CORRELATION OF SEQUENCE STRATIGRAPHIC SURFACES OF THE MID-CRETACEOUS DAKOTA GROUP FROM SUBSURFACE TO OUTCROP SOUTHERN DENVER BASIN, COLORADO

by

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Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN GEOLOGY

THE UNIVERSITY OF TEXAS AT ARLINGTON

August 2011

ACKNOWLEDGEMENTS

My great gratitude is to Allah for his blessings and guidance. Then I'm grateful to Dr. John Holbrook my thesis advisor and committee chairman for his unlimited help, assistance, advice and patience. Also, I would like to thank him for providing me with his well-logs, outcrop cross-sections, and papers which helped me greatly in my research. I would also like to thank my committee members Dr. John Wickham and Dr. Harold Rowe for their participation and help in my thesis.

Special thanks to Kuwait University for sponsoring my scholarship and giving me the opportunity to peruse my higher education in the United States of America. Also a special thanks for Denver Earth Resource Library for giving me access to their well-log database and their journal and book collections.

I would like to dedicate this thesis to my beloved family especially my parents (Yousef Alrefaei, Mariam Ali) whom I could not made it without and whose prayers and encouragement sustain me. Most of all, I wish to thank my dear wife Hanan and children Mariam and Yousef for their patience, sacrifices, help and endless support.

May 9, 2011

ABSTRACT

CORRELATION OF SEQUENCE STRATIGRAPHIC SURFACES OF THE CRETACEOUS DAKOTA GROUP FROM SUBSURFACE TO OUTCROP SOUTHERN DENVER BASIN, COLORADO

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The D and J sandstone of the Cretaceous Dakota Group are considered as the major oil and gas producing units within in the Denver Basin. Denver Basin is a sub-basin of the Early Cretaceous Western Interior Basin .These units are well understood within the northern Denver Basin and the linkage between the subsurface units and their equivalents in outcrop in the Front Range is well-established. These strata have gained less attention in southern parts of the basin and the linkage between the subsurface units and their equivalents in southern outcrop is not yet established. The main purpose of the study is to investigate the linkage between the subsurface Dakota Group units within the southern Denver Basin and their equivalents in outcrop of southeastern Colorado. This was achieved by correlating sequence stratigraphic surfaces within Dakota Group strata in the Denver Basin using well-log data and then correlating these surfaces with their age-equivalents in outcrop of southeastern Colorado. By proving this linkage, a better understanding for the correlation of Dakota Group strata from subsurface to outcrop is represented in the southeastern part of Denver Basin which can be used as a tool in future research in the area and can forward regional paleogeographic reconstruction for this time interval. Paleogeography, deposition and distribution of the J and D Sandstone were illustrated in the study using the Buffer and Buttress model. Valley intersection of different generation at the same stratigraphic level in both the J and D Sandstone were observed in the study area and were explained also by using the Buffer and Buttress model. The subsurface Huntsman Shale continuation in southern the Denver Basin to surface exposure in southeastern Colorado outcrops was supported based on thickness trend, fossil assemblage, and facies which constrained the correlation of the subsurface Dakota Group units with their surface equivalents in outcrop southeast Colorado.

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CHAPTER 1

INTRODUCTION

The mid-Cretaceous (Albian-Cenomanian) Dakota Group consists of marine and non-marine siliciclastic units that record deposition of the Kiowa-Skull Creek eustatic cycles during early formation of the Cretaceous Western Interior Seaway (Holbrook,1992) (Fig. 1). This Basin extended from the Arctic to the Gulf of Mexico and from central Utah to eastern Kansas by late Cretaceous (Porter and Sonnenberg,1994) covering a distance about 3,000 Km (1,864.11 mi) of length (Miall, 2008). This basin was later partitioned by uplifts of the Laramide Orogeny in late Cretaceous. Dakota Group units crop-out in the Dakota Hogback on the western flank of Denver Basin (only the J "Muddy" Sandstone) (Clark,1978) ,northeastern New Mexico, southeastern Colorado, and in the Oklahoma panhandle (Holbrook,1992).

Subsurface Dakota Group units (the D and J Sandstone) are considered as the major oil and gas producing units throughout the Denver Basin (Sonnenberg,1987). Over 90% of total oil and gas production in Denver Basin is from D and J sandstone units of Dakota Group which yielded an estimated 1.5 billion bbl of oil-equivalent in the J 'Muddy' Sandstone alone in the years leading up to the early 1990's (Dolson et al.,1991). Production is mainly from stratigraphic traps within the D and J sandstone units with minor production from structural traps (Sonnenberg, 1987). Most of this production is from oilfields within the northern Denver Basin where the major productive oilfields are located (e.g. Wattenberg field). As a result of this major production, Dakota Group units are well understood and heavily studied in the northern part of Denver Basin (e.g. Martin,1965; Peterson and Janes,1978; Weimer et al.,1986;Weimer and Sonnenberg,1989;Sonnenberg,1987; Dolson,1991; Weimer,1992;Weimer et al.,1998;

Graham,2000;Higley et al. ,2003) and correlation between subsurface Dakota Group units and their equivalents (the J "Muddy" Sandstone only) in outcrop along the Dakota

Hogback and Colorado Front Range is already well established. The opposite situation is true in the southern and southeastern Denver Basin, where Dakota Group units gain less attention, the complexity of the Group increases, and production from these units is much lesser than the production from the northern oilfields. Because of this lack of drilling in the southern part of Denver Basin, very little detailed research has been conducted on Dakota Group units in the southern Denver Basin and the linkage between the subsurface units and their equivalents in outcrop in southeastern Colorado is still poorly understood.

An issue that is still not well-understood in the Denver Basin is the D Sandstone unit distribution and interpretation. The D sandstone major production is concentrated in the eastern flank of Denver basin where the unit is thick, whereas in northern and northwestern Denver Basin areas, production from this unit is very low because of the local-absence or near absence of the D Sandstone, -along with Huntsman shale-, in both subsurface and outcrop. Although potential equivalents of the D Sandstone and Huntsman Shale are in outcrops of southeastern Colorado, the linkage between these units and the subsurface is still not well established.

In this study, sequence stratigraphic surfaces within Dakota Group strata were correlated throughout the southern Denver Basin using well-log data. Strike and dip cross-sections and isopach maps were constructed and used to investigate the linkage between the subsurface Dakota Group and their equivalents in outcrop of southeastern Colorado. By proving this linkage, a better understanding for correlation and continuation of the Dakota Group from subsurface to outcrop can be represented in the southeastern part of the Denver Basin which can be used in turn as a tool in future research of the area and can forward regional paleogeographic reconstruction for this time interval particularly, this study will help elucidate the surface expression of the D Sandstone.

Fig. 1: The Cretaceous Western Interior Seaway extent during Late Cretaceous time (Henry and Finn, 2003)

1.1 The study area

The study area is located in the southern part of the Denver Basin, Colorado (Fig.2). The area covers about 10 counties with an estimated area of 552 square miles. It extends from I-70 near Denver, Colorado in the North to the Arkansas River in the South (township T1S to T22S), and from the Kansas-Colorado borderline in the East to the Colorado Front range in the West (range R47W to R71W).

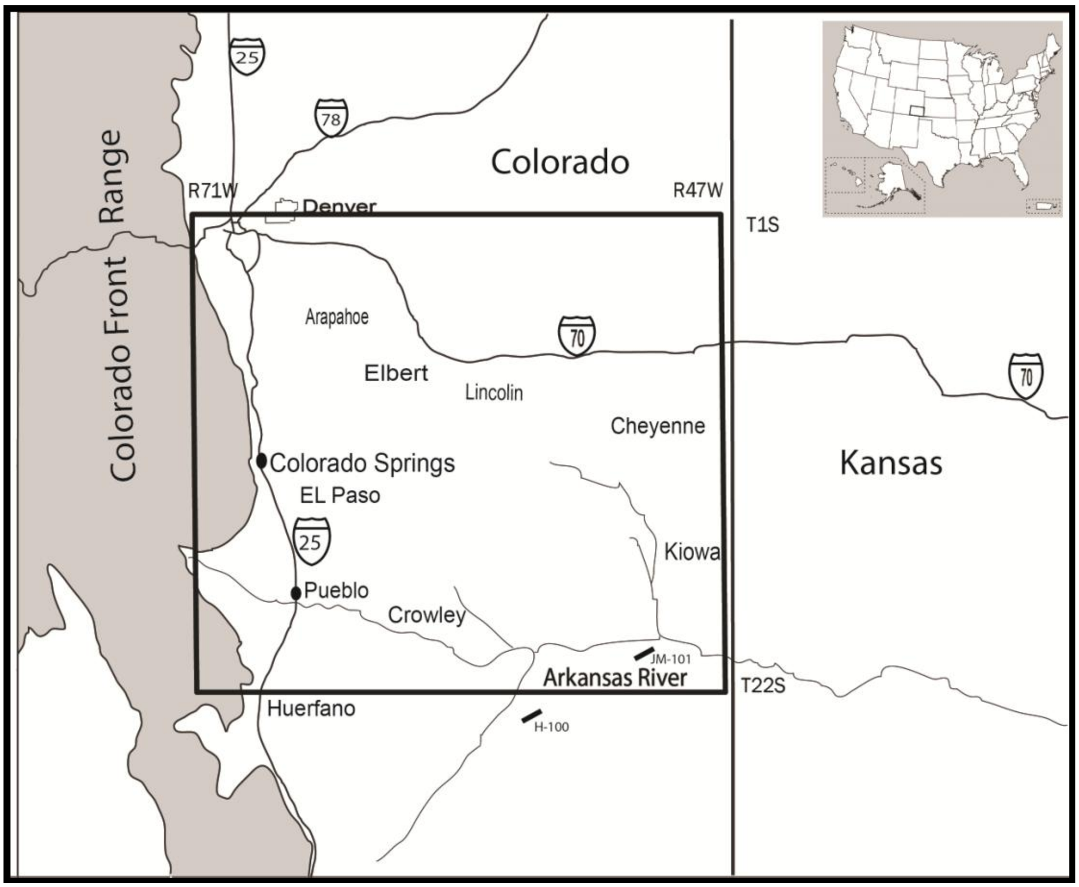

Fig. 2: Location of the study area and outcrop sections that were used in the study: JM-101= John Martin's Reservoir section, H-100= Higbee section.

1.2 Denver Basin

Denver Basin which is also known as the Denver-Julesburg or “D-J” basin (Graham,2000) (Fig.3) is a foreland basin that formed during Laramide orogeny (Sonnenberg,1987). This orogeny, which spanned from Late Cretaceous to Paleogene (75-50 Ma) (Lawton,2008) changed the paleogeography of Rocky Mountain region from an interior sea way to a number of smaller foreland structural basins partitioned by basement-cored uplifts (Lawton, 2008). The Denver Basin is one of the largest of these partitioned sub-basins (Kaufman,1977). These basins were later filled by fluvial and lacustrine deposits derived from the adjacent Laramide uplift blocks (Lawton, 2008) in the West and the East.

