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BEDROCK GEOLOGIC MAP OF SOUTHWEST IOWA

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INTRODUCTION TO BEDROCK MAP
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The new bedrock geologic map of southwest Iowa presented herein is an entirely new compilation, which incorporates all available sources of bedrock information for the region. The mapping area encompasses a 14-county block of southwest Iowa, bordered to the south by the Missouri-Iowa line and to the west by Nebraska-Iowa line along the Missouri River. The southwest Iowa mapping area is bordered to the north and east by recently-completed bedrock maps (STATEMAP projects) for northwest Iowa (Witzke et al., 1997) and south-central Iowa (Pope et al., 2002). Southwest Iowa is primarily a rural agricultural area dotted by numerous towns and communities. The Council Bluffs area (Pottawattamie Co.) comprises the largest urban region in the map area.

The mapping area includes classic bedrock exposures of Pennsylvanian rocks in the northern Midcontinent region, and the type localities of several Pennsylvanian stratigraphic units are located in southwest Iowa. These lithologically-varied Pennsylvanian strata include the primary sources of limestone aggregate for the region, a vital economic resource. The Pennsylvanian strata are also of historic significance in the region, having produced significant quantities of coal from underground mining operations as well as building stone (mostly limestone) and clay for brick and tile manufacturing. Mississippian strata form the bedrock surface in small bedrock-incised areas of southwest Iowa, but these are nowhere exposed at the surface. The carbonate-dominated Mississippian units form a productive bedrock aquifer in portions of the map area. Cretaceous sandstone-dominated strata are widespread in southwest Iowa, forming an important bedrock aquifer in the region. This aquifer provides municipal water sources for communities in parts of Pottawattamie, Cass, and Montgomery counties (Hansen et al., 1992). In addition, Cretaceous sand and gravel units have provided economically-important aggregrate resources from pit exposures in areas of Montgomery, Cass, Pottawattamie, and Mills counties.

THE QUATERNARY MANTLE AND BEDROCK TOPOGRAPHY

Southwest Iowa is largely covered by a mantle of Quaternary sediments of varying thickness, and areas of shallow bedrock and bedrock exposure are limited to scattered stream and river drainages (see map inset for areas of shallow bedrock). Limestone quarry operations are largely restricted to areas of shallow Pennsylvanian bedrock, thereby minimizing the costs of removing Quaternary overburden. The Quaternary sediments in southwest Iowa are dominated by glacial till (diamicton) with varying amounts of intra- and inter-till clastic sediments. Much of the region is mantled by Quaternary loess (primarily the Wisconsinan Peoria Loess). A prominent loess-mantled landscape region comprises the distinctive Loess Hills area bordering the Missouri River Valley, where the loess mantle averages about 70 feet (20 m) thick (Ruhe, 1969) and locally exceeds 100 ft (30 m) in thickness. The southwest Iowa map area includes three landform regions with contrasting erosional landscapes developed across differing successions of Quaternary sediments (Prior, 1991): 1) the western Loess Hills, thickly-mantled with loess, marginal to the Missouri River Valley, commonly deeply dissected with steep valleys and bluffs; 2) southern Iowa Drift Plain, a rolling and dissected landscape largely developed on pre-Illinoian glacial deposits and mantled by a cover of loess (with local bedrock exposure in some valleys); and 3) the Missouri Alluvial Plain, the broad and flat alluvial valley of the Missouri River (generally lacking glacial till and loess deposits).

Although the bedrock map of southwest Iowa does not directly map the Quaternary cover, the Quaternary sediments must be distinguished from bedrock strata to constrain interpretations of bedrock topography. The distinctions between Quaternary and bedrock units usually are apparent from an examination of lithologic logs and outcrop information. However, such distinctions are difficult to constrain in some well records, particularly with respect to Cretaceous mapping units (see later discussion). In addition, it is likely that Miocene and Pliocene sediments occur in bedrock upland areas of southwest Iowa, but, at present, these deposits cannot be readily distinguished from Quaternary strata and thereby are included with the Quaternary cover (see later discussion).

Based on all available data (primarily well penetrations), the elevation of the bedrock surface was interpreted and a bedrock topographic map was assembled (R. Anderson primary editor of bedrock topography). The bedrock topography outlines several bedrock-incised features of special note: 1) a deep north-south bedrock channel, the Fremont Channel, that transects portions of Fremont, Mills, Pottawattamie, Shelby, and Crawford counties (and northward); 2) a bedrock-incised channel that largely corresponds to the modern-day Missouri Alluvial Plain; and 3) the Albany Channel (Hansen et al., 1992), a broad bedrock valley across eastern Adams and Taylor counties (and adjoining areas of south-central Iowa). The distribution of these bedrock valleys strongly influenced the development of the new bedrock geologic map, significantly constraining the regional incision and distribution of bedrock mapping units. The lowest bedrock elevation (approximately 650 feet above sea level) for the map area is located in southeastern Fremont County within the Fremont Channel. This indicates that the Fremont Channel is more deeply incised into bedrock than is the Missouri River channel (bedrock elevations below 750 feet). The highest bedrock is identified in the northeastern map area across portions of Carroll, Audubon, and Cass counties, where bedrock elevations in excess 1250 feet are recognized.

The Fremont Channel is filled with a complex succession of glacial till (diamicton) and inter-till deposits. These Quaternary deposits reach thicknesses within the Fremont Channel of Crawford County in excess of 600 feet (180 m), the thickest known in Iowa. Quaternary thicknesses in excess of 300 to 400 feet are noted along the length of the Fremont Channel in the map area. The Albany Channel contains Quaternary deposits in excess of 300 feet (90 m) thick. The bedrock channel of the modern-day Missouri River Valley is largely filled with sand and gravel alluvium, commonly about 100 feet (30 m)thick and locally reaching thicknesses in excess of 200 feet (60 m). The Missouri River bedrock channel likely was incised during the late Pleistocene, whereas the Fremont Channel is entirely of earlier Pleistocene age (filled with pre-Illinoian deposits)(Witzke and Ludvigson, 1990). The Fremont Channel may have been the main trunk system of an earlier drainage analogous to the modern Missouri River.

Outside of the area of these major bedrock channels, much of the "upland" interfluve bedrock surface in southwest Iowa lies at elevations between about 950 and 1200 feet. These "upland" areas are transected and dissected by a complex of smaller-scale bedrock channels reflecting recurring episodes of bedrock erosion during the Quaternary and pre-Quaternary. This dissected "upland" bedrock surface is mantled by a thick succession of glacial till and various unconsolidated sediments that reach thicknesses in excess of 200 feet (60 m) within portions of every county on the map area. In parts of Crawford, Shelby, Monona, Mills, and Carroll counties, these sediments exceed 400 feet (120 m) thick.

The Quaternary mantle of southwest Iowa arguably contains the most complete record of pre-Illinoian glacial till (diamicton) deposition in the northern hemisphere, but, surprisingly, this remarkable Quaternary succession has not been stratigraphically defined, and much work remains. A succession of at least seven or eight major pre-Illinoian glacial stages are identified in the region, all apparently older than about 0.5 Ma (Boellstorff, 1978). The complex succession of glacial and inter-glacial deposits in southwest Iowa includes at least two glacial tills ("C" tills) older than 2.0 million years (Boellstorff, 1978). Thereby, these tills, as well as potentially older sub-glacial sediments in the area, are of Pliocene, not Quaternary, age (international Pliocene-Pleistocene boundary defined at 1.8 Ma). These Pliocene glacial deposits of southwest Iowa are lumped with the Quaternary deposits as part of the mantle of unconsolidated sediments above the Cretaceous and Paleozoic bedrock.

Sub-till successions are identified in well penetrations above the bedrock "uplands" in portions of southwest Iowa. These sediments are dominated by poorly-consolidated mudstones, silts, and sands ("salt and pepper" sand) of western (Rocky Mountain) origin. These successions variably pre-date or are coeval with the oldest glaciations (early Pleistocene and Pliocene). These sediments are primarily known from subsurface well penetrations in the area, although good exposures are noted along the Missouri River Valley near Folsom in Mills County (Witzke and Ludvigson, 1990). Correlation of these sub-till successions remains largely unconstrained, but the lithologic character of the sediments closely resembles certain Pliocene and Miocene intervals of eastern Nebraska (Witzke and Ludvigson, 1990). Reworked Miocene vertebrate fossils (rhinoceros, three-toed horses) have been identified at several localities in southwest Iowa, lending credence to the possibility of that sub-till Miocene (Ogallala Group) units may be present in the area (ibid.). Regardless of the age of these sub-till successions, these sediments have been included with the Quaternary mantle because of their unconsolidated nature and because the regional stratigraphic relationships of these strata remain undefined.

DATA SOURCES AND APPROACHES TO MAPPING

The geologic map of southwest Iowa is an entirely new compilation using all available sources of information on the distribution and stratigraphy of bedrock units. Data were derived from a number of sources including: 1) field studies and mapping programs of bedrock exposure (new investigations undertaken for this mapping effort as well as all published and unpublished prior field studies); 2) extensive subsurface well records archived at the Iowa Geological Survey (IGS); 3) bridge-boring records originally archived at the Iowa Department of Transportation (IDOT); and 4) re-study and correlation of all available bedrock cores and core logs (IGS, IDOT). Unlike the recently-completed bedrock maps of north-central and south-central Iowa (Witzke et al., 2001; Pope et al., 2002), the detailed county-scale soils maps of the Natural Resources Conservation Service (NRCS) provided almost no new information on the distribution of bedrock exposure or shallow bedrock-derived soils in southwest Iowa, even though the digital soils maps were searched exhaustively. The paucity of soils-derived data for southwest Iowa probably reflects the overall scarcity of bedrock exposure as well as differing styles of soils mapping across the area.

Regions of bedrock exposure were evaluated in the field as part of the larger mapping investigation (B. Witzke, G. Ludvigson), and number of new exposures were located and stratigraphically constrained. Of particular importance, a series of new Cretaceous exposures were identified in Mills, Pottawattamie, and Montgomery counties, significantly expanding the known distribution of Cretaceous strata. Personal correspondence with John Pope (Northwest Missouri State University) and Marvin Carlson (Nebraska Conservation and Survey Division) provided information about previously unknown bedrock exposures in Page and Montgomery counties. Paper archives at the Iowa Geological Survey provided the primary source of information on the distribution and character of bedrock exposure across southwest Iowa, and the information contained within these records was digitally archived (GIS) as part of the mapping project. The highway construction materials report for southwest Iowa (Hershey et al., 1960) contains a duplicate listing of most bedrock exposures for the area, derived from the IGS files. Unpublished files at the Iowa Department of Transportation (IDOT), Office of Materials, contain considerable information on areas of bedrock exposure, operating and inactive quarry sites, shallow bedrock coring, and bridge boring information. We are grateful to the DOT geologists in Ames, especially Brian Gossman, Adriana Reyes-Phelps, and Neal Tieck, for their time and assistance in retrieving this valuable information. Although much of the DOT outcrop information was also duplicated in the IGS files, the DOT quarry and core files proved to contain much information not found in the IGS archives.

