

DIAGENESIS OF SANDSTONES FROM THE DOUGLAS CREEK  
MEMBER OF THE GREEN RIVER FORMATION (EOCENE) AT  
RED WASH FIELD, UINTAH COUNTY, UTAH

A Thesis

by

EARL SCOTT RAY

Submitted to the Graduate College of  
Texas A&M University  
in partial fulfillment of the requirement for the degree of  
MASTER OF SCIENCE

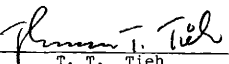
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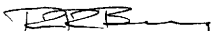
Major Subject: Geology

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## ABSTRACT

Diagenesis of Sandstones from the Douglas Creek  
Member of the Green River Formation(Eocene) at  
Red Wash field, Uintah County, Utah. (August 1985)

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The sandstones of the lower Green River Formation (Douglas Creek member) at Red Wash field were deposited in a fluvio-deltaic environment and are bounded by lacustrine shales. They presently occur at depths of 5200 to 5700 ft (1590-1740 m); the maximum depth of burial was approximately 9800 ft (2990 m).

Sample analysis shows that the sandstones are fine-grained quartz arenites to sub-litharenites; the average detrital composition is 76% quartz, 9% rock fragments, 2% feldspars and 12% other minerals. Diagenesis has altered the the sandstones through grain alteration, cementation, and dissolution. The major authigenic minerals are carbonate cement, and quartz overgrowths. Clay minerals within the sandstones are volumetrically small (less than 1%) and typically consist of kaolinite, illite, smectite and interlayered illite/smectite. Rock fragments are typically altered to illite, and feldspars to kaolinite.

The diagenetic sequence was 1) physical compaction,

2) dolomitization of carbonate particles, 3) quartz overgrowth development, 4) precipitation or recrystallization of clay minerals, 5) precipitation of carbonate cement, 6) carbonate dissolution, 7) further clay precipitation, and 7) hydrocarbon migration.

Diagenesis, influenced by texture and composition, is the primary regulator of porosity and permeability. Dissolution of intergranular carbonate cement, which is grain size dependent, has produced a major part of the porosity now present. This has resulted in porosities as high as 22%. Dissolution of carbonate cement, and an absence of abundant clay minerals account for the high permeabilities (average 41 md).

Similarities in the diagenetic minerals and diagenetic sequence of the sandstones indicate that depositional environment, such as fluvial versus deltaic, did not play a major role in diagenesis. Depositional environments, whether fluvial or deltaic, do control such sandstone properties as texture and composition, which can in turn exert direct control over diagenesis.

To my wife, Denise, and to my parents  
Stanley and Florence Ray

## ACKNOWLEDGEMENTS

I would like to thank Dr. Thomas Tieh, as the chairman of my advisory committee, for his advice, consideration and above all, his patience throughout the preparation of this thesis. Many thanks also go to Dr. Robert Berg and Dr. Robert Burghardt, the other members on my advisory committee. Their help, suggestions, and comments were greatly appreciated.

I want to thank Chevron Oil Company for providing financial support for this research, as well as providing cores, core analyses, and other information upon which this study was based.

Special thanks also go to my fellow graduate students Tony McClain, Steve Stearns, Rick Bott, Steve Conner, and John Whynot who lent their encouragement and advice.

Finally, I would like to give my deepest thanks and heart-felt appreciation to my parents and my wife, Denise for their undying love, support, and patience.

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## INTRODUCTION

Secondary porosity in sandstones has been the subject of intensive study in recent years. Due to the increased difficulty in finding obvious structural traps, emphasis on finding stratigraphic traps has become of increased importance. Both depositional and diagenetic processes place controls on such traps. Present-day porosity and permeability are frequently the result of diagenetic modifications of original porosity.

Sandstones at Red Wash field present a unique problem because they were deposited in an environment on which few diagenetic studies have been performed. Fluvio-lacustrine sequences are found throughout much of the world including Asia, North America, and Africa, but until recently they have not been intensely studied.

The objectives of this study are to determine 1) the sequence of diagenetic events, 2) the factors controlling diagenesis, and 3) the effects of diagenesis on reservoir rock properties of the Green River Formation, Douglas Creek member, at Red Wash field, Uintah County, Utah.

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This thesis follows the style of the Bulletin of The American Association of Petroleum Geologists.

## Regional Geology

At the end of Cretaceous time the Laramide Orogeny produced the Rocky Mountains of the western-central United States and intermontane basins were filled by Tertiary continental sediments. During Eocene time, fluvial and lacustrine deposits were laid down in parts of Wyoming, Colorado and Utah. Sandstones, silts and coals of the Wasatch Formation were overlain by the diverse Green River Formation (Bradley, 1931). Deposition of this formation took place in two areas; the largest of these, Lake Uinta, covered about 23,000 sq km of northeastern Utah, where a maximum of at least 3000 m of sediment were laid down (Selley, 1970). Lake Gosiute, the smaller lake, with its depocenter in southwestern Wyoming was separated from Lake Uinta by a ridge now called the Uinta Mountains.

Redwash field is one of several oil and gas fields in the Uinta basin and is located in the eastern part of Uintah County (Figure 1). Lying at the eastern end of the Uinta basin, it is bounded by four positive structural features: 1) the northwest-southeast trending Uncompaghe uplift on the southeast, 2) the north-south Douglas Creek arch on the east, and two prominent anticlines, 3) Split

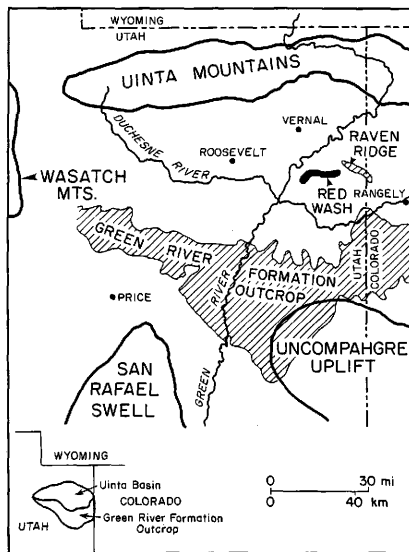


Figure 1 - Index map showing location of Red Wash field and surrounding structural features.

Mountain and 4) Blue Mountain, both parts of the Uinta Mountain uplift to the north.

The structure at Red Wash Field is dominated by a gentle west-plunging anticlinal nose. The discovery well and most early development were concentrated along the axis of this structure. South of the nose lies the Red Wash syncline which deterred drilling in that direction until much later when production was extended across the syncline.

#### Depositional Environment

Sediments in the lower Green River Formation at Red Wash originated in the Uinta Mountains to the north and were deposited along the northern margin of Eocene Lake Uinta in shallow water by streams that meandered across an extensive flood plain. Deltas were formed where the streams entered the lake and deposition continued in this manner throughout lower Eocene time (Bradley, 1931). Coarse detritus was deposited in point bars and delta front bars, while the finer sediments were carried offshore to settle on the lake bottom, creating the massive shale units found in, what was then, the offshore environment. Repeated fluctuation in the water level acted to partially destroy these facies and make interpretation difficult.

## Stratigraphy

The regional stratigraphy has been described by several authors. The sediments deposited in Lake Uinta were first described and named by Hayden (1869) as the Green River Formation. Later it was age dated by Osborne (1929) as lower Eocene. Berry (1924) compared it to the Claiborne and the lower part of the Jackson of the Gulf Coast, but later it was assigned to the middle Eocene.

Bradley (1931) divided the Green River Formation into four members (Table 1). Beginning with the oldest, they are the Douglas Creek, Garden Gulch, Parachute Creek and Evacuation Creek members. These members persist throughout the basin, although they vary in thickness from place to place and merge together in the shore facies (Bradley, 1931). Each member represents depositional conditions different from those above and below. The whole formation lies conformably on the fluviatile Wasatch Formation of lower Eocene age and is overlain by the Eocene Uinta Formation. The Douglas Creek Member, the subject of this study, is the principal producing zone in the Red Wash Field, where it is 440 ft (135 m) thick (Picard, 1957). Individual producing sandstones vary in thickness from three to more than 30 feet, and the total producing interval for the better wells approaches 150 ft (45 m) (Chatfield, 1965). Cored sandstones are usually massively





bedded but thin intervals of low angle cross-bedding do occur. Sandstone bodies toward the western margin of the field are thicker and more continuous, and therefore are more readily mapped, while sandstones in the east, at the location of this study, are thinner, more lenticular and much more difficult to map as separate units (Chatfield, 1965).

The Douglas Creek, often called the delta facies, is composed of varying amounts of sandstone, siltstone, shale, limestone and minor dolomite beds. The high quartz content and minor feldspar and rock fragment content of the sandstones in this field places them in the sub-litharenite class. Calcite is the principal cementing agent although dolomite and silica also serve to bond the grains. Sorting ranges from poor to excellent and grain size from very fine to coarse. Ooids are common in the limestones and in places make distinct beds as do ostracode-rich siliciclastic sandstones.