The basin is considered as one of the largest in Rocky Mountains region as it covers an area of about 70,000 square miles (181,000 Square Km) (Higley et al.,2003) and extends across parts of eastern Colorado, southeastern Wyoming, northwestern Kansas and the Nebraska panhandle. The basin is bordered by the Laramie Front Ranges from the West, the Hartville uplift from northwest, the Cambridge-Chadron arch from northeast, the Apishapa uplift from southwest, and by Las Animas arch from southeast (Fig.3). The Basin is asymmetrical with an axis parallel and close to the Front Range (Martin,1965). The eastern flank of the Basin is gently dipping 0.5° to the West, while the western flank is steeply dipping and faulted with 10° or greater (Weimer et al.,1998). The deepest point along the axis in Denver Basin is located near Denver, Colorado where it’s total fill is more than 13,000 feet thick of sedimentary rocks exist (Martin,1965).

Oil and gas production in the Denver Basin is mainly from the Cretaceous units. The majority of production is from D and J sandstone of the Dakota Group as previously discussed with a minor production from the Niobrara Formation. The main source rock for these Cretaceous units are Mowry Shale, Huntsman Shale, Graneros Shale, Greenhorn Shale, Carlile Shale, and Niobrara Formation (Clayton and Swetland,1980).

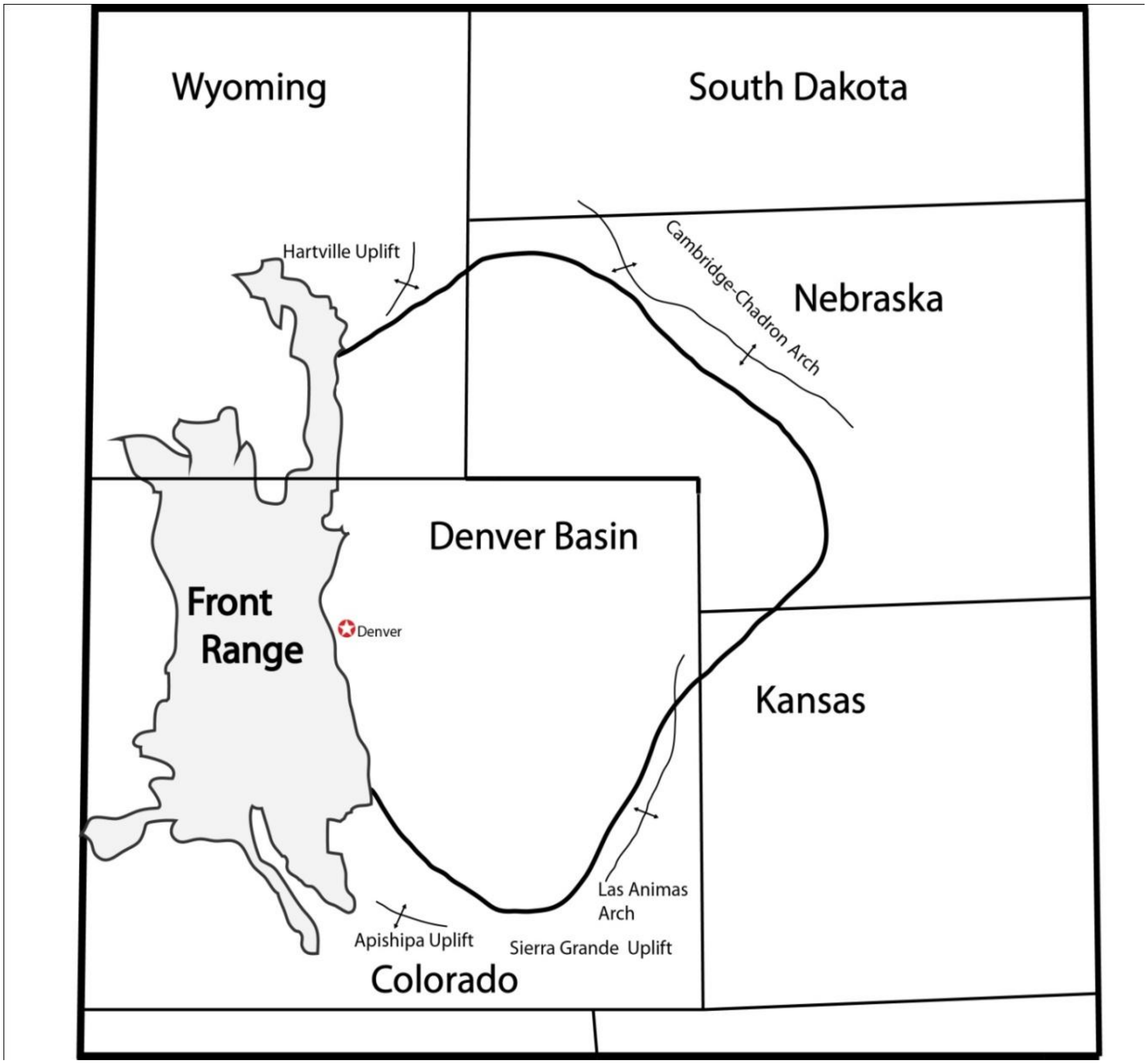

Fig. 3: Denver Basin outline and surrounding structural zones modified from (Martin, 1965).

1.3 Purpose

The main hypothesis which was tested in the study stated that “subsurface units (J sandstone, Huntsman, and D Sandstone) and sequence stratigraphic surfaces of Dakota Group in the southern Denver Basin subsurface correlate to their surface equivalents units (Mesa Rica Sandstone, Dry Creek Canyon, and Romeroville Sandstone) in outcrop of southeastern Colorado”. This hypothesis was tested by achieving the following:

1. Correlating sequence stratigraphic surfaces within Dakota Group units throughout southern Denver basin using well logs.
2. Indicating any changes in thickness within Subsurface Dakota Group units throughout southern Denver Basin.
3. Investigating the linkage between subsurface Dakota Group unit trends in southern Denver Basin and their equivalents in outcrop in southeastern Colorado.

By applying the previous tests, a better understanding of paleogeography and regional depositional model of the Dakota Group strata will be presented particularly for the D Sandstone unit. The correlation of sequence stratigraphic surfaces within Dakota Group units throughout southern Denver Basin will demonstrate the regional extension of these units in subsurface of the southern parts the Denver Basin, thickness changes of Dakota Group strata will illustrate the valley incision locations and trends (up-dip and down-dip), and sediment source directions, while the investigation of the linkage between subsurface Dakota Group unit trends in southern Denver Basin and their age-equivalents in southeastern outcrop of Colorado will prove the continuation of the subsurface Dakota Group units to the surface.

Based on outcrop correlation of the Dakota Group age-equivalents, I test the existing presumption that correlation of the sequence stratigraphic surfaces and units within the Dakota Group in subsurface and outcrop were true, where sequence stratigraphic surfaces within Mesa Rica Sandstone, Dry Creek Canyon Formation, and Romeroville Sandstone in outcrop are the same sequence stratigraphic surfaces within the subsurface J Sandstone, Huntsman, and D

Sandstone in Denver Basin (Holborook,1992). This assumption will be tested in this study to investigate whether this outcrop correlation is valid in subsurface well-logs or not.

1.4 Background and previous work

The Dakota name was first proposed by Meek and Hayden(1862) for outcrop along the Missouri River in Dakota County, Nebraska. Darton(1904) and Lee(1923,1927) later recognized the regional extent of Dakota Group strata. The first detailed study of the Dakota Group was undertaken in northern Colorado Front Range foothills particularly from Rainbow Creek in Douglas County to Boxelder Creek in northern Larimer County by Waage(1955). Waage divided Dakota Group strata into two units: the Lower Lytle Formation and Upper South Platte Formation. Waage(1955) also interpreted the depositional environment for Upper South Platte Formation as deltaic, eustrine, littoral and neritic environments around the margins of the Western Interior seaway. Later on, Mackenzie(1971) studied the stratigraphy and depositional environment of Dakota Group strata from Deer Creek south of Morrison, Colorado to Boxelder Creek near the South Wyoming border. Mackenzie(1971) divided the Upper South Platte Formation of Waage(1955) into three members. These three members are: Plainview, Skull Creek, and Muddy (now the J Sandstone). Before that, Muddy strata were already divided into two members in the eastern Hogback of the Colorado Front Range by Mackenzie(1965) which are Fort Collins and Horsetooth members.

The first illustration of subsurface distribution of Dakota Group strata in the Denver Basin was by Haun(1959,1963). Haun(1959,1963) also correlated the subsurface Dakota Group strata to the surface equivalents previously recognized by Waage(1955). Mackenzie(1965,1971) also studied the depositional environment and stratigraphy of subsurface Dakota Group strata in the western flank of the Denver Basin along with the previously mentioned studies of Dakota Group outcrop in Colorado Front Range. Martin(1965) described two regressive deltaic systems within Dakota Group strata with eastward and northeastward sediment sources. Martin(1965) assigned the depositional environment for the J sandstone as “complex swamp, lagoon, alluvial plain, channel, delta, tidal flat and tidal channel deposits” whereas he assigned the depositional environment of the D sandstone as coastal plain deposits. Weimer(1970) discussed the stratigraphy of Dakota Group along the Southern Front Range and in South and Middle parks in Colorado. Weimer(1970) described Dakota Group sediments as a large shallow marine delta that prograded eastward between Denver and Colorado Springs. Weimer(1988) proposed a depositional model for the J “Muddy” Sandstone in northern Denver Basin. Sonnenberg(1987) proposed a depositional model for the D Sandstone in western and central Denver Basin. Sonnenberg(1987) also proposed a new depositional environment for the D sandstone as a channel origin within a valley-fill complex.

1.5 Dakota Group stratigraphy in Colorado

Dakota Group terminology differs regionally throughout the Cretaceous Western Interior Basins in North America and correlation between Dakota Group strata and their equivalents on both flanks of the Seaway has been confused. The main reason for this confusion is that correlation of Dakota Group equivalents is primarily based on lithological variation within Dakota Group section regardless the age of the unit.

The recognition of the lower most of Dakota Group strata within the type section of Meek and Hayden(1862) along the eastern edge of the Western Interior Seaway was based on the sharp vertical lithological change from red oxidized-to-carbonaceous shale, to sandstone deposits above the Jurassic Morrison formation (Dolson,1991). This vertical variation was used to recognize and correlate all Dakota Group equivalents, even those located hundreds of miles westward, southward, and southwestward of the type section, without considering the age as recognition criteria. As a result, the Muddy Sandstone of Dakota Group in Wyoming is equivalent to the fully younger Dakota Sandstone of northwestern Colorado and Utah (Dolson,1991).

Likewise surface and subsurface nomenclatures are different in northern and northwestern, and southern and southeastern parts of Colorado and Denver Basin.

1.5.1 Surface Dakota Group nomenclature in Colorado

Dakota Group strata have two different surfacial nomenclatures in Colorado (Fig.4), one for northern outcrops in Colorado Front Range, and another for southern and southeastern outcrops near the New Mexico and Kansas borders. The surfacial equivalents of subsurface Dakota Group strata in the northern Colorado Front Range consist of two members: Fort Collins Member and Horsetooth Member. The lower Fort Collins Member consists of fine to very fine-grained, clayey sandstone with abundant trace fossils (invertebrate track, trail and burrows) and it was interpreted as a delta front sandstone deposited during the shoreline regression of Skull Creek Sea (Mackenzie,1965).The Horsetooth Member is composed of medium to fine-grained, well sorted, cross stratified sandstone with wood fragments that deposited in channel environments (Mackenzie,1965).

