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Stratigraphy and depositional environments in the Silurian Red Mountain Formation of the southern Appalachian basin, USA

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ABSTRACT

The Red Mountain Formation is an unconformity-bounded unit including all Silurian strata in the Appalachian Valley and Ridge province of Alabama and Georgia. It is also host to the well-known Birmingham iron-ore field. The formation is divided by paraconformities into six members that generally coincide with depositional sequences. From biostratigraphy, the lower four members are established as Llandoverian: Taylor Ridge (Rhuddanian), Duck Springs (? early Aeronian), Birmingham (middle Aeronian–early Telychian), and Ruffner (late Telychian). Upper members are: Rocky Row (Wenlockian) and Sparks Gap (Pridolian). Facies indicate deposition on a storm-dominated shelf with coarse-grained, cross-bedded sandstone in the shoreface passing seaward into hummocky cross-bedded sandstone and shale on the inner shelf, and interbedded shale and graded sandstone or limestone (storm beds) on the outer shelf. Unless truncated by erosion, all Llandoverian sequences consist of thin retrogradational facies successions in transgressive systems tracts and thick progradational successions in highstand systems tracts. Accommodation on the shelf was provided by a combination of flexural subsidence, driven by tectonic loading of the Appalachian orogen during waning stages of the Taconic orogeny and glacial eustasy. It is possible to recognize similar lithofacies and sequences at least as far north as New York State.

Coarse-grained, ferruginous, cross-bedded sandstones (ironstones) occur as sharp-based shoreface facies associated with sequence boundaries; at the base of the transgressive systems tract, or making up the lowstand systems tract or falling stage systems tract. Such shoreface deposits are commonly highly condensed with ooids of

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hematite-chamosite and skeletal debris coated and replaced by hematite. Mineralization was evidently favored by periods of sediment starvation and reworking on wave (transgressive systems tract) and tidal (lowstand systems tract) ravinement surfaces. However, the richest ores in the Birmingham district (Big and Irondale seams) developed in a falling stage systems tract apparently as a consequence of meteoric diagenesis during forced regression.

INTRODUCTION

The Red Mountain Formation of the southern Appalachian Valley and Ridge (Fig. 1) is arguably one of the most notable formations in the southeastern United States, host to the famous iron ores that led to the meteoric development of the Birmingham industrial complex at the end of the nineteenth century (Armes, 1910; McCarl, 1978). Yet, no type section has ever been designated and the stratigraphy is poorly understood. The purpose of this paper is to provide a type section and to formalize stratigraphy as a foundation for future work on the sedimentology of the ironstones and associated facies.

During this trip, we will visit the type area and integrate lithostratigraphic, biostratigraphic, and sequence stratigraphic concepts to provide a better framework for the interpretation of depositional facies. The traverse from Birmingham to Chattanooga will allow us to assess changes in lithofacies and ichnofacies related to water depth on the Silurian shelf, in both vertical and horizontal section. In general, we will proceed from nearshore facies around Birmingham to offshore shelf at Chattanooga (in the correlative Rockwood Formation).

Iron ore, coking coal, and carbonate rock (for flux) were all famously present in Jefferson County, Alabama, and the opening of a geological survey, construction of railroads, and development of mines were related and contemporaneous events (Owen, 1921), although complicated by the Civil War. Beginning with the work of Tuomey (1850), the first state geologist from 1848 to 1857, the opening of the Birmingham ore field is documented by the Geological Survey of Alabama (Smith, 1876a, 1876b; McCalley, 1896, 1897) and later the U.S. Geological Survey (Butts, 1910, 1926, 1927; Butts and Gildersleeve, 1948; Burchard and Butts, 1910; Burchard and Andrews, 1947). These publications remain fundamental to our understanding of the stratigraphy of the Red Mountain Formation.

The name "Red Mountain" was first introduced by Tuomey (1850, p. 10), in the very first publication of the Geological Survey of Alabama, to include Cambrian through basal Carboniferous strata cropping out in Jones and Opossum valleys along the Birmingham anticlinorium. However, Smith (1876a, 1876b) and McCalley (1896, 1897) later restricted it to strata intervening between the Chattanooga Shale (Devonian) and Chickamauga Limestone (Middle Ordovician). While mapping the Birmingham folio, Butts (1910) referred these strata to the Clinton and Rockwood formations, in recognition of correlations with New York and Tennessee, but later substituted the local name Red Mountain (Butts, 1926, 1927). Usage has been standardized since that time (Raymond et al., 1988), and currently includes all Silurian strata within the Valley and Ridge province of Alabama and Georgia. Identical strata in Tennessee are still assigned to the Rockwood Formation (Milici and Wedow, 1977). Strata belonging to the Devonian Frog Mountain Sandstone (Ferrill, 1983; Berdan et al., 1986) and Upper Ordovician Sequatchie Formation (Neathery and Drahovzal, 1985) have sometimes been mistakenly included, but the formation is unambiguously defined by unconformities at the top and bottom.

From the beginning, the main emphasis was on the stratigraphy of the ore beds, and four seams were named from the local mining vernacular: Irondale, Big, Ida, and Hickory Nut (McCalley, 1897; Butts, 1910; Burchard and Butts, 1910). Much confusion arose as terminology, originating from the first mines south (Eureka No 1), and north (McElwain Furnace) of Birmingham, spread to new mines. In particular, the Ida and Hickory Nut seams were confused (Chowns, 2006a). The rest of the formation received little attention, although Butts (1927) attempted to separate Medina and Clinton equivalents on the basis of faunal lists compiled by Ulrich (*in* Butts, 1927). A paper by Reed (1953) is significant for the first attempt to divide the formation into members using the Hickory Nut seam (identified as the Ida) as a datum.

During the early part of the present study, the senior author was guided by R.P. Sheldon (1970, 1971), who measured numerous sections from 1959 to 1964 in the declining years of the ore field. His measured sections were invaluable to the interpretation of stratigraphy presented in this paper. Depending on the situation, thicknesses were either measured directly using a Jacob staff or calculated trigonometrically from dip and outcrop width (measured by tape or alidade). For well-exposed sections, sandstone percentages were estimated by cumulating the total thickness of sandstone per 5 foot interval measured by Jacob staff. Lithologies were confirmed from thin sections and scanning electron microscope with energy-dispersive spectrometer (SEM/EDS).

STRATIGRAPHY

Type Section

None of the early researchers provided a type or reference section for the Red Mountain Formation. Here, we designate the well-studied Red Mountain Expressway cut on the southeast side of Birmingham as the type section (Thomas et al., 1971;

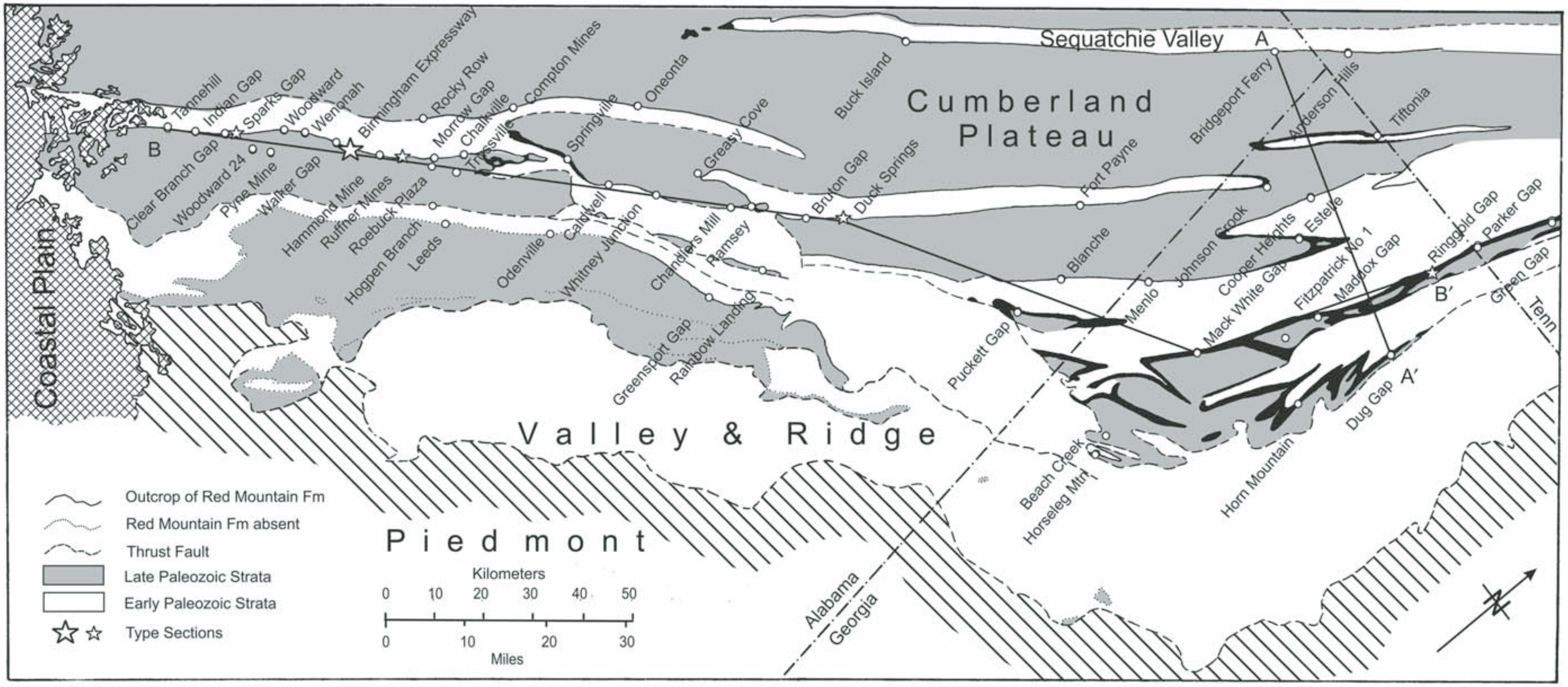


Figure 1. Map showing location of measured sections and stratigraphic cross sections (Figs. 7 and 8). Type sections located by stars. Heavy black lines indicate cross sections A–A′ and B–B′ (after Chowns, 2006b).

Thomas and Bearce, 1986; Chowns and McKinney, 1980; Baarli et al., 1992; and Rindsberg et al., 2007). Located in the middle of the ore field on east Red Mountain, it lies 0.5 miles northeast of the section described and figured by Butts (1926, p. 135; 1927) as "one of the best and most convenient exposures." Although minor amendments have been made (Chowns, 2006a, 2006b; Rindsberg et al., 2007), the unit numbers of Thomas et al. (1971) have been retained for consistency (Figs. 1, 2; Stop 1). All major members are represented except for the youngest.

Lithostratigraphy

The Red Mountain Formation can be divided into six members defined on the basis of lithology and separated by unconformities or ravinement surfaces. Measured stratigraphic columns (Fig. 2) are provided and used to characterize the members. Starting with the oldest these are:

1. Taylor Ridge Member—a generally coarsening- and thickening-upward sequence of shale and sandstone between the basal unconformity, and either a thin distinctive ironstone seam (Crudup seam) or associated channel facies. Named for the section on Interstate Route 75 (I-75) at Ringgold Gap, in Taylor Ridge, northwest Georgia (Chowns, 1972, 1996; Rindsberg and Chowns, 1986).
2. Duck Springs Member—a poorly exposed, mainly shaly interval between the Crudup ironstone and the unconformities and ravinements at the base of the succeeding member. Includes basal channel sandstones in some eastern strike belts. Named for the section on Interstate Route (I-59) through Big Ridge, near the community of Duck Springs north of Gadsden, Alabama (Neathery and Smith, 1971; Chowns and McKinney, 1980; Chowns, 2006a, 2006b).
3. Birmingham Member—a distinctive sequence of fossiliferous sandstones (or limestones) in Alabama passing into reddish-gray shale in Georgia. In the type area, includes the Hickory Nut seam and Big-Irondale seam complex at the base. Named for the Red Mountain Expressway cut in Birmingham, Alabama (Thomas et al., 1971; Chowns and McKinney, 1980; Chowns, 2006a, 2006b).
4. Ruffner Member—a heterolithic sequence of shale and fine-grained sandstone, with minor fossiliferous limestone. Locally, in the type area, includes the Ida seam at the base. Usually the uppermost member, truncated by overlying beds. Named for exposures and drill core at the Ruffner Mines near Irondale, Alabama (Chowns, 2006a, 2006b).
5. Rocky Row Member—red and gray, fine- to coarse-grained sandstone and shale. Formerly mapped as Frog Mountain Sandstone (Devonian) but since shown to be Silurian and included in the Red Mountain Formation (Ferrill, 1984; Berdan et al., 1986; Chowns, 2006a, 2006b). Named for exposures made during road construction (1975) along Carson Road, through Rocky Row, West Red Mountain.
6. Sparks Gap Member—interbedded limestone, sandstone, and shale. Absent from the type section due to limited exposure south of Birmingham. Named for Sparks Gap, Red Mountain, based on descriptions by Ferrill (1984), Berdan et al. (1986), and Stock (1996).

Biostratigraphy

The biostratigraphy of the Red Mountain Formation is based on the ranges of three main brachiopod lineages: *Pentamerus-Pentameroides, Eocoelia*, and *Stricklandia-Costistricklandia* (Baarli et al., 1992; Baarli, 1996). Some additional information is provided by conodonts (Manzo, 2002; Manzo et al., 2002). Because they are divided by unconformities, members are generally characterized by distinct faunas, although some species range through several members.

Index fossils are rare in the Taylor Ridge Member, but the occurrence of *Stricklandia lens lens* in unit 51 at Duck Springs (see field-trip Stop 6) establishes that this member is Rhuddanian (A3–4). No useful macrofossils have been recovered from the Duck Springs Member, but conodonts from beds in Sequatchie Valley that are judged to be equivalent include *Icriodella deflecta, Distomodus kentuckyensis, Rexroadus kentuckyensis, Pseudooneotodus beckmanni, Panderodus serratus, Ozarkodina hassi, O. oldhamensis*, and *Walliserodus curvatus* (Bolton, 1992). These are long-ranging species but no younger than middle Aeronian (C1; Manzo, 2002; Zhang and Barnes, 2002a). These are the youngest faunas preserved in Sequatchie Valley and indicate that the Birmingham and younger members have been removed there.

The Birmingham Member includes the most fossiliferous beds in the formation. In particular, the Hickory Nut beds at Duck Springs (unit 65) and equivalent beds at Green Springs Gap, Birmingham, contain *Stricklandia lens progressa* accompanied by *Pentamerus oblongus*, an assemblage indicative of the middle to late Aeronian (C1–2; Brett et al., 1998). Conodonts from unit 76 at Duck Springs also support a middle Aeronian designation (Manzo, 2002). Coeval red shale at Ringgold, Georgia, (unit 44) contains *Eocoelia hemispherica* at the base followed above by *E. intermedia* (C1–2; Baarli, 1989, personal commun.). However, some specimens of *P. oblongus*, perhaps a little higher in the section, are transitional to *Pentameroides subrectus*, a transition generally encountered in earliest Telychian strata (C4; Baarli et al., 1992; Johnson, 1996; 2014, personal commun.). Below the Hickory Nut beds, *P. oblongus* definitely occurs at the base of the Walker Gap beds but doubtfully in the Big seam. Confusion between seams throws doubt on the interpretation of the faunal lists given by Ulrich (*in* Butts, 1927, p. 9). Some fossils described from the "Big seam" may have derived from younger beds. Most likely the unconformity described by Butts (1926, 1927) occurs between the Big-Irondale seams and overlying Morrow Gap–Walker Gap beds. According to Uyeno (*in* Norford, 1972), conodonts from the Kidney bed between the Big and Irondale seams are

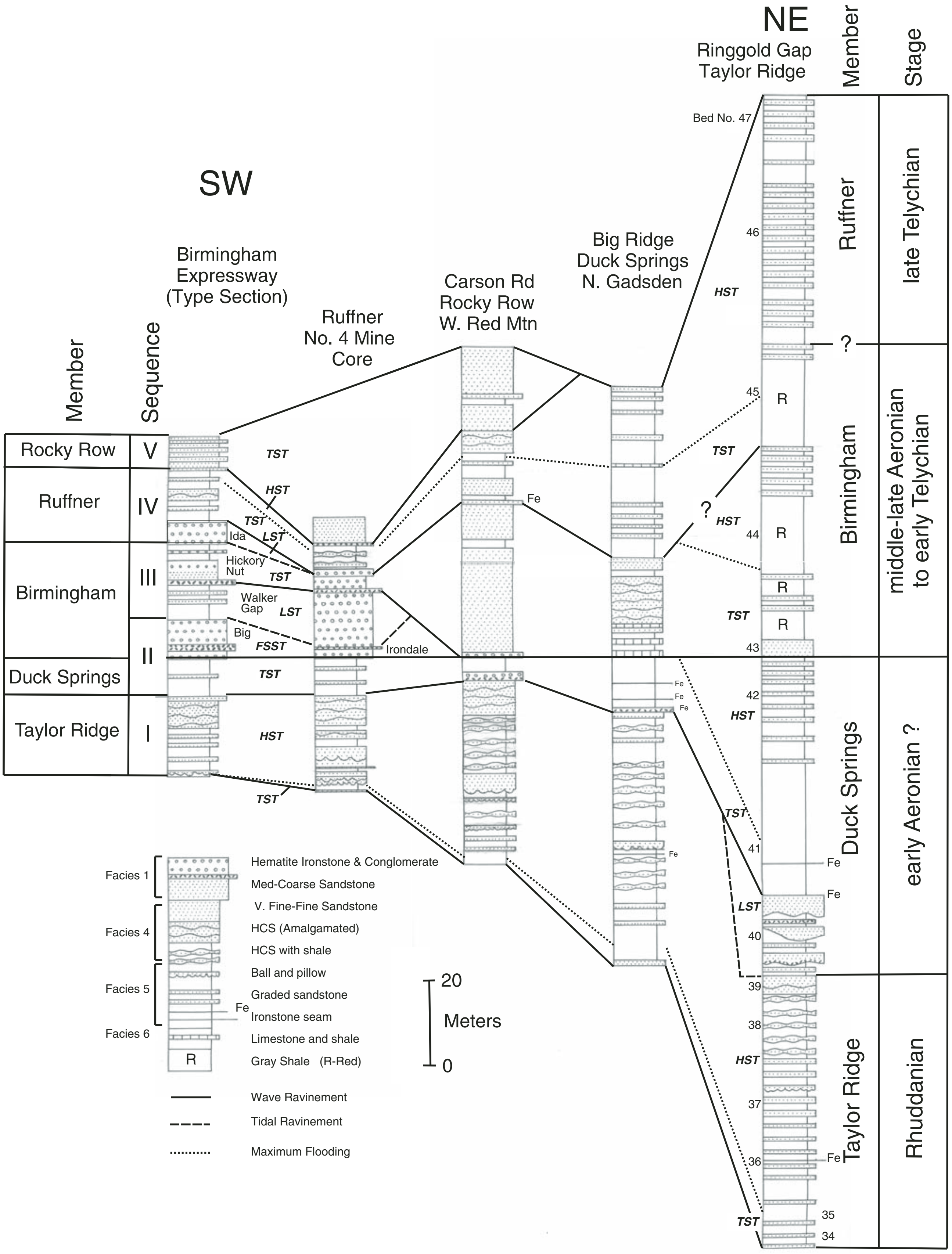


Figure 2. Correlation of key stratigraphic columns illustrating members, sequences, and systems tracts making up the Red Mountain Formation. HCS—hummocky cross-stratification; LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; FSST—falling stage systems tract.

no younger than Aeronian. Beds assigned to the Birmingham Member, therefore, span the middle to late Aeronian time interval possibly including some early Telychian strata.

The Ida seam (unit 53 of the type section) contains *Stricklandia laevis* (C4–5), succeeded by *Costistricklandia lirata* in unit 56 (C5–6 to lower Wenlockian), a characteristic Telychian fauna. *P. oblongus,* with a range of C1–5 (Holland and Bassett, 1989; Stott and von Bitter, 1999), continues through this interval (Baarli et al., 1992; Boucot *in* Ferrill, 1984). The Ruffner Member therefore dates to the Telychian Stage.

The Rocky Row Member was originally mapped as Frog Mountain Sandstone and assumed to be Devonian in age. However, the occurrence of *Eocoelia angelina* at Clear Springs Gap and *Costistricklandia lirata* at Century Plaza (Ferrill, 1984; Berdan et al., 1986) conclusively demonstrates that these beds are Wenlockian and should be included in the Red Mountain Formation (Ferrill, 1984).

According to Berdan et al. (1986) and Stock (1996), limestones of the Sparks Gap Member contain a rich Pridolian fauna including the chonetid brachiopod *Eccentricosta* cf. *jerseyensis* and the ostracode *Welleriopsis* aff. *pustulosa.* This confirms a major unconformity at the base of this member, marked by the complete absence of Ludlovian faunas.

DEPOSITIONAL SETTING AND FACIES

During Early Silurian times, Laurentia lay mainly south of the equator with the Appalachian foreland basin oriented approximately northeast-southwest between 20° and 30° S latitude (Fig. 3; Ziegler et al., 1977, 1979; Scotese, 2001). To the southeast (modern east), Taconic highlands were undergoing orogenesis (Ettensohn and Brett, 1998, 2002), loading the foreland basin and supplying clastic sediment, while to the northwest (modern west), the craton was flooded by shallow shelf seas during transgression or exposed as carbonate lowlands during regression (Berry and Boucot, 1970). Late Ordovician to Early Silurian glaciations in Gondwana (Grahn and Caputo, 1992; Caputo, 1998) were responsible for repeated transgressions and regressions, which have been traced on the basis of sequence stratigraphy and faunal assemblages (Johnson et al., 1985, 1991, 1998; Johnson, 1996; Brett et al., 1998; Zhang and Barnes, 2002b). Both shelf and basin lay in the track of tropical storms that strongly influenced depositional facies (Driese et al., 1991; Baarli, 1998). These facies have been described elsewhere (Easthouse and Driese, 1988; Driese et al., 1991; Chowns, 1996, 2006b), but a short summary is in order.

Red Mountain facies (Table 1, Fig. 4) are most conveniently divided on the basis of their position relative to wave base both during fair weather and storms (Walker and Plint, 1992; Hampson and Storms, 2003; Plint, 2010). Six major facies are recognized and divided into various subfacies. As a consequence of changing sea levels during transgression and regression, the six facies described below are repeated several times in the Red Mountain Formation and are used to define members that are essentially sedimentary sequences. Facies were often reworked and condensed during retrogradation, but well preserved during progradation. Figure 5 models the complete spectrum of facies encountered in the Birmingham area, although never in a single member. In order of increasing depth and waning wave energy these facies are:

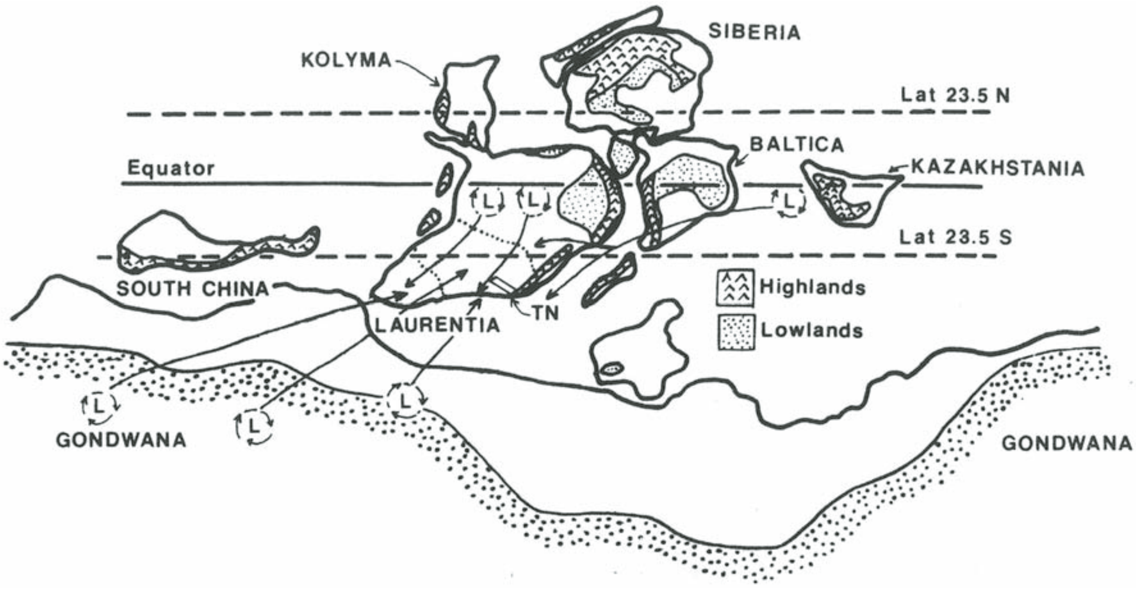


Figure 3. Early Silurian paleogeography and paleoclimatology (from Driese et al., 1991). Possible storm tracks are suggested by (L). TN—Tennessee.

TABLE 1. INTERPRETATION OF MAJOR DEPOSITIONAL FACIES IN THE RED MOUNTAIN FORMATION

	Depositional facies	Description	Trace fossils	Interpretation
1	**Hematite ironstone facies** (Coarse-grained, conglomeratic, hematitic sandstone and ooidal ironstone)	Medium–coarse-grained, ooidal sandstone or ironstone with ripples and cross-bedding (sometimes bimodal). Often in channels. Includes intraclastic conglomerate and shale rip-ups. Skeletal debris highly abraded. May be interbedded with shale or with shale drapes.	*Arthraria*, *Arthrophycus brongniartii*, *Asterosoma*, *Chondrites*, *Petalichnus*, *Palaeophycus*	Tidal sand bars deposited in tidal channels and tidal deltas with lag gravels. Interbedded with shale in estuarine or lagoonal settings. Water depths <10 m.
2	**Cross-bedded sandstone facies** (Medium–coarse-grained, cross-bedded, gray quartz sandstone)	Medium–coarse-grained, gray sandstone. Planar tabular–trough cross-bedded. Interbedded with highly bioturbated beds. Body fossils rare.	*Arthrophycus brongniartii*, *Asterosoma*, *Diplocraterion*, *Palaeophycus*, *Planolites*, *Rusophycus*, *Scotolithus*	Dunes and sand waves deposited in the shoreface and subject to mobilization by storm waves. Bioturbated when stabilized. Water depths 5–10 m.
3	**Bioturbated sandstone facies** (Bioturbated fine-grained sandstone may contain pentamerids in life position)	Massive, highly bioturbated fine-grained sandstone. Locally with relict hummocky cross-bedding. May include pentamerid brachiopods in life position. Mainly nonferruginous, except in association with Hickory Nut seam.	Mostly indistinct bioturbation	Inner shelf deposits as above, but with a prolific infauna probably due to lower sedimentation rates. Water depths 10–50 m.
4	**Hummocky cross-stratified sandstone facies** (Hummocky cross-bedded sandstone, amalgamated or interbedded with shale)	Fine-grained hummocky sandstones with low-angle cross-stratification. May be interbedded with shale or amalgamated in thick beds. May include ball-and-pillow structures. Sometimes hematitic. Only minor bioturbation in sandstones.	*Arthraria*, *Arthrophycus brongniartii*, *Asterosoma*, *Diplocraterion*, *Lockeia*, *Monocraterion*, *Nereites biserialis*, *Planolites*	Storm-generated bedforms on the inner shelf, between normal and storm wave base. Shale during fair weather. Water depths 10–50 m.
5	**Graded-bedded sandstone facies** (Thin graded-bedded sandstone and interbedded shale)	Fine-grained, graded, silty sandstone with plane- and ripple lamination. Soles eroded with tool marks, gutters, rare flutes, and load structures. Interbedded with bioturbated silty shale, usually gray, but reddish in Birmingham Member.	*Arthrophycus brongniartii*, *Asterosoma*, *Chondrites*, *Nereites biserialis*, *Palaeophycus*, *Planolites*, *Scotolithus*	Outer shelf with sandstones deposited by storm-generated geostrophic currents below storm wave base. Shale during fair weather. Water depth 50–100 m.
6	**Limestone facies** (Skeletal limestone Interbedded with shale)	Shaly limestone with brachiopods, crinoids, bryozoans, and corals. Some corals, stromatoporoids, and brachiopods in life position.	Mostly indistinct bioturbation	Inner–outer shelf deposits as above but isolated from sand influx. Low sedimentation rates.

