by H. Richard Lane[1], Paul L. Brenckle[2], J. F. Baesemann[3], and Barry Richards[4]

The IUGS boundary in the middle of the Carboniferous: Arrow Canyon, Nevada, USA

1 National Science Foundation, 4201 Wilson Blvd., Room 785, Arlington, Virginia 22230, USA.
2 1 Whistler Point Rd., Westport, Massachusetts 02790, USA.
3 1400 River Edge Blvd., Kent, Ohio 44240-2389, USA.
4 Geological Survey of Canada, 3303 33rd St. N. W., Calgary, Alberta, Canada T2L-2A7.

Arrow Canyon, chosen by the Subcommission on Carboniferous Stratigraphy to be the Global Boundary Stratotype Section and Point (GSSP) for the Mid-Carboniferous Boundary, is located near Las Vegas, Nevada, in the arid Basin and Range Province of the southwestern United States. The GSSP has been approved by the International Commission on Stratigraphy and ratified by the IUGS Executive Committee in January 1996. The GSSP coincides exactly with the historically stable Mississippian-Pennsylvanian boundary.

During the Carboniferous, the Arrow Canyon Section was situated in a subtropical to tropical seaway extending from southern California northward into Alaska. Deposition was along a shelf-edge separating deeper water, western basinal facies from nearshore-continental beds eastward on the craton. The boundary interval and contiguous strata are completely exposed at Arrow Canyon. They can be traced laterally for many kilometers and are essentially undisturbed structurally. Access for study and sampling is unrestricted on United States government land.

The GSSP is located at 82.90 m above the top of the Battleship Wash Formation in the lower Bird Spring Formation at the first evolutionary appearance of the conodont Declinognathodus noduliferus *s. l. The latter is a cosmopolitan species that occurs abundantly in most marine environments, thus facilitating reliable correlations between deep and shallow water environments and carbonate and clastic facies. In the Mid-Carboniferous Boundary interval the Arrow Canyon section is composed of numerous glacio-eustatic, shallow-water, transgressive-regressive sequences. The boundary occurs within the continuously deposited shallow neritic part (Unit G of TR Sequence 3, herein) of one of them.*

The Arrow Canyon GSSP biostratigraphic succession is more complete than that in the classic Namurian outcrops of northwestern Europe. In particular, two key sections that define the standard ammonoid chronology in Britain lack the unicornis *through* noduliferus-primus *conodont zones that span the GSSP. The discontinuous occurrence of the British fauna and flora at these localities preclude their use as boundary stratotype sections.*

A partially correlative trenched section (South Syncline Ridge, SSR) basinward of Arrow Canyon contains homoceratid ammonoids with conodonts. The SSR conodonts demonstrate that the same faunas attributed to shelf facies in Arrow Canyon occur abundantly in basinal sections with ammonoid faunas.

Introduction

Early in 1995 the International Subcommission on Carboniferous Stratigraphy selected Arrow Canyon to be the GSSP for the Mid-Carboniferous Boundary. That decision, based on guidelines set forth by the International Commission on Stratigraphy (Cowie, et al., 1986; Remane et al., 1996), culminated more than 10 years of work by the Mid-Carboniferous Boundary Working Group and represented a milestone in attempts to standardize intra-Carboniferous chronostratigraphy worldwide. This paper describes the litho/sequence stratigraphy of the boundary interval and reviews the biostratigraphic criteria that demonstrate why the Arrow Canyon GSSP was chosen over other proposed candidate sections. Lane et al (1985c) and Paproth et al (1995) summarized the activities of the Mid-Carboniferous Boundary Working Group and the decisions leading to the selection of Arrow Canyon. Additional information on the boundary interval can be found in Lane and Baesemann (1982), Baesemann and Lane (1985), Lane et al. (1985a) and Brenckle et al. (1997a, b).

Geographic and geological setting

Arrow Canyon (Figures 1, 2) is located in the southwestern United States approximately 75 km northeast of Las Vegas, Nevada, on land administered and protected by the Federal government; it is readily accessible via a four-wheel drive road that runs along Arrow Canyon and is connected to Highway 168 by a paved secondary road. Arrow Canyon lies within the arid eastern Great Basin, which is composed of multiple parallel, block-faulted mountain ranges separated by intermontane basins. Because of the topography and

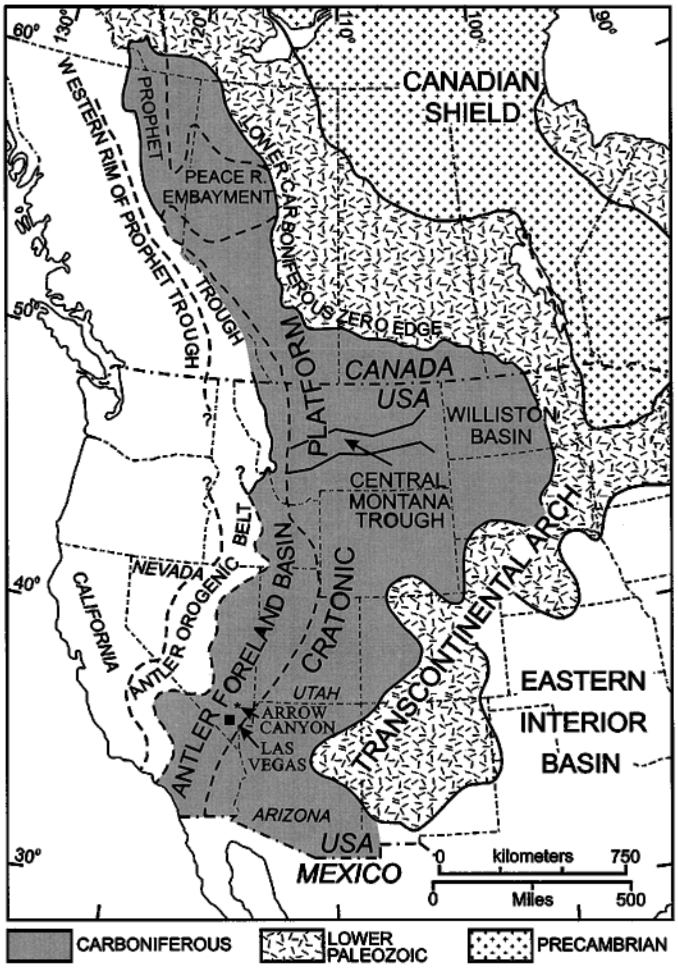

Figure 1 Map showing location of Arrow Canyon, Clark County, Nevada and principal Late Mississippian paleogeographic elements (modified from Richards et al., 1994).

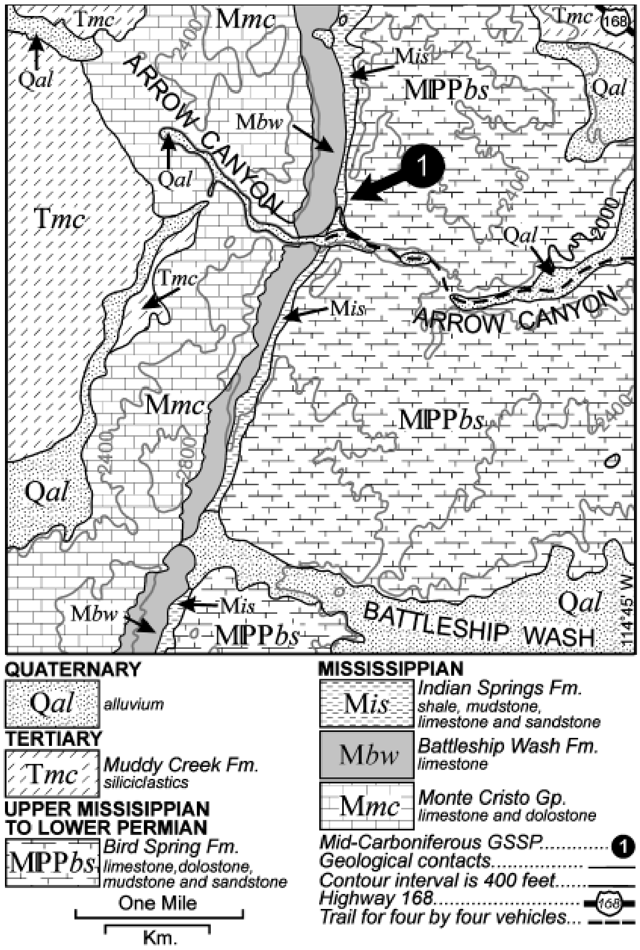

Figure 2 Location of measured section including Mid-Carboniferous boundary at Arrow Canyon. Base map: U. S. Geological Survey 15 minute Arrow Canyon Quadrangle (1958 edition); intervals in feet (1 ft. = 0.3 meter).

desert climate, the section containing the GSSP (Figures. 3, 5, 6) is almost completely exposed, and the beds can be traced laterally north and south for many kilometers in a fault block containing relatively undeformed Carboniferous strata. This situation provides an excellent opportunity to relate the boundary facies and fossil succession at the GSSP to the regional geology, and has facilitated correlation with neighboring shelf and basinal sections. The ease of placing the exposure within local and regional geologic contexts was unparalleled among the GSSP candidate sections examined by the Mid-Carboniferous Boundary Working Group. It ensures that a sizeable area is available to test future techniques or processes that may be developed to refine boundary correlations.

