Burial and Thermal History of the Central Appalachian Basin, Based on Three 2-D Models of Ohio, Pennsylvania, and West Virginia

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BURIAL AND THERMAL HISTORY OF THE CENTRAL APPALACHIAN BASIN, BASED ON THREE 2-D MODELS THROUGH OHIO, PENNSYLVANIA, AND WEST VIRGINIA

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INTRODUCTION

Three regional-scale, cross sectional (2-D) burial and thermal history models are presented for the central Appalachian basin based on the detailed geologic cross sections of Ryder and others (2004), Crangle and others (2005), and Ryder, R.T., written communication. The models integrate the available thermal and geologic information to constrain the burial, uplift, and erosion history of the region. The models are restricted to the relatively undeformed part of the basin and extend from the Rome trough in West Virginia and Pennsylvania northwestward to the Findlay arch in Ohio (Fig. 1). This study expands the scope of previous work by Rowan and others (2004) which presented a preliminary burial/thermal history model for a cross section (E-E') through West Virginia and Ohio. In the current study, the burial/thermal history model for E-E' is revised, and integrated with results of two additional cross sectional models (D-D' and C-C'; Fig. 1).

The burial/thermal history models provide calculated thermal maturity (Ro%) values for the entire stratigraphic sequence, including hydrocarbon source rocks, along each of the three cross sections. In contrast, the Ro and conodont CAI data available in the literature are sparse and limited to specific stratigraphic intervals. The burial/thermal history models also provide the regional temperature and pressure framework that is needed to model hydrocarbon migration.

MODEL ASSUMPTIONS

The burial/thermal history models simulate sediment accumulation, compaction, uplift, and erosion, as well as temperatures and thermal maturities through time. The modeling approach discussed in Rowan and others (2004) is utilized also in the models presented here and the text below focuses on revisions and additions to the earlier study. The most significant changes include a revision in the basement heat flow value specified in the models and the addition of bottom hole temperature (BHT) data to calibrate the models.

Heat Flow

The initial model of section E-E' (Rowan and others, 2004) used a heat flow of 60 mW/m^2, consistent with the heat flow assumed in study of western Pennsylvania (Cercone and others, 1996). The models presented here, including the revised model of E-E', use a heat flow of 52 mW/m^2 based on a recent map-based heat flow compilation for North America (Blackwell and Richards, 2004). The revised heat flow value is considered to be a better representation of basement heat flow across the study area. For comparison, the average surface heat flow for the North American continent is reported to be 54.4 mW/m^2 and the global continental average to be 56.6 mW/m^2 (data from Sclater and others, 1980, see Allen and Allen, 1990, Table 2.2).

Bottom Hole Temperatures

Bottom hole temperature (BHT) data for 28 of 31 wells were compared with model-calculated temperature-depth profiles and were used to calibrate the models. BHT corrections were made using the equations of Waples and others (2001, 2004a, b). Model-calculated temperature profiles and corrected BHT data are shown in Figure 2 for the deepest wells on sections C-C' and E-E', the Svetz and Gainer-Lee wells, respectively. These profiles are typical of the 28 wells for which BHT data were available in that they show fair to good overall agreement between the model and corrected BHT data although a small number of outlying data are not matched by the model. The inclusion of BHT data represents a significant improvement over the previous model (Rowan and others, 2004) because these data permit verification that the models' thermal parameters (heat flow, surface temperature, and lithology-specific thermal conductivities) reproduce measured, present day temperatures.

Lithologies and their Properties

Lithologies are defined for each model unit in 26 of the 31 wells for which lithologic logs were available (Table 1). In wells for which logs were not available, average lithologies were determined based on the lithologies of the neighboring wells. This approach provides more detail than in the earlier version of model E-E' (Rowan and others, 2004) in which lithologies of each model unit were averaged over the cross section. The physical properties of individual lithologies are unchanged from the earlier study (Rowan and others, 2004).

Thermal Maturity

Throughout this report thermal maturity is quantified in terms of vitrinite reflectance (Ro%), whether or not vitrinite or other organic matter is actually present; thus, a few words of explanation may be helpful to the reader. Vitrinite reflectance (Ro%) is one of numerous indicators of thermal maturity and like all such indicators it increases both with time and temperature. Ro data have been collected widely from vitrinite samples from sedimentary basins worldwide, including the Appalachian basin. Vitrinite reflectance is perhaps the most commonly measured and widely quoted thermal maturity parameter, and serves as a de facto reference scale for the thermal maturity of organic matter. Ro% values of approximately 0.6 and 1.4, respectively, mark the approximate onset of oil generation and the shift from predominantly oil to predominantly gas generation in oil-prone source rocks. The range, 0.06 $\leq$Ro%$\leq$1.4, is referred to as the "oil window" or thermal maturity range for significant oil generation in oil-prone source rocks. Ro% values between approximately 1.4 and 3.0

represent the "gas window" or maturity range for thermal generation of hydrocarbon gases (see for example, Kübler, B., and Jaboyedoff, M., 2000, Fig. 8).

The terms "oil window" and "gas window" are widely used, but they should be used with caution because the equations used to calculate vitrinite reflectance incorporate a number of assumptions, including kerogen type and the kinetics of the transformation reactions (Sweeney and Burnham, 1990). In this report these terms terms are used to give only a general indication of thermal maturity level with respect to oil or gas generation. Vitrinite reflectance is readily calculated in numerical models allowing Ro% values to be predicted for strata throughout the model domain and through time.

Restoration of Eroded Strata

Numerous authors have noted that that thermal maturity measurements made in Paleozoic strata in the Appalachian basin require significantly greater burial depths and temperatures than are present today (e.g., Epstein and others, 1977; Cercone and others, 1996; Hulver, 1997; Reed and others, 2005). As in earlier models, the temperature ranges required to match measured temperatures and thermal maturities are attained in the current study by restoring the sediment thicknesses at maximum burial. Permian sediments comprise the majority of the strata restored in the models, but smaller amounts Pennsylvanian and older units were restored where they were eroded on the Findlay arch, based on regional trends in stratigraphic thickness. The model stratigraphic units for section D-D' (representative also of section C-C' and E-E') are shown at maximum burial (Fig. 3) and in present day, post-erosion configuration (Fig. 4). The individual formations that comprise the model units are listed in Table 2. Thicknesses of the restored units at individual wells at maximum burial and present day are shown graphically in Figure 5. In model C-C', which terminates farthest to the southeast and closest to the basin depocenter, a maximum of 12,500 ft of Permian and Pennsylvanian strata were restored (Fig., 1; Fig. 5a). For comparison, Reed and others (2005) estimated that burial of burial of Pennsylvanian strata on the Allegheny Plateau in West Virginia exceeded ~4.4 km (14,432 ft) in the mid Permian. Similarly, Hulver (1997, Fig.

8.06) estimated 4.5 – 5 km (14,760 – 16,400 ft) of erosion along the Allegheny structural front in West Virginia and Pennsylvania since the end of the Allegheny Orogeny.

In an earlier version of model E-E', Rowan and others (2004), specified that maximum burial occurred during the mid-Triassic (230 Ma), consistent with the timing of maximum burial assumed by Ryder and Zagorski (2003). In the current study, this timing is revised to approximately match the results of Reed and others (2005) who combined (U-Th)/He and apatite fission track dating methods with paleotemperatures from fluid inclusions and vitrinite reflectance to define an uplift and erosion history of the Appalachian Plateau of West Virginia. In models C-C', D-D', and E-E' presented here, maximum burial occurs during the mid-Permian (270 Ma) and is followed by steady erosion until present day.

Each cross-sectional model (C-C', D-D', and E-E') specifies the thickness of Permian strata during maximum burial, with the greatest thickness to the southeast and thinning northwestward. The thicknesses of restored Permian strata were adjusted to match the following thermal maturity data: 1) vitrinite reflectance (R_o%) measurements on Pennsylvanian coals, 2) reflectance (R_o%) measurements of dispersed vitrinite in the Devonian Marcellus Shale, and 3) color alteration index (CAI) values measured in conodonts in the Devonian Onondaga and Ordovician Trenton-Black River limestones (Hower, 1978; Cole and others, 1979; Rimmer, 1985; Chyi and others, 1987; Hower and Rimmer, 1991; Repetski and others, 2002, 2004, 2005). Model-calculated vitrinite reflectance-depth profiles for the Gainer-Lee and Svetz wells are shown in Figure 6 with Ro% and CAI data from the vicinity of the wells superimposed. As with the BHT data discussed above, the model-calculated Ro-depth profiles are in fair to good overall agreement with the thermal maturity measurements, however, a small number of data are not matched by the model.

MODEL RESULTS

The results of the burial history models are presented in several ways, 1) over the entire 2D model domain at present day (Fig. 7), and 2) for a several key hydrocarbon source rock units over the length of the cross section and through time (Figs. 8-10). Figure 8 shows profiles of thermal maturity (shown as vitrinite reflectance, Ro%) for the Ordovician 'Utica' model unit (comprised almost entirely of Utica Shale) along cross sections C-C', D-D' and E-E' at present day and at selected earlier times. In this figure, the Utica Shale reached thermal maturity (i.e., entered the oil window) as early as Middle to Late Devonian time (360 – 390 Ma) in wells located in the deepest portion of the basin in Pennsylvania and West Virginia. Thus, from Middle – Late Devonian onward there was the potential for Utica-sourced hydrocarbons to migrate through the basin. The Utica Shale reached thermal maturity at progressively younger ages from southeast to northwest due to the decreasing overburden thickness away from the basin depocenter. At wells located near the crest of the Findlay arch the model predicts a thermal maturity for the Utica Shale below that of the oil window.

Similar figures show the evolution of thermal maturity through time for the base of the Devonian 'Ohio Shale' model unit (Fig. 9) and the base of 'Pennsylvanian' model unit (Fig. 10). The 'Ohio Shale' model unit is comprised primarily of Upper Devonian Shales of which the Ohio Shale is among the thickest. The 'Pennsylvanian' model unit includes all strata of Pennsylvanian age (see Table 2). According to the burial/thermal history models, the base of the 'Ohio Shale' model unit was in the oil window as early as the close of Mississippian (320 Ma) in the deepest parts of the basin (sections C-C' and D-D', Pennsylvania and West Virginia; Figs. 9a, b) and could have generated hydrocarbons from that time forward.

The model results indicate that the base of the Pennsylvanian strata entered the oil window (Ro% > 0.6) as early as mid-Permian time (270 – 280 Ma) at the southeastern ends of cross sections C-C', D-D', and E-E' (Fig. 10).

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Table 1. Location and other information for wells used in constructing models C-C', D-D', and E-E' (data sources: Crangle et al., 2005, Ryder et al., 2004, and Ryder, R.T., written communication).

Model Well No.	Short Name	Lease Name	State	County	Latitude	Longitude	API (from State)	Lithologic Log Available
				Model C - C'				
1	Krysik	Krysik-Wakefield et al.	OH	Erie	41.30430	-82.35046	34-043-20011	yes
2	Born	A. & A. Born	OH	Lorain	41.28930	-82.32085	34-093-20794	yes
3	Smith	F.L. Smith Estate	OH	Medina	41.22891	-81.70270	34-103-21143	yes
4	Westfall	B. Westfall	OH	Stark	40.95247	-81.26263	34-151-21081	yes
5	Murray	Frank Murray	OH	Columbiana	40.78578	-80.87042	34-029-20648	yes
6	Minesinger	S. Minesinger	WV	Hancock	40.53972	-80.55611	47-029-00080	yes
7	Ashcroft	Richard J. Ashcroft	PA	Beaver	40.60155	-80.43412	37-007-20060	yes
8	Ricks	E. C. Ricks	PA	Fayette	39.84346	-79.65427	37-051-20056	yes
9	Svetz	Leonard Svetz	PA	Somerset	39.97776	-79.33387	37-111-20045	yes
				Model D - D'				
1	Haff	V. & I. Haff	OH	Sandusky	41.37085	-82.90661	34-143-2-0077	yes
2	Kerbel	Paul Kerbel	OH	Sandusky	41.43770	-83.31652	34-143-20147	yes
3	Wheeler	I.M. Wheeler	OH	Huron	41.10610	-82.70442	34-077-2-0025	no
4	Empire	Empire Reeves Steel Div.	OH	Richland	40.77921	-82.51903	34-139-20448	yes
5	Drake	Alonzo Drake, Jr.	OH	Wayne	40.86050	-81.90569	34-169-2-1419	yes
6	Troyer	Dan E. Troyer	OH	Holmes	40.65712	-81.77225	34-075-21283	yes
7	Huebner	Huebner	OH	Tuscarawas	40.30405	-81.42453	34-157-21030	yes
8	Zechman	Thomas Zechman	OH	Harrison	40.19500	-81.19717	34-067-2-0737	no
9	Birney	Roy Birney	OH	Harrison	40.26188	-80.96636	34-067-20103	yes
10	Burley	John Burley	WV	Marshall	39.76167	-80.53000	47-051-00539	yes
11	Finch	R.R. Finch	WV	Marion	39.43194	-80.01222	47-049-00244	yes
				Model E - E'				
1	Carter	Carter	OH	Wood	41.41492	-83.60898	34-173-20237	yes
2	Kerbel	Paul Kerbel	OH	Sandusky	41.43770	-83.31652	34-143-20147	yes
3	Asphalt	M. and B. Asphalt Co.	OH	Seneca	41.22640	-83.19891	34-147-60840	no
4	Leonhardt	V.E. Leonhardt	OH	Crawford	40.90996	-82.88333	34-033-20050	no
5	Windbigler	A.C. Windbigler	OH	Morrow	40.69033	-82.68222	34-117-20047	yes
6	Palmer	J. Palmer	OH	Richland	40.64802	-82.58955	34-139-20289	yes
7	Lee	Edwin L. Lee	OH	Coshocton	40.32292	-82.00095	34-031-22053	yes
8	Marshall	W. R. Marshall	OH	Guernsey	40.03672	-81.72047	34-059-20782	yes
9	Ullman	Robert Ullman	OH	Noble	39.61067	-81.34730	34-121-21278	yes
10	Deem	Howard H. Deem et ux	WV	Wood	39.08057	-81.50795	47-107-00756	yes
11	McCoy	Walter McCoy et al.	WV	Jackson	38.73055	-81.56944	47-035-01366	yes
12	Gainer-Lee	Gainer-Lee	WV	Calhoun	38.87500	-81.09760	47-013-02503	no

Table 2. Model unit names and ages, and stratigraphic units (groups, formations and members of formations) that comprise the model units. Bold type indicates a stratigraphic unit for which the model unit was named. Stratigraphic information is based on Crangle et al. (2005), Ryder et al. (2004), and Ryder, written communication. Not every stratigraphic unit is present in every well. Model unit ages approximate the formation ages defined in Ryder et al. (2004). Abbreviations are listed at the end of the table.