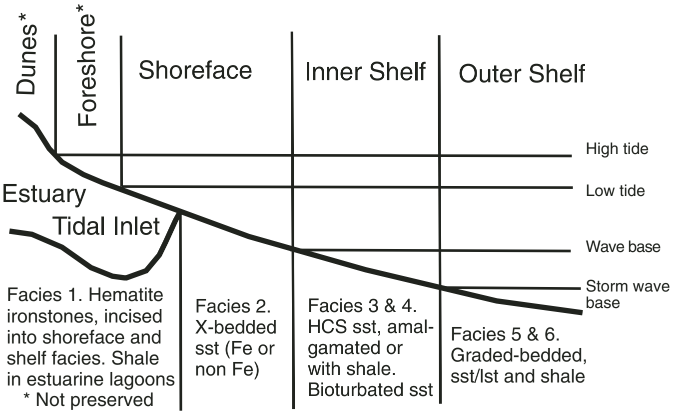


Figure 4. Generalized depositional environments and facies on the Silurian shelf determined by relation to wave base. sst—sandstone; lst—limestone.

1. Hematite Ironstone Facies: Coarse-Grained, Conglomeratic, Hematitic Sandstone, and Ooidal Ironstone

This facies is generally ferruginous and consists of both quartz and skeletal debris coated and replaced by iron oxide (hematite) prior to cementation. Depending on the percentage of iron, this was the lithology exploited as iron ore. The ironstones consist of 'flaxseed-shaped' (discoidal) ooids with a cortex of hematite (often interlaminated with chamosite) around various nuclei; usually abraded skeletal fragments. The chamosite is generally obscured by opaque hematite in thin section but is clear from SEM/EDS images. Analyses show that laminae of alternating composition fall on a mixing line between chamosite and hematite, and strongly suggest that hematite was formed by the oxidation and replacement of chamosite (Foos, 1983; Maynard, 1986). Similar unoxidized 'flaxseed' chamosite ooids occur in the shelf limestone facies (Chowns, 2006a). Composite sand grains are replaced by hematite along intergranular boundaries, indicating long periods of reworking and alteration. Skeletal grains also show a broad spectrum of replacement from pristine to almost unrecognizable, due to prolonged winnowing and alteration; steinkerns and intraclasts are also commonly replaced by collophane. The richest ores of the Big-Irondale seam are cemented by bladed crystals of hematite with lesser percentages of calcite and ferroan dolomite. Grain size varies from medium to coarse sand and granules, with common intraclasts derived from the ironstones and adjacent lithologies (Fig. 6A). Some intraclasts were soft, others partially lithified and bored when incorporated (Bearce, 1973; Baarli et al., 1992). Basal contacts are always sharp and conspicuous channels with intraclastic lag gravels are present. Bedforms include wave and current ripples and dunes, generating wedge or trough cross-beds usually less than 0.5 m thick (Fig. 6B). In some cases, cross-bedding is bimodal (herringbone; Fig. 6C). Shale occurs as thin mud drapes between cross-beds or sometimes as thicker beds (Fig. 6D). Rip-ups of shale are common.

Bioturbation is virtually absent in the ironstone seams, except where interbeds of shale are present, as in the Walker Gap beds. However, the hematitic sandstone regularly includes a restricted assemblage of surficial locomotion traces (e.g., *Petalichnus*), horizontal feeding burrows (e.g., *Chondrites*, *Planolites, Palaeophycus, Arthrophycus*) and vertical living burrows (e.g., *Monocraterion, Arthraria*) (Rindsberg and Osborne, 2001; Rindsberg and Martin, 2003). Specimens of *Arthrophycus*—restricted to the

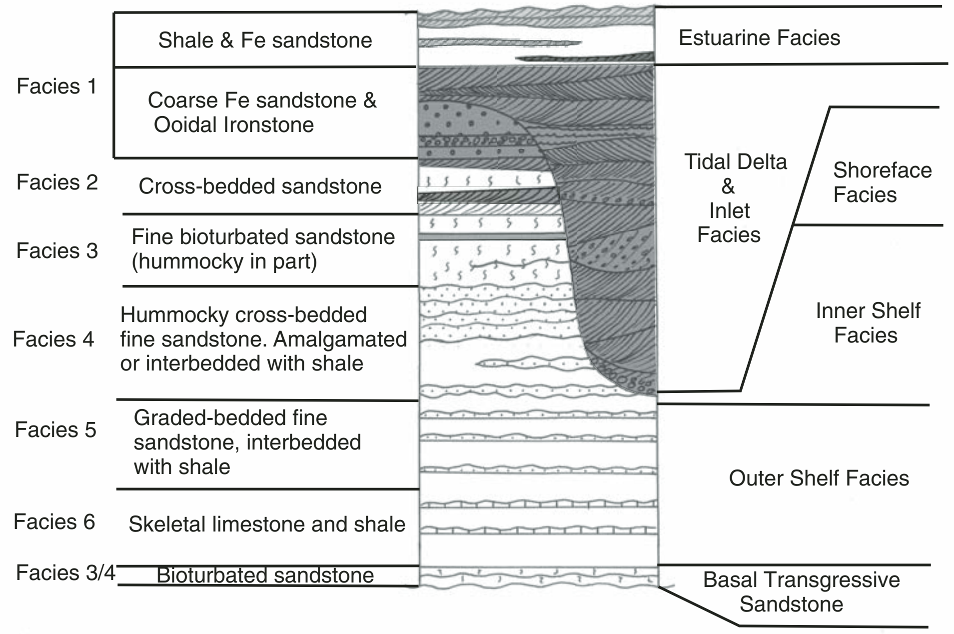


Figure 5. Ideal succession of progradational facies on the Silurian shelf. Shaded lithologies are strongly hematitic. All facies (with the exception of facies 2) are present in the type area around Birmingham, but never in one sequence.

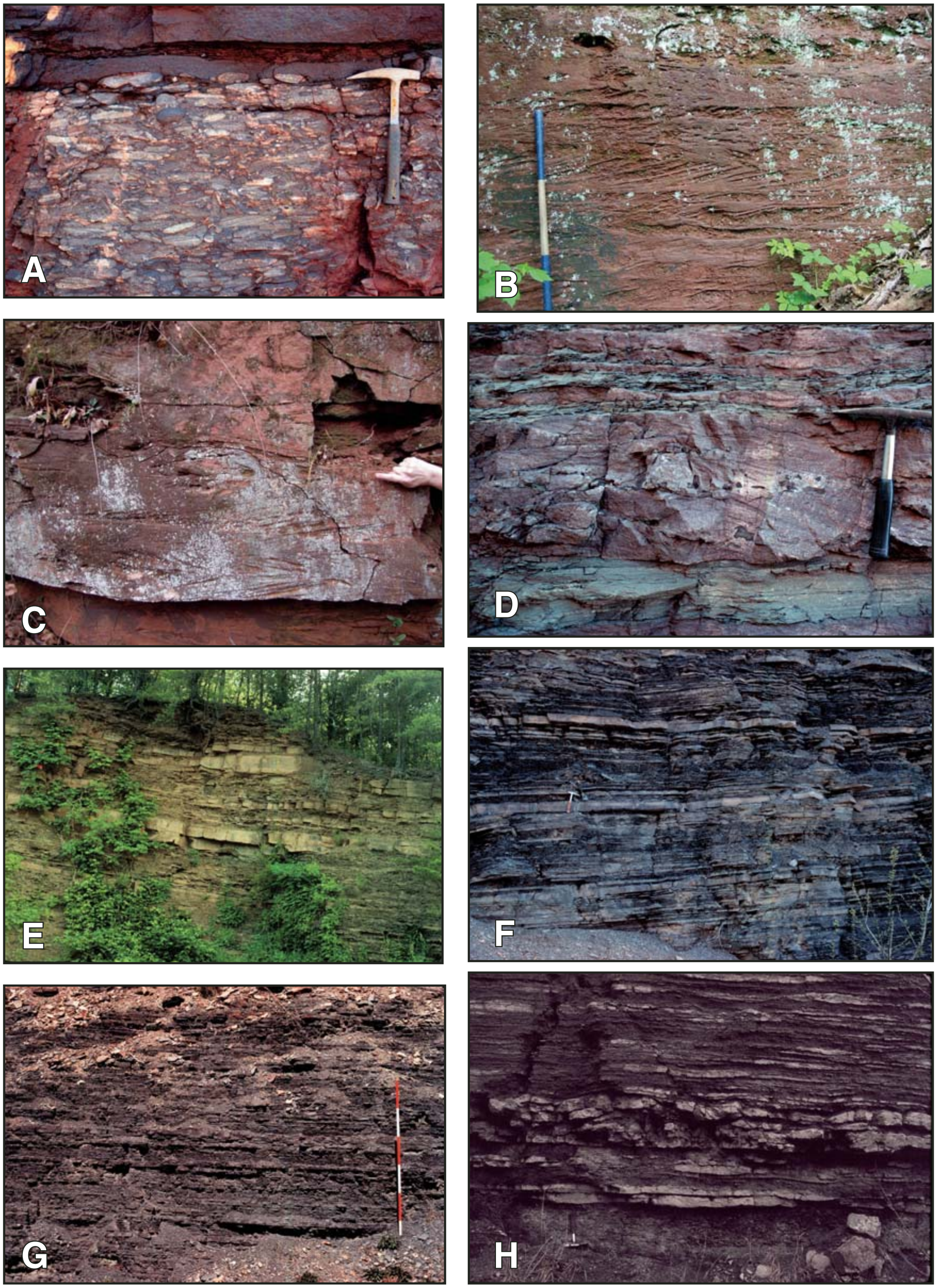


Figure 6. Major lithofacies in Red Mountain Formation. Jacob staff scaled in feet, hammer ~1 foot. (A) Facies 1. Conglomeratic ravinement lag from the Kidney bed between the Big and Irondale seams at the type section. Intraclasts include lithified and unlithified ironstone and limestone. (B) Facies 1. Cross-bedded ironstone from tidal inlet facies, Morrow Gap beds at Ruffner Mines, Alabama. (C) Facies 1. Bimodal (herringbone) cross-beds from Morrow Gap tidal channel, Ruffner Mines, AL. (D) Facies 1. Cross-bedded tidal-delta sandstone interbedded with estuarine shale, Walker Gap beds, type section. (E) Facies 3. Hummocky cross-bedded sandstone facies, Taylor Ridge Member, Estelle, Georgia. (F) Facies 5. Thin, fine-grained graded sandstones (storm beds) interbedded with shale, Taylor Ridge Member, Ringgold, GA. (G) Facies 5. Shale with thin siltstone storm beds, base of Taylor Ridge Member, Ringgold, GA. (H) Facies 6. Interbedded limestone–shale facies; base of Birmingham Member, Duck Springs, AL.

unbranched form, *A. brongniartii*—reach their largest size in this facies; some beds contain no other trace fossils.

Ferruginous sandstones belonging to this facies are most conspicuous at the base of the Birmingham and Ruffner members around Birmingham, but also occur in channels at the base of the Duck Springs Member along Taylor Ridge in Georgia. Channel facies that lack iron coatings also occur elsewhere at the base of the Duck Springs Member, and possibly at the base of the Taylor Ridge Member in easternmost strike belts in Georgia (Figs. 7 and 8). The latter are trough cross-bedded with a single westerly mode, lack macrofauna and ichnofossils, and although, generally gray-white, contain patches of red coloration. They are currently included in the Sequatchie Formation (Martin, 1992a, 1992b; Dorsch and Driese, 1995).

Similar facies have been described from the ironstones of New York (Alling, 1947; Hunter, 1970; Sullivan et al., 2012) and also in ferruginous sandstones of the Clinch and Tuscarora formations in Tennessee, Virginia, and Pennsylvania (Folk, 1960; Cotter, 1983; Cotter and Link, 1993; Driese et al., 1991; Castle, 1998).

Interpretation

This ferruginous-sandstone-ironstone facies represents the highest energy, shallowest water environments in the Red Mountain Formation, and is one of only two facies with high-angle cross-bedding. A detailed description of the petrography and genesis of these enigmatic ooidal deposits is beyond the scope of the present paper, but key discussions may be found in Van Houten and Bhattacharyya (1982), Maynard (1983), and Young and Taylor (1989).

The facies is interpreted to include a variety of littoral environments. Reworking was apparently common, allowing for the thorough abrasion of skeletal fragments and coating by iron. Where channels and bimodal cross-beds occur, tidal channels or deltas are interpreted. Cobble intraclasts were ripped up and covered by migrating dunes during energetic periods, while mud drapes and bioturbation developed under quieter conditions. Some conglomerates may be intertidal beach gravels (Bearce, 1973). The presence of residual chamosite in the ooids suggests that the ooids originated elsewhere, probably offshore on the shelf, judging by the occurrence of chamosite ooids in the limestone facies. They are probably microbial structures and were formed under post-oxic conditions on the shelf, subsequently to be winnowed, concentrated, and replaced by oxyhydroxides in the shoreface (Chowns et al., 2011). The oxyhydroxide was later converted to hematite during burial (Hodych et al., 1985). The presence of iron oxide as a cement indicates highly oxidizing conditions, which are unusual during early marine diagenesis (Berner, 1981). It supports the conclusion that meteoric groundwater may have been present during early diagenesis.

Thicker shale beds (in the Walker Gap beds) indicate more protected environments, and suggest that some tidal inlets were connected to lower-energy estuaries or lagoons (cf. Frey and Howard, 1986; Dalrymple et al., 1992). Lagoonal sandstones are less ferruginous and ooidal than higher-energy subfacies, indicating that contrary to Sheldon (1970), ooids were not derived from lagoonal environments.

The occurrence of *Petalichnus* in the Walker Gap beds is significant because this ichnogenus has been interpreted as an estuarine form in the Mississippian Hartselle Sandstone.

The unimodally cross-bedded channel sandstones at the base of the Taylor Ridge Member in easternmost outcrop belts in Georgia are probably lowstand alluvial deposits. Originally, they may have been red beds, but were reduced and bleached by connate water emanating from overlying transgressive marine beds.

2. Cross-Bedded Sandstone Facies: Medium- to Coarse-Grained, Cross-Bedded, Gray Quartz Sandstone

This facies occurs mainly in easternmost strike belts in Georgia where it makes up the upper part of the Taylor Ridge Member, and in Tennessee where it typifies the Clinch Sandstone (Driese et al., 1991). Similar lithologies are common in the Tuscarora and Grimsby formations of Virginia, Pennsylvania, and New York (Folk, 1960; Cotter, 1983; Castle, 1998). It does not occur in the Birmingham area. It consists of trough or planar-tabular cross-sets up to 2 m thick, interrupted by reactivation surfaces and sometimes clay drapes. In Tennessee, cross-bedding is generally unimodal to the northwest (offshore). Some beds contain shale intraclasts or small pebble and granule lags but less commonly than in the conglomeratic ironstones. Current ripples are also common. Lithologies resemble those in the cross-bedded ironstone facies, but channels are absent and ferruginous beds less common. Body fossils are also rare. The ichnofauna at Clinch Mountain itself includes vertical (especially *Diplocraterion*) and horizontal components (*Arthrophycus*, *Rusophycus*, and others) (Driese et al., 1991; AKR, field observations). *Arthrophycus,* including fan-shaped branching *A. alleghaniensis* as well as simple *A. brongniartii*, is again relatively large in this facies. Horizontal burrows are particularly well preserved where sandstones rest on shale drapes. Burrow density varies from low in cross-bedded units to intense in some interbedded massive sandstones. The facies grades both vertically and laterally into the hummocky cross-bedded sandstone facies (described below), and also locally into the hematitic sandstone facies.

Interpretation

Driese et al. (1991) interpreted this facies to have been deposited as short-crested dunes (trough cross-beds) and long-crested sand waves (planar-tabular cross-beds) in shoreface environments subject to periodic storm waves. Bedforms migrated offshore during storms and were subject to bioturbation during fair weather. The low diversity of trace fossils, and the prevalence of *Diplocraterion* and *Arthrophycus*, suggest relatively high energy such as wave action even between storms. In protected locations, clay drapes accumulated. Driese et al. (1991) envisage an environment similar to the modern North American Atlantic shelf, in water depths between ~5–10 m.

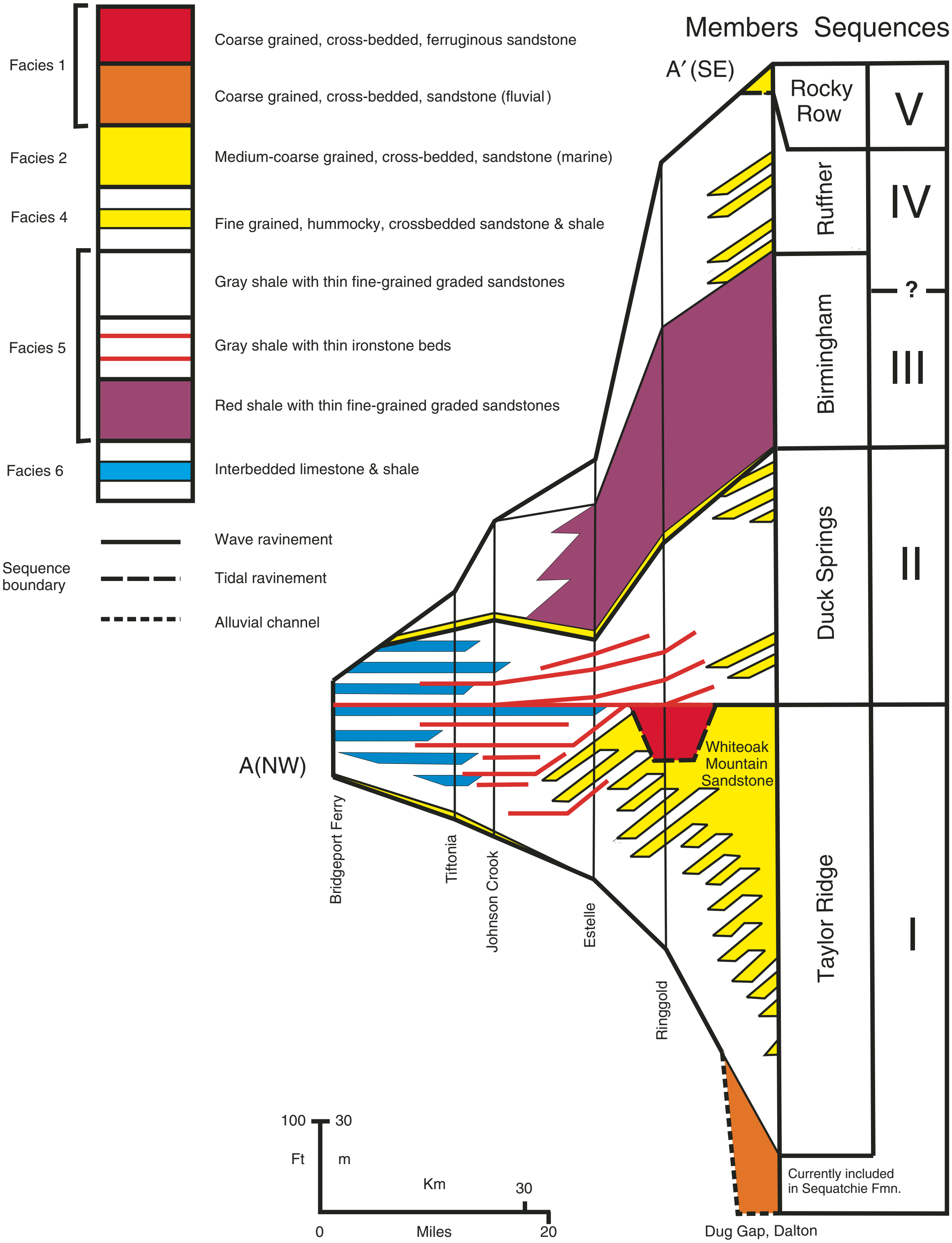


Figure 7. Stratigraphic cross section A–A′ showing facies changes between Dug Gap, Dalton, Georgia, and Bridgeport Ferry, Alabama. See Figure 1 for locations. Section is drawn perpendicular to depositional strike. Heavy lines are sequence boundaries, and ravinements. All other contacts are gradational facies.

Birmingham Platform

1. Silurian section condensed but all sequences (I-VI) represented
2. Stratigraphy dominated by transgressive systems tracts with LSTs and FSSTs
3. Stratigraphy complicated by intersecting paraconformities and channels
4. Accommodation space available for preservation of sequences V & VI
5. Strong eustatic control on accommodation space
6. Shoreface facies (often ferruginous) interbedded with shelf facies
7. Upper Ordovician strata mainly absent due to erosion on basal unconformity

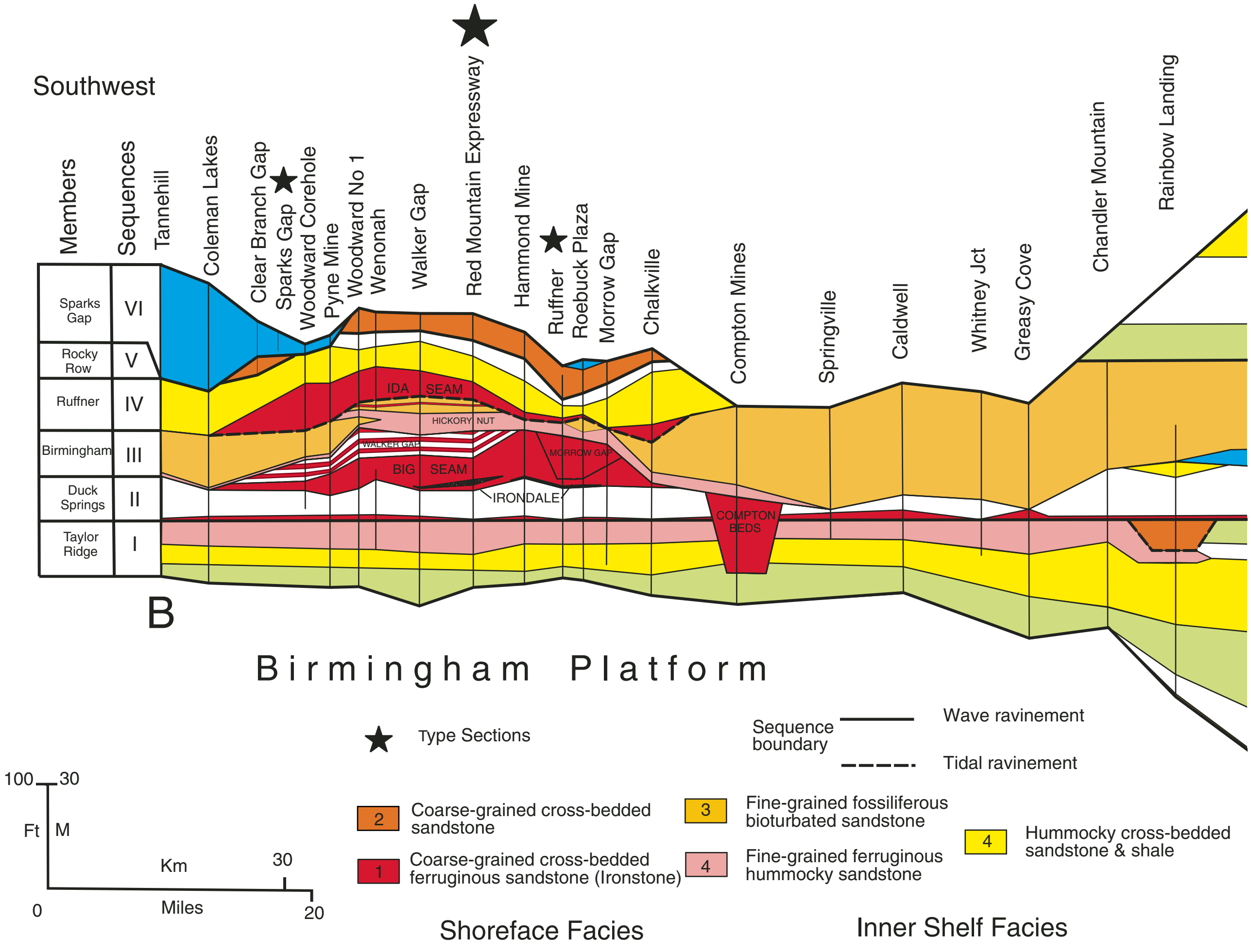
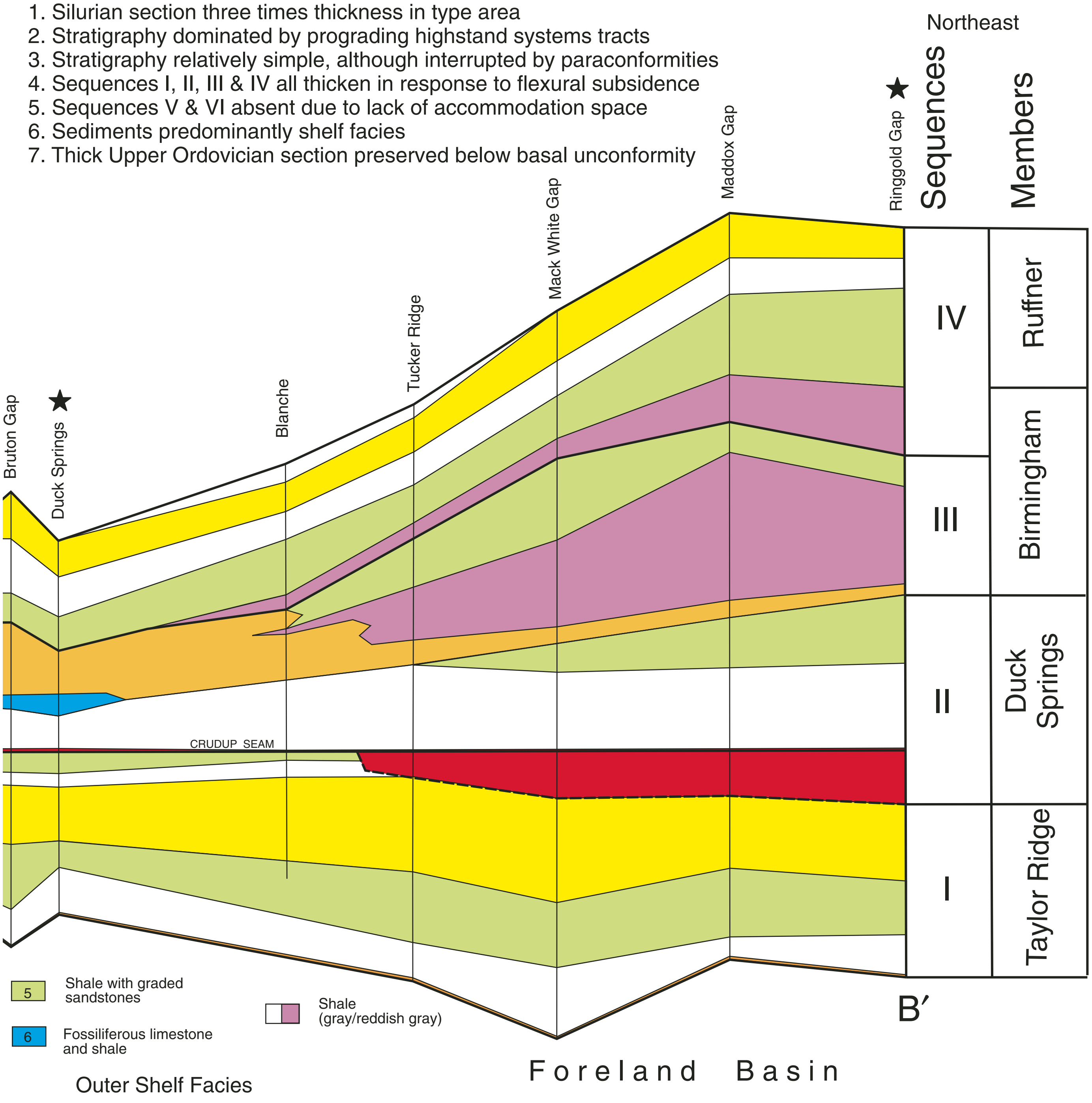


Figure 8 (*Continued on facing page*). Stratigraphic cross section B–B′ showing facies changes between Tannehill, Alabama, and Ringgold, Georgia. See Figure 1 for locations. Heavy lines are sequence boundaries, and ravinements. All other contacts are gradational facies (after Chowns, 2006b). FSST—falling stage systems tract; LST—lowstand systems tract.