In south and southeastern Colorado, surfacial possible equivalents of Dakota Group strata consist -from base to top- consist of Mesa Rica Sandstone (Fort Collins and Horsetooth Member of the North), Dry Creek Canyon Formation, and Romeroville Sandstone. These units are underlained and overlained by marine shale which are Glencairn Formation and Graneros Shale respectively. The Mesa Rica Sandstone is mainly composed of well-sorted, medium-size, planar and cross-bedded sandstone that deposited as active channel-fill and bar deposits (Odien, 1997; Holbrook et al.,2006). Mesa Rica Sandstone consists of Lower, Middle, and Upper members and they are all merged up-dip into one unit in southeastern Colorado where it is hard to differentiate between them (Holbrook,2001). The Dry Creek Canyon Formation consists of dark-colored marine shale that deposited during a transgression event in down-dip area and transitions to fluvial channel-belt and floodplain strata up-dip.

The uppermost Romeroville Sandstone is composed of well-sorted, medium-grained, planar and cross-bedded sandstone interpreted as channel-fill and bar deposits within nested valley-fill (Holbrook et al.,2006).

North Front Range (Mackenzie, 1965)	Southeastern Colorado (Holbrook et al. 2006)	Sequence Stratigraphy (Holbrook & Wright Dunbar,1992)
Graneros Shale	Graneros Shale	Sequence 4
Mowry Shale	Romeroville Sandstone	
		SB4
	Dry Creek Canyon Shale	Sequence 3
Horsetooth Member	Mesa Rica Sandstone	
Fort Collins Member		
		SB3
Skull Creek Shale	Glencairn Formation	Sequence 2

Fig. 4: Surface nomenclature and sequence stratigraphy of mid-Cretaceous (Albian and Cenomanian) Dakota Group in northern and southeastern Colorado.

1.5.2 Subsurface Dakota Group nomenclature in Colorado

The confusion in terminology also can be found in subsurface Dakota Group strata of Denver Basin. Drillers terminology in well-log data is one of the causes of confusion as they commonly use various names for the same units (e.g. the J sandstone in north and south or Muddy in northwest), add some units to the overlaying or underlying unit (e.g. Huntsman Shale is added to the J sandstone as the upper portion of the unit ,or adding the D sandstone to Muddy Sandstone) or even combine all units within one formation (e.g. the J sandstone, Huntsman Shale and D sandstones are all combined as “Dakota Formation” in some northwestern Denver Basin well-log data).

Subsurface Dakota Group strata are divided in most of literature into three marine and non-marine units (Weimer & Sonnenberg,1989), which are overlain (Graneros Shale) and underlain (Skull Creek shale) by marine shale units. Subsurface Dakota Group units are from bottom to top: the J Sandstone (Muddy), Huntsman Shale, and the D Sandstone (Fig.5). The J Sandstone is Lower Cretaceous (Albian) in age (Kauffman,1977) and it is equivalent to the surface Fort Collins and Horsetooth members in northern and northwestern Colorado Front Range (Weimer and Sonenberg,1989) and possibly to Mesa Rica Sandstone (Holbrook,2006) in southern and southeastern parts of Colorado. The J sandstone is composed of fine-to-medium grained sandstone, interbedded with shale and siltstone originally presumed to be deposited in delta environments (Haun,1963) which prograded eastward and southeastward (Weimer,1992). The Huntsman shale is composed of black organic-rich shale that deposited during the transgression of the Mowry Sea (Sonnenberg,1987). The D Sandstone is early-late Cretaceous (Cenomanian) in age (Haun,1963) and it is composed of well-sorted, fine-grained sandstone that deposited in channels within valley-fill complexes (Sonnenberg,1987) which are presumed to derive by delta from the East (Weimer et al.,1998).

In this study, the surface nomenclature of southern and southeastern Colorado and the subsurface nomenclature of Denver Basin are used in correlation where Mesa Rica Sandstone, Dry Creek Canyon Formation, and Romeroville Sandstone are age-equivalents to the J sandstone, Huntsman Shale, and the D Sandstone respectively.

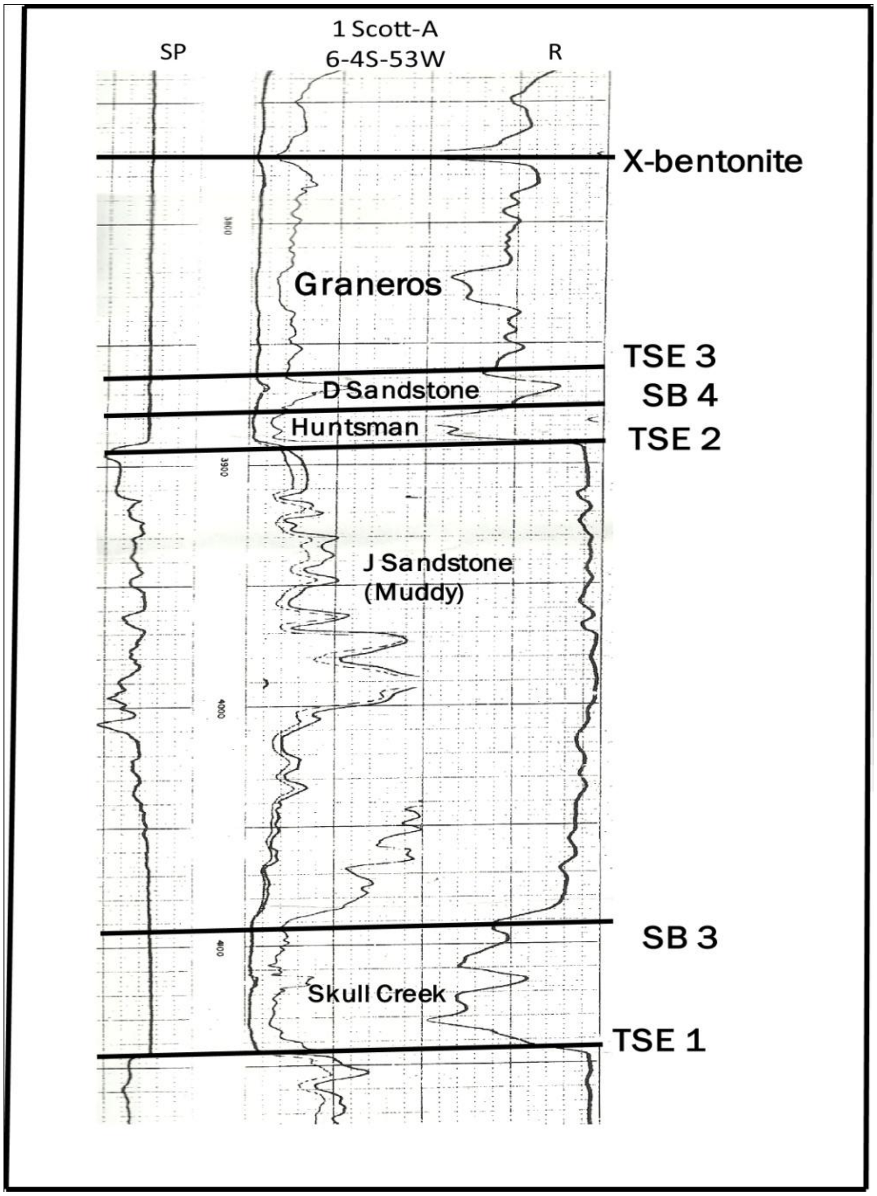

Fig. 5: Subsurface nomenclature and sequence stratigraphic surfaces of Dakota Group in Denver Basin, Colorado.

1.6 Sequence stratigraphy and previously proposed depositional models of Dakota Group

1.6.1 Sequence stratigraphy of Dakota Group

Sequence stratigraphy is defined by Posamentier et al.(1988) and Van Wagoner(1995) as "the study of rocks relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non deposition, or their correlative conformities" (see Catuneanu,2006). Sequence stratigraphic interpretation, deposition, and distribution of Dakota Group strata in Denver Basin are constrained within the Cretaceous Western Interior Basin from transgressive-regressive cycles during mid-Cretaceous time (Albian-Cenomanian). Sequence stratigraphic interpretation of Dakota Group strata is based on well log, core, and outcrop data studies in northern and central Denver Basin in Colorado (Weimer,1992). In Southeastern Denver Basin, Dakota Group strata are part of two sequences (Sequence.3 and Sequence.4) (Fig.4) (Holbrook,2006;Holbrook, 2001) where sequence is defined as succession of genetically related strata bounded by unconformities or their submarine correlative conformities (Mitchum,1977). The J Sandstone (potential Mesa Rica Sandstone subsurface age-equivalent) and Huntsman Shale (potential Dry Creek Canyon Formation subsurface ag- equivalent) are the constituents of Sequence.3 which is bounded by sequence boundary (SB.3) (Lowstand surface of erosion (LSE) of Weimer,1988) at the base of the J sandstone, and sequence boundary (SB.4) (LSE: Weimer,1988) at the top of Huntsman Shale whereas, The D Sandstone (potential Romeroville Sandstone subsurface age-equivalent) belongs to the lowermost part of Sequence.4 which is bounded by sequence boundary (SB.4) at the base of the D Sandstone and by sequence boundary at the top of the upper Cretaceous Carlile Formation.

Sequence stratigraphic surfaces are surfaces that separate deposits with different genetic origin and indicate a change in depositional environments manifest, sediment load and environmental energy flux that are created by the interaction of base-level changes and sedimentation (Catuneanu,2006). Recognition of these sequence stratigraphic surfaces is based on numerous criteria that include: nature of the contact (unconformable or conformable), nature of facies above and below the surface, the depositional trend below and above the contact, type of ichno-facies that associated with the contact, and type of strata-termination that associated with the contact (Catuneanu,2006).

Four sequence stratigraphic surfaces were identified in well-log within Dakota Group strata in Denver Basin (Fig.5):

1. Subaerial Unconformity (SU)

   Subaerial Unconformity is a surface that records an erosional or non-deposition event during base-level fall which formed by subaerial processes such as fluvial valley-incision, sediment bypass and pedogenesis (Catuneanu,2006). The subaerial unconformity is generally assigned as a sequence boundary where it separates two sequences that each belong to a different depositional cycle. The main criteria to recognize this type of stratigraphic surfaces in subsurface data are the abrupt change in facies along the SU surface and the presence of non-marine deposits above the extensively traceable erosional surface.

   In this study, two subaerial unconformities (sequence boundaries) were identified in well-log within subsurface Dakota Group strata. These are sequence boundary (SB3) between the base of the J Sandstone (i.e. the base of Dakota Group) and the Skull Creek Formation, and the sequence boundary (SB4) at the base of the D Sandstone.