Published reports on the bedrock geology of southwest Iowa are relatively few in number, but all of these publications are well over 50 years old. Stratigraphic syntheses of local to regional scope have included descriptions of outcrops in southwest Iowa, especially the reports of Smith (1909), Tilton (1920), Condra (1927, 1933), Condra and Upp (1933), Condra and Reed (1937), and Hershey et al. (1960). These reports document bedrock outcrop areas of historical interest, but stratigraphic interpretations are of varied quality in these reports.

Because southwest Iowa is extensively covered by a thick mantle of unconsolidated Quaternary materials, the subsurface well records archived at the Iowa Geological Survey provided the largest source of information about the bedrock geology and topography in the region. These well records are accessible to the public at the Iowa Geological Survey's website (Geosam records at http://gsbdata.igsb.uiowa.edu/geosam). Well logs that contain lithologic information about well cuttings samples (generally taken every 5 feet) are of variable quality, but, in general, these logs, when tied to surface elevation, provide good descriptive evidence enabling critical interpretations of stratigraphy, bedrock structure, and bedrock topography. All existing well logs were examined and systematically re-evaluated for bedrock elevation and stratigraphy as part of the new mapping program. This involved the support of student aides (Univ. Iowa Dept. of Geoscience) working in cooperation with IGS staff, who logged previously-undescribed cuttings samples to provide critical information in areas of limited bedrock control. Stratigraphic picks were coded into an expanding stratigraphic database to facilitate mapping and promote further accessibility of IGS data in an electronic medium. Various driller's logs and other well penetrations that lack detailed lithologic logs were used to supplement and refine our interpretations of bedrock geology and topography. Driller's logs are highly variable in descriptive quality, and their utility in southwest Iowa was predicated on having higher-quality well logs available in nearby areas to facilitate comparisons. Approximately 5000 well logs were examined and stratigraphically re-evaluated as part of the southwest Iowa mapping project.

The highest quality source of subsurface bedrock information was derived from cores archived at the Iowa Geological Survey's Oakdale core library. These cores originally were drilled for a variety of reasons, including hydrogeologic investigations, stratigraphic tests, oil exploration, and quarry aggregate evaluation and exploration. All told, the IGS core library contains 46 cores from the southwest Iowa map area, and each of these was logged and stratigraphically correlated as part of the mapping project, many for the first time (logged by B. Witzke). Four of the deepest cores served as primary reference sections against which well records and outcrop information could be compared lithologically and stratigraphically: 1) Logan core, Harrison Co., 585 ft (177 m) continuous core, Upper Mississippian through Bronson Group; 2) Bedford core, Taylor Co., 573 ft (175 m) continuous core, lower Bronson Group through upper Shawnee Group; 3) Malvern core, Mills Co., 249 ft (76 m) continuous core, Kansas City Group through lower Shawnee Group; and 4) Riverton core, Fremont Co., 942 ft (287 m) continuous core, upper Marmaton Group through upper Wabaunsee Group. Stratigraphic interpretations for these reference cores were discussed and reviewed by Prof. Philip Heckel (Univ. Iowa, Dept. Geoscience), and we are grateful for his expertise and input.

Our approach to bedrock mapping was an interative effort, building regional stratigraphic and geologic interpretations based on a study of all available data, in general succession: 1) identify all areas of bedrock exposure; 2) log all available bedrock core; 3) build composite stratigraphic reference sections for the region; 4) re-evaluate all stratigraphic picks for outcrop and core logs; 5) identify all subsurface well points; 6) log previously unstudied bedrock well samples; 7) examine and interpret all driller's logs (for bedrock elevation and bedrock lithology, where possible); 8) determine elevations for all bedrock wells penetrations and outcrop; 9) assign stratigraphic picks to all outcrop and well points; 10) build a bedrock topographic map using all available data; 11) review and edit bedrock topography for consistency; 12) determine elevations of stratigraphic contacts of bedrock mapping units and interpret local bedrock structure; 13) intercept local bedrock structure with bedrock topoography to produce a bedrock geologic map; 14) build all line work (topography and geology) using GIS software (ESRI's ArcView 3.2); 15) produce a final map product available in an electronic format.

The mapping style reflected on the new bedrock geologic map of southwest Iowa provides a simple way to evaluate the density of data coverage and the confidence of the stratigraphic picks. Areas of bedrock exposure are well constrained geologically, and the map is correspondingly the most detailed in those areas. Relatively detailed mapping coverage is also possible in other areas with geographically dense data coverage (i.e., numerous bedrock well penetrations). By contrast, less detailed line work characterizes other regions of the map area, especially in portions of the northern and southeastern map area, where bedrock exposure is sparse to absent and well control is locally limited. In areas of more limited data coverage, the stratigraphic contacts and bedrock topography are correspondingly portrayed with less detail, and the line work is drawn in a more generalized style. The bedrock geologic map in those areas is generally marked by broadly sweeping or arcuate line work lacking intricate detail.

COMPARISON WITH PREVIOUS GEOLOGIC MAPS OF SOUTHWEST IOWA

The first bedrock geologic map for southwest Iowa, albeit highly generalized, was published by White (1870), who assigned the primary bedrock of the region to the "Upper Coal Measures" (subsequently termed the Upper Pennsylvanian) and portrayed scattered Cretaceous strata in portions of Cass, Montgomery and Pottawattamie counties. Subsequent work by the Iowa Geological Survey presented slightly more detailed bedrock geologic maps for individual counties in southwest Iowa in the its Annual Reports between 1895 and 1916 (Lonsdale, 1895; Udden, 1901, 1903; Calvin, 1901; Shimek, 1910; Arey, 1916; Tilton, 1916). Adams County geology was presented subsequently (Wood, 1941). These county-scale geologic maps were incorporated into a series of bedrock geologic maps for Iowa published between 1894 and 1937. Each of these compilations presented an informative but generalized view of the bedrock geology of southwest Iowa. However, significant new data and stratigraphic refinements are now available that make most of these early geologic maps of limited value outside of their historical interest.

A small-scale bedrock geologic map of southwest Iowa was produced by Hershey et al. (1960) as part of the investigation of bedrock materials for the State Highway Commission. Although it is a highly generalized geologic map, it attempted to incorporate all available outcrop and subsurface data for the region. Their map portrays Middle and Upper Pennsylvanian strata across southwest Iowa overlain by Cretaceous units in the central and northern regions. The Geologic Map of Iowa produced by the Iowa Geological Survey in 1969 (Hershey, 1969) marked a major improvement over previous versions, as it incorporated a more extensive array of subsurface well points and a generally thorough survey of bedrock exposure. The 1969 Hershey map represents the most recent effort to present the bedrock geology of southwest Iowa, but its main construction directly parallels the earlier map of Hershey et al. (1960) with little change.

Subsequent work has identified several significant mapping issues with the Hershey (1969) map in need of improvement for southwest Iowa. 1) The bedrock topography was not accurately reflected across large portions of the map area. 2) Geologic units in some areas were miscorrelated and thereby mismapped. 3) Subsequent group-level reclassification of Missourian stratigraphy has necessitated a re-evaluation of mapping units. In particular, the thin Pleasanton interval is no longer accorded group status in Iowa (Ravn et al., 1984), and the interval is not considered to be a practical bedrock mapping unit (shown as a thin pencil-line-width mapping unit on the Hershey map). Instead, the Pleasanton is mapped as the basal formation of the Bronson Group, and the Kansas City Group has been reformulated accordingly. 4) The Thurman-Redfield Fault Zone, a re-activated Proterozoic fault that with recurring movements through the Paleozoic, was not accommodated on the Hershey (1969) map, but significant displacements (200 to 300 ft; 60-90 m) of Pennsylvanian strata are recognized along the fault in the southwest map area.

The bedrock geologic map of southwest Iowa presented herein represents an entirely new compilation that shows significant contrasts with the Hershey (1969) map, as summarized here. 1) Mississippian strata are mapped in bedrock channels in northern Monona and Crawford counties, in areas shown as Pennsylvanian bedrock on the Hershey map. 2) The new map shows extensive Cherokee Group subcrop in Monona and Harrison counties in areas formerly mapped as Kansas City Group on the Hershey map. No Kansas City or Bronson Group strata are identified in Monona or western Harrison counties. 3) Marmaton Group bedrock is mapped in Carroll and Harrison counties. The Hershey map shows these areas as Cherokee Group or Kansas City Group, respectively. 4) Cherokee Group bedrock is mapped the full extent of the Fremont Channel in Shelby County. 5) A broadly sweeping belt of Marmaton Group strata is shown on the Hershey map across Monona, Crawford, Shelby, and Audubon counties. This region is now portrayed as a complex and dissected area cut by bedrock channels (including the Missouri Valley and Fremont Channel). 6) The Lansing and Douglas groups extend northward in Pottawattamie County compared to their distribution on the Hershey map. The Shawnee Group is more restricted in Pottawattamie County than shown on the Hershey map. 7) The distribution of the Wabaunsee Group differs from the Hershey map in being more dissected in Page and Adams counties and more widespread across western Taylor County. The Wabaunsee Group is mapped through most of the Fremont Channel in Fremont County, unlike the Hershey map which shows Shawnee Group in the bedrock channel.

8) The Thurman-Redfield Fault Zone is not shown on the Hershey map, although the distribution of the Wabaunsee Group on that map is largely restricted to areas south of the presently-recognized fault trace. By contrast, the fault prominently transects Pennsylvanian strata on the new map, and its trace consistently separates mapping units between up-thrown (north) and down-thrown (south) sides of the fault.