Age	Age of top of model unit (m.y.)	Model unit name	Formations
Permian	270	'Permian'	Dunkard Gp
Pennsylvanian	300	'Pennsylvanian'	Monongahela Gp Conemaugh Gp (incl Mahoning Ss) Allegheny Gp Pottsville Gp (incl Kanawha Fm, New River Fm & Sharon Congl)
Mississippian	320	'Mississippian'	Mauch Chunk Fm Greenbrier Ls, Maxville Ls, Wynps Ls Loyalhanna Fm, Logan Fm Cuyahoga Fm (incl Big Injun Ss & Weir Ss), Price Fm, Shenango Fm & Burgoon Ss Sunbury Shale, Berea Ss
Devonian	360	'Ohio Shale'	Bedford Sh, Upper Devonian strata undiv, Cussewago Ss, Riceville Fm & Hampshire Fm **Ohio Sh** (incl Cleveland Mbr, Three Lick Bed, & Huron Mbr), Chagrin Sh, Venango Gp, Greenland Gap (Foreknobs) Fm, Chadakoin Fm, Bradford Gp, Elk Gp, Perrysburg Fm (Dunkirk Mbr), Braillier Fm Olentangy Sh (upper), Java Fm
Devonian	375	'Rhinestreet'	West Falls Fm (Angola & **Rhinestreet** Mbrs) Sonyea Fm (incl Cashaqua Sh & Middlesex Sh Mbrs), Genessee Fm (incl West River Sh & Genneseo Mbrs), Harrell Sh, Tully Ls Plum Brook Sh, Prout Ls, Olentangy Sh (lower), Hamilton Gp (incl Mahantango Fm, Marcellus Sh)

Table 2 cont.

Age	Age of top of model unit (m.y.)	Model unit name	Formations
Devonian	390	'Onondaga'	Delaware Ls, Columbus Ls**, Onondaga Ls**, Huntersville Chert, Detroit River Gp Bois Blanc Fm, Oriskany Ss, Ridgeley Ss, Hillsboro Ss Helderberg Ls, Licking Creek Ls Mandata Sh Keyser Ls (upper; Corriganville / New Creek Ls)
Silurian	415	'Salina'	Bass Islands Dol, Big Mountain Sh Keyser Ls (lower) **Salina** Gp, Tonoloway Ls, Wills Creek Fm, Bloomburg Fm
Silurian	420	'Lockport'	**Lockport** Dol, Tymochtee & Greenfield Dols undiv, McKenzie Ls, Keefer Ss
Silurian	425	'Medina'	Rose Hill Fm (incl Cacapon Mbr), Rochester Sh, Mifflintown Fm (McKenzie & Rochester Mbrs), Dayton Ls Cabot Head Sh, "Clinton" Ss, **Medina** Ss, Tuscarora Ss (incl Castanea Mbr) Brassfield Ls, Manitoulin Dol
Ordovician	445	'Reedsville'	Queenston Sh, Juniata Fm, Oswego Ss Whitewater Fm, Cincinnati Gp undiv, **Reedsville** Sh
Ordovician	450	'Utica'	**Utica** Sh, Antes Sh, Trenton Ls (upper)
Ordovician	455	'Trenton'	**Trenton** Ls, Trenton Gp (incl Coburn & Salona Fms) Black River Ls, Black River Gp (incl Linden Hall, Snyder, & Hatter Fms) St Paul Gp (incl Loysburg Fm)

Table 2 cont.

Age	Age of top of model unit (m.y.)	Model unit name	Formations
Ordovician - Cambrian	460	'Beekmantown'	Wells Creek Fm, Row Park Ls **Beekmantown** Gp Gatesburg Fm (incl Mines & Ore Hill Mbrs) Knox Dolomite (incl Rose Run Ss & Kyrsik Ss), Copper Ridge Dol
Cambrian	495	'Conasauga'	Kerbel Fm Eau Claire Fm, **Conasauga** Gp (incl Nolichucky Sh, Maryville Ls) Mt. Simon
Cambrian	510	'Rome trough'	Conasauga Gp (incl Rogersville Sh, Rutledge Ls, Pumpkin Valley Sh) Rome (Waynesboro) Fm Shady Dol, Tomstown Dol Warrior Fm, Pleasant Hill Fm, Waynesboro Fm Tomstown Fm
Precambrian	520	'Basement'	Igneous/metamorphic basement rocks

Abbreviations:

Gp	Group
Fm	Formation
Mbr	Member
Congl	Conglomerate
Ss	Sandstone
Sh	Shale
Ls	Limestone
Dol	Dolomite
incl	including
undiv	undivided

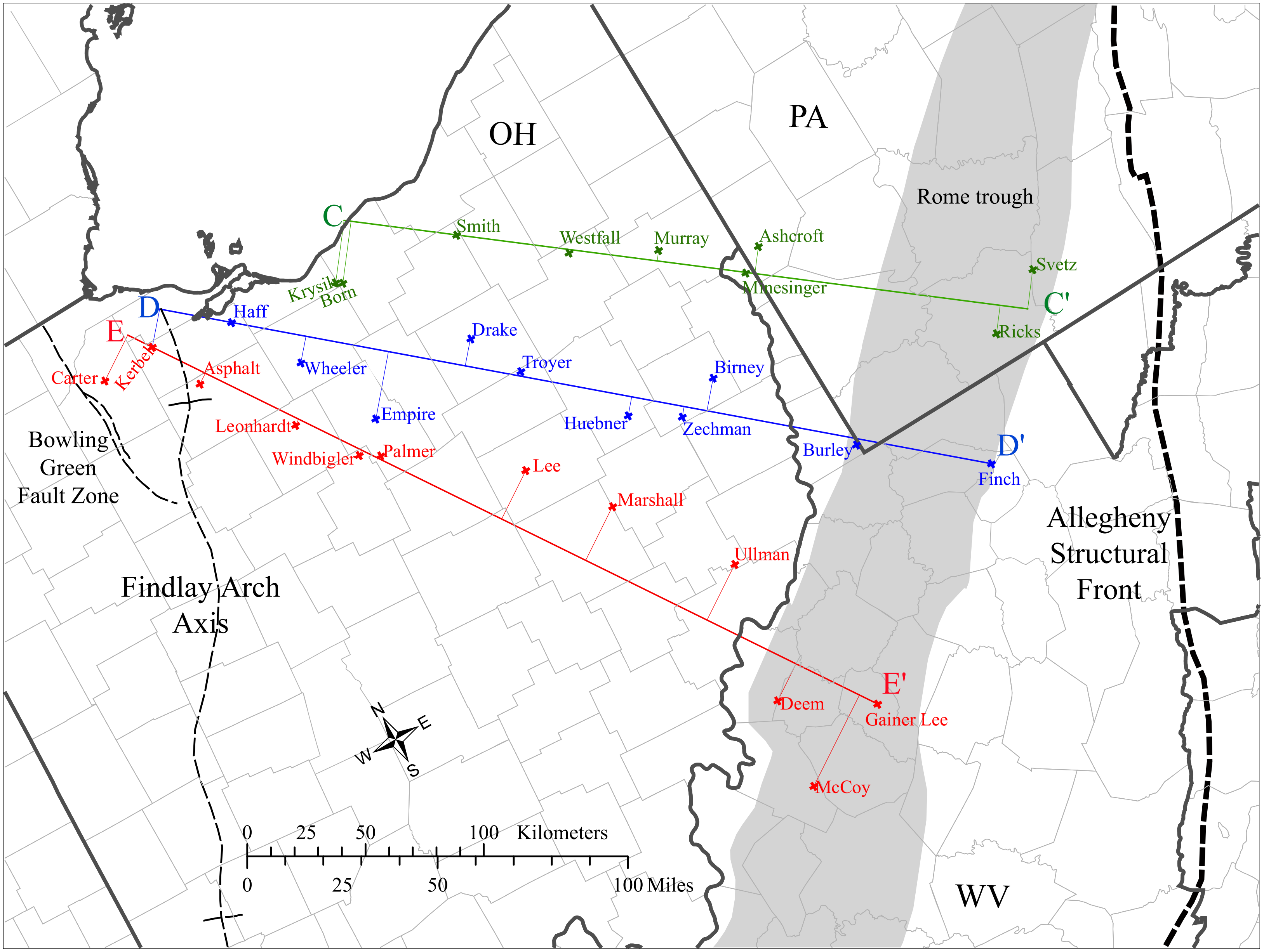

Figure 1. Map of the study area showing the three cross sections and the individual wells on which they are based. Well locations are projected onto a straight lines, as shown, to define the cross sections. The sections extend from the crest or eastern flank of the Findlay arch across the undeformed part of the Appalachian basin and terminate east of the Allegheny structural front. The gray shading indicates the Rome trough (Repetski and others, 2002, 2005). Note that the Kerbel well is used on section D-D' as well as section E-E'.

a

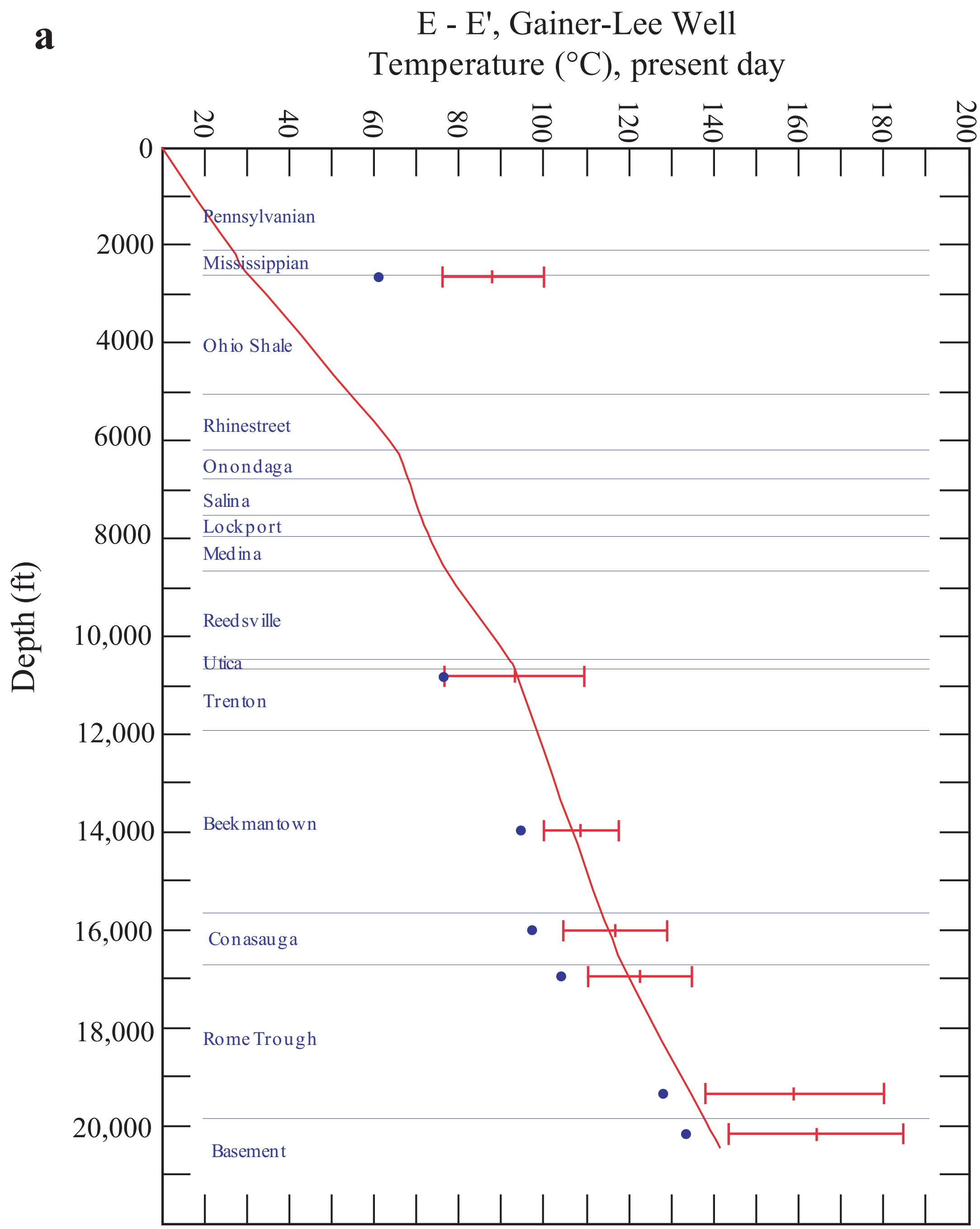

Figure 2. Bottom hole temperature (BHT) data compared with model-calculated temperature-depth profiles for two of the deepest wells in the study, (a) Gainer-Lee well on section E-E', and (b) Svetz well on section C-C'. Blue dots represent the actual BHT measurement. The red bar indicates a range (high, low, and best estimate) of corrected BHT values. In a perfect match the model Ro-depth curve would intersect the center tick in the corrected BHT range.