Overlying the Douglas Creek Member is the Garden Creek Member composed primarily of shale, sandstone and some limestone and dolomite beds. The Garden Creek Member at Red Wash Field is about 550 ft (168 m) thick. The Parachute Creek Member, overlying the Garden Creek, is largely oil shale, gray shale, and limestone and dolomite beds representing deeper water deposition. Very little sand is

found in this member or in the overlying Evacuation Creek Member, which consist primarily of shales interbedded with very thin sandstone units (Chatfield, 1965).

## LITERATURE REVIEW

## Sandstone Diagenesis

Diagenesis is the process involving the chemical and physical changes in a sediment after deposition and before metamorphism. From a practical standpoint, diagenesis is important because it controls the preservation or reduction of primary porosity and the development of secondary porosity, both of which have a direct bearing on the quality of a reservoir rock.

According to Hayes (1979) the dominant porosity reducing processes are: 1) chemical, 2) mechanical, and 3) combination (alteration of detrital grains, authigenesis and simultaneous compaction). The chemical aspect of diagenesis includes cementation, chemical dissolution of grains and/or cement, and recrystallization of detrital or authigenic minerals. Original composition can play an important role in the chemical aspect of diagenesis by influencing the type and extent of diagenesis which takes place.

Mechanical compaction can be defined as the adjustments which takes place between grains as a result of overburden pressure. Reduction of porosity is the first step in the normal progression of sandstone diagenesis and, during the initial 1500 meters of burial, mechanical compaction is the dominant porosity reducing mechanism

(Fuchtbaur, 1967). Increased compaction of sand is inversely related to the porosity so that there is a general decrease in porosity with increased depth. Readjustment of grain orientation associated with grains slipping past one another, ductile grain deformation (mainly shale clasts and rock fragments), flexible grain deformation (i.e. micas), and brittle grain deformation are described by McBride (1978). According to laboratory experiments by Athy (1930) and Rittenhouse (1971) quartz-rich sands not only compacted slower than sands containing ductile grains, but they also compacted less, leaving a larger proportion of primary porosity. Blatt (1979) found that the amount of compaction increases significantly with increasing proportions of ductile rock fragments such as mud clasts or mica.

Destruction of primary porosity by compaction is only one stage of porosity reduction that can be accomplished through diagenesis. Chemical diagenesis is possibly the most important diagenetic factor since chemical diagenesis can reduce primary porosity as well as create secondary porosity. Chemical diagenesis includes cementation by precipitation of minerals from migrating pore fluids, recrystallization of framework or authigenic minerals, and replacement of grains, but it also includes the leaching of cements and detrital and authigenic grains. Cementation involves the precipitation of mineral matter into the pores

of a clastic sediment and is the principal way in which sandstones become lithified (Pettijohn, 1957).

Composition, pH, and temperature of the pore fluids also determine whether precipitation, dissolution, recrystallization, or other alteration occurs and of which minerals (Schmidt and McDonald, 1979).

In a typical arenite framework, such as the Green River sandstones in this study, clay is a very minor constituent and the open pore space between sand grains may be the site for crystallization of mineral cement. Two types of mineral cement occur. One type is compatible with the detrital grains, that is, it can join itself structurally to individual grains, whereas another variety is structurally incompatible and is formed in interstitial openings with crystallographically conflicting boundaries with detrital grains (Dapples, 1972). Compatible cements are those in which the chemical composition of the cement is identical to that of the grains being cemented (Dapples, 1972). Examples of this include silica-cemented quartzose sandstones and fossiliferous sandstones with calcite cement (McBride, 1977). The boundaries between incompatible cements and grains are not chemically active, and the detrital grain behaves as an inert body surrounded by cement, while the boundaries between compatible cement and grains may be modified by some recrystallization. Calcite,

dolomite, siderite, iron oxide, anhydrite, and gypsum are common incompatible cements in quartzose arenites, but wherever it is in contact with grains of like composition it can behave as a compatible cement (Dapples, 1972). The source of the cementing agent is often derived from reaction products of the framework grains themselves and it may not be necessary to look for a distant source.

Many workers believe that a large amount of silica cement is generated through pressure solution due to increased solubility of quartz at grain contacts. However pressure solution cannot account for all of the silica found. For this reason, other sources for silica have been suggested such as expulsion of silica-rich waters from shales. The difficulty with a water expulsion theory is that the shales probably contain insufficient volumes of water. The volumes of pore water expelled from shales and their concentrations of dissolved matter is not great enough to generate significant amounts of cement. It is true however that both pressure solution and shale dewatering can be important sources of silica. Another important source of silica is the dissolution of unstable volcanic rock fragments. Any or all of these mechanisms may supply cementing agents during the burial history of a sediment.

Carbonates are another common cement of which calcite

is the most important. In many sandstones, the volume of cement may be near that of the original porosity, and sandstones with poikilotopic cement invariably have loose packing, indicating that cementation took place very early in its burial history. It is well-known that calcite solubility is controlled by the acidity of the surrounding fluid. The solubility of silica however is unaffected by pH values below about pH 9, but below pH 7 calcite becomes increasingly soluble. Therefore changes in  $H^+$  concentration may cause solution of one phase and precipitation of another. With an increase in temperature (depth) the partial pressure of  $CO_2$  decreases and a subsequent increase in pH occurs, therefore allowing precipitation of calcite as a pore filling cement. Although sands can undergo cementation with calcite from surface conditions to very deep subsurface, the majority of sandstones obtain calcite cement after burial of 1000 ft (300m) or more (McBride, 1977). This is shown by the degree of compaction and by the fact that, if quartz cement is present, it precedes the calcite.

Other carbonate minerals which are commonly seen are dolomite and siderite. Dolomite often replaces authigenic and detrital calcite and some framework grains such as feldspars.

Another important role of chemical diagenesis is the



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generation of secondary porosity. In the subsurface, secondary porosity results from the dissolution of carbonates by circulating acidic solutions (Schmidt and McDonald, 1979). The carbonate minerals may be shell fragments, calcite, dolomite or siderite cements. According to McBride (1977) and others, acidic pore waters may be rich in  $\text{CO}_2$  derived from thermal or bacterial degradation of hydrocarbons. Bjorlykke (1984), however, discounts the importance of this theory since the volume of  $\text{CO}_2$  produced by hydrocarbon degradation is too small to be significant. He claims that, even in a kerogen-rich source rock (10% TOC), it would be necessary to have only a few percent of finely distributed carbonate to neutralize most of the  $\text{CO}_2$ . But because the amount of carbonate that may be dissolved during hydrocarbon maturation is a function of the volume of the total organic carbon available, the volume of carbonates dissolved could be large in basins such as the Uinta basin which contain large volumes of kerogen.

Another theory, regarding chemical diagenesis, is put forth by Hower et al, (1976). As the temperature increases with depth, smectite becomes unstable and may form illite, chlorite, and quartz. Kaolinite becomes unstable at temperatures between 120 and 150°C and if  $\text{K}^+$  ion is present then kaolinite can react with it to produce illite plus two

$H^+$ . This lowers the pH and carbonate dissolution is possible (Bjorlykke, 1984).

It is important to know the textural and genetic aspects of the various types of secondary porosity in order to differentiate between porosity of primary and secondary origin. Schmidt and McDonald (1979) define five different genetic classes of secondary porosity. Two are mechanical and three chemical in nature. Fracturing and shrinkage, the two mechanical classes, include newly formed fractures due to stresses within the rock, and shrinkage due to dehydration or recrystallization of certain minerals. The three chemical classes all stem from dissolution. The first is dissolution of sedimentary material such as detrital carbonate and silicate grains. Second is porosity resulting from the dissolution of authigenic cement and is probably the most important class. The third chemical class, porosity resulting from dissolution of authigenic replacive minerals, is formed by the dissolution of soluble materials such as calcite, dolomite and siderite that previously replaced sedimentary grains.

Schmidt and McDonald (1979) define five descriptive groups of porosity textures. These textures are: 1) intergranular porosity, 2) oversized pores, 3) moldic porosity, 4) intragranular porosity, and 5) fracture porosity.

Previous Diagenetic Studies of The  
Green River Formation

Pitman et al(1982) have reported, in some detail, the diagenesis of the Green River sandstones at Parriette Bench approximately 20 miles to the southwest of the study area. Here the Douglas Creek member is composed dominantly of sandstones, calcareous silty claystone, ostracodal and pisolitic grainstone, and stromatolitic, mud-supported carbonate rock formed in the subsiding depositional intermontane Uinta Basin. The Douglas Creek member represents sedimentation along the fluctuating shoreline of ancient lake Uinta where there was an abundant influx of clastic sediments.

Mechanical compaction began as the first phase of diagenesis and continued until the introduction of cementing agents. Early authigenic silica that halted compaction is present in small amounts in the clean, well-sorted channel sandstones, and occurs as syntaxial overgrowths on detrital quartz grains. In many cases at Pariette Bench, well developed quartz overgrowths have completely filled intergranular pores and have coalesced to form cement. In rocks showing carbonate cement the overgrowth margins are commonly corroded (Pitman et al, 1982). Dolomite and ankerite are present in varying amounts, dolomite occurring as discrete grains and as authigenic fine-grained replacement cement.

At Parriette, cement ranges from 0 to 42% forming a pervasive cement in some cases and in other cases it is found as partially to completely dissolved remnants (Pitman et al, 1982).

