A summary of the stratigraphy and depositional environments of Jurassic and related rocks in the San Juan Basin, Arizona, Colorado, and New Mexico

Morris W. Green and C. T. Pierson, 1977, pp. 147-152

in:

San Juan Basin III (northwestern New Mexico), Fassett, J. F.; James, H. L.; [eds.], New Mexico Geological Society 28th Annual Fall Field Conference Guidebook, 319 p.

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A SUMMARY OF THE STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF JURASSIC AND RELATED ROCKS IN THE SAN JUAN BASIN, ARIZONA, COLORADO AND NEW MEXICO

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INTRODUCTION

In 1950, just prior to the first New Mexico Geological Society field conference in the San Juan Basin, Paddy Martinez, a Navajo prospector, discovered uranium in Jurassic rocks near Grants, New Mexico (Melancon, 1963). This discovery on the southern margin of the basin led to the development of one of the world's most productive uranium regions, now known as the Grants mineral belt. With the exception of small uranium deposits in rocks of Cretaceous age, all uranium production in the mineral belt and elsewhere in the basin is from strata of Late Jurassic age. The uranium development in the San Juan Basin and the geology of the Grants region are discussed in reports by Hilpert (1969), Kelley (1963a) and Trauger (1967).

An intense scientific and economic interest in the stratigraphy of Jurassic rocks of the Colorado Plateau was created by the initial discoveries and subsequent mining of uranium during the "boom" of the 1950's. Government, industry and many private individuals actively participated in or sponsored numerous uranium-related stratigraphic investigations. Because of today's growing energy shortage, scientific investigations and uranium-prospecting activity are continuing in Jurassic rocks throughout the Colorado Plateau, because they still are considered to be the most favorable host rocks for yet undiscovered deposits of high-grade uranium ore.

Prior to the atomic age, Paleozoic and Mesozoic redbeds of the Colorado Plateau were studied by a number of geologists, beginning in 1853 with Jules Marcou, a member of the Whipple Railroad Expedition (Ash, 1972). The work on redbeds, prompted in part by the spectacular outcrops, bright red colors and eye-catching sedimentary structures displayed in the canyon lands, was done at first as part of the reconnaissance of new railroad routes. Later efforts were the result of growing academic interest in stratigraphy.

Prior to 1940, some of the more important papers on redbed stratigraphy were written by the following authors: Dutton (1885), Cross and Larsen (1915), Gilluly and Reeside (1928), Gregory and Moore (1931), Baker and others (1936) and Gregory (1938).

This report is a brief summary of the stratigraphy of Jurassic and related rocks within the San Juan Basin. Also included are summary descriptions of the inferred ancient depositional environments for the sequence in the basin.

GENERAL GEOLOGY

Jurassic rocks crop out along the margins of the major uplifts which form the boundaries of the San Juan Basin (fig. 1). These structural features are described in detail by Kelley (1951, 1955, 1963a, b and 1967). Sedimentary rocks of continental, marginal-marine and deep-marine origin that fill the San Juan Basin are about 3,600 meters thick. They range in age from Paleozoic through Cenozoic. In general, these rocks dip gently basinward at 2° to 5° away from the flanks of the marginal uplifts. Jurassic rocks lie buried beneath Cretaceous and Tertiary formations over most of the basin, at depths to as much as about 2,500 meters in the central part.

Jurassic rocks vary in thickness from 0 meters a short distance south of the San Juan Basin to over 450 meters in the west-northwest part of the basin. South of the Zuni uplift, an erosion surface at the base of the Dakota Sandstone of Early(?) and Late Cretaceous age truncates the entire Jurassic sequence.

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS

Jurassic rocks are dominantly interlayered redbeds consisting of crossbedded sandstone and structureless, flatbedded siltstone. Lesser amounts of claystone, limestone and gypsum are also present. Lithofacies relationships and primary sedimentary structure in stratigraphic sections that crop out around the basin margins indicate that the sequence was deposited in fluvial, eolian and lacustrine depositional environments.