During Carboniferous time, Arrow Canyon was situated near the paleoequator in a pericratonic tropical to subtropical seaway extending from southeastern California through western Canada (Figure 1) and into Alaska. Deposition of the succession occurred along a hinge zone that separated cratonic beds 75 km to the east from the axial region of the Antler Foreland Basin 100 km to the west. The succession containing the Mid-Carboniferous Boundary interval comprises numerous high-order transgressive-regressive (TR) sequences that resulted mainly from glacio-eustatic fluctuations driven by ongoing glaciation in Gondwana. The boundary horizon (GSSP) lies within skeletal limestone that resulted from essentially continuous shallow neritic sedimentation and is preserved in a 1.68-meter thick TR sequence (sequence 3, Figure 5).

The Arrow Canyon section

Because of its nearly complete exposure, its cyclical but relatively continuous stratigraphic succession, and its open accessibility, Arrow Canyon has proven to be a popular place for geological investigations. Over the past 40 years, academic, government, and industry geologists have published numerous papers on its paleontology, biostratigraphy and sedimentology. These investigations have provided documentation showing Arrow Canyon to be one of the most depositionally complete Carboniferous exposures in North America and the world. Papers dealing with the Mid-Carboniferous (=Mississippian-Pennsylvanian) Boundary at this locality are listed in Brenckle et al (1997a, b).

Mid-Carboniferous Boundary TR sequences

The Mid-Carboniferous boundary section was measured on the east side of a strike valley immediately north of the Arrow Canyon gorge (Figures 2, 3). The section begins at the top of the Battleship Wash Formation, goes up through the overlying Indian Springs Formation and into the lower part of the Bird Spring Formation, where the GSSP boundary horizon is located (Figures 4, 5). Photographic documentation of sample 61B immediately above the GSSP (TR sequence 3, Unit G) is shown in Figure 4.

The cliff-forming Battleship Wash Formation comprises Meramecian to lower Chesterian (late Visean) shallow-marine limestone deposited on a shelf margin of a carbonate platform. Stumps, rhizoliths and stem fragments of terrestrial plants (mainly lycopods)

Figure 3 Section containing the Mid-Carboniferous boundary on east side of strike valley immediately north of Arrow Canyon. View is toward east from northeastward dipping upper beds of Battleship Wash Formation. Large black arrow indicates the GSSP within the lower Bird Spring Formation; small black arrows indicate contact between Indian Springs and Bird Spring formations; white arrow indicates base of stratigraphic section represented by Figure 5.

are embedded in its upper surface, which disconformably underlies the late Chesterian (late Serpukhovian) Indian Springs Formation. The contact between these two formations marks the base of the Arrow Canyon section herein. In its lower part, the recessive Indian Springs Formation consists of black marine shales and pale red to greenish gray and variegated pedogenic mudstones that are intercalated with widely separated beds of skeletal limestone, marine to fluvial sandstone and minor conglomerate. The proportion of limestone increases upward and is more abundant that fine-grained siliciclastics in its upper part. The Indian Springs Formation is overlain by the Bird Spring Formation, which comprises limestone with subordinate mudstone, sandstone and dolostone. The boundary between the two formations is a mixed gradation and the contact is placed at a level above which limestone is the main rock type and the succession is cliff and ledge forming. The lower Bird Spring and underlying Indian Springs Formation jointly constitute a regionally developed second order TR sequence.

Lithostratigraphy

The lower part of the Bird Spring Formation, which contains the Mid-Carboniferous boundary horizon, consists of high-order transgressive-regressive sequences. Five of these TR sequences near the boundary are illustrated and briefly described on Figure 5, which represents a subsection measured in detail by Richards in late 1989 within the main Arrow Canyon section (Figure 6). Sequence 3, containing the boundary, lies between 6.95 and 8.63 m above the base of the subsection (Figure 5) and comprises lithologic units G and H. Components of the underlying and overlying TR sequences are also described on Figure 5 to place sequence 3 in its stratigraphic context and demonstrate the typical nature of the sequences.

Depositional environment

Some of the interpretations presented here are of a tentative nature because they are based largely one detailed section (Figure 5). A more definitive treatment requires measurement of additional detailed sections in the Arrow Canyon area.

Units L, N and lower two thirds of C, G and O (Figure 5) are of similar aspect and depositional origin; in addition, they resulted from relatively continuous marine deposition. In these units, the predominance of relatively coarse grained lime grainstone and packstone consisting mainly of pelmatozoan ossicles, bryozoans and fragmented to well preserved brachiopods indicate deposition in a spectrum of moderately high to medium-energy shelf environments in relatively shallow (above fair-weather wave base) but

Figure 4 Close-up view of Cycle TR-3 showing position of GSSP at arrow (sample 61B) within carbonate bed containing boundary.

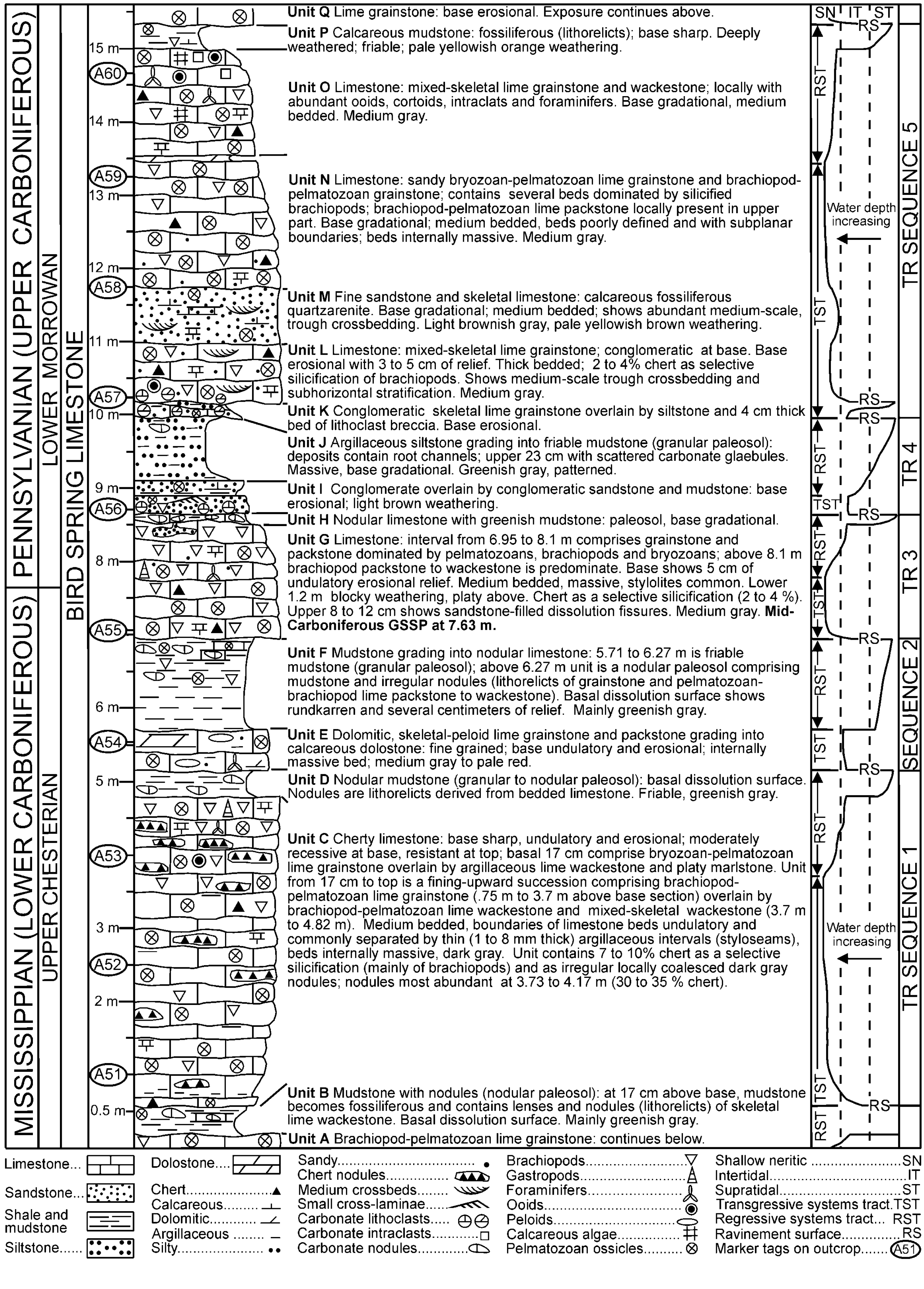

Figure 5 Columnar section representing lower Bird Spring Formation at Arrow Canyon, Nevada; shows lithology of five TR sequences in the section containing the Mid-Carboniferous boundary.