Pitman et al (1982) also describe a progression from iron-free to iron-rich carbonates with depth. Early iron-free calcite and dolomite may have formed on detrital clasts. Dissolution of iron-free calcite may have been followed by precipitation of iron-bearing calcite which recemented corroded framework grains and residual pores and replaced earlier carbonate cements. Evolution of carbonate cements from early low-iron to later higher iron varieties has been reported by Boles (1978), Curtis (1978), and Land and Dutton (1978).

At Parriette Bench clay development apparently post-dated carbonate dissolution since clays are best developed in sands that have undergone extensive carbonate dissolution. Authigenic illite may have resulted from pore fluids reacting with detrital feldspar grains. According to Perry and Hower (1970) and Hower et al (1976), the presence of partly ordered interstratified illite-smectite indicates that the maximum burial depth was no more than 9800 ft (3000 m).

## STUDY METHODS

The study was based on cored sections from two wells containing the Douglas Creek member of the Green River Formation. These wells, units 271 and 278 (Figure 2) are located near the edge of Red Wash field. Samples from Chevron unit 278 were used in this study.

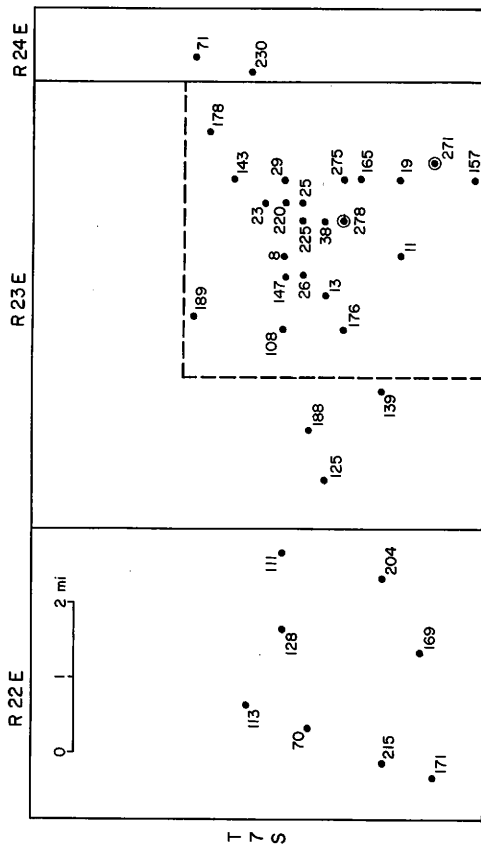
### Petrography

Petrographic sections were prepared from core samples at intervals varying from .25 to 10 m. A total of 51 thin sections were studied. Samples were impregnated with blue epoxy before thin sections were cut. Colored epoxy impregnation allows one to observe the pore geometry (from which primary and secondary pores can be differentiated) and distinguish actual pores from holes produced when grains were plucked out during thin section preparation. All slides were treated with alizeran red stain to distinguish calcite from dolomite.

Textural properties such as mean and maximum grain size and sorting were determined by measuring the apparent long axes of 50 monocrystalline quartz grains per thin section. Monocrystalline quartz grains were chosen to eliminate any size variations due to compositional differences.



Figure 2 - Map showing study area and well locations. The two wells from which data were obtained, 271 and 278, are circled. (after Chatfield, 1965).





One hundred and fifty points were counted per thin section to resolve composition into detrital, authigenic and porosity components. Detrital composition was divided into six categories: 1) quartz, 2) feldspar, 3) rock fragments, 4) clay, 5) ooids, and 6) other minerals. Other minerals included hornblende, zircon, and micas. The authigenic composition was divided into four categories: 1) silica cement, 2) calcite cement, 3) dolomite cement, and 4) other authigenic minerals. Other authigenic minerals included pyrite, authigenic clay, and hematite. Porosity values were arrived at from point counting 50 randomly chosen pores per thin section and were divided into three classes: 1) intergranular porosity, 2) intra-granular porosity and 3) shrinkage/fracture porosity. Criteria defined by Schmidt and McDonald(1979) were used to distinguish the porosity types mentioned above.

#### X-ray Diffraction

Samples were prepared for x-ray diffraction using the methods outlined by Carroll(1968) and Calvert and Dixon (1981). Fifteen samples from sandstone units and six from shale units were selected for x-ray analysis. All except two of the sandstone samples were usually taken from areas with petrographic data. Shale samples were

taken from units adjacent to the sandstone samples. The samples were first disaggregated followed by the removal of the sand and coarser fractions by sieving. The silt and clay fractions were then separated using centrifugal methods. Clays were analyzed by preparation of untreated as well as glycerol and  $K^+$  and  $Mg^+$  saturated samples. magnesium saturation with glyceration at  $25^\circ C$  causes the expandable clay minerals to expand to their characteristic d-spacings. Potassium saturation causes collapse of expandable clays. The samples were then mounted on glass slides. Diffractograms were obtained with a Phillips Norelco diffractometer using monochromatic  $CuK\alpha$  radiation. Each sample was scanned from  $2^\circ$  to  $30^\circ 2\theta$ . Diffraction analysis was repeated after the K-saturated samples were subjected to temperatures of  $300^\circ C$  and  $550^\circ C$ . This  $550^\circ C$  heat treatment causes destruction of the kaolinite structure and eliminates it from the diffractogram. Chlorite peaks remain at approximately 14 and 7 Å at the higher temperature.

Eight samples from variously colored shales were analyzed for bulk composition by manually grinding the sample and applying a slurry onto glass slides. The relative abundance of various minerals was measured by peak height.

### Scanning Electron Microscopy

Samples were chosen for scanning electron microscopy (SEM) analysis based on porosity and permeability. Samples from sands which showed a wide variation in porosity and permeability were analyzed. Samples were mounted on aluminum stubs with carbon paint and then coated with approximately 200Å of gold/palladium alloy using a Techniques, Inc. sputter coating system. Samples were then viewed with a JEOL JSM-25 scanning electron microscope using secondary electron imaging.

Scanning electron microscopy was used to determine the fabrics and occurrence of clay minerals, as well as secondary porosity features not visible in petrographic thin sections. It was possible with SEM to observe the three dimensional nature of delicate authigenic clay structures.

### Energy Dispersive X-ray Analysis

Energy dispersive x-ray analysis was employed to determine, qualitatively, the relative composition of carbonate cement using a JEOL JSE-35CF 35 Scanning Electron Microscope fitted with a Tracor-Northern TN-2000 x-ray analyzer.

### Trend Analysis

Rock properties which are thought to control porosity and permeability were plotted against one another to find any important relationships that might exist between them. Petrographic data, SEM, and x-ray diffraction analysis were used to determine the diagenetic sequence of events in the Green River Sandstones at Red Wash field.

PETROLOGY AND MINERALOGY OF SANDSTONES FROM  
THE DOUGLAS CREEK MEMBER

Sandstone Texture

The mean grain size of all Green River samples based on the measurement of the apparent long axes of monocrySTALLINE quartz is .18 mm; they are fine-grained sand. Mean grain size varied from a low of .04 mm(coarse silt) to a high of .43 mm(coarse sand). The Green River sandstones at Red Wash field were deposited in a fluvio-deltaic environment(McClain, 1985), and therefore can be divided into two the facies. The average grain size of fluvial sands is .17 mm while that of the deltaic is .20 mm. Sorting values(standard deviation) range between a high of .02 and .03 for fluvial and deltaic respectively and a low of .10 and .21 with an overall average of .08 for fluvial and .04 for deltaic. Although the individual sorting values vary considerably, overall the sands are well sorted.

Composition

The detrital mineralogy of the Green River sandstones at Red Wash field is dominated by quartz, with an average composition of 76 %. Rock fragments, the second most abundant species, average 7 % with the majority

consisting of unstable volcanic rock fragments, many of which show advanced stages of dissolution. This composition places the sandstones between quartz arenites and sub-litharenites (Figure 3). Other rock fragments include chert, shale clasts, and limestone clasts. Feldspar content averages 2 % and is dominated by plagioclase. Ooids are present in many samples and are locally abundant with a high of 41% and an average of 5 %. Other minerals average 7 % and include muscovite, biotite, zircon, and hornblende.

Matrix is a rare constituent in these sands and only occasionally was an appreciable amount (>1%) encountered. Matrix constitutes much less than 1 percent of a typical sample (Appendix 1).

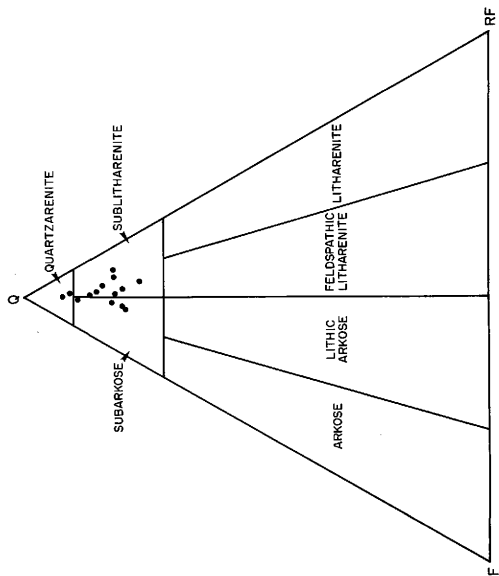
#### Cements

Three types of authigenic cements were observed. Calcite, the most common, averages 7% of the bulk volume. Dolomite the second most abundant cement rivals calcite in abundance with an average of 6%. Silica cement occurring as compatible syntaxial overgrowths on detrital quartz grains averages 2%. Intervals with well-developed quartz overgrowths are generally limited to sands with low carbonate content and large grain size. Two areas are notably absent of silica cement, sediments that are high in detrital



Figure 3 - Detrital composition of sands from the Douglas Creek member, Chevron Unit 278, Red Wash Field, Uintah County, Utah (McClain, 1985).



