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Burial and exhumation history of Pennsylvanian strata, central Appalachian basin: an integrated study

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ABSTRACT

An inferred burial and exhumation history of Pennsylvanian strata in the central Appalachian foreland basin is constrained by integrating palaeothermometers, geochronometers and estimated palaeogeothermal gradients. Vitrinite reflectance data and fluid inclusion homogenization temperatures indicate that burial of Lower and Upper Pennsylvanian strata of the Appalachian Plateau in West Virginia exceeded $\sim$4.4 km during the late Permian and occurred at a rate of $\sim$100 m Myr^{-1}. Exhumation rates of $\sim$10 m Myr^{-1} from the late Permian to the early Cretaceous are constrained using maximum burial conditions and published apatite fission track (AFT) ages. AFT and radiogenic helium ages indicate exhumation rates of $\sim$30–50 m Myr^{-1} from the early to late Cretaceous. Radiogenic helium dates and present day sampling depths indicate that exhumation rates from the late Cretaceous to present were $\sim$25 m Myr^{-1}. Exhumation rates for Upper and Lower Pennsylvanian strata within the Appalachian Plateau are remarkably similar. Early slow exhumation was possibly driven primarily by isostatic rebound associated with Triassic rifting. The later, more rapid exhumation can be attributed to thermal expansion followed by lithospheric flexure related to sediment loading along the passive margin.

INTRODUCTION

Combining various geothermometers can be a valuable means to address many important geologic problems including thermal calibration of subsidence histories of sedimentary basins, resolution of inversion histories of foreland basins, and understanding the post-orogenic evolution of ancient mountain systems like the Appalachians. Foreland basins present a unique opportunity to study the geodynamic behaviour of the upper crust including orogenic evolution because mountain belts and their forelands are dynamically connected. In addition, reconstructing the burial and exhumation histories of foreland basins filled with nearly flat-lying sedimentary rocks using palaeothermometers and thermochronometers is more effective than for igneous and metamorphic terrains because horizontal strata are ideal for resolving vertical paths through the upper crust.

Reconstructions of thermal and burial histories of ancient sedimentary basins traditionally have been based on vitrinite reflectance (e.g. Chyi *et al.*, 1987; Hower & Rimmer, 1991; Zhang & Davis, 1993), fluid inclusion microthermometry (e.g. Burruss, 1989; Goldstein & Reynolds, 1994; Walderhaug, 1994; Wojcik *et al.*, 1994), or a combination of both methods (e.g. Barker & Goldstein, 1990; Tobin & Claxton, 2000). More recently, exhumation histories of sedimentary basins have been constrained using thermochronology. Apatite fission track (AFT) dating is the most widely used thermochronologic technique to evaluate the exhumation of sedimentary rocks (e.g. Naeser *et al.*, 1989; Roden, 1990; Blackmer *et al.*, 1994; Boettcher & Milliken, 1994) and can be integrated with vitrinite reflectance for more comprehensive reconstructions of exhumation history (e.g. Feinstein *et al.*, 1989; Arne & Zentilli, 1994; Kamp *et al.*, 1996; O'Sullivan, 1999). Integrating palaeothermometers and thermochronometers is desirable because: (1) palaeothermometers help to justify the use of thermochronometers by predicting whether or not closure temperatures (T_c) were exceeded (Arne & Zentilli, 1994), and (2) tracking the complete thermal evolution of sedimentary basins can be useful for studies involving hydrocarbon generation, basin analysis, diagenesis and geomorphology.

Recent studies of helium diffusion in apatite have validated the use of the (U–Th)/He system for low-temperature thermochronology (Wolf *et al.*, 1996; Farley, 2000; Ehlers & Farley, 2003). Traditionally, radiogenic helium dating of apatite has been used in diverse geologic settings to resolve cooling histories related to erosional exhumation and tectonic uplift and denudation (e.g. House *et al.*, 1998; Spotila *et al.*, 1998; Reiners *et al.*, 2000; Kirby *et al.*, 2002). This method has been applied less frequently to basin analysis, although it can be an effective tool for constraining the latest exhumation history of sedimentary basins (Crowhurst *et al.*, 2002; House *et al.*, 2002).