The expanded distribution of Cretaceous strata on the new southwest Iowa map is the most significant difference with the Hershey map, as outlined here. 9) Cretaceous strata are expanded into south-central Crawford County and southwest Carroll County. 10) A major expansion of Cretaceous strata is interpreted across large areas of Harrison, Shelby, and northwest Audubon counties. 11) Extensive Cretaceous strata are mapped in areas of central and western Pottawattamie County and northern Mills County, whereas Cretaceous units are entirely absent from this region on the Hershey map. 12) Cretaceous strata are more widespread in central Montgomery, northern Page, and northwest Adams counties.

THURMAN-REDFIELD STRUCTURAL ZONE

Background

Todd (1890) noted a “sharp fold” in Pennsylvanian strata in Fremont County between Thurman and the “Wilson section” of White (1870), with similar folding displayed on the Nebraska side of the Missouri River at Jones Point. Todd (1890) suggested that this structure “may become a fault south of Wilson’s.” Smith (1909) also recognized a “fault north of Thurman” and south of the “Wilson section,” which he interpreted to trend N60ºE and show 320 feet (98 m) of downthrow on the south. Because of intermittent exposure, Smith (1909, p. 19) acknowledged that the structural feature could be “a fault or an abrupt monocline.” Keyes (1916) proposed that the structure near Thurman was part of a much larger fault system that trends for 300 miles from eastern Nebraska to central Iowa. Keyes (1916, p. 106) named this the “Red Oak fault” (after the southwest Iowa community in Montgomery County), and he proposed that the fault shows a “maximum displacement of not less than 400 feet” (120 m). Tilton (1919, 1920) termed this the “Thurman-Wilson fault” (intercepting the Missouri River bluffs between Thurman and the Wilson section), which he interpreted to show 300 feet (90 m) of vertical displacement north of Thurman. Like Keyes, Tilton also proposed that this fault is of regional extent across several counties of southwest Iowa, and he interpreted vertical displacements along this fault in the Grant area (southwest Cass Co., northeast Montgomery Co.) of 284 feet (57 m).

Condra (1927) described the “Jones Point deformation” on the Nebraska and Iowa sides of the Missouri River Valley near Thurman, and he concluded that the structural feature represents an anticlinal fold with little or no faulting. This interpretation was reiterated by Condra and Reed (1938), who considered the structure to be an “asymmetric anticlinal fold.” They concluded that “there is no positive evidence of faulting in the structure [at Thurman] . . . all of the section in the southeast limb of the anticline, except 30 to 60 feet in covered areas near Thurman and south of Jones Point, can be accounted for by folding”(Condra and Reed, 1938, p. 17). Like Tilton and Keyes, Condra and Reed (1938, p. 15-16) considered this structural feature to extend from eastern Nebraska towards central Iowa, connecting a number of previously named structural features:

> “The better known names applied to this structure are the Redfield anticline [named after Redfield, Dallas Co.], Thurman-Wilson fault, Red Oak fault, and Jones Point deformation. Because folding is the primary factor, the ‘fault’ names are not tenable . . . [and, hence, the term] Redfield anticline [is applied to the entire structural feature].”

Hershey et al. (1960, p. 35) reiterated the regional character of this structural feature, and proposed the name Thurman-Redfield Structural Zone for it:

> “. . . a structural zone marked by a series of domes and anticlines with some faulting extending from north of Thurman and Red Oak, through Grant and contuing to the northeast. The zone extends southwestward into Nebraska [Union Fault] and northeastward in Iowa through Redfield, Ames, and beyond. Some of the names applied to it in the past are the Thurman-Wilson fault, Thurman-Wilson deformation, and Redfield Anticline. . . . the term ‘structural zone’ appears to describe this occurrence most accurately. The name Thurman-Redfield structural zone is here proposed for it.”

Like Condra, Hershey et al. (1960) minimized the significance of faulting along the Thurman-Redfield Zone, suggesting that most of the deformation is accommodated by anticlinal folding. They interpreted the structure to probably be “an anticline with faulting,” but indicated that “faulting must be of very minor extent” (ibid., p. 60). Daut (1980, p. 22) also supported the idea that “the Thurman-Redfield Structural Zone is not a single feature, but a series of related domes and anticlines, with faulting of minor displacement in the Pennsylvanian rocks.” Although the magnitude of faulting of Paleozoic strata was undetermined in Daut’s study, he nevertheless acknowledged that “gravity profiles indicated that vertical post-Precambrian movement on individual faults may range up to 300 meters or more” (Daut , 1980, p. 84).

The Thurman-Redfield Structural Zone in Iowa parallels the southern flank of an outstanding positive gravity anomaly (Midcontinent Geophysical Anomaly), at a position that generally corresponds to a major faulted boundary on the deeply-buried Precambrian bedrock surface within the Proterozoic Midcontinent Rift System. This system represents a failed continental rift that stretches from the Lake Superior outcrop southwestward across Minnesota and Iowa into northeast Kansas, and it transects the southwest Iowa map area. The rift system was filled with Keweenawan mafic volcanics and thick sedimentary sequences that were juxtaposed by high-angle post-rift faulting during subsequent regional compression, creating a central horst of dense mafic rocks bordered by deep flanking basins of less dense sediments. The strong gravity contrasts along the trend of the rift reflect these density differences. Modeled displacements of Precambrian rocks on the bounding faults of the central horst locally exceed 30,000 feet (9000 m) (Anderson, 1992).

In southwest Iowa, Paleozoic displacements along the Thurman-Redfield Structural Zone apparently developed in response to reactivation of Precambrian basement structures associated with the southern bounding fault of the central horst. Paleozoic strata (up through the Virgilian section) show clear evidence of deformation along the structural zone, but, as first noted by Tilton (1919. p. 390), there is no evidence for displacement or deformation of Cretaceous strata in southwest Iowa. It seems likely that there were recurring and episodic movements along the Thurman-Redfield Zone throughout the Paleozoic, and the deformation of Virgilian strata indicates post-latest-Pennsylvanian movement (probably Permian). Although deep well penetrations are few in southwest Iowa, the limited data suggest that relative displacements of Paleozoic strata increase with depth, consistent with the idea of recurring movements (growth faulting).

Not surprisingly, no actual fault plane or fault zone has been clearly recognized in the field, largely because of limited bedrock exposure in the southwest Iowa map area and because fault gouge/breccias and faulted sections are less likely to hold up to exposure than more coherent unfaulted strata. The general absence of actual fault exposures, however, cannot serve as evidence for the presumed absence or insignificance of faulting along the structural zone as some previous authors seem to have concluded (e.g., Condra and Reed, 1938; Hershey et al., 1960). Interpretations concerning the presence or absence of faulting along the Thurman-Redfield Zone are of considerable importance to the construction of the bedrock geologic map, and, therefore, a reasonable conclusion about the structural character of the Zone is necessary.

Field and Subsurface Data Provide Structural Constraints

Closely-spaced outcrop and/or well sections in a few areas indicate significant vertical stratigraphic displacements over relatively short distances along the trend of the Thurman-Redfield Structural Zone. The simplest way to accommodate such large-scale displacements would be to place a relatively narrow fault zone between control points, particularly in the absence of steeply-dipping strata that might alternatively account for such displacements by folding alone. A review of areas that constrain closely-spaced stratigraphic displacements is offered here to explain our rationale for the structural interpretations portrayed on the bedrock geologic map.

Adair and Dallas Counties. Structural interpretations for the southwest Iowa bedrock map represent an extension of the mapping philosophy presented for the south-central Iowa bedrock map (Pope et al., 2002). Following major stratigraphic revision of outrops along the Middle River in Adair County (15 miles east of the southwest Iowa map edge), it is now apparent that 200 feet (60 m) of stratigraphic displacement separates bedrock exposures located only 2000 feet (600 m) apart near the town of Howe (see discussion by Pope et al., 2002). In the absence of any observable dips of sufficient magnitude to produce this deformation by folding alone, it seems more likely that the displacement between these exposures is accommodated by faulting in the intervening area. Similarly, areas of closely-spaced exposures along the Thurman-Redfield Zone south and southeast of Redfield in Dallas County constrain stratigraphic displacements of about

200 feet (60 m) between exposures located less than one mile (1.6 km) apart (J. Pope, 2003, pers. comm.).

Thurman Area. The best constraints for structural interpretations along the Thurman-Redfield Zone in the southwest Iowa map area are located a short distance north of the town of Thurman in Fremont County, primarily exposures in sections 23, 26 and 35 (T70N, R43W). As noted previously, Smith (1909) interpreted a fault with about 300 feet (90 m) of vertical displacement in this area, although others, most notably Condra and Reed (1938), inferred that folding alone was sufficient to accommodate the stratigraphy displayed in the area with little or no faulting. Outcrops and quarries along the base of the Missouri River Valley bluffs in sections 14, 23, and northwest 26 expose strata of the upper Shawnee and basal Wabaunsee groups (Deer Creek, Topeka, and Severy-Howard formations) across its extent. The observed dips in this area are gentle (less than 1-3º), with slight northwestward dips in sections 14 and 23, and southeastward dips in northwestern section 26 (Wood, 1935; Condra and Reed, 1938). Condra and Reed (1938) noted (or inferred?) small-scale faulting (their "Union fault" with an offset of 10 ft; 3 m) near the southwest corner of section 23, which they located immediately south of the crest of the broad "Redfield anticline." Although Condra and Reed (1938, p. 15) stated that beds south of the old quarry in W½ NW¼ sec. 26 "dip sharply under the bottomland level," this must be an inference on their part as there are no known bedrock exposures to the south for one-half mile (0.8 km). Farther south, however, a series of outcrops in SE¼ SW¼ sec. 26 and NE¼ sec. 35 expose strata considerably higher stratigraphically in the middle part of the Wabaunsee Group. Therefore, vertical stratigraphic displacement of approximately 240 feet (73 m) is indicated within the west-central area of section 26. While it is possible to accommodate such a deformation with a dip of about 6º over the entire half mile or so of covered section, it seems ad hoc that such significantly increased dips would be exclusive to an area that lacks exposure, as exposures both northward and southward from this area display more gentle dips. Hershey et al. (1960, p. 60) also indicated that the "dip measured on the outcrop [in the Thurman area] is not enough to account for the structure that is known to exist," providing compelling evidence for faulting (contra Condra). For these reasons, a fault zone that accommodates the displacement is inferred to occur in the covered area. [As an aside, Condra and Reed (1938, p. 15) make reference to an exposure of mid Wabaunsee Group strata "one mile northwest of Thurman." An exposure at that location (NE NW SW sec. 26) has not been observed for this study, but if their location is accurate, the 240-foot (73 m) vertical displacement would be even more tightly constrained between sites only 0.3 miles (0.5 km) apart.]