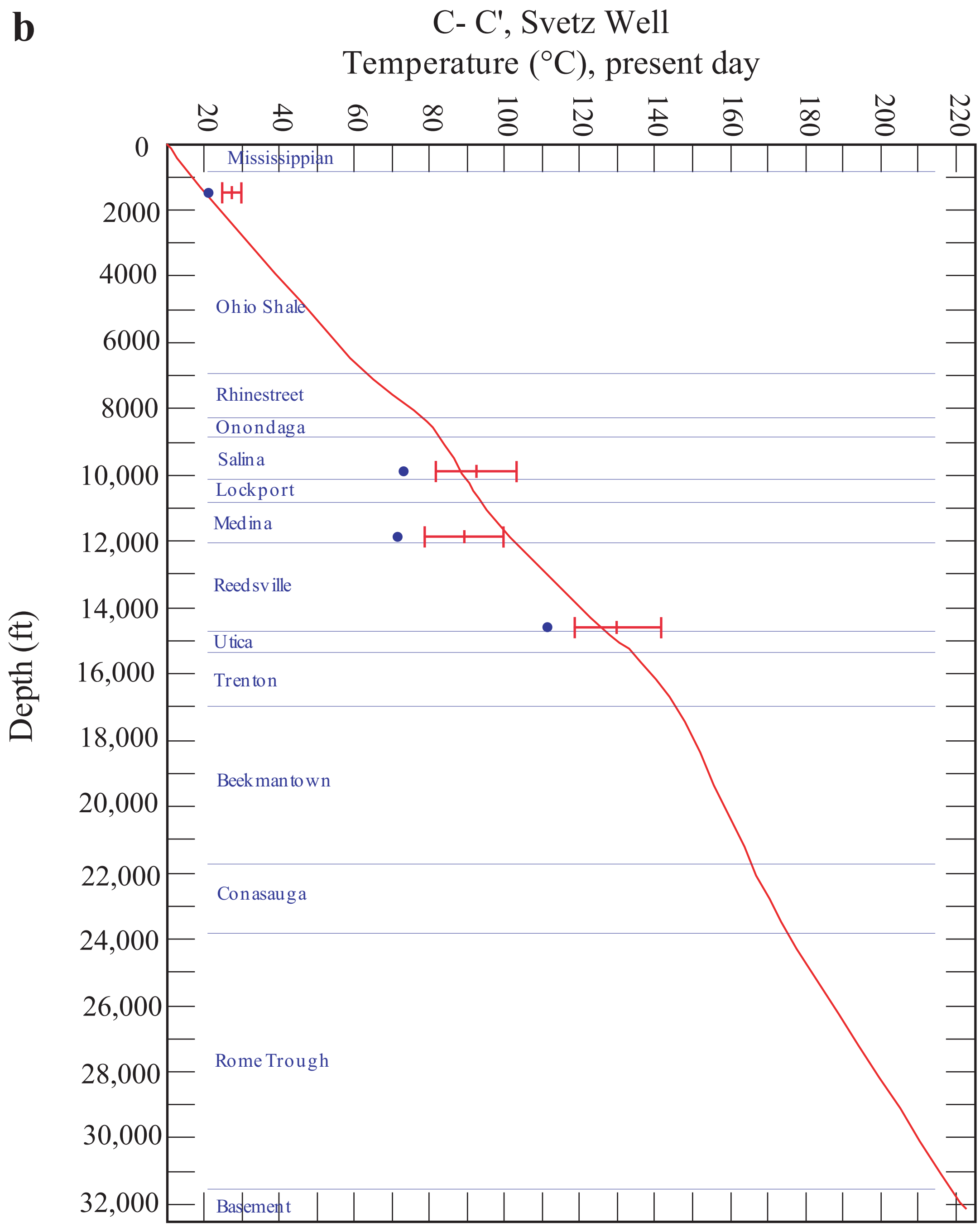
b
C- C', Svetz Well
Temperature (°C), present day
20
40
60
80
100
120
140
160
180
200
220
Depth (ft)
0
2000
4000
6000
8000
10,000
12,000
14,000
16,000
18,000
20,000
22,000
24,000
26,000
28,000
30,000
32,000
Mississippian
Ohio Shale
Rhinestreet
Onondaga
Salina
Lockport
Medina
Reedsville
Utica
Trenton
Beekmantown
Conasauga
Rome Trough
Basement

Figure 2b.

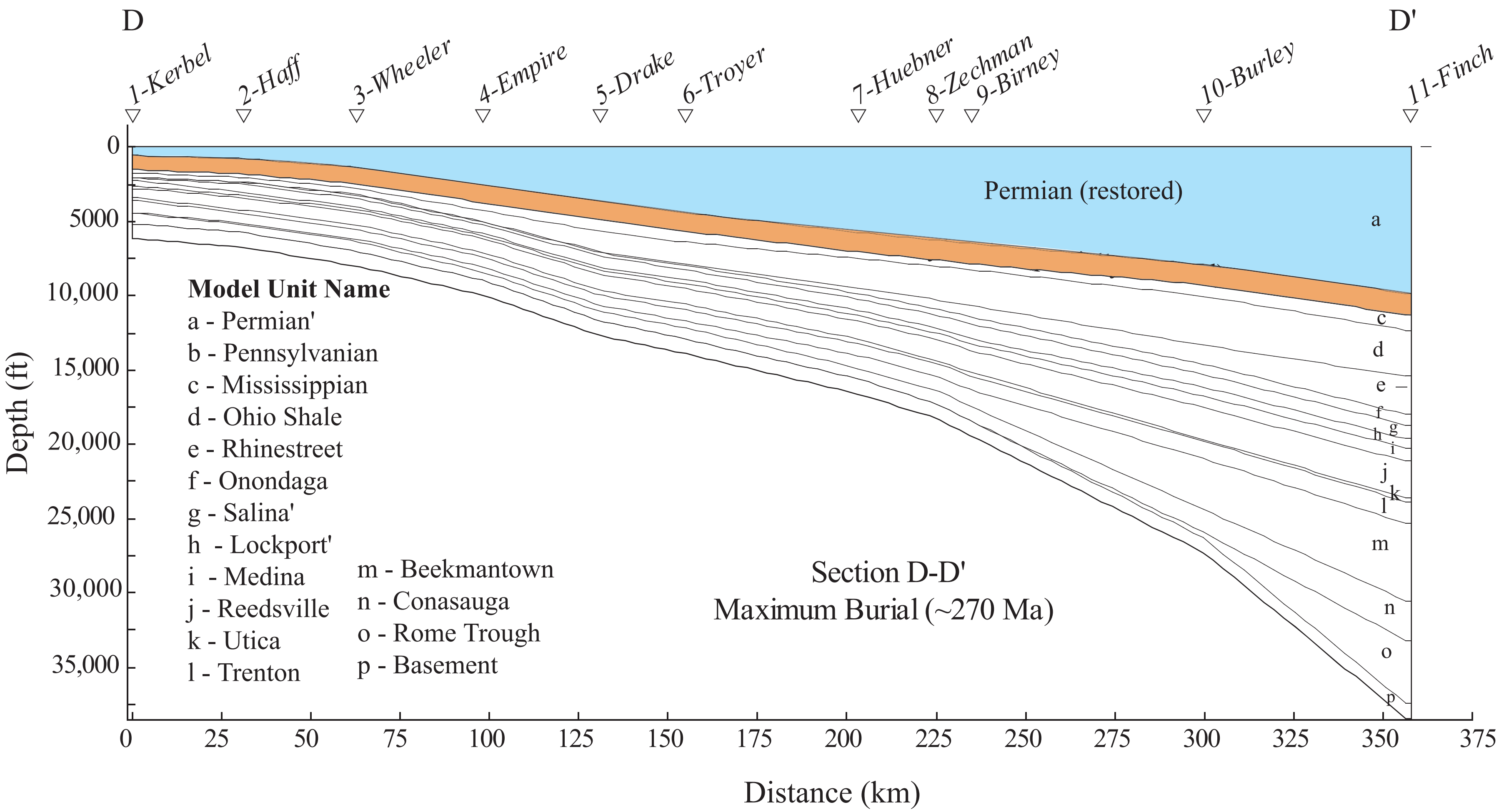

Figure 3. Cross section D-D' shown at maximum burial, ~270 Ma, in the model. Pennsylvanian strata (orange) have been restored based on trends stratigraphic thickness and Permian strata (blue) were restored so as to match the model-calculated thermal maturities with the available data. Refer to Fig. 5 for a more detailed plots of measured and restored thicknesses. The wells that define section D-D' are indicated along the top and their locations are given in Fig. 1 and Table 1. Table 2 gives model unit ages and the stratigraphic units that comprise each model unit.

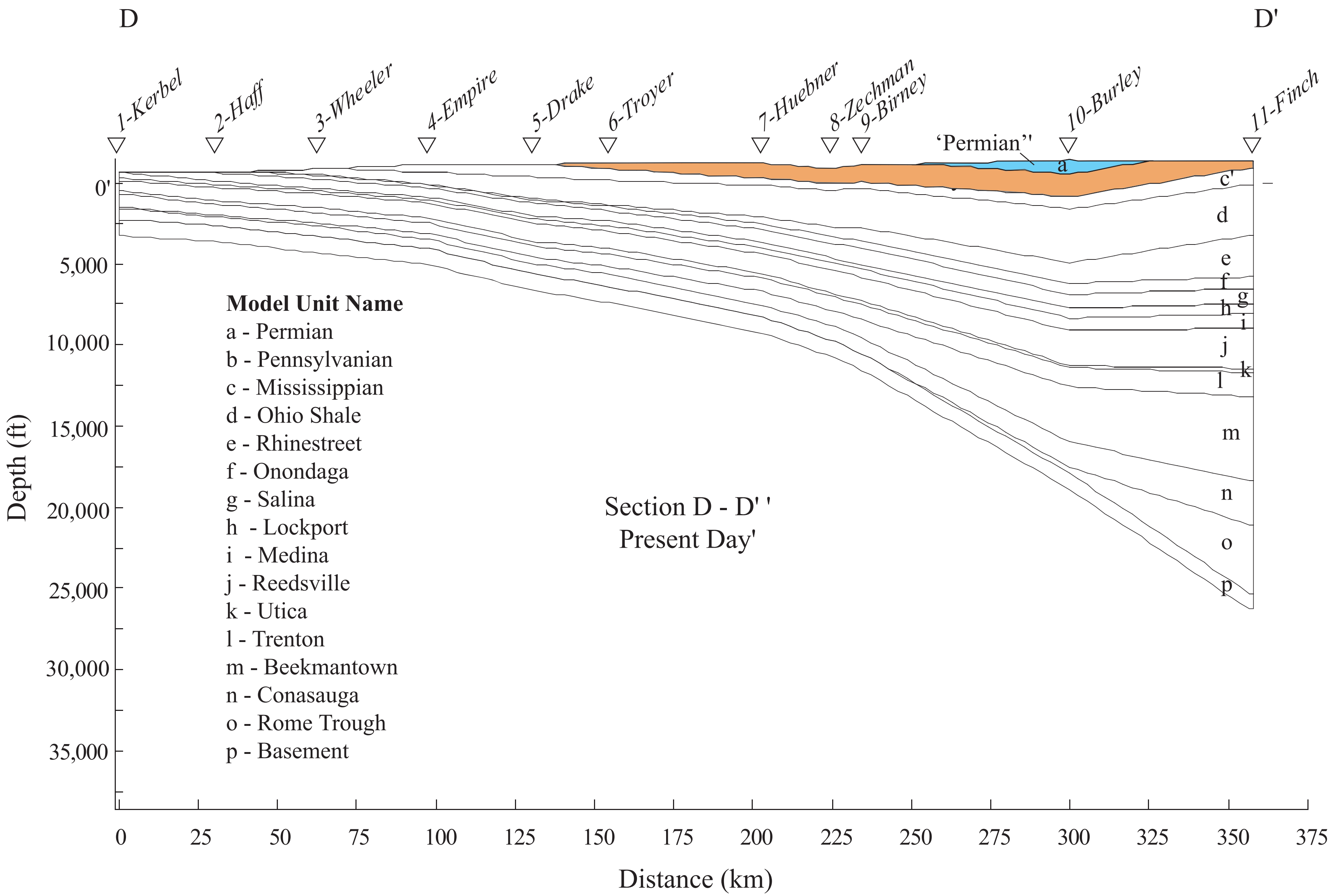

Figure 4. Cross section D-D' showing the model units at present day. Pennsylvanian strata (orange) have been truncated by erosion over most of the section, and completely removed over the crest and eastern flank of the Findlay arch. Only a thin sliver of Permian strata (blue) remains uneroded.

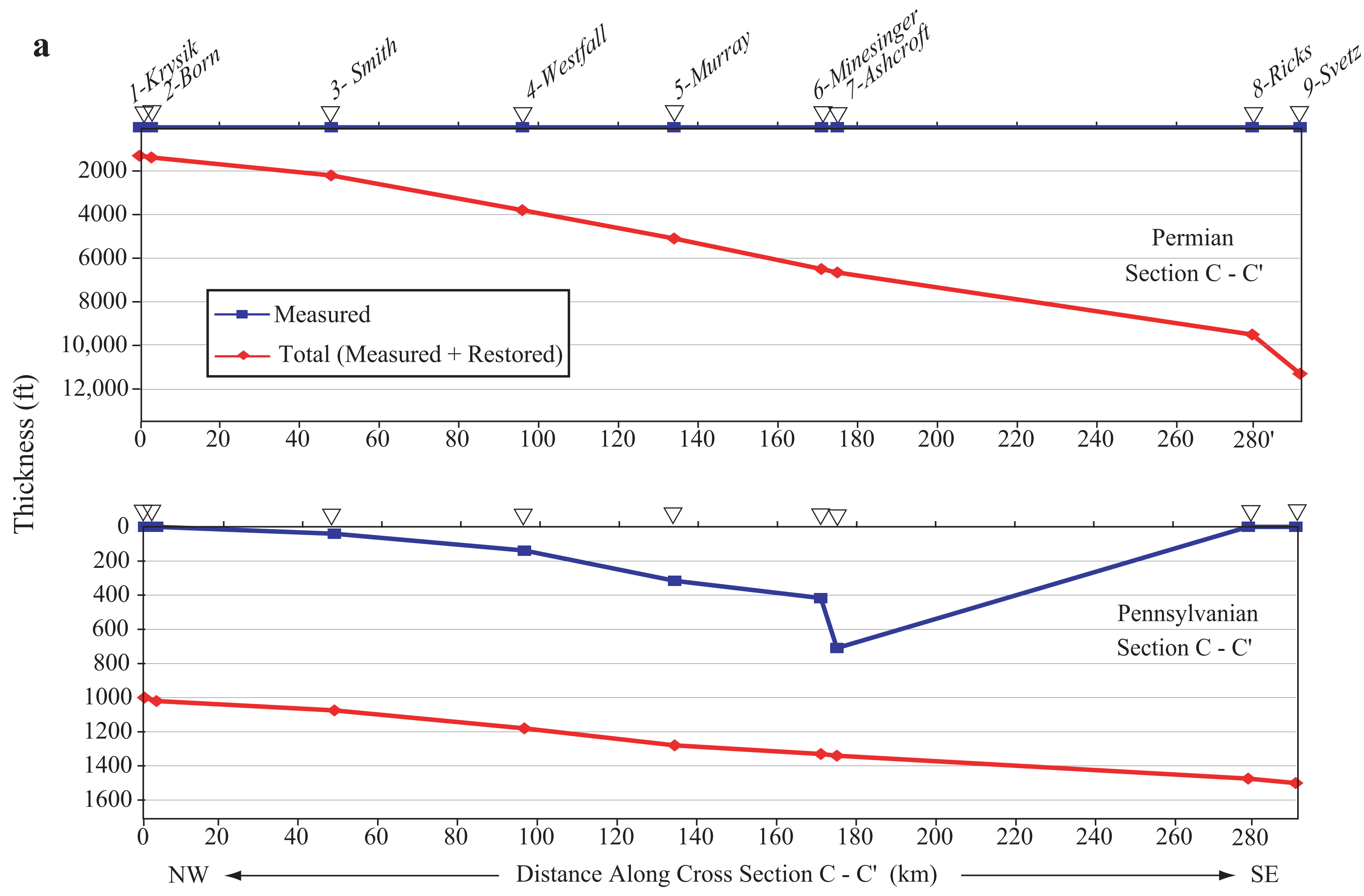

Figure 5. Thicknesses of restored Permian and Pennsylvanian model units are shown for sections C-C' (a), D-D' (b), and E-E' (c). In each plot the upper curves (blue) show actual sediment thicknesses measured at individual wells. The lower curves (red) show total (measured + restored) thickness specified in the model at maximum burial. Note that the Kerbel well is used on section D-D' as well as section E-E'.