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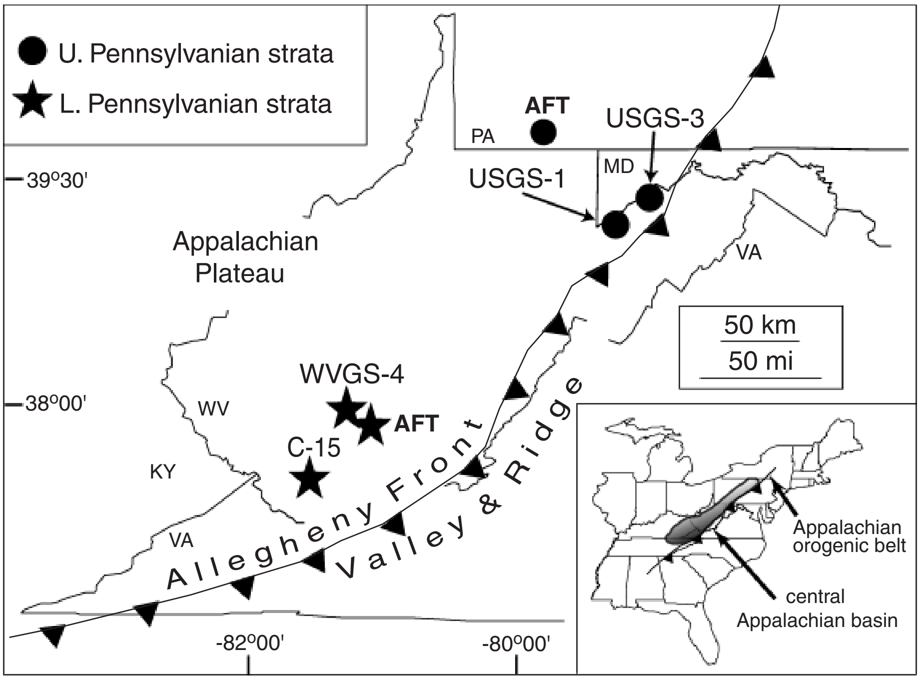

Fig. 1. Map showing the location of borehole cores and published apatite fission track ages used for this study in relation to the Alleghany Thrust Front. Borehole names are labelled.

The purpose of this study is to use an integrated approach to evaluate the thermal, burial and inversion history of Pennsylvanian rocks in the Appalachian foreland basin (Fig. 1). Specific goals are to (1) investigate the post-orogenic evolution of an ancient foreland basin, (2) demonstrate the applicability of combined techniques to evaluate the burial and exhumation history of the basin and (3) establish a thermal framework from deposition to deep burial that can be applied to sandstone diagenesis. Sandstones and associated strata in the Appalachian foreland basin are ideally suited to apply these techniques. Fluid inclusions in quartz cements and vitrinite extracted from stratigraphically adjacent coal and shale provide the means to study the burial history, whereas AFT and (U–Th/He) data from detrital apatite grains recovered from the sandstones constrain exhumation. A secondary contribution of this study supplements our current understanding of the post-Alleghanian evolution of the central Appalachian orogenic belt (e.g. Beaumont *et al.*, 1987; Slingerland & Furlong, 1989).

GEOLOGIC SETTING

The Appalachian foreland basin formed in response to three orogenic events; the final episode of subsidence was caused by the Alleghanian orogeny (Quinlan & Beaumont, 1984). This orogeny produced highlands to the east–southeast of the basin that served as an important source of sediment during the late Palaeozoic. Basin subsidence dynamics varied during each of the orogenies and the basin was relatively wide and shallow during the Alleghanian event (Tankard, 1986). Major causes of subsidence during the late Palaeozoic were related to tectonic flexure of the lithosphere and sediment loading associated with the rejuvenation of the Appalachian foreland basin. Basin geometry was primarily controlled by the long-term rheological response of the lithosphere to tectonic loading and a general thickening of the crust, which is typical for foreland basins (e.g. Dickinson, 1974; Allen *et al.*, 1986, 1991; Klein, 1991; Sinclair, 1997; Castle, 2001), although short-term responses to tectonic loading have also been proposed for the Appalachian basin (Tankard, 1986).

Various stratigraphic markers subdivide the late Phanerozoic stratigraphic record. Coals and unconformities have been especially useful for regional correlations of Carboniferous strata in the central Appalachian basin. Upper and lower Pennsylvanian sections, Glenshaw and New River Formations, respectively, used in this study are identified and dated by such markers. The New River Formation in southern West Virginia consists predominantly of nonmarine strata that filled the basin following development of the early Pennsylvanian unconformity (Korus, 2002). The Upper Pennsylvanian Glenshaw Formation (lower Conemaugh Group) in northeastern West Virginia and western Maryland also consists predominantly of continental siliciclastic rocks (Belt & Lyons, 1989). Both of the study intervals contain quartz and lithic arenites as well as carbonaceous rocks, which, in combination, are ideal for palaeothermometric and thermochronologic studies (Fig. 2).

Upper Mississippian and Pennsylvanian basin fill is primarily composed of siliciclastic sedimentary rocks including sandstone, mudstone, conglomerate (rare), bituminous