Outcrops of mid Wabaunsee strata (Bern, Auburn, Emporia, Willard formations) are seen southward in and around the town Thurman (secs. 35, 36, T70N, R43W). Continuing farther southward along the bluffline, exposures of the highest Wabaunsee strata in Iowa (Stotler and Root formations) are identified in sections 1, 12, and 13 (T69N, R43W). Because exposures are closely spaced in this area, the absence of certain Wabaunsee units (Zeandale, Pillsbury formations) along the bluffline outcrop is curious and may indicate that additional small-scale stratigraphic displacements are possible in the area (especially near the northwest corner of sec. 1). Overall, the bluffline exposure in the Thurman area displays about 340 feet (104 m) of total structural relief, most of it interpreted to be accommodated along a relatively narrow fault zone located about one mile (1.6 km) north of the town of Thurman. This location occurs about one mile (1.6 km) north of the interpreted location of the southern bounding fault of the central horst on the Precambrian basement surface (whose location is inferred from gravity profiles), suggesting that a major fault zone cuts across the Paleozoic section with a moderately steep southeastward dip in this area.

Additional constraints on the character of the Thurman-Redfield Structural Zone are displayed in areas a short distance (< 6 miles) from Thurman. To the west across the Missouri River in Nebraska, a series of bluffline bedrock exposures between the mouth of Ervine Creek and Jones Point (secs. 17, 21, 28, T10N, R14E, Cass Co., Nebraska) have been described by

Condra (1927) and Condra and Reed (1938). The stratigraphy and structural relationships are closely similar to those seen across the river north of Thurman (north-to-south transect): 1) Shawnee Group strata show a slight northward dip across the northern exposure (sec.17, NW sec. 21); 2) small-scale faulting (~9 ft; 3 m; "Union Fault") is identified near the crest of the "Redfield anticline" (NW sec. 21); 3) more pronounced southward dips are recognized to the south, progressively adding stratigraphically higher upper Shawnee and basal Wabaunsee units to the outcrop (across SW sec. 21); 4) a "covered stretch" obscures relationships southward (near the boundary between sec. 21/sec. 28); and 5) higher strata of the mid Wabaunsee Group are identified farther to the south (sec. 28). Although the similarities with the Thurman exposure are striking, total structural relief along the crest of the so-called "Redfield anticline" at Jones Point is higher than seen at Thurman, as lower Shawnee strata (upper Oread, Lecompton formations) are exposed there (Condra, 1927). Condra (1927, p. 127) identified about 300 feet (90 m) of total structural relief across the Jones Point transect, and he suggested that "all of the deformation is due to warping" not faulting, although he did acknowledge that some minor faulting is possible across the "covered stretch." This interpretation was reiterated by Condra and Reed (1938). However, there is the considerable stratigraphic disparity between Condra's two reports in the correlation of Wabaunsee Group strata in the southernmost sections at "Sand Point" that has significant bearing on structural interpretations [note: Condra discussed the bluff in sec. 28 as "Sand Point" and the bluff in sec. 21 as "Jones Point," whereas the McPaul sheet 7 ½ minute topographic quadrangle labels the bluff in sec. 28 as "Jones Point"]. Condra (1927, p. 123) interpreted the Sand Point section to show a succession of lower Wabaunsee Group strata (White Cloud, Scranton, basal Bern formations) -- he considered the stratigraphy to reflect a simple southward progression of the dipping units seen to the north at Jones Point, and hence concluded that faulting between the two areas was absent or minimal. By contrast, Condra and Reed (1938) clearly showed the section above river level at Sand Point on their cross section to be entirely in the mid Wabaunsee Group (Wakarusa Member and higher). Although they do not discuss the ramifications of this stratigraphic reassignment, this recorrelation makes the supposed progression of dipping strata championed by Condra (1927) a much more difficult proposition. Instead, about 200 feet (60 m) of vertical deformation needs to be accommodated across the relatively "narrow stretch" of covered section (less than one-third mile across). This seems directly analogous with the situation on the other side of the river at Thurman, where a fault zone is interpreted in the covered area that separates Shawnee Group and mid Wabaunsee Group exposure.

Additional outcrop areas along Plum Creek northeast of Thurman also constrain the locus of vertical deformation. Quarries and exposures to the north (sec. 17, NW sec. 20, T70N, R42W) reveal upper Shawnee Group strata (Deer Creek, Topeka formations), but mid-Wabaunsee Group strata (Auburn, Emporia formations) are seen a short distance downstream (especially NW sec. 31). These exposure areas are separated by about 240 feet (73 m) of stratigraphic displacement. The southernmost quarry in the northern area (NW sec. 20) is of particular note, as a series of northeast-trending subparallel fractures and small-scale faults (less than one-foot [30 cm] displacement) are displayed there (Hershey et al., 1960, p. 60; Daut, 1980). The trend of these features suggests a close relationship with the larger Thurman-Redfield Zone, and large-scale faulted displacements are interpreted to occur only a short distance to the south of this quarry.

Mills County. The geophysical trend of the Thurman-Redfield Zone trends northeastward from the Thurman area into southeastern Mills County. The northern up-thrown portion of the zone is constrained by Shawnee Group exposures east of Tabor that occur less than one-mile from the geophysical trend of the structural zone, but no exposures are seen to the south (down-thrown side). Nevertheless, several deep exploration wells were drilled along this trend northeast of Tabor and south of Malvern that provide significant insights into the character of the structural zone. Using the base of the Bronson Group (base of Missourian) as a datum, the well sites display 360 to 425 feet (110-130 m) of structural relief between up-thrown and down-thrown sides of the Thurman-Redfield Zone. Therefore, it appears that there is considerably greater displacement of basal Missourian strata in Mills County than seen in the stratigraphically-higher Virgilian succession in the Thurman area (200-300 ft; 60-90 m). Of particular note, shifting the datum to an even lower stratigraphic position at the top of the Mississippian section in these well penetrations produces even more dramatic vertical deformations, ranging from 705 and 831 feet (215-253 m) between up-thrown and down-thrown sides of the structure. This significantly greater structural displacement is also reflected by major changes in the thickness of the Cherokee Group (Desmoinesian), which is 135 to 205 feet (41-63 m) thick on the north side (up-thrown) and 580 to 600 (177-183 m) thick to the south (down-thrown side). These observations suggest that major structural movements accompanied or immediately preceded deposition of the Cherokee Group. In addition, increasing displacement with depth within the Pennsylvanian succession suggests that recurring movements apparently occurred along the fault zone, producing growth-fault geometries. It should be noted that the geophysical trend of the basement fault across this portion of Mills County appears to be laterally offset by a “dog-leg” intrepreted as a lateral fault or transform (Anderson, 1992) or fault splay (Daut, 1980). The area of this lateral shift appears to be marked by doming of Pennsylvanian strata on the up-thrown side of the structure (the “Malvern anticline” of Hershey et al., 1960).

Red Oak Area. The geophysical trend of the Thurman-Redfield Structural Zone passes northeastward near the north edge of Red Oak in central Montgomery County. The up-thrown side of the structure displays numerous outcrops and quarries exposing lower Shawnee Group strata (Oread, Lecompton formations) along the East Nishnabotna River Valley between Stennett and Red Oak. These exposures were reputed to show easterly dips in the north and southwestward dips to the south by Hershey et al. (1960, p. 80), who suggested the possibility of a “dome structure” in this area (their “Red Oak anticline”). They reported a “strong easterly dip” at Stennett. However, Condra and Upp (1933) reported southeastward dipping strata between Red Oak and Stennett, and Tilton (1920, p. 269) illustrated northward dipping beds in the same area. Exposures to the south on the down-thrown side of the structure (in Red Oak proper and farther downstream) primarily belong to the Cretaceous Dakota Formation, and the position of the Thurman-Redfield structure is not adequately constrained. An exposure of Wabaunsee Group strata was reported by Tilton (1920, p. 261) near the southwest edge of Red Oak, which if correctly identified, constrains any faulted displacement to an area within 3 miles (5 km) to the north. In addition, well sections immediately north of Red Oak (SW corner sec. 15, NW SW sec. 17) show about 250 feet (76 m) of stratigraphic displacement, which constrain any faulting to an area about 1.4 miles (2.2 km) across when measured perpendicular to the geophysical trend of the structure. Daut (1980) interpreted complex basement faulting in the Red Oak area. In Montgomery County, all Wabaunsee Group exposures are found south of the Thurman-Redfield Zone, whereas Shawnee Group exposures are exclusive north of the zone.

Grant Area. The geophysical trend of the Thurman-Redfield Structural Zone runs east-northeastward near the south edge of the town of Grant in northeastern Montgomery County, and continues eastward into the northwestern corner Adams County and adjoining southern Cass County. Lower Shawnee Group strata (Oread, Lecompton formations) form the bedrock surface in the up-thrown area north of the structural zone, and good bedrock control is available in that area (quarries, natural exposures, bedrock cores). Bedrock data on the down-thrown side are relatively sparse, but some important structural constraints can be derived from the available information. A few exposures of Wabaunsee Group strata are found in northwestern Adams County (secs. 10, 19, T73N, R35W), and numerous subsurface mines into the Nodaway Coal also indicate the presence of Wabaunsee Group strata across much of western Adams County (Wood, 1941; Keyes, 1894; Hinds ,1909). Of particular note is a small area northeast of Grant (sec. 1, T73N, R36W) where small limestone exposures (NW SW sec. 1) and an adjoining core penetration (NW NW NW SE sec. 1) display lower Shawnee strata (Oread Formation). The old Westrope Mine (SW SE sec. 1), which mined the lower Wabaunsee Nodaway Coal, was located a short distance to the south along a minor tributary, where the coal was once "exposed in a small runnel" (Keyes, 1894, p. 444). The close juxtaposition of lower Shawnee and lower Wabaunsee strata in this area constrains a major stratigraphic displacement of about 205 feet (63 m) over a lateral distance of only 1600 feet (490 m). In the absence of dipping strata of sufficient magnitude to explain the displacement, a fault zone is interpreted between the two closely-spaced exposure areas.