Foreland Basin

1. Silurian section three times thickness in type area
2. Stratigraphy dominated by prograding highstand systems tracts
3. Stratigraphy relatively simple, although interrupted by paraconformities
4. Sequences I, II, III & IV all thicken in response to flexural subsidence
5. Sequences V & VI absent due to lack of accommodation space
6. Sediments predominantly shelf facies
7. Thick Upper Ordovician section preserved below basal unconformity



3. Bioturbated Sandstone Facies: Bioturbated Fine-Grained Sandstone with Pentamerids in Life Position

This indistinct facies is common in the lower part of the Birmingham Member (Hickory Nut beds). It is characterized by thick, structureless beds of gray, fine sandstone and siltstone and little shale. It may grade into fine-grained sandy ironstone or contain beds of coarse-grained ironstone. In places, amalgamated hummocky cross-beds have survived an indistinct bioturbation. Elsewhere, pentameroid brachiopods (*Pentamerus* and *Stricklandia*) occur either in life position (Ziegler et al., 1966) or locally transported.

Interpretation

The association of this facies with ferruginous shoreface lithologies on the one hand, and hummocky cross-stratified sandstones on the other suggests deposition on the inner shelf close to fair-weather wave base. Highly bioturbated lithologies are characteristic of the transition zone between shelf and shoreface (Howard and Reineck, 1981; Walker and Plint, 1992; Plint, 2010). Pentameroid brachiopods are thought to have lived on the inner shelf at water depths of 10–20 m for *Pentamerus* and 20–60 m for *Stricklandia* (Boucot et al., 1993).

4. Hummocky Cross-Bedded Sandstone Facies; Either in Thick Amalgamated Beds or Interbedded with Shale

Hummocky cross-bedded sandstones are fine-grained, laminated with low-angle bedforms that cause the beds to pinch and swell unevenly (Fig. 6E). The beds range from 0.3 to 1 m thick with sharply eroded tops and soles. Most were deposited as single units separated by shale (40%–90% sandstone) but some amalgamated beds (up to 4 m) are present. Some beds contain a lag of abraded shell debris, and tool marks may occur on soles. Spectacular ball-and-pillow structures and slumps are sometimes present (Fig. 6F), in some cases distorting trace fossils. Bioturbation is diverse but patchy, including vertical dwelling burrows (*Monocraterion, Diplocraterion, Lockeia, Arthraria*) and oblique to horizontal feeding traces (*Chondrites, Planolites, Nereites, Asterosoma, Arthrophycus brongniartii*).

Interpretation

Hummocky cross-stratification is attributed to large three-dimensional wave ripples generated by a combination of unidirectional currents and oscillatory wave motion associated with waning storms (Dott and Bourgeois, 1982; Myrow and Southard, 1991; Duke et al., 1991). They typically form between normal and storm wave base in the transition zone between shoreface and shelf at water depths between ~10–50 m (inner shelf of Duke et al., 1991; Driese et al., 1991). Slumps and large load structures indicate rapid deposition and unstable slopes. Interbedded shales record fair-weather conditions between storms. The ichnofauna is similar to the shelfal *Cruziana* ichnofacies described below, but with a common shoreface indicator, *Asterosoma*, suggesting slightly shallower water (particularly in beds transitional to those dominated by *Arthrophycus brongniartii*).

5. Graded-Bedded Sandstone Facies: Thin Graded-Bedded Sandstone and Interbedded Shale

Sandstones of facies 4 are often interbedded in upward-coarsening cycles and grade down-section into shale with thin, fine-grained graded sandstones (0%–60% per 5-foot interval). The sandstones are generally less than 10 cm thick with sharp soles, sometimes with a lag of shell debris, overlain by plain lamination, and capped by ripples or ripple lamination (Fig. 6F). Some are micro-hummocky. Tops are commonly bioturbated and grade into shale, while soles show tool marks, gutters, and sometimes flutes. Thicker sandstones may develop ball-and-pillow structures due to loading. Shale beds are silty and bioturbated with thickness inversely proportional to the sandstones (Fig. 6G). They are generally dark gray, but may be reddish due to coating of the clay minerals by hematite (in the Birmingham Member). Trace fossils reach their highest diversity in this facies, dominated by feeding burrows such as *Chondrites, Nereites*, *Planolites, Dictyodora, Paleophycus, Phycodes, Arthrophycus, Asterosoma*, and *Scotolithus*, although vertical dwelling burrows (*Lockeia, Monocraterion*) and other forms are also present (Frey and Chowns, 1972; Rindsberg and Martin, 2003). Specimens of *Arthrophycus brongniartii* are relatively few, and smaller in this facies than in the more proximal facies described above. Shell lags, including crinoid columnals, brachiopods, and tentaculitids, thicken to the west (cratonward), and sandstones eventually give way to bioclastic limestones. Solitary rugosan corals and colonial tabulate corals and stromatoporoids are present in life position at certain horizons.

Interpretation

This shaly facies is clearly one of the most distal, quietest-water environments on the Silurian shelf. The graded sandstones are distal equivalents of the hummocky cross-stratified sandstones of the previous facies, and were probably deposited by geostrophic currents below storm wave base. Based on measurements from gutter casts, flutes, and tool marks, flow was southwestward (relative to modern coordinates), approximately parallel to depositional strike and consistent with Coriolis effect on a northwest-facing shelf in the Southern Hemisphere. The ichnofauna is a typical *Cruziana* assemblage commonly encountered in shelf facies. The relatively small size of *Arthrophycus brongniartii* may indicate a preference of juveniles for more distal facies.

Similar facies have been described on the shelf of the Gulf of Gaeta in the Tyrrhenian Sea (Reineck and Singh, 1975), the northeast Bering Shelf (Nelson, 1982), and numerous ancient settings (Walker and Plint, 1992; Plint, 2010). Driese et al. (1991) estimate water depths between ~50–200 m for similar facies in Tennessee.

6. Limestone Facies: Skeletal Limestone Interbedded with Shale

In western strike belts, siliciclastic sands pass gradationally into bioclastic sands (Fig. 6H). Shell lags increase in thickness at the expense of quartz sand, and interbedded sandstone and shale passes into sandy skeletal packstone-wackestone and shale. Limestones are generally less than 10 cm thick, with eroded soles and bioturbated tops. They may be laminated, hummocky, rippled, and graded, but sedimentary structures are often lost due to indistinct bioturbation. Shell debris includes crinoid columnals, bryozoans, brachiopods, and solitary rugosan corals locally partially replaced by iron minerals. Colonial corals may also occur and are sometimes overturned.

Interpretation

Bedforms and distribution suggest that this facies accumulated in similar shelf environments to facies 4 and 5, but in distal settings isolated from siliciclastic influx (Easthouse and Driese, 1988; Driese et al., 1991). In Iowa, Witzke and Johnson (1999) note that discoidal tabulate corals are commonly associated with pentameroid brachiopods in Silurian carbonate communities that lived close to the fair-weather wave base on the shelf. This facies is common in Sequatchie Valley as well as Lookout Valley and McLemore Cove in northwest Georgia, but is uncommon in the type area except in the Pridolian Sparks Gap Member south of Birmingham.

DEPOSITIONAL SEQUENCES

All the members described in foregoing paragraphs are separated by unconformities that are defined by abrupt lithologic and faunal changes, and erosional truncation on cross sections (Figs. 7 and 8). In effect, each member is a stratigraphic sequence divisible into systems tracts. However, because members are defined objectively on the basis of lithology, while sequences are interpreted subjectively, some discrepancies occur (see discussion in Raymond et al., 2012). In particular, while the Big-Irondale seam is included in the Birmingham Member on the basis of lithology, it is interpreted as a falling stage deposit within sequence II. The sequence boundary between the Birmingham and Ruffner members is also in doubt in thick, poorly exposed, shaly sections in northwest Georgia (Figs. 2, 7, and 8).

Sequence Stratigraphic Tracts and Surfaces

Sequences include transgressive systems tracts (TST), highstand systems tracts (HST), lowstand systems tracts (LST), and falling stage systems tracts (FSST). Critical stratigraphic surfaces used to define sequences and systems tracts are the maximum flooding surface (MFS), transgressive ravinement surface (TRS), subaerial unconformity (SU), sequence boundary (SB), and regressive surface of marine erosion (RSME) (Catuneanu, 2006; Catuneanu et al., 2009).

MFSs generally coincide with outer shelf facies, and are marked by a change from retrogradational to progradational sediment stacking as interpreted from trends in sandstone-shale ratios. Shale facies associated with MFSs are present basin-wide and readily correlated unless truncated by later erosion.

TRSs occur at or near the base of each member and generally show up as an erosive contact succeeded by a retrogradational succession of condensed offshore facies, indicating an abrupt increase in water depth and presumed coastal onlap. Most TRSs are planar, signifying wave ravinement and reworking. Like MFSs, they are regionally persistent and easily correlated. Important exceptions occur where channel structures emerge from beneath a wave ravinement surface. Such channels occur at the base of the Duck Springs, Birmingham, and Ruffner members; and possibly at the base of the Taylor Ridge Member. They range as deep as 20 m and are recognized from the presence of abnormal thicknesses of fluvial, estuarine, or shoreface facies, which interrupt the planar stratigraphy of shelf facies. Most channel fill is characterized by bimodal cross-beds and highly abraded fossil debris indicating tidal ravinement. Some unfossiliferous channel sandstones with unimodal cross-beds that occur in the easternmost outcrop belts in Georgia may be of fluvial origin.

Subaerial facies are rare in the Red Mountain Formation, and direct evidence of exposure on paraconformities is therefore lacking. Nevertheless, evidence of erosional truncation and missing faunal zones strongly suggest that large parts of the shelf were exposed and that these unconformities were subaerial. With few exceptions, evidence of exposure was removed during wave ravinement on the TRS.

RSMEs occur where sharp-based shoreface facies are superposed on shelf facies, indicating a major loss of accommodation resulting from forced regression. This appears to be the case where shoreface facies of the Big-Irondale seam are sandwiched between outer shelf facies below and a tidal ravinement surface above.

SBs are generally chosen to reflect the end of base level fall, and coincide with the base of the LST or the base of the TST when lowstand facies are lacking (Catuneanu, 2006).

Systems Tracts

Based on the recognition of the critical surfaces described above, the Red Mountain sequences are divided into systems tracts as shown in Figure 2. The basic motif repeated in several Red Mountain sequences (Figs. 7–8; I, II, III, IV) consists of wave-dominated shelf facies arranged in a series of deepening-upward then shallowing-upward successions each separated by an MFS and TRS. These retrogradational and progradational units are interpreted as transgressive and highstand systems tracts, respectively. Parasequences are rarely evident, but overall trends are clear from plots of sandstone percentage and changes in sedimentary structures. The Rocky Row and Sparks Gap members are exceptions in which no overall shallowing or deepening trends have been identified because of poor exposure and limited distribution and thickness. Nevertheless, their unconformable contacts indicate they are separate sequences (probably TSTs).

LSTs occur only locally at the base of sequences I, II, III, and IV, where incised channels preserve fluvial, estuarine, or shoreface facies between wave and tidal ravinement surfaces (TRSs) of regional significance. The LSTs consist predominantly of high-energy shallow-water facies (facies 1) ideally deposited as progradational parasequences prior to the initiation of retrogradation at the TRS. The association of tidal ravinements with regional erosion surfaces indicates that they have greater significance than local tidal channels formed as part of the highstand systems tract. This interpretation is reinforced by the superposition of shoreface facies on outer shelf facies, implying not only incision but also a fall in relative sea level. This is especially evident at the base of the Birmingham Member (sequence III) where channel structures not only truncate outer shelf facies of sequence II but also outer shelf facies in sequence I (Fig. 8).

The massive shoreface facies that constitute the Big-Irondale seam are unique within the Red Mountain Formation. They rest on a regressive wave ravinement surface (RSME), and are succeeded by transgressive tidal and wave ravinement surfaces at the base of the Walker Gap–Morrow Gap and Hickory Nut beds, respectively. This indicates that they belong to a falling stage systems tract, and explains their unusual diagenetic history, massive lithology, and importance as ore bodies.

Isopachs (Figs. 9A–9E)

With the exception of the Rocky Row and Sparks Gap members, which are limited by erosion, all sequences are thicker in the foreland basin than on the Birmingham platform. This is evidently a consequence of tectonic loading related to orogeny further east in Piedmont terranes (Quinlan and Beaumont, 1984; Beaumont et al., 1988; Ettensohn and Brett, 1998, 2002). Much of the difference in thickness may be traced to expansion of HSTs to the east. While TSTs are present in all sections and all sequences, HSTs thicken dramatically in the foreland basin. The greater thickness of the HSTs close to source no doubt reflects greater accommodation space and higher sedimentation rates during progradation. However, it may also result, partly, from erosional truncation of HSTs on the platform. Unconformities at the base of sequences I, III, and IV all cut down-section to the west, as would be expected as a consequence of flexural subsidence in the foreland basin. In the case of the unconformity at the base of the formation, small angular discordances have been measured at outcrop; 1.6° at the Birmingham Expressway (Thomas and Bearce, 1986) and 0.2° at Ringgold (Chowns, 1989), but in general, angular discordances are visible only through the vertical exaggeration used in stratigraphic cross sections.

Preservation of Sequences

Generally, the preservation of sequences decreases through time. Thus Rhuddanian strata are more widely distributed than Aeronian and Telychian beds, and Wenlockian and Pridolian beds are mainly limited to the Birmingham platform. In part, this results from Acadian erosion, but it also reflects erosion on the Silurian paraconformities. More space was available for the preservation of earlier sequences. With time, the locus of maximum thickness also shifted from the foreland basin to the Birmingham platform. This suggests that space for the preservation of the Red Mountain clastic wedge was initially provided by flexural subsidence during the Rhuddanian. Further space was added by glacial eustasy during the Rhuddanian, Aeronian, and Telychian (Johnson, 1996). The migration of the depocenter from the foreland basin to the Birmingham platform may reflect rebound and isostatic adjustment with the cessation of orogeny. Unloading due to erosion in the east led to uplift and erosion in the foreland basin, coupled with relaxation and subsidence of a peripheral bulge on the Birmingham platform, perhaps related to inversion of the Birmingham graben (Bayona and Thomas, 2003; Thomas, 2007).

Given a time span of ~16 Ma for the Llandoverian stage (Gradstein et al., 2004; Sadler et al., 2009), each of the Llandoverian sequences (Taylor Ridge, Duck Springs, Birmingham, Ruffner) probably encompasses 2–3 Ma, depending on the amount of time represented by unconformities. They therefore approximate the third-order sequences of Vail et al. (1977).

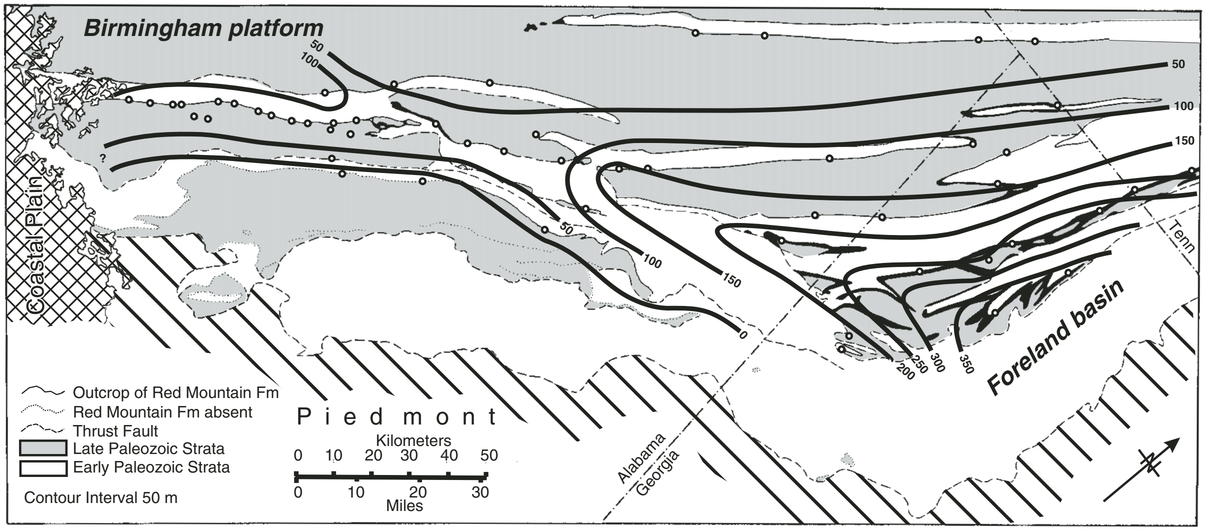
Ironstones and Sequence Boundaries

All the major ironstone seams are associated with sequence boundaries: the Crudup seam at the base of the Duck Springs Member, Big-Irondale seam complex and Hickory Nut seam at the base of the Birmingham Member, and Ida seam at the base of the Ruffner Member. Thin ironstones occur in all members (except the Sparks Gap) and in both transgressive and highstand systems tracts, but it is clear that the reduced sedimentation rates and reworking characteristic of marine transgression provided the ideal setting for the deposition of ironstone, especially in shoreface facies. Minor occurrences unrelated to sequence boundaries may indicate local starvation and reworking on the shelf, or hematitic grains carried from the shoreface and resedimented during storms.

Three types of occurrence are present in the Red Mountain Formation (Fig. 10), corresponding to several types of

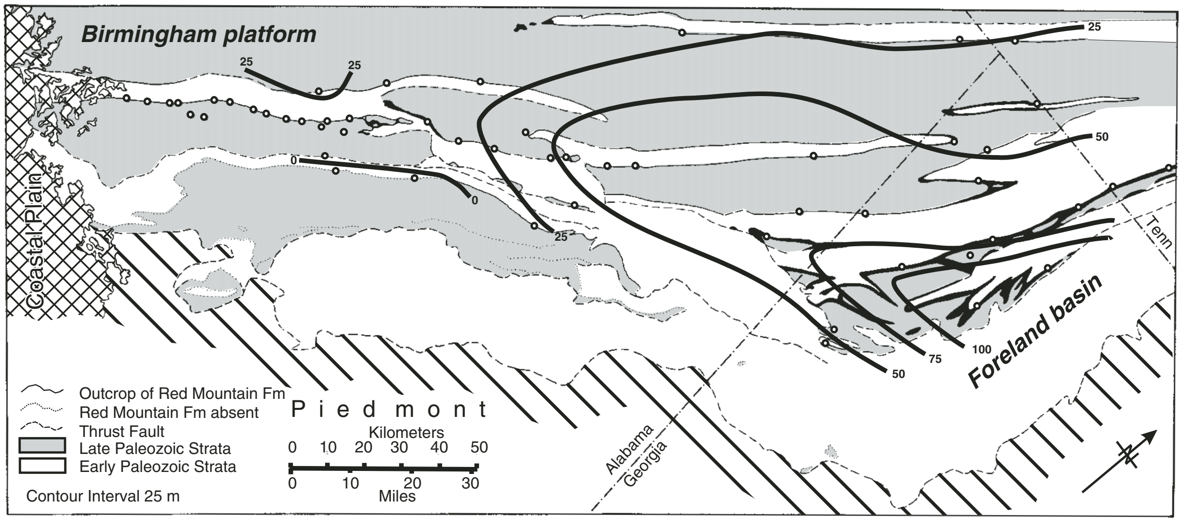
Figure 9 (*Continued on following pages*). Isopach maps of the Red Mountain Formation with the foreland basin in the northeast and Birmingham platform to the southwest. (A) Total thickness. (B) Taylor Ridge Member (sequence I) excluding basal channel sandstones (mapped with the Sequatchie Formation). (C) Duck Springs Member (sequence II excluding FSST [falling stage systems tract]). (D) Birmingham Member (sequence III with addition of Big-Irondale seams, FSST of sequence II). Tidal channel and estuarine beds (lowstand systems tract) enclosed by dashed lines. (E) Ruffner Member including Ida Seam (sequence IV), Rocky Row (short-dashed contours), and Sparks Gap (long-dashed) members.

A



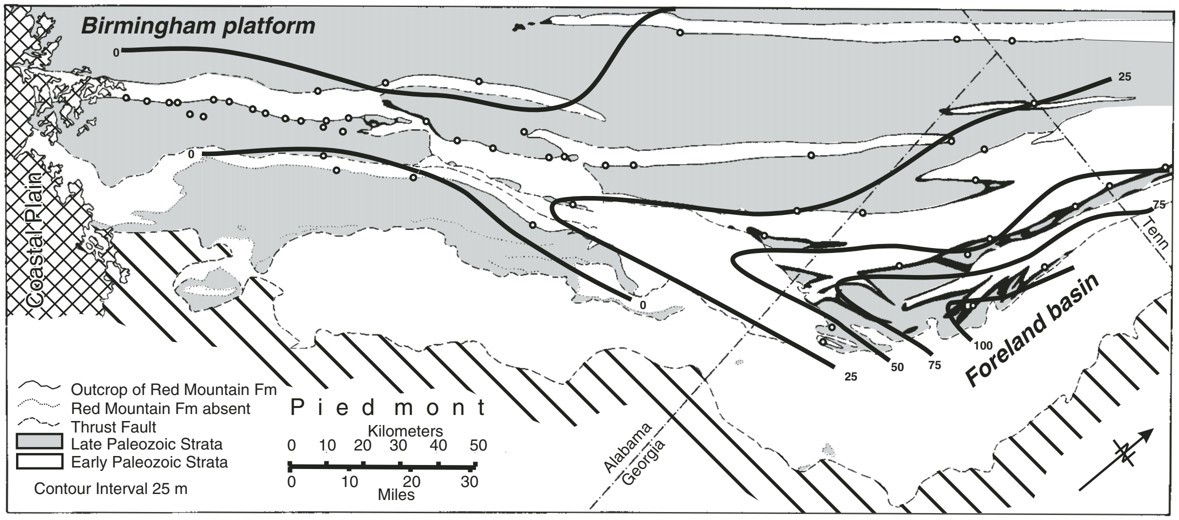
Isopach Map of Red Mountain Formation

B

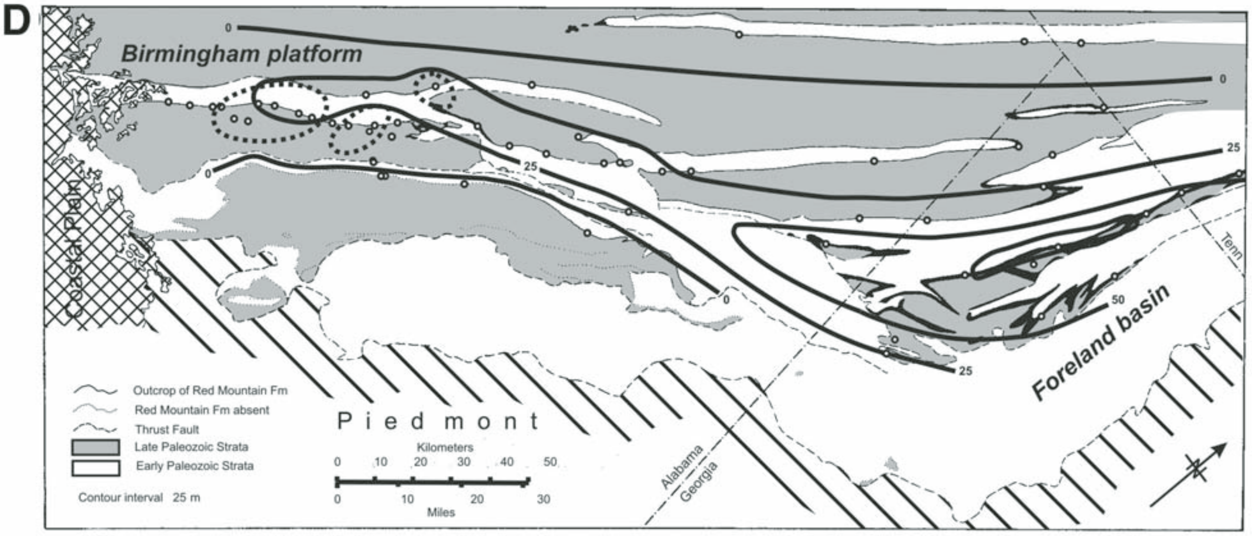


Isopach Map of Taylor Ridge Member (Sequence I)

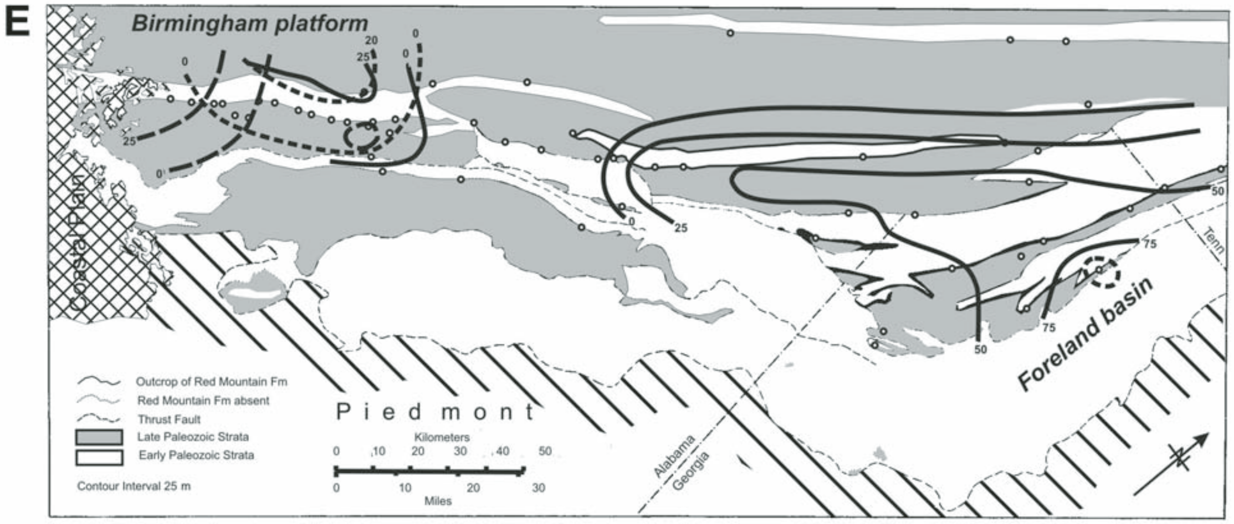
C



Isopach Map of Duck Springs Member (Sequence II excluding Big-Irondale FSST)



Isopach Map of Birmingham Member (Sequence III including Big-Irondale FSST)



Isopach Map of Ruffner, Rocky Row & Sparks Gap Members (Sequences IV, V, & VI)

Figure 9 (*Continued*).