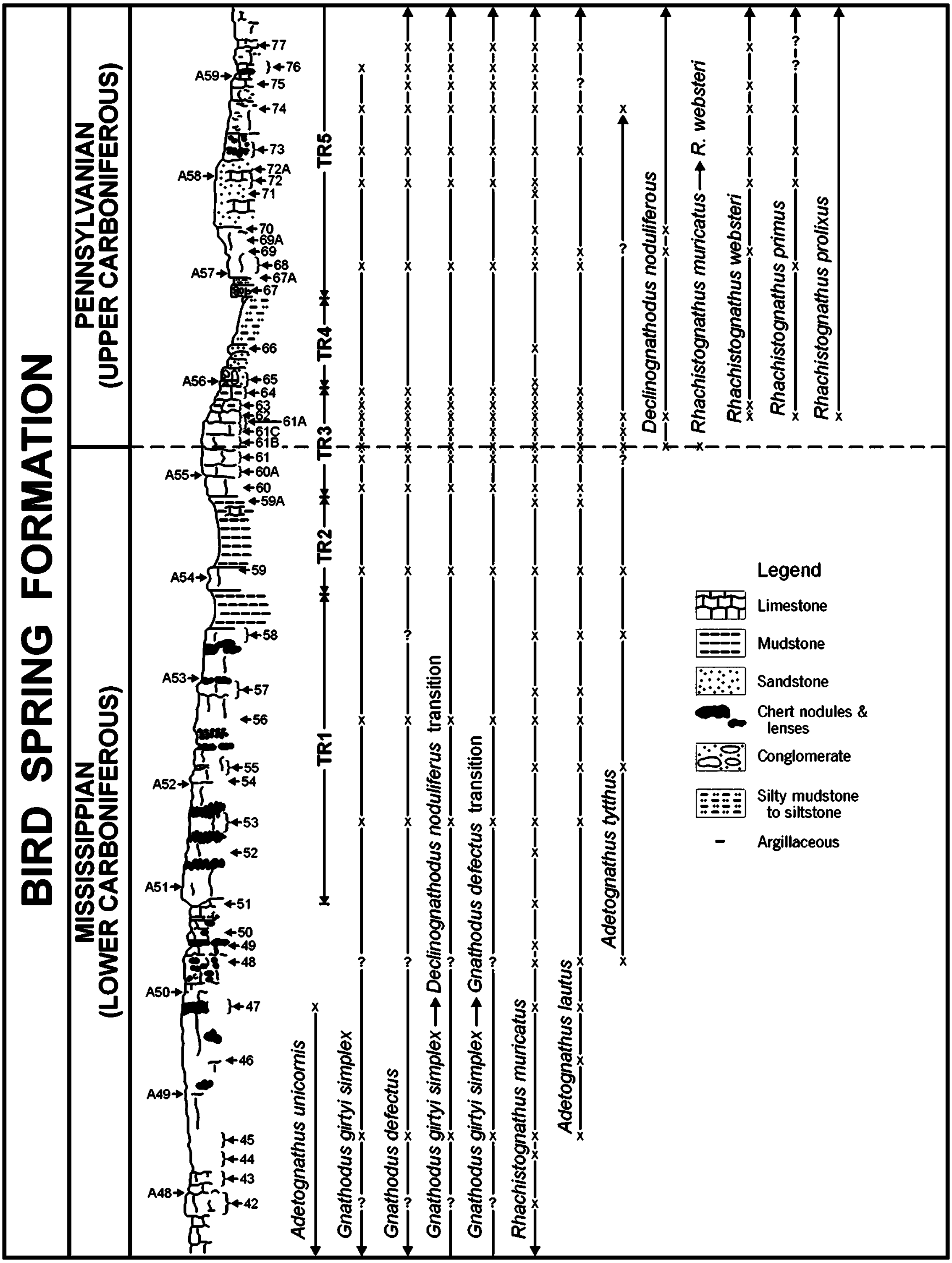

Figure 6 Selected conodont range/occurrences through 18-meter interval across Mid-Carboniferous Boundary (sample 61B). Numbers on right side of lithology column are samples; "A" numbers on left are spaced at 1.5m intervals. Positions of TR sequences are shown on right of stratigraphic column.

open-marine water. On a Carboniferous carbonate ramp, such settings could be expected on offshore shoals and in the slightly protected shallow-neritic to lower intertidal settings of bays and leeward sides of shoals or barrier islands. Abundant ooids, superficial ooids and rounded to well rounded skeletal remains characteristic of very high-energy beach and shoal settings are generally lacking. Deposition largely above fair-weather wave base in shallow-neritic to lower-intertidal environments is indicated by the predominance of grainstone and the local presence of wave-formed crossbedding. However, red algae are substantially more abundant than green codiacian algae, thereby suggesting most of the grainstone and packstone originated at moderate water depths (middle part of euphotic zone). The presence of both medium-scale trough cross bedding and horizontal (swash?) stratification in unit L suggests shoreface deposition. Overlying cross-stratified sandstone of unit M is of lower shoreface aspect.

The upper parts of units C, G and O were deposited in low-energy settings and probably in somewhat shallower water than the grainstone discussed above. Upper C, G and O are mainly lime wackestone to packstone and show a general upward increase in the proportion of micritic matrix, thereby indicating a trend toward deposition in progressively lower energy settings. The fining trend is accompanied by an upward increase in the abundance of foraminifers, gastropods, algae, cortoids and coated grains. In Carboniferous successions, an upward increase in the abundance of these allochems accompanied by upward fining typically records shallowing. Upper unit O locally contains abundant ooids and superficial ooids preserved in skeletal lime wackestone. Most ooids develop in high-energy settings at water depths of less than 2 m but may form down to depths of about 15 m (Newell et al., 1960; Fluegel, 1982), The presence of the ooids records deposition near a high-energy beach, shoal or tidal channel from which they were resedimented.

Units B, D, F, H, J and P are granular to nodular paleosols. This interpretation is based mainly on the close resemblance of these units to paleosols that developed on limestone in other regions and have been described by Ettensohn et al. (1988) and others. Numerous features and facies diagnostic of paleosols are preserved in units B, D, F, H, J and P; they include: nodular to granular peds, pedogenic breccias, argillans (argillic cutans), root channels and rhizocretions, evidence for extensive gleization, and the absence of primary sedimentary structures (Figure 5). A pedogenic origin for the units is also indicated by the common presence of underlying dissolution surfaces showing well developed rundkarren (small karstic features that develop below soil). For example, dissolution pans resembling kamenitza are well developed on the dissolution surface below nodular mudstone of unit F; sand-filled dissolution fissures (grikes) are preserved in upper unit G; and karstic breccias occur in unit E. All of the paleosols have undergone extensive gleization, as recorded by greenish-gray facies associated with remnants of pale red deposits.

Thin-section analyses indicate the carbonate nodules in the paleosols resulted largely from pedogenic dissolution of fossiliferous shallow-marine limestone instead of insitu precipitation of carbonate minerals from soil plasma to produce glaebules. However, the nodules of upper unit J lack marine fossils and are glaebules to rhizocretions resulting from carbonate precipitation within soil.

Most of the paleosols comprise only the C horizon of the standard soil profile (comprises A, B and C horizons), but unit J probably represents a nodular B horizon. The A and B horizons, and commonly much of the C horizons, have been eroded during the early phases of transgressions leading to the deposition of overlying marine conglomerate and limestone containing lithoclasts from paleosols.

Unit E is tentatively interpreted to be either a lagoonal or tidal-flat facies. Deposition in such settings is suggested by the presence of abundant peloids in this fine-grained, extensively dolomitized and pedogenically altered unit of skeletal-peloid grainstone and packstone. On Carboniferous ramps and platforms, peloids are generally most abundant in low-energy peritidal settings. Its position above the paleosols of unit D records shallow-water deposition during the early phase of a minor transgression. Upper unit E was substantially modified by subsequent pedogenic process as indicated by presence of pale red cutans, karstic breccias and an overlying nodular paleosol.

The conglomeratic units I, K and basal L are high-energy marine deposits recording transgression and peritidal erosion of underlying paleosols and carbonates. In these units, marine sedimentation is indicated by the common occurrence of marine macrofossils that have not been reworked from other units. The stratigraphic relation of the conglomeratic facies to underlying paleosols indicates intertidal to shallow-neritic sedimentation. The local presence of small-scale, wave-formed cross lamination in unit I and trough cross beds in unit L also indicate shallow-water deposition. Unit I and the conglomerate-sandstone couplet of unit K closely resemble fining-upward tempestites. Their juxtaposition on largely eroded paleosols, however, indicates substantial shoreline ravinement and transgressive deposition.

Sequence stratigraphy

Several types of sequences have been defined, including: tectonostratigraphic sequences (Sloss, 1963), depositional sequences (Vail et al., 1977; Van Wagoner et al., 1988) and transgressive-regressive sequences. The TR sequence model, as refined by Embry and Johannessen (1992) and Embry (1993), is applied herein because the TR sequences are readily recognized in surface and subsurface Carboniferous sections using objective criteria.

The TR sequences comprising the succession represented by Figure 5 are classified as third- to fourth-order sequences using the hierarchal system developed by Embry (1993). At Arrow Canyon, the lower boundaries of sequences 1 to 5 are surfaces of transgressive ravinement developed on subaerial erosion surfaces (tops of soil profiles). In sequences 1, 3 and 5 the transgressive systems tracts (TST) cannot be readily differentiated from the lower part of the overlying regressive systems tracts (RST) because maximum flooding surfaces are not clearly developed. In sequence 3, which contains the boundary stratotype, the top of the transgressive systems tract is provisionally placed at the transition from pelmatozoan lime grainstone to mixed-skeletal lime grainstone and overlying brachiopod lime packstone to wackestone. A similar position is used in sequences 1 and 5. The GSSP, 68 cm above the base of sequence 3, lies within the TST/RST transition, an interval recording essentially continuous marine deposition. The position chosen marks the first clearly defined onset of shallowing. The regressive systems tracts are well developed and dominated by paleosols.