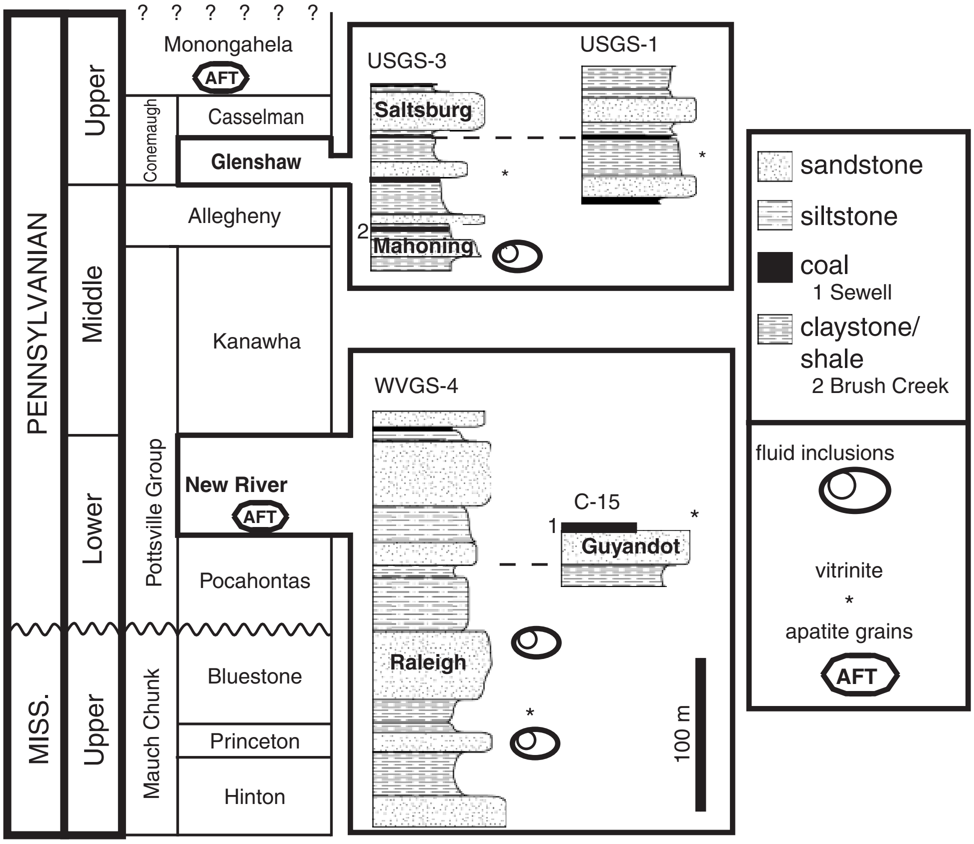

Fig. 2. Stratigraphy of Upper Mississippian and Pennsylvanian strata. Study intervals are represented on lithostratigraphic columns based on borehole cores. Selected sandstones and organic-rich intervals are labeled. Apatite grains for radiogenic helium dating were collected from labeled sandstones. Published AFT dates are reported from the New River and Monongahela Formations. Stratigraphic intervals yielding fluid inclusion and vitrinite reflectance results are labeled accordingly.

coal seams and subordinate limestone. Major sandstone bodies in the Upper Mississippian Mauch Chunk Formation, Lower Pennsylvanian New River Formation and Upper Pennsylvanian Glenshaw Formation are interpreted as incised-valley fill deposits (Belt & Lyons, 1989; Miller & Eriksson, 2000; Martino & Belt, 2001). Various stratigraphic markers subdivide the late Phanerozoic stratigraphic record. The Upper Mississippian Mauch Chunk Group is bound by the Stony Gap sandstone (base) and marine Bramwell Member (top), which marks the top of the Mississippian system in the central Appalachian basin (Miller & Eriksson, 2000). Coals and unconformities have been especially useful for regional correlations of Pennsylvanian strata in the central Appalachian basin. The Lower Pennsylvanian New River Formation in southern West Virginia consists predominantly of nonmarine strata that filled the basin following the development of the early Pennsylvanian unconformity (Korus, 2002). The Upper Pennsylvanian Glenshaw Formation (lower Conemaugh Group) in northeastern West Virginia and western Maryland also consists predominantly of siliciclastic units and subordinate carbonate rocks (caliche and minor marine units; Belt & Lyons, 1989).

Carboniferous sandstones in the central Appalachian basin vary in composition between quartzose and lithic with variable amounts of feldspar. In general, lower Pennsylvanian sandstones are quartzose whereas those from the upper Pennsylvanian are more lithic (Houseknecht, 1980; Donaldson *et al.*, 1985; McDowell, 1986). However, lithic sandstones are locally developed in the lower Pennsylvanian of West Virginia whereas in southwestern Virginia correlative sandstones contain significant concentrations of feldspar (Davis & Ehrlich, 1974). Metamorphic rock fragments dominate the lithic fraction. Most workers relate the sandstone compositions to recycling of Appalachian orogenic provenances (Houseknecht, 1980; Dickinson *et al.*, 1983; Donaldson *et al.*, 1985; McDowell, 1986), although cratonal sources have been inferred for correlative quartzose sandstones in Pennsylvania (Robinson & Prave, 1995). Moreover, Archean-age zircons from Pennsylvanian sandstones in the central Appalachian basin indicate sediment derivation from the Superior Province (Eriksson *et al.*, 2004). The higher concentration of feldspar in the southern part of our study area (southwestern Virginia) is attributed to dissection of the orogen down to a plutonic source (Davis & Ehrlich, 1974).