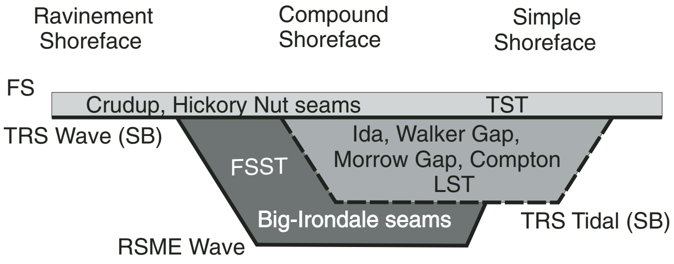


Figure 10. Idealized model showing depositional setting of Birmingham ironstone seams at sequence boundaries. Based on Proust et al. (2001) and Al-Ramadan et al. (2005). Abbreviations FS—flooding surface; TRS—transgressive ravinement surface; RSME—regressive surface of marine erosion; SB—sequence boundary; TST—transgressive systems tract; LST—lowstand systems tract; FSST—falling stage systems tract. Dashed lines are tidal ravinements, solid lines are wave ravinements.

sharp-based shoreface deposit (SBS) described by Proust et al. (2001) and Al-Ramadan et al. (2005). Transgressive wave-ravinement ironstones occur immediately above a TRS at the beginning of a TST, and are often relatively thin and regionally extensive. By contrast, transgressive tidal-ravinement ironstones occur in localized channels within the LST. The third and least common type is a regressive wave-ravinement ironstone, which occurs in the FSST and is particularly significant because weathering during regression can lead to additional iron mineralization. Depending on whether or not erosion surfaces are clustered around a sequence boundary, these shorefaces and ironstones may be either simple or compound.

The thin, regionally persistent Crudup seam is an example of a simple transgressive wave-ravinement deposit at the base of a TST, while the Ida seam (Ruffner Member) is a simple transgressive tidal-ravinement deposit within an LST. By contrast, the Hickory Nut (TST), Walker Gap, Morrow Gap, and Compton beds (LSTs) are parts of a compound shoreface at the base of the Birmingham Member. Most significantly, the Big-Irondale seam belongs to the FSST at the base of this compound shoreface. While ironstones deposited in LSTs and TSTs were subject to normal post-oxic marine pore-water during the course of transgression, FSST ironstones reworked during forced regression were, probably, invaded by oxic meteoric pore-water. This, most likely, accounts for the prevalence of hematite as a cement in the Big and Irondale seams, which were the most productive ore bodies.

REGIONAL CORRELATION

Proposed regional correlations are shown in Figure 11. Although Smith (1876a, 1876b) utilized the name Red Mountain Formation, his first inclination was to assign these rocks to the Clinton Group. Similarly, Butts (1910) initially used the term Clinton, but later substituted the name Red Mountain and suggested correlation with the Clinton and Medina groups of New York (Butts, 1927). Many of the lithofacies described in the Red Mountain of Alabama have widespread distribution through the Appalachian Valley and Ridge (Cotter, 1983, 1988, 1996; Driese et al., 1991; Brett and Goodman, 1996a, 1996b; Driese, 1996). The recurrence of storm-dominated shelf deposits and hematite ironstones is particularly notable.

Not only the facies, but also the depositional sequences correlate over long distances in the Appalachian basin; there are striking similarities between the sequences in Alabama and New York more than 800 miles apart (Brett et al., 1998). The present work confirms these similarities and recent revision of the Alabama section helps to refine correlations (Fig. 11).

Sequence I (Taylor Ridge Member) of Rhuddanian age is recognized in Georgia, Tennessee, Virginia, Pennsylvania, Ohio, and New York as the Medina Group and its equivalents. Everywhere it is dominated by a westward-prograding wedge of storm-dominated shelf deposits that make up the Cabot Head and Grimsby formations in New York (Castle, 1998).

The age of sequence II is less certain. It may equate to the Cambria Shale–Kodak Sandstone sequence at the top of the Medina Group of New York (Brett and Goodman, 1996a; Castle, 1998; Brett et al., 1998). However, more likely, it correlates with the lithologically similar Maplewood and Neahga shales of New York and the Plum Creek Shale of Kentucky. In this case, the Crudup seam is equivalent to the thin Densmore Creek phosphate bed of New York. More biostratigraphic information is needed to test whether sequence II is early Aeronian.

The Big-Irondale seam occurs in much the same stratigraphic setting as the Furnaceville–Brewer Dock ironstone in New York. Both are complex, amalgamated units that occur locally on the western side of the basin overlain by highly fossiliferous beds of middle to late Aeronian age (C1–2). Brett et al. (1998) regard the Furnaceville as the TST of the middle Aeronian highstand, while the Irondale-Big seam is interpreted as an FSST at the top of sequence II, but still middle Aeronian.

Sequence III, including the Walker Gap, Morrow Gap, Compton, and Hickory Nut beds up to the base of the Ida seam, appears to match the Reynales-Sodus-Walcott section in New York (lower Clinton of Brett and Goodman, 1996a; Brett et al., 1998). This interval, divided into two subsequences, includes the main *Pentamerus*-bearing limestones in New York and several significant ironstones including the Sterling Station and Walcott Furnace beds.

The Hickory Nut beds are coeval with the Wallington Member of the Reynales Limestone. The same red shale facies with *Eocoelia* that occurs at the base of the Birmingham Member in northwest Georgia appears in the Rose Hill Formation in Tennessee and Virginia, and in the Sodus Shale of New York. Both in New York and in Alabama, these strata span the middle Aeronian to early Telychian interval (C1–4). A similar succession of faunas is also encountered in a relatively thin succession in the Bruce Peninsula, Ontario (Stott and von Bitter, 1999). The base of this sequence is highly discordant in both areas, and bevels progressively older Silurian strata toward the craton.

There is no clear equivalent in the Red Mountain Formation of the Sauquoit-Otsquago (middle Clinton) sequence, encountered along the Niagara escarpment. However, this is a localized unit and may be absent in the southern Appalachians. Alternatively, it may also be included within the upper part of the Birmingham Member in Georgia and Tennessee, in beds containing questionable *Eocoelia curtesi* (Baarli, 1989, personal commun.). Based on sandstone percentages in the Ringgold section (units 43–45), two sequences are possible but lack clear definition.

Sequence IV spans the middle to late Telychian interval (C5–6), and most likely correlates with the upper Clinton sequence in New York (Brett and Goodman, 1996a). This includes the Westmoreland ironstone (the quintessential "Clinton iron ore") overlain by the Willowvale (Williamson) Shale. Both the Ida and Westmoreland ironstones are highly discordant with respect to older beds, and they probably record the same transgression. However, the Ida seam (C5) appears to carry a somewhat older fauna than the Westmoreland (C6). The recent recovery of

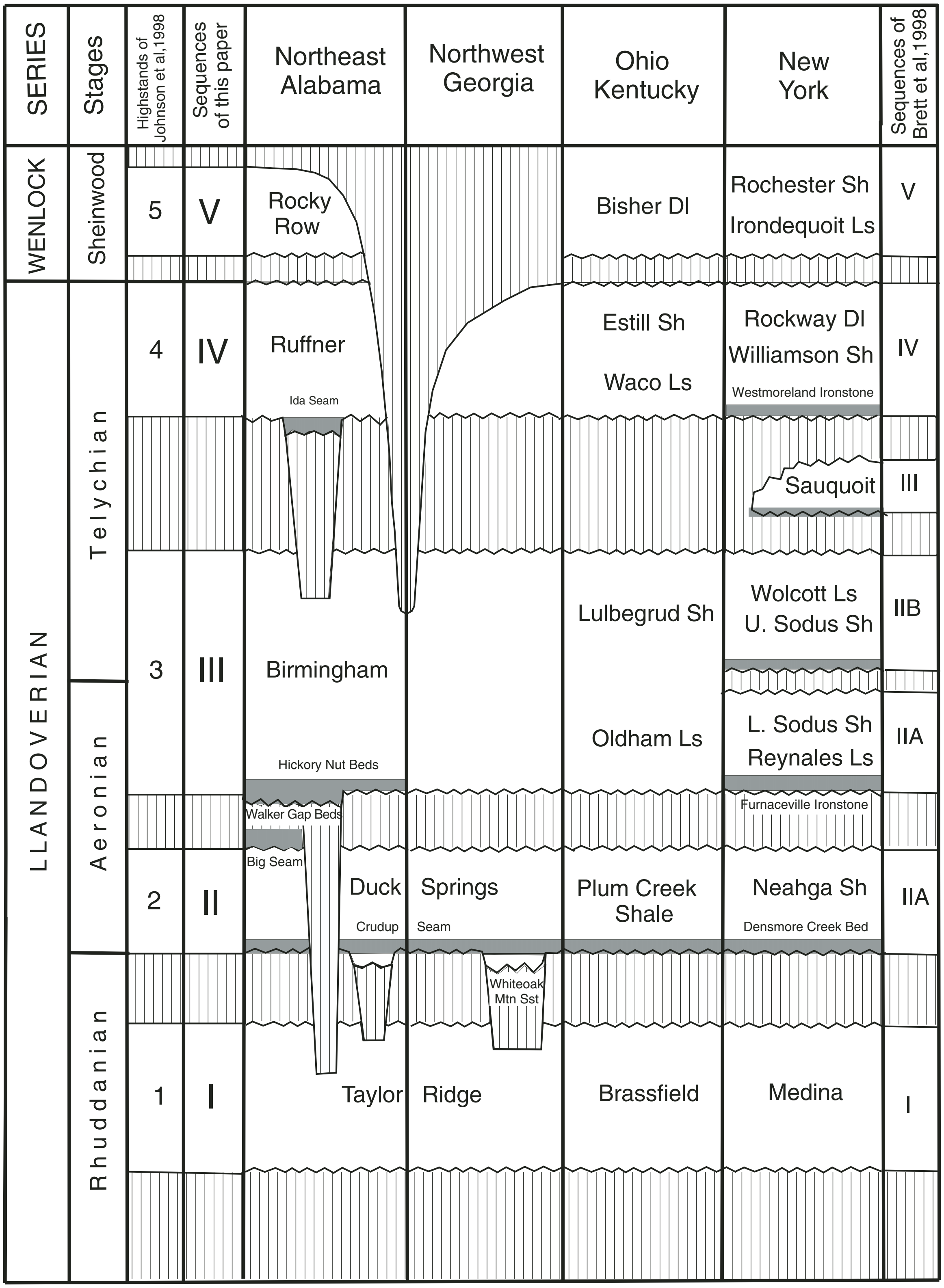


Figure 11. Chronostratigraphic correlations of sequences between Alabama and New York State (revised from Brett et al., 1998). Dl—Dolostone; Ls—Limestone; Sh—Shale.

Pterospathodus celloni Zone conodonts from the Westmoreland (Brett, 2004, personal commun.) strengthens this interpretation.

The Rocky Row Member forms sequence V, and correlates with the Keefer Sandstone in Virginia (Diecchio and Dennison, 1996) and the Irondequoit–Rochester Shale sequence, including the youngest Silurian ironstones (Kirkland iron ore), in New York (Brett and Goodman, 1996b; Brett et al., 1998). This interval also includes distinctive slump folds in the DeCew Formation, perhaps similar to the penecontemporaneous structures described by Ferrill (1982).

No Ludlovian sequences are preserved in the southern Appalachian basin. However, the Sparks Gap Member (sequence VI) includes facies similar to the Keyser Formation in Virginia and the Cobleskill Member of the Rondout Formation in New York. All are Pridolian.

SUMMARY OF CONCLUSIONS

1. The Red Mountain Formation may be conveniently divided into six members that generally coincide with depositional sequences.
2. These sequences have been dated on the basis of biostratigraphy, and match major marine transgressions related to interglacial periods in Gondwana: four during the Llandoverian and one each in the Wenlockian and Pridolian.
3. Llandoverian sequences were deposited on a storm-dominated shelf, and similar depositional facies recur in all members and are widely distributed in the Appalachian basin from Alabama to New York State.
4. Outer shelf facies consist of bioturbated silty shale, interbedded with fine-grained, graded-bedded sandstones or thin limestones deposited by storm-generated geostrophic currents.
5. Inner shelf facies consist of fine-grained, hummocky cross-bedded sandstones, either interbedded with shale or amalgamated. Some amalgamated sandstones are intensely bioturbated.
6. Most of the Llandoverian section consists of inner and outer shelf facies arranged in deepening-upward (TST) or shallowing-upward (HST) systems tracts.
7. Shoreface facies are less common. They occur mainly in eastern outcrop belts, and are better known from the Clinch Sandstone of Tennessee. They pass westward into the characteristic shelf facies of the Red Mountain and Rockwood formations. This facies is mainly gray in color.
8. The ironstones of the Birmingham ore field are coarse-grained, hematitic sandstones, containing ooids and abraded skeletal grains coated with hematite. Ooids were originally chamosite, and were derived by the reworking of offshore deposits either during transgression or forced regression. These highly condensed deposits were concentrated in the shoreface, less so in associated tidal inlets and estuarine lagoons.
9. Ironstones occur in all systems tracts, but the most significant ores, including those around Birmingham, are associated with sequence boundaries. They occur at the base of the TST or within the LST or FSST.
10. The most productive ores, which constitute the Big and Irondale seams of the Birmingham district, occur within an FSST and owe their productivity to the overprinting of depositional facies by meteoric diagenesis.

FIELD-TRIP STOPS

Day 1 (Fig. 12B; updated from Chowns, 2006a)

Cum. miles	*Miles*	*Directions*
0.0	0.0	Depart Holiday Inn Express and turn left on Chalkville Road.
0.4	0.4	Turn left on I-59 S.
10.6	10.2	I-59 merges with I-20. Continue south in right lane.
14.6	4.0	Exit 126; exit right on U.S. 31/280. Keep bearing left through exit.
17.5	2.9	Exit from expressway and turn left on 21st Avenue South.
18.1	0.6	Turn left onto Cahaba Road and continue through English Village (name changes to Arlington). Keep left through next two intersections.
18.8	0.7	Turn left onto 22nd Street.
18.9	0.1	Access to Red Mountain Expressway cut through gate at small park.

Stop 1. Red Mountain Expressway Cut

The Red Mountain Expressway cut (Fig. 13) was completed in 1970 to improve access to suburbs southeast of Birmingham. A major engineering feat, the cut is 560 m long, 65 m deep, tapering from 143 m wide at the top to 46 m at road level, and required the excavation of more than 2 million cubic yards of material (LaMoreaux and Simpson, 1970). It is registered as a National Natural Landmark and exposes beds from Middle Ordovician to Mississippian age. It was originally served by a small museum at the base of the section (northwest), but the museum was closed in 1994 and the condition of the cut has deteriorated. The Alabama Paleontological Society is currently attempting to maintain access by clearing trees and vines. The cut exposes the complete thickness of the Red Mountain Formation including all but the youngest member (Fig. 14). It is located in the heart of the Birmingham Ore Field just 0.5 miles northeast of the 20th Street crossing described by Butts (1926) and the Vulcan statue. The cut has been described in detail by Thomas et al. (1971), Chowns and McKinney (1980), and Baarli et al. (1992), and designated as the type section (Chowns, 2006b; this chapter).

We will begin our traverse in the Chickamauga Limestone (Middle Ordovician). Most of this unit (251 ft; 76.5 m) consists

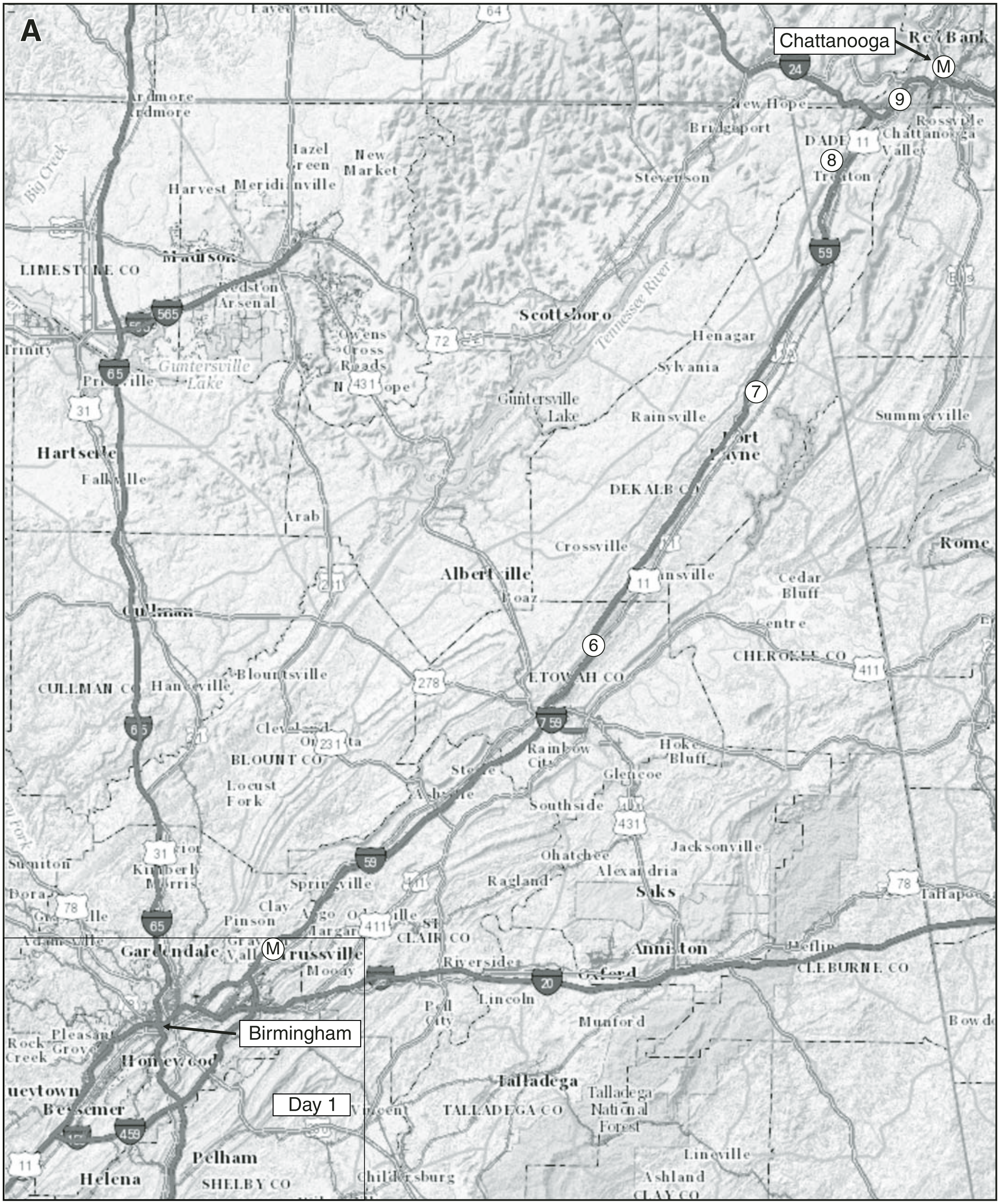


Figure 12 (*Continued on facing page*). Highway maps showing location of field-trip stops during Day 1 (B) around Birmingham and Day 2 (A) between Birmingham and Chattanooga. Figure 12A base map is courtesy of the U.S. Geological Survey. Circled Ms represent motel locations.

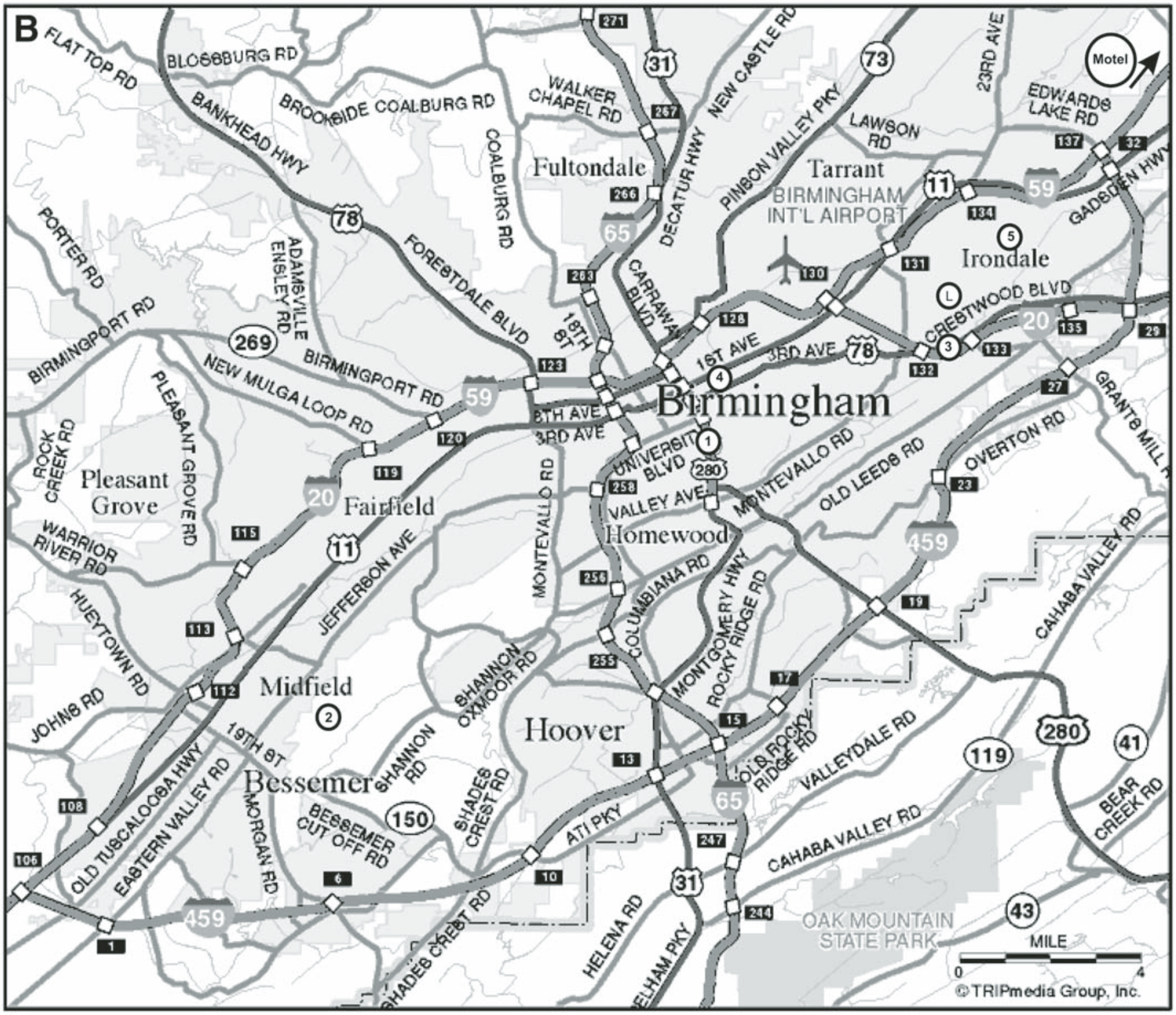


Figure 12 (*Continued*).

of thin-bedded micritic limestone with thin shale partings. Exceptions include some massive micritic bioherms and several thin beds of volcanic ash (sealed by gunite) that serve as useful marker beds. Further north in Georgia the uppermost T4 ash bed occurs ~170 m below the base of the Red Mountain Formation, but here it is just 5 m below the contact.

Taylor Ridge Member. The base of the Red Mountain Formation is an angular unconformity (Fig. 15A) but with a discordance of less than 2° (Thomas and Bearce, 1986). Truncation increases to the northwest. The Taylor Ridge Member (units 33–37) consists of a bed thickening, coarsening-upward sequence of graded-bedded sandstone and shale passing up into hummocky cross-bedded sandstones. Maximum flooding occurs within the first few meters of section. This dominantly retrogressive sequence of heterolithic storm-laid facies is typical of this member at most localities in both Alabama and Georgia.

Duck Springs Member (Fig. 15B). The base of the Duck Springs Member (unit 38) is signaled by a pronounced deepening and a return to distal shelf facies. The contact is marked by a thin reworked ironstone (Crudup seam) consisting of comminuted fossil debris and flaxseed hematite ooids. This horizon is obscured by normal faulting at this particular level in the cut.

Birmingham Member (Fig. 15B). The base of the Birmingham Member (unit 41) coincides with another major change in lithology from distal shelf facies at the top of the Duck Springs Member to shoreface facies that make up the Irondale and Big seams. Here the Irondale seam includes 1.8 m of conglomeratic, cross-bedded hematitic sandstone grading into hematitic

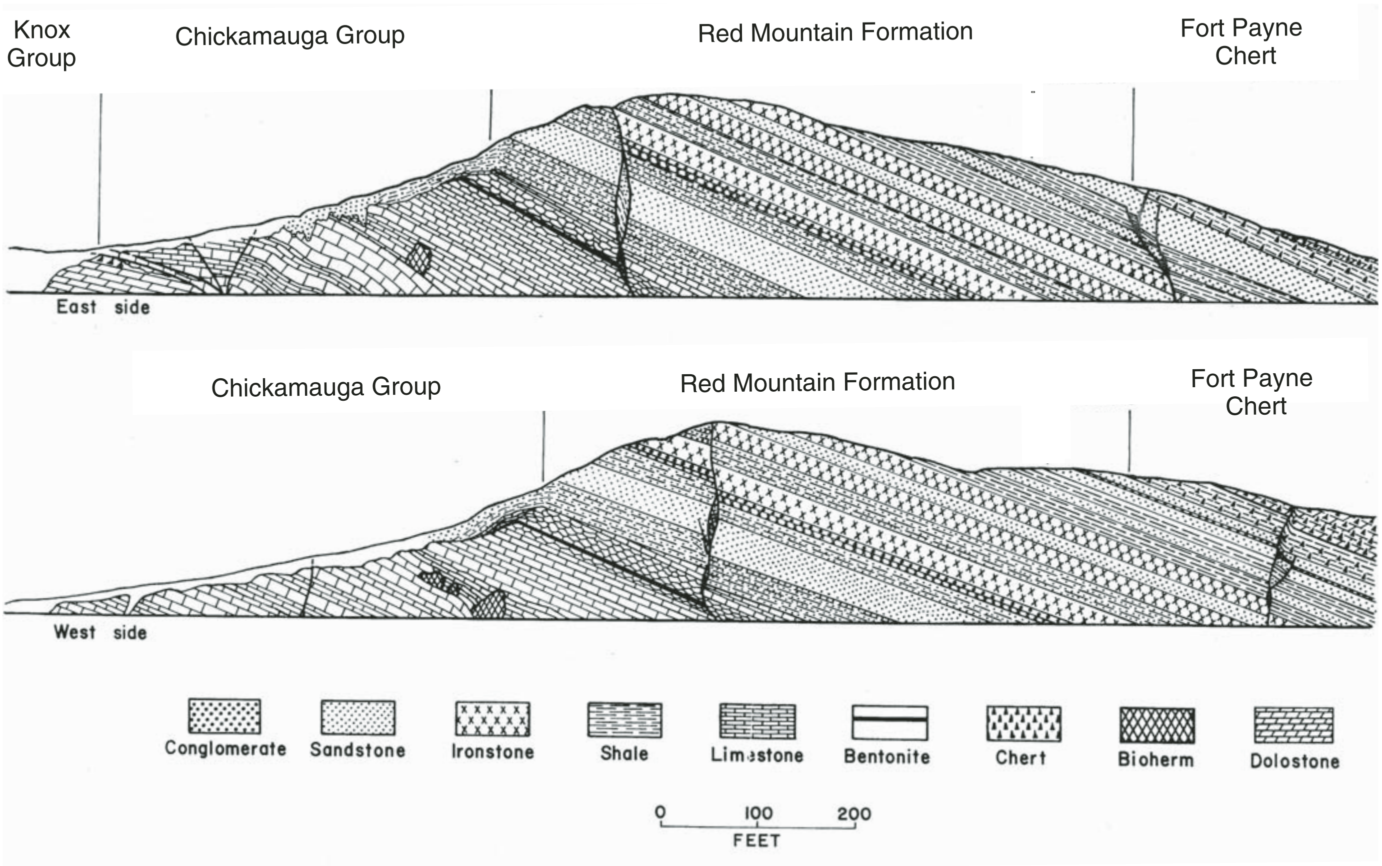


Figure 13. Cross-section sketch of the type section of the Red Mountain Formation on U.S. 280/U.S. 31 Expressway in Birmingham. (From Chowns and McKinney, 1980.)

siltstone and shale. Iron content was apparently too low to attract interest at this locality, but some of the richest ores are recorded at this horizon in the vicinity of Irondale. South of this locality, the Big seam (unit 43) was the main ore producer. The Big seam is easily identified by its massive bedding and dearth of sedimentary structures. It consists of highly abraded skeletal debris, hematite-chamosite ooids, and siliciclastics (from clay and silt to coarse-granular grains) partially replaced by hematite and cemented by bladed hematite. The original mineral in the ooids was likely chamosite, but this was oxidized (to nanogoethite?) and later converted to hematite during burial (Hodych et al., 1985). This impregnation and cementation by oxhydroxide is apparently responsible for the massive lithology and significance as an ore body.