Previous workers in the San Juan Basin and Colorado Plateau have divided Jurassic and related rocks into groups, formations and members, in large part, on the basis of vertical contrast in rock type. Correlations, nomenclature and age of the sequence have been controversial because of complex lithofacies relationships and the general lack of diagnostic fossils. The lack of fossils is due to the rather lifeless environments which were common during parts of Jurassic time in the basin and to the poor conditions of preservation in the harsh post-depositional environments of the redbeds. In vertical section, boundaries between contrasting rock types are usually distinctive and easy to locate, and geologic names have been easily assigned. Laterally, however, change from one rock type to another within the same time interval often is subtle and takes place over a considerable distance. This characteristic of the sequence is difficult to recognize at single localities and often has caused problems in regional correlations. As an additional tool for use in correlation studies and resource investigations, research emphasis is now being placed on the study and interpretation of the ancient depositional systems responsible for the Jurassic sequence. The main objective of the depositional-environment approach is to gain a better understanding of the relationship between lateral rocks (lithofacies)

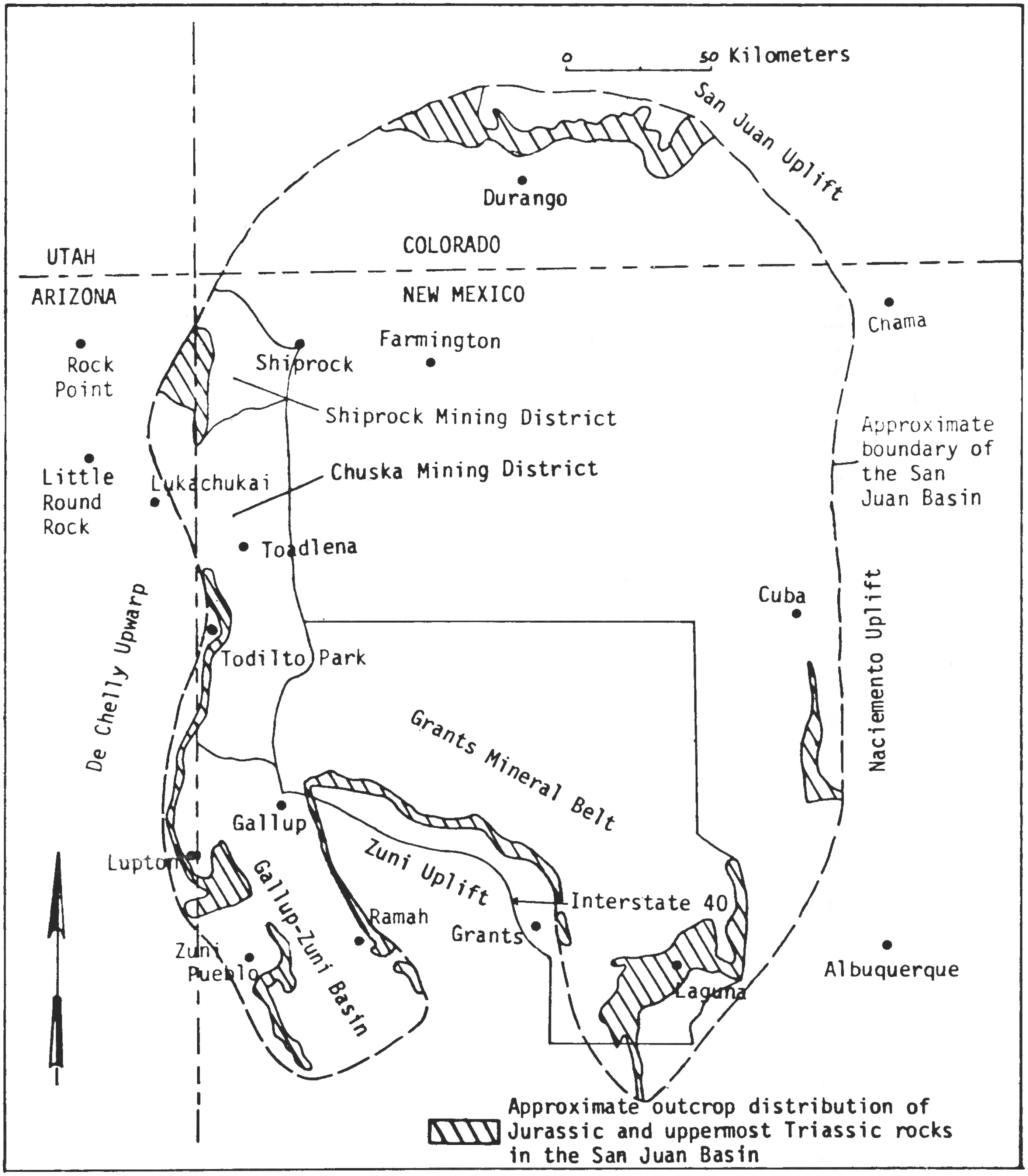

Figure 1. Index map of the San Juan Basin and adjacent areas showing major tectonic features, outcropping uppermost Triassic and Jurassic sedimentary rocks (lined), and uranium mining areas.

and time in the sequence. As an example of this approach, the entire Jurassic sequence in the Grants mineral belt in the basin has been stratigraphically divided into three units of genetically related rocks (Green, 1975).

Rock units considered to be of Jurassic age in the area of this report (table 1) include the San Rafael Group, Cow Springs and Morrison Formation. Also discussed is the Wingate Sandstone of Late Triassic age (Dutton, 1885; Baker and others, 1947); it is the basal formation of the Glen Canyon Group and the only one that is present in the basin. The younger formations of the Glen Canyon Group, the Moenave Formation, Kayenta Formation and Navajo Sandstone, are present in adjacent areas of northeastern Arizona and will not be discussed in this report.