Both the lower and upper sequence boundaries of sequences 1, 2, and 5 are classified as third- to fourth order boundaries. However, the contact between sequences 3 and 4 is a first-order boundary defining the top of the regionally developed second-order sequence comprising the Indian Springs and lowermost Bird Spring Formation. The first-order boundary also marks the cratonward-expanding hiatus between the Kaskaskia and overlying Absaroka tecto-stratigraphic sequences of Sloss (1963), readily identifiable throughout most of North America. However, at Arrow Canyon, the unconformity between sequences 3 and 4 represents a hiatus of short duration because beds on both sides lie within the *noduliferus-primus* conodont zone (Figure 6, Table 1).

Sequence 3, containing the Mid-Carboniferous boundary, records the passage of a shoreline, but all or most of the high-intertidal to restricted-marine supratidal facies that typically result from such a regression were either not deposited or eroded prior to deposition of the conglomerate bed between 8.63 and 8.90 m. Similarly, sequences 1, 2 and 5 record the passages of shorelines but lack characteristic high-intertidal to peritidal-supratidal lithofacies (fenestral cryptalgal laminites, evaporites, algal lime wackestone, stromatolitic deposits). The paleosols that cap the sequences developed on relatively open-marine limestone, as indicated by the lithology of the lithorelicts they contain. The absence of the high-intertidal to supratidal carbonates records forced regressions resulting from relatively rapid eustatic drops driven by well documented glaciations in Gondwana. Similar sequences resulting from forced regressions have been recognized elsewhere in North America at this stratigraphic level (Ettensohn et al., 1988).

Biotic Characteristics

Conodonts

Because of its synchronous first appearance in shelf to basinal facies worldwide, *Declinognathodus noduliferus* s. l. was chosen at the 10th International Congress of Carboniferous Stratigraphy and Geology (1983) in Madrid to serve as a guide for the Mid-Carboniferous Boundary. At that time, *D. noduliferus* s. l. included the subspecies *D. n. noduliferus, D. n. inaequalis, D. n. lateralis*, and *D. n. japonicus* (Higgins, 1975, 1982). Some paleontologists have subsequently separated those forms, as well as other unnamed forms formerly included within the species concept, into discrete species of *Declinognathodus*. Nevertheless, *Declinognathodus noduliferus* s. l. is retained as the biotic guide for recognition of the GSSP because its utility for intercontinental correlation remains the same as at the time of the Madrid agreement. Subsequent investigations of candidate GSSP stratotype sections in England, France, Ukraine, Uzbekistan, China and the United States confirmed its suitability as a worldwide marker for the Mid-Carboniferous Boundary. The fossil information generated by these investigations, both for conodonts and for other fossil groups, satisfies the biostratigraphic criteria for boundary selection as outlined by ICS (Cowie et al., 1986 and Remane et al., 1996).

The overall fossil succession at Arrow Canyon is relatively continuous in its development (Figure 6, Table 1), especially when compared with other fossil successions elsewhere in the world that are claimed to be continuous. Similar conodont sequences have been reported from Idaho (Skipp et al., 1985) and Arctic Alaska (Krumhardt et al., 1996; Harris et al., 1997; Baesemann et al., 1998) and may occur in central Asia and south China, although further study is necessary to confirm these successions.

Table 1 details conodont occurrence from the top of the Battleship Wash into the lower part of the Bird Spring formations. Information is based on samples reposited in the Amoco Conodont Collection in the Museum of the Department of Geology, The University of Iowa, Iowa City, Iowa, USA. Representative conodont specimens have been illustrated in Brenckle et al. (1997a,b).

The lowest conodont fauna (spl. 1) comes from the top of the Battleship Wash Formation. It is late Visean (early Chesterian) in age. Conodont faunas occurring in the Battleship Wash Formation below sample 1 are typical of those found in the Meramecian and early Chesterian (middle to late Visean) of the type Mississippian. These faunas are overlain by late Serpukhovian conodonts of the *unicornis* Zone (=*Streptognathodus unicornis* Assemblage Zone of Collinson et al., 1962) in the lower Indian Springs Formation from 10.3- to 46.7-meters above the base of the measured section (spls. 5-19, Table 1). Conodonts of the *unicornis* Zone have been described from the Grove Church Shale (highest Chesterian) in the type Mississippian of southern Illinois (Rexroad and Burton, 1961; Rexroad and Merrill, 1985), other late Mississippian localities in North America (Lane, 1967; Repetski and Henry, 1983; Titus et al., 1997), the Tramaka beds (Mississippian) of Belgium (Austin et al, 1974), from the highest Mississippian in the Bechar Basin of Algeria (Weyant, 1982; Manger et al., 1985) and in the Donets Basin, Ukraine (Nemirovskaya, 1987).

The *unicornis* Zone has never been found in Great Britain. The youngest age diagnostic Mississippian conodont faunas there are from sample CAS 3 at the Castleton section, north Derbyshire (Higgins, 1975, p. 84, Figure 3), samples 26024-26974 at Stonehead Beck (Varker et al., 1991, Figure 1), and samples ED 0 and ED 7-9 at Edale (Higgins, 1975, p. 83, Figure 3). These faunas belong in the *Gnathodus bilineatus bollandensis-Cavusgnathus naviculus* Zone of Higgins (1975, p. 14) which, in North America, is equivalent to the mid- to late-Chesterian *naviculus* Zone of Baesemann and Lane (1985). Varker and Austin (1975) mistakenly identified *Adetognathus unicornis* at the Mirk Fell locality.

Above the *unicornis* Zone at Arrow Canyon is the Lower *muricatus* Zone of Baesemann and Lane (1985). It is defined as the range of the name-bearer, *Rhachistognathus muricatus*, below the appearance of the conodont element-pair, *Adetognathus lautus* (=*A. lautus* and *A. gigantus*). At Arrow Canyon, this zone is well represented in the upper Indian Springs and lower Bird Spring formations from samples 21 through 42 (Table 1). Transitional specimens in the evolutionary sequence from *Adetognathus unicornis* to *Adetognathus lautus* are present in the Lower *muricatus* Zone and give rise to *A. lautus* at the base of the overlying Upper *muricatus* Zone.

The Upper *muricatus* zone was defined by Baesemann and Lane (1985) as the overlap in range of *Rhachistognathus muricatus* and the element-pair species *Adetognathus lautus* below the appearance of *Declinognathodus noduliferus* s. l. This zone occurs in samples 45 through 61 (Table 1). The appearance of *Adetognathus lautus* within the evolutionary sequence from *Adetognathus unicornis* to *A. lautus* was a strong contender for the GSSP guide. However, *D. noduliferus* s. l. is more widely distributed than *A. lautus*, and thus its evolutionary appearance is more suitable as a boundary-identifying event. Specimens transitional from ancestral *Gnathodus girtyi simplex* to *D. noduliferus* s. l. occur as low as the base of the Upper *muricatus* Zone at Arrow Canyon, but extend lower at South Syncline Ridge, Nevada based on a single occurrence of "*D. noduliferus* morphs" from the Lower *muricatus* Zone as reported by Titus et al. (1997, Figure 2, Pl. 1, Figure 5).

The Mid-Carboniferous Boundary GSSP is coincident with the base of the *noduliferus-primus* Zone of Baesemann and Lane (1985). At the time of that publication, both species were thought to appear simultaneously. Subsequent work has shown that *Declinognathodus noduliferus* s. l. is located slightly below *Rh. primus* at Arrow Canyon (spl. 61B vs. spl. 62).

The appearance of *Rhachistognathus minutus* and *I. sinuatus* in sample 89 (Figure 5, Table 1) defines the base of the *sinuatus-minutus* Zone of Lane and Baesemann (1985). The zone is restricted to an approximate 2-meter interval between samples 87 and 90 (Figure 5 and Table 1). The occurrence of *Neolochriea hisaharui* in sample 89 provides a direct correlation to the *Neolochriea koikei* Zone in the Hina Limestone of Japan (Mizuno, 1997).

The appearance of *Neognathodus symmetricus* in sample 90 defines the base of the *symmetricus* Zone of Lane (1967). This is the level at which *D. noduliferus* s. l. appears at the Edale (Higgins, 1975, Figure 3) and Stonehead Beck (Varker et al., 1991, Figure 1, sample 26032) sections in England.