Much importance has been attached to the so-called Kidney bed (unit 42), an interval of intraclastic conglomerate separating the Big and Irondale seams. Butts (1926) regarded it as evidence of an important unconformity, and Bearce (1973) suggested the Birmingham anticlinorium may have been emergent. However, the Kidney bed is of only local occurrence, and similar conglomerates are common at various horizons within different seams. More likely they are lag gravels from the base of wave ravinement surfaces or tidal channels.

A more important stratigraphic break occurs at the base of units 44–46 (Walker Gap beds). The interbedding of coarse-grained ferruginous sandstone with fissile shale is unique to this interval and indicates an unusual depositional environment. These beds are interpreted to be estuarine or lagoonal facies related to tidal inlet facies that we will examine at Ruffner (Morrow Gap beds). The coarse-grained, cross-bedded units are probably tidal-delta sands separated by low-energy suspension deposits.

Unit 47 is another conglomeratic ironstone, and marks the base of the Hickory Nut beds (47–52; see "Note on Revised Terminology" below). With the exception of coarse-grainey lithologies in units 47 and 51, the Hickory Nut beds are mainly fine-grained sandstones and siltstones. Iron content decreases upward, and cross-bedded ironstones give way to bioturbated siltstones with traces of hummocky cross-bedding. Whereas the underlying ironstone seams are limited to the Birmingham ore field, the Hickory Nut beds are widespread and highly transgressive (Fig. 8).

The base of the Hickory Nut beds and the base of the Irondale seam are interpreted as wave ravinement surfaces, while the base of the Walker Gap beds is a tidal ravinement. In terms of sequence stratigraphy, the base of the Hickory Nut beds is a transgressive ravinement (TRS), the base of the Walker Gap

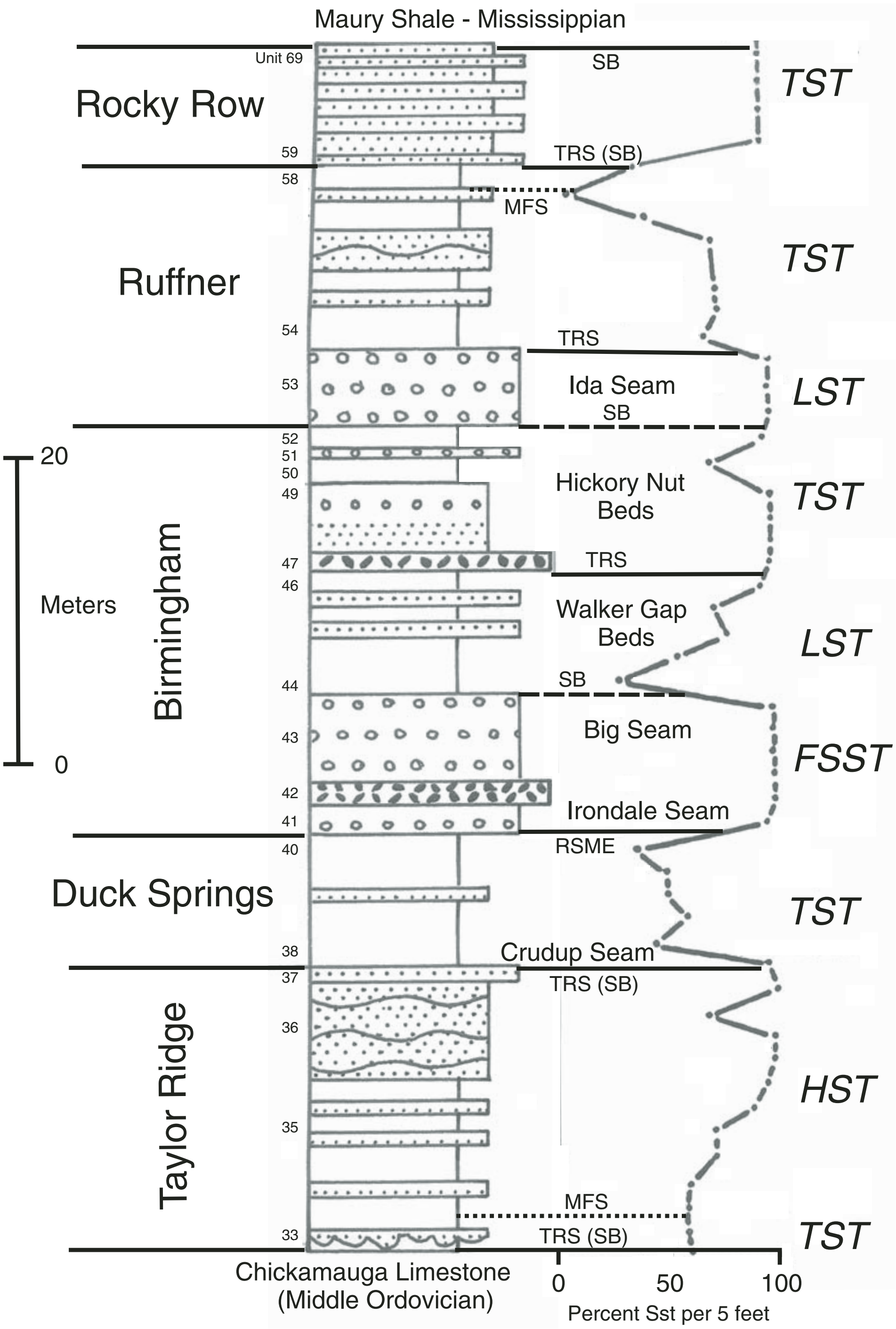


Figure 14. Sequence stratigraphic interpretation of the stratigraphic column for the type section of the Red Mountain Formation. All members are represented with the exception of the Sparks Gap (Pridolian). Legend as for Figure 2. SB—sequence boundary; TRS—transgressive ravinement surface; RSME—regressive surface of marine erosion; LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; FSST—falling stage systems tract.

beds the sequence boundary (SB), and the base of the Irondale a regressive surface of marine erosion (RSME). The lithologies of the Big and Irondale seams are very similar, and the ravinement at the base of the Kidney bed is interpreted to be within sequence. Thus the Hickory Nut beds belong to a TST, the Walker Gap beds to an LST, and the Big-Irondale seams to an FSST. In this case, the sequence boundary at the base of the Walker Gap beds is distinct from the lithologic boundary at the base of the Irondale seam. We think it is important to retain this distinction since the members are defined objectively on the basis of lithology, while sequence boundaries are interpretive.

P. oblongus (‘hickory nuts’) are abundant in units 47–49, and occur in life position in these beds at Ishkooda (Baarli et al., 1992). The lowest occurrence of *Pentamerus* appears to be at the base of the Walker Gap beds (Baarli, 1996) rather than within the Big and Irondale seams.

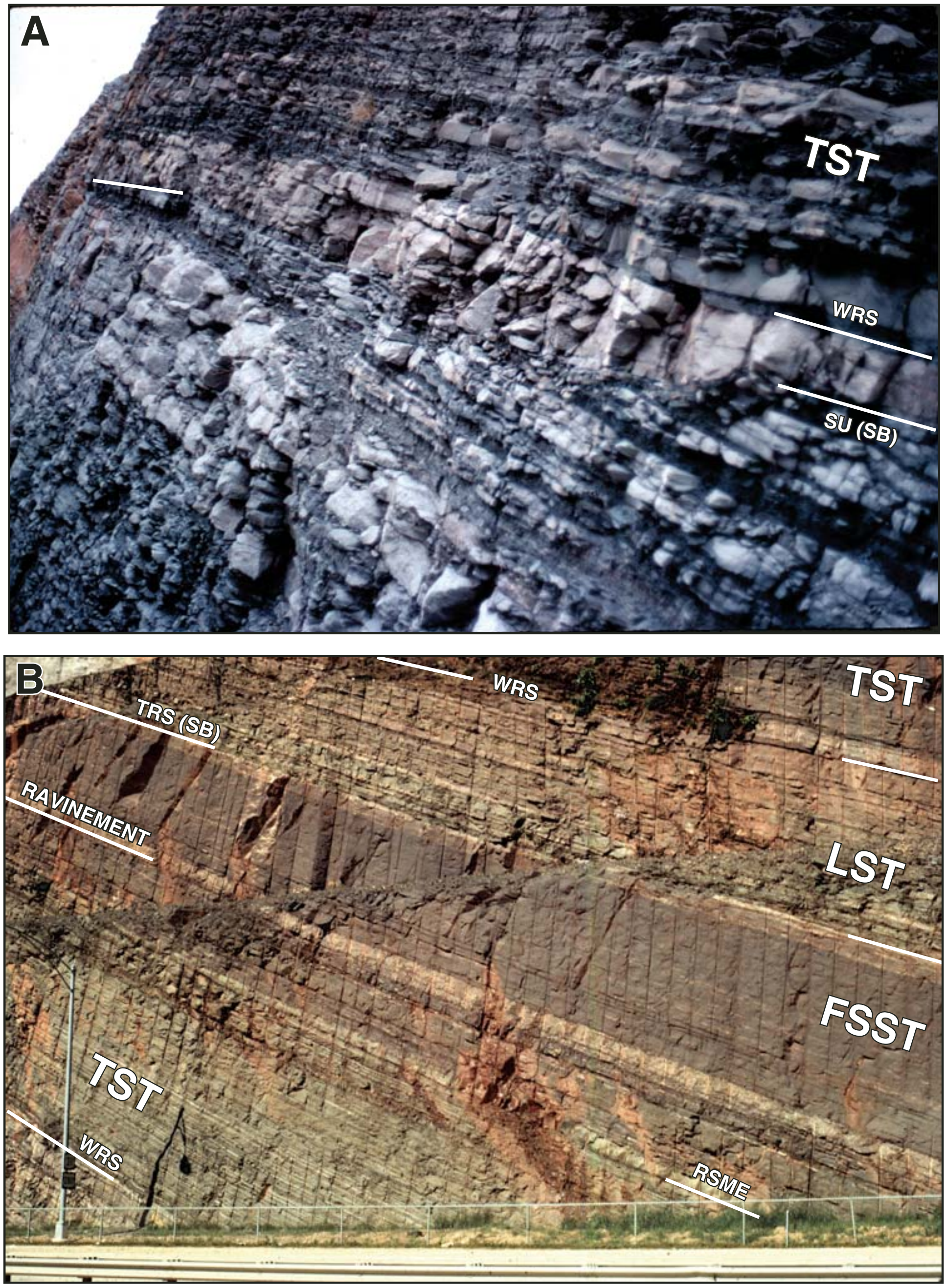


Figure 15. (A) Unconformity between Silurian and Ordovician strata at the type section. WRS is a wave ravinement surface and sequence boundary (SB) that obscures an original subaerial unconformity (SU). Note the downlap of beds at the base of the TST. (B) Stratigraphic section between the Crudup seam (lower wave ravinement—WRS) and base of the Hickory Nut beds (upper WRS) at the type section. RSME is the regressive surface of erosion at base of the Irondale and Big seams (FSST). TRS is the tidal ravinement surface and sequence boundary at the base of the Walker Gap estuarine beds (LST). RAVINEMENT is the in sequence ravinement at the base of the Kidney bed.

Ruffner Member. Unit 53 (Ida seam of revised terminology) is another coarse-grained, cross-bedded ironstone similar to the Big and Irondale seams but more quartzose, and thus unimportant as an orebody. It belongs to another shallow shoreface facies, possibly a tidal channel, and signals another sequence boundary. Overlying transgressive facies (units 54–58) are fine-grained hummocky bedded sandstones and silty shales. This unit contains a rich fauna with *Costistricklandia lirata* and coincides with the major late Telychian marine transgression identified by Johnson (1996).

Rocky Row Member. Units 59–69 were formerly referred to the Frog Mountain Formation but were shown by Ferrill (1984) and Berdan et al. (1986) to be Wenlockian in age. Chowns (2006b) introduced the new name Rocky Row Member for this stratigraphic sequence, for a type section where Carson Road cuts through West Red Mountain at Rocky Row. Lithologies consist mainly of interbedded coarse- and fine-grained gray sandstones with some ferruginous beds that are now poorly exposed. Thomas and Bearce (1986) describe penecontemporaneous faulting and slumping in these beds.

The expressway cut lies midway between the two main iron-mining districts centered at Irondale in the north and Bessemer to the south (Fig. 16). Although the dip slope was stripped, no major underground mines were developed, apparently because the ore was siliceous. Mines to the north were identified with the Irondale seam and mined from the dip slope of Red Mountain. Mines to the south were located in the Big seam and mined from the northwest escarpment.

A Note on Revised Terminology

Following the work of Butts (1910, 1927), most workers (but not all; e.g., Bearce, 1973) have referred to unit 49 as the 'Ida' seam and unit 53 as the 'Hickory Nut' seam. Chowns (2006b) proposed to switch these two names in order to remove terminological confusion and recognize priority. The reasons for this proposal are as follows:

1. The Ida seam was named for Ida McElwain, daughter of Wallace S. McElwain, ironmaster at the Cahaba Iron Works (Irondale). It is therefore inferred that the seam was named from the original McElwain Furnace (Dago) mine south of Irondale. This is substantiated by a reading of McCalley (1897) who describes the Ida seam in these workings.
2. Both McCalley (1897) and Burchard and Butts (1910) confirm the location of the Ida seam as the highest seam in the sections around Irondale, separated from the Big seam by a couple feet of ferruginous sandstone. They do not distinguish the Hickory Nut around Irondale.
3. The term Hickory Nut seam derives from the Ishkooda Mines (West 2 and Smythe), where it is described as lying 28–30 feet above the Big seam (McCalley, 1897).
4. Based on apparent juxtaposition to the Big seam, it is easy to understand why stratigraphic order was interpreted to be Big–Ida–Hickory Nut, but this does not take into account the complex stratigraphic relationship between these beds (Fig. 8).
5. Recent work demonstrates that the bed defined as Ida near Irondale is unit 53 of the type section. At Ishkooda, the beds crowded with *Pentamerus* in life position occur

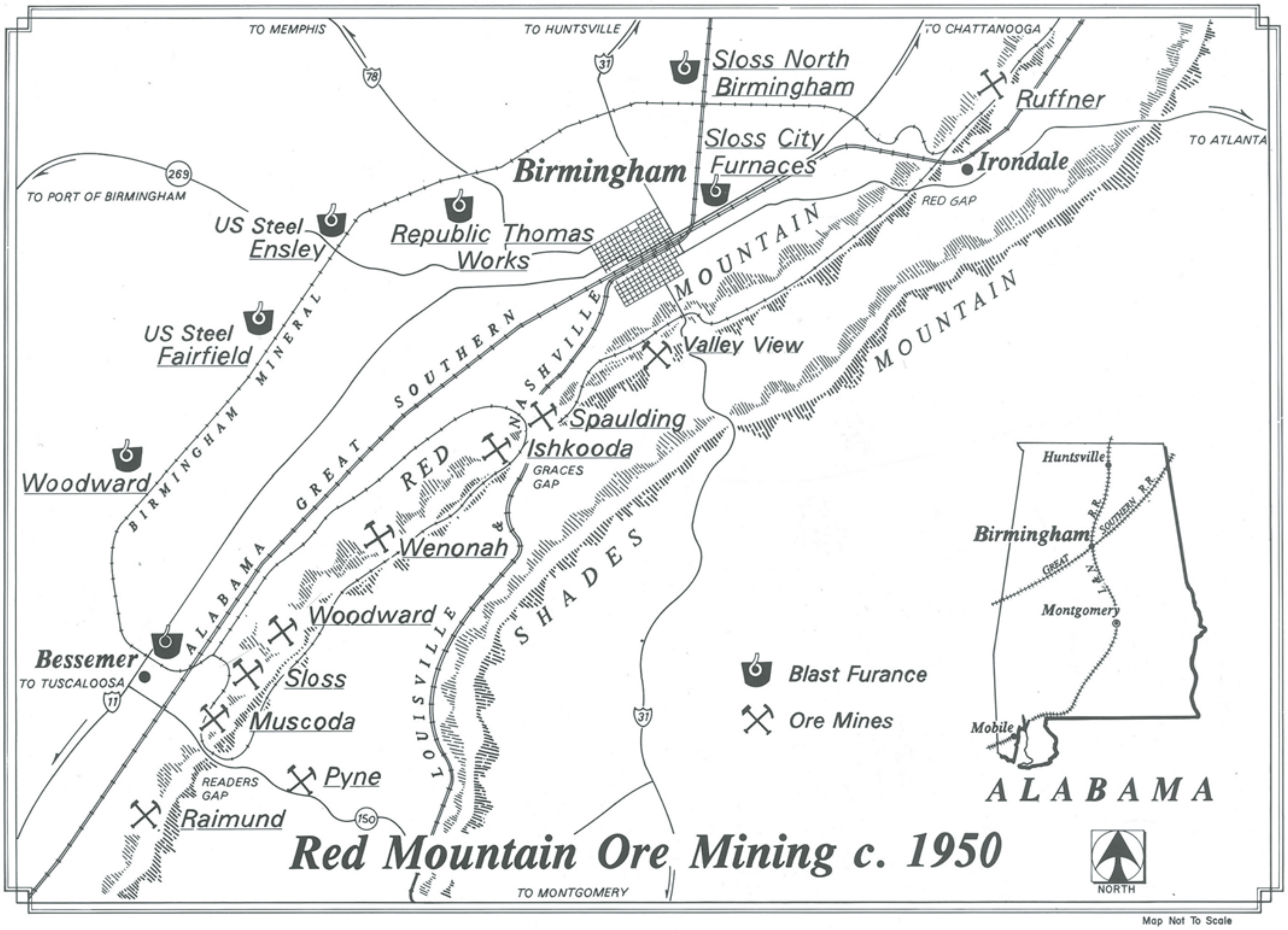


Figure 16. Location of major mines along Red Mountain. (From Morris and White, 1997.)

below unit 53 (Baarli et al., 1992), separated from the Big seam by the Walker Gap beds (~30 feet thick).

19.1	0.2	Retrace 22nd Street South, heading north.
19.2	0.1	Turn left onto Arlington Avenue South, heading west.
19.3	0.1	Turn right on Highland Avenue South, heading north.
19.4	0.1	Turn right onto ramp of U.S. Highway 31/280, southbound.
20.4	1.0	Continue on U.S. Highway 31 while U.S. Highway 280 forks to left.
22.0	1.6	Exit right onto Lakeshore Drive (Parkway) (Alabama Highway 149).
32.0	10.0	Park on roadside beyond power substation. Walk on dirt road to Sloss No. 2 Mine (~10 min).

Stop 2. Sloss No. 2 Mine. (Leader: Andrew Rindsberg)

The location of mines was determined by terrain and accessibility of the outcrops to rail (Fig. 16). Depending on the terrain several types of mine developed. The dip slope was especially favorable for development in the early days, because soft, rich, weathered ores could be obtained by strip-mining or driving drifts along strike from ravines. The mines between Morrow Gap and Valley View were all located on the dip slope and utilized self-acting inclines. South of Graces Gap (Spaulding Mine), overburden increased substantially and it was necessary to open slope mines on the northwest escarpment. Gravity was less efficient here and mules were needed to haul ore out of the workings. Finally, with depletion of ore at outcrop, shaft mines were constructed down-dip at the Pyne (in 1918) and Shannon mines (in 1920). Including the Redding shaft at Woodward's Songo mine, there were only three shaft mines in the district (McFerrin, 2009). The Shannon Mine closed in 1930 while the Pyne Mine remained undeveloped after the end of World War I, but was refurbished and opened in 1942. In 1970, it was the last mine to close.

To supply ore for their City Furnaces, Sloss Iron and Steel Company opened mines both north and south of Birmingham (referred to as upper or Ruffner mines in the north and lower or Sloss Nos. 1 and 2, to the south). Sloss No. 2 Mine is typical of the slope mines opened along the scarp face of Red Mountain between Graces Gap (Birmingham) and Readers Gap (Bessemer). Remains include the mine portal and foundations of hoist houses and crushers. Flanked by the mines of the Woodward Iron Company and the Tennessee Coal and Iron Division of U.S. Steel, these were the most productive mines in the district. Sloss No. 1 dates to 1889; the main slope of Sloss No. 2 was opened in 1890 and the mine was operated until 1959. Originally, haulage was by mule. The main hoist and ore crusher was first run by steam but converted to electricity in 1920 (Morris and White, 1997). According to McCalley (1897), the section in the neighboring Sloss No. 1 Mine was as follows:

Gray seam [Ida], fossiliferous	5.5′
Sandstone and Shale	8.0′
Ida [Hickory Nut] seam	6.0′
Ferruginous sandstone and interbedded shale [Walker Gap beds]	10.0′
Big Seam (upper bench)	14.0′
Sandstone, shaly, weathering greenish yellow	4.7′
Big Seam, (lower bench), [Irondale seam?]	3.9′
Sandstone, flaggy	

Spoil piles from Sloss No. 2 provide good collecting, including a variety of ore types, characteristic body fossils, and ichnofossils. The majority of tailings probably derive from the Big seam but with an admixture from adjacent beds encountered during the construction of ventilation shafts and access tunnels. Mine timbers are also present; be careful rambling around.

The spoil pile is remarkably fresh compared to the material generally seen in roadcuts and other surface exposures of the Red Mountain Formation. Although no section is currently exposed here, it is possible to reconstruct trace-fossil assemblages based on the co-occurrence of ichnotaxa on single blocks of spoil. The trace fossils, then, belong to at least one sequence of assemblages representing onshore to offshore facies (Table 1, Fig. 17, Appendix)—a sequence mirrored at several other localities, especially in the Taylor Ridge Member. The ironstone itself contains almost no evidence of bioturbation, suggesting very difficult living conditions for the tracemakers. Alternating sandstone and shale contain increasingly diverse trace fossils offshore. *Arthrophycus brongniartii* dominates what is presumably the most difficult environment that tracemakers could live in, presumably intertidal flats and associated facies. It is joined by vertical burrows (*Monocraterion*) in what may be the upper shoreface, then by a patchy (commonly monoichnospecific) assemblage of more diverse marine trace fossils (notably *Asterosoma*) in the lower shoreface. *Arthrophycus* is represented in this assemblage mainly by relatively small individuals, suggesting that its tracemaker had its juvenile stage here and then migrated toward the flats as it matured. Shelf deposits are represented by an even more diverse assemblage with less patchiness. The *Petalichnus* assemblage does not quite fit into this pattern, being typically found *above* the *Arthrophycus* assemblage in outcrops, and is thought to represent lagoonal facies where epichnial traces stood a reasonable chance of being preserved.

39.3	7.3	Retrace part of route on Lakeshore Parkway.
44.6	5.3	Take ramp (left) onto Interstate Highway 65 heading north.
49.8	5.2	At exit 261A, take ramp to right onto Interstate Highway 20/59, passing through downtown Birmingham with the Red Mountain to the right.
50.1	0.3	Take exit 130 onto Interstate Highway 20 toward Atlanta.
51.8	1.7	Take exit 130A.

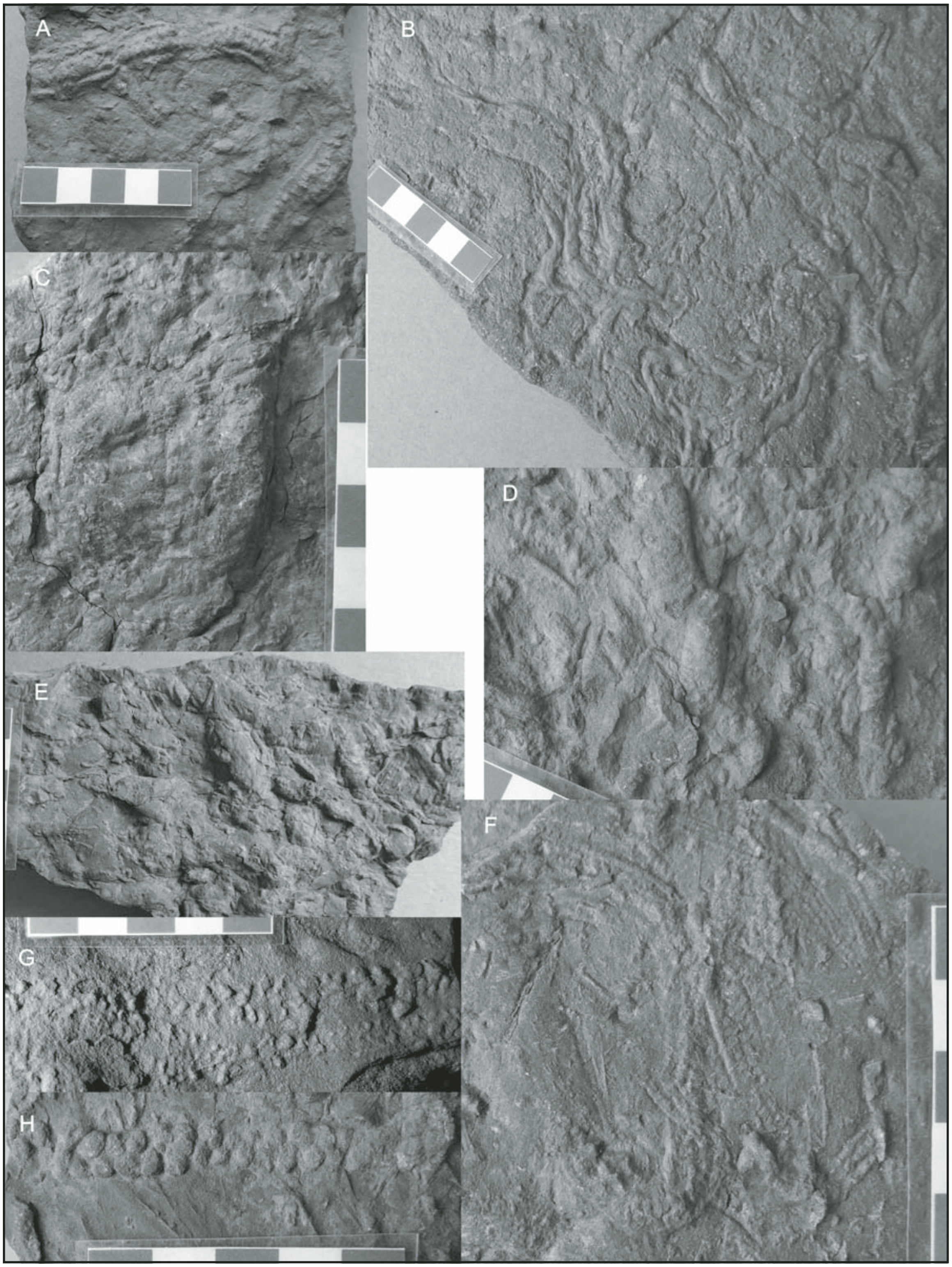


Figure 17 (*Continued on following page*). Red Mountain Formation trace fossils from the Sloss No. 2 Mine tailings pile. All are hypichnia unless otherwise indicated. Scales in cm. (A) *Arthrophycus brongniartii* incorporating a series of resting traces (*Rusophycus*). Epichnion. (B) *Asterosoma templus*. (C) *Rusophycus* isp. (D) *Arthrophycus brongniartii*. Epichnia. (E) *Asterosoma* isp. (F) *Cruziana quadrata*. (G) *Petalichnus* isp. (H) *Nereites biserialis*.