Tilton (1919, 1920) was the first to recognize the structural signficance of exposures in the Grant area, and he calculated 285 feet (87 m) of stratigraphic displacement between the limestone quarries near Grant (Oread Formation) and the Nodaway Coal mines at "Briscoe" (an obscure historic name for a now-defunct town in sec. 2 or 3, T73N, R35W; see Keyes, 1894, p. 446 and Hinds, 1909, p. 391). Tilton inferred a major fault ("Thurman-Wilson fault") southeast of Grant, but he indicated that the Cretaceous strata showed no apparent displacement in the area and that fault movements were entirely pre-Cretaceous. Hershey et al. (1960, p. 80) observed various dips in Shawnee strata in the Grant area (up-thrown side of the structure), and they interpreted this to be "an area of [complex] doming" with the crest of the dome located just "east of Grant" (the "Grant dome"). Daut (1980) interepreted complex basement faulting in the Grant area.

Subsidiary and Parallel Structures

Condra (1927, p. 18) and Condra and Reed (1938) recognized a shallow anticline that parallels the trend of the Thurman-Redfield Fault Zone (as presently recognized) about 3 miles (5 km) to the north. They termed this feature the "Bartlett Syncline" (after Bartlett, Iowa), and identified it in Fremont County, Iowa, and adjacent Nebraska. This syncline probably has less than 50 feet (15 m) of structural relief (Shawnee Group datum). Additional structural elements that trend sub-parallel to the Thurman-Redfield Zone were identified in Pennsylvanian strata northward in Mills County by Hershey et al. (1960), including the "Lyon anticline" (Burr Oak area) and "Glenwood syncline" (axis near Glenwood). The Lyon Anticline is about 5 miles (8 km) wide and exhibits approximately 85 feet (26 m) of structural relief along the bluffline near Burr Oak.

The Glenwood Syncline is a broad asymmetrical syncline evident across northwestern Mills and southwestern Pottawattamie counties, and it is interpreted to trend east-northeastward subparallel to the Thurman-Redfield Zone at least as far as eastern Pottawattamie and western Cass counties. This syncline is a major structural feature with relatively large relative movements indicated in its axial region. Immediately north of the axis, 160 feet (50 m) of structural relief is noted between wells in northwestern Mills County located less than 4 miles (6 km) apart, indicating southward dips in this area.. In central Pottawattamie County, about 300 feet (90 m) of structural deformation is apparent between data points 6 miles (10 km) apart. The trend of the Glenwood Syncline is clearly reflected on the bedrock geologic map where Shawnee Group strata are shown to occupy the central Fremont Channel near the Mills-Pottawattamie county border (but Missourian units are mapped in the channel to the north and south). In addition, the northernmost occurrences of the Shawnee Group are located along the axial trend of the Glenwood Syncline, including the quarries near Folsom, Silver City, Macedonia, and Lewis. The axial trend of the Glenwood Syncline is located directly over the "Mineola Basin" of Anderson (1992), an elongate Precambrian sedimentary basin on the central horst of the Midcontinent Rift System. It seems likely that the Glenwood Syncline formed in response to later reactivation of this deep basement structure. It is unclear why there is no evidence in the map area of Paleozoic reactivation and deformation along the basement trend of the Northern Boundary Fault of the central horst of the Midcontinent Rift (see Anderson, 1992, for location of NBF).

Summary of Structural Interpretations

Conclusions about the character and extent of structural deformation associated with the Thurman-Redfield Zone are needed to interpret and map the bedrock geology of southwest Iowa.

Based on the observations and interpretations discussed above, the following conclusions are presented. 1) The primary structure of the Thurman-Redfield Structural Zone is interpreted as a faulted flexure (monocline), with most of the deformation accommodated along a relatively narrow fault zone. 2) The fault zone is interpreted to extend the entire width of the map area, generally trending east-northeast. 3) Fault displacements of the shallow Upper Pennsylvanian bedrock (Missourian-Virgilian) range between 200 and 300 feet (60-90 m) in the map area. The up-thrown side of the fault is to the north. 4) Fault displacements increase with stratigraphic depth, supporting growth-fault genesis and a history of recurring fault movement during the Paleozoic. 5) Doming of Paleozoic strata is locally developed along the up-thrown side of the structural zone. 6) A series of anticlines, synclines, and small-scale faults are displayed in the Paleozoic strata that trend sub-parallel to the main structural zone. These subsidiary features are primarily recognized within a span of 25 miles (40 km) to the north of the main zone. 7) The Thurman-Redfield Structural Zone corresponds directly with the south boundary fault of the central horst of the Proterozoic Midcontinent Rift System, and its development results from reactivation of this basement feature. 8) No deformation of Cretaceous or younger strata has been recognized along the trend of the structural zone.

CRETACEOUS STRATA

Dakota Formation

Cretaceous strata are identified in 12 of the 14 counties in the map area (not recognized in Fremont and Taylor counties). All Cretaceous bedrock in this area is assigned to the lower Dakota Formation, Nishnabotna Member, a sandstone-dominated interval of upper Albian age (Witzke and Ludvigson, 1994, 1996). The Dakota Formation unconformably overlies an erosionally beveled and channeled surface developed on Pennsylvanian units. Dakota strata in the map area were deposited in westward-draining fluvial and fluvial-estuarine systems, and sub-Dakota channeling and erosion formed during episodes of fluvial incision. The sub-Dakota surface displays up to 100 feet (30 m) of local relief in southwest Iowa, and the highly irregular nature of the Pennsylvanian-Cretaceous contact made mapping the Cretaceous edge difficult in many areas. Dakota strata are known to reach thicknesses in excess of 100 feet (30 m) in most counties of the map area, and thicknesses up to 200 feet (60 m) are inferred in parts of Carroll County.

The Dakota Formation, Nishnabotna Member, is dominated by fine-grained sandstone (quartzarenite) in the map area, but coarse-grained and pebbly sandstones also occur. Quartz/chert gravels and conglomerates are locally well developed in the lower part, and these have been utilized locally as an important aggregate resource (especially in Montgomery County). The sandstones and conglomerates are commonly cemented by iron oxides on exposure, forming resistant ledges. However, many exposures (and most well penetrations) of the Dakota sandstones are poorly consolidated. Mudstones also occur within the Dakota Formation of the map area, but these typically are subordinate to the sandstones. The mudstones are kaolinitic and often pale gray to red in color; some mudstones contain small pellets of sphaerosiderite (paleosol fabrics).

Surface exposures of Dakota strata are recognized in Carroll, Pottawattamie, Cass, Montgomery, Adams, and Mills counties, and numerous well penetrations constrain the widespread extent of the Dakota Formation in the map area. A number of previously unrecognized exposures of Dakota strata were identified during the course of this mapping project. The most significant of these new exposures for the construction of the bedrock geologic map include the first Cretaceous exposures noted in the Missouri River Valley of southwest Iowa (ditch-side exposure NE SW NE SE SW sec. 17, T73N, R43W; ditch near West Oak Forest Park entrance NW SW SW SE sec. 32, T73N, R43W, Mills Co.). The identification of Cretaceous strata in northwest Mills and southwest Pottawattamie counties coordinates nicely with the mapping of a deep westward-draining sub-Cretaceous paleovalley in southeast Nebraska

(Douglas-Sarpy counties), where basal Cretaceous strata are recognized at elevations of about 270-310 m (885-1016 ft)(see Joeckel et al., 2003), comparable to elevations of Cretaceous strata in nearby Iowa. This Cretaceous-filled paleovalley logically trends eastward from Nebraska into adjoining Iowa.

The Dakota Formation serves as an important source of groundwater in southwest Iowa (the Dakota aquifer), primarily for farm and residential use. In addition, the Dakota aquifer is used as a municipal water source for a number of communities in Cass, Pottawattamie, and Montgomery counties (Hansen et al., 1992). Because of its importance as a regional aquifer, the recognition that Dakota strata are significantly more widespread in southwest Iowa than previously interpreted is of potential societal and economic importance to the region.

Recognition of Dakota Sandstone

The new bedrock map of southwest Iowa identifies significantly more area underlain by the Dakota Formation than recognized in any previous map or report. The notable expansion of the Dakota Formation in southwest Iowa shown on the new map differs dramatically from the statements of Hansen et al. (1992, p. 2), who instead proposed further constricting the Dakota distribution over that shown by Hershey (1969) and others:

> "The extent of the Dakota aquifer, as shown in figure 17 [where they show the Dakota to be of relatively limited extent in southwest Iowa], is different than previously published maps of the Cretaceous rocks in southwest Iowa (Hershey and others, 1960; Hershey, 1969; Witzke and Ludvigson, 1982). Presently (1991) available information indicates that the Dakota aquifer is more dissected and restricted than previously mapped. Interpretation of its extent is difficult because there are many driller's logs that do not distinguish sand from sandstone . . . "

Considering the potential importance of the Dakota Formation's distribution to the region, the diametrically opposed mapping conclusion of Hansen et al. (1992) versus those of the new map deserves comment. 1) It is apparent from their mapped distribution as well as their statement above that Hansen et al. (1992) did not identify Dakota strata from many, if any, driller's logs. Because of the poorly consolidated nature of most Dakota sandstones, it is probable that many Dakota Formation penetrations are identified as "sand" on driller's logs, as they recognized. However, these logs need to examined on a case-by-case basis, and should not automatically be excluded from consideration as a Dakota well point. 2) Hansen et al. (1992) apparently excluded some logs at the Iowa Geological Survey in which the sample logger tentatively identified Dakota strata. In addition, many well sample logs (strip logs) prepared after 1991 recognize Dakota strata in areas that lack them on the Hansen et al. (1992) map. 3) Newly-identified Dakota exposures, especially in Mills County, are shown by Hansen et al. (1992) to occur in areas lacking Cretaceous strata. In general, the discrepencies between the Hansen et al. (1992) map and the current bedrock map result from several factors: utility of driller's logs, incorporation of new data, and identification of areas of elevated bedrock topography.

The new map extensively utilized driller's logs (that lack samples) in some areas of southwest Iowa, and a set of criteria were used to interpret whether or not these logs include reasonable reference to the Dakota Formation. A combination of these criteria were used to provide a rationale in our intepretations of Cretaceous bedrock from driller's logs. 1) Dakota sandstones are potentially considered where the driller reports "sandstone" or "hard" sand; generally yellow or white. All varicolored and salt-and-pepper sands were excluded from the Cretaceous. 2) Dakota sand or sandstone is dominantly "fine" or "very fine"; some coarse and conglomeratic sand can exist especially in the basal part. Thick intervals of coarse sand and "sand & gravel" were not included in the Cretaceous. 3) Some Dakota sandstones contain intervals of "rusty" cement or hard "red" or "brown" cements. We generally excluded calcite-cemented sands and calcareous sands from the Cretaceous. 4) The Dakota Formation can contain thin intervals or interbeds of “white” or “pink” clay or shale. Thick intervals of gray or brown “clay” were excluded from the Cretaceous. 5) Cretaceous strata must consistently overlie Pennsylvanian bedrock in southwest Iowa (Pennsylvanian strata identified on driller’s logs as “limestone,” “coal,” or dark gray to black “shale”). No intervening glacial deposits (till) can occur between the Pennsylvanian and Cretaceous. 6) Cretaceous strata potentially identified on driller’s logs must be consistent with the elevations and descriptions of Dakota lithologies in nearby well logs.