Wingate Sandstone of the Glen Canyon Group

The distribution of the Wingate Sandstone, comprising the Rock Point (basal) and Lukachukai (upper) members (Harshbarger and others, 1957, p. 8), is restricted to the western margin of the San Juan Basin where the Wingate forms a relatively thin wedge of sandstone and siltstone lying unconformably between the Chinle Formation of Late Triassic age and the San Rafael Group. The Lukachukai Member pinches out along a northeast-trending line passing just west of Shiprock and Toadlena (O'Sullivan and Green, 1973, fig. 3D). The Rock Point Member is present southward around the Gallup-Zuni basin.

The two members of the Wingate show contrasting lithologies. The Rock Point Member is composed predominantly of flat-bedded dark-red calcareous siltstone. The origin of flat-bedded siltstone and thin interbedded silty sandstone beds of the Rock Point has been variously explained. Harshbarger and others (1957, p. 23) attributed the Rock Point to deposition in a subaqueous lagoonal environment. Stewart and others (1972, p. 99) believed that it was the result of alternating cycles of shallow lacustrine and eolian deposition. The Lukachukai Member consists of reddish-brown to orange, fine- to medium-grained, crossbedded sandstone. The high-angle, crossbedded sandstones of the Lukachukai Member are generally agreed to be of eolian origin throughout the Colorado Plateau.

Harshbarger and others (1957, p. 11) described an extensive intertonguing relationship between the Lukachukai and Rock Point members. Later work (O'Sullivan and Green, 1973, p. 76) showed the existence of a disconformable relationship between the Rock Point and Lukachukai members of the Wingate in the area west of the San Juan Basin, in the vicinities of Little Round Rock and Rock Point, Arizona. At Little Round Rock, Lukachukai Mountain and Todilto Park, the base of the Rock Point Member grades downward into the underlying Owl Rock Member of the Chinle Formation. This stratal relationship indicates that the Rock Point as defined by Harshbarger and others (1957, p. 8) should, in fact, be considered an upper member of the Chinle Formation. Such an assignment would be more in agreement with that described by Stewart and others (1972, p. 43) in the Monument Valley area, where the Church Rock Member of the Chinle is present as the lateral equivalent of the Rock Point.