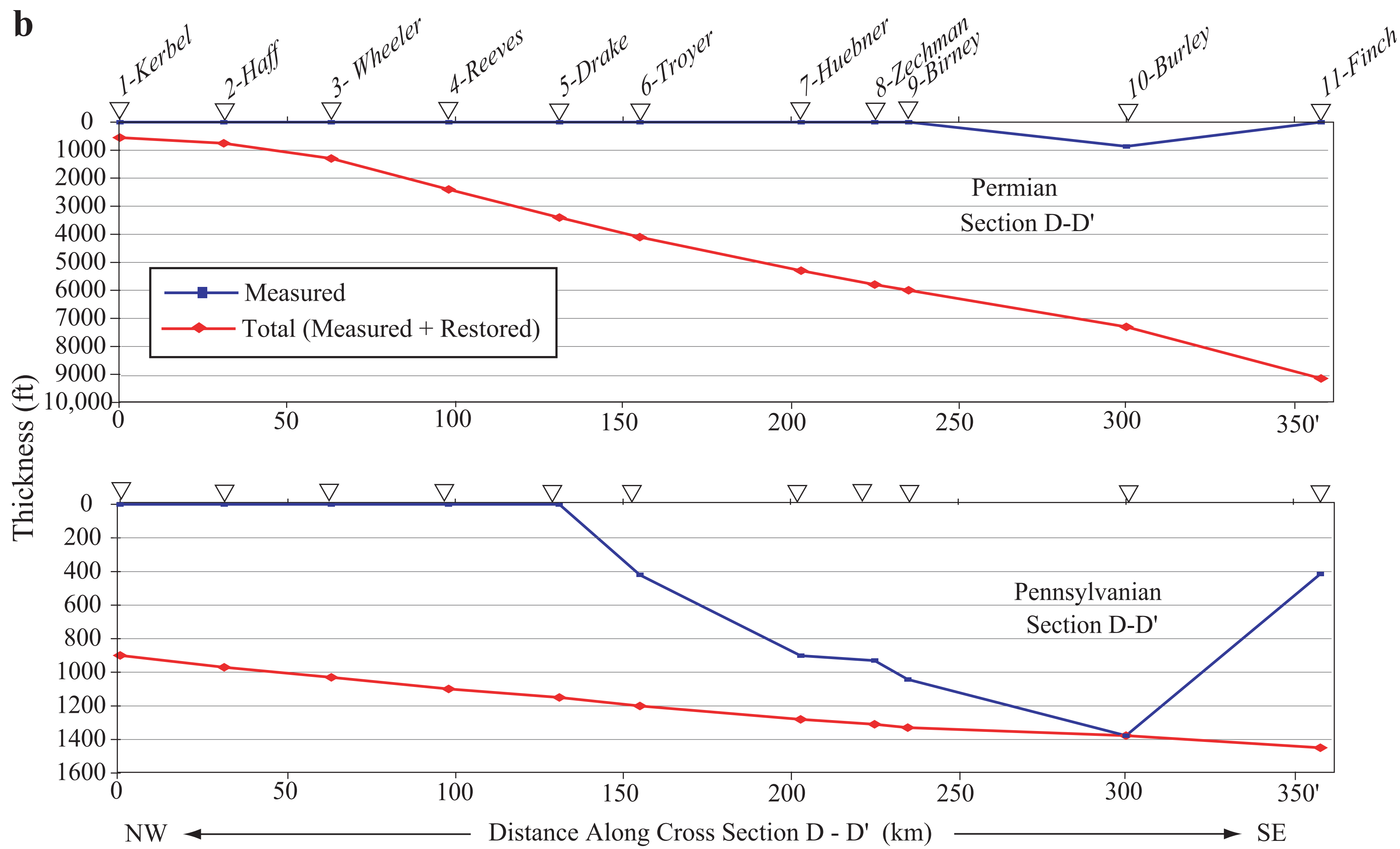
b
1-Kerbel
2-Haff
3- Wheeler
4-Reeves
5-Drake
6-Troyer
7-Huebner
8-Zechman
9-Birney
10-Burley
11-Finch
Permian
Section D-D'
Measured
Total (Measured + Restored)
Pennsylvanian
Section D-D'
Thickness (ft)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10,000
200
400
600
800
1000
1200
1400
1600
0
50
100
150
200
250
300
350'
NW
Distance Along Cross Section D - D' (km)
SE

Figure 5b.

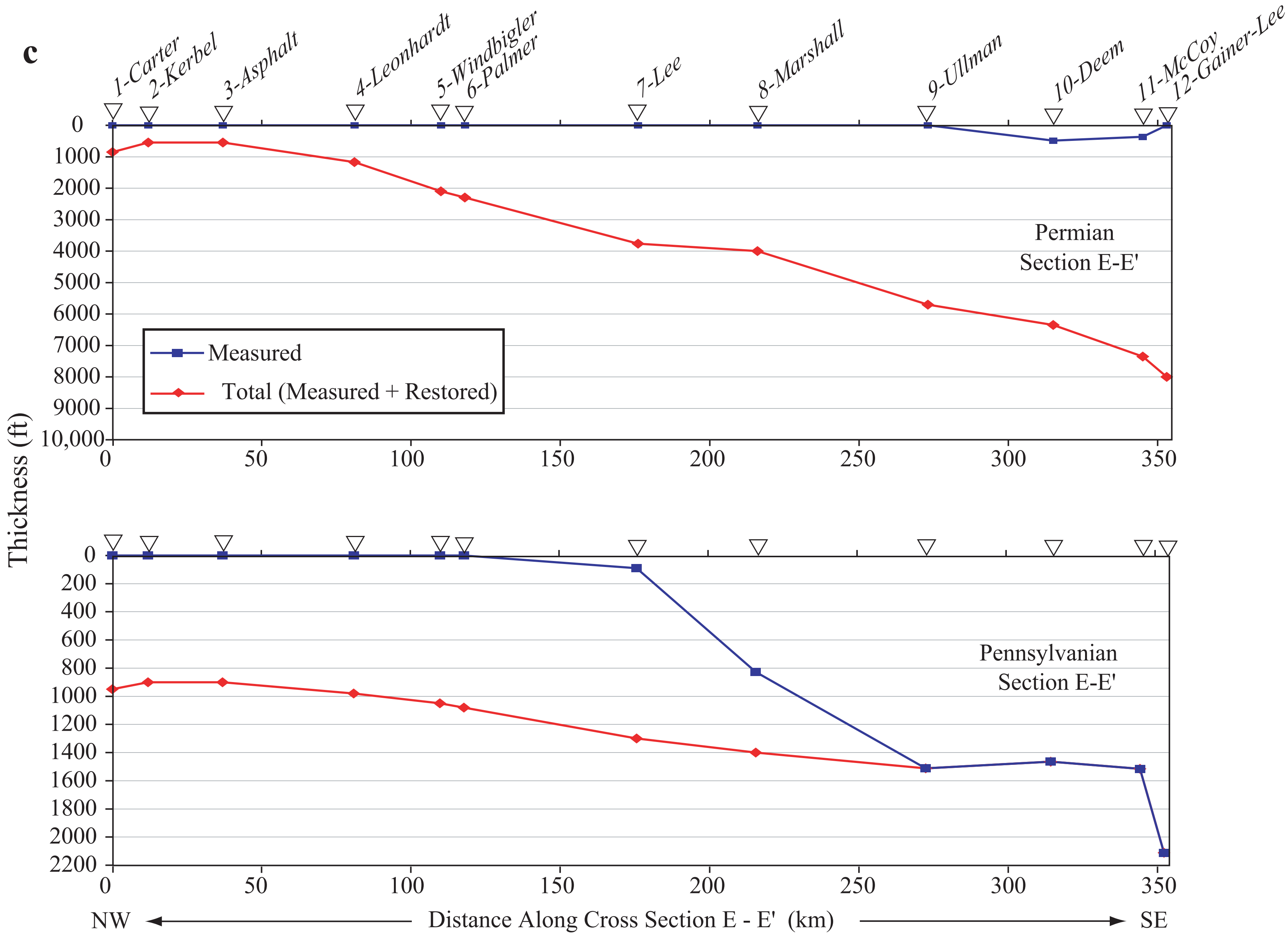
c
1-Carter
2-Kerbel
3-Asphalt
4-Leonhardt
5-Windbigler
6-Palmer
7-Lee
8-Marshall
9-Ullman
10-Deem
11-McCoy
12-Gainer-Lee
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10,000
Measured
Total (Measured + Restored)
Permian
Section E-E'
Thickness (ft)
0
50
100
150
200
250
300
350
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
Pennsylvanian
Section E-E'
NW
Distance Along Cross Section E - E' (km)
SE

Figure 5c.

a

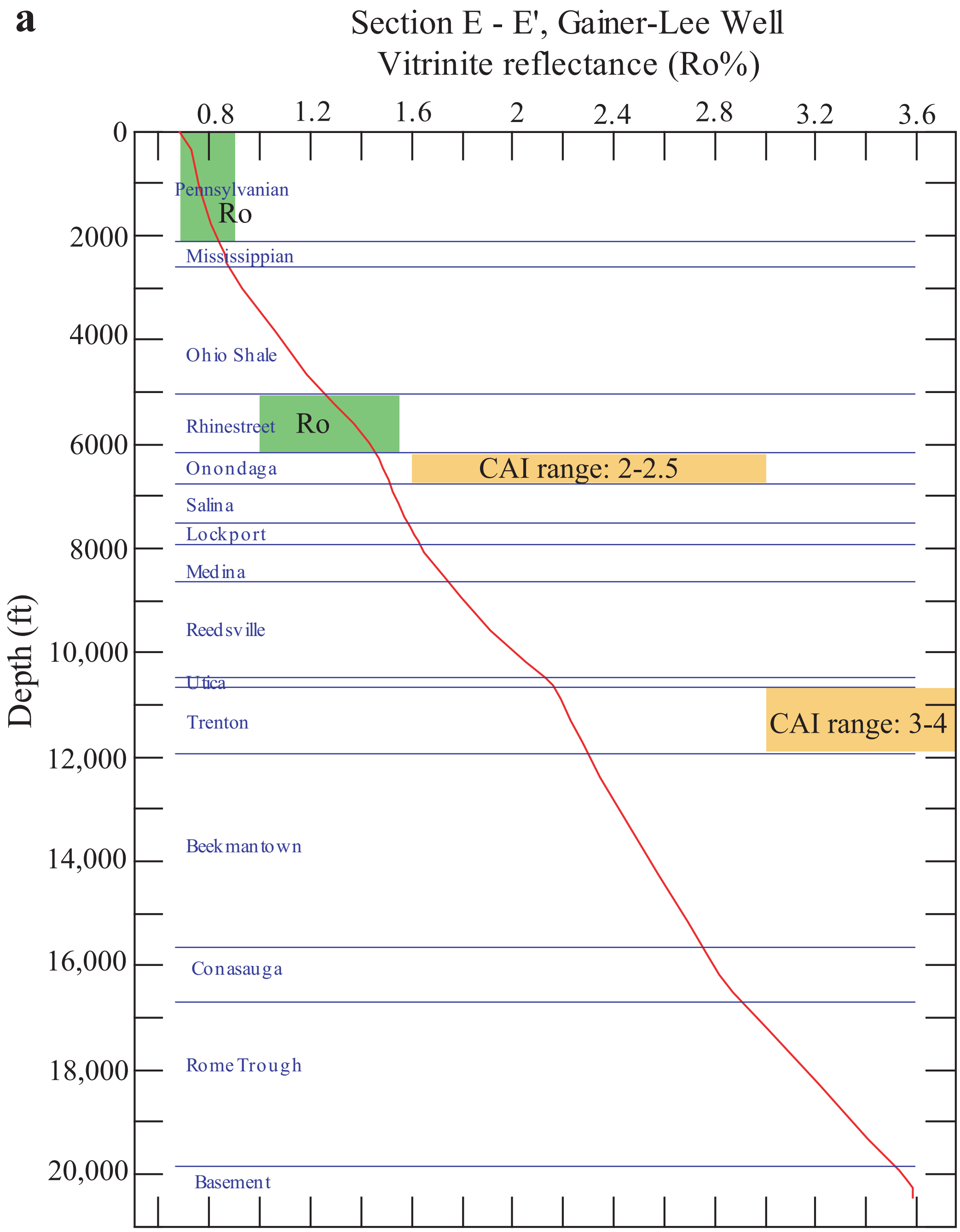

Figure 6. Vitrinite reflectance (Ro%) and conodont CAI data compared with model-calculated Ro-depth profiles for two of the deepest wells in the study, (a) Gainer-Lee well, section E-E', and (b) Svetz well, section C-C'. Ro data are indicated by the green shaded rectangles and conodont data are shown by orange shaded rectangles. Additional, proprietary Ro% data from Pennsylvanian through Silurian strata support the current positions of the modeled Ro-depth results. Model units and their thicknesses are also shown. In model C-C', vitrinite reflectances were not calculated above values of 4.5 Ro%. In (b) Ro values greater than 4.5 are indicated by a dashed line and are extrapolated from lower values.