2. Transgressive Surface of Erosion (TSE) or Transgressive Ravinement Surfaces:

   Transgressive Surface of Erosion is a surface that is characterized by scours formed by waves and/or tidal action during shoreline transgression (Catuneanu,2006). The main characteristic of this surface is that shallow marine deposits are always on the top of the surface whereas variable type of deposits (fluvial, coastal, or marine) can be found below it. The sharp change from non-marine (e.g. fluvial deposits) to marine and the presence of the erosional truncated surface at the top of valley-fill deposits are the main criteria that were used to distinguish the TSE surface in well-log within the study area.

Two transgressive surfaces of erosion (TSE3) and (TSE2) were identified where the (TSE3) is at the top of the D Sandstone (i.e. the top of Dakota Group) and overlain by a transgressive marine deposit of the Graneros Shale and (TSE2) is at the top of the J Sandstone and overlained by the marine Huntsman Shale.

1.6.2 Previously proposed depositional models for Dakota Group in northern, western and central Denver Basin

Numerous depositional models have been proposed for Dakota Group strata or at least for specific units within the Group (e.g. the Muddy “J” Sandstone, the D Sandstone alone) in the Denver Basin (e.g. Martin,1965; Dolson,1991; Weimer,1988; Sonnenberg,1987; Weimer,1992). The major two depositional models in Denver Basin are the depositional model for the J “Muddy” Sandstone in northern and central Denver Basin that was proposed by Weimer(1988) and Weimer(1992), and the depositional model for the D sandstone in northern and central Denver Basin that was proposed by Sonnenberg(1987). The main reasons of choosing these two models to aid and support the paleogeographic interpretation of this study are that they were developed based on the regional recognition of sequence-stratigraphic surfaces (Sequence boundaries, unconformities or LSE, TSE) and facies models in well-logs, cores and outcrop within and near the study area, and they can be used regionally across most of the northern parts of the Cretaceous Western Interior Basins (Sonnenberg,1987).

Although these models can explain Dakota Group strata deposition for the northern areas and in certain areas in the North-central parts of the study area, they can not explain the D and J Sandstone deposition and paleogeography in southern and southeastern parts of the study area. Therefore, these models were modified and added to the depositional model and paleogeographic interpretation that I proposed further in this study.

1.6.2.1Depositional model for the J "Muddy" Sandstone of Dakota Group

Figure.6 illustrates the depositional stages of the J Sandstone starting with time.1 (T1) and ending with time.4 (T4). During early Cretaceous (Albian) a regression event occurred and deltaic and shallow marine sandstone was deposited transitionally on the top of the Skull Creek Shale. These deltaic deposits and their associated streams occupied the low structural areas above the fault blocks (Fig.6, A:T1). The shoreline retreated towards the sea and sheet-like sandstone (the base of the J Sandstone) was deposited in large areas. Then a major drop in sea level occurred about 98 Ma (Weimer,1992) leading to subaerial exposure and erosion of a large area of the Skull Creek Shale forming a Lowstand surface of erosion LSE (Subaerial unconformity SU). Rivers and their drainages were incised into the Skull Creek Shale especially in the structurally low areas (Fig.6, B:T3). Then a rise in sea level occurred and the incised valleys started to be filled with fluvial and estuarine sandstone, siltstone and shale (Fig.6, C:T4). As shoreline transgressions proceed, waves and tides scoured the top of valley-fills forming the transgressive surface of erosion TSE (transgressive ravinement surfaces) across the top of these deposits. Sea level continued to rise and anoxic organic rich shale of Huntsman (and/or Mowry Shale) deposited overlaying the transgressive surface of erosion.

1.6.2.2 Depositional model for the D Sandstone

The D Sandstone depositional model (Fig.7) was proposed by Sonnenberg(1987) and it is similar to Weimer(1988) and (1992) model for the J Sandstone. The Huntsman Shale was deposited in marine environments overlaying the TSE above the J sandstone. A regressive event occurred and shallow marine sandstone was deposited transitionally above the Huntsman shale with the progadation of rivers and deltas (Fig.7, T1). Rivers and deltas occupied the low structural areas above the faulted blocks whereas inter-deltaic deposits occupied the higher areas. The shoreline retreated seaward and a regressive sandstone was deposited (the base of the D sandstone). Then a major drop in sea level occurred at 95 MA (Sonnenberg,1987) and a large area was exposed to erosion forming the lowstand surface of erosion LSE. As a result of sea level drop, base level was lowered leading to the incision of river drainages into the regressive sand and the Huntsman Shale (fig.7, B:T3). Following T3, sea level raised and the incised valleys were filled with fluvial and estuarine sandstone, siltstone and shale (Fig.7,C: T4). The shoreline continued transgressing and scours at the top of valley-fills formed by waves and tidal action and formed the transgressive surface of erosion TSE (transgressive ravinement surfaces) at the top of D sandstone unit. After T4, sea level rise continued and marine shale of Graneros deposited overlaying the D sandstone.

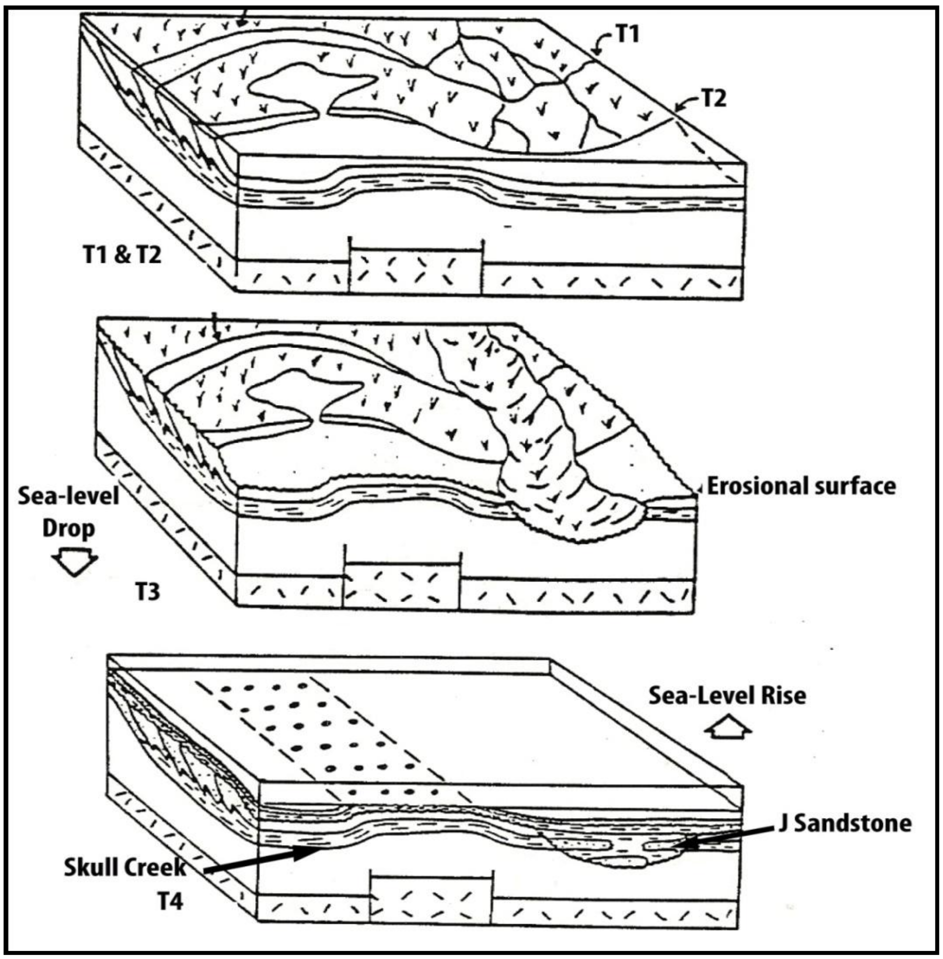

Fig. 6: Depositional model for the J "Muddy" Sandstone in northern Denver Basin proposed by Weimer (1988) and Weimer (1992). Modified from (Weimer,1992)

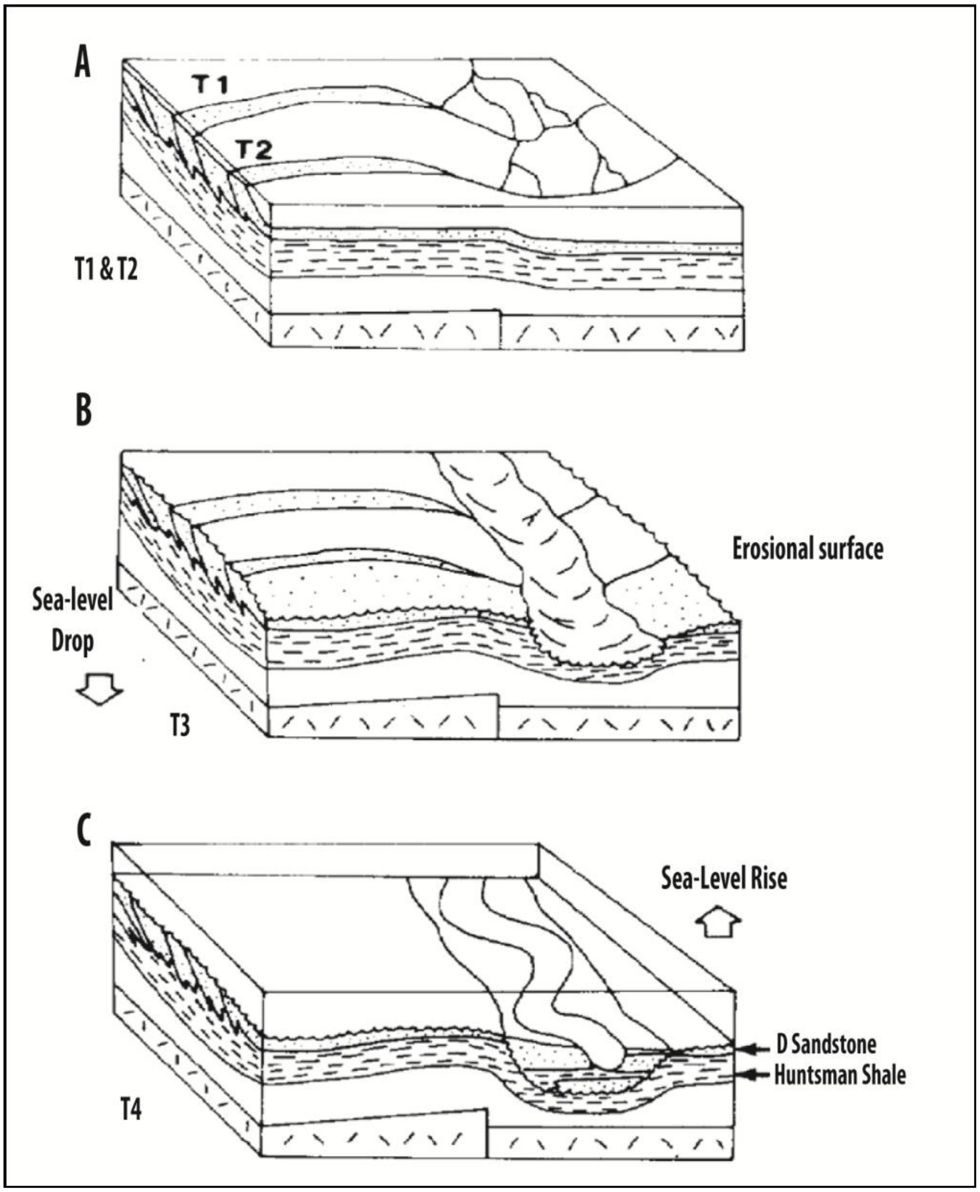

Fig. 7: Depositional model for the D Sandstone in northern Denver Basin proposed by Sonnenberg,1987). Modified from (Sonnenberg, 1987)

CHAPTER 2

METHODS

The majority of the work was done by using electric, gamma ray, and spontaneous potential logs from about 417 wells within the study area. The work included identification and correlation of sequence stratigraphic surfaces, correlation of marker beds and the X-bentonite bed, construction of strike and dip well-log cross-sections and isopach maps for Dakota Group units, and correlation of subsurface well-log cross-sections of Dakota Group units with their surface equivalents in outcrop measured sections in southeastern Colorado (e.g. Holbrook, 2001; Holbrook et al., 2006; and Oboh-Ikuenobe et al.,2008).