In the Gallup-Zuni Pueblo area, the Rock Point Member contains a coarse-grained lithology designated informally as the "Beds at Lupton" (O'Sullivan and Green, 1973, p. 77). Conglomerate and conglomeratic sandstone facies of high energy fluvial origin in the "Beds at Lupton" occur south and southwest of the Zuni uplift in the vicinities of Ramah and Zuni Pueblo, New Mexico. This coarse-grained facies grades west and northwest into sandy and clayey siltstone beds of low-energy fluvial and lacustrine origin in the vicinity of Lupton on the New Mexico-Arizona boundary. Both lateral coarsening and directional sedimentary transport structures in the sequence indicate a sediment transport direction from south-southeast to north-northwest.

The Glen Canyon Group on the Colorado Plateau is of Triassic and Jurassic age; however, because of the general lack of diagnostic fossils in the Glen Canyon, the position of the Triassic-Jurassic boundary in the sequence remains in doubt. In the San Juan Basin the Wingate Sandstone is considered to be of Triassic age; however, recent age determinations (Peterson and others, 1977) using fossil palynomorphs from the Whitmore Point Member of the Moenave Formation in southeast Utah and northeast Arizona suggest that at least part of the Wingate Sandstone may also be Early Jurassic in age, because the Lukachukai Member of the Wingate and the Moenave Formation intertongue. The new evidence for the age of the Moenave and its comparison with the Late Triassic age assigned to the vertebrate fossils in other formations in the Glen Canyon have not been fully evaluated.

San Rafael Group

The San Rafael Group in the San Juan Basin consists of, in ascending order, the Carmel Formation, Entrada Sandstone, Todilto Limestone, Summerville Formation and Bluff Sandstone (table 1). In the northern part of the San Juan Basin, located in southwest Colorado, the Pony Express Limestone Member, unnamed member and Junction Creek Sandstone Member (top) of the Wanakah Formation are also included in the San Rafael Group. The Pony Express is a possible equivalent of the Todilto Limestone. Ekren and Houser stated (1965, p. 12) that the Junction Creek correlates with the Bluff Sandstone. In the San Rafael Swell area of central Utah and the adjacent region, the San Rafael Group also includes the Curtis Formation. The Curtis Formation is of marine origin and grades laterally southward into the Summerville Formation. Although the Curtis is not recognized in the San Juan Basin, Baker and others (1947, p. 1668) believed that the Todilto is a correlative of the Curtis. In the Grants mineral belt, Smith (1954) used the name Thoreau Formation to refer to the rocks of the Summerville, Bluff and part of the overlying Cow Springs.

Within the San Juan Basin the San Rafael Group generally rests unconformably on the Chinle Formation of Late Triassic age; on the western margin of the basin and in adjacent areas to the west, the group lies unconformably on formations of the Glen Canyon Group. Formations underlying the unconformity become progressively younger toward the west and northwest part of the basin. Primarily through the efforts of G. N. Pipiringos, the pre-San Rafael unconformity, known informally as the "chert pebble unconformity" (Pipiringos and O'Sullivan, 1975), has been traced throughout most of the western interior of the United States.

Lithology, Sedimentary Structures and Mode of Origin—General

In general, the red quartzose sandstone and siltstone beds as well as the thin limestone and gypsum beds of the San Rafael Group in the San Juan Basin are the products of eolian and

Table 1. Nomenclature for Jurassic and related rocks in the San Juan Basin.