METHODS

Data were collected from core-sampled sandstones and organic-rich strata from four different locations and two stratigraphic intervals within the central Appalachian basin (Figs 1 and 2). Samples were collected adjacent to the Allegheny structural front, which divides sub-horizontal strata of the Appalachian Plateau from folded Palaeozoic sedimentary rocks of the Valley and Ridge province of the Appalachian fold thrust belt. Two additional locations were selected well within the Appalachian Plateau (Fig. 1) to evaluate potential differences in the burial and exhumation histories between these sites. Core samples were targeted to ensure that weathering had not significantly altered quartz overgrowths and apatite grains. Quartz-rich intervals were sampled to maximize the probability of finding primary fluid inclusions within quartz overgrowths, whereas lithic-rich sandstones were selected for potentially high apatite yield. Lower Pennsylvanian samples were recovered from 300 and 640 m above sea level (300 and 40 m below the surface, respectively) in the Appalachian Plateau of south-central West Virginia. Upper Pennsylvanian samples are from 460 and 370 m above sea level (180 and 270 m below the surface, respectively) in northeastern West Virginia (Figs 1 and 2). Spatial separation of the Upper and Lower Pennsylvanian samples was necessary because Upper Pennsylvanian strata are not present in southern West Virginia and Lower Pennsylvanian strata was not intercepted during drilling in western Maryland.

Palaeothermometric data were collected using standard techniques for fluid inclusion and vitrinite reflectance palaeothermometry. Vitrinite was extracted from shale and coal sampled from USGS-3, USGS-1, WVGS-4 and C-15 (Fig. 2), mounted in epoxy and polished. Reflectance measurements were made using a McCrone MPA1 photometer. Mean maximum reflectance values were recorded and calibrated using glass standards. Vitrinite reflectance temperature estimates were determined using the thermal model SIMPLE-R_o (Suzuki *et al.*, 1993). A heating rate of $\sim 2\,^{\circ}\mathrm{C\,Myr^{-1}}$ was used for thermal reconstructions and was estimated based on sedimentation rates and an average geothermal gradient for the region (Hulver, 1997). Homogenization temperatures (T_h's) of primary fluid inclusions found within quartz overgrowths were measured with a Linkam THMSG 600 heating and cooling stage following techniques outlined by Goldstein & Reynolds (1994). We assume that T_h is approximately equal to the trapping temperature (T_t) because of the abundance of methane in Carboniferous strata in the central Appalachian basin. The minimum concentration of methane required for $T_h = T_t$ is relatively low (4450 p.p.m.). This concentration is the minimum value required to increase the methane bubble point curve to the pressure along the hydrostatic gradient at the measured homogenization temperature.

Apatite grains used for (U–Th)/He dating were hand selected from crushed sandstone ($\sim$10 grains per age determination). Radiogenic helium was outgassed at 920 °C and measured by ^{3}He spike using a quadrupole mass spectrometer at Virginia Tech, following procedures of Wolf *et al.* (1996), Farley (2000) and Spotila *et al.* (2004). Helium line calibration was verified using Durango fluorapatite age determinations. Uranium and thorium concentrations of dissolved apatite grains were measured using ICP-MS at Yale University. Individual age determinations for samples should have uncertainties of $\sim$10% ($2-\sigma$), based on reproducibility of Durango age measurements (30.5 ± 3 Ma, $n = 25$). Because of the small grain sizes of pristine apatites available in our samples and the higher uncertainty in measuring alpha ejection correction factors for small grain radii (Farley *et al.*, 1996), actual error bars for some samples may be higher than 10%. Reported uncertainties ($1-\sigma$) for average helium ages are given as observed standard deviation divided by the square root of the number of replicates (Table 2). Fission-track ages were not measured in this study. Published AFT ages are limited for the central Appalachian basin, although a few ages are available for samples from comparable locations and stratigraphic intervals selected for this study (Figs 1 and 2; Roden *et al.*, 1992; Blackmer *et al.*, 1994).

RESULTS

Fluid inclusion homogenization and vitrinite reflectance temperatures are comparable (Table 1). Therefore, we conclude that these methods serve as reasonable proxies for burial conditions. Homogenization temperatures for lower Pennsylvanian samples range from 143 to 163 °C (mean = 150 °C) and temperatures derived from reflectance values range from 139 to 147 °C (mean = 143 °C). The temperatures cited here are consistent with values from other sources collected from comparable stratigraphic intervals in the central Appalachian basin (Hower, 1978; Pennsylvania State University Coal Database; West Virginia Geological and Economic Survey, unpublished data). In addition, conodont alteration indices for Upper Mississippian strata in southern West Virginia range from 2 to 2.5 (Epstein *et al.*, 1977) and are consistent with our vitrinite reflectance results. Vitrinite reflectance values reported for the Glenshaw Formation appear to be good burial proxies, because they are consistent with values accumulated by other studies.