2.1 Identification and correlation of sequence stratigraphic surfaces

The main sequence stratigraphic surfaces that were identified and correlated (Fig.5) are the transgressive surface of erosion (TSE3) at the top of the D sandstone (i.e. the top of Dakota Group), the sequence boundary (SB4) at the base of the D sandstone, the transgressive surface (TSE2) at the top the J Sandstone (i.e. base of Huntsman), the sequence boundary (SB 3) between the base of the J sandstone (i.e. the base of Dakota Group) and the Skull Creek Formation, and the transgressive surface of erosion (TSE1) at the base of the Skull Creek Formation. Even though this transgressive surface of erosion (TSE1) is not within Dakota Group units it is important to correlate this surface to increase the accuracy of correlation. The characteristics and recognition criteria of the following stratigraphic surfaces were previously discussed in this study. In addition to the previous criteria, identifying these surfaces in well-log can be achieved by recognizing the marker beds and spikes (peaks) above and below each surface and using top depths that are provided by well-drillers in well-log header and scout ticket.

2.2 Correlation of marker beds and the X-bentonite

Marker beds such as flooding surfaces within the Skull Creek Shale and the recognizable and widespread X-Bentonite marker bed at the top of the Graneros Shale were correlated and used to constrain the correlation of the sequence stratigraphic surfaces. The main flooding surface within Skull Creek Shale that was used is an organic rich layer (condense section) characterized by its very low resistivity (Weimer et al.,1998). Correlation of marker beds will progress using well-established pattern matching techniques (Evenick,2008; Van Wagoner et al,1990).

2.3 Construction of strike and dip well-log cross-sections and isopach maps

Several cross-sections were constructed using the correlated well-logs of Dakota Group to illustrate both strike and dip thickness trends of surface correlation within the study area. The recognizable and widespread X-bentonite marker bed was used as correlation datum in these cross-sections.

Two isopach maps were constructed, one for the entire Dakota Group interval (from SB3 at the base of the J sandstone to TSE3 at the top of the D Sandstone) and the other for the Huntsman Shale only. The purpose of constructing Dakota Group isopach map is to demonstrate thickness variations of these intervals in the study area whereas, the Huntsman map was constructed to locate the D sandstone incisions into the Huntsman Shale and to illustrate the Huntsman Shale thickness variation. Both cross-sections and isopach maps were used to investigate valley-fill incision and valley trends within the study area.

2.4 Correlation of subsurface well-log cross-section of Dakota Group with measured outcrop sections in southeastern Colorado (e.g. Holbrook, 2001; Holbrook et al., 2006; and Oboh-Ikuenobe, et al., 2008)

Subsurface well-log cross-sections of the Dakota Group with the D sandstone, Huntsman shale and the J sandstone units with sequence stratigraphic surfaces within them were correlated with measured outcrop sections of their surface potential equivalent units of Romeroville Sandstone, Dry Creek Canyon Formation and Mesa Rica Sandstone with their sequence stratigraphic surfaces in southeastern Colorado. The outcrop sections that were used in correlation are illustrated in (Fig.13, and Fig.14) and their location is shown in (Fig.2). Holbrook(2001), Holbrook et al.(2006) and Oboh-Ikuenobe et al.(2008) described the sequence stratigraphy and paleogeography of Dakota Group strata in these sections and in the surrounding areas in southeastern Colorado. Sequence stratigraphic surfaces, markers, thickness trends, and lithology and morphology of Dakota Group units were correlated from subsurface to outcrop. The main purpose of correlating the subsurface cross-sections with surface sections is to investigate the continuation of the subsurface Dakota Group units to the surface and to prove the linkage between the two sections.

CHAPTER 3

DATA AND RESULTS

3.1 Dakota Group distribution and thickness variation

Dakota Group thickness and thicknesses of its individual units (the J Sandstone, Huntsman Shale, and the D Sandstone) were estimated using the correlated well-log cross-sections and isopach maps. In the study area, Dakota Group thickness ranges from 100-290 feet (Fig.8). The thickest trends are eastward to northeastward and westward to northwestward whereas the major thinning is toward the South and South-central part of the study area.

The J Sandstone thickness range is 40-220 feet. The thickness increases toward the northwest and northeast of the area and thins in general to the south-central and south where the unit thickness become relatively more uniform (about 80-100 feet thick). Huntsman Shale thickness ranges from 0-60 feet. The thickest section is concentrated in the northern and central parts of the study area and the thinnest in the eastern and southeastern flank of the area (Fig.9). Huntsman Shale thins toward the south as shown in cross-sections (Fig.11). Thickness distribution of Huntsman Shale is inversely related to the D Sandstone unit locally. Areas where Huntsman thickness is zero or around zero are where the D Sandstone thickening trends occur. The D Sandstone in the study area ranges from 7 to 140 feet. Thickness distribution of the D Sandstone in the area is not uniform and very thick deposits can be found next to very thin deposits (Fig.10). In general, the thickening trend of the D Sandstone is towards the East and northeast, southeast, and the West in the study area.

3.2 Strike and dip cross-sections of Dakota Group strata

Two strike and dip cross-sections were constructed for subsurface Dakota Group strata in the study area and their locations are illustrated in the J Sandstone isopach map (Fig.8). The first cross-section is from East to West (A - A', in Fig.8) and was constructed to demonstrate valley incision of the J and D Sandstone (Fig.10), while the second is from North to South (B - B', in Fig.8) and was constructed to show thickness changes of Huntsman Shale towards the South (Fig.11). in the East-West cross-section, valley incision of both the J and D Sandstone are illustrated in 12-33 Weineiger-Davis well whereas in 1 Jacobson-A and Bennz 1-24 wells only the J Sandstone was incised into the Skull Creek Shale. The incision of the D Sandstone is about 120 ft in 12-33 Weineiger-Davis well where the D Sandstone was fully incised through Huntsman Shale (i.e. Huntsman thickness is zero) and into the upper part of the J Sandstone. In this particular location a very thick D Sandstone deposits found near very thin deposits in the adjacent wells (Fig.10). TSE2 is truncated into SB4 in both sides of the incised valley where Huntsman Shale is absent. In case of the J Sandstone, valley incisions are about 110 ft thick in 12-33 Weineiger-Davis well, 205 ft in 1 Jacobson-A well, and 160 ft in Bennz 1-24 well. The incision of the J Sandstone caused major thinning in Skull Creek Shale but no full incision was observed in both isopach maps and cross-sections.

In the North- South cross-section (Fig.11), there is no major valley incisions of both the J and the D Sandstone and the main observed changes were in Huntsman Shale thickness. The Huntsman Shale thickness in the North (UPRR Jolly well) is about 34 ft and it gradually thins towards the South until it reached zero thickness in 1-11 S-S-M Jolly well. TSE2 is also truncated by SB4 where Huntsman thickness is zero in the South.

3.3 Sequence stratigraphic surface correlation within the Denver Basin

Sequence stratigraphy of Dakota Group strata in the Denver Basin was earlier discussed in details in separate section. In this section only the results of correlation of the sequence stratigraphic surfaces within the Dakota Group are demonstrated.

Sequence boundary (SB3) at the base of the J Sandstone, sequence boundary (SB4) at the top of Huntsman Shale and the base of the D Sandstone, transgressive surface of erosion (TSE3) at the top of the D Sandstone, transgressive surface of erosion (TSE2) at the top of the J Sandstone, and transgressive surface of erosion (TSE1) at the base of Skull Creek Shale were correlated throughout the study area using well-log data (Fig.10 and Fig.11). All of the sequence stratigraphic surfaces were traced through the entire study area except the TSE2 in certain areas. TSE2 can not be traced in areas where the Huntsman thickness is zero in (Fig.9). In these particular areas sequence boundary (SB.4) cuts the transgressive surface of erosion (TSE2) at the top of the J sandstone (Fig.10).