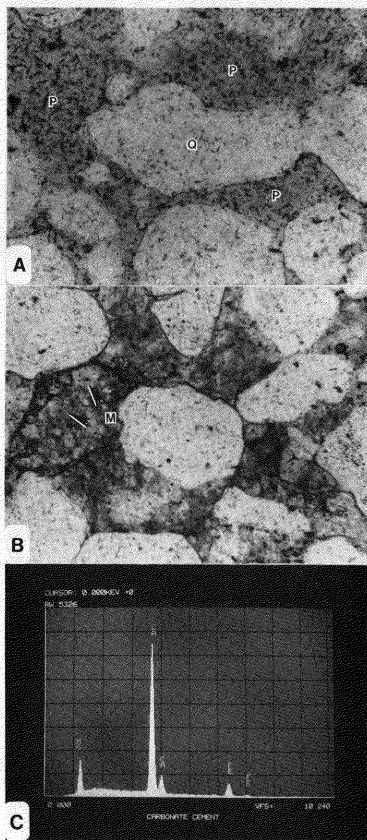


carbonate, and those that are fine grained. In high carbonate sandstones porosity was reduced or eliminated before silica precipitation took place, and the low porosity was the result of mechanical compaction and the early recrystallization and precipitation of carbonate cement. In sands with very fine grained texture (and its accompanying low permeability) interstitial fluid flow, and the opportunity for mineral precipitation, has been reduced.

Carbonate cement usually occurs as incompatible cement but, in the high carbonate sands it sometimes occurs as a compatible cement in contact with limestone grains or ooids. Calcite is present in nearly all samples although its occurrence is highly variable. The most common carbonate form is sparry calcite and occurs either as isolated patches in pores or it completely cements the sand. Several samples contain large amounts (up to 22%) of calcite that completely fill the pores in some intervals. In some cases the calcite has replaced the edges of quartz grains to give them a floating appearance (Figure 4a). In the basal portions of the fluvial sands and the upper portions of the deltaic sands (coarser sediments) where carbonate dissolution developed extensively, calcite is nearly absent except for patchy remnants of sparry cement. Calcite that had replaced feldspars sometimes retained the



- Figure 4a - Thin section photomicrograph in plane polarized light of "floating" quartz grain (Q) in sandstone that has experienced complete cementation and then replacement by calcite. Calcite cement replaced much of the grain boundary, and then subsequent dissolution created secondary intergranular porosity. Picture width = 250 microns. (RW278-5261)
- Figure 4b - Thin section photomicrograph in plane polarized light of carbonate cement (C) exhibiting a mottled or zoned appearance. The dark patches are stained red by alizeran red stain while the lighter areas are unstained. Picture width = 250 microns. (RW278-5438)
- Figure 4c - Qualitative energy dispersive x-ray spectrogram of carbonate cement found in a typical intergranular pore. The relative abundance of calcium(CA), magnesium(MG), and iron(Fe) show that it is calcite in composition. Picture width = 85 microns.



appearance of Carlsbad twinning even when the original grain had been completely replaced. Volcanic rock fragments that experienced dissolution have sometimes been replaced by small rhombic dolomite crystals and well formed pyrite cubes. Dolomite occurs in two principal forms: 1) well formed rhombic crystals in pores, and 2) dolomicrite in the form of aggregates of very small crystallites within pores. Euhedral dolomite crystals occur commonly throughout the section as either large crystals that completely filled the pore, or as smaller crystals that partially or completely fill the intragranular porosity within dissolved rock fragments. Dolomicrite, a very common form occurs as 5 to 10 micron sized microcrystals or crystalites lying between framework grains or within ooid accretion layers. When in this form it often has a yellowish brown color and sugary texture suggesting that the dolomicrite contains impurities from what may have been its precursor calcite mud. This micritization has often destroyed the concentric layer structure characteristic of ooids leaving a single layer of structureless dolomicrite.

When viewed in thin section, well developed sparry calcite often appears to contain zones of dolomite (Figure 4b). Further investigation using microprobe techniques however, did not show the expected zonal nature that was observed in thinsection. Neither magnesium nor iron showed

any variation in concentration across the "zonal" boundaries. Incomplete staining of the carbonate minerals is the probable origin of this phenomenon and its importance can therefore be discounted.

Using a JEOL 35 JSM Scanning Electron Microscope equipped with a Tracor Northern TN-2000 x-ray analyzer semiquantitative microprobe analysis was performed on several intergranular cements to determine their composition. The analyses indicated that the composition is calcite with small amounts of iron and magnesium (Figure 4c). A beam current of 15 KeV, take-off angle of 35 degrees and a berillium window thickness of 12 microns were the parameters for this analysis. The data was normalized to K. Mineral standards were not available, therefore all analyses were strictly qualitative.

#### Clay Mineralogy

Petrographic analysis showed the authigenic clay content to be volumetrically insignificant. The average amount found in the sands is much less than 1%.

Six sandstone and six shale samples were prepared and scanned with an x-ray diffractometer to determine clay composition. The results indicate that illite, mixed-layer illite and smectite, kaolinite and chlorite are present.

An x-ray diffractogram of Mg saturated, glycerol

solvated clays from the shale intervals is shown in Figure 5. The strongest peak, which corresponds to a d-spacing of 3.34 Å, is from quartz. The remaining peaks are characteristic of clay minerals. The peak at 7.20 Å is either a first order kaolinite or second order chlorite peak. The peak at 10.04 Å is characteristic of illite. The peak at 13.87 Å corresponds to the first order reflections of several clays including chlorite, vermiculite, or interlayered vermiculite.

Upon heating the samples to 550° C, the large peak at 7.20 Å remained indicating that chlorite is present. When heated to this temperature the kaolinite structure collapses and its peak disappears, but if chlorite is present the peak remains.

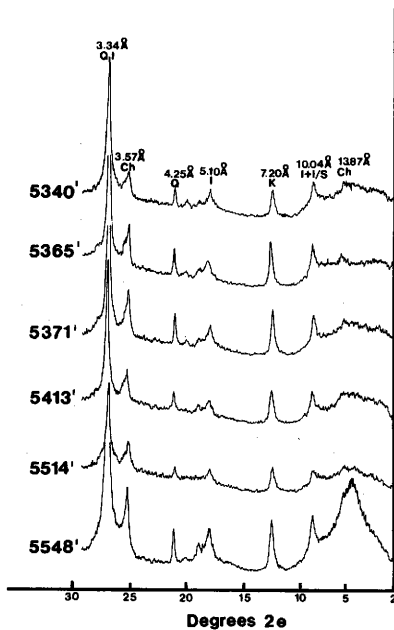
Semiquantitative estimates of the clay percentages were made on the basis of relative peak height. Estimates show that in the shale intervals kaolinite and illite are the dominant clays with averages of about 40% each. Chlorite averages about 10-15% of the total clay although in some samples the chlorite comprised approximately 20 to 30% of the clay fraction.

Authigenic clays in the Douglas Creek sandstones are rare, but when present, they occur as pore liners and fillers derived from interaction of pore fluids with volcanic rock fragment and feldspar. Some recrystallization





Figure 5 - X-ray diffractograms of clays from several shale intervals in unit 278. Diffractograms are of Mg-glycerol solvated samples. Q= quartz, K = kaolinite, Ch = chlorite, I = illite, S = smectite.



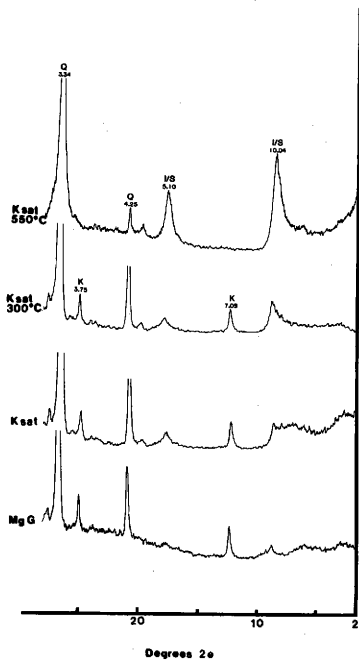
of detrital clays may have also occurred. X-ray diffraction shows that illite and kaolinite are the primary clay minerals within the sandstones (Figure 6). SEM analysis showed that illite and illite/smectite clays occur as pore fillers although they never completely fill the pores. Kaolinite most often occurs as small aggregates that are alteration products of rock fragments. These aggregates sometimes are vermicular and are often confined within the altered grain. Occasionally kaolinite formed on detrital grains and along with illite was incorporated into quartz overgrowths (Figure 7a). In many instances kaolinite has been incorporated into the overgrowth. This observation does not necessarily mean that it formed simultaneously, since the quartz may have formed around the clay material, though it may be safe to say that at least some clay formed during or before silica cementation. Chlorite was occasionally detected in thin section as a thin grain coating but was never found during SEM analysis.