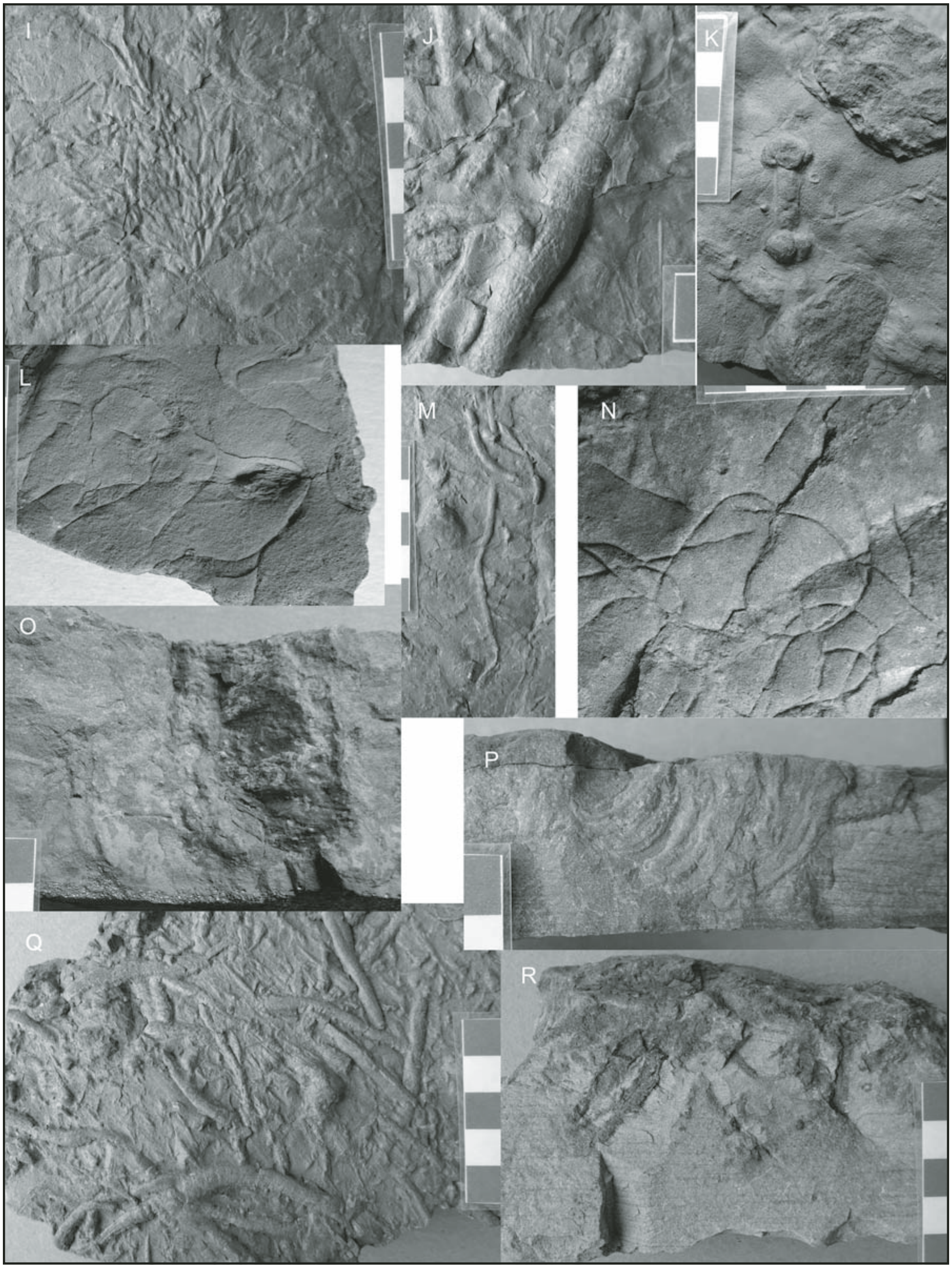


Figure 17 (*Continued*). (I) *Chondrites* isp. (J) *Scotolithus mirabilis* (“*Halopoa*” aspect), showing tension fractures. (K) *Arthraria* isp. (L) *Lockeia* isp. connected with *Dictyodora* isp. Epichnion. (M) *Planolites montanus*. (N) *Dicytodora* isp. (O) *Diplocraterion parallelum*. Endichnion in vertical section. (P) *Dictyodora* isp. Endichnion in vertical section. (Q) *Scotolithus mirabilis* (“*Halopoa*” aspect). (R) *Scotolithus mirabilis*. Endichnion in vertical section.

52.1	0.3	Take the exit 132B ramp toward Oporto-Madrid Boulevard.
52.3	0.2	Turn right (south) onto Oporto-Madrid Boulevard.
52.5	0.2	Turn right (west) onto Crestwood Boulevard (U.S. Highway 78).
52.7	0.2	Turn right into Century Plaza, then left on perimeter road.
52.9	0.2	Follow perimeter road to the northwest corner of mall (unoccupied as of this writing).

Stop 3A. Century Plaza (Hammond Mine)

When R.P. Sheldon worked the Red Mountain Formation from 1959 to 1964, there was a well-exposed section along U.S. Highway 78. Most of this section is now covered, but it is possible to observe partial sections at Century Plaza, Crestwood Festival Mall, and I-20. Century Plaza is located over the old Hammond Mine, and two plugged adits are visible on the northwest side of the parking lot, inclined southeast beneath the shopping center. The composite section is as follows:

Chattanooga Shale	
Rocky Row Member: massive thick-bedded, channeled sandstones and interbedded shale involved in large-scale slumping and other penecontemporaneous deformation.	43.0′
Ruffner Member: Fine-grained hummocky cross-bedded sandstone and shale, grading up into siltstone with interbeds of fine-grained sandstone and limestone. *Pentamerus, Stricklandia.*	36.5′
Ida seam: massive, cross-bedded, coarse-grained, sandy ironstone. *Pentamerus.* Weathers grayish red.	8.0′
Birmingham Member	
Hickory Nut beds: fine-grained, thin-bedded, cross-bedded conglomeratic ironstone with some shale partings. Lower contact sharp and eroded. Contains pentamerid brachiopods. Weathers rusty red.	12.5′
Big seam: massive weathering, coarse-grained, sandy ironstone with quartz granules. Cross-bedding indistinct. Occurs in two massive beds separated by distinct parting. Unfossiliferous. Lower 10 concealed*.	37.0′
Shale*	2.0′
Irondale seam: hematitic ironstone, fossiliferous. Interbedded with shale at base*.	7.0′
Duck Springs Member: shale with thin sandstones. Ferruginous at base*.	39.0′
Taylor Ridge Member (exposed at Crestwood Mall)	
Sandstone, fine-medium–grained, hematitic. Amalgamated hummocky cross-bedded*.	22.0′
Sandstone and shale interbedded. Includes two thick sandstones with spectacular ball-and-pillow structures	38.5′
Chickamauga Limestone with ash bed 2.2′ from top.	

*Irondale seam and adjacent beds covered beneath parking lot. Details from unpublished section of Sheldon (1971).

The Hammond Mine section is located ~5 miles northeast of the expressway cut. Although all the major members are present with comparable thicknesses, there are important changes in the ironstone seams (Fig. 18A).

1. The Ida seam is much thinner here than at the expressway, and rests directly on top of the lower, ferruginous Hickory Nut beds.
2. The Hickory Nut beds are also thinner and the Walker Gap beds completely absent.
3. By contrast, the Big-Irondale combination has increased in thickness from 31 ft (9.4 m) at the expressway to 46 ft (14.0 m) at Hammond.
4. As a consequence, there is a combined thickness of 66.5 ft (20.3 m) of iron-bearing rock.

In the absence of the Walker Gap beds (LST), the sequence boundary is located at the base of the Hickory Nut beds (TST) that rest directly on the Big-Irondale seams (FSST). Exposure of the FSST to meteoric groundwater was important for the precipitation of iron oxyhydroxide cements (later converted to hematite), critical in raising ironstones to ore grade. It is this hematite cement that is responsible for the massive weathering and poor preservation of sedimentary structures in the Big-Irondale seams.

Large-scale penecontemporaneous deformation has been noted in the Rocky Row Member both here and at the type section (Ferrill, 1982; Thomas and Bearce, 1986), and is thought to indicate seismicity related to basement faults beneath the Birmingham anticlinorium.

53.1	0.2	Return to Crestwood Boulevard and turn right, move into left lane.
53.5	0.4	Turn left into Crestwood Festival Mall. Outcrop is at rear of Home Depot.

Stop 3B. Crestwood Festival Mall

Exposures at Crestwood Mall are limited to the Taylor Ridge Member. The sequence is similar to that at the expressway, but is interrupted by two fine-grained sandstone beds with massive ball-and-pillow structures (Fig. 18B), also perhaps related to local seismicity. The unconformity at the base of the Red Mountain Formation has truncated all but 0.7 m of Chickamauga Limestone above what is presumed to be the T4 ash bed.

This locality is also of interest for the disastrous mass wasting that occurred in 1987–1988 as a result of construction on the dip slope. As a result of grading for the parking lot, the T4 ash bed was exposed on the dip slope and support for part of the Silurian sandstone shale sequence removed. In consequence, a large slump developed parallel to bedding and part of an apartment building at the top of the hill was lost. Following a lawsuit, the slope was stabilized by a combination of massive rock bolts, drainage pipes, excavation, and grouting (Bearce, 1990).

53.7	0.2	Return to entrance of mall and turn right on U.S. Highway 78, Crestwood Boulevard.
55.0	1.3	Turn left on 16th Street South.
55.6	0.6	Turn right on 2nd Avenue North.
55.7	0.1	Take second right onto 19th Street North, then left onto 1st Avenue North. Irondale Café is on the left.

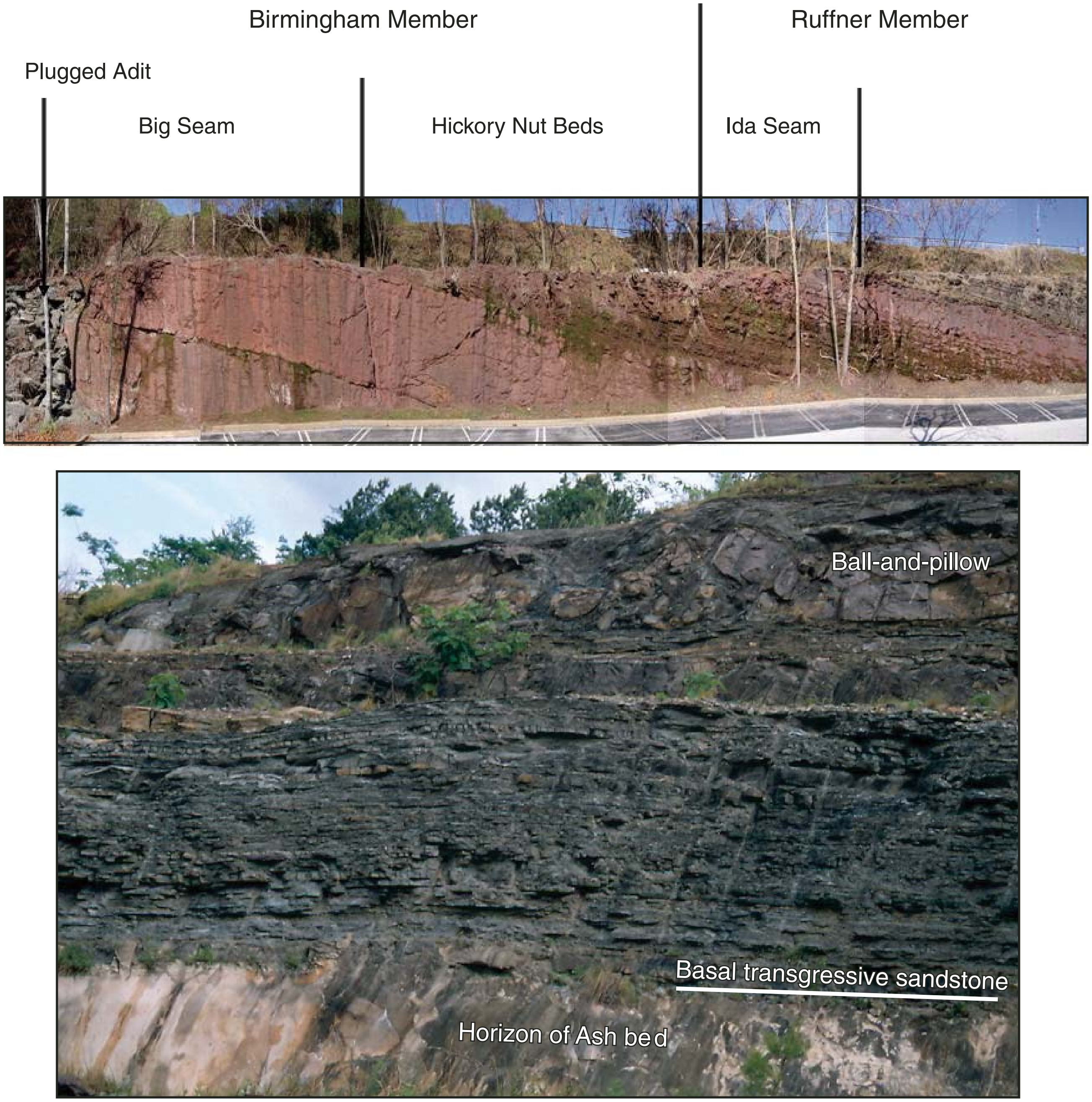


Figure 18. (A) Superposition of Ida, Hickory Nut, and Big seams at the Hammond Mine, Century Plaza, Birmingham. The Irondale seam was the only seam worked extensively at the locality, and it lies below the level of the parking lot. Note that the photomontage has been foreshortened and dip is exaggerated. (B) Base of the Taylor Ridge Member at Crestwood Festival Mall, Birmingham, including large ball-and-pillow structures. Note basal unconformity and ash bed within the underlying Chickamauga Limestone (covered with cement).

Lunch. Irondale Cafe.

56.4	0.7	Return to Crestwood Boulevard (U.S. 78) and turn right.
61.7	5.3	Turn right on 32nd Street South.
62.0	0.3	Entrance to Sloss Furnaces.

Stop 4. Sloss Furnaces

Prior to the Civil War, pig iron was smelted using charcoal for fuel. Several old charcoal smelters are preserved locally, most notably at Tannehill. Similar furnaces were subsequently opened up in Shades Valley, at Oxmoor (in 1863) and near

Irondale (in 1864), but were destroyed by James H. Wilson's troops in 1865. After the war, ironmasters struggled to rebuild these furnaces but could not compete with northern iron. Then in 1876, Levin S. Goodrich managed to utilize coke produced from local coal in the smelter at Oxmoor (http://miningartifacts.homestead.com/AlabamaMines.html). Following this success, Henry F. DeBardeleben began construction on the Alice Furnaces in 1879 (www.bhamrails.info/Alice_Furnace/alice_furnace_02.htm) and James Withers Sloss the Sloss Furnaces in 1882. The present Sloss Furnaces in Birmingham were built during a major period of technological advance from 1927 to 1931. They operated up until 1970, at which time they were deeded to the Alabama State Fair Authority by Jim Walter Corporation for development of an industrial history museum. At first, preservation did not seem feasible and the authority recommended the furnaces be dismantled. Fortunately, there was great public outcry, and the Sloss Furnace Association was organized to save the site (www.encyclopediaofalabama.org/face/Article.jsp?id=h-2036). Through the efforts of this group, the furnaces were deeded to the City of Birmingham, a special bond referendum was passed, and the site was recognized by the U.S. Department of the Interior as a National Historic Landmark. The Furnaces were opened to the public on Labor Day 1983 as Sloss Furnaces National Historic Landmark. They are the only twentieth-century furnaces in North America open to the public as a museum (http://slossfurnaces.com/).

The making of iron requires three raw materials all famously present within a few miles of Birmingham: iron ore, coal (for coke), and limestone. Details of the smelting process may be found online at the website of the American Iron and Steel Institute (www.steel.org) upon which this summary is based.

Iron ore. Initially, no beneficiation was needed for soft-weathered ores provided iron content ran between 50%–70% Fe. Iron content first became a problem in the 1890s with depletion of soft ore. It required time for the furnace masters to adapt furnace design for the leaner hard ores. The Tennessee Coal and Iron Company (TCI) first began experiments to improve ore quality in the mid-1890s, and all other major furnace operators followed suit. Again in the declining years of the ore field further efforts were made to upgrade ores at some mines. Modern blast furnaces use magnetite ores, which lend themselves to magnetic separation and are transported as rounded pellets and/or scrap iron.

Coke. Apart from its high carbon content (and calorific value), coke is used in the blast furnace because of its strength. An open framework of coke particles is needed to allow hot reducing gases to circulate through the furnace. Upon heating, the coke is converted first to carbon dioxide then to carbon monoxide, necessary to reduce the iron oxide.

Limestone or dolostone. Limestone or dolostone is used as a flux for the separation of gangue minerals, or impurities, from the molten iron in the furnace. These impurities include silica, alumina, and magnesia. Some of the more calcareous ores were at least partly self-fluxing. During the smelting process, these impurities are floated off the liquid iron as a calcium silicate slag. The carbonates are also a further source of carbon monoxide. Sulfur and phosphorus were also present as contaminants, but were removed at a later stage.

The mixture of iron ore, coke, and limestone is fed into the top of the furnace and subjected to a forced draft (or blast) introduced through "tuyeres" near the base of the stack. Early furnaces used a cold blast of unheated air, but greater efficiency was obtained by recirculating the furnace gases as a "hot blast." The raw materials take between 6 and 8 h to descend, during which time the iron oxide is reduced in the presence of carbon monoxide, then melted and separated from the slag. There are three stages as temperature rises toward the base of the furnace:

1. 850 °F (454 °C) $3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$
2. 1100 °F (593 °C) $Fe_3O_4 + CO = 3FeO + CO_2$
3. 1300 °F (704 °C) $FeO + CO = CO_2 + Fe$ *or* $FeO + C = Fe + CO$.

Early furnaces poured their charge of molten iron directly into runners, or pigs, molded in the sand floor of the casting shed. In 1927, the process was automated at Sloss Furnaces by the installation of a mechanized pig caster. Liquid slag was discarded and the hot exhaust gases recirculated to provide the necessary "hot blast." Once a furnace was put into blast, it might run continuously for years with only short breaks for maintenance.

The Sloss Furnaces produced only pig iron. A further step was necessary to reduce the carbon content and remove sulfur and phosphorus in order to convert brittle cast iron into steel. This involved the "basic process" using either a Bessemer converter lined with clay or the Siemens-Martin open hearth furnace. The converter is in essence a huge ladle with tuyeres to allow the introduction of oxygen to oxidize the carbon, and clay to react with the phosphorous, giving more slag. The Bessemer converter was invented in 1856 and the Gilchrist-Thomas open hearth modification in 1878. The first Sloss furnace was put in blast in 1882. Without the introduction of hot blast, the Bessemer converter, and the basic process (first brought to Birmingham in 1888), the meteoric success of the Birmingham district in the 1890s would have been impossible.

The following self-guided tour (Fig. 19) is adapted from pamphlets published by the Sloss Museum:

1. *The Visitors Center.* Originally an electrical repair shop and bath house for the furnacemen, this now serves as the administrative offices for Sloss Furnaces National Historic Landmark. It includes a bookstore and gift shop as well as restrooms.
2. *Furnace and Casting Shed.* As you leave the visitors center, the long building to your left is the casting shed with the No. 1 Furnace at the end. Walk around the furnace to identify the tuyeres and the holes (notches) through which iron and slag were emptied from the hearth at the bottom of the furnace. The slag was bled off as fiery flows that provided a spectacular fireworks display, especially

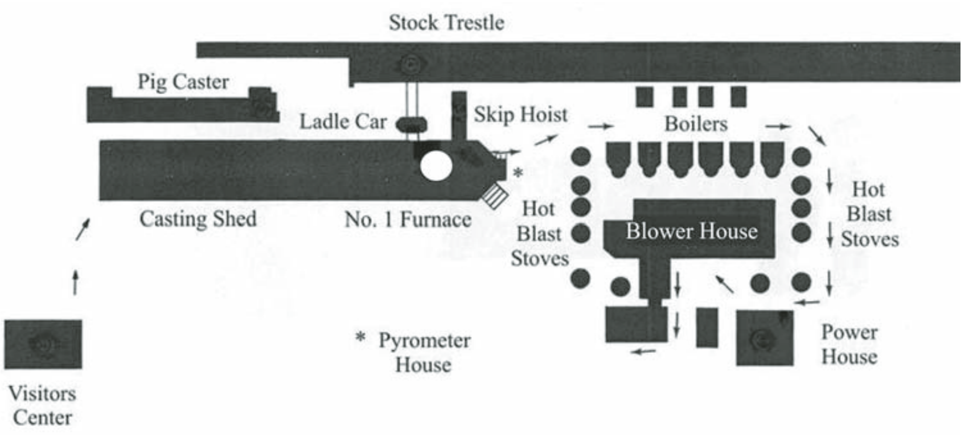


Figure 19. Map of walking tour of Sloss City Furnaces and Museum. (From Chowns, 2006a.)

at night. The iron was channeled through a curved "runner" into a ladle car.

3. *Ladle Car and Pig Caster.* Follow the runner across the elevated walkway to the ladle car—a brick-lined kettle mounted on wheels that was used to transfer molten iron to the pig caster. This lies ahead of you (to the left) as you look down the rails beside the casting shed. Iron was poured from the ladle via a system of runners into a series of shallow molds linked together like tank treads. The molds moved forward as a conveyor belt from the ladle, were sprayed with cooling water, and tipped into waiting railroad cars.
4. *Stock Trestle and Skip Hoist.* Across the tracks from the furnace is the elevated stock trestle. Railroad cars arrived here and dumped ore, coke, and flux into bins below the trestle. Other railroad cars ran in a tunnel below the bins and transferred the requisite charge to the skip hoist and thence to the top of the furnace via two small skip cars driven by steam-powered pulleys.
5. *Pyrometer (Dog) House.* Return to the casting shed and descend the stairs from the furnace. At the foot of the stairs is the two-story brick pyrometer house. The upper floor housed pyrometers for measuring temperatures in the furnace, while downstairs was the millwright's shop used by furnace repairmen. In case of an emergency at the furnace, workers would run to this "dog house" for safety—the furnace sent them to the "dog house."
6. *Hot Blast Stoves.* Ahead of you as you leave the furnace, along the side of the plaza, are six large cylindrical hot blast stoves used to heat air fed to the tuyeres. The iron cylinders are lined with a brick lattice known as the checkers. Waste gases from the blast furnace were burned in the stoves to heat the checkers. The gas was then shut off, air circulated and heated to 1400 °F (760 °C) and then blown into the blast furnace.
7. *Boilers.* Turn left and walk clockwise around the complex of buildings behind the hot blast stoves. A wooden walkway leads between the railroad tracks and the boilers. The boilers (1906, 1914) were heated by furnace gases, supplemented by coal or natural gas, and used to generate steam, essential for running the blowing engines, skip hoist, mechanical charger, and electric generator.
8. *Power House.* At the end of the wooden walkway, turn right and follow the paved sidewalk to the power house. On your left is the No. 2 Furnace (closed) and to the right another range of hot blast stoves. The power house dates to the electrification of the plant in 1929. Upstairs are a steam-driven turbine and generator; below rectifiers for converting alternating to direct current.
9. *Blower House.* Exit the power house to the left and enter the open doorway into the blower house. Ahead are eight huge steam-driven air compressors used to supply the hot blast stoves. Each stands 30 feet tall with 20 foot fly wheels. These are the oldest surviving engines at the furnace and date from 1900 to 1902. They were later replaced (1949–1951) by two much smaller centrifugal compressors driven by steam turbines located in adjacent wings of the building.

62.1	0.1	Depart Sloss Furnaces via 2nd Avenue North and turn left on 33rd Street North.
62.3	0.2	Turn left on Messer Airport Highway.
62.5	0.2	Turn right on 31st Street.
63.0	0.5	Entrance ramp to I-20/I-59; turn right.
66.2	3.2	Exit on I-59 toward Gadsden.
67.7	1.5	Exit at 130B on Oporto-Madrid Boulevard. Turn right.
68.6	0.9	Turn left at 5th Avenue onto Rugby Avenue.
69.3	0.7	Turn right onto 81st Street.
69.8	0.5	Entrance to Ruffner Mountain Nature Preserve. Access mines via Crusher and Buckeye trails (about 2-mile return trip).

Stop 5. Ruffner Mines No. 3 and 1

The Ruffner group of mines (originally known as Sloss Upper Mines) opened in 1886 and ran until 1953 by which time depletion of the best ore, increasing cost of labor, and competition from imported pelleted magnetite ores made them uneconomical. They are now preserved as part of the Ruffner Mountain Nature Preserve. The layout and operation of the mines on the dip slope of Ruffner Mountain was evidently highly efficient, and taken as the epitome of mining practice during the early days of the mine (see McCalley, 1897, who quotes the *Engineering and Mining Journal* of 1892).

Along the southeast slope of Ruffner Mountain, the ore seams lie close to the surface and are intercepted by numerous ravines draining the dip slope. These ravines provided convenient access to the several mines (Fig. 20). As described by McCalley (1897) and Burchard and Butts (1910), a spur line was run into each ravine and a tipple and crusher erected on a bridge. Mining generally developed in four overlapping stages; stripping, drift mining, slope mining, and second working (see HAER, 1968, and Yuill, 2006). The first mines were open strip mines developed from inclines running up both sides of the ravines. As overburden increased and mining proceeded underground, drifts or entries were driven into the spurs at 50 foot intervals with a gentle grade (1:200) out of the workings. In some cases, these drifts would pass through the spurs and cross neighboring ravines. Successive entries were connected by "upsets"; arranged alternately with pillars, up through each level to the surface, where they provided ventilation for the mine. Gradually soft ore gave way to semihard then hard (unweathered) ore.

While mining was above the level of the tipple, ore could be carried out cheaply and efficiently using self-acting inclines. Ore was loaded into mine cars and manhandled from the working face to landings, where pairs of cars were placed on a carriage and run down to the tipple. The weight of the full carriage was sufficient to raise a balance car with empty cars from the tipple. To accommodate the dip slope, the carriage was built with wheels set at 18° to the platform in order to keep the mine cars horizontal. As long as the cable was well lubricated and the rollers on the incline in good repair, it was possible to work the mine out to ~1000 feet. The operation was controlled by a brakeman in a tower at the top of the incline.

Once mining extended below the bottom of the ravines (below the water table), slope mining commenced with access to the drifts via a portal and system of roadways (slopes) driven directly down-dip or at an angle designed to give a suitable grade. Ruffner Nos. 1, 2, and 3 all developed as slope mines equipped with steam hoists, pumps and crushers, and pneumatic drills. Ruffner Nos. 4 and 5 remained as drift mines. After the limit of mining was reached second working began; the face was propped with timber and the pillars were extracted, longwall fashion, allowing the roof to collapse.

At Ruffner No. 1 mine, ore was removed from two different levels, an upper level thought to represent the Big seam, and a lower level in the Irondale seam (Burchard and Butts, 1910, plate viii b). Mining was abandoned in the upper seam soon after slope mining commenced ~1910, and the arrangement of inclines, drifts, and hoist foundations is well preserved. In other mines, only the Irondale seam was mined underground.

In 1892, miners were paid by contract at a rate of $0.60 per car (cubic yard) for the first 400 feet from the entry with an additional $0.025 for each additional 400 feet out to 1000 feet. Included in this price was not only the mining, but also loading, tramming, propping, and laying track. Maintenance of the track was not included.

Total cost per ton was estimated as:

Mining, etc.	0.50
Outside handling	0.03
Repairs to cars and track	0.01
Props	0.05
Boss's salary	0.01
Transport to furnace	0.25
Royalty	0.25
Total	$1.10

The workforce, not including the contract miners, consisted of a mine boss, blacksmith, and carpenter, plus for each tipple a ticket clerk, switchman, brakeman, plane-runner, and tippleman.

With electrification in 1929, the focus of mining shifted to Ruffner No. 2. The most extensive collection of buildings and latest equipment occurs here. In 1939, an ore concentration plant was constructed at Ruffner No. 4, and in 1949, a heavy media plant, near the portal to Ruffner No. 2. The concentration plant roasted hematite to magnetite in order to allow magnetic separation, while the heavy media plant used flotation and Denver mineral jigs to remove gangue minerals and beneficiate the ore. However, faced with increasing competition from imported ores, the results were insufficient, and mining was abandoned with the closure of Ruffner No. 2 in 1953.