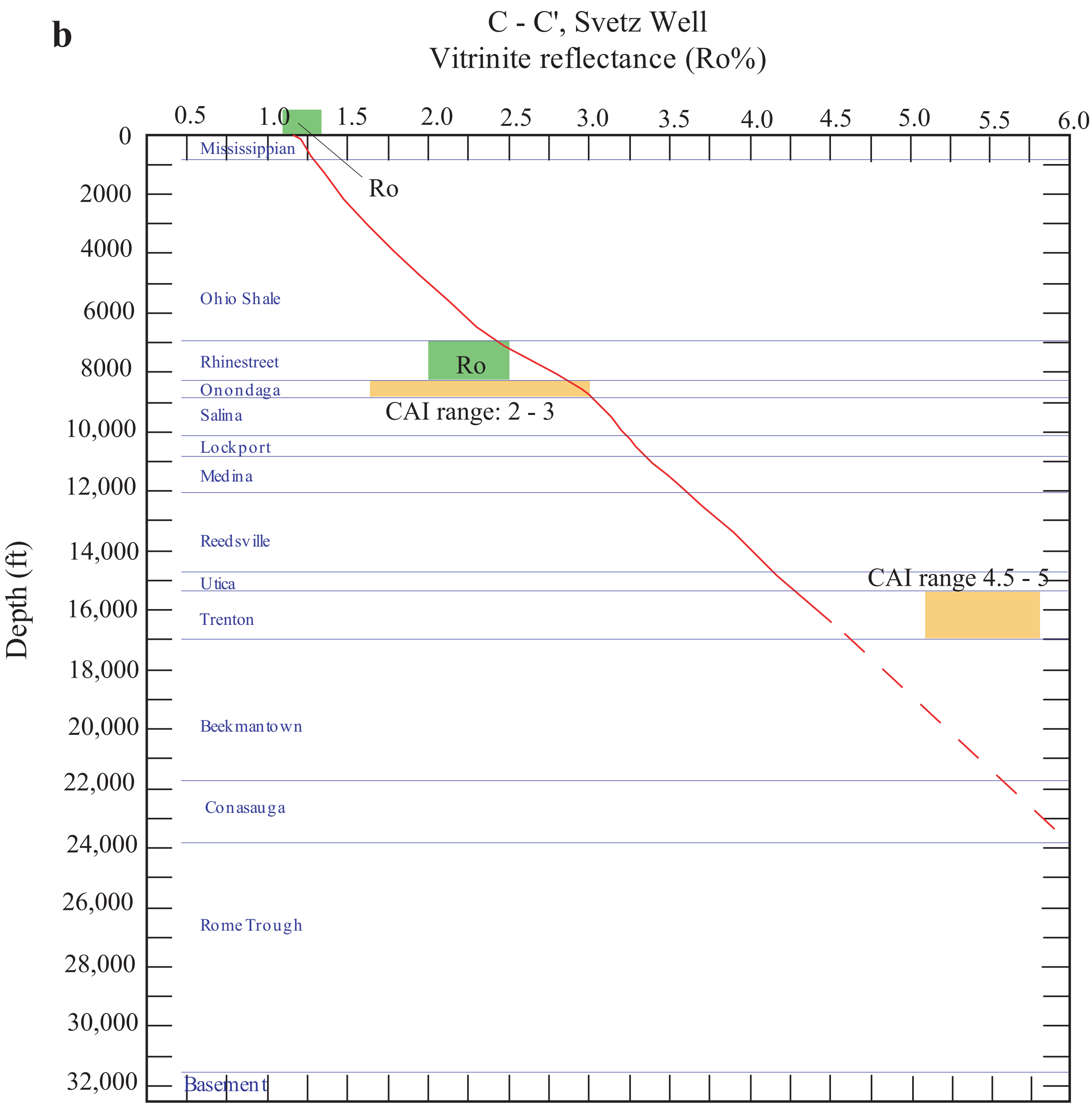
b
C - C', Svetz Well
Vitrinite reflectance (Ro%)
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
Depth (ft)
0
2000
4000
6000
8000
10,000
12,000
14,000
16,000
18,000
20,000
22,000
24,000
26,000
28,000
30,000
32,000
Mississippian
Ro
Ohio Shale
Rhinestreet
Ro
Onondaga
CAI range: 2 - 3
Salina
Lockport
Medina
Reedsville
Utica
CAI range 4.5 - 5
Trenton
Beekmantown
Conasauga
Rome Trough
Basement

Figure 6b.

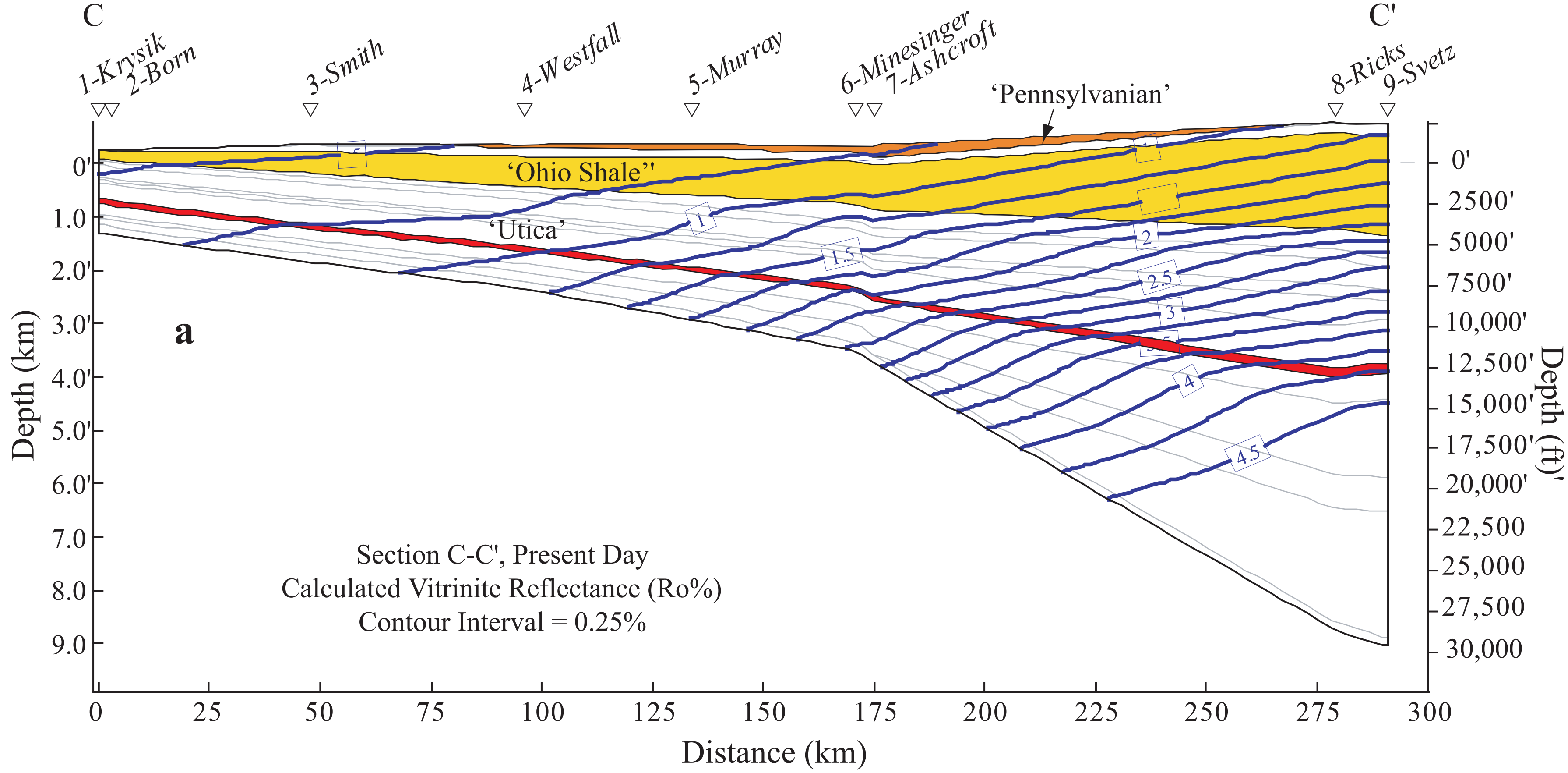

Figure 7. Model-calculated vitrinite reflectance contours (present day) for cross sections C-C' (a), D-D' (b), and E-E' (c). Three model units ('Pennsylvanian', Ohio Shale', and 'Utica') that contain hydrocarbon source rocks are shaded orange, yellow, and red.

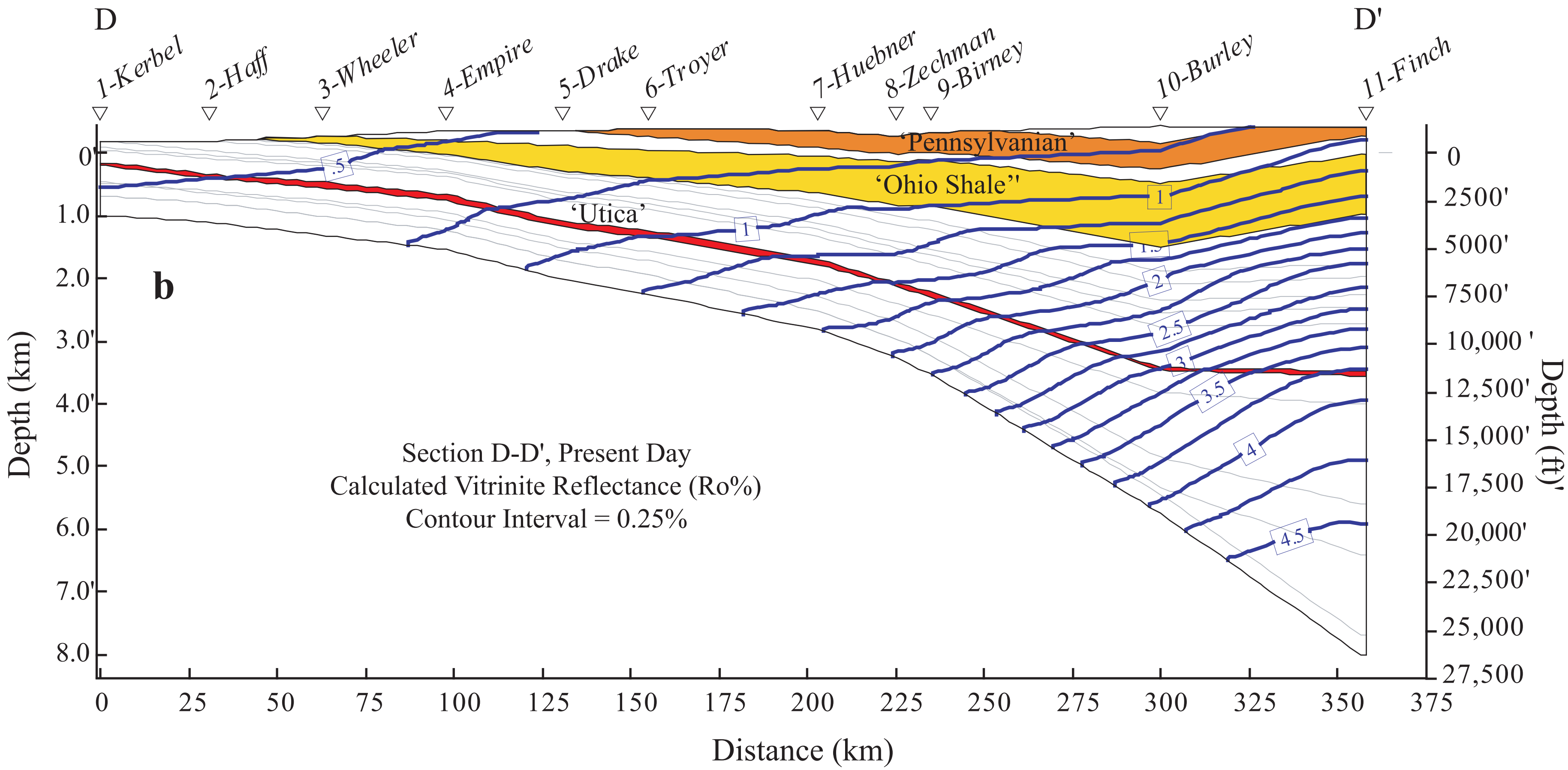
D
D'
1-Kerbel
2-Haff
3-Wheeler
4-Empire
5-Drake
6-Troyer
7-Huebner
8-Zechman
9-Birney
10-Burley
11-Finch
'Pennsylvanian'
'Ohio Shale''
'Utica'
b
.5
1
1.5
2
2.5
3
3.5
4
4.5
Section D-D', Present Day
Calculated Vitrinite Reflectance (Ro%)
Contour Interval = 0.25%
Depth (km)
0'
1.0
2.0
3.0'
4.0'
5.0
6.0
7.0'
8.0
Depth (ft)'
0
2500'
5000'
7500'
10,000 '
12,500'
15,000'
17,500
20,000'
22,500'
25,000
27,500
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
Distance (km)

Figure 7b.