PENNSYLVANIAN STRATIGRAPHY

Introduction

Pennsylvanian strata form the bedrock surface over much of southwest Iowa. The Pennsylvanian stratigraphic succession of southwest Iowa occupies the northern part of the Forest City Basin, a structural basin that occupies part of a broad depositional region known as the Northern Midcontinent Shelf within the vast Midcontinent Basin (Heckel, 1999). Pennsylvanian strata in this region overlie a major erosional unconformity developed on the underlying Mississippian carbonate-dominated succession. It is now recognized that most lithologic units in the Pennsylvanian of the Midcontinent were deposited in various marine and non-marine environments that resulted from glacial-eustatic rise and fall of sea level (Heckel, 1994). These cycles of marine transgression and regression are termed cyclothems, which in southwest Iowa are disconformably bounded at surfaces of subaerial exposure (commonly expressed by paleosol development and pedogenic alteration, and locally by fluvial incision).

Interpretations of the magnitude and depth of marine transgression onto the Midcontinent Shelf constrain three general categories of cyclothems (Heckel, 1999,2001a). Major cyclothems are characterized by the development of widespread conodont-rich phosphatic black shale facies (representing the deepest depositional environments of the Iowa Pennsylvanian) sandwiched between a thin transgressive limestone and a thicker regressive (shallowing-upward) limestone interval. Intermediate cyclothems lack the phosphatic black shale interval, but include widespread marine shale and limestone facies. Minor cylothems record smaller-scale changes in sea level, usually marked by relatively thin intervals of nearshore shale and/or shallow-water to coated-grain limestone facies. Regressive limestone intervals commonly shallow upward from subtidal open-marine facies to shoal and tidal-flat facies. Nearshore to nonmarine siliciclastic facies commonly were deposited during episodes of falling sea level and seaway withdrawal (these are termed “outside shales”; Heckel, 2001b).

The Pennsylvanian succession in southwest Iowa spans most of the Middle and Upper Pennsylvanian, including the Atokan (and possibly upper Morrowan), Desmoinesian, Missourian, and much of the Virgilian. This succession reaches thicknesses in excess of 1800 feet (550 m) in southwest Iowa. The Pennsylvanian bedrock of southwest Iowa is mapped at the group level. Each lithostratigraphic Group includes a series of formations (see nomenclature of Ravn et al., 1984), but each formation is constrained using different criteria depending on which part of the succession is being considered. Four formations within the Cherokee Group, the oldest of these groups (Atokan-Desmoinesian), are subdivided at the base of certain widespread coals (ibid.), and each of these formations includes multiple cyclothems (most are minor to intermediate cycles). By contrast, the Marmaton, Bronson, Kansas City, and Lansing groups (upper Desmoinesian and Missourian) are subdivided into a series of formations that, with some exceptions, each correspond to a portion of a single marine cyclothem. While this is, in part, an over-generalization, the marine limestone part of each cyclothem (which also includes offshore shale facies) typically forms a formation (with transgressive limestone, “core” shale, and regressive limestone intervals each given member status). Siliciclastic-dominated intervals (which include nearshore shales, nonmarine/fluvial mudstones and sandstones, and paleosol intervals deposited during marine regression and withdrawal) above and between these limestone formations generally are accorded formational status, as well.

Virgilian formations of the Douglas, Shawnee, and Wabaunsee groups do not follow the Missourian pattern, where instead limestone- and shale-dominated intervals have been arbitrarily grouped together into a series of formations. With some exceptions, many of these formations contain two or three marine cyclothems, and one formation includes four cyclothems (Topeka Formation). Many individual marine limestone units, which represent intermediate marine cyclothems, have been given member names within these formations. However, within parts of the Douglas and Shawnee groups, a few major marine cyclothems include member subdivisions analogous to those used in the Missourian. No attempt is made here to reformulate and re-define the Virgilian lithostratigraphy of southwest Iowa, which largely follows the existing lithostratigraphic nomenclature developed in Nebraska and Kansas. However, it is recommended that an allostratigraphic (genetic) framework based on cyclothems will provide a better basis for regional correlation of Virgilian strata than the existing lithostratigraphic scheme (see cyclothemic subdivisions of Heckel, 1999; Boardman, 1999).

Wabaunsee Group

The Wabaunsee Group, whose name derives from Wabaunsee County, Kansas, is an upper Virgilian shale- and mudstone-dominated interval in southwest Iowa. It is largely restricted to the area south of the Thurman-Redfield Structural Zone in Iowa, although basal Wabaunsee strata occur in the Missouri River bluffs north of Thurman. Wabaunsee exposures are relatively limited in southwest Iowa, and are best seen in the area around Hamburg and Thurman (Fremont Co.), the Tarkio River drainage (southern Montgomery and Page counties), West Nodaway River drainage (near Clarinda and Braddyville, southeast Page Co.), the Dickieville area (along the Montgomery-Adams Co. line), the Carbon area (Adams Co.), and the Hawleyville area (Page-Taylor Co. line). The Wabaunsee Group reaches thicknesses up to 320 ft (98 m) in Fremont County, but the stratigraphically highest Wabaunsee strata are erosionally removed in Iowa (highest recognized units in Iowa are assigned to the Root Shale, one and a half formations and nine members below the top of the Wabaunsee Group in nearby Nebraska and Kansas). The dominant Wabaunsee facies in Iowa are siliciclastic, including 1) marginal-marine shale facies, commonly with rich bivalve-dominated faunas; 2) silt-laminated mudstone and shale, part ripple-laminated, with scattered burrows or plant fossils; 3) pedogenic mudstones, commonly containing calcareous nodules, part hard-cemented or red-brown mottled; and 4) siltstone, locally with minor interbedded sandstone. These siliciclastic facies were deposited in a range of marginal-marine, nearshore, tidal-flat/estuarine, and nonmarine (soil-forming) environments.

The Wabaunsee Group is subdivided into a series of intermediate and minor cyclothems (Boardman, 1999), most of which display relatively thin limestone units deposited during maximum marine transgression. These limestone units, generally less than 5 feet (1.5 m) thick, are widely traceable, and most have been defined as members within the Wabaunsee Group. These limestone facies variably display skeletal mudstone to packstone fabrics, commonly with brachiopods, bryozoans, crinoid debris, and molluscan grains, and some beds contain common to abundant fusulinids. Many limestone units contain intervals with algal-coated grains ("*Osagia* calcarenite"). A single major cyclothem is identified at the base of the Wabaunsee Group, Howard Formation, which includes a thin transgressive limestone (Wauneta), a black phosphatic conodont-rich "core shale" (upper Aarde), and a thicker regressive limestone (Church Ls.).

Most Wabaunsee cyclothems in Iowa show similar depositional patterns, in ascending order: 1) basal fossiliferous limestone, 2) marginal-marine shale unit with bivalve faunas, 3) silt-laminated shale and siltstone (usually the dominant facies), and 4) a capping pedogenic mudstone (paleosol). In some cyclothems a transgressive shale unit (with bivalve faunas) is recognized below the limestone. The pedogenic facies are calcareous to varying degrees, and several pedogenic mudstones in the middle part of the Wabaunsee succession are mottled to pervaded with prominent red, red-brown, or maroon colors (Wamego, Willard, upper Auburn, and upper Soldier Creek shales). Some Wabaunsee cyclothems in Iowa are marked by coal beds or coaly (carbonaceous) shales at their base including 1) the widespread Nyman Coal (below the Dover Limestone), 2) an unnamed coaly unit locally below the Reading Limestone, 3) an unnamed coaly unit locally in the upper Soldier Creek Shale, 4) an unnamed carbonaceous shale in the middle Cedar Vale Shale, and 5) a locally prominent coal below the Rulo marine horizon.

Stratigraphic studies of the Wabaunsee succession in southwest Iowa undertaken for this mapping project (Witzke, 2003) have recognized most of the cyclothems delineated by Boardman (1999) in the Kansas and Nebraska succession. However, two additional minor cyclothems are provisionally identified in the Iowa Wabaunsee succession that were not noted by Boardman (1999). These include 1) a carbonaceous to fossiliferous shale (linguloids, bivalves, burrows) above a rooted to nodular pedogenic horizon about two-thirds of the way up through the Soldier Creek Shale (this minor cyclothem is capped by the prominent pedogenic mudstone at the top of the Soldier Creek Shale); and 2) an unnamed thin limestone (with brachiopods, crinoid debris, bivalves) and overlying burrowed shale in the middle Cedar Vale Shale, which occurs above a thin carbonaceous shale and underclay. Three minor Wabaunsee cyclothems of Boardman (1999) were not recognized in Iowa, probably because these marine incursions did not reach as far north as Iowa (Wamego, Silver Lake, and upper White Cloud cyclothems not identified).

Shawnee Group

The Shawnee Group (Virgilian) is a succession of limestone and shale strata reaching full thicknesses of 190 to 220 feet (58-67 m) in southwest Iowa. Its name derives from the type exposures in Shawnee County, Kansas. In contrast to the siliciclastic-dominated Wabaunsee Group, the underlying Shawnee Group is a limestone-rich interval in southwest Iowa (approximately 50% of the interval is limestone). Prominent limestone units have been and are extensively quarried for aggregate resources in the map area, especially the thick limestone intervals in the Oread and Deer Creek formations (primarily the Plattsmouth and Ervine Creek members). Additional limestone units in the Shawnee Group also serve as important aggregate sources locally, especially within the Lecompton and Topeka formations. Natural exposures and quarries (both active and abandoned) of Shawnee Group strata are seen at a number of localities in southwest Iowa, including: 1) Missouri River Valley, Folsom and Burr Oak areas (Mills Co.), area north of Thurman (Fremont Co.); 2) West Nishnabotna drainage, Tabor and Malvern areas (Mills Co.), Silver City quarry and Macedonia area (Pottawattamie Co.); 3) East Nishnabotna drainage, Stennett and Red Oak areas (Montgomery Co.), Lewis area (Cass Co.); 4) West Nodaway drainage, Grant area (Montgomery-Cass cos.), Clarinda area (Page Co.); 5) East Nodaway drainage, Mt. Etna and Corning areas (Adams Co.), Hawleyville area (Page-Taylor Co. line), Braddyville area (Page Co.); and 6) 102-River drainage, Bedford area (Taylor Co.).