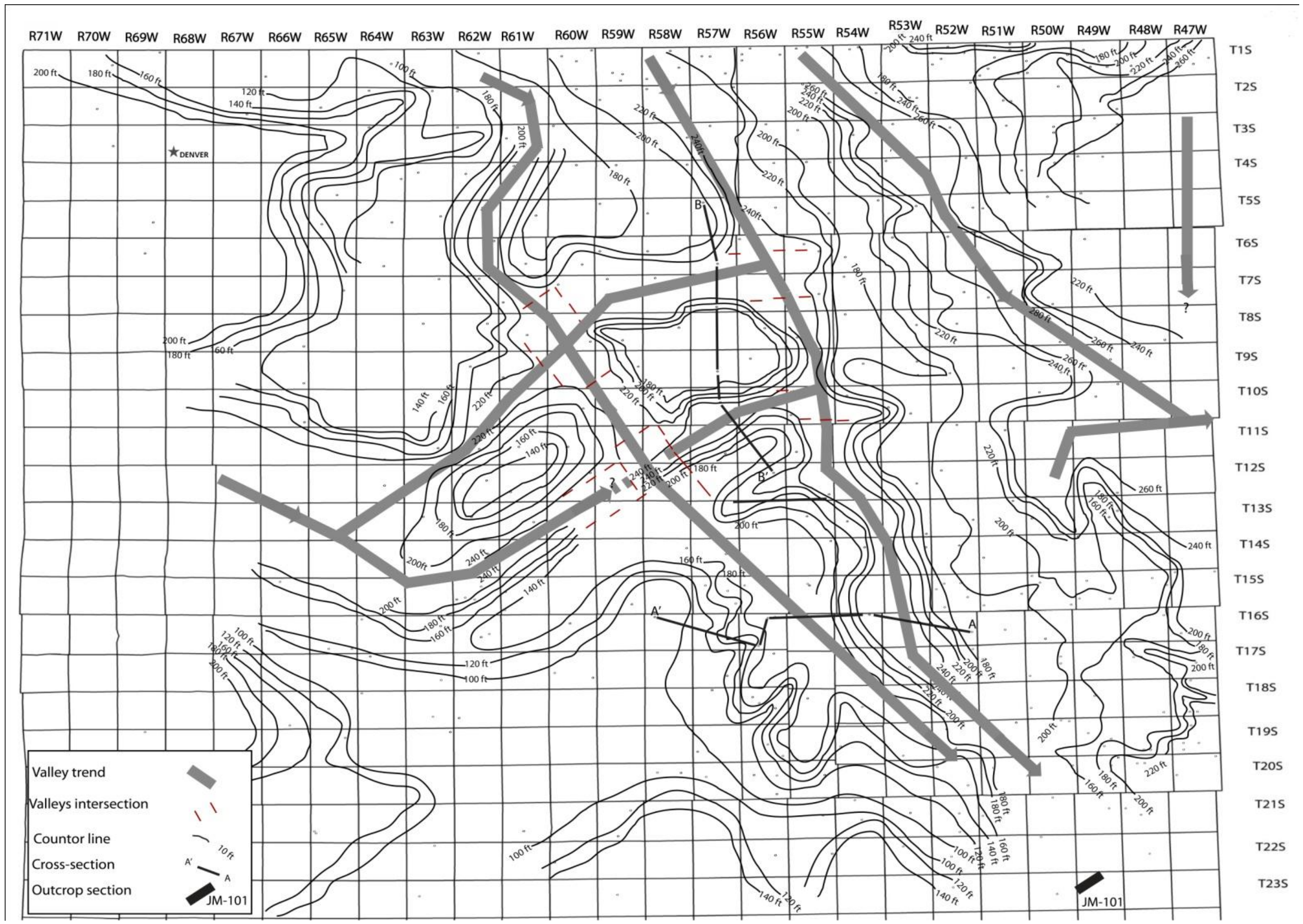

Fig. 8: Isopach map of Dakota Group strata from the base of the J Sandstone (SB3) to the top of the D Sandstone showing the incision of the J Sandstone into the Skull Creek, valley trends and valley intersections.

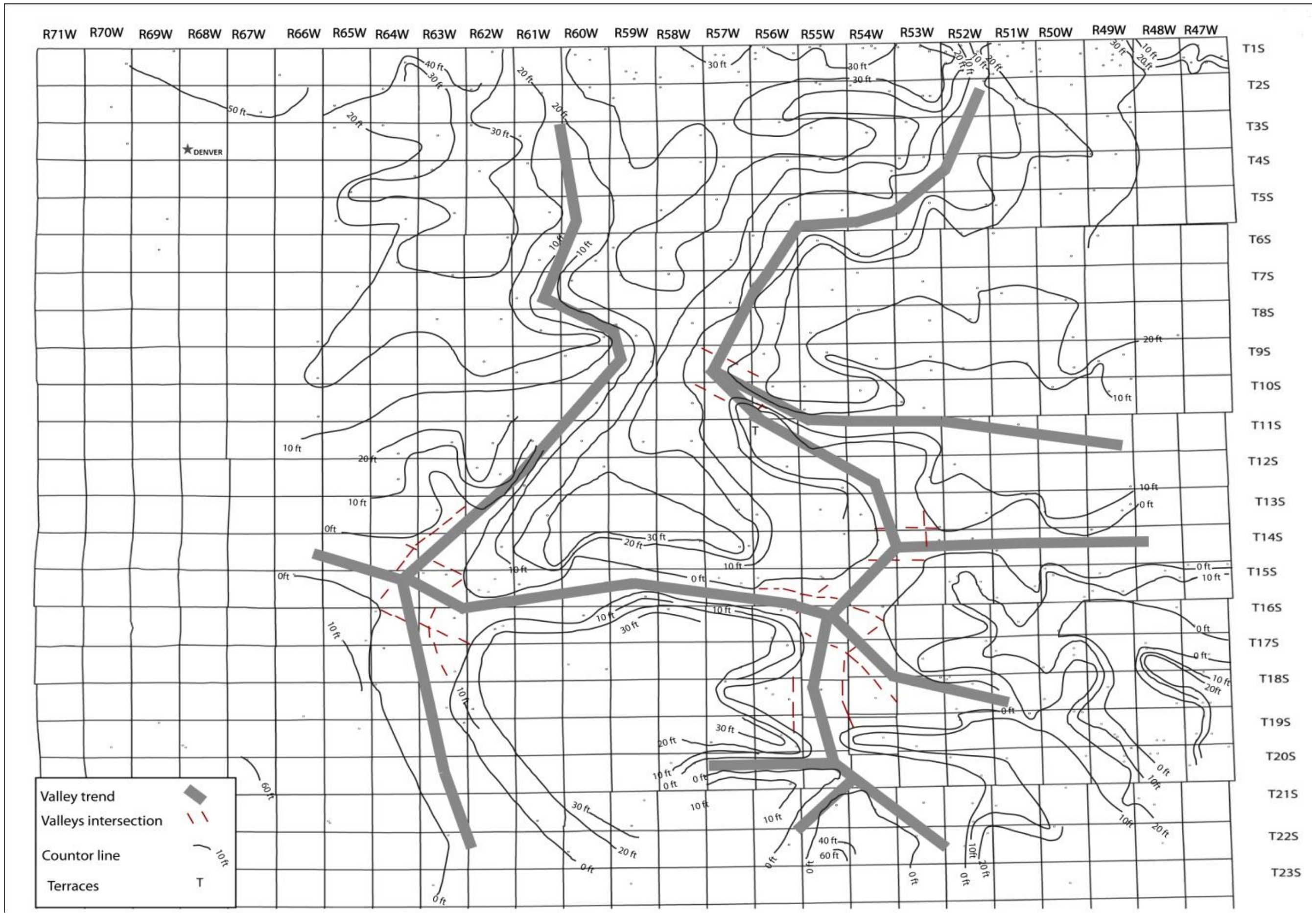

Fig. 9: Isopach map of Huntsman Shale showing the incision of the D Sandstone into the Huntsman, valley trends and valley intersections.

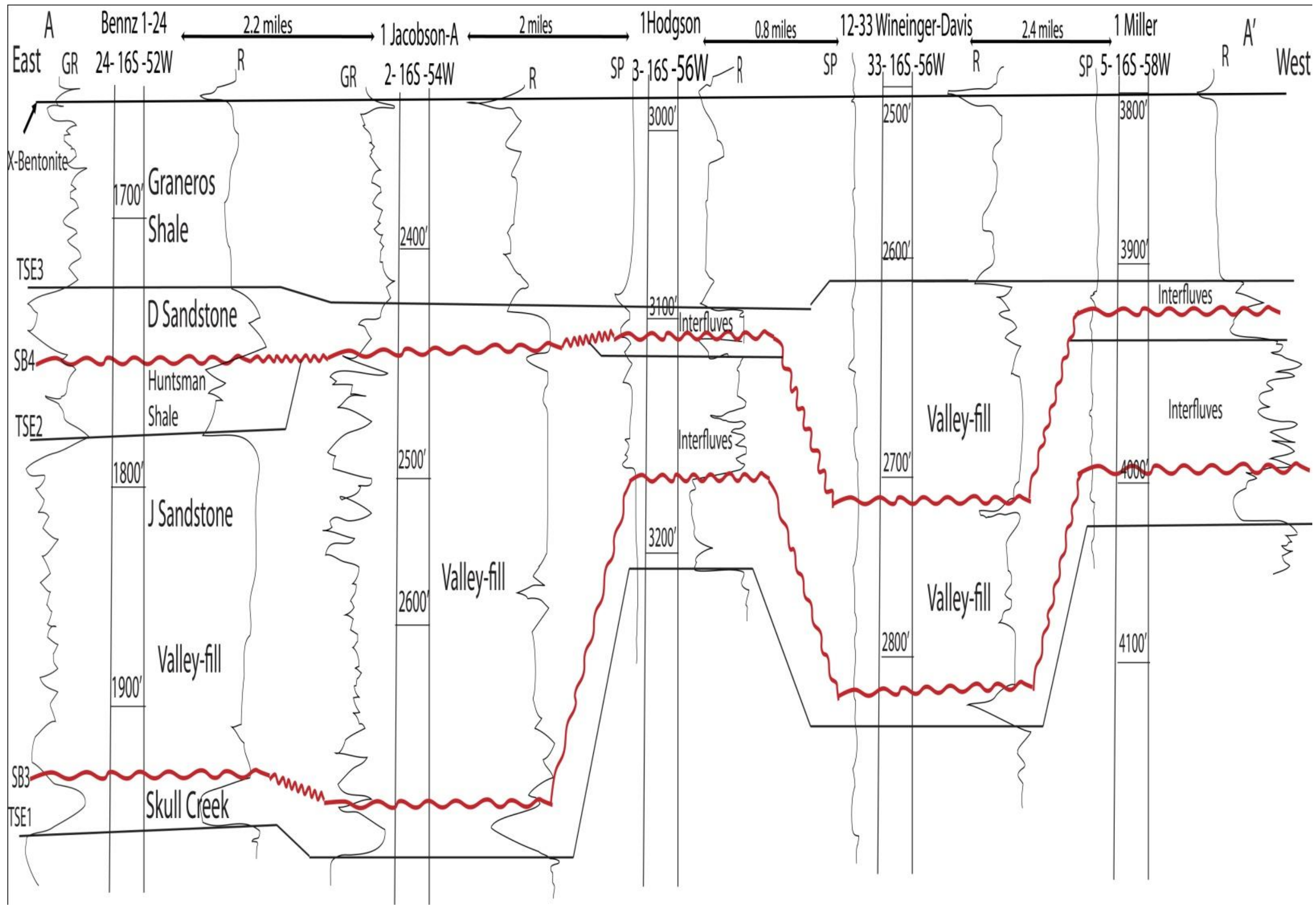

Fig. 10: E-W strike and dip well-log cross-section of subsurface Dakota Group strata.