Most of the section from the Ida seam down to the base of the Irondale seam may be observed with the best outcrops around the portal to the No. 3 Mine (Fig. 21). The highest exposures consist of gray hummocky bedded sandstones and shales belonging to the Ruffner Member. Below is ~5 feet of massive coarse-grained hematitic sandstone assigned to the Ida seam, which forms the bottom of the Ruffner Member. Next comes 9 feet of medium- to fine-grained cross-bedded ferruginous sandstone underlain by intraclastic conglomerate. Holes in the outcrop were originally calcareous concretions or pebbles of calcareous ironstone. This is the local representative of the Hickory Nut beds and the TST of the Birmingham Member. Beneath the conglomerate is ~47 feet of highly cross-bedded, coarse-grained ironstone with lenticular calcareous concretions partially exposed in the slope down into the portal. The upper 8 feet of this unit was mined at Ruffner No. 1 and thought to represent the Big seam. It may have been stripped as soft ore at No. 3, but there is no evidence of underground mining. The Irondale seam (6 feet) was the principal economic objective at Ruffner. It must be present at the base of the portal, but is inaccessible in the flooded workings. It may be observed in a small hollow down slope from the portal.

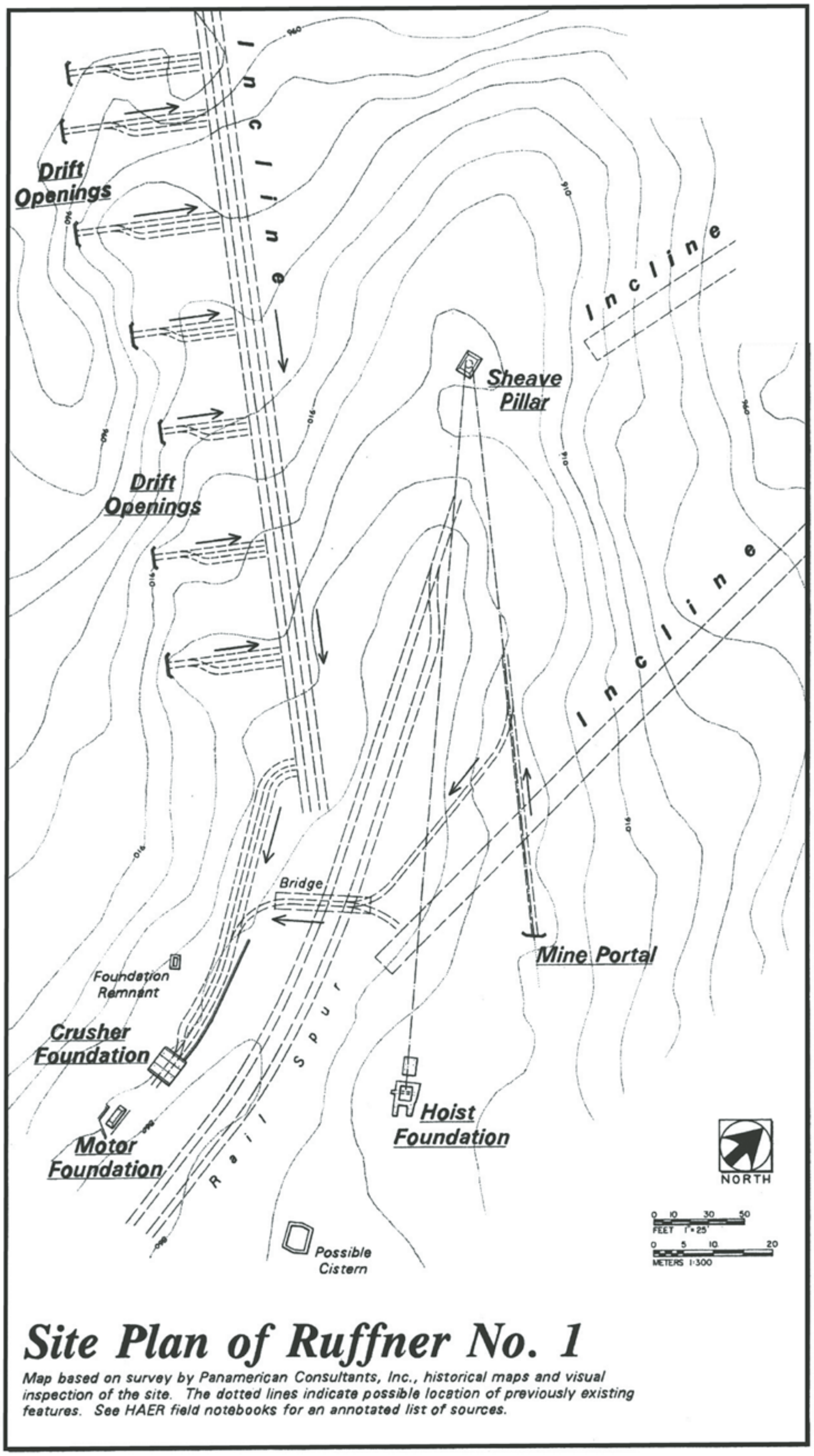


Figure 20. Topographic map showing the arrangement of mine workings at Ruffner No. 1 Mine. (From HAER, 1968.)

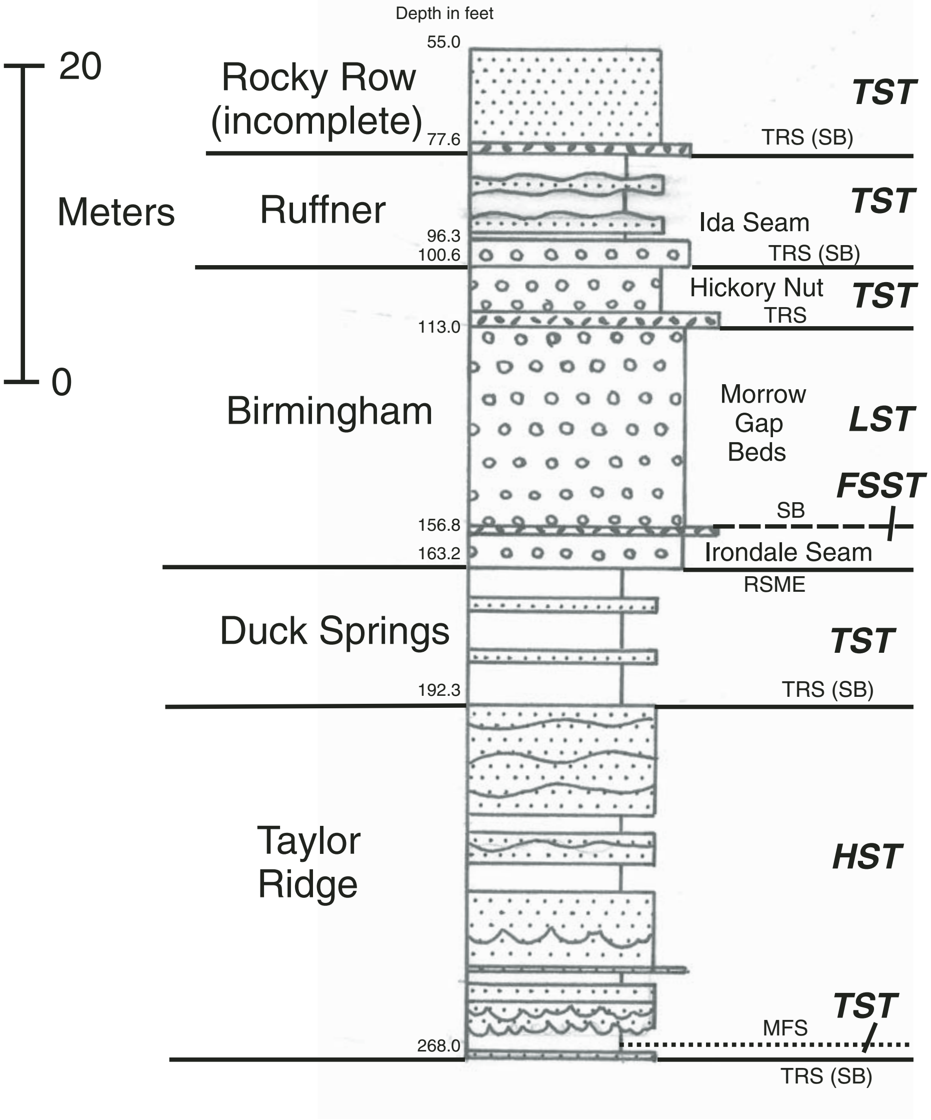


Figure 21. Stratigraphic column based on core hole at Ruffner No. 4 Mine. Legend as for Figure 2. SB—sequence boundary; TRS—transgressive ravinement surface; RSME—regressive surface of marine erosion; MFS—maximum flooding surface; LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; FSST—falling stage systems tract.

Because exposure is only partial and there were questions about the correlation of sections north and south of Ruffner, and especially because of the importance of this locality to Butts' (1926) interpretation of the stratigraphy, Vulcan Materials (in 2005) generously agreed to drill a test hole. A site at the entry to the ravine leading to the No. 4 Mine was chosen as the most accessible location.

From an examination of the core and available exposures, it is clear that the highly cross-bedded ironstones between the Hickory Nut and Irondale seams are tidal channel facies with bimodal currents trending approximately east-west. The massive facies characteristic of the Big seam at Century Plaza and the type section is missing at Ruffner. Most likely it is truncated by the channel. Butts (1926) was correct in identifying a major erosion surface above the Irondale seam, but incorrect in locating it below the Big seam. Rather it occurs at the base of the Morrow Gap beds and truncates the Big seam. It is in no way related to the pebbles in the Kidney bed.

The present authors interpret five important stratigraphic boundaries associated with the ironstones at this locality:

1. The top of the Ida seam is an obvious marine flooding surface marked by storm-bedded sandstones resting on shoreface facies.
2. The Ida seam is interpreted as a lowstand deposit (LST) resting on a tidal ravinement surface and sequence boundary; the base of the Ruffner Member.
3. The base of the Hickory Nut beds is a transgressive wave ravinement surface (TRS).
4. The Morrow Gap channel is most likely a lowstand deposit (LST), and the erosion surface at the base a sequence boundary.
5. The Irondale seam at Ruffner and the Irondale-Big seam at Century Plaza lie below this erosion surface on top of a regressive surface of marine erosion (RSME), and are part of a falling stage systems tract (FSST).

Whenever falling stage deposits are present in a stratigraphic sequence, there is uncertainty over the placement of the sequence boundary. Should it be located above the FSST (Hunt and Tucker, 1992), or below (Posamentier and Allen, 1999)? The recent consensus (Catuneanu, 2006) is for placement between the LST and FSST (i.e., at the base of the Morrow Gap beds).

In many instances, sequence boundaries are formed by the amalgamation of several erosional surfaces. The ironstones of the Birmingham district correspond to three types of sharp-based shoreface (SBS) deposits showing varying degrees of amalgamation (Proust et al., 2001; Al-Ramadan et al., 2005):

1. A ravinement shoreface consisting of a thin TST resting on a wave ravinement (amalgamated RSME, TRS, and SB), e.g., Crudup seam.
2. A ravinement shoreface consisting of a thicker LST resting on a tidal ravinement (amalgamated RSME, TRS, and SB), e.g., Ida seam.
3. A compound SBS consisting of separate TRS, SB, and RSME, e.g., Hickory Nut (TST), Morrow Gap (LST), and Big-Irondale seams (FSST).

An important distinction between these types is that while 1 and 2 lie above the sequence boundary and are subject to early marine diagenesis, the lower part of 3 lies below the sequence boundary, and may be invaded by meteoric groundwater.

70.6	0.8	Depart on 81st Street North and turn left on 4th Avenue South.
70.7	0.1	Turn right on 80th Street South.
71.0	0.3	Turn right at entrance ramp to I-59N.
79.4	8.4	Exit 141; exit onto Chalkville Road.
79.6	0.2	Turn right on Valley Road.
79.8	0.2	Holiday Inn Express.

DAY 2 (Fig. 12A; updated from Chowns, 2006a)

Cum. miles	*Miles*	*Directions*
0.0	0.0	Depart Holiday Inn Express and turn left on Chalkville Road.
0.4	0.4	Turn right on I-59 (toward Chattanooga).
47.4	47.0	Exit 188 (Noccalula Falls). Keep straight on.
52.4	5.0	At top of hill, pull onto shoulder and park.

Please observe extreme caution, especially if crossing the highway.

Stop 6. Duck Springs, Alabama

The complete thickness of the Red Mountain Formation is exposed where I-59 crosses Big Ridge near the small community of Duck Springs, on the North Gadsden topographic quadrangle. This is the most important section outside the ore field for the definition of members and fossil zones (Fig. 22). The formation has almost doubled in thickness, mainly as a result of the expansion of the Taylor Ridge and Ruffner members. This thickening continues to the northeast in Georgia and is a consequence of

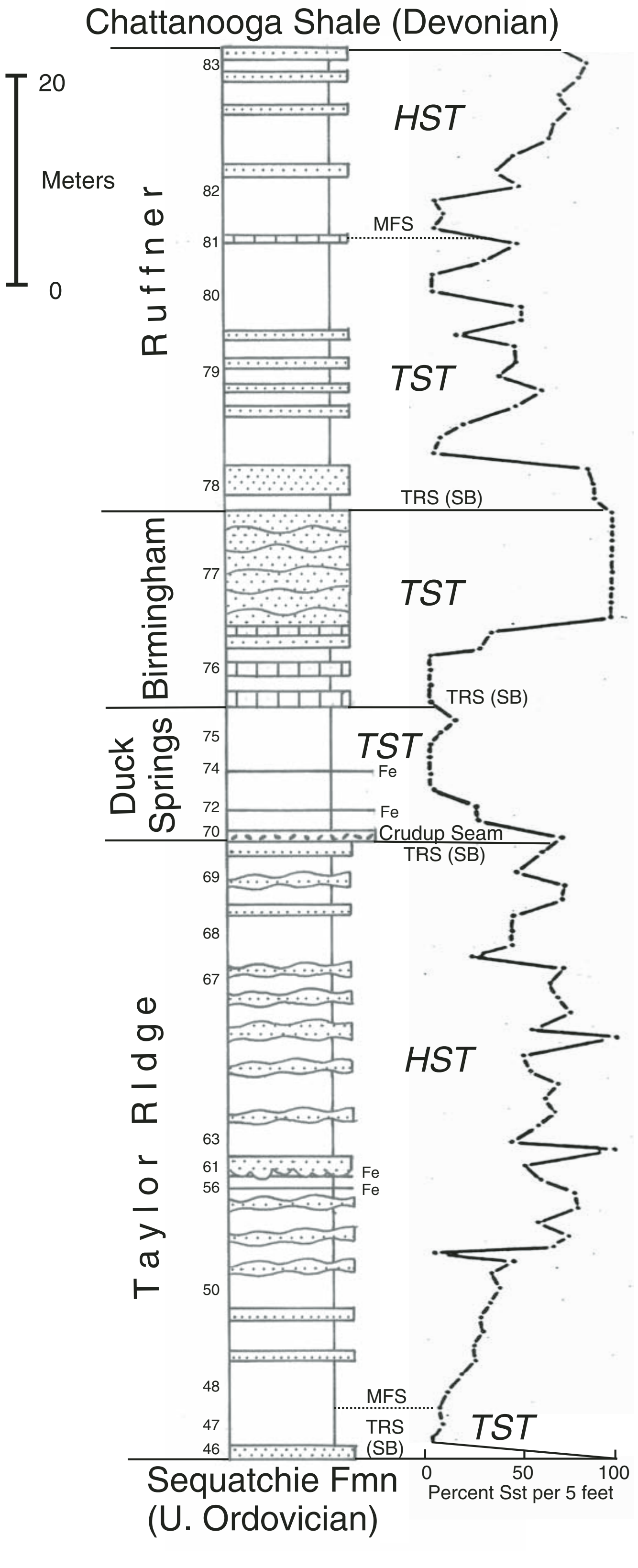


Figure 22. Stratigraphic column of reference section where I-59 cuts through Big Ridge near Duck Springs. Legend as for Figure 2. See Figure 21 for explanation of abbreviations.

subsidence in the foreland basin. All facies, with the possible exception of the Crudup ironstone, were deposited in wave-dominated shelf environments. Shoreface facies, so prominent in the ore field around Birmingham, are completely absent from the Birmingham Member. While lowstand-transgressive deposits are well represented in the type area around Birmingham, highstand clastic wedges increase in importance in the foreland basin.

The outcrop spans both lanes of the interstate but is best approached from the northbound lane. We will park on the shoulder close to the top of the Taylor Ridge Member. Start by identifying the Crudup seam (unit 70) at the base of the thick shale interval. Up-dip, to the north, is the Taylor Ridge Member; down-dip the Duck Springs, Birmingham, and Ruffner members are exposed. The Birmingham Member may be examined in both north- and southbound lanes of the interstate, as well as in the median. The Ruffner Member is best exposed in the southbound lane.

Taylor Ridge Member. The Sequatchie Formation is mainly covered, but the massive, fine-grained transgressive sandstone (unit 46) at the base of the Red Mountain Formation is easily identified beneath the trees at the north end of the outcrop. It is characteristically succeeded by a shallowing-upward sequence of shale, first with thin graded-bedded sandstones (47–50) then thicker hematitic, hummocky-bedded sandstones (51–67). This is a good section in which to examine hummocky cross-stratification.

Several thin ironstones are present among the hummocky sandstones (units 54, 56, and 60); the earliest evidence of iron mineralization. Although, these beds appear to have been resedimented by storms rather than formed in place, they indicate that the necessary conditions for ironstone development were present in more proximal environments. Sandstones with ball-and-pillow structures are also present, and may correlate with similar beds at Crestwood Mall, Ruffner, and other localities.

Bolton (1992) collected *Stricklandia lens lens* from unit 51, establishing that this sequence is lower Llandoverian (Baarli, 1996).

At the top of the Taylor Ridge Member at this locality is a shaly unit (units 68–69) apparently absent in most sections. This may be a sequence or parasequence that has been truncated elsewhere. Less likely, it may be interpreted as a lowstand channel that has been infilled with outer shelf facies.

Duck Springs Member. The base of this member is marked by the thin but persistent Crudup ironstone (unit 70), named for the Crudup Mines ~3 miles south of this locality. Although generally less than a meter thick, this bed was mined along the length of Wills Valley, from Attalla to Rising Fawn, Georgia; also at numerous, other localities in northwest Georgia and probably in Greasy Cove, Alabama. In most cases, mining was restricted to surficial ores enriched by weathering, but in some cases underground mines were developed. Most mining seems to have terminated by the end of World War I, but it continued until 1926 at the Attalla Mine and 1938 in Greasy Cove. No mines were active in 1942 at the time of the last survey by Burchard and Andrews (1947). The ore consists mainly of crinoid debris and bryozoa replaced and coated by hematite. The stereom of the crinoids is beautifully preserved by invading hematite, indicating very early mineralization before infilling by syntaxial calcite. This suggests that mineralization may have accompanied iron bacteria invading the tissue within the stereome. Some chamosite is present but mainly as a secondary replacement. This bed is evidently highly condensed and marks a major flooding surface. Above the Crudup seam, the Duck Springs Member consists mainly of shale containing abundant small horn corals. Two more thin ferruginous limestones are present near the base (beds 72 and 74), and may onlap and amalgamate with the Crudup seam elsewhere.

Birmingham Member. The Birmingham Member (units 76–77) is relatively thin and consists of shaly limestones at the base (TST) overlain by fine-grained, bioturbated sandstones with amalgamated hummocky cross-beds (HST). The base is an important unconformity marked by an abrupt change from shale to interbedded limestone and shale. Although the contact appears conformable at outcrop, the horizon is highly discordant in cross section. This is the horizon at which the Big-Irondale complex occurs at the type section. Here this FSST is absent and most of the Duck Springs HST has been removed. The limestones contain a rich fauna including *Pentamerus oblongus* and *Stricklandia lens progressa*, which date this sequence as mid- to late Aeronian (Baarli, 1996). Also present are colonial corals (some overturned), dendroid graptolites, and occasional intraclasts of siderite mudstone, perhaps eroded nodules. This fauna indicates that these beds are coeval with the Hickory Nut beds of the type section.

Ruffner Member. The shales of unit 79 signal another abrupt marine flooding surface again with pebbles of siderite mudstone. Maximum flooding probably occurs at the top of unit 80, a shaly limestone with large discoidal colonies of *Favosites* and stromatoporoids. Above this horizon, hummocky sandstones (unit 83) make up the highstand systems tract, truncated below the Chattanooga Shale. Bolton (1990) collected *Costistricklandia lirata* near the base of these sandstones, indicating a late Telychian or even early Wenlockian age.

Continue north on I-59.

81.4	29.0	At exit 222, leave interstate and turn right on U.S. 11.
81.9	0.5	Outcrop is at construction site on left side of road.

Stop 7. Fort Payne, Alabama (Lunch)

The section beside U.S. 11 north of Fort Payne is similar to that at Duck Springs but more convenient for collecting. Most of the Taylor Ridge Member is covered, but the Crudup seam that defines the base of the Duck Springs Member is easily located at the foot of the outcrop. The lower part of the slope consists of fissile shale with thin ferruginous limestone beds belonging to the Duck Springs Member. The base of the Birmingham Member is marked by the occurrence of shaly limestone with molds of *Pentamerus oblongus* and *Stricklandia lens progressa*. Sandstone ledges at the top of the slope contain abundant *Pentamerus oblongus* transitional to *Pentameroides subrectus*, as well as colonial corals (*Favosites, Halysites, Heliolites*). The pentamerids indicate an age range from C1 or C2 to C4 (middle or late Aeronian to early Telychian) for the Birmingham Member. The shale at the top of the slope signals marine flooding at the base of the Ruffner Member. The upper part of the Ruffner Member, up to the faulted contact with the Chattanooga Shale, may be examined in a separate exposure further north along U.S. 11. The maximum flooding surface (equivalent to the top of unit 80 at Duck Springs), with numerous colonial corals, is located near the base of this outcrop. Sandstones increase in importance through the HST at the top of the Ruffner Member.

Bedding plane thrusting is common in the Chattanooga Shale wherever it is exposed around Lookout Mountain, and indicates that overlying Mississippian–Pennsylvanian strata are detached along a décollement. Most deformation is contained within the Devonian section, but in places, the upper part of the Silurian is also involved.

82.4	0.5	Return to I-59 and continue north. Cross state line into Georgia (change to eastern time).
112.0	29.6	At Trenton (exit 11), leave interstate and turn left on GA 136.
112.5	0.5	Locality is on private property on the left side of the road. *Please obtain permission to visit this site if you are not on the GSA Section Meeting trip.*

Stop 8. Trenton, Georgia (Leaders: Ann Holmes and Tim Chowns)

This locality lies on the northwest limb of the Lookout Valley anticline. Beds dip northwest at ~25°, and the Red Mountain shale is being stripped for fill. Beneath the Fort Payne Chert (Mississippian), the Chattanooga Shale (Devonian) is faulted and sheared by décollement. The highest Silurian beds are greenish-gray weathering shales probably belonging to the Birmingham Member. They correlate with the distinctive reddish-gray shales with *Eocoelia* encountered in northwest Georgia. The base of this member consists of fine-grained sandstone with the molds of *Pentamerus*. The shales of the Duck Springs Member are mainly covered, but the Crudup seam (~1 m but divided by shale) is evident. The underlying Taylor Ridge Member contains much less sandstone than at Duck Springs and Fort Payne. It consists mainly of shale with thin limestones and fine-grained calcareous sandstones. Fossils are abundant and include well-preserved *Streptelasma, Eoplectodonta, Resserella, Leptaena, Spirigerina, Plectatrypa*, etc. (Fig. 23). This is among the most distal facies in the Taylor Ridge Member and characteristic of the transition into the Brassfield Limestone.

The Crudup seam was strip-mined extensively in Lookout Valley and in Johnson Crook, where the Rising Fawn blast furnaces operated intermittently from 1875 at least to 1908. Locally, a small furnace was constructed by the Empire State Coal and Iron Mining Company under a contact from the Confederate government, but it was abandoned in 1863. It still stands on the west side of Lookout Creek ~3 miles south of Trenton. Ore from this ridge was mined by the Cherokee Iron Company in 1865 to supply a furnace located about one mile north of Trenton. According to McCallie (1908), James Hall visited the area in 1866 and wrote favorably of the prospects for mining. Around 1888, a group of Eastern capitalists laid out New England City (5 miles north of Trenton) as a model manufacturing town to include smelting furnaces, rolling mills, and a coking plant. However, apart from a three-story hotel and a few other buildings, little development took place (McCallie, 1908).

113.0	0.5	Return to I-59 and continue north.
120.9	7.9	Intersection with I-24. Take right fork toward Chattanooga.
126.8	5.9	Take exit 174 (U.S. 41) and leave interstate. Outcrops are in parking lots on the south and north side of the interstate along U.S. 41.

Stop 9. Tiftonia, Tennessee (Leaders: Ann Holmes and Tim Chowns)

Following the construction of I-24, there was a complete section of the Red Mountain (Rockwood) Formation in roadcuts between Hooker and Tiftonia (Milici and Wedow, 1977; Driese, 1996). Conodont studies by Manzo (2002) confirm that Telychian beds were truncated by erosion prior to the deposition of the Devonian Chattanooga Shale, but the Taylor Ridge, Duck Springs, and basal Birmingham members (Rhuddanian–middle Aeronian) are present. We will examine outcrops at the top and bottom of the formation north and south of the intersection with U.S. 41 at Tiftonia. Most of the Duck Springs Member is now covered.

The base of the Taylor Ridge Member is marked by a fine-grained transgressive sandstone that rests unconformably on shale and limestone belonging to the Sequatchie Formation (Upper Ordovician). The sandstone contains abundant phosphate granules apparently derived from underlying strata. It represents a highly condensed succession of inner shelf facies deposited between fair-weather and storm wave base. This is followed by a retrogradational succession of shale with thin fine-grained, distal, graded, storm sandstones (~3.5 m), deposited below storm wave base. Within this unit, Gogola (*in* Driese, 1996) reported the occurrence of the planktonic graptolite *Climacograptus pseudonormalis.* Above the maximum flooding surface is a progradational succession of highly fossiliferous, shale, calcareous-dolomitic sandstone and bioclastic limestone, including the brachiopods *Resserella, Spirigerina, Eoplectodonta, Leptaena, Platystrophia, Dolerorthis, Anastrophia, Glyptorthis, Hesperorthis*, and *Strophonella* together with solitary rugose corals (*Streptelasma* and *Anisophyllum*) and colonial tabulate corals (*Favosites* and *Paleofavosites*) (Fig. 23). Some limestones in this highstand systems tract are ferruginous due to skeletal grains partially replaced by hematite.

The base of the Duck Springs Member is tentatively located at the base of a relatively thick ironstone (0.6 m) that is equated with the Crudup seam and occurs ~39 m above the base of the formation. Overlying lithologies are similar to those in the Taylor Ridge Member but with a higher percentage of shale.