New (U–Th)/He ages are younger than published AFT ages (Roden *et al.*, 1992; Blackmer *et al.*, 1994) from apatite in the Lower Pennsylvanian New River Formation and Upper Pennsylvanian Monongahela Group. Average, multi-grain detrital apatite helium ages from two sandstone intervals of the Lower Pennsylvanian in cores C-15 and WVGS-4 are 84.5 ± 4 Ma (sample 'G', Guyandot) and 96.3 ± 3 Ma (sample 'LR', Raleigh) (Figs 1, 2; Tables 1, 2). These ages are well-reproduced and nearly overlap in error bars, consistent with stratigraphic separation of < 100 m (Fig. 2). Because these samples are from similar core depths of less than 300 m, they were above the helium partial retention zone (typically $\sim$1–2 km depth (Ehlers & Farley, 2003)) when collected and thus their ages represent cooling through closure depths or the helium partial retention zone in the Late Cretaceous. A well-reproduced

Table 1. Summary of palaeothermometric and thermochronologic results: vitrinite reflectance (R_o), fluid inclusions (FI), apatite fission track (AFT), and radiogenic helium (^{4}He).

Phase	Method	Palaeotemp.1	Age (Ma)*	Sample interval
Upper Pennsylvanian, Allegheny Front				
Burial	R_o	132 °C (μR_o = 0.85)	263 ± 3	Unamed shale
Burial	R_o	143 °C (μR_o = 1.03)	263 ± 3	Unamed shale
Burial	R_o	171 °C (μR_o = 1.39)	263 ± 3	Brush Creek Sh.
Lower Pennsylvanian, Appalachian Plateau				
Burial	R_o	147 °C (μR_o = 1.07)	274 ± 4	Sewell coal
Burial	R_o	144 °C (μR_o = 1.04)	274 ± 4	Unamed shale
Burial	R_o	141 °C (μR_o = 1.00)	274 ± 4	Unamed shale
Burial	R_o	139 °C (μR_o = 0.89)	274 ± 4	Unamed shale
Burial	FI	148 °C	274 ± 4	Upper Raleigh Ss.
Burial	FI	145 °C	274 ± 4	Upper Raleigh Ss.
Burial	FI	163 °C	274 ± 4	Upper Raleigh Ss.
Burial	FI	143.5 °C	274 ± 4	Quinnimont Ss.
Upper Pennsylvanian, Allegheny Front				
Exhumation	^{4}He	~60 °C	105.5 ± 3.9	Saltsburg Ss.
Exhumation	^{4}He	~60 °C	123.6 ± 19.8	Mahoning Ss.
Exhumation	AFT	100 ± 20 °C	142 ± 12†	Monongahela Fm.
Lower Pennsylvanian, Appalachian Plateau				
Exhumation	^{4}He	~60 °C	84.5 ± 4.0	Guyandot Ss.
Exhumation	^{4}He	~60 °C	96.3 ± 2.5	Lower Raleigh Ss.
Exhumation	AFT	100 ± 20 °C	138‡	New River Fm.

[1]Values reported for vitrinite reflectance and fluid inclusions are palaeotemperatures, whereas those reported for AFT and (U–Th)/He dating are based on annealing and closure temperatures for apatite.
*Age reported for vitrinite reflectance and fluid inclusions marks time of maximum burial (see text). Age was constrained by rates calculated using estimated subsidence, palaeothermometers and burial estimates of Blackmer *et al.* (1994). ^{4}He ages are mean values.
†From Blackmer *et al.* (1994).
‡From Roden *et al.* (1992); no standard deviation reported.

Table 2. Summary of (U–Th)/He results.

Sample	Grains	Mass	F_T	U (p.p.m.)	Th (p.p.m.)	MWAR	He (pmol)	Age (Ma)	Sample average
LR-1	16	0.01399	0.638	26.2	26.9	35.1	0.1509	98.6	96.3 ± 2.5 Ma
LR-3	19	0.0129	0.626	16.2	29.8	35.8	0.0929	93.9	n = 2, ± 2.5%
G-1	14	0.01127	0.647	16.2	72.4	36.9	0.0936	72.7	84.5 ± 4.0 Ma
G-2	7	0.0052	0.606	16.6	34.7	32.1	0.0329	80.2	n = 5, ± 4.7%
G-3	10	0.0054	0.585	14.8	26.8	30.1	0.0348	96.2	
G-4	14	0.0116	0.619	20.3	71.2	33.5	0.1127	79.6	
G-5	1	0.0019	1.0	11.4	15.6	41.4	0.0142	93.6	
S-1	13	0.00866	0.635	20.5	60.8	35.5	0.1065	105.0	105.5 ± 3.9 ± Ma
S-2	7	0.0033	0.566	33.8	17.2	29.3	0.0416	113.3	n = 4, ± 3.7%
S-3	9	0.0060	0.624	47.4	129.6	35.1	0.1697	110.6	
S-4	5	0.0044	0.677	16.0	90.8	37.9	0.0549	93.2	
M-1	12	0.00794	0.612	27.4	28.9	31.9	0.1495	169.9	123.6 ± 19.8 Ma
M-2	8	0.00524	0.648	15.3	27.5	37.3	0.0272	69.6	n = 4, ± 16.0%
M-B1	7	0.0058	0.652	48.3	165.8	37.6	0.1822	103.4	
M-B3	8	0.0069	0.619	18.6	19.1	33.9	0.0789	151.5	