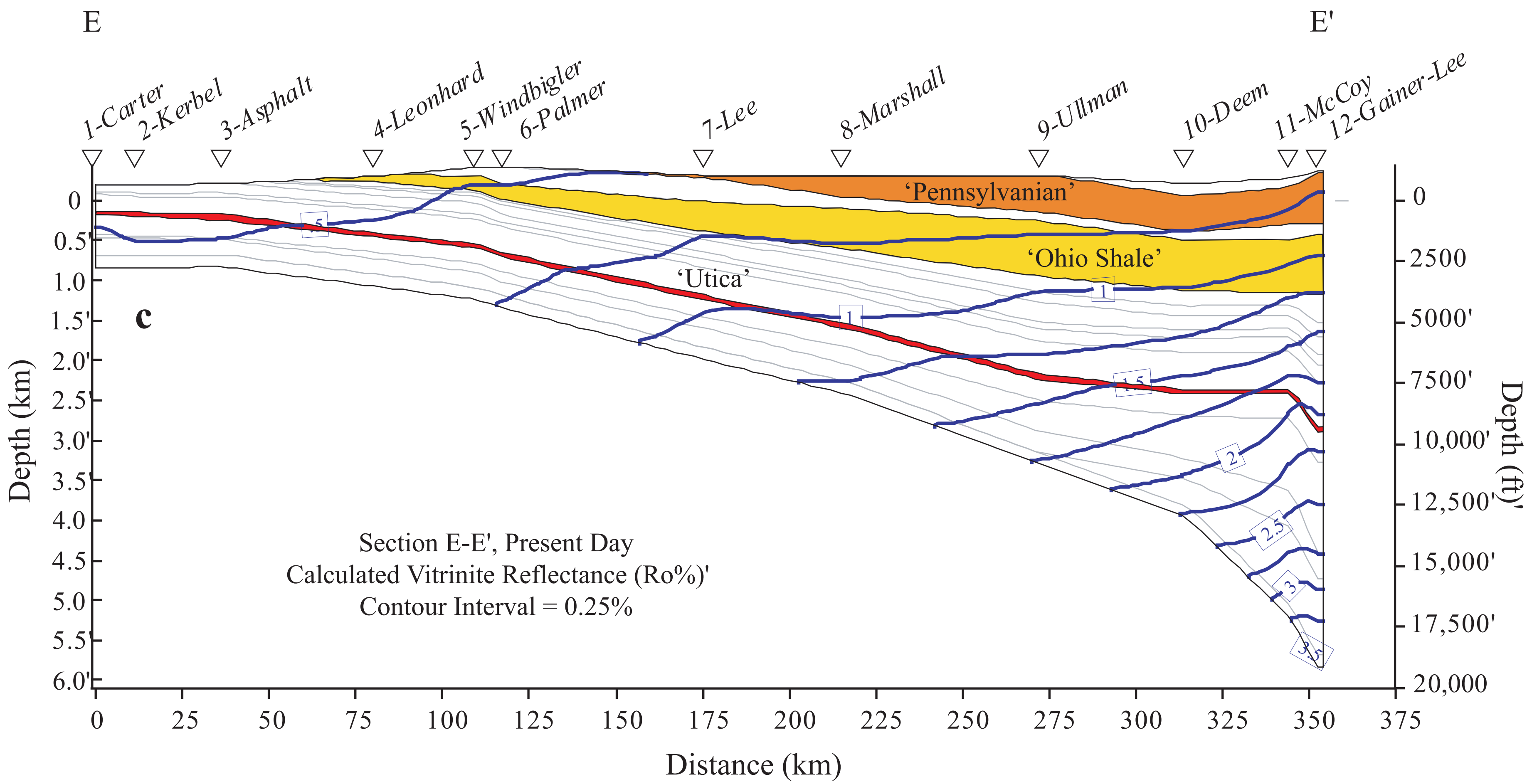
E
E'
1-Carter
2-Kerbel
3-Asphalt
4-Leonhard
5-Windbigler
6-Palmer
7-Lee
8-Marshall
9-Ullman
10-Deem
11-McCoy
12-Gainer-Lee
'Pennsylvanian'
'Ohio Shale'
'Utica'
c
Depth (km)
Depth (ft)'
Distance (km)
Section E-E', Present Day
Calculated Vitrinite Reflectance (Ro%)'
Contour Interval = 0.25%

Figure 7c.

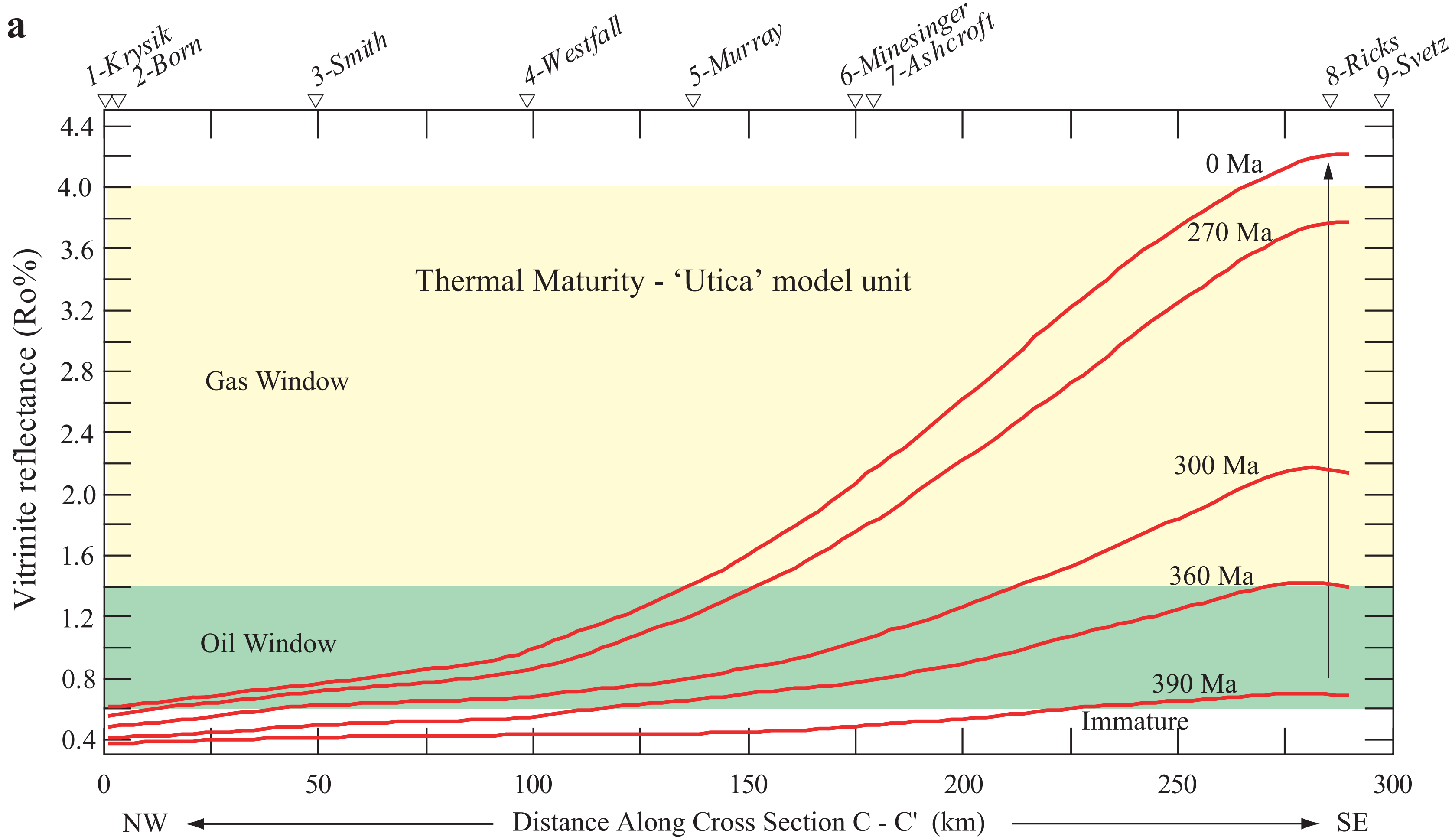

Figure 8. Calculated thermal maturity (vitrinite reflectance, Ro%) profiles for the Orodovician Utica Shale along sections C-C' (a), D-D' (b), and E-E' (c). The profiles were calculated for specific times including present day (0 Ma), maximum burial (270 Ma), and earlier times selected to shown the evolution of thermal maturation through time. The approximate top of the gas window is indicated by the top of the yellow shaded region (see text for discussion).

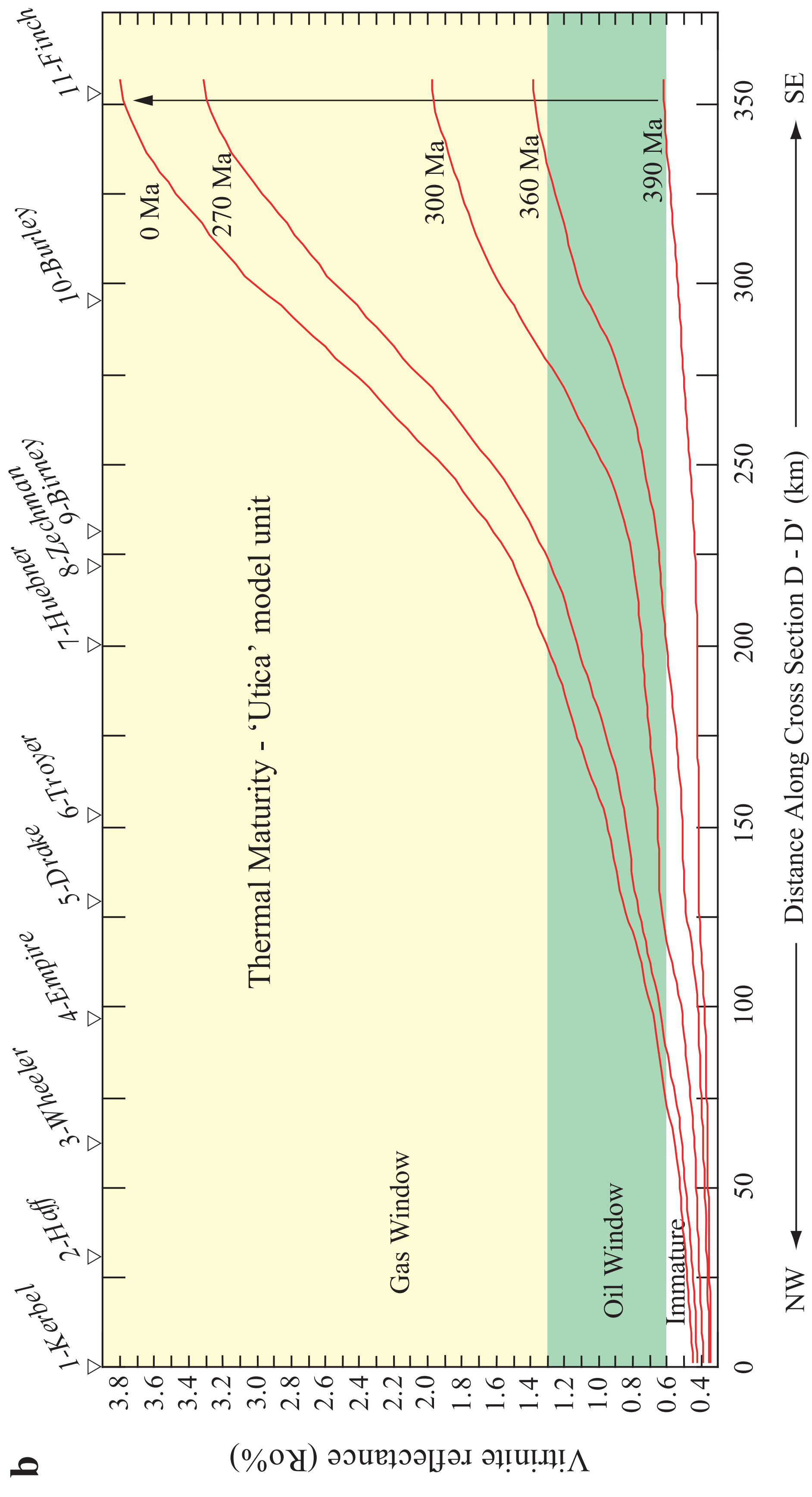
b
Vitrinite reflectance (Ro%)
Thermal Maturity - 'Utica' model unit
Gas Window
Oil Window
Immature
0 Ma
270 Ma
300 Ma
360 Ma
390 Ma
1-Kerbel
2-Hoff
3-Wheeler
4-Empire
5-Drake
6-Troyer
7-Huebner
8-Zechman
9-Birmey
10-Burley
11-Finch
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
50
100
150
200
250
300
350
NW
SE
Distance Along Cross Section D - D' (km)

Figure 8b.