Age	Group	Formation	Member
Late and Early(?) Cretaceous	Unconformity	Dakota Sandstone	
Early Cretaceous		Burro Canyon Formation	
Late Jurassic		Morrison Formation	Brushy Basin Mbr.
			Westwater Canyon Mbr.
			Recapture Mbr.
			Salt Wash Mbr.
		Cow Springs Sandstone	
	San Rafael Group	Bluff Sandstone	
		Summerville Formation	
		Todilto Limestone	
		Entrada Sandstone	Upper sandstone mbr.*
			Middle siltstone mbr.*
			Iyanbito Member*
Late and Middle Jurassic	Unconformity	Carmel Formation	
Late Triassic	Glen Canyon Group	Wingate Sandstone	Lukachukai Mbr.
			Rock Point Mbr.
		Chinle Formation	

* Usage of Green (1974 in the Grants-Gallup area, southern San Juan Basin)

lacustrine deposition. Deposits of fluvial origin are rare and are restricted mainly to the marginal areas of the ancient basin or to basins of deposition into which the San Rafael sequence was deposited. In the northern part of the Colorado Plateau, fossil evidence indicates that parts of the San Rafael Group are of marine and marginal-marine origin. Geologists correlating the San Rafael Group southward have thus interpreted a marine origin for a part of the group in the San Juan Basin. The present authors do not believe that limestone and gypsum beds of the Todilto Limestone or siltstone beds of the Summerville and Entrada are related to Jurassic marine invasions from the north, because evidence of marine origin for these rocks has not been found. Sedimentary structures and vertical and lateral geological relationships suggest continental origin. With the exception of some fish fossils (Imlay, 1952, p. 960) of questionable environmental affinity (Anderson and Kirkland, 1960, p. 44) and freshwater ostracods found on the southern outcrops of the Todilto Limestone (Swain, 1946, p. 553), fossils have not been found in the San Rafael Group in the San Juan Basin.

The amount of sandstone in the San Rafael Group is about four times that of siltstone. Sandstone beds typically display three types of internal sedimentary features, which, in combination with textural characteristics, are indicative of certain modes of origin. Most sandstone beds exhibit medium- to high-angle sets of foreset crossbeds developed in fine- to medium-grained, well-sorted quartzose sandstone. Other sandstone beds of similar grain size display either a massive, structureless character or a planar, thin-bedded character. Crossbedded units are, by comparison with modern deposits of sand described in the literature, obviously of eolian origin. Massive and planar bedded sandstone units are, because of stratal association with adjacent crossbedded units, also interpreted to be primarily of eolian origin. Massive beds are interpreted to be the result of deposition in interdune areas. Planar beds of sandstone are relatively much thinner than adjacent crossbedded and massive sandstone beds. These beds frequently are interbedded with thin siltstone beds and are restricted to interdune areas and to the base of crossbedded units. Siltstone beds in the interdune areas are interpreted as airborne clastic material winnowed from adjacent dune fields and deposited from suspension into the interdune areas (Green, 1975, p. 8). Because thin planar sets of sandstone beds probably formed in interdune areas, these beds may mark the pathways of ancient migrating sand dunes.

Thick siltstone beds in the Entrada Sandstone and the Summerville Formation are interpreted to have formed in a similar manner to that of the thin interdune siltstone beds. However, instead of forming in areally restricted interdune areas, these thicker, more widespread deposits formed in the central part of the depositional basin in inland sabkhas (Amiel and Friedman, 1971) and saline lakes of large areal extent. Recharge of these sabkhas and lakes probably occurred both through subsurface recharge and surface runoff. Limestone and gypsum of the Todilto were apparently deposited in association with a large saline lake.

Carmel Formation

The Carmel Formation (Gregory and Moore, 1931, p. 72-74) is the lowermost formation in the San Rafael Group. In the San Juan Basin the formation is restricted to the extreme northwestern margin, in the vicinity of the Four Corners (Harshbarger and others, 1957, p. 21 and 45). The main part of the Carmel lies in northeastern Arizona and Utah, where red sandy siltstone facies of probable inland and coastal sabkha origin grade laterally northward into limy sandstone and limestone facies of marine origin. The formation ranges from 0 to approximately 85 meters in thickness and, there present, unconformably overlies rocks of the Glen Canyon Group.