MWAR, mass weighted average radius, microns; F_T, alpha-ejection correction factor; Mass, mg; Grains, number of apatite grains used per age determination.
Error on average age is 1σ, as (SD)/$(n)^{1/2}$; where SD = standard deviation of the age replicates and n = number of age determinations. The percentage error based on this is listed below each average age. Note that for sample LR, only two ages were measured, so the uncertainty reported is simply the standard deviation (1σ). Uncertainties on individual age determinations are estimated to be 10% (2σ), as described in the text.

average helium age from Upper Pennsylvanian sandstone in core USGS-3 to the northeast is 105.5 ± 4 Ma (sample 'S', Saltsburg). Average apatite helium age from a sandstone ~100 m lower in the same core (sample 'M', Mahoning) is older (~124 Ma), but was poorly reproduced (± 16%, 1 − σ). We suspect that this variation partly results from U-bearing micro-inclusions that were missed during sample screening, which could have made several age determinations anomalously old (e.g. 170 Ma). In this case, the true cooling age for this sample would be younger than our reported average age. Without secondary evidence for micro-inclusions in the grains analysed, however, we cannot be sure of the cause of this sample's variance. Therefore, we do not use the average age for sample M in our interpretations. Published AFT ages from detrital apatite in these same formations are significantly older than our new helium ages. AFT ages from the New River Formation and Monongahela Group are 138 Ma (no error reported) and 142 $\pm$ 12 Ma, respectively (Roden *et al.*, 1992; Blackmer *et al.*, 1994).

Well-constrained geothermal gradients are necessary to accurately estimate burial depths using palaeothermometric and thermochronologic data. The average present day geothermal gradient for the study area is $\sim$20 °C km^{-1} (Blackwell *et al.*, 1989; Hulver, 1997). Assuming the geothermal gradient in the Appalachian foreland basin was 50% higher than today at the time of sedimentation (Vitorello & Pollack, 1980; Chyi *et al.*, 1987), then a palaeogeothermal gradient of $\sim$30 °C km^{-1} can be assumed for the late Palaeozoic. This estimate is consistent with thermal model results (31 to $\sim$33 °C km^{-1}) based on vitrinite reflectance and heat flow parameters compiled by Zhang & Davis (1993) for the Appalachian Plateau near the Alleghany structural front. In addition, Hulver (1997) calculated the palaeogeothermal gradient for the Permian to be $\sim$36 °C km^{-1} for the study area using various thermal indicators including vitrinite reflectance, conodont color alteration indices and AFT. Thus, a present day value of 20 °C km^{-1} and palaeogeothermal gradient of 35 °C km^{-1} were used to calculate burial depths. The inferred palaeogeothermal gradient is consistent with values cited for Cenozoic foreland basins (e.g. Bachu *et al.*, 1995; Law *et al.*, 1998; O'Sullivan, 1999). Geothermal gradients corresponding to the estimated time of maximum burial, AFT and (U–Th)/He ages (i.e. instantaneous values) have been interpolated using an exponential decay function (assuming conductive heat loss) fit to the past and present geothermal gradients cited above. Resulting maximum burial depths for Pennsylvanian strata in the central Appalachian basin are $\sim$4.4 km.