X-ray diffraction patterns for the clay fraction from the sandstones indicates that illite is the dominant clay mineral and averages of about 50% of the clay fraction. Kaolinite follows illite in abundance with an average of 30-40% and chlorite averages less than 10%.

Clay authigenesis in the Douglas Creek sandstones appears to have taken place both early and late in the



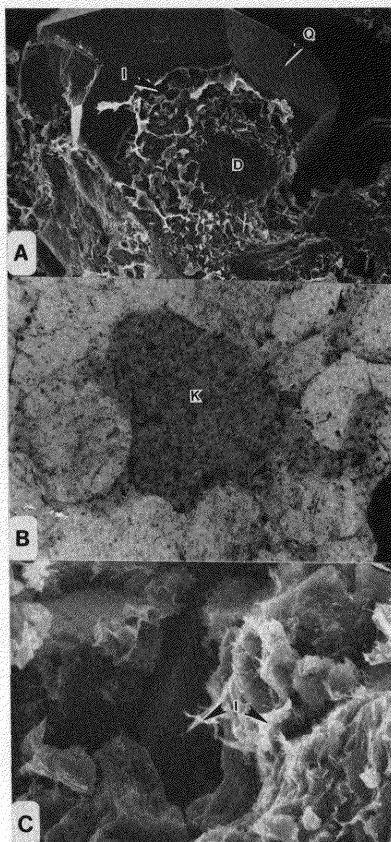
Figure 6 - Typical x-ray diffractograms at varying conditions of saturation and temperature for the clay fraction (<2microns) of the sandstones. (RW278-5359)



/



- Figure 7a - Scanning electron photomicrograph of quartz overgrowth (Q) engulfing authigenic clay (in this case illite, a common alteration product of volcanic rock fragments) on the surface of a detrital quartz grain (D). Its position (beneath the quartz overgrowth) indicates that clay authigenesis occur prior to or during silica cementation. Picture width 85 microns. (RW278-5450)
- Figure 7b - Thin section photomicrograph in plane polarized light of kaolinite (K) as an alteration product of detrital volcanic rock fragment. Individual kaolinite crystals are barely visible (arrow). The altered rock fragment has been deformed to take the shape of the enclosing grain boundaries. Picture width = 250 microns.
- Figure 7c - Scanning electron micrograph of authigenic illite (I) formed as a coating on detrital grains. (RW278-5450)



burial history where ever carbonate cement was absent. Early diagenesis included the formation of illite/smectite and/or kaolinite on grain surfaces and within altered grains during or before silica cementation. The formation of kaolinite favors an acidic environment while illite/smectite precipitation favors an alkaline environment. At near-surface conditions the pore waters would tend to be acidic due to influences from slightly acidic meteoric water.

The shales in the Green River Formation vary widely in their color as seen with the naked eye. Using the color scheme outlined by the Society of Economic Paleontologists and Mineralogists, it was found that the shales in unit 278 range in color from light greenish-gray to olive-black. X-ray diffractograms were obtained from bulk shale samples of varying colors. It is difficult to arrange the shales into colors in a meaningful way. But if the shales are arranged from lightest to darkest and from green to black then a correlation can be seen relating composition to color, however subjective it may be. The main constituents of the bulk shale samples are quartz, calcite, ankerite, illite/smectite, orthoclase, and kaolinite. Most of the shales analyzed were made up exclusively of these minerals.

Shales with lighter shades of color, especially those with a greenish hue can be associated with a high

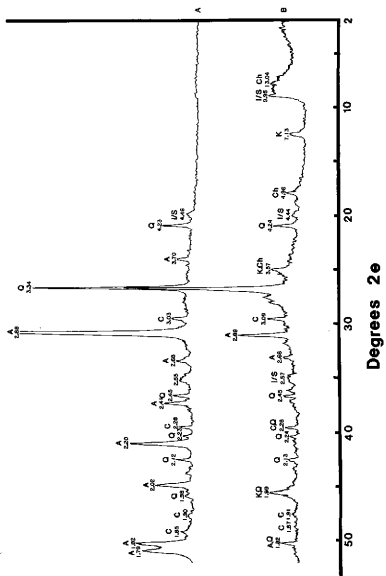
ankerite, calcite, and quartz content and a low clay content (Figure 8a). Shales at the other end of the color scheme, those being darker have significantly more clay minerals and less ankerite, calcite, and quartz (Figure 8b). There tends to be a continuum of these compositions between light green and black shales. So in essence those shales with lighter color have a higher carbonate content than those with a darker color.

#### Clay Morphology and Distribution

Optical petrography is not very useful for analyzing clay morphology due to its limited resolution at high magnification. Scanning electron microscopy is much better suited for clay morphology analysis due to its greatly increased resolution over a large range of magnification. kaolinite was easily identified by its large, distinctive crystals which occur as pseudohexagonal plates. It occurs as a pore lining clay and rarely fills the pores. Kaolinization of rock fragments was commonly seen (Figure 7b, pg.41). Illite was recognized as irregular aggregates appearing in a "cornflake" morphology (Figure 7c, pg.41). Illite is likely the result of alteration of rock fragments or of kaolinite (Dunoyer de Segonzac, 1970). Dunoyer de Segonzac noticed that when associated with kaolinite, illite alters the booklets around the periphery of the



Figure 8 - Bulk x-ray diffractogram of a light green shale(A). Note the large peaks that represent the carbonate minerals and the absence of clay mineral peaks. RW278-5573. Bulk x-ray diffractogram of a dark shale(B). Note that it contains smaller carbonate mineral peaks and larger clay mineral peaks. Q = quartz, C = calcite, D = dolomite, A = ankerite, K = kaolinite, I = illite, S = smectite, Ch = chlorite. RW278-5365



cluster while leaving the interior booklets intact. This type of association was not observed in the samples, but instead illite occurs as a pore lining clay on the surfaces of detrital quartz grains. Chlorite was not observed during SEM analysis although its presence was observed occasionally within altered volcanic rock fragments.

#### Secondary Rock Property Measurements

Secondary rock property measurements for the intervals analyzed were accomplished with the aid of petrographic analyses and core analyses data from by Core Laboratories of Dallas, Texas. Petrographic analysis gives an average of 6.2% porosity which is much less than the 12 % reported by laboratory tests. Petrographically determined porosity is always lower than the effective porosity determined by core laboratories because of limits of resolution. Therefore all porosity values used in this study were derived by core analysis unless otherwise specified. Fluvial and deltaic sands have porosities which average 11 % and 13 % respectively. Most samples measured have porosity in the 9 to 17 % range. Those intervals that exhibited coarse grains and/or low detrital carbonates have the highest porosities regardless of the facies in which they were deposited. Permeabilities for all samples studied average 40 md (Appendix 1).



DIAGENESIS OF THE DOUGLAS CREEK MEMBER  
OF THE GREEN RIVER FORMATION

The Douglas Creek sandstones at Red Wash field have undergone considerable post-depositional alteration. After the petrographic and mineralogic analyses, a history including several episodes of diagenetic activities become apparent. During, or shortly after deposition, diagenesis began in the Douglas Creek sandstones.

Mechanical Diagenesis

Early mechanical processes imposed on these sands were grain rotation and slippage. These mechanisms reduced primary porosity to an average of 25 to 30 percent. The clean, carbonate poor sands experienced an early episode of silica cementation. In the absence of matrix or carbonate cement, silica-rich waters were able to move through the pores and deposit silica in the form of quartz overgrowths. The silica rapidly inhibited compaction and preserved much of the original porosity from further reduction and permanent loss. Porosity after compaction and before cementation can be calculated using the expression:

$$\phi_o = \phi_p + \text{cement}$$

where  $\phi_o$  is porosity before cementation,  $\phi_p$  is present porosity and cement is present cement. By applying this

equation some of the samples showed porosities (before cementation) approaching 30 percent.

Clean, uncompacted, uncemented sands commonly have porosities ( $\phi_p$ ) approaching 45 percent, therefore, it becomes apparent that mechanical processes are responsible for about 15 percent loss in primary porosity. This equation assumes that no framework grain dissolution has occurred, and therefore it is only usable in sandstones that have not experienced this process.

Brittle grain deformation was apparently a minor contributing factor to reduction of primary porosity and but was not observed. Ductile grain deformation, the most common primary porosity reducing mechanism, resulted in "squeezed" rock fragments. Unstable volcanic rock fragments were often deformed when exposed to the compacting pressures and took the shape of the surrounding pores (Figure 9a). McBride (1978) claims that up to 15% of primary porosity may be lost due to this mechanism, but the volume of volcanic rock fragments in these sands was probably not large enough to significantly reduce primary porosity. Although elastic deformation of mica grains was common, the percentage of micas is low. Evidence for brittle grain deformation was not encountered in the Douglas Creek sandstones.