Entrada Sandstone

The Entrada Sandstone (Gilluly and Reeside, 1928, p. 76-78) is present throughout the San Juan Basin and adjacent

Colorado Plateau. Except in areas where the underlying Carmel Formation is absent, such as in the San Juan Basin, the Entrada is conformable with underlying and overlying formations. The Entrada is composed exclusively of reddish-orange, fine- to medium-grained, well-sorted quartzose sandstone beds of eolian origin and relatively thinner, interbedded, dark reddish-brown siltstone beds of inland sabkha and interdune origin. The thickness of the formation in the San Juan Basin ranges from about 18 to 100 meters. The bright orange cliffs north of Interstate 40 in the southern San Juan Basin are composed of Entrada Sandstone and are capped by Todilto Limestone.

The Entrada has been variously divided by past workers in the basin. What is now called Entrada on the southern margin of the basin was originally described by Dutton (1885, p. 136-137) and named the Wingate Sandstone. Later, Baker and others (1947, p. 1667) extended the name Entrada to replace the name Wingate in the Fort Wingate area, because the sandstone in that area is younger than the sandstone accepted elsewhere as Wingate. Various members of the Entrada, both formal and informal, have since been designated. Previously, some of these members had variously been assigned to other formations of the San Rafael and Glen Canyon groups. (See Baker and others, 1947, p. 1666-1667; Harshbarger and others, 1957, p. 8, 35, and 36; Moench and Schlee, 1967, p. 6-10; O'Sullivan and Craig, 1973, p. 79; Green, 1974, p. 8). In the eastern and northern part of the basin, the Entrada is undifferentiated.

Todilto Limestone

The Todilto Limestone (Gregory, 1917, p. 55 and 56), is present mainly in the San Juan Basin and adjacent regions to the east, and lies conformably between the Entrada and Summerville over an area of approximately 90,000 square kilometers. The formation is composed of a lower limestone facies present throughout the depositional area of the Todilto and a gypsum-anhydrite facies which is restricted to the deeper part of the lacustrine basin centered along the eastern boundary of the present San Juan Basin. Thickness of the limestone facies ranges from 0 to about 10 meters. The gypsum-anhydrite facies ranges from 0 to about 30 meters.

The first uranium deposits in the Grants mineral belt were discovered in the Todilto Limestone near Haystack Butte, approximately 16 kilometers northwest of Grants, New Mexico. According to Hilpert (1969, p. 97), most of the deposits are controlled by intraformational folds that formed during Late Jurassic or Early Cretaceous time. Hilpert further stated that where the gypsum-anhydrite facies is absent, relationships between the Todilto and the overlying Summerville Formation suggest folding before consolidation of the sediments. The present authors believe that deformation of the limestone facies of the Todilto probably was caused by loading during Summerville deposition at the margins of the regressing Todilto lake. Deformation occurred while the lime mud at the bottom of the lake was still wet. Consequently, the deformation would be restricted to Late Jurassic time.

Summerville Formation

The Summerville Formation was first described by Gilluly and Reeside (1928, p. 80). In the San Juan Basin, the formation is composed of 10 to 20 meters of massive to planar bedded sandy siltstone and fine-grained silty sandstone of probable inland sabkha origin. The Summerville has a close stratal relationship to the underlying Todilto Limestone; and the gypsum-anhydrite facies of the Todilto and lower part of the Summerville may be, in part, lateral time equivalents.

The stratal relationships and the interpreted modes of origin for the Todilto Limestone and Summerville Formation suggest that siltstone of sabkha origin in the Summerville may have encroached into low-lying areas adjacent to the margins of the regressing Todilto lake.