Burial rates were constrained using two complementary methods. Subsidence rates were calculated based on average stratigraphic thicknesses in the study area and chronostratigraphic markers for upper Mississippian, lower Pennsylvanian and upper Pennsylvanian strata. Age estimations for the New River (*ca*. 316 Ma) and Glenshaw (*ca*. 306 Ma) Formations are based on megafloral zones (Blake, 1997), chrono- and lithostratigraphic correlations in the central Appalachian basin (Gillespie & Pfefferkorn, 1979), and the timing of the Wanganui palaeomagnetic reversal (Opdyke *et al.*, 2000). All stratigraphic thicknesses reported here are decompacted based on ratios established for nonmarine deposits of sandstone, shale/siltstone and coal (Nadon & Issler, 1997; Nadon, 1998). The ratios were derived from strata that are very similar study with respect to the relative distribution and thicknesses of mudstone, sandstone and coal. Miller & Eriksson (2000) estimated that the 750 m-thick upper Mississippian Mauch Chunk Formation was deposited in approximately 7 Myr, whereas the $\sim$350 m-thick New River Formation spanned approximately 3 Myr (Chesnut, 1994; Korus, 2002). Upper Pennsylvanian rate estimates have been constrained using sedimentary cycles. Up to 12 palaeosol-bounded cycles have been identified within a 160 m section of the Glenshaw Formation (Martino & Belt, 2001). Upper Pennsylvanian cycle duration of 143 $\pm$ 64 kyr ($\sim$100 kyr Milankovitch cyclicity) has been constrained using U–Pb dating of palaeosols in the western United States (Rasbury *et al.*, 1998). Milankovitch cyclicity presumably forces eustatic sea level fluctuations and therefore absolute cycle durations are applicable in the Appalachian basin. Based on the above thicknesses and age constraints, the average subsidence rate is estimated at 102–116 m Myr^{-1} for all three Carboniferous intervals. In addition, Blackmer *et al.* (1994) used vitrinite reflectance (Levine & Davis, 1989) and the timing of remagnetization of Palaeozoic rocks in the Appalachian basin (Miller & Kent, 1988) to estimate that it took approximately 40 Myr for maximum burial to occur in the central Appalachian basin. Therefore, subsidence (using estimated stratigraphic thickness and decompaction ratios) and thermal calculations (above) as well as the estimate from the timing of remagnetization, maximum burial for the New River and Glenshaw Formations occurred at approximately 274 $\pm$ 4 and 263 $\pm$ 3 Ma, respectively. Using the estimated geothermal gradient cited above, vitrinite reflectance and fluid inclusion homogenization temperatures (Table 1) provide an independent means of constraining maximum burial depth and thereby subsidence rates. If maximum temperatures ($\sim$150 °C) correlate with maximum or near maximum depths ($\sim$4.4 km), then subsidence averaged 99 and 103 m Myr^{-1} for the Lower and Upper Pennsylvanian, respectively (Fig. 3). Therefore rates calculated based on stratigraphic thicknesses and palaeothermometry are comparable.

Exhumation rates were calculated using the estimated timing of maximum burial, AFT and (U–Th)/He ages (Fig. 3). (U–Th)/He ages within the New River (88 Ma) and Glenshaw (87 Ma) Formations were averaged because our goal was to evaluate the overall behavior of the Upper and Lower Pennsylvanian intervals. Burial depths corresponding to AFT and (U–Th)/He ages were constrained using an annealing temperature of 100 $\pm$ 20 °C and closure temperature (T_c) of 60 °C, the interpolated palaeogeothermal gradients cited above, an average surface temperature of 15 °C, and average present day formation temperature of $\sim$19 °C (from present day depth and geotherm). The annealing temperature is based on previous AFT studies in the Appalachian Plateau (e.g. Roden & Miller, 1989) and T_c is a function of apatite grain size (Table 2; Farley, 2000).

Inferred exhumation histories of New River and Glenshaw formations are very similar and are based on calculations and assumptions discussed above (Fig. 3). The first phase of exhumation from $\sim$4.4 to $\sim$3.1 km burial depth between $\sim$270 and $\sim$140 Ma, as constrained by AFT, was $\sim$10 m Myr^{-1}. The second phase of exhumation from

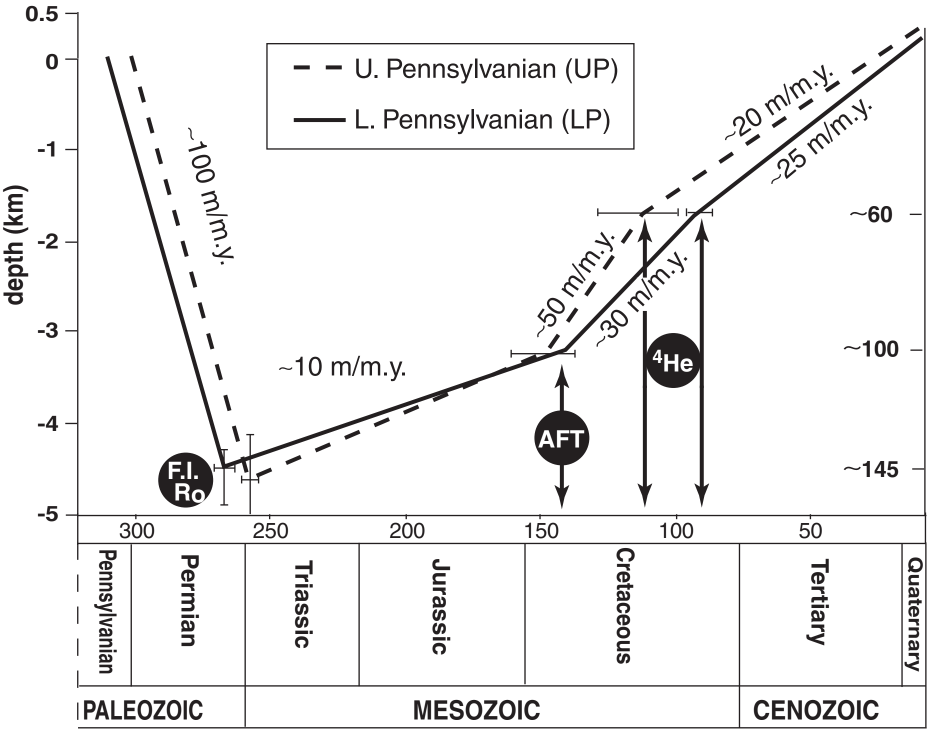

Fig. 3. Summary of the burial and exhumation history of the central Appalachian basin inferred in this study. Reported rates are average values defined by mean palaeothermometric and thermochronologic constraints from Upper and Lower Pennsylvanian strata. Error bars correspond to measured values reported in Table 1.