Cyclothems are prominently developed in the Shawnee Group of southwest Iowa, including four major cyclothems (with phosphatic black “core” shales), five or six intermediate cyclothems, and one or two minor cyclothems. Each major cyclothem in the Shawnee Group (upper Topeka, upper Deer Creek, Lecompton, Oread cyclothems of Boardman, 1999) is developed above a paleosol or subaerial exposure surface, with a succession of facies, in ascending order: 1) a transgressive nearshore to marine shale, usually thin; 2) a thin transgressive limestone unit; 3) a “core” shale interval containing dark-gray shale (part fossiliferous) and conodont-rich phosphatic black shale (phosphatic laminae and/or nodules); 4) a relatively thick regressive limestone succession that includes fossiliferous mudstones to packstones (part fusulinid-rich), argillaceous to shaly interbeds, nodular to bedded cherts locally, algal-coated and *Osagia* calcarenites (especially upward); 5) nearshore-marine bivalve-bearing to silt-laminated shales (absent in Deer Creek cyclothem); and 6) development of paleosol mudstones and limestone “rubble”/breccia units (subaerial-weathering and pedogenic processes). This general pattern is repeated in each major Shawnee cyclothem, but additional complexities are noted in the Deer Creek and Oread.

The Deer Creek cyclothem shows a typical basal transgressive limestone (the Rock Bluff Ls.) overlain by a black shale (Larsh Sh.), but this is, in turn overlain by additional limestone and black shale units below the regressive Ervine Creek Limestone. In particular, the thin Haynies Limestone, which resembles a transgressive limestone, overlies the Larsh Shale and underlies another phosphatic black shale (the Burroak Sh.). In addition, above the Burroak Shale, a limestone bed (which also resembles a transgressive limestone) is overlain by an additional thin black shale bed at most Iowa localities. The apparent "triplet" of limestone-black shale couplets in the lower Deer Creek cyclothem suggests a relatively complex transgressive succession, and each couplet might be considered a smaller-order cyclic unit within the larger cyclothem. Overlying strata of the Ervine Creek Limestone constrain a more "normal" regressive limestone succession, in which skeletal and fusulinid-rich limestones (locally cherty) shallow-upward into algal-coated and *Osagia* calcarenites with a prominent "rubble" zone at the top.

The Oread cyclothem shows a more "normal" transgressive limestone (Leavenworth Ls.) and "core" black shale (Heebner Sh.) succession, above nearshore-marine shales of the upper Snyderville Shale. The overlying Plattsmouth Limestone is dominated by skeletal and fusulinid-rich limestone beds (locally cherty) not unlike lithologies seen in the regressive Ervine Creek Limestone. However, the Plattsmouth succession is not capped by a regressive shale or "rubble" zone, but is, instead, overlain by an additional interval of shaly limetone and limestone strata (skeletal and fusulinid-rich to algal-coated) in Iowa. These strata likely correlate with the Kereford Limestone in Kansas (see Hershey et al., 1960), which Boardman (1999) considered to be an intermediate cyclothem (Kereford cyclothem) separate from the underlying Oread cyclothem. In Iowa, it is difficult to separate the lithologically-similar Plattsmouth and "Kereford" intervals, although a thin shaly limestone to shale unit in Iowa likely marks the position of the Heumader Shale of Kansas (which includes the maximum-transgressive deposits of the Kereford cyclothem). Maximum regression is marked by a "rubble"/breccia zone at the top of the "Kereford" with paleosol mudstones in the overlying lower Jackson Park Shale, but no exposure surface or paleosol is seen to separate the Plattsmouth and "Kereford" intervals in Iowa. In Iowa, therefore, it may be better to consider the "Kereford" as a smaller-scale cycle within the larger Oread cyclothem, as marine deposition continued across the Plattsmouth-"Kereford" boundary in southwest Iowa. All other Virgilian intermediate cyclothems of Boardman (1999) display evidence of subaerial exposure and paleosol development across southwest Iowa during maximum regression.

A number of intermediate cylothems are well displayed in the Shawnee Group of southwest Iowa, and each is marked by fossiliferous to algal/coated-grain limestone beds below and by an interval of nearshore-marine shale to pedogenic mudstone above. Black shales are absent in the intermediate cyclothems. Except for the Avoca cyclothem, each intermediate Shawnee cylothem forms a relatively thin interval only 5 to 20 feet (1.5-6 m) thick. The Avoca cyclothem in Iowa contains a relatively thick (up to 35 ft; 11 m) regressive marine to nonmarine shale (Tecumseh Shale). The Sheldon minor cyclothem of Boardman (1999) comprises the thin Sheldon Limestone (dominated by *Osagia* calcarenite) and overlying lower Turner Creek Shale (with calcareous paleosol) in Iowa. Erosional incision must have accompanied the maximum regressive phases of some cyclothems, as the Sheldon cyclothem is erosionally absent in the Riverton core (Fremont Co.), where strata of the upper Topeka major cyclothem directly overlie stata of the Curzon intermediate cyclothem. The Ost minor cyclothem of Boardman (1999) was not identified in Iowa.

One or two additional minor cyclothems not recognized in Boardman's (1999) synthesis may occur within the Shawnee Group of Iowa. The Calhoun Shale overlies the "rubbly" weathered zone at the top of the Ervine Creek Limestone everywhere in southwest Iowa, and at most localities, the bulk of the Calhoun Shale represents the transgressive marine shale of the Hartford cyclothem. However, a thicker Calhoun Shale in the Riverton core (Fremont Co.) contains an additional 9-foot (2.7 m) thick cyclic succession with marine shale (brachiopods, bivalves) at the base, overlain by silt-laminated mudstone and capped by a paleosol. This succession may record a complex step-wise transgression of the Hartford cyclothem, or, alternatively, it could be considered an additional minor cyclothem within the Shawnee Group. Likewise, an even less developed succession in the upper Oskaloosa Shale could represent part of a minor cyclothem. Above the prominent lower Oskaloosa paleosol, the Riverton core (Fremont Co.) shows a 10-foot (3 m) thick succession of laminated shale capped by a paleosol), and a similar succession in the Bedfrod core (Taylor Co.) is capped by a coal smut (probably the transgressive coal of the succeeding cyclothem).

A prominent and historically important coal bed (Nodaway Coal) occurs near the top of the Shawnee Group (which marks the base of the overlying Howard cyclothem). The Nodaway Coal was extensively mined in areas of southwest Iowa, and represents the primary coal resource in the region. Additional coaly beds in the Shawnee succession include an unnamed coal smut in the upper Oskaloosa Shale, and a widespread unnamed coal to coaly shale in the middle Jackson Park Shale (base of Clay Creek cyclothem). Unlike the Wabaunsee and Douglas groups, the Shawnee Group generally lacks red mudstones (paleosols), although red-brown mottling is locally seen in the lower Snyderville Shale near Lewis (Cass Co.).

Douglas Group

The Douglas Group apparently is nowhere exposed in southwest Iowa, but minor exposures are noted eastward in the south-central map area (Pope et al., 2002; Hershey et al., 1960). Nevertheless, the Douglas succession in southwest Iowa is well displayed in a number of bedrock cores (Malvern, Red Oak, Grant, Riverton, Bedford) and numerous well penetrations. Strata of theDouglas Group form the bedrock surface over large areas of Adams, Taylor, Montgomery, Pottawattamie, Cass, and Mills counties, where it reaches thicknesses of 90 to 135 feet (27-41 m). The Douglas Group is named for type exposures in Douglas County, northeast Kansas. In contrast to the limestone-rich to limestone-dominated Shawnee, Lansing, Kansas City and Bronson groups, the Douglas Group is overwhelmingly dominated by shale and mudstone. In many respects, the dominant lithologies of the Douglas Group in southwest Iowa resemble those seen in the younger Wabaunsee Group, including bivalve-bearing nearshore-marine shale, silt-laminated shale and mudstone (locally with siltstone and sandstone), minor limestone, minor coal, and prominent paleosols (especially red-brown). The top of Douglas Group (upper Lawrence Fm.) is marked by a widespread and prominent thick (8-16 ft; 2.4-4/9 m) red to red-brown paleosol. A thin red-mottled paleosol occurs in the mid Lawrence Formation, a prominent red-brown to red-mottled paleosol (9-13 ft; 2.7-4 m thick) is seen in the lower Douglas Group ("Stranger" Shale), and a thin red-mottled paleosol is locally noted in the basal Douglas Group (Weston Shale).

The Missourian-Virgilian boundary is now drawn within the lower Douglas Group, at the position of the Haskell Member of the Cass Formation (Heckel and Watney, 2002). The Douglas succession has been subdivided into a series of cyclothems by Heckel (1999) and Boardman (1999), based largely on the Kansas section. Most of these cyclothems are identified in the Douglas Group of southwest Iowa, in ascending order, the intermediate Iatan cyclothem, the major Cass cyclothem (which contains the black phosphatic Little Pawnee Shale), and the minor Amazonia cyclothem. The Amazonia cyclothem is marked above the widespread "Williamsburg Coal" by a fossiliferous bivalve-rich shale, locally with thin limestone shell beds or limestone septaria, and capped by a relatively thin paleosol. The minor Westphalia cyclothem of Heckel (1999) has not been identified in Iowa. However, two previously unrecognized minor cyclothems may be represented in the Douglas Group of southwest Iowa. A thin unnamed marine interval of limestone (part with coated-grains) and fossiliferous shale occurs in the upper Lawrence Formation above the Amazonia cyclothem and below the prominent red paleosol at the top of the Douglas Group (noted in Mills, Montgomery, and Fremont counties). An additional unnamed marine interval containing limestone (skeletal to *Osagia*-rich) and bivalve-rich shale is seen in the lower Lawrence Formation of Montgomery County. While this interval could be interpreted as a minor cyclothem, it instead may mark a secondary transgressive phase within the upper part of the Cass cyclothem (a paleosol does not separate it from underlying Cass strata).