Bluff Sandstone and Cow Springs Sandstone

The Bluff Sandstone (Gregory, 1938, p. 58) and the Cow Springs Sandstone (Harshbarger and others, 1951, p. 97) have both been recognized in the southwestern part of the San Juan Basin, primarily in the Grants mineral belt. The formations are considered together in this report because both are composed of well-sorted, fine- to medium-grained quartzose sandstone of eolian and interdune origin. In the areas where the Bluff and Cow Springs are separately recognized, the contact between the formations is considered to be intertonguing and arbitrary. The Bluff and Cow Springs sandstone interval ranges in thickness from 0 to a maximum of about 135 meters. Maximum thickness occurs at the west end of the Grants mineral belt.

The Bluff Sandstone is the uppermost formation in the San Rafael Group in southeast Utah (Craig and others, 1955, p. 133-134), whereas the Cow Springs Sandstone is considered to be a formation separate from the San Rafael. Harshbarger and others (1957, p. 48) stated that the Cow Springs intertongues with several Upper Jurassic units, including the Summerville Formation and Morrison Formation. For this reason, they stated that the Bluff cannot be considered either a formation of the San Rafael Group or a member of the Morrison. Harshbarger and others (1957, p. 42) also believed that the Bluff Sandstone is a lower tongue of the Cow Springs.

Morrison Formation

The Morrison Formation (Cross, 1894, p. 2) is recognized throughout the San Juan Basin. It is as much as 300 meters thick and is composed mainly of arkosic to subarkosic, medium- to coarse-grained, locally conglomeratic sandstone and interbedded sandy siltstone and claystone beds of high- to low-energy fluvial and lacustrine origin. The Morrison has been divided into four members (Craig and others, 1955). These members, in ascending order, are the Salt Wash Member (Lupton, 1914, p. 127), Recapture Member, Westwater Canyon Member and Brushy Basin Member (Gregory, 1938, p. 58-59). The Morrison is overlain unconformably by the Dakota Sandstone in all areas of the San Juan Basin except northwest of Shiprock where a thin wedge of the Burro Canyon Formation of Early Cretaceous age conformably overlies it.

Fluvial sandstone and interbedded siltstone beds of the Salt Wash Member of the Morrison are recognized only in the northwestern part of the San Juan Basin. Near Toadlena, Salt Wash intertongues laterally (Craig and others, 1955, p. 137) with the Recapture Member, consisting of sandy siltstone and claystone beds of low-energy fluvial and lacustrine origin. In the area along the western margin of the basin, where the transition occurs between Salt Wash and Recapture members, uranium in the Chuska and Shiprock mining districts has been mined from both Salt Wash and Recapture rocks.

High-energy fluvial sandstone and conglomeratic sandstone beds of variable thicknesses in the Westwater Canyon Member have been recognized and correlated into all areas of the San Juan Basin. Grain size in the Westwater Canyon becomes increasingly coarser toward the southwest, indicating (Craig and others, 1955, p. 156-157) a source area south-southwest of the Grants mineral belt for the member. At the east end of the mineral belt, the Westwater Canyon intertongues with the Recapture Member and the Brushy Basin Member. At the west end of the belt, the Westwater Canyon rests unconformably on the Recapture (Saucier, 1967, p. 143). For further detail concerning the Westwater Canyon-Brushy Basin stratal relationships, reference should be made to the reports by Saucier (1967) and Green (1975). **[Editor's note: see paper by Kelly elsewhere in this volume.]**

In the Grants mineral belt, the largest uranium deposits in the Morrison occur in the Westwater Canyon Member and in overlying sandstones similar to the Westwater Canyon and known informally as the Jackpile sandstone of the Brushy Basin.

The Brushy Basin Member of the Morrison is composed mainly of sandy siltstone and smaller amounts of claystone of low-energy fluvial and lacustrine origin. Fine-grained clastic sediment of the Brushy Basin is, in large part, representative of the distal facies of a large coalescing alluvial fan complex.

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