Foraminifers

Beds below the Mid-Carboniferous boundary contain an abundant archaediscacean foraminiferal assemblage that is dominated by the eosigmoilines *Eosigmoilina robertsoni* and *Brenckleina rugosa*. Operationally, these two species have been considered to be latest Mississippian indicators, but they disappear respectively in samples 62 and 63 above the GSSP and the Mid-Carboniferous (Mississippian-Pennsylvanian) boundary as defined by the conodonts. The same relationship has also been noted in Idaho (Skipp et al., 1985) and Arctic Alaska (Harris et al., 1997; Baesemann et al., 1998). *Globivalvulina bulloides,* which descended from the *Biseriella parva* group, appears above the boundary in sample 67A at the base of TR Sequence 4. In Japan (Mizuno & Ueno, 1997), Arctic Alaska (Harris et al., 1997; Baesemann et al., 1998), the Pyrenees (Perret, 1993), and possibly the Donets Basin (Vdovenko et al. 1990), *G. bulloides* first occurs slightly below the boundary. Therefore, although *G. bulloides* is a useful marker to approximate the boundary, its appearance is not consistent relative to *D. noduliferus* s. l. *Millerella pressa* and *M. marblensis* appear respectively in samples 83 and 85 (8.75 and 9.75 meters above the GSSP), although some poorly oriented millerellins found lower in the Pennsylvanian may possibly belong to these species. They probably evolved from primitive *Millerella*, which first appeared in the Late Mississippian. A

Table 1 Detailed conodont occurrence chart in a 150-meter interval that includes the Mid-Carboniferous boundary GSSP at Arrow Canyon. Samples are shown along top of spreadsheet and are the same as those shown partly on Figures 6. The position of samples 79–102 are not illustrated on aFigure 6 and lie from 90.00 to 108.95 meters above the base of the Indian Spring. Individual sample measurements within the measured section are available in Brenckle et al, (1997a,b, Appendix 2). Names of conodont species occurring in this interval at Arrow Canyon are shown along the far-left column. Key lithic and biostratigraphic horizons are shown in heavier black lines. Explanatory comments are given on the spreadsheet.

Taxon \ Sample #	1	5	8	10	11	14	19	21	24	26	29	31	35	37	39	42	45	47	51	53	55	57	58	59	59a	60	60	61
Gnathodus texanus	25																											
Cavusgnathus sp.	6	1					2																					
Spathodgnathodus sp.	2	2						1																				
Gnathodus girtyi simplex		1			2		3	15	1				1	3	9	4	7		7	3	11	2	4	12		18	4	5
Gnathodus bilineatus		2		8						1																		
Adetognathus unicornis			1	1	6	6	35	24			1	1	120		1			1	5									
Spathognathodus minutus			1	2									7															
Neoprioniodus n. sp.				2																								
Apatognathus n. sp.				1																								
Spathognathodus campbelli				9							1																	
Spathognathodus cristulus				1									27															
Gnathodus bilineatus gamma					8			2						1														
Gnathodus bilineatus delta					4																							
Gnathodus bilineatus bollandensis					13									2														
Gnathodus bilineatus beta								1	1																			
Rhachistognathus muricatus								3						13	18	9	17	5	33	7	1	1	1	8	1	63	12	42
Cavusgnathus naviculus								1																				
Neoprioniodus camurus								1																				
Synprioniodina denticamura								2					6															
Hindeodella sp.								1																				
Gnathodus bilineatus alpha									1																			
Gnathodus girtyi									1																			
Cavusgnathus altus													119															
Cavusgnathus unicornis													35															
Ozarkodina compressa															2													
Adetognathus lautus																	4		8	7	1	2	5	3	1	10	5	7
Adetognathus gigantus																	2	3	10	3	1	1	1	8	1	18	4	11
G. girtyi simplex==>G. defectus																	2		9	4				12		7		14
G.girtyi simplex==>D. noduliferus																	3		6	8				8		11		4
Hibbardella ortha																		1										
Ozarkodina sp.																		1						1				11
Gnathodus defectus																			2	5			5	7		8	1	6
Adetognathus tytthus																					4		8					
Cavusgnathus n. sp.																								1				8
Synprioniodina sp.																										1		
Declinognathodus noduliferus inaequalis																												
Rh. muricatus==>Rh. websteri																												
Rhachistognathus primus																												
Rhachistognathus prolixus																												
Rhachistognathus websteri																												
Neoprioniodus n. sp.																												
Adetognathus spathus																												
Ozarkodina n. sp.																												
Synprioniodina microdentata																												
Neoprioniodus sp.																												
Idiognathoides sulcatus																												
Neolochriea hisaharui																												
Idiognathoides sinuatus																												
Rhachistognathus minutus																												
Rhachistognathus havlenai																												
Rhachistognathus higginsi																												
Neognathodus bassleri symmetricus																												
Rhachistognathus sp.																												
Idiognathoides corrugatus																												
Idiognathoides attenuatus																												
Neoprioniodus conjunctus																												

Taxon \ Sample #	61	61c	61a	62	63	64	65	68	73	74	76	79	83	85	86	87	89	90	91	92	95	96	97	98	99	102
Gnathodus texanus																										
Cavusgnathus sp.																										
Spathodgnathodus sp.																										
Gnathodus girtyi simplex	12	3	22		3	38		2	4		23															
Gnathodus bilineatus																										
Adetognathus unicornis																										
Spathognathodus minutus																										
Neoprioniodus n. sp.																										
Apatognathus n. sp.																										
Spathognathodus campbelli																										
Spathognathodus cristulus																										
Gnathodus bilineatus gamma																										
Gnathodus bilineatus delta																										
Gnathodus bilineatus bollandensis																										
Gnathodus bilineatus beta																										
Rhachistognathus muricatus	26	10	30	13	16	6	2	15	3	2	16	10	13	16	19	3	16			12						
Cavusgnathus naviculus																										
Neoprioniodus camurus																										
Synprioniodina denticamura																										
Hindeodella sp.																						1		1		
Gnathodus bilineatus alpha																										
Gnathodus girtyi																										
Cavusgnathus altus																										
Cavusgnathus unicornis																										
Ozarkodina compressa																										
Adetognathus lautus	16	10	1		2	1		2	9	3		7			4	1				3				4		
Adetognathus gigantus	16	11		4		1		1	2	2		11	4	2	25					3				7		
G. girtyi simplex==>G. defectus	6	5		10	2	6			2		4															
G.girtyi simplex==>D. noduliferus	9			8		4		10	5		7															
Hibbardella ortha																										
Ozarkodina sp.								1					3						2		1					1
Gnathodus defectus	1	8	103		13	9				3	2															
Adetognathus tytthus		2		4																4						
Cavusgnathus n. sp.																										
Synprioniodina sp.																										
Declinognathodus noduliferus inaequalis	7			5									8				14			7						4
Rh. muricatus==>Rh. websteri	6																									
Rhachistognathus primus				7	2			2	6		3	9	5	2	1		2									1
Rhachistognathus prolixus				8								13					7						1	2		15
Rhachistognathus websteri				10	3				5	7			7	3					1		1	1		9	1	10
Neoprioniodus n. sp.				1									1		7				1					4		
Adetognathus spathus					23									19	6		2		25		19			5	7	1
Ozarkodina n. sp.					1									1												
Synprioniodina microdentata								1							4											
Neoprioniodus sp.								1																		
Idiognathoides sulcatus																	1									
Neolochriea hisaharui																	2									2
Idiognathoides sinuatus																	1									4
Rhachistognathus minutus																	1	6								
Rhachistognathus havlenai																		1								
Rhachistognathus higginsi																		9								
Neognathodus bassleri symmetricus																		12								1
Rhachistognathus sp.																						2				
Idiognathoides corrugatus																								2	1	
Idiognathoides attenuatus																										2
Neoprioniodus conjunctus																										1

Lower *muricatus* Zone

Upper *muricatus* Zone

noduliferus-primus Zone

symmetricus Zone

unicornis Zone

sinuatus-minutus Zone

Mid-Carboniferous Boundary

Lowest occurrence of *D. noduliferus s. l.* at Edale and Stonehead Beck, England.

Late Serpukovian-Permian, Bird Spring Formation

Top Type Mississippian, top Bramwell Member, Bluestone Limestone in the type area of the Pennsylvanian, and ~top *Eumorphoceras* Zone in UK and Europe.

Late Visean, Battleship Wash Form.

Late Serpukovian, Indian Springs Formation

Mississippian (L. Carboniferous)

Pennsylvanian (U. Carboniferous)

ARROW CANYON, NEVADA
CONODONTS AT THE MID-CARBONIFEROUS BOUNDARY
By: J. F. Baesemann and H. Richard Lane

representative suite of calcareous foraminifers, algae and incertae sedis from the boundary interval is figured in Brenckle et al. (1997a, b) and sample occurrences can be found in Appendix 2 of the same publications.

Cephalopods

Webster & Lane (1967) have summarized ammonoid occurrences at Arrow Canyon and nearby sections. Most importantly, Titus et al. (1997) reported eumorphoceratid-homoceratid zonal faunas from a trenched section at South Syncline Ridge (SSR), 110 km west of Arrow Canyon. At South Syncline Ridge, *Eumorphoceras* Zone ammonoids do not occur at the section but are known to be present in nearby strata at a level approximately 30 meters below the lowest homoceratids, which are interpreted to be latest Mississippian in age (Titus et al., 1997).

Palynology

Palynomorphs were not recovered in any of the siliciclastic samples taken from the Arrow Canyon measured section, but their absence most likely can be attributed to oxidation caused by desert weathering. A borehole (Texaco Federal No. 1, SEC. 18-T12S-R65E, Lincoln Co., Nevada) 15-km north of Arrow Canyon yielded palynomorphs throughout the Indian Springs-lower Bird Spring interval (Gerry Waanders, unpublished information 1984). A coring program is needed at Arrow Canyon to provide unweathered material for palynological analysis so that this important fossil group can be calibrated to the boundary section.