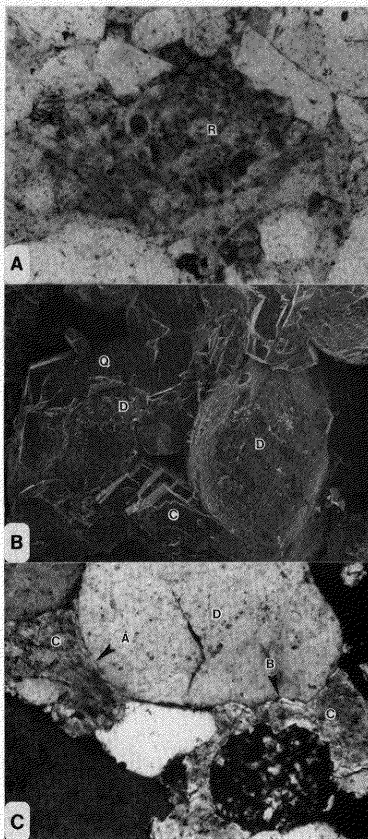
Grain contacts between framework grains in the



Figure 9a - Thin section photomicrograph in plane polarized light of altered volcanic rock fragment whose shape has conformed to the surrounding grain boundaries due to overburden pressures. Picture width = 250 microns.

Figure 9b - Scanning electron micrograph of the two dominant cementing agents, carbonate (probably calcite(C)), and quartz (Q). Calcite occurs as blocky crystals that fill intergranular pores while quartz forms as a thin rind that is syntaxial with the detrital quartz grains (D). Picture width = 60 microns. (RW278-5294)

Figure 9c - Thin section photomicrograph in cross polarized light of apparent interaction between calcite cement (C) and a detrital silicate grain (D). The arrow at (A) points to unaffected quartz overgrowth while the arrow at (B) points to a ragged grain boundary that indicates replacement of the silicate grain by calcite cement. Picture width = 250 microns.



Douglas Creek sandstones are point or line contacts with each grain touching an average of 2 to 4 adjacent grains. Sutured contacts, an indication of extreme pressure and pressure solution, were not found in these sandstones. This may be the result of early silica and later carbonate cements that reduced the stresses at points of grain contact and eliminated the effects of pressure solution. This idea is supported by work done by Smith (1983) on some Miocene sandstones in southern Louisiana.

#### Chemical Diagenesis

Chemical processes during the diagenesis of the Douglas Creek member included precipitation of cements, replacement of detrital grains and dissolution of detrital grains and cements. Chemical diagenesis is the principal factor controlling the present state of the sandstone.

Carbonate cement is widespread and abundant in the Douglas Creek sandstones comprising up to 22% of the bulk volume. Petrography, SEM, and x-ray analysis indicate that two forms of carbonate cement occur. Calcite, the most abundant, is found as a sparry cement (Figure 9b). Energy dispersive x-ray analysis indicates the calcite is low in magnesium and iron composition (Figure 4c, pg. 31). This differs from the iron-rich calcites encountered by Pitman et al (1982) at nearby Pariette Bench. Dolomite, as cement,

occurs as recrystallized calcite cement or detrital grains. In sandstones with high detrital carbonate, most of the cement occurs as fine-grained dolomicrite. Most detrital carbonate particles have been converted from calcite to dolomicrite.

Carbonate cement occurs in all samples analyzed and ranges from patchy remnants to complete cementation of all primary porosity and takes the form of both interstitial and replacive cement. This variation is controlled in part by the original sand composition. Those with the lowest porosities generally had the highest detrital carbonate composition which contributed large amounts of carbonate material for recrystallization as intergranular cement. The interstitial cements take several forms. In sandstones with well developed secondary porosity, the cement occurs as small poikilotopic patches that fill individual pores. Cements in this form are usually clean with no clay material included within them indicating that, at least in these sandstones, calcite cementation took place before clay authigenesis. Another form that interstitial cements often take is that of carbonate micrite usually of dolomite composition. These cements fill the interstitial pores of sands containing a high percentage of detrital carbonates, and exhibit a finely crystalline, granular texture. In some cases it is difficult to determine whether the micrite is

of detrital or authigenic origin although the occurrence of small amounts of clay material indicate that it is probably recrystallized calcite mud. Wolfbauer and Surdam (1974) indicate that dolomite may have precipitated in an environment of intense evaporation and was either precipitated directly out of solution or simply replaced detrital calcite. Water drawn up from the water table evaporated and concentrated  $Mg^{+}$  in the upper part of a unit.

In many cases the silicate grains show evidence of replacement by calcite. This type of replacement is characterized by the sawtooth appearance of framework grain boundaries and gives evidence of previous calcite cement (Figure 9c). Since these features are common in many samples including those that presently contain little calcite cement, it can be inferred that calcite was widespread at one time. In the most extreme cases of grain replacement "floating" framework grains developed by systematic replacement of much of the grain by calcite. This degree of replacement is uncommon in these samples although, where it does occur, it is well developed.

Dissolution of detrital silicate grains and precipitation of carbonate cement can occur simultaneously as the result of certain chemical and thermal conditions. The solubility of quartz increases with increasing temperature and pH. Conversely, carbonate cement decreases in solu-



bility with increasing temperature and pH. Increasing depth is accompanied by temperatures which drive  $\text{CO}_2$  out of solution. As  $\text{CO}_2$  is decreased, the pH may be raised to the point at which carbonates can precipitate. Silica can be dissolved at the same time that carbonates are precipitating and replacing it. The abundance of carbonate cement in sands with large amounts of carbonate detritus indicates that the source was local rather than external. The main source of carbonate cement was probably the dissolution of ooids, shell fragments and carbonate clasts. Detrital dolomite or circulating magnesium-rich water which selectively replaced calcite may have been the sources of dolomite cements.

Silica cement has precipitated in sands containing small amounts of detrital carbonate and usually takes the form of optically continuous syntaxial overgrowths on detrital quartz grains. In most instances silica forms as a thin rind that leaves large pores between grains, but if the overgrowths are allowed to continue to develop, prismatic crystal faces and terminations become apparent. Blatt (1979) indicates that silica cementation occurs at shallow depths of burial and therefore considerable volumes of primary porosity may be saved.

Silica cement does not seem to favor either facies but is most common in the coarser fractions of both. Fine-

grained sands and those containing large percentages of detrital carbonate material contain the least amount of silica cement, while the coarse, clean sands found in the upper few feet of the deltaic and lower portions of the fluvial sands showed the highest degree of silica cement. Petrographic evidence agrees with Blatt's findings in suggesting that silica cementation occurred simultaneously with compaction and retarded it to some degree.

Numerous possibilities exist for the source of silica cement. Blatt (1979) described several possible sources. Alteration or dissolution of volcanic rock fragments and feldspar may be one source. This possibility is strengthened by the presence of rock fragments throughout the interval. Another possible source is the circulation of silica rich water expelled from nearby shales during compaction. Although thick shale units are abundant in and around these sands, appreciable burial depth and the pressures necessary for significant water expulsion probably had not occurred at the shallow depth at which silica cementation developed. Silica from pressure solution and thermal clay dehydration are other reactions that may make silica available for cement, but the importance of these reactions can probably be discounted in this study since the temperatures ( $220^{\circ}\text{F}$ ) and pressures needed to induce those reactions are not encountered until depths

much greater than those at which cementation occurred (Burst, 1969). Vertical migration of such silica-rich fluids probably did not occur since the sandstones are enclosed by thick sequences of impermeable shale.

The most probable source is the release of silica from the alteration of unstable volcanic rock fragments and feldspars. Optical petrography and scanning electron microscopy revealed abundant partially dissolved rock fragments and feldspars.

## CONTROLS ON DIAGENESIS

### Factors Controlling Diagenesis

The sequence of diagenetic events can be summarized in several steps. The sequence of events in a given sand may follow one of the two paths outlined in Figure 10 depending on the original sandstone composition. This interpretation is based on SEM and petrographic analysis. Several factors control the processes of diagenesis in the Douglas Creek member. The controls are:

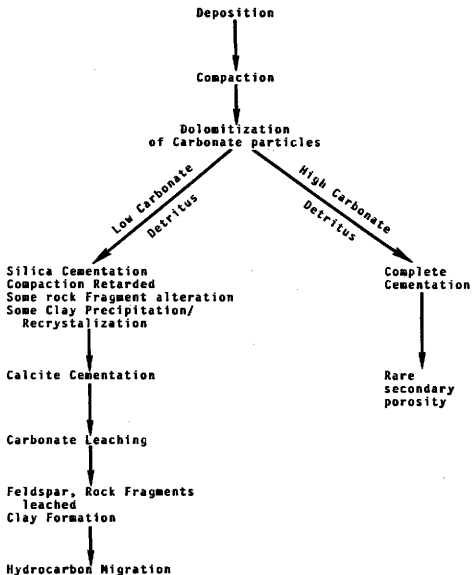
- 1) Textural features: Grain size seems to play a role in determining the degree of secondary porosity present.
- 2) Detrital composition: the degree of cementation is controlled by the amount of detrital carbonate particles.
- 3) Flow rate: the rate of flow of interstitial pore fluids has influenced the rate of chemical reactions.

