinorium in northeastern Pennsylvania in which the feature is a graben system that is localized by the pinch-out of halite in the Upper Silurian Salina Group evaporite sequence. In this scenario, the concave-to-the-northwest geometry is inherited from the shape of the southeast margin of the Upper Silurian salt basin. The graben system in this interpretation would have a genesis similar to faults along the west and northwest perimeter of the East Texas salt basin (Mexio-Talco fault system) that are localized by the depositional pinch-out of the Middle Jurassic Louann salt.

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