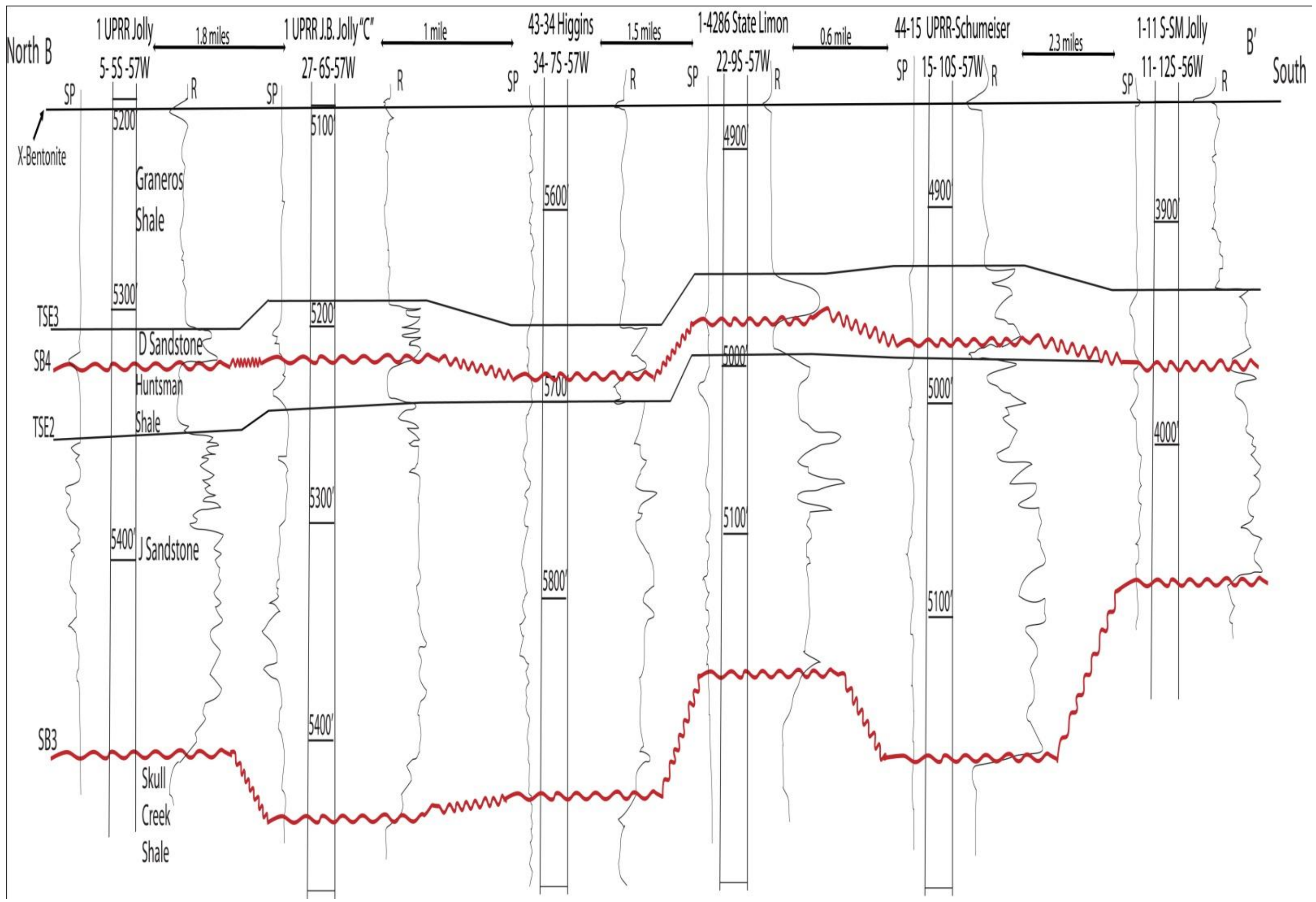

Fig. 11: N-S strike and dip well-log cross-section of subsurface Dakota Group strata.

CHAPTER 4

DISCUSSION

4.1 Correlation of Dakota Group strata from subsurface Denver Basin to Southeastern outcrop, Colorado

This study is an attempt to investigate the linkage and continuation between the subsurface Dakota Group strata in Denver Basin and their age equivalents in outcrops of southeastern Colorado using well-log cross-section of the subsurface Dakota Group strata with sequence stratigraphic surfaces within these strata and measured sections of their surface age equivalents in outcrops southeastern Colorado. The measured outcrop sections were studied by Holbrook (2001),and Holbrook (2006) from up-dip to down-dip (Fig.12) and Oboh-Ikuenobe et al. (2008) in southeastern Colorado and their locations are illustrated in (Fig.2). Two outcrop sections from Oboh-Ikuenobe et al. (2008) were chosen as standards correlation. The first is located in Higbee (H-100) (Fig.13) South La Junta, southeastern Colorado (T26S, R54E, Sec.17), and the second is located in John Martin's Reservoir (JM-101) northeastern La Junta (T23S, R46W, Sec.5) (fig.14, Fig.15). The Higbee (H-100) section consists of Mesa Rica Sandstone (Lower, Middle, and Upper Members), Dry Creek Canyon, and the Romeroville Sandstone with the absence of the top of Romeroville (i.e. the top of Dakota Group and the TSE1) , the top of Graneros Shale (i.e. X-Bentonite marker bed) and the base of the Glencairn Shale (i.e. TSE1). The John Martin's Reservoir (JM-101) section contains Mesa Rica Sandstone, Dry Creek Canyon (and/or Huntsman Shale), and the Romeroville Sandstone with the absence of the base of the Mesa Rica Sandstone (i.e. SB3), the Glencairn Shale, and Graneros Shale top (i.e. X-Bentonite marker bed).

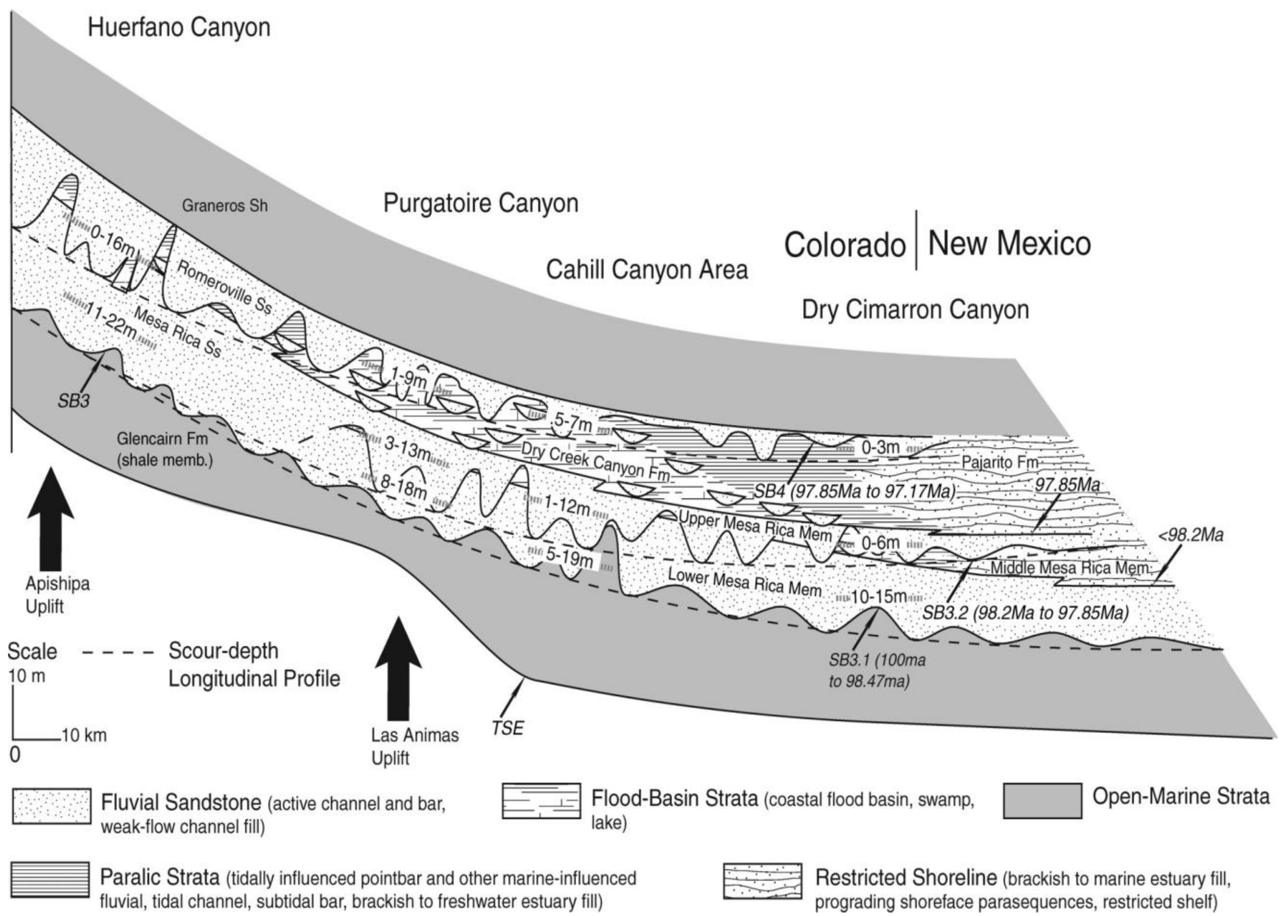

Fig. 12: Longitudinal profile section of surface Dakota Group strata in southeastern Colorado from down-dip to up-dip studied by Holbrook (2006). From (Holbrook,2006)

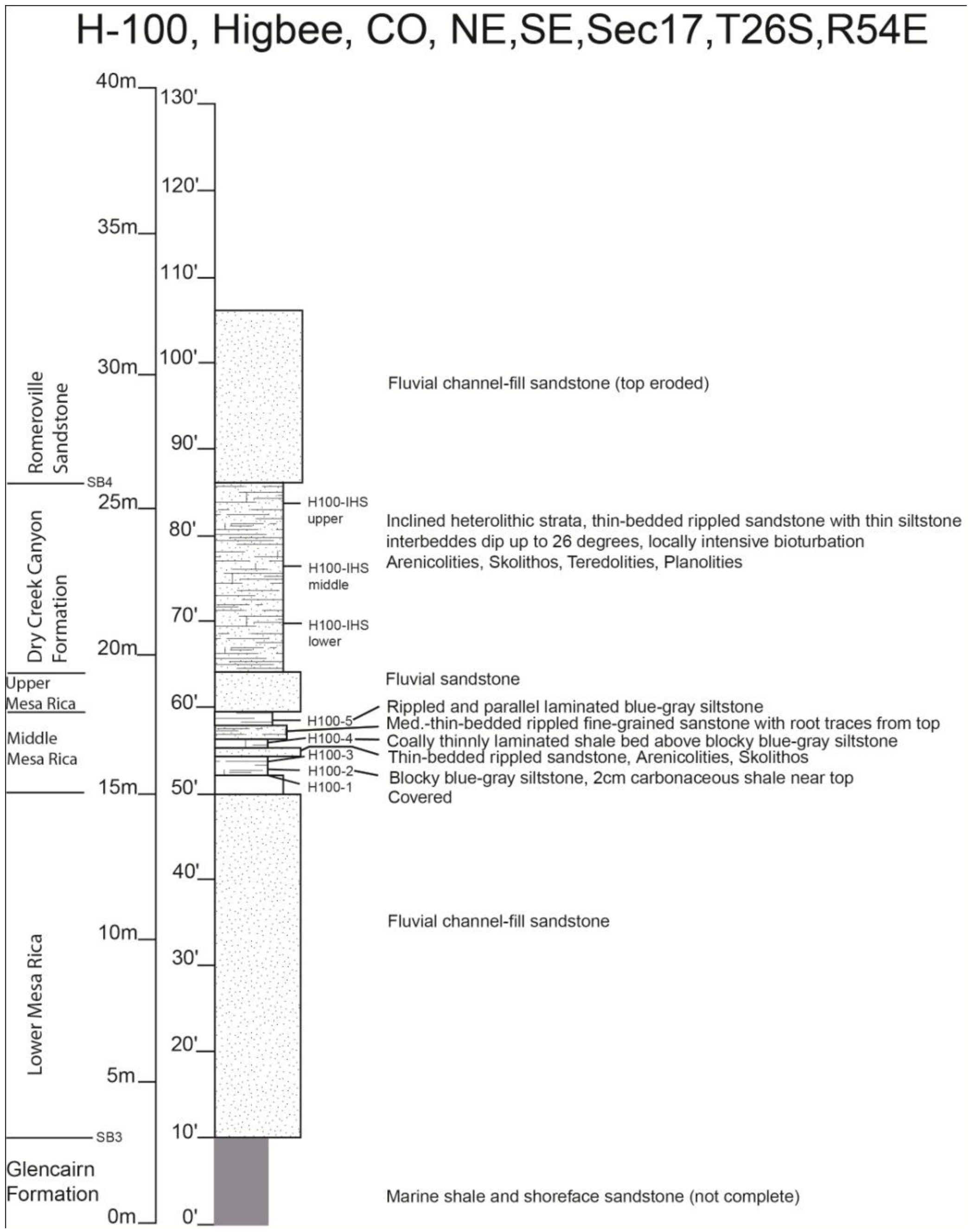

Fig. 13: Measured outcrop section of Dakota Group in Higbee (H-100) that was used in correlation. (Oboh-Ikuenobe, et al., 2008)