### Secondary Porosity Analysis

Diagenesis has played an important role in porosity and permeability development in the Douglas Creek sandstones. Initially all the primary porosity was destroyed



Figure - 10 Sequence of diagenetic events at Red Wash  
Unit 278.



by the combined effects of mechanical and chemical diagenesis. In sands with few detrital carbonate particles mechanical compaction was arrested by early silica cementation and some primary porosity was spared. Later the remaining primary porosity was filled with calcite cement which eventually reduced primary porosity to irreducible values. Development of secondary voids can be attributed to nearly complete dissolution of interstitial carbonate cements and dissolution of some rock fragments and feldspars. The fact that secondary porosity is so widespread in this case is presumably because interstitial fluids were able to move along cement/grain boundaries and begin to dissolve the cement. In the situation described below where carbonate detritus is more abundant the ability of interstitial fluids to move was inhibited because the bond between carbonate cement and particles (compatible cement) is more complete. This results in fewer paths for dissolving fluids to follow and perform their task of dissolution. Development of secondary porosity is nearly equal in the fluvial and deltaic facies, so controls on porosity can therefore be attributed primarily to original composition and texture. The porosity in sandstones containing large amounts of detrital carbonate was not spared by early silica cementation and as a result were destroyed by mechanical compaction, recrystallization and precipitation



of the carbonate material.

Clays, in this study, play a very minor role in the control of porosity and permeability. Clays, when present, will restrict the flow of interstitial fluids and result in reduced permeability. With petrographic results indicating that authigenic clay composes less than 1 percent of the bulk rock and permeabilities averaging 40 millidarcys, it is clear that clay does not play an important part in the control of permeability in the samples studied.

#### Secondary Porosity Development

Porosity is found in all samples analyzed. Petrographic analysis yielded an overall porosity estimate of 6.2% while core laboratory test results showed 12%. The bulk of all porosity was secondary in origin. Slight variations in porosity were found between the two facies with the fluvial sandstones containing 11% and the deltaic 13% porosity. This variation is slight compared to the variation in porosity found within each facies. The porosities in both facies are controlled to a great degree by carbonate cement. Sandstones that are low in carbonate cement generally exhibit higher porosities than those that are well cemented. Furthermore, cement distribution appears to be controlled by depositional factors. High porosity (>15%) in either facies is characteristic of sand with mean

grain size larger than .20 mm. Good porosity was able to form in sands containing large or small amounts of detrital carbonate if the grain size was large enough (larger than .20 mm).

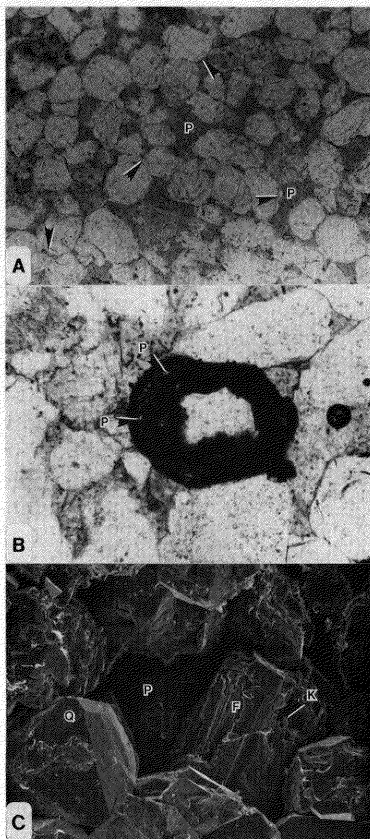
Primary porosity is uncommon in the samples analyzed and occurs as incompletely cemented pores. Secondary porosity occurs in several textures including intergranular pores, intragranular pores, and shrinkage fracture pores. Although porosity occurs both in clean and clay-filled pores clean pores are dominant. Porosity in clay-filled pores is classified as microporosity which consists of minute pores between clay crystals and particles.

Intergranular porosity is the most abundant form of secondary porosity and occurs as leached authigenic cement (Figure 11a). In both facies, intergranular pores were found to contain little authigenic clay.

Intrapartical porosity is the second most common porosity type, and occurs as differentially dissolved ooid layers (Figure 11b) or as altered volcanic rock fragments and feldspar (Figure 11c). Nearly all altered volcanic rock fragments contain authigenic kaolinite and dolomite surrounded by micro-intrapartical porosity which is similar to normal intrapartical porosity except that micro-intrapartical porosity has a much finer texture. In many cases the blue epoxy used to aid in porosity analysis can



- Figure 11a - Thin section photomicrograph in plane polarized light showing typical secondary intergranular porosity (P) found in a sandstone that contains only small amounts of carbonate detritus. Arrows point to well developed quartz overgrowths that appear as thin rinds on the quartz grains. Picture width = 1.5 mm. (RW278-5261)
- Figure 11b - Thin section photomicrograph in plane polarized light of secondary porosity (P) found between concretionary layers in an ooid. Picture width = 250 microns.
- Figure 11c - Scanning electron micrograph of a detrital plagioclase(?) feldspar grain that has experienced some dissolution which has given it a honeycombed appearance. P = intergranular pore, Q = quartz overgrowth, K = kaolinite. Picture width = 60 microns. (RW278-5307)



scarcely be seen in these extremely small pores. Micro-intrapartical porosity constitutes approximately 5 % of the total porosity.

Shrinkage porosity, the rarest texture, occurs as thin fractures propagating along boundaries of clay or siltstone clasts. Presumably dewatering of the shales in the clasts caused them to shrink and form porosity.

#### Secondary Porosity, Grain size, and Facies relationships

A plot of secondary porosity versus grain size in the sandstones gives a correlation coefficient of .65 which is quite low (Figure 12). Figure 13 shows the relationship between secondary porosity and total cement. Despite the low correlation coefficient of .42, it appears that secondary porosity is greater in sands with larger grain sizes and smaller volumes of cement. The two properties are indirectly proportional to one another in a log relationship.

The facies in which a given sand was deposited, whether it be fluvial or deltaic, apparently does not place any controls on the present porosities and permeabilities. Porosity and permeability are primarily controlled by grain size and detrital composition.



Figure 12 - Plot of secondary porosity versus sandstone  
grainsize. (RW278)



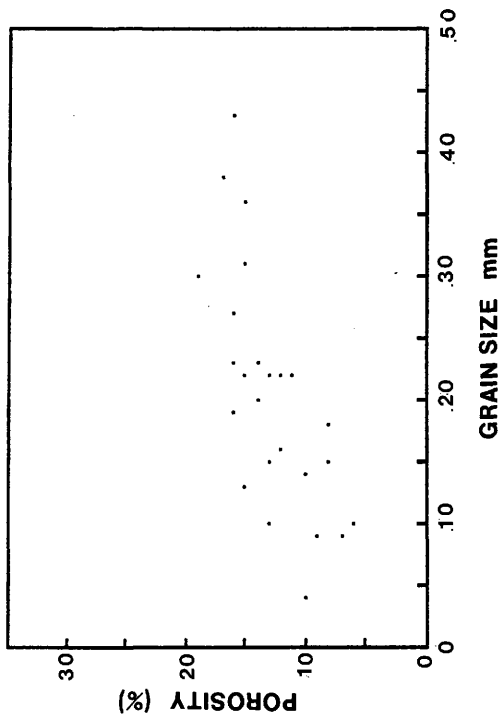
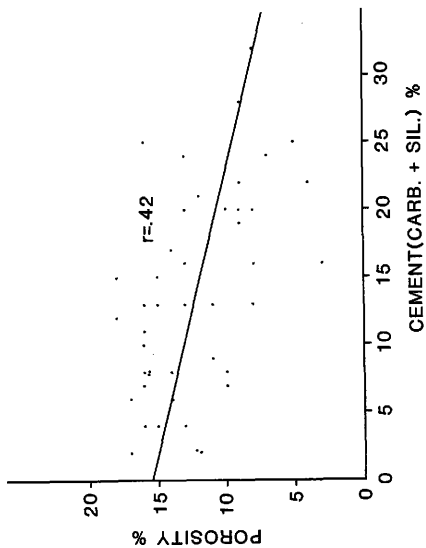




Figure 13 - Secondary porosity versus total cement in the sandstones.



### Sequence of Diagenetic Events

Petrographic and mineralogic analyses suggest that the Douglas Creek sandstones at Red Wash field have undergone the following diagenetic sequence (Figure 10, page 59).

- 1) Onset of mechanical compaction.
- 2) In samples with low detrital carbonate composition (Figure 14).
  - A) Mechanical compaction halted by silica cementation shortly after deposition. Some clay mineral authigenesis or recrystallization.
  - B) Dolomitization of ooids, shell fragments, and other carbonate particles.
  - C) Calcite cementation.
  - D) Carbonate leaching.
  - E) Feldspars and rock fragments leached and clay authigenesis.
  - F) Migration of hydrocarbons.
- 4) In samples with high detrital carbonate composition (Figure 15).
  - A) Recrystallization and dolomitization of carbonates and complete cementation of rock.
  - B) Some secondary porosity created within carbonate particles.

The early arrest of mechanical compaction by silica cementation is indicated by the general loose packing of the sandstones. This is especially true of the high quartz



Figure 14 - Stages of burial diagenesis within sandstones containing small volumes of detrital carbonate material.