Brachiopods

Brachiopods, although restricted provincially, are very useful in delineating the Mid-Carboniferous Boundary. Gordon et al. (1982) noted four geographically distinct brachiopod successions within the conterminous United States, each exhibiting major phylogenetic change at the Mississippian-Pennsylvanian (Mid-Carboniferous) Boundary. In the Great Basin, and specifically at Arrow Canyon, the *Rhipidomella nevadensis* Zone (Sadlick, 1955, p. 54) is latest Mississippian in age and extends to the Mid-Carboniferous Boundary GSSP where it is overlain by the *Rugoclostus* Zone of Early Pennsylvanian age (Gordon et al., 1982). The top of the *Rhipidomella nevadensis* Zone has been used widely by USGS cartographers to precisely identify the Mississippian-Pennsylvanian (=Mid-Carboniferous Boundary) in the Great Basin.

Comparison to the Arrow Canyon Conodont succession

The conodont succession across the Mid-Carboniferous Boundary at Arrow Canyon in many ways resembles that found elsewhere in North America and parts of the Far East. Northern European conodont faunas, however, are much less diverse, compositionally different, and their correlation to other areas more controversial. Cases in point are the closely studied Edale and Stonehead Beck sections in England, the latter of which is an auxiliary section for the Mid-Carboniferous Boundary. While these sections are claimed to contain a continuous depositional regime across the boundary based on the ammonoid succession (Riley et al., 1987; Varker, Owens and Riley, 1991; Manger and Sutherland, 1992), the conodont distribution suggests a different age interpretation.

Late Mississippian conodont faunas in Britain are dominated by a few long ranging platform species that are difficult to relate precisely to conodont faunas of similar age in other parts of the Eastern Hemisphere and North America. The youngest, unequivocally dated British Mississippian conodont in terms of the North American zonation of Lane and Baesemann (1985) is *Cavusgnathus naviculus*, which was reported by Higgins (1975) from the Castleton section where it is associated with the platform species *Gnathodus bilineatus bollandensis*. This association was named the *G. b. bollandensis-C. naviculus* Zone (Higgins, 1975) that is equivalent to the late Mississippian *naviculus* Zone of Baesemann and Lane (1985), and correlated to the *Eumorphoceras* ammonoid zone. Only *G. b. bollandensis* occurs in the same biostratigraphic level at Edale (Higgins, 1975) in the sample below a bed containing the conodont *Rhachistognathus minutus* and a single, poorly preserved ammonoid assigned to *Cravenoceras* (Hudson and Cotton, 1945). Based on this one poorly preserved ammonoid, the bed has always been correlated to the highest part of the *Eumorphoceras* Zone (Higgins, personal communication, 1981, as reported by Lane and Baesemann, 1985), thus suggesting that the first occurrence of *Rh. minutus* is within the Late Mississippian in England. *Declinognathodus noduliferus* s. l. enters at a slightly higher level in sample ED 5 of Higgins (1975, p. 83, Figure 3). At Stonehead Beck, *Rh. minutus* occurs in eight samples between highest *G. b. bollandensis* (sample 26974) and lowest *Declinognathodus noduliferus* s. l. (=*D. inaequalis*) in sample 26032 (Varker et al., 1991, Figure 1). The lowest occurrence of *Rh. minutus* within this eight sample interval is placed within highest *Eumorphoceras* Zone by Varker et al (1991), even though the sample is in an interval lacking ammonoids (Riley et al., 1987). The upper seven occurrences of *Rh. minutus* below *D. noduliferus* s. l. at Stonehead Beck are in strata dated as belonging in the lower *Homoceras* Zone. The latter seven occurrences are also considered Mississippian because they lie below *D. noduliferus* s. l. (Riley et al., 1987, Figure 7; Varker et al., 1991, Figure 1).

These correlations conflict with conodont interpretations. Outside Great Britain, *Rh. minutus* first appears within the Early Pennsylvanian *sinuatus-minutus* conodont zone (Baesemann and Lane, 1985) that is separated from the *naviculus* Zone by the Late Mississippian *unicornis*, Lower *muricatus*, and Upper *muricatus* zones and the earliest Pennsylvanian *noduliferus-primus* Zone. Faunas of the *sinuatus-minutus* Zone are widespread in the Early Pennsylvanian and are commonly the first to occur above a depositional break separating Mississippian-Pennsylvanian strata, especially in northern and western Europe. The assignment of *Rh. minutus* to the Mississippian in Great Britain would necessitate a very diachronous appearance for the species worldwide, yet the evidence supporting such a scenario is tenuous. The *Eumorphoceras* age call at Edale is based on a poorly preserved ammonoid specimen from a sample that lacks a supporting diagnostic assemblage of either cephalopods or other fossils. At Stonehead Beck the *Eumorphoceras* age of the initial *Rh. minutus* sample is based only on its stratigraphic position below *Homoceras* because other fossils are absent. Nevertheless, all these *Rh. minutus* samples, including the one within the lower *Homoceras* Zone at Stonehead Beck, would seemingly be Mississippian because they appear before *D. noduliferus* s. l. However, at both localities the latter species occurs simultaneously within the range of *Neognathodus symmetricus*, whose appearance defines the next Pennsylvanian conodont zone above *sinuatus-minutus*.

Our interpretation of these occurrences reiterates the conclusions of Baesemann and Lane (1985) and Lane et al. (1985b) that there is a major break in the British section separating Mississippian *G. bilineatus bollandensis* faunas from Pennsylvanian *Rh. minutus*. The missing interval at Edale and Stonehead Beck represents at least 84 m of section at Arrow Canyon encompassing the unicornis through the *noduliferus-primus* zones. In addition, the appearance of *D. noduliferus* s. l. in Britain is delayed until the base of the symmetricus Zone so that the initial part of its range at Arrow Canyon is unrepresented there.

The conclusion of Krumhardt et al. (1996) that *Rh. minutus* appears earlier in Europe than North America is herein rejected. Not only does this contradict their Arctic Alaska distributional data that reinforces the first evolutionary appearance of *Rh. minutus* to be above the *noduliferus-primus* zone, but also invokes a complex migrational pattern to account for range variations in *Rh. minutus*, *D. noduliferus* s. l., and *N. symmetricus*, and for the lack of typical post-*naviculus* Late Mississippian conodonts in Britain. A more parsimonious hypothesis is that there is an unrecognized gap in the ammonoid succession. Rather than belonging to the *Eumorphoceras* Zone, the first *Rh. minutus* in Britain represents an initial

Pennsylvanian transgression within the lower *Homoceras* Zone. This argument is bolstered by the co-occurrence of homoceratids and typical Mississippian conodonts at the South Syncline Ridge section (Titus et al., 1997) and at the Aksu section in Uzbekistan (Nemirovskaya and Nigmadganov, 1994), which may represent early *Homoceras* sequences not preserved in Britain.

Another serious problem with the British sections concerns continuity of fossil occurrence. Ramsbottom (1969, p. 219, Figure 3) noted the marine/non-marine cyclicity of the British Namurian and the existence throughout of thick stratigraphic intervals that are barren of fossils separating very thin marine intervals (bands) containing cephalopods. At both Edale and Stonehead Beck, there are major barren intervals across the Mid-Carboniferous Boundary Higgins (1975, p. 84). Edale section is very discontinuous, consisting of 9 samples taken from small isolated exposures along a 5.5-kilometer stretch of Crowden Brook and River Noe. Intervals containing no recorded fossils at Edale (Higgins, 1975, Figure 1) separate:

1. the last definite Mississippian conodonts from the first occurrence of *Rh. minutus* and,
2. the first occurrence of *Rh. minutus* from the lowest occurrence of *H. subglobosum*.

At Stonehead Beck, barren intervals include:

1. an approximate 10 meter interval barren of cephalopods between the top of *Eumorphoceras* and the base of *Homoceras* (from approximately 25.5 meters to approximately 15.5 meters of Riley, 1987, Figure 7),
2. an approximate two+ meter interval barren of palynomorphs straddling the *Eumorphoceras-Homoceras* transition (samples 26975 to 27211 of Varker et al., 1991, Figure 1) and,
3. an approximate 1.5 meter interval barren of conodonts immediately below the appearance of *Rh. minutus*.

These gaps in the fossil succession coupled with the low conodont faunal diversity cast doubt on the suitability of these sections for boundary definition.

Summary

The Mid-Carboniferous Boundary Working Group of the Subcommission on Carboniferous Stratigraphy was established after the 10th Congress on Carboniferous Stratigraphy and Geology in Madrid, Spain, 1983. The charge of the Working Group was to find a GSSP for a boundary in the middle of the Carboniferous System that would coincide with the evolutionary first appearance of the conodont *Declinognathodus noduliferus* s. l. in its evolutionary sequence from *Gnathodus girtyi simplex*. The Working Group completed its charge in 1995 when it recommended to the SCCS that a GSSP for the middle of the Carboniferous be established at 82.90 meters above the top of the Battleship Wash Formation (base of sample 61B, Figs. 4-6 and Table 1, herein) and within the lower part of the Bird Spring Formation at Arrow Canyon, Nevada, USA. This GSSP proposal was overwhelmingly approved by the voting members of the Subcommission on Carboniferous Stratigraphy and later ratified by the Executive Committee of the IUGS in January 1996.