Lansing, Kansas City, and Bronson Groups

Missourian strata of the Lansing, Kansas City, and Bronson groups form a limestone-dominated succession in southwest Iowa containing six major and five intermediate cyclothems. Stratigraphic units within this interval are regionally persistent across southwest Iowa, and the general stratigraphic and cyclothemic succession is adequately presented by Pope et al. (2002) and Heckel and Watney (2002) and need not be reiterated here. These three groups show minor thickness variations in the area: Bronson Group 100-130 feet (30-40 m), Kansas City Group 100-140 ft (30-43 m), and Lansing Group 45-78 ft (14-24 m). Basal Missourian strata in southwest Iowa were at one time included within the "Pleasanton Group," but this relatively thin interval of basal clastic-rich strata was re-classified as the Pleasanton Formation within the basal Bronson Group in Iowa (Ravn et al., 1984). Although the Pleasanton interval previously was considered to be a lower Missourian unit, the newly-proposed Desmoinesian-Missourian Stage boundary occurs within the Pleasanton succession, and is drawn at the base of the Exline Limestone (Heckel, 1999; Heckel and Watney, 2002).

Exposures of Missourian strata in southwest Iowa are relatively limited, restricted to portions of Harrison, Pottawattamie, and Cass counties. Quarries and scattered exposures along the Boyer River drainage near Logan, Harrison County, expose limestone strata of the Dennis and Swope formations, upper Bronson Group. The quarry at the base of the Missouri River bluffs near Crescent City, Pottawattamie County, exposes strata of the upper Bronson and lower Kansas City groups in the Dennis, Cherryvale, and Dewey formations. The Crescent City quarry is remarkable for the thick section of Quaternary materials (greater than 100 ft; 30 m) that must be stripped to reach the limestone beds at the base of the bluff. An abandoned quarry and small exposures are located in the Mosquito Creek drainage along the eastern edge of Council Bluffs, Pottawattamie County; these exposures are included in the Kansas City Group, likely the Iola and Wyandotte formations. Quarry and mining operations at Atlantic, Cass County, primarily extract aggregate from the thick limestones of the Bronson Group (Swope and Dennis formations), but exposures of lower Kansas City strata (Cherryvale Formation) occur above.

Marmaton Group

Although the Marmaton Group (Middle Pennsylvanian, upper Desmoinesian) forms the bedrock surface across large areas in the northern half of the map area (Monona, Crawford, Carroll, Harrison, Shelby, Audubon, Pottawattamie counties), no surface exposures of Marmaton strata are known in this region. The primary reference section for the Marmaton Group in the southwest map area is a core hole drilled by the Iowa Geological Survey in 1981 near Logan, Harrison County (W-26516), and permanently archived at the Survey's Oakdale facility. The complete Marmaton Group is 148 feet (45 m) thick in the Logan core, and the group varies between 125 and 170 feet (38-52 m) in thickness across the map area. The stratigraphic nomenclature of the Marmaton Group in the southwest Iowa map area follows that established by Ravn et al. (1984) and Pope et al. (2002) for south-central Iowa, and need not be reiterated here. The Marmaton Group includes a succession of limestone units (all less than 5 feet thick; 1.5 m) separated by thicker siliciclastic intervals (shale, mudstone, sandstone). The upper Marmaton interval is dominated by prominent and thick red paleosol units in western Iowa (lower and upper Bandera Shale, Nowata-Memorial Shale). Coals and carbonaceous shales occur at several positions within the Marmaton succession.

The Marmaton Group can be subdivided into a series of intermediate and major cyclothems in western Iowa. Black phosphatic shales mark major cyclothems in the basal (Excello Shale, Mouse Creek Fm.) and lower (Anna Shale, lower Pawnee Fm) Marmaton Group in the Logan core. Intermediate cyclothems that include fossiliferous marine shale to skeletal limestone facies and capped by mudstone paleosols are identified in the Logan core in the Stephens Forest Formation, upper Pawnee Formation (Coal City Limestone), mid Bandera Shale (Farlington bed), Altamont Formation, and Lost Branch Formation. Minor Marmaton cyclothems seen in Kansas within the Higginsville Limestone and Lenapah Formation (Heckel, 1999) are not clearly identified in the Logan core succession.

Cherokee Group

The Cherokee Group (Atokan-Desmoinesian) is a thick siliciclastic-dominated succession that unerlies almost all of the map area. Like the overlying Marmaton Group, strata of the Cherokee Group form the bedrock surface over large areas in the northern map area, but surface exposures of Cherokee strata are absent. The primary reference section of the Cherokee Group for the map area is the Logan core (Harrison Co.), where the complete Cherokee succession is 349 feet (106 m) thick. This thickness is characteristic across the area of Cherokee subcrop in the northern map area, where complete penetrations of the Cherokee Group range between about 300 and 400 feet (90-120 m) thick. However, farther south in the map area, where the Cherokee Group is entirely covered by younger Pennsylvanian strata, Cherokee penetrations vary between about 100 and 750 feet (30-230 m) thick. These major thickness variations likely reflect active southward subsidence of the Forest City Basin and fault movements along the Thurman-Redfield Zone during Cherokee deposition.

The Cherokee Group has been subdividied into four formations (Ravn et al., 1984) in south-central Iowa, in ascending order, Kilbourn, Kalo, Floris, and Swede Hollow. The Swede Hollow Formation is widely recognizable in well cuttings logs across much of the southwest map area, as its lower boundary is drawn at the base of the distinctive Oakley black shale-Ardmore (double) limestone interval (and above the widespread Whitebreast Coal). The lower three Cherokee formations, however, are not readily distinguishable on well logs from western Iowa. The Cherokee Group of western Iowa is dominated by dark-gray to black shale and mudstone, but sandstone is common to locally dominant. Most sandstones are very fine- to medium-grained, but coarse-grained sandstones locally occur in the lower 100 feet (30 m) or so of the Cherokee Group. The upper Cherokee interval (upper Floris, Swede Hollow formations) contains red to red-mottled mudstone paleosols, but gray mudstones dominate in the lower Cherokee. Multiple coal horizons and carbonaceous mudstones occur in the Cherokee succession, and some coal beds locally reach thicknesses in excess of 5 feet (1.5 m). Thin marine limestone beds also occur within the Cherokee Group. The most prominent and widespread limestone and phosphatic black shale package, as noted above, is the Oakley-Ardmore interval in the lower Swede Hollow Formation (base generally about 70 to 90 feet [21-27 m] below the top of the Cherokee Group in western Iowa). This marine interval marks the major Verdigris cyclothem, the most widespread and well defined of all Cherokee cyclothems.

Additional minor and intermediate cyclothems occur within the Cherokee succession, but the correlation and definition of the many marine horizons have not yet been worked out in full detail for Iowa. Marine-influenced depositional facies in the Cherokee Group include: 1) skeletal limestone (espcially fine-skeletal to brachiopodal mudstone and wackestone); 2) skeletal lenses/shell beds (crinoidal or brachiopodal), 3) gray to black shale (part with bivalves, linguloids, and/or orbiculoids), and 4) laminated mudstone to sandstone with scattered burrow mottles. The latter facies locally displays ripple laminae and tidal bundles, and these facies were likely deposited in nearshore and estuarine settings. Some sandstone units may also represent estuarine channel fills. Fossiliferous marine shale and limestone units are recognized in the Cherokee Group of the Logan core in the mid Swede Hollow Fm. (post-Bevier marine unit), basal Swede Hollow (Oakley-Ardmore), upper Floris Formation (above Carruthers Mbr.), and the mid Floris Formation (two marine units within the Carruthers Mbr.). Burrowed estuarine or nearshore facies are noted in the lower Floris Formation (Laddsdale Member) and probably within the Kilbourn Formation.

MISSISSIPPIAN STRATA

Mississippian strata underlie the entire southwest Iowa map area, but only small areas of Mississippian rock are interpreted to form the bedrock surface within four buried bedrock channels in northern Monona and Crawford counties (including the Fremont Channel). These Mississippian windows are entirely an artifact of the bedrock topographic construction, as no well penetrations verify Mississippian rock at the bedrock surface within these buried valleys. Nevertheless, the elevation of the sub-Pennsylvanian Mississippian surface is constrained in nearby wells, intercepting elevations within these bedrock channels. A large regional unconformity separates Mississippian and Pennsylvanian strata across Iowa, and significant erosional relief (locally in excess of 100 ft; 30 m) is developed in the map area. In Monona and Harrison counties, Pennsylvanian strata directly overlie the Mississippian Augusta Group, but in northern Crawford County the Pennsylvanian locally overlies higher Mississippian strata of the "St. Louis" Formation.

The so-called "St. Louis" Formation in Iowa is not a lithostratigraphic or biostratigraphic equivalent of the St. Louis Formation in its type area, but, at present, no replacement stratigraphic name has been proposed for this interval in Iowa (Witzke and Bunker, 2001). The "St. Louis"”interval in western Iowa is characterized by dolomite, limestone, and sandstone, and the carbonate rocks are sandy in part. In adjoining map areas, the Meramecian "St. Louis" and Pella formations have been combined into a single map unit (Msp). However, the stratigraphically-highest Mississippian unit in Iowa, the Pella, has not been confirmed to occur in the northern area of the southwest Iowa map, where the map unit likely only includes the "St. Louis" Formation. The "St. Louis" disconformably overlies the Augusta Group with some erosional relief.

The Augusta Group in the southwest Iowa map area includes the Osagean succession of dolomite, cherty dolomite, and fossiliferous limestone strata above the Gilmore City Formation (see Witzke and Bunker, 2001). Because upper Augusta strata are locally beveled and eroded beneath the Pennsylvanian, the thickness of the Augusta Group varies significantly in the map area (135-240 ft; 41-73 m). Although correlation of the Augusta Group has not been verified for western Iowa, it is likely that these strata correlate with the Keokuk and Warsaw formations of southeast Iowa (Witzke and Bunker, 2001). The Osagean Burlington Formation of southeast Iowa may correlate with part of the Gilmore City Formation of northern and western Iowa, although the Gilmore City interval is of upper Kinderhookian age at its base (ibid.). The Gilmore City interval is characterized by fossiliferous to coated-grain and oolitic limestones. The Gilmore City Formation is interpreted to occur at the bedrock surface in a small area within the buried bedrock valley associated the Missouri Valley incision in Monona County. This map construction was driven entirely by the bedrock topography and not by actual well penetrations.

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