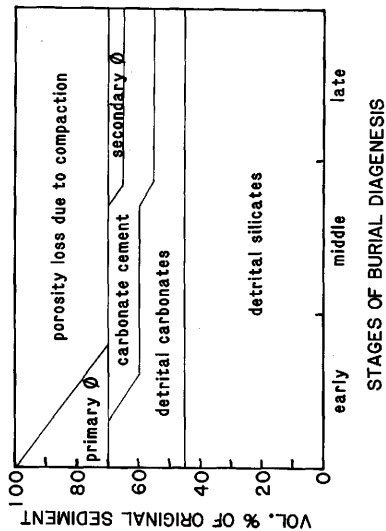
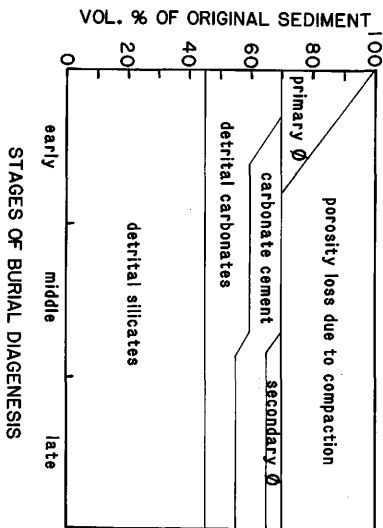






Figure 15 - Stages of burial diagenesis within sandstones  
containing large volumes of detrital  
carbonate material.



sandstones. At least some degree of clay authigenesis at this point can be inferred by the incorporation of clay crystals into the quartz overgrowths. As discussed earlier, dissolved silica has several possible sources. Partial dissolution of feldspars and rock fragments are the most probable sources.

In sandstones containing low percentages of detrital carbonate material the next diagenetic event was dolomitization of carbonate particles that created some secondary porosity. Using SEM techniques it seems evident that as the interiors of many carbonate particles (such as ostracodes and ooids) recrystallized intraparticle porosity was produced.

Carbonate cement followed silica as calcite recrystallized and filled all remaining porosity. This change in cement phases indicates a change in pore fluid chemistry from acidic to alkaline. One possible mechanism responsible for this change is an increase in pH and/or an increase in dissolved carbonate matter. Etched surfaces on many quartz grain boundaries gives evidence of widespread calcite cementation. Many samples that presently contain little or no calcite cement exhibit this feature. At the onset of silica cementation, the pore waters were likely of low pH as would be found in near surface conditions under the influence of meteoric flushing. Under such conditions

calcite would be highly soluble. But later, as depth of burial and temperature increased the pH began to increase to the point at which calcite could no longer remain in solution. At the end of this period of calcite cementation most primary porosity had been significantly reduced.

Calcite dissolution followed as the next diagenetic event after its formation. In the quartz-rich sands this dissolution was nearly complete. Most quartz-rich samples contain remnant calcite which is restricted to small isolated patches. Calcite dissolution was accompanied by rock fragment alteration and the formation of clay minerals that are usually confined to the interior of altered rock fragment. Rock fragment alteration in the carbonate-rich samples is not evident primarily because pore fluids were restricted in their movement.

Several mechanisms responsible for calcite dissolution are possible. The dilution of pore waters by expelled shale waters during compaction, or an increase in  $\text{CO}_2$  resulting from hydrocarbon generation are two possibilities. The abundant kerogen-rich shales near by strengthen the possibility that hydrocarbon generation is the source of acidic waters. Quartz-poor (high detrital carbonate) samples did not experience the same degree of dissolution, and often showed little or no secondary porosity development except in rare cases of dissolution between ooid concret-

ionary layers.

## CONCLUSIONS

The Douglas Creek sandstones at Red Wash field have experienced significant alteration since burial. From a textural and mineralogical study the following conclusions are drawn:

- 1) The sandstones are quartz arenites to sub-litharenites in composition.
- 2) Reservoir quality is, to a large degree, controlled by the diagenesis of the sandstones.
- 3) Diagenesis has been controlled largely by the sandstone textural properties and detrital composition regardless of whether the depositional environment was fluvial or deltaic.
- 4) Early silica cementation reduced the effects of compaction in some sandstones.
- 5) Large amounts of detrital carbonate material in the sandstone prevented silica cementation and caused increased primary porosity loss by carbonate recrystallization.
- 6) The distribution of carbonate cements controls porosity and permeability.
- 7) Present porosity is of secondary origin, and is dominated by intergranular pores produced by carbonate dissolution.
- 8) Clay minerals, both detrital and authigenic, are

rare. Kaolinite, illite and mixed-layer clays are present in small amounts.

- 9) Fine-grained sands, and those containing large volumes of detrital carbonate material exhibit poorly developed secondary porosity. Coarser grained sands have higher secondary porosity.
- 10) The introduction of  $\text{CO}_2$  derived from maturing hydrocarbons may have created fluids able to dissolve the carbonate cement.
- 11) Similarities in the diagenetic minerals and diagenetic sequences between the fluvial and deltaic facies suggest that depositional environment, in the broad sense, played a minor role in diagenesis. Both fluvial and deltaic sediments contain sands in a wide range of textures and compositions, and in this respect, depositional environment had an indirect role in controlling diagenesis.



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## APPENDIX

## PETROGRAPHIC ANALYSIS

Depth Ft	Grainsize mm		Detrital Composition							Auth. Comp.			Porosity Pet's Lab	Perm. md
	Max	Mean	Qtz %	F %	RF %	Clay	Och	Si %	Cal %	Dol %				
5258	1.02	.27	68	2	5	-	3	1	3	7	9	11	9	1.25
5261	1.1	.28	71	2	12	-	1	-	3	4	-	11	15	104.17
5264	.75	.15	62	2	14	-	1	-	3	22	7	13	10	3.17
5265	.45	.14	64	3	11	-	1	-	-	-	20	-	10	5.09
5270	.25	.16	83	5	8	-	1	-	-	-	2	-	15	12
5274	.18	.10	104	61	6	7	-	1	1	6	18	-	6	.07
5283	1.32	.42	63	1	16	-	1	-	1	5	14	20	10	50.
5284	.17	.09	60	5	6	-	2	-	4	12	16	-	4	-
5289	.60	.30	64	2	11	-	1	-	-	4	11	8	15	10.
5295	.23	.13	94	97	5	-	1	-	-	3	10	3	10	1.60
5299	.59	.29	75	5	5	-	2	-	-	15	7	-	14	.04
5299	.59	.24	68	3	5	-	1	-	-	15	7	-	14	.04
5307	.17	.08	83	24	-	-	68	-	-	8	0	-	13	19.
5309	.27	.15	84	2	6	-	T	3	-	1	3	10	13	64
5317	.40	.23	82	1	2	-	-	-	6	5	6	13	14	41.
5323	.75	.23	71	2	3	-	1	20	-	T	2	-	12	1.59
5324	.20	.11	93	73	1	-	1	-	7	9	9	-	16	46.
5326	.35	.22	96	73	2	4	1	T	5	10	2	9	13	41.
5327	.33	.10	95	70	3	-	4	-	-	3	21	1	13	3.87
5328	.36	.09	93	3	2	-	4	-	-	2	4	-	10	41.
5328	.46	.22	76	4	3	-	14	-	-	6	2	9	11	1.06

## Red Wash Unit 278 (continued)

Depth Ft	Grainsize mm		Qtz			Detrital Composition			Si	Auth. Comp.		Porosity Pett Lab	Perm. md
	Max	Mean	Qz	P	RF	Clay	Oth	Ooid		Cal.	Dol.		
5334	.24	.14	72	7	9	-	2	1	6	2	1	T	-
5345	.41	.10	9	-	1	-	52*	22	-	12	4	2	4
5351	.50	.23	57	-	9	-	5	-	3	21	4	1	9
5356	.24	.12	33	1	21	-	9	24	-	2	11	T	1
5358	.41	.13	76	4	3	-	1	21	-	19	11	T	18
5359	.40	.18	51	2	19	-	10	4	-	12	1	T	8
5364	.37	.19	76	3	8	-	2	-	6	3	2	1	11
5368	.39	.22	86	3	3	-	4	-	1	1	-	2	17
5381	.28	.15	65	4	5	5	4	-	1	1	-	7	15
5384	.28	.15	65	4	5	5	4	-	1	1	-	7	15
5386	1.00	.17	74	3	2	-	3	10	5	1	1	1	16
5388	.45	.20	49	1	4	-	10	19	4	1	8	2	13
5389	.44	.22	68	2	7	-	26	41	-	10	1	T	18
5391	.25	.05	72	8	9	2	1	7	5	4	2	1	12
5392	.25	.05	72	8	9	2	1	7	5	4	2	1	12
5393	.31	.16	72	3	6	-	7	-	-	3	13	T	18
5396	.58	.21	28	3	6	-	7	-	-	2	10	T	15
5398	.58	.23	28	3	6	-	7	-	-	2	10	T	15
5399	.58	.23	28	3	6	-	7	-	-	2	10	T	15
5403	.38	.09	20	68	8	1	2	22	1	1	2	6	17
5433	1.04	.38	80	-	10	-	5	-	-	5	19	-	7
5436	1.12	.43	77	1	7	-	8	-	2	4	-	T	16
5438	.70	.36	79	3	8	1	4	-	1	7	-	-	15
5447	.73	.20	86	5	-	1	1	-	1	3	2	-	14

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