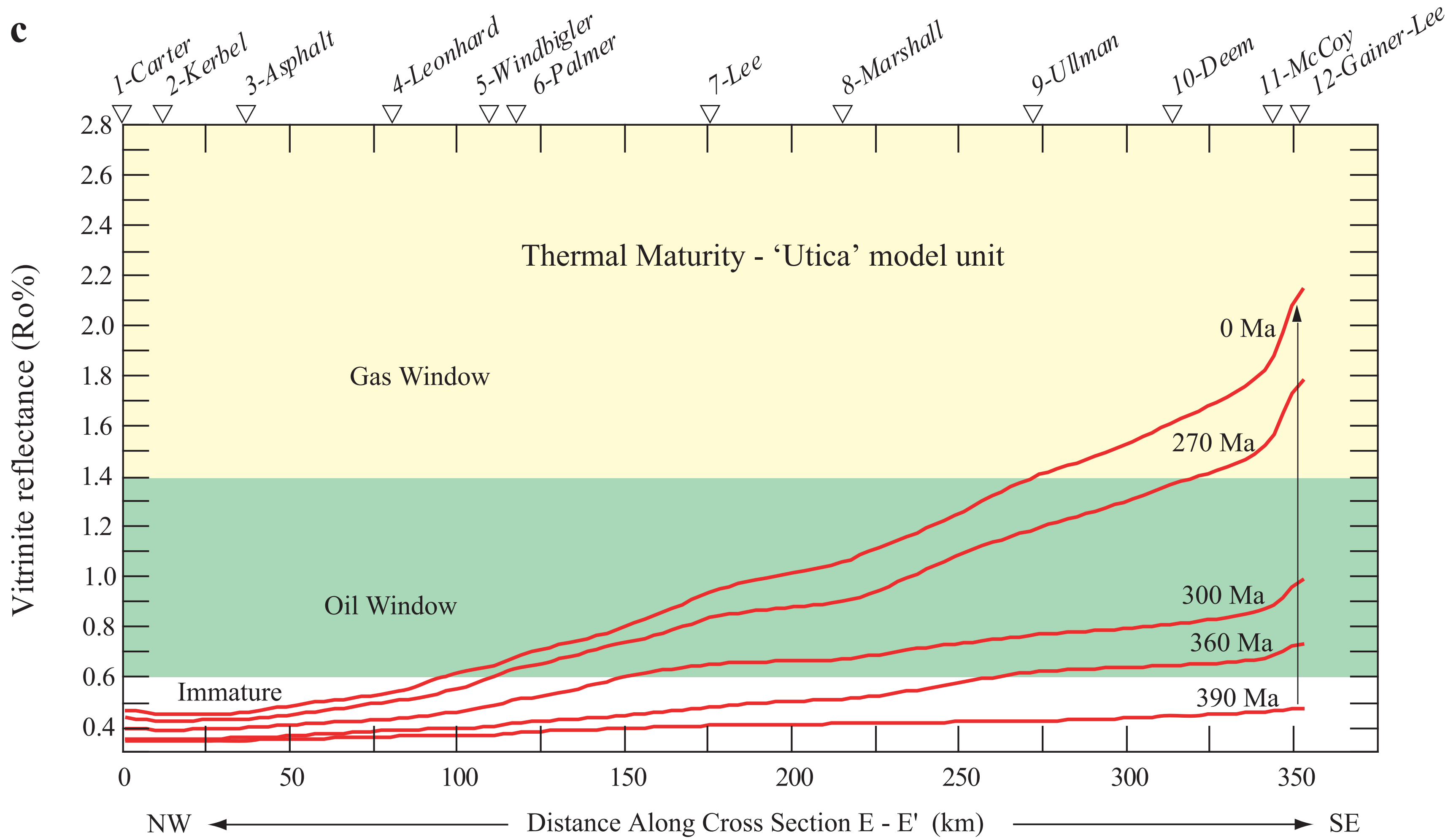
c
1-Carter
2-Kerbel
3-Asphalt
4-Leonhard
5-Windbigler
6-Palmer
7-Lee
8-Marshall
9-Ullman
10-Deem
11-McCoy
12-Gainer-Lee
Thermal Maturity - 'Utica' model unit
Gas Window
Oil Window
Immature
0 Ma
270 Ma
300 Ma
360 Ma
390 Ma
Vitrinite reflectance (Ro%)
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
50
100
150
200
250
300
350
NW
Distance Along Cross Section E - E' (km)
SE

Figure 8c.

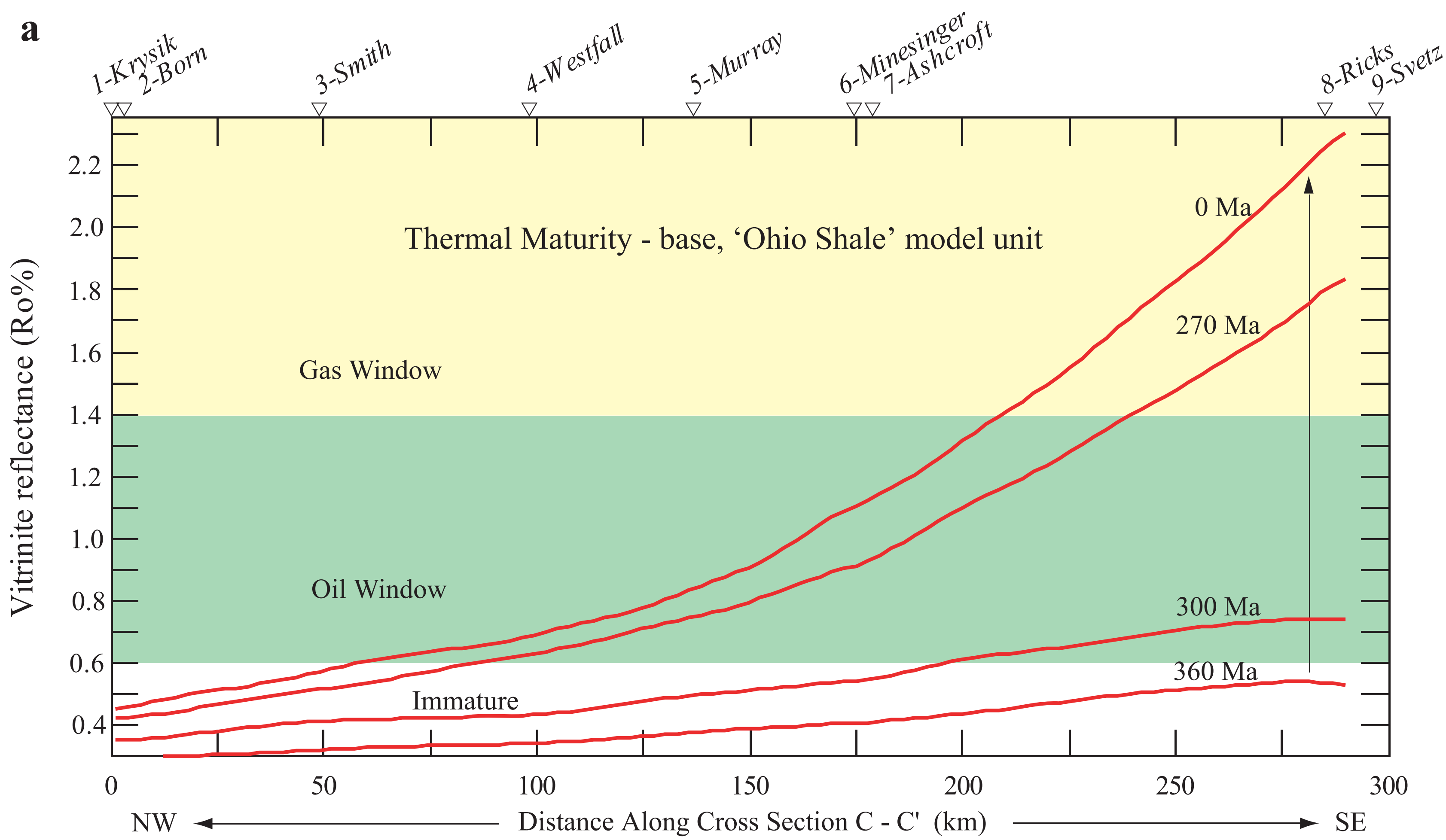

Figure 9. Calculated thermal maturity (vitrinite reflectance, Ro%) profiles for the base of the Devonian 'Ohio Shale' model unit along sections C-C' (a), D-D' (b), and E-E' (c). The profiles were calculated for specific times including present day (0 Ma), maximum burial (270 Ma), and earlier times selected to shown the evolution of thermal maturation through time.

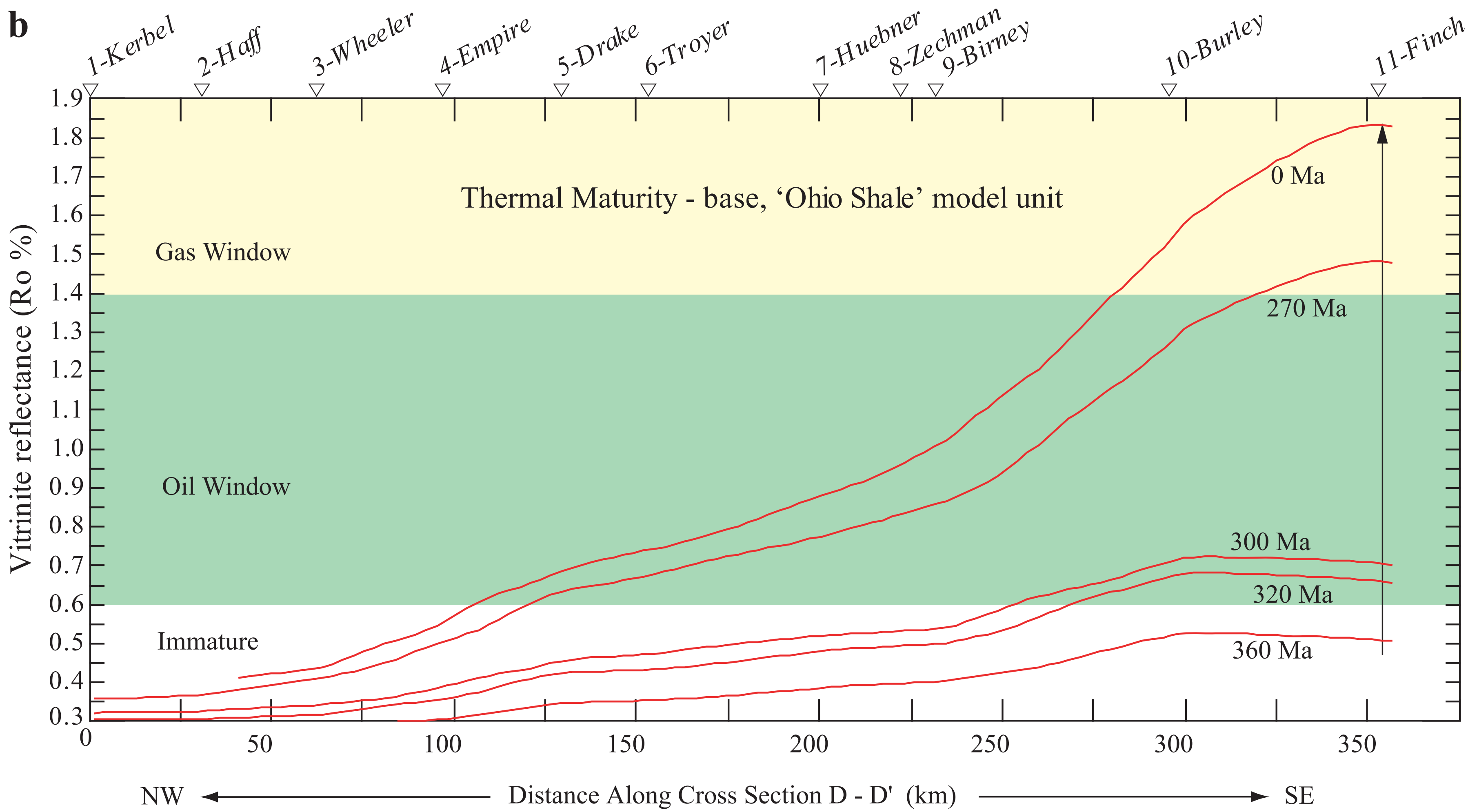
b
1-Kerbel
2-Haff
3-Wheeler
4-Empire
5-Drake
6-Troyer
7-Huebner
8-Zechman
9-Birney
10-Burley
11-Finch
Thermal Maturity - base, ‘Ohio Shale’ model unit
Gas Window
Oil Window
Immature
0 Ma
270 Ma
300 Ma
320 Ma
360 Ma
Vitrinite reflectance (Ro %)
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
50
100
150
200
250
300
350
NW
Distance Along Cross Section D - D' (km)
SE

Figure 9b.

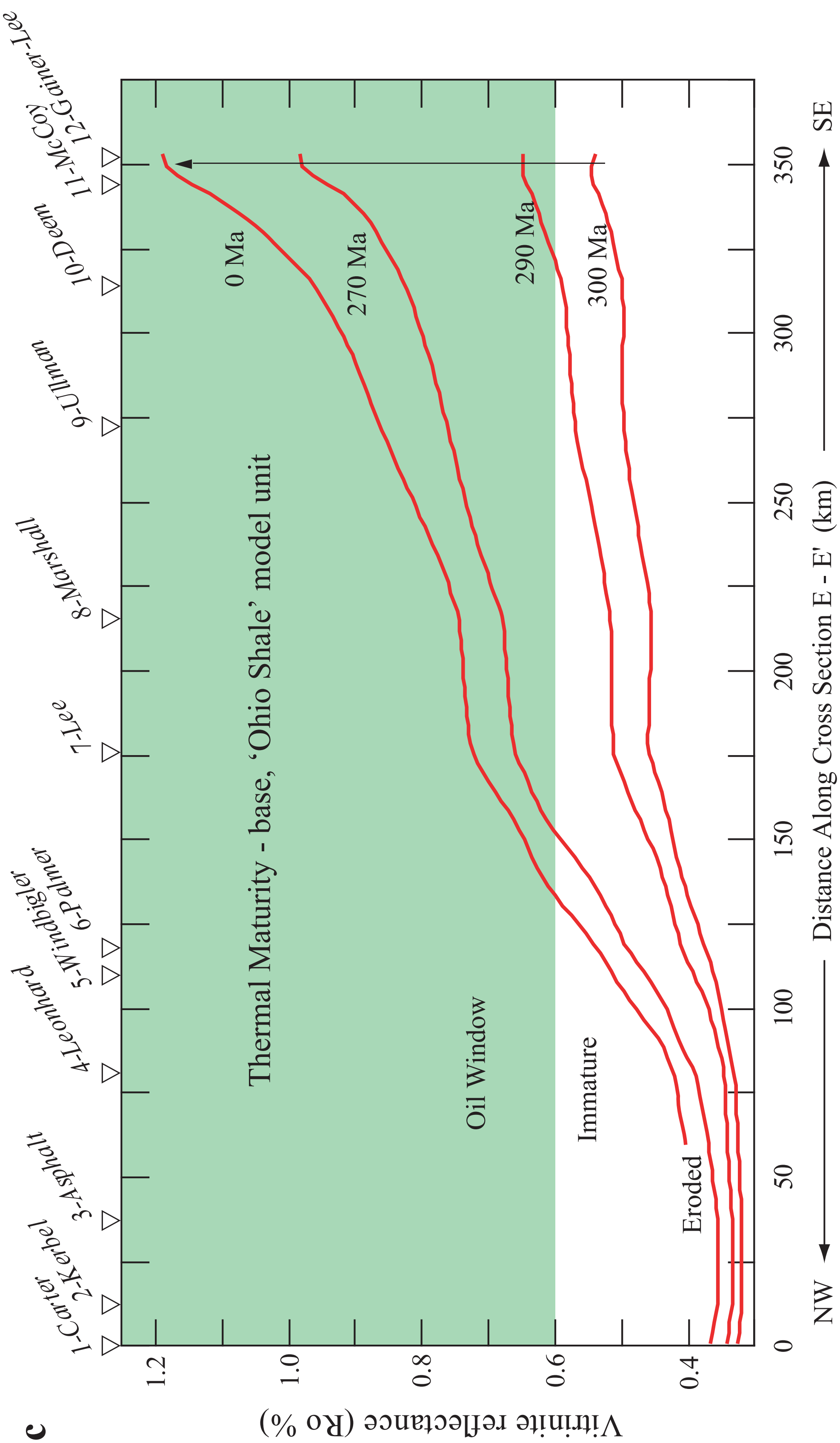
c
Vitrinite reflectance (Ro %)
Thermal Maturity - base, ‘Ohio Shale’ model unit
Oil Window
Immature
Eroded
0 Ma
270 Ma
290 Ma
300 Ma
1-Carter
2-Kerbel
3-Asphalt
4-Leonhard
5-Windbigler
6-Palmer
7-Lee
8-Marshall
9-Ullman
10-Deem
11-McCoy
12-Gainer-Lee
1.2
1.0
0.8
0.6
0.4
0
50
100
150
200
250
300
350
NW
SE
Distance Along Cross Section E - E’ (km)

Figure 9c.