~3.1 to ~1.7 km between ~140 and ~90 Ma, as constrained by (U–Th)/He ages was ~50 m Myr^{-1} for the Upper Pennsylvanian section and ~30 m Myr^{-1} for the Lower Pennsylvanian. The final phase from ~1.7 km below the surface to 0.4 km above sea level (s.l.) between ~114 Ma for the Upper Pennsylvanian and ~90 Ma for the Lower Pennsylvanian and the present occurred at slightly slower rate (~20–25 m Myr^{-1}) when compared with the second phase.

The results of this study supplement existing knowledge concerning post-Alleghanian evolution of the central Appalachians (e.g. Poag & Sevon, 1989; Roden & Miller, 1989; Slingerland & Furlong, 1989; Pazzaglia & Gardner, 1994; Pazzaglia & Brandon, 1996) and are comparable with AFT studies involving upper Palaeozoic strata in areas to the north and south of our sample locations. Mesozoic and Cenozoic exhumation rates for the Appalachian Plateau in central Pennsylvania range from ~10 to 15 m Myr^{-1} (Blackmer *et al*., 1994) whereas average rates from the mid-Mesozoic to the present for eastern Kentucky are ~29 m Myr^{-1} (Boettcher & Milliken, 1994). Our study location and average exhumation rates for the equivalent time interval fall between the locations and results cited above.

DISCUSSION & CONCLUSIONS

Palaeothermometric and thermochronologic results constrain the long-term burial and exhumation history of the Appalachian Plateau (Fig. 3). Palaeothermometers are consistent and yield reasonable values of maximum burial depth and average rates of subsidence. In addition, burial indicators correlate well with AFT results to constrain earliest exhumation. Thermochronometers appear to corre late well and provide reasonable rates of exhumation, although the relationship between AFT and (U–Th)/He dating techniques are not fully understood. However, recent studies (e.g. Stockli *et al*., 2003) have demonstrated that the closure temperature systematics of AFT and (U–Th)/He ages known from laboratory studies are consistent with field tests. The validity of combining these methods for basin studies would benefit from additional research.

The exhumation histories of the New River Formation of southern West Virginia and Glenshaw Formation of northern West Virginia are comparable and similarities of exhumation rates between regions, stratigraphic intervals and other studies are striking. If the difference between early and late exhumation rates is significant, tectonic, thermal and isostatic driving forces warrant consideration. The initial slow (~10–15 m Myr^{-1}) exhumation phase of the Appalachian Plateau can be interpreted in two ways. The value could reflect isostatic rebound following thrust cessation and erosion of the thrust belt and/or footwall uplift during Triassic rifting (e.g., Barr, 1987). Alternatively, the rate could be influenced by averaging late-stage burial with early exhumation, because our calculations assume that exhumation occurred immediately following maximum burial.

The second and third phases of exhumation defined by AFT and (U–Th)/He (~30–50 m Myr^{-1}) is higher than the first and reflects a higher denudation from the mid-Cretaceous onwards. Since major climatic changes resulting in enhanced weathering rates are not recognized during this time, other possible explanations must be sought. Pazzaglia & Brandon (1996) have suggested that magmatic activity deep in the crust drove uplift during the Cretaceous, perhaps related to migration of the Atlantic margin over hotspots (de Boer *et al.*, 1988). In addition, a significant increase in sedimentation rates during the mid to late Cretaceous occurred on the middle Atlantic continental margin (Poag & Sevon, 1989). Therefore, a combination of driving mechanisms including hotspot migration and relatively high sedimentation accumulation rates could account for the higher rates of exhumation during the Cretaceous. The last phase of exhumation defined by (U–Th)/He ages and the present day depth ($\sim$20–25 m Myr^{-1}) was probably mainly driven by lithospheric flexure induced by increased sediment loading of the Atlantic passive margin during the late Cenozoic (Poag & Sevon, 1989; Pazzaglia & Gardner, 1994; Pazzaglia & Brandon, 1996). The highest sediment accumulation rates recognized by Poag & Sevon (1989) occurred during the mid to late Cenozoic with the lowest, since the early Jurassic, immediately preceding this large pulse.

An understanding of long-term subsidence and inversion rates of foreland basins containing flat-lying sedimentary rocks can place important constraints on the evolution of ancient mountain belts such as the Appalachians. Specifically, rapid subsidence in the Pennsylvanian–Permian recorded by palaeothermometric data reflects thrust loading associated with assembly of Pangea, whereas Mesozoic–Cenozoic inversion revealed by thermochronologic data records the degradation phase of the mountain belt associated with break-up of Pangea and accompanying passive-margin sedimentation.

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