The Mid-Carboniferous GSSP horizon fulfills all of the requirements of a boundary stratotype (Cowie et al., 1986; Remane et al., 1996). Comparison of conodont occurrences between Arrow Canyon and England suggest that at least an 84-m interval across the Mid-Carboniferous Boundary at Arrow Canyon is unrepresented in the British sections at Edale and Stonehead Beck. This gap indicates a major hiatus within the standard British ammonoid sequence equivalent to the *unicornis* through *noduliferus-primus* conodont zones. Oldest *Homoceras* Zone conodont faunas in England are thus no older than the *sinuatus-minutus* Zone (Pennsylvanian).

Acknowledgements

We acknowledge Prof. Philip Heckel, The University of Iowa, for multiple in depth critiques of the manuscript and Jurgen Remane for pertinent comments on an early draft.

REFERENCES

Austin, R., Conil, R., Groessens, E. and Pirlet, H., 1974, Étude Biostratigraphique de L'Encrinite de Tramaka: Bull. Soc. Belge Géol. Paléont., Hydrol. T. 83, pp. 113-129.

Baesemann, J. F., Brenckle, P. L., and Gruzlovic, P. D., 1998, Composite standard correlation of the Mississippian-Pennsylvanian (Carboniferous) Lisburne Group from Prudhoe Bay to the eastern Arctic National Wildlife Refuge, North Slope, Alaska, *in* Clough, J. G., and Larson, F (eds.), Short notes on Alaska geology 1997: Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys, Professional Report 118, pp. 23-36.

Baesemann, J. F. & Lane, H. R., 1985, Taxonomy and evolution of the genus *Rhachistognathus* Dunn (Conodonts; Late Mississippian to early middle Pennsylvanian), *in* Lane, H. R. and Ziegler, W., eds., Toward a Boundary in the Middle of the Carboniferous: Stratigraphy and Paleontology: Cour. Forsch.-Inst. Senckenberg, Bd. 74, pp. 93-136.

Brenckle, P. L., Baesemann, J. F., Lane, H. R., West, R. R., Webster, G. D., Langenheim, R. L., Brand, U., and Richard, B. C., 1997a, Arrow Canyon, the Mid-Carboniferous Boundary Stratotype, *in* Brenckle, P. L. and Page, W. R.,eds., Paleoforams '97 Guidebook: Post-Conference Field Trip to the Arrow Canyon Range, Southern Nevada U. S. A.: Cushman Foundation Foraminiferal Research Supplement to Special Publication No. 36, pp. 13-32

Brenckle, P. L., Baesemann, J. F., Lane, H. R., West, R. R., Webster, G. D., Langenheim, R. L., Brand, U., and Richard, B. C., 1997b, Arrow Canyon, the Mid-Carboniferous Boundary Stratotype: XIIIth International Congress, Carboniferous Stratigraphy and Geology, Krakow (1995) Proceedings, part 3, pp. 149-164.

Collinson, C., Scott, A. J. and Rexroad, C. B., 1962, Six Charts Showing Biostratigraphic Zones, and Correlations Based on Conodonts from the Devonian and Mississippian Rocks of the Upper Mississippi Valley: Ill. St. Geol. Surv., Circ. 328, pp. 32.

Cowie, J. W., Ziegler, W., Boucot, A. J., Bassett, M. G. & Remane, J., 1986, Guidelines and Statutes of the International Commission on Stratigraphy (ICS): Cour. Forsch.-Inst. Senckenberg, 83, pp. 1-14.

Gordon, M., Jr., Henry, T. W. and Sutherland, P. K., 1982, Brachiopod Zones Delineating the Mississippian-Pennsylvanian Boundary in the United States, *in* Ramsbottom, W. H. C., Saunders, W. B and Owens, B., eds., Biostratigraphic Data for a Mid-Carboniferous Boundary: ICS Subcommission on Carboniferous Stratigraphy Biennial Meeting, Leeds, England (1981), pp. 69-76.

Embry, A. F., 1993, Transgressive-regressive (T-R) sequence analysis of the Jurassic succession of the Sverdrup Basin, Canadian Arctic Archipelago: Canadian Journal of Earth Sciences, v. 30, pp. 301-320.

Embry, A. F. and Johannessen, E. P., 1992, T-R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic-Lower Jurassic succession, western Sverdrup Basin, Arctic Canada, *in* Vorren, T.O., Bergsager, E., Dahl-Stamnes, O. A., Holter, E., Johanasen, B., Lie, E. and Lund T. B., eds., Arctic Geology and Petroleum: Norwegian Petroleum Society (NPF), Special Publication no. 2, pp. 121-146.

Ettensohn, F.R., Dever, G.R., Jr., and Grow, J.S., 1988, A paleosol interpretation for profiles exhibiting subaerial exposure "crusts" from the Mississippian of the Appalachian Basin, *in* Reinhardt, J. and Sigleo, R., eds., Paleosols and Weathering Through Geologic Time: Principals and Applications: Geological Society of America Special Paper 216, pp. 49-79.

Fluegel, E., 1982, Microfacies analysis of limestones: Springer-Verlag, Berlin, pp. 1-633.

Gordon, M., Jr., Henry, T. W. and Sutherland, P. K., 1982, Brachiopod Zones Delineating the Mississippian-Pennsylvanian Boundary in the United States, *in* Ramsbottom, W. H. C., Saunders, W. B. and Owens, B., eds., Biostratigraphic Data for a Mid-Carboniferous Boundary: ICS

Subcommission on Carboniferous Stratigraphy Biennial Meeting Leeds, England (1981), pp. 69-76.

Harris, A. G., Brenckle, P. L., Baesemann, J. F., Krumhardt, A. P. and Gruzlovic, P. D., 1997, Comparison of Conodont and Calcareous Microfossil Biostratigraphy and Lithostratigraphy of the Lisburne Group (Carboniferous), Sadlerochit Mountains, Northeast Brooks Range, Alaska, *in* Dumoulin, J. A. and Gray, J. L. (eds.), Geologic Studies in Alaska by the United States Geological Survey, 1995: U. S. Geological Survey Professional Paper 1574, pp. 195-220.

Higgins, A. C., 1975, Conodont Zonation of the late Visean-early Westphalian Strata of the South and Central Pennines of Northern England: Geol. Surv. Great Britain, Bull. 53, pp. 1-90.

Higgins, A. C., 1982, A Mid-Carboniferous Boundary in the Western Europe Conodont Sequence, *in* Ramsbottom, W. H. C., Saunders, W. B. and Owens, B. (eds.), Biostratigraphic Data for a Mid-Carboniferous Boundary: ICS Subcommission on Carboniferous Stratigraphy Biennial Meeting, Leeds, England (1981), pp. 13-14.

Hudson, R. G. S. and Cotton, G., 1945, The Carboniferous Rocks of the Edale Anticline, Derbyshire: Q. Jour. Geol. Soc. London, V. 101, pp. 1-36.

Krumhardt, A. P., Harris, A. G. and Watts, K. F., 1996, Lithostratigraphy, Microlithofacies, and Conodont Biostratigraphy and Biofacies of the Wahoo Limestone (Carboniferous), Eastern Sadlerochit Mountains, Northeast Brooks Range, Alaska: U. S. Geological Survey Professional Paper 1568, pp. 1-70.

Lane, H. R., 1967, Uppermost Mississippian and lower Pennsylvanian Conodonts from the Type Morrowan Region, Arkansas: Jour. Paleont., v. 41, pp. 920-942.

Lane, H. R. and Baesemann, J. F., 1982, A Mid-Carboniferous Boundary Based on Conodonts and Revised Intercontinental Correlations, *in* Ramsbottom, W. H. C., Saunders, W. B., Owens, B. (eds.), Biostratigraphic Data for a Mid-Carboniferous Boundary: ICS Subcommission on Carboniferous Stratigraphy Biennial Meeting, Leeds, England (1981), pp. 6-12.

Lane, H. R., Baesemann, J. F., Brenckle, P. L. and West, R. R., 1985a, Arrow Canyon, Nevada: A Potential Mid-Carboniferous Boundary Stratotype: Xth International Congress, Carboniferous Stratigraphy and Geology, Madrid (1983), v. 4, pp. 429-440.

Lane, H. R., Baesemann, J. F. and Groves, J. G., 1985b, Is the Base of the *Reticuloceras*-Zone a Reliably Recognizable Biostratigraphic Level? *in* Lane, H. R. and Ziegler, W. (eds.), Toward a Boundary in the Middle of the Carboniferous: Stratigraphy and Paleontology: Cour. Forsch. Inst. Senckenberg, Bd. 74, pp.137-148.

Lane, H. R., Bouckaert, J., Brenckle, P., Einor, O. L., Havlena, V., Higgins, A. C., Yang J.-Z., Manger, W. L., Nassichuk, W., Nemirovskaya, T., Owens, B., Ramsbottom, W. H. C., Reitlinger, E. A. and Weyant, M., 1985c, Proposal for an International Mid-Carboniferous Boundary: Xth International Congress, Carboniferous Stratigraphy and Geology, Madrid (1983), v. 4, pp. 323-339.

Manger, W. L. and Sutherland, P. K., 1992, Analysis of Sections Presumed to be Complete Across the Mississippian-Pennsylvanian Boundary, Southern Midcontinent: Oklahoma Geol. Surv Circular 94, pp. 69-79.