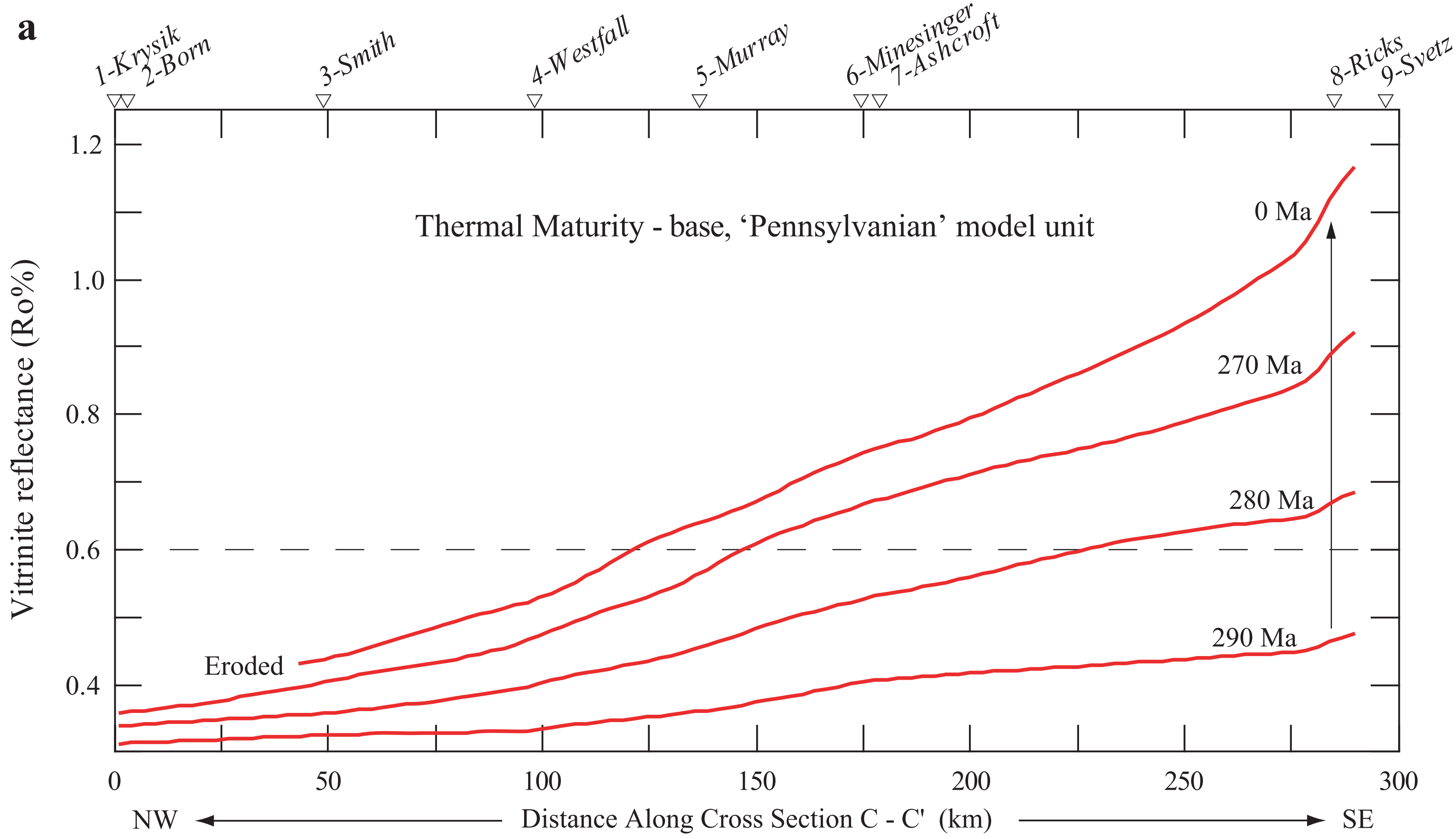

Figure 10. Calculated thermal maturity (vitrinite reflectance, Ro%) profiles for the base of the Pennsylvanian model unit along sections C-C' (a), D-D' (b), and E-E' (c). The profiles were calculated for specific times including present day (0 Ma), maximum burial (270 Ma), and earlier times selected to shown the evolution of thermal maturation through time.

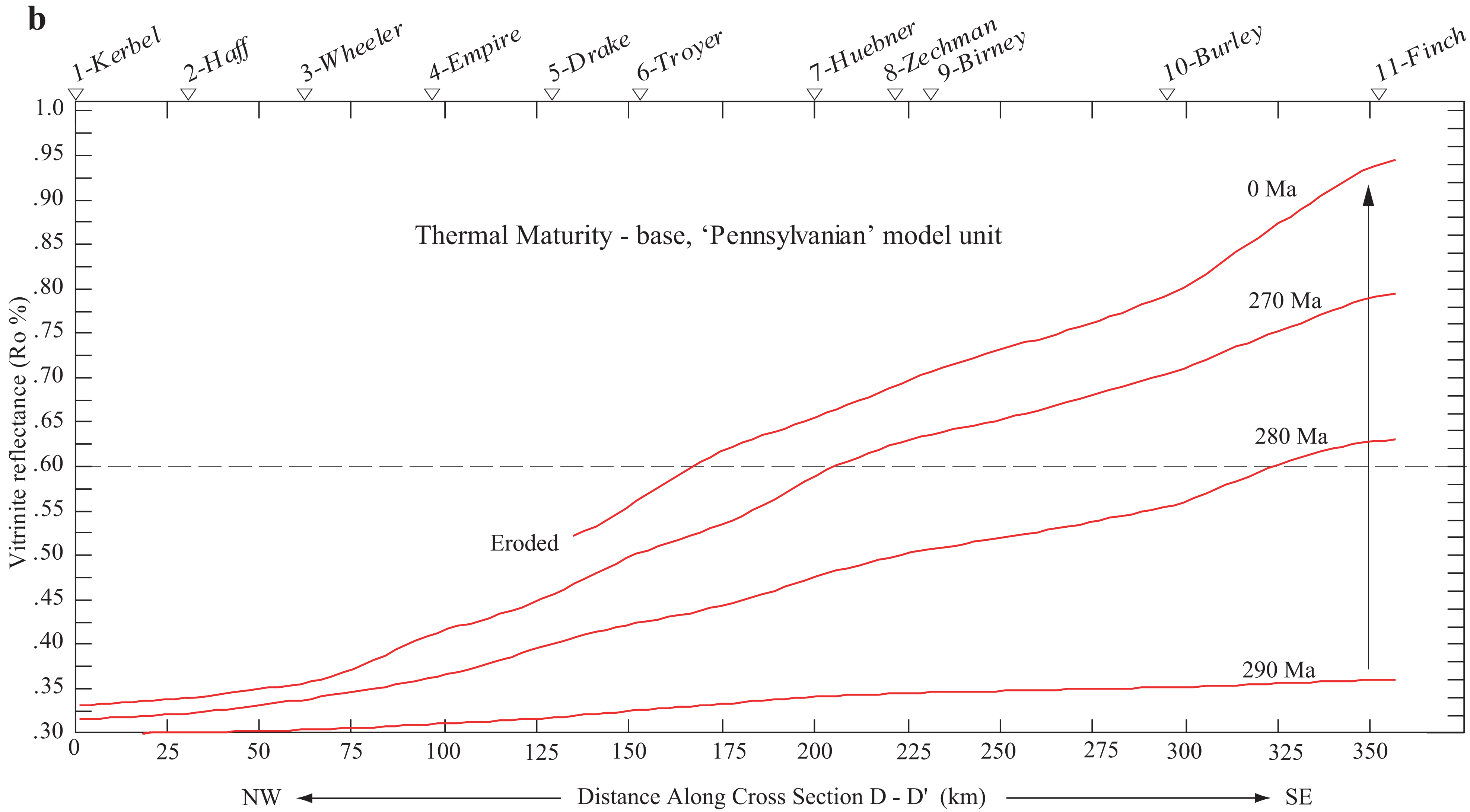
b
1-Kerbel
2-Haff
3-Wheeler
4-Empire
5-Drake
6-Troyer
7-Huebner
8-Zechman
9-Birney
10-Burley
11-Finch
Thermal Maturity - base, 'Pennsylvanian' model unit
0 Ma
270 Ma
280 Ma
290 Ma
Eroded
Vitrinite reflectance (Ro %)
1.0
.95
.90
.85
.80
.75
.70
.65
.60
.55
.50
.45
.40
.35
.30
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
NW
Distance Along Cross Section D - D' (km)
SE

Figure 10b.

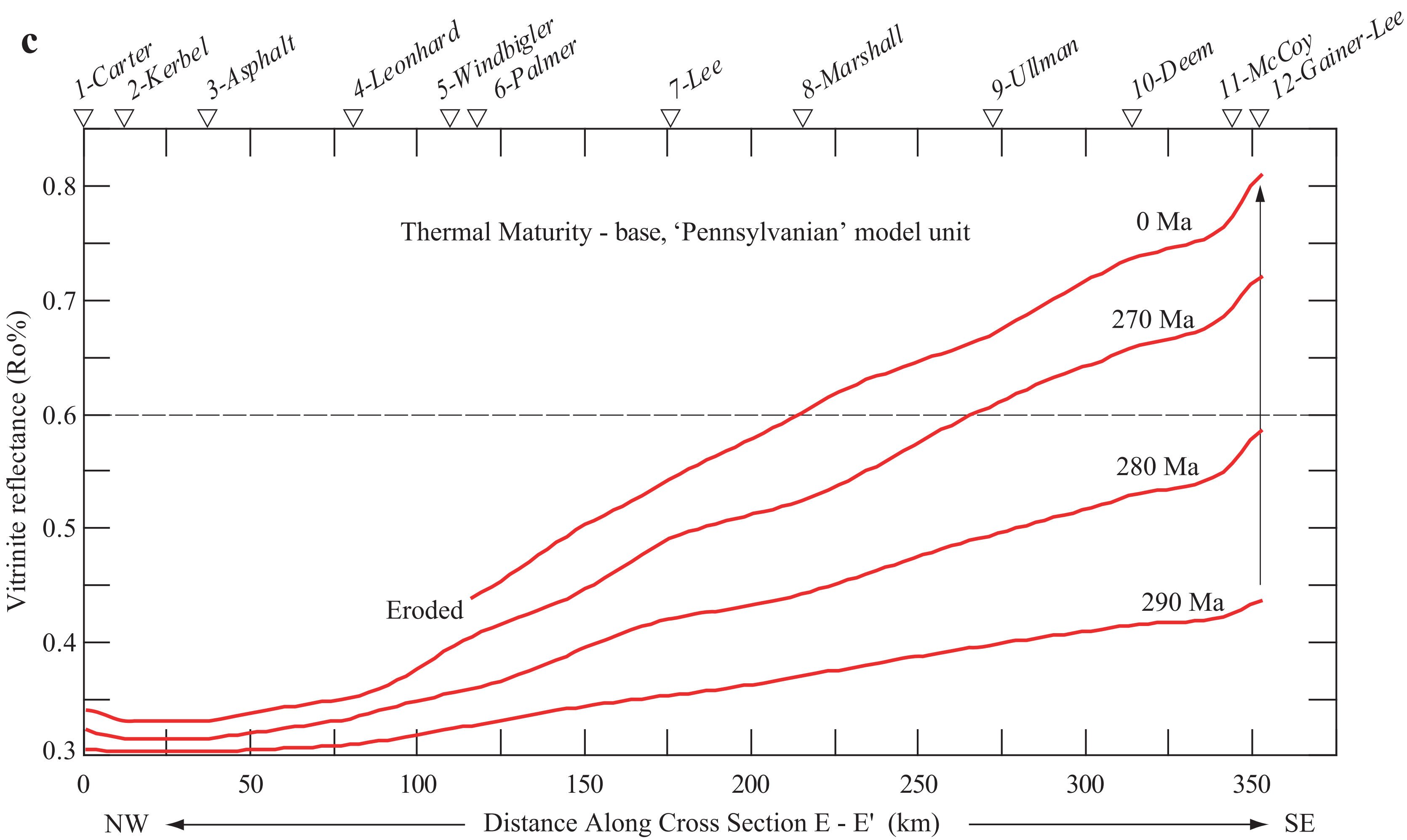
c
1-Carter
2-Kerbel
3-Asphalt
4-Leonhard
5-Windbigler
6-Palmer
7-Lee
8-Marshall
9-Ullman
10-Deem
11-McCoy
12-Gainer-Lee
Thermal Maturity - base, 'Pennsylvanian' model unit
0 Ma
270 Ma
280 Ma
290 Ma
Eroded
Vitrinite reflectance (Ro%)
0.8
0.7
0.6
0.5
0.4
0.3
0
50
100
150
200
250
300
350
NW
Distance Along Cross Section E - E' (km)
SE

Figure 10c.