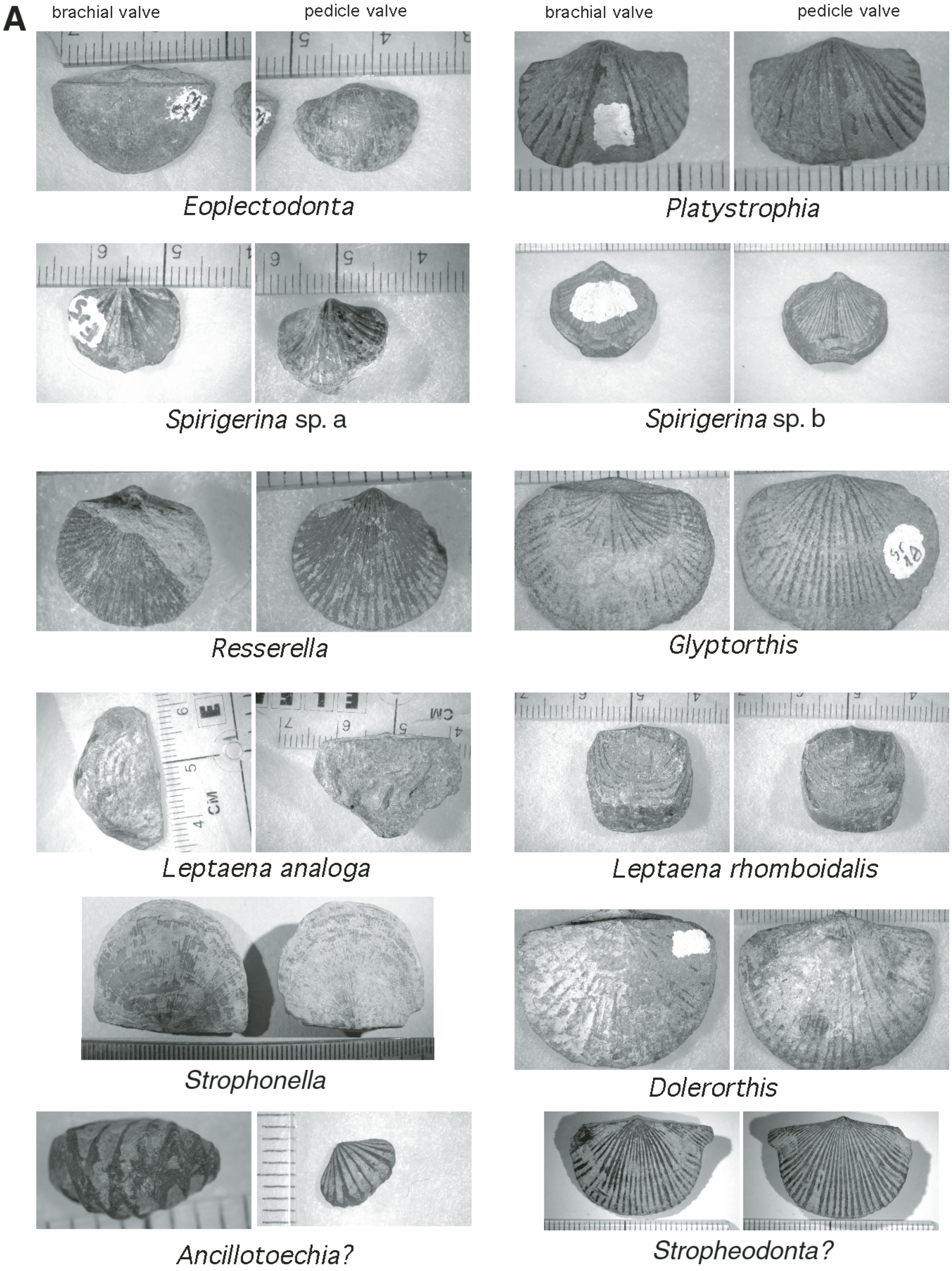
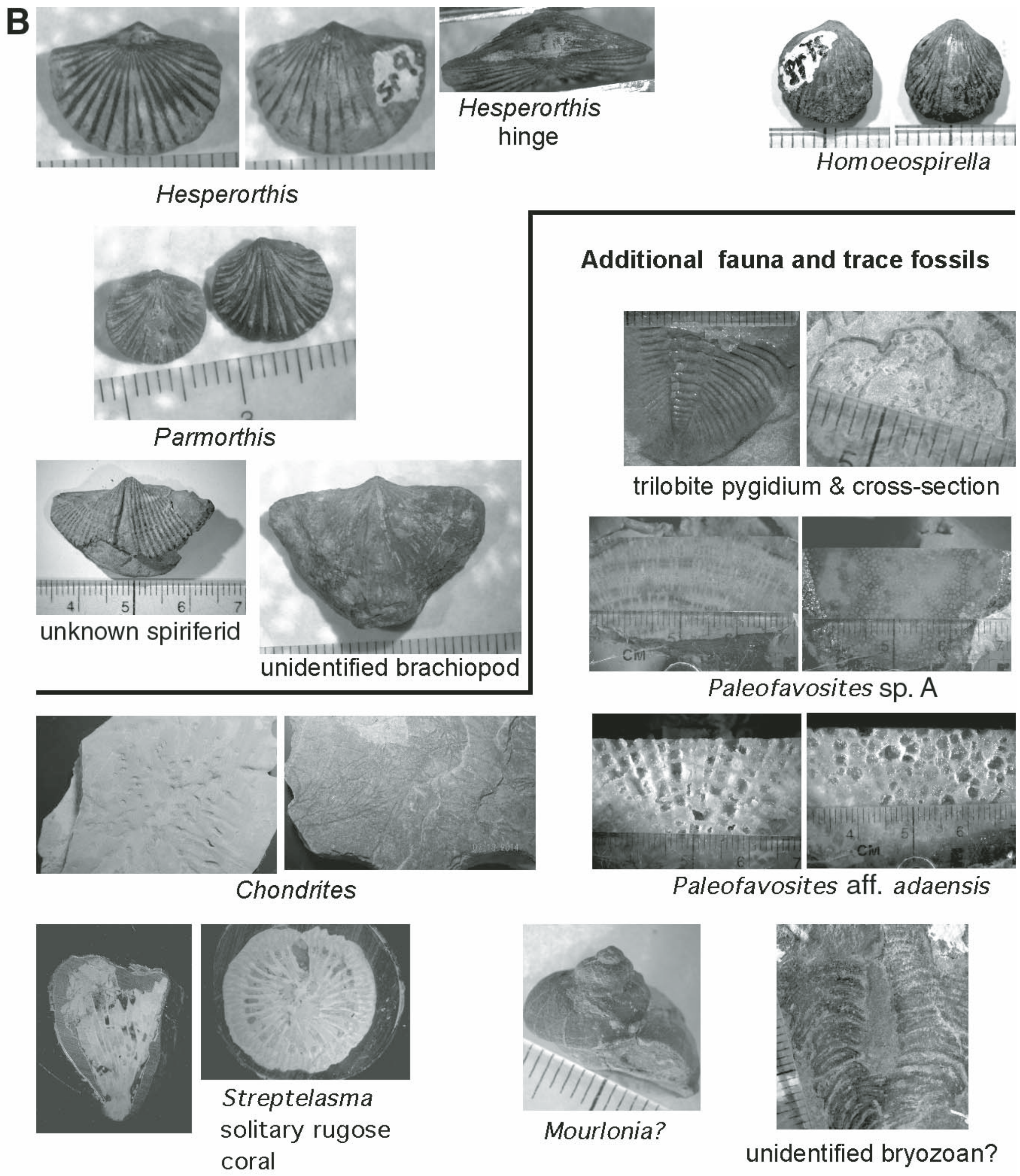


Figure 23 (*Continued on following page*). (A, B) Illustrations of fauna collected from the Taylor Ridge Member at Trenton, Georgia; Tiftonia, Tennessee; and elsewhere in the greater Chattanooga area.



Silurian (Rhuddanian) Fossils from the Rockwood/Red Mountain Formation, Taylor Ridge Member. Collection and identification made by UT Chattanooga Historical Geology and Paleontology classes as well as by senior research projects of Shinpaugh & Holmes (2007), Beard & Holmes, (2010), and Landis & Holmes (2010).

Figure 23 (*Continued*). Illustrations of fauna collected from the Taylor Ridge Member at Trenton, Georgia; Tiftonia, Tennessee; and elsewhere in the greater Chattanooga area.

Specimens of *Pentamerus* were collected from a fine-grained fossiliferous sandstone ~64 m above the base of the formation. This is assumed to mark the base of the Birmingham Member, which is then ~13 m thick. While fine-grained sandstone predominates over shale in the lower 7 m, the upper 6 m up to the base of the Chattanooga Shale, is mainly shale. These are the beds exposed behind the Covenant Motel (former Holiday Inn) on the north side of I-24.

The entire thickness of the Red Mountain (Rockwood) Formation at this locality consists of just two facies. In the first, shale is interbedded with fine-grained dolomitic sandstones that represent distal storm beds derived from the east. In the second, shale is interbedded with skeletal limestones reminiscent of the Brassfield Formation. These, too, are interpreted as storm deposits, but derived locally in areas starved of coarser-grained siliciclastics. Both facies are considered to be typical of the middle to outer shelf, mainly below storm wave base. While the limestones and sandstones were deposited by geostrophic currents set up by storms, the shales represent the background of fair-weather conditions. Hematite-replaced skeletal grains were derived locally from parts of the shelf where sedimentation rates were sufficiently low to allow intense reworking and mineralization.

Return to interstate and continue into Chattanooga.

131.4	4.6	Exit 178 (U.S. 11, U.S. 41, U.S. 64); leave interstate and keep right for N. Broad Street.
132.8	1.4	Chattanoogan Hotel is located on the left-hand side of Broad Street.

ACKNOWLEDGMENTS

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APPENDIX. READING TRACE FOSSILS IN THE RED MOUNTAIN FORMATION

Seeing, Thinking, and Talking about Trace Fossils

Of the thousands of references on ichnology, only a handful discuss how to find, observe, and "read" trace fossils. Among them are publications by Chamberlain (1978), Howard (1978), Bromley (1996), Frey and Wheatcroft (1989), Seilacher (2007), and Rindsberg (2012).

In strata with alternating lithologies, as are common in the Red Mountain Formation, the tools of the trade are simple. Bring your eyes and a hammer, and a marking pen and paper for labeling and collecting specimens. A handlens is occasionally useful, but the details of trace fossils are generally macroscopic. Seilacher (*in* Seilacher and Rindsberg, 2000) recommended using a brass brush to whisk away shale from the sandstone surfaces on which trace fossils are preserved in semirelief; the junior author uses a stiff umpire's brush made of plastic. A small scale (ruler), pencil, and notebook are essential for recording information, as is a camera.

In sequences of alternating lithology, such as the alternating shale and sandstone beds of the Red Mountain Formation, sedimentary structures are preserved either in *full relief* or in *semirelief,* casts on the upper and lower contacts of sandstone beds (Bromley, 1996; Rindsberg, 2012). These are studied in markedly different ways, the semireliefs being generally more amenable to study by beginners.

Semireliefs generally consist of grooves and ridges on the surface of resistant beds, and are often most conveniently studied in float. Trace fossils preserved on the upper surfaces of resistant beds are called *epichnia*; those on the lower surfaces are known as *hypichnia*. As sandstone slabs weather on a talus pile, the shale layers flake off to reveal the semireliefs. This process can be sped up by whisking the shale off with the brush. Further weathering tends to dull the details of the trace fossils. At outcrops where the slopes have stabilized and rocks have stopped falling, trace fossils become dulled within a few years and difficult to study.

Because these structures are generally preserved in low relief, viewing and photographing them can be enhanced by canting the slab at different angles to the light, creating shadows that sharpen the image.

Full reliefs are less amenable to study than semireliefs, and convey different sorts of information. Where hypichnia are commonly mere casts of burrows that were scoured away, full reliefs contain the original internal structure of the burrows. Sectioning them may therefore reveal additional details. In outcrop, natural sections must be used, especially those that are suitably weathered, increasing contrast. Fresh rock tends to be uniformly colored, with low contrast.

The same outcrop will reveal different details in different lighting and weather. Morning and evening, times of raking light, are generally best for observation of trace fossils. The strong overhead light of noon tends to wash out details, though this can be a good time to investigate trace fossils on selected steep slopes with slabs naturally canted at suitable angles to the sunlight. It is important to pick slabs up and move them at different orientations to the light, because low semireliefs and weathered full reliefs can be virtually invisible unless enhanced by shadow. Similarly, the observer will see different things on overcast and sunny days. A light rain can make for extraordinary viewing by increasing the contrast of *Chondrites* and other full-relief trace fossils.

The influential teacher Louis Agassiz (1807–1873) said, "A pencil is one of the best of eyes" (*in* Scudder, 1917). By this, he meant that the discipline of drawing an object forces the observer to see details and relationships that would otherwise be missed. The invention of the camera has made it easier to record visual information, and is an indispensable tool. But cameras have not improved the ability to observe. More than once, we have been startled to see a previously unnoticed trace fossil appear in a photograph.

Sharp observation is a trainable skill. The ability to spot trace fossils (or any other object) relies on a number of strategies that are probably innate, but are improved with practice. One of the strategies is simply to look for a particular pattern, the *search image*. For instance, a person looking for shark teeth would keep his or her eyes open for small, dark, shiny surfaces of triangular form, and it is intriguing that this search image can be conveyed in words as well as visually. The concept of the search image explains why trilobites suddenly seem to be everywhere after the first one is found, though years may have passed before any were noticed.

Another strategy is subtler: not to look for any particular search image, but to look for anything out of the ordinary. This is the more powerful of the two in discovering fossils and structures in unknown terrain, but it is harder to teach.

Many hands make light work, and many pairs of eyes see more than one pair. A group may be able to make short work of one station at an outcrop.

For the scientist, as opposed to the aesthete, observation is not enough; interpretation must follow, and also communication to others: seeing, thinking, and talking. These reinforce one another. The case of Adolf Seilacher (1925–2014), the world's most accomplished ichnologist, is instructive. He would select interesting slabs or boulders—those with an interesting and detailed pattern—and proceed to discuss them with other people at the outcrop. The first item of business with his method is to determine the orientation of the slab; therefore, a search is made for geopetal structures ("way-up" indicators). It makes an enormous difference to the interpretation if, for instance, a ridge represents an impressed trail or a raised one. The structures are then inspected carefully and interpreted. Hypotheses may be offered that can be tested by fracturing the slab, observing the opposite side, or examining other float. The give-and-take of question-and answer-results in additional observations, interpretation, and discussion, with the result that science is advanced farther by the group than by any one person.

For Seilacher, as well as his predecessor Agassiz, the act of communication sharpened the act of observation. For both educators, the most comfortable way to write an article is not to sit alone, but to give an illustrated lecture. Agassiz could scarcely write without first lecturing at the blackboard; Seilacher gave a slide show on a subject, generally several times to different audiences, before publication on paper. Both were artists. Even in a private conversation, Seilacher kept pencil and paper close at hand to illustrate visual concepts. A pencil is not only one of the best of eyes, but one of the best of mouths.

For accurate work, slabs must be traced back to their point of origin, or at least to an interval within the section. At a little-visited outcrop, the investigator may assume that the rocks have moved only under the influence of gravity, so he looks up. Talus cones usually derive from well-defined gouges in the cliff; large boulders can often be traced to an exact cavity by matching form. This information is recorded and later can be tabulated to make better sense for interpretation. Without it, only a vague notion can be derived of the distribution of fossils within a formation.

The importance of time is the hardest lesson to learn. The young student tends to believe that things will always be as they are today. Twenty years later, he or she returns to the outcrop to see marked changes. The shale, tough and glistening with oils when freshly exposed, is now dull and flaking, and whole shale beds may be covered with soil and plants. Sharp-edged rocks have been blunted and surfaces obscured by lichen. Talus covers beds that were formerly exposed. Collectors may have stripped the outcrop of most of the fossils and destroyed others while trying to extract them. The whole outcrop may be fenced off. It is difficult not to feel melancholy or nostalgia under such circumstances.

Trace fossils are best viewed when rocks are falling frequently from the cliffs; when the shale has had a year or two to weather off the sandstone slabs, but not long enough for the slabs to be dulled or buried under other debris; and when weathering has developed the contrast of the structures to a maximum against the host rock. Also, a few rare objects may be seen on each visit, but can hardly all be seen at once. These processes do not proceed at the same rate, so visits over a period of years will continue to yield new data.

The processes of seeing, recording, thinking, and talking are interconnected and reinforce one another. It makes sense to encourage students to develop skills in all four areas at once. The skills learned in one area can be applied to another for a lifetime.

Trace-Fossil Assemblages

The trace fossils of the Red Mountain Formation were first noticed by Bensko and Conway (1953) in the Birmingham iron ore district of Alabama. Although they named a new physical sedimentary structure, "Clintonidus," in an abstract, the structure is neither biogenic nor validly named. Frey and Chowns (1972) conducted the first rigorous research on the ichnology of the formation following the opening of large roadcuts for Interstate Highways 24 and 75 in Georgia and Tennessee, particularly at Ringgold Gap, Georgia. Rindsberg (1983) wrote a thesis on the paleoecology and ichnology of the Red Mountain Formation and underlying Sequatchie Formation, and Rindsberg and Chowns (1986) summarized the geology of Ringgold Gap. Later, Rindsberg and Martin (2003) investigated the behavior of one trace fossil, *Arthrophycus brongniartii*, in the Red Mountain Formation of the Birmingham region.

Trace-fossil assemblages of the Red Mountain Formation at Ringgold are strongly related to lithofacies (Frey and Chowns, 1972; Rindsberg and Chowns, 1986; Chowns, 2006; this paper). They are summarized in Table 1.

Trace Fossils: A Few Search Images

The following discussion focuses on the most conspicuous trace fossils in the Red Mountain Formation, with biologic and ethologic interpretation. However, it should be emphasized that this should just be the starting point for discussion. Every time we visit these outcrops, we see something new.

Monocraterion Torell, 1870 is a simple, vertical shaft with a funnel-shaped top. The shaft typically occurs in sandstone and is accompanied by a zone of deformation in which the laminae of the surrounding sediment are sharply downturned toward the shaft. One possibility is that the deformed zone was made by collapse of the underlying sediment, as would occur if the animal fed in a head-down position, as occurs in some families of polychaetes. But some "*Monocraterion*" may just be segments of *Asterosoma*.

Skolithos isp. is a vertical shaft similar to *Monocraterion* cf. *tentaculatum,* but lacks the funnel and zone of deformed laminae. The simple shafts are probably dwelling burrows; the animals living therein presumably fed by filtering suspended particles from the water, by extending probes onto the substrate surface, or by lying in wait to capture prey.

Several ichnospecies of feeding burrows are common in the Red Mountain Formation: *Asterosoma templus, Arthrophycus brongniartii, Nereites biserialis, N. missouriensis, Chondrites gracilis, C. flexuosus, Dictyodora major*, and *Scotolithus mirabilis*.

Asterosoma templus (Han and Pickerill, 1994) is a subhorizontal burrow with many overlapping branches that radiate in a fan from a common gallery (Fig. 17B). In some specimens, branching is pinnate, and the burrow branches in a series of fans for some distance. The branches are thick and fusiform, with a wrinkled surface of tension fractures; transverse sections show concentric lamination. Evidently, the tracemaker overstuffed each branch with sediment after feeding, and then moved on to a new location. No exact analog has yet been recognized among modern animals.

Han and Pickerill (1994) reported the repeated pinnate branching as representing a distinctive new ichnospecies, but did not recognize the internal structure and placed the species in *Phycodes*, which has structureless fill. However, *Phycodes* does not have the fusiform branches that are typical of *Asterosoma*, and one of their own photographs shows indistinct concentric structure (Han and Pickerill, 1994, their figure 4). The ichnospecies is therefore transferred to *Asterosoma*.

Arthrophycus is a branched or unbranched burrow with a complex internal structure (Figs. 17A, 17D). Unlike the better known *Arthrophycus alleghaniensis* of the Lower Silurian in the northern and central Appalachians, *A. brongniartii* (Harlan, 1832) is unbranched, though the tracemakers' tendency to cross repeatedly in one place creates specimens that look stellate. Occasional resting traces embedded within specimens show that they were made by small trilobites (Rindsberg and Martin, 2003). In the Red Mountain Formation, most specimens are preserved on the upper surfaces of sandstone beds, so the appearance of the trace fossil is generally as shown in Fig. 17D.

The smaller examples of these burrows tend to be found in lower shoreface sediments, while the larger examples occur in upper shoreface or tidal flat sediments, suggesting that the tracemakers migrated toward the shore as they matured. Whatever animal made *Arthrophycus brongniartii* also made *Nereites biserialis*, which is occasionally found connected to it, and perhaps also some *Asterosoma*.

Nereites biserialis Seilacher, 1960 (Fig. 17H) consists of unbranched, subhorizontal burrows with an inner zone, generally filled with relatively fine sediment, and an outer zone of biserially arranged beads of relatively coarse material. *Nereites* was long ascribed to polychaete worms, but Martin and Rindsberg (2007) showed that at least some *Nereites* is the work of arthropods, including juvenile horseshoe crabs in modern substrates, and Rindsberg and Martin (2003) showed that the same animals could make both *Arthrophycus brongniartii* and *Nereites biserialis*.

Burrows similar to *Nereites biserialis* but with a very irregular outer zone and irregular overall path are called *Nereites missouriensis* Weller, 1899. The inner zone, in contrast, is regularly meniscate. In fine-grained sediments, the outer zone may become indistinguishable with the surrounding sediment, leaving only the inner zone visible; this is called the "*Scalarituba*" aspect of *Nereites*, after an ichnogenus that is now recognized as a junior synonym.

Chondrites is a dendritic burrow that shows branching of at least two orders, and commonly of several orders (Fig. 17I). The branches generally do not interpenetrate one another. Branch junctions are lateral, that is, T-shaped rather than Y-shaped, and the secondary branch tends to be pinched at the base. Lateral junctions indicate that the burrow system was made over a period of time; students can, in fact, determine the sequence of branching by observation and interpretation. Pinching of a junction suggests that it was used only once, not maintained as an open burrow for the animal to travel back and forth. In fact, it is possible that only part of the burrow was open at any one time, as no one has found a modern, open example of *Chondrites,* although Pleistocene examples are common. This would suggest that the animal fed on sediment from one branch at a time, and later stuffed the digested sediment into an unused branch, keeping only a few trunklines open.

The complexity of the *Chondrites* system shows up only after collection of a number of slabs with intermediate sections. The distal part of the system consists of a series of multibranched fronds that radiate from the center at different levels. The tracemaker burrowed outward at different levels, but these fronds tend to be subhorizontal to horizontal, commonly following a single clay-shale lamina within a sandstone bed. Sand is not avoided altogether, but organic-rich clay was clearly preferred. The proximal part of the burrow system is relatively vertical, and consists of a bundle of shafts diverging from a common center. No one has yet traced the branches to a single shaft, however, and it is not known whether a relatively thick-bodied animal sent narrow probes downward to feed, or a narrow-bodied animal traveled throughout the system.

Two ichnospecies of *Chondrites* are common in the Red Mountain Formation, *Chondrites gracilis* (Hall, 1843) and *Chondrites flexuosus* (Emmons, 1844), which were first described from the Upper Ordovician of New York. *C. gracilis* has relatively narrow branches (0.4–3 mm wide) that are relatively straight or tend to curve slightly inward. The initial system was relatively sparsely branched, the tracemaking animal filling in the interstices later. *C. flexuosus* has relatively thick branches, but is not simply a larger version of *C. gracilis*. The branches of *C. flexuosus* are relatively sinuous, and new branches were made laterally, typically from the outer curves of older branches. Branching is sparse. It is not uncommon for two ichnospecies of *Chondrites* to coexist. *C. gracilis* and *C. flexuosus* have close analogs from the European Cretaceous–Tertiary flysch, *C. targionii* (Brongniart, 1828) and *C. recurvus* (Brongniart, 1823), which may be synonyms of the American ichnospecies.

Dictyodora is another complex feeding burrow, but one of a very different form than *Chondrites* (Fig. 17N, 17P). In plan view, which is most often seen, *Dictyodora* resembles a loose, arcuate scribble that cuts through itself in many places without disturbing the same sediment much. The burrows are composed of dark clay that completely penetrates sandstone beds, and slabs are commonly broken along the thin, wall-like burrows. This reveals that the burrow is not only wall-like, but finely striated, showing previous positions of the burrow as the animal moved through the substrate. This is called a *spreite*. More rarely seen is the lower part of the burrow, which is a subhorizontal tunnel and has a width of 1.2 to 3.0 mm, constant in any one individual. The spreite is relatively thin at 0.6 to 2.0 mm, and this figure is not constant within individuals. Seilacher (1967) interpreted the lower tunnel as a feeding-locomotion burrow, and the upper spreite as the trace of a siphon used to maintain a connection to the substrate surface for oxygen. More detailed work by Benton and Trewin (1980) corroborates this hypothesis. Intriguingly, some Red Mountain specimens are connected with bivalve burrows (*Lockeia*). The delicate spreite would then appear to be the trace of the siphons of deposit-feeding bivalves.

Scotolithus mirabilis Torell, 1870 is a feeding burrow having a relatively simple organization. From a central axis, branches extend obliquely downward radially or in a fanlike pattern, then taper to horizontal at depth. Some of the branches are themselves branched at an acute angle. Internally, the branches were refilled by the tracemaker, creating an internal concentric lamination and an external sculpture of longitudinal tension fractures, in some cases with transverse swellings and sculpture as well. If only short segments of the horizontal segments were found, they might be called *Halopoa* or *Palaeophycus*, but enough specimens have been found showing the connection between vertical to oblique and horizontal elements to determine that they all belong to one system.

This is only the second place in the world where *Scotolithus* has been reported. It was originally discovered by Torell (1870) in the Lower Cambrian of Sweden and was redescribed by Jensen (1997, p. 87–88). Torell described the vertical and horizontal components respectively as *Scotolithus mirabilis* and as *Halopoa imbricata* and *H. composita*. Jensen realized that the two could be connected, but conservatively retained both ichnotaxa, although he placed *Halopoa* in synonymy with *Palaeophycus*. We take a more holistic approach to trace-fossil taxonomy and regard *Halopoa* as a synonym of *Scotolithus*. Nomenclature aside, the chief function of these burrow systems seems to have been deposit feeding, but the backfilling of branches—as we saw in *Asterosoma*—is curious. It is possible that they had a chemosymbiotic function.

Subhorizontal burrows include forms that are consistently short and show signs of being originally open, and other forms that are indefinitely long and were filled by the tracemaker. The long forms evidently were made by animals that moved through the substrate, feeding on it without living in any one place; by contrast, the short forms are dwelling structures. However, without observation of many specimens, the two types are easily confused (Pemberton and Frey, 1982). *Planolites* is one of the long forms; *Palaeophycus*, one of the short forms.

Planolites montanus Richter, 1937 is one of the most common Red Mountain burrows, but is also among the most nondescript. These burrows are subhorizontal, but are irregularly sinuous both horizontally and vertically, so only short segments are generally visible on any one slab. These segments, unlike those of *Palaeophycus,* show no consistent length. Burrow width is constant within individuals at 1–3 mm. The fill is modified from that of the host substrate, but clearly derived from it; the animal itself must have digested and emplaced it. These feeding burrows may have been the work of many different kinds of animals including polychaetes or other free-living worms.

Palaeophycus striatus Hall, 1852 is a subhorizontal burrow of definite length; the largest observed specimen is 13 cm long and incomplete. Generally they are much shorter, with a width of 3 to 15 mm, and are upturned at both ends, suggesting that they are actually U-shaped. The burrows commonly are nodose, i.e., they pinch and swell along their length. A clue to the maker of the burrow is present in the longitudinal striae that are commonly present; in some specimens, transverse striae crosscut longitudinal striae, particularly at swollen nodes. Evidently, the tracemaker had sharp appendages such as arthropod claws or polychaete setae. Pemberton and Frey (1982) named Ringgold specimens with both transverse and longitudinal striae as *Palaeophycus alternatus*, but the two ichnospecies are intergradational, so they are treated here as synonyms. Morphologically similar forms with a smooth surface are called *Palaeophycus tubularis* Hall, 1847, which may be a senior synonym of both *P. striatus* and *P. alternatus*. The situation is complicated by the fact that the burrows' appearance was changed dramatically by different modes of preservation.

Trails and trackways are fairly diverse in the Red Mountain Formation, though no single form is common. They include ichnospecies of *Fraena, Cruziana*, and *Petalichnus*.

Fraena sanctihilairei Rouault, 1850 is the simplest of the batch, a smooth, unilobate trail that shows no patterned activity other than simple locomotion. *Cruziana* is a bilobate (in some cases quadrilobate) trail showing a sculpture of oblique striae, and many examples are probably the work of trilobites (Osgood, 1970). *Petalichnus* isp. is a trackway showing multiple tiny imprints in Vs, again, the work of trilobites (Osgood, 1970) and perhaps other arthropods.

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