Manger, W. L., Weyant, M., and Pareyn, C, 1985, Mid-Carboniferous Ammonoid Biostratigraphy, Bechar Region, Algeria, *in* Lane, H. R. and Ziegler, W. (eds.), Toward a Boundary in the Middle of the Carboniferous: Stratigraphy and Paleontology: Cour. Forsch. Inst. Senckenberg, Bd. 74, pp. 181-195.

Mizuno, M., 1997, Conodont Faunas across the Mid-Carboniferous Boundary in the Hina Limestone, Southwest Japan: Paleontological Research, v. 1, pp. 237-259.

Mizuno, Y. and Ueno, K., 1997, Conodont and Foraminiferal Faunal Changes across the Mid-Carboniferous Boundary in the Hina Limestone Group, Southwest Japan. XIIIth International Congress on Carboniferous-Permian, Krakow (1995), Proceedings, pp. 189-205.

Nemirovskaya, T. I., 1987, Konodonty nizhney chasti bashkirskogo yarusa Donbassa (Lower Bashkirian conodonts of Donets Basin). Bulletin MOIP, Otdel Geology, v. 64. pp. 106-126.

Nemirovskaya, T. I. and Nigmadganov, I. M., 1994, The Mid-Carboniferous Conodont Event: Cour Forsch. Inst. Senckenberg, Bd. 168, pp. 247-272.

Newell, N. D., Purdy, E. G. and Imbrie, J., 1960, Bahamian oolitic sand: The Journal of Geology, v.68, pp. 481-497.

Paproth, E., Engel, B. A., Lane, H. R. and Brenckle, P. L., 1995, Proposal for a Mid-Carboniferous Boundary Stratotype and Point: Unpublished submission of the results of the Mid-Carboniferous Boundary stratotype search for ratification by the IUGS Executive Committee, 21 p.

Perret, M. F., 1993, Recherches Micropaléontologiques et Biostratigraphiques (Conodontes-Foraminfères) dans le Carbonifère Pyrénéen: Strata, Series 2, v. 21, pp. 1-597.

Ramsbottom, W. H. C., 1969, The Namurian of Britain: Sixiéme Congrès International de Stratigraphie et de Géologie du Carbonifère, Sheffield, V. 1, pp. 219-232

Remane, J., Bassett, M. G., Cowie, J. W., Gohrbundt, K. H., Lane, H. R., Michelsen, O. and Wang Naiwen, 1996, Revised Guidelines for the Establishment of Global Chronostratigraphic Standards by the International Commission on Stratigraphy (ICS): *Episodes*, V. 19, pp. 77-81.

Repetski, J. E. and Henry, T. W., 1983, A Late Mississippian Conodont Faunule from Area of Proposed Pennsylvanian System Stratotype, Eastern Appalachians: Fossils and Strata, No. 15, pp. 169-170.

Rexroad, C. B. and Burton, R. C., 1961, Conodonts from the Kinkaid Formation (Chester) in Illinois: Jour. Paleont., v. 35, pp. 1143-1158.

Rexroad, C. B. and Merrill, G. K., 1985, Conodont Biostratigraphy and paleoecology of Middle Carboniferous Rocks in Southern Illinois, *in* Lane, H. R. and Ziegler, W., eds., Toward a Boundary in the Middle of the Carboniferous: Stratigraphy and Paleontology: Cour. Forsch. Inst. Senckenberg, Bd. 74, pp.35-64.

Richards, B. C., Barclay, J.E., Bryan, D., Hartling, A., Henderson, C.M. and Hinds, R.C., 1994, Chapter 14 - Carboniferous Strata of the Western Canada Sedimentary Basin, *in* Mossop, G.D. and Shetson, I., eds., Geological Atlas of the Western Canada Sedimentary Basin: Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, pp. 221-250.

Riley, N. J., Varker, W. J., Owens, B., Higgins, A. C. and Ramsbottom, W. H. C., 1987, Stonehead Beck, Cowling, North Yorkshire, England: A British Proposal for the Mid-Carboniferous Boundary Stratotype, *in* Brenckle, P. L., Lane, H. R. and Manger, W. L., eds., Selected Studies in Carboniferous Paleontology and Biostratigraphy: Cour. Forsch. Inst. Senckenberg, Bd. 98, pp. 159-177.

Sadlick, W., 1955, Carboniferous Formations of Northeastern Uinta Mountains: Wyoming Geol. Assoc. Guidebook, Green River Basin Field conference, pp. 49-58.

Skipp, B., Baesemann, J. F. and Brenckle, P. L., 1985, A Reference Area for the Mississippian-Pennsylvanian (Mid-Carboniferous) Boundary in East-Central Idaho, U. S. A.: Xth International Congress, Carboniferous Stratigraphy and Geology, Madrid (1983), v. 4, pp. 403-428.

Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geological Society of America, Bulletin, v. 74, pp. 93-114.

Titus, A. L., Webster, G. D., Manger, W. L. and Dewey, C. P., 1997, Biostratigraphy of the Mid-Carboniferous Boundary, South Syncline Ridge Section, Nevada Test Site (NTS), Southern Nye County, Nevada, United States: XIIIth International Congress on Carboniferous-Permian, Krakow (1995) Proceedings, pp. 207-213.

Vail, P. R., Mitchum R. M. Jr. and Thompson, S. III, 1977, Seismic stratigraphy and global changes of sea level, part 4: global cycles of relative changes of sea level, *in* Payton, C. E. ed., Seismic Stratigraphy–Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists, Memoir 26, pp. 83-97.

Van Wagoner, J. C., Posamentier, H. W., Mitchum, R. M., Vail, P. R., Sarg, J. F., Loutit, T. S. and Hardenbol, J., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions, *in* Wilgus, C. K., Hastings, B. S., Posamentier, H. W., Van Wagoner, J. C., Ross, C. A. and Kendall C. G. St. C. eds., Sea-level Changes: an Integrated Approach: Society of Economic Paleontologists and Mineralogists, Special Publication no. 42, pp. 39-45.

Varker, W. J. and Austin, R. L., 1975, The Significance of *Adetognathus unicornis* (Rexroad and Burton) in the Mirk Fell Beds (E2c) of the North of England: J. Earth Sciences, Leeds, pp. 399-408.

Varker, W. J., Owens, B. and Riley, N. J., 1991, Integrated Biostratigraphy for the Proposed Mid-Carboniferous Boundary Stratotype, Stonehead Beck, Cowling, North Yorkshire, England, *in* Brenckle, P. L. and Manger, W. L. eds, Intercontinental Correlation and Division of the Carboniferous System: Cour. Forsch. Inst. Senckenberg, Bd. 130, pp. 221-235.

Vdovenko, M. V., Aisenverg, D. E., Nemirovskaya, T. I. and Poletaev, V. I., 1990, An Overview of Lower Carboniferous Biozones of the Russian Platform: Jour. Foraminiferal Research, v. 20, no. 3, pp. 184-194.

Webster, G. D. and Lane, N. G., 1967, Mississippian-Pennsylvanian Boundary in Southern Nevada, *in* Teichert, C. and Yochelson, E. L. eds., Essays in Paleontology and Stratigraphy, R. C. Moore Commemorative Volume: Department of Geology: University of Kansas Special Publication, v. 2, pp. 502-522.

Weyant, M.,1982, A Proposal for a Major Boundary in the Carboniferous System based upon Conodont Evidence from the Bechar Basin (Algeria), *in* Ramsbottom, W. H. C., Saunders, W. B. and Owens, B. eds, Biostratigraphic Data for a Mid-Carboniferous Boundary: ICS Subcommission on Carboniferous Stratigraphy Biennial Meeting, Pub. 8, Leeds, England (1981), pp. 19-21.

Dr. H. Richard Lane *spent 29 years with Amoco where he rose from Research Scientist to Worldwide Manager of Paleontology and Stratigraphy. He specializes in mid-Paleozoic conodonts and stratigraphy and served as the Chairman of the International Commission on Stratigraphy's Mid-Carboniferous Boundary Working Group. He is a Titular Member of the Subcommission on Carboniferous Stratigraphy and the First Vice Chairman of the International Commission on Stratigraphy. Currently Dr. Lane is employed as the Program Director for Geology and Paleontology at the National Science Foundation in Arlington, Virginia.*

Dr. Paul Brenckle *specializes in the evolution, morphology and biostratigraphy of foraminifers and algae from the Late Devonian to Early Pennsylvanian. Following his retirement in 1997 from Amoco Production Company, he consults internationally on these microfossils and continues research on their distribution within North America and Eurasia. Dr. Brenckle is a longstanding corresponding member of the Carboniferous Subcommission and a titular member since 1992.*

Baesemann J.F. *is a bio-stratigrapher specializing in Carboniferous conodonts. His interests include Paleozoic conodont biostratigraphy, conodont thermal alteration and graphic correlation. He retired from Amoco (now BP Amoco) in 1997 and now resides in Kent, Ohio, USA.*

Barry C. Richards *received his Doctor degree in 1983 from The University of Kansas, USA. He began his geological career as a field geologist with British Columbia Ministry of Energy Mines and Petroleum Resources and worked for them during the summers of 1968 to 1974. From 1974 to 1979, he was employed as a curatorial assistant at the Museum of Invertebrate Paleontology, University of Kansas. From 1979 to the present, he has been employed as a carbonate sedimentologist and stratigrapher by the Geological Survey of Canada (Calgary).*