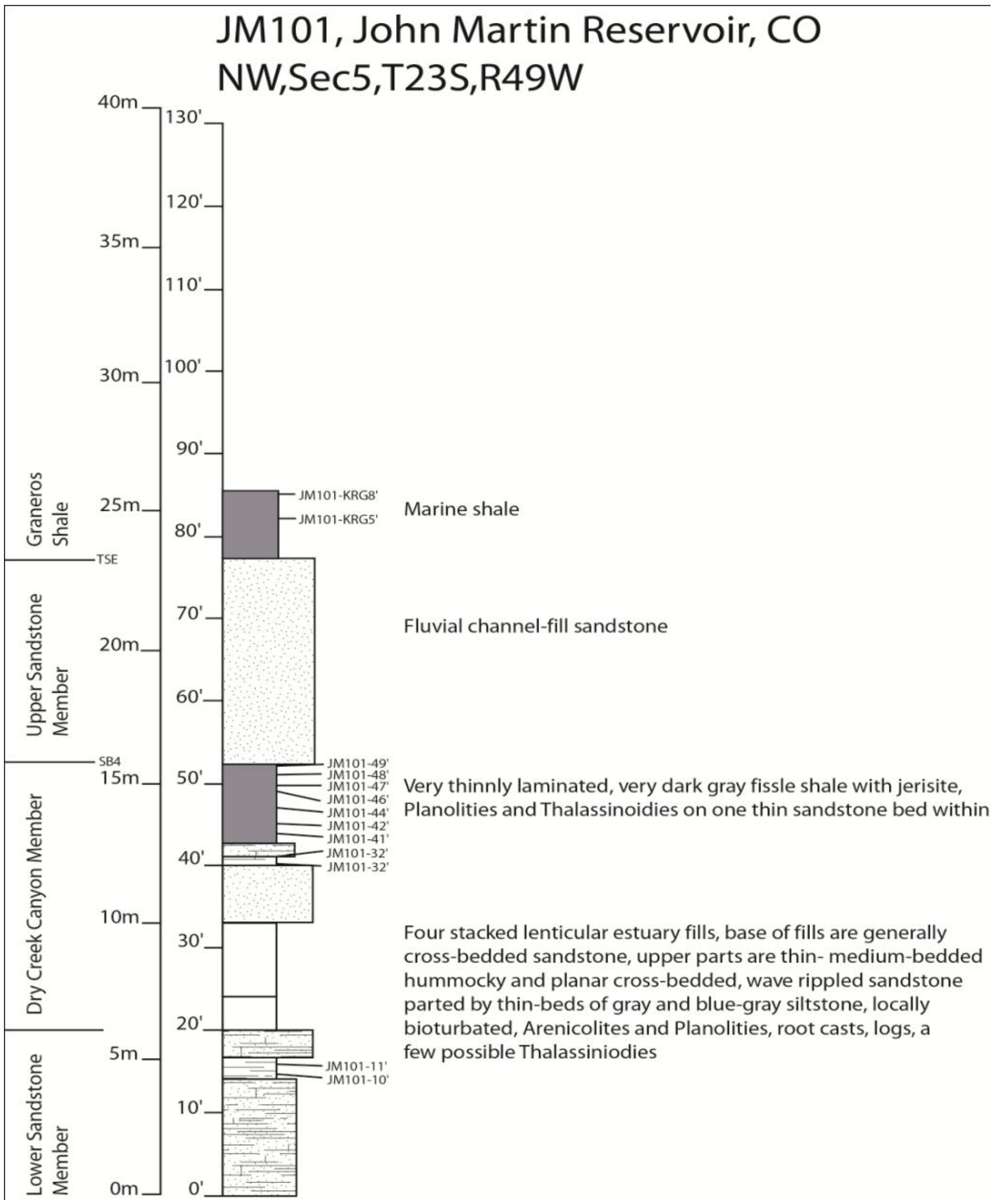

Fig. 14: Measured outcrop section of Dakota Group in John Martin's Reservoir that was used in correlation. (Holbrook, personal communication)

Fig. 15: photograph y of the John Martin's Reservoir outcrop measured section showing stratigraphy of Dakota Group strata showing the presence of Huntsman Shale in upper Dry Creek Canyon formation.

After correlating these two outcrop measured sections of southeastern Colorado with the subsurface well-log cross-section of southern Denver Basin (Fig.16), I concluded that the subsurface J Sandstone, Huntsman Shale, and D Sandstone units of Dakota Group in Denver Basin can be traced to the surface and are correlated to their surface age equivalents which are respectively Mesa Rica Sandstone, Dry Creek Canyon Formation, and Romeroville Sandstone. This conclusion was based on the following:

1. All sequence stratigraphic surfaces (SB3, SB4, TSE3, and TSE2) in both subsurface and outcrops are confined within the same two well-dated marine units and their markers within (e.g. TSE1). The Graneros Shale (with its markers) overlain the subsurface and surface Dakota Group units in southeastern Colorado, where as Skull Creek/ Glencairn Shale underlies these units.
2. Both subsurface and surface Dakota Group units are bounded between the same sequence boundary (SB3 from the base, SB4 from top) and have the same sequence stratigraphic surfaces that can be regionally correlated in both subsurface Denver Basin and outcrop. Both surface and subsurface Dakota Group units have the same stratigraphic surfaces within (SB3, SB4, TSE3, and TSE2) and in the same order. The SB3 is at the base of both Mesa Rica and the J Sandstone, SB4 is at the base of both Romeroville and the D Sandstone, TSE3 is at the top of both Romeroville Sandstone and the D Sandstone, and TSE2 is locally found in down-dip areas at the top of Mesa Rica and the J Sandstone.
3. Thickness trends in outcrop measured sections and in well-log cross-section are relatively matched and surface morphology are similar in both cases (Fig.16).

4. Lithology, internal characteristics, and morphology of the surface units of southeastern Colorado outcrops are similar to those in subsurface units of Denver Basin. Lithologic characteristics and morphology of both subsurface and surface Dakota Group were previously discussed in the Dakota Group stratigraphy section and it showed that Mesa Rica Sandstone, Dry Creek Canyon and Romeroville Sandstone have similar lithologic characteristics and morphology as the subsurface J Sandstone, Huntsman Shale and the D Sandstone respectively.
5. The subsurface units of Denver Basin can be traced to the southeastern outcrop and the facies in both cases are consistent. The Mesa Rica Sandstone consists of coastal, estuarine and/or fluvial facies which are consistent with the J sandstone facies, the upper Dry Creek Canyon formation contains shallow marine facies which is similar to the Huntsman Shale facies, while the Romeroville Sandstone has fluvial origin facies that matches the D Sandstone facies. Subsurface facies analysis of core in Denver Basin from literature were used to confirm this facies consistency (e.g. Sonnenberg,1987; Sonnenberg and Porter,1995; Weimer et al.,1998) .

4.2 Valley incisions and valley trends of the D and J Sandstone

Valley incisions are generally thinning toward down-dip and thickening towards up-dip directions. The thinning and thickening trends down-dip and up-dip can be observed in both subsurface well-logs and in the southeastern Colorado outcrops (Fig.12) in the study area. This thickness variation can be explained using the Buffer and Buttress model that was proposed by Holbrook (2006) (Fig.17),where the buttress is the physical erosional barriers such as sea-level or lake-level and buffer is the zone that confined between maximum aggradation profile (upper buffer zone) and maximum incision profile (lower buffer zone). Rising, lowering and shifting the buttress can cause several changes in buffer zone down-dip with minor effect in up-dip (Fig.18) (for more information about Buffer and Buttress see Holbrook,2006). In brief explanation of the thinning and thickening of Dakota Group valleys using buffer and buttress model, the incision and aggradation occur between the upper buffer zone and lower buffer zone limits between which channels can migrate freely horizontally and vertically (Holbrook,2006). In down-dip, the buffer zone is thin (Fig.17) which limits the incision and aggradation of the channels, resulting in thinning of valley-fill deposits. While in up-dip, the buffer zone is much thicker than down-dip which gives more space for incision and aggradation leading to thicker valley-fill deposits in up-dip.

Valley incisions trends and valley patterns of the D and J Sandstone units of Dakota Group were illustrated using isopach maps and well-log cross-sections:

4.2.1 Valley incisions and valley trends of the J Sandstone

Valley-fill locations and valley trends of the J Sandstone were determined by using an isopach map for the interval from SB3 at the base of the J sandstone (top of Skull Creek) to TSE3 at the top of the D Sandstone (Fig.8) and well-log cross-sections (Fig.10 and Fig.11). The major valley directions in the study area are from western and northwestern areas out of the study area with some indications of valleys trending from the East.

The major valley in the study area is with northwest-southeast trend and cutting across the entire study area. There are smaller valleys with the same trend and others with west-east trends on the western parts of the area. The continuation of these smaller valleys is uncertain because of lack of information on the westernmost parts of the study area. Intersections between the main valley and the smaller ones in the West were observed in the western part of study area.

4.2.2 Valley incisions and trends of the D Sandstone

The isopach map for the Huntsman Shale interval (Fig.9) and well-log cross-sections illustrate valley incision locations and valley trends of the D Sandstone. The zero value or the very thin sections in Huntsman isopach map indicates full incision and/or deep incision of the D

Sandstone and the removing of Huntsman Shale. The main valley trends within the study area are from the East and northeast (Fig.9) where the major thickening in the D sandstone occurred with presence of another minor western and southern valley trends. The eastern and western valley trends change from eastward and westward to southward as valleys from both sides reach the center of the study area. Valleys cross-cut and join reflecting different valley generations as observed by intersecting thinning trends on the isopach map in southern parts of study area.

4.3 Synchronous valleys vs. Asynchronous valleys

The main assumption that most researchers made to represent valleys and their trends in isopach maps is that valleys are synchronous (i.e. occurred at the same time) (e.g. Fig.19). They impose this assumption into their isopach maps to construct one large drainage system that contains all the smaller valleys within which only shows the major trend of this large drainage without illustrating the individual smaller valleys trends (e.g. Weimer,1992; porter and Sonenberg,1994, Holbrook,2001).

In this study, I assume that valleys of the J and D Sandstone that I identified in the isopach maps and cross-sections are asynchronous where younger valley generation cut and fill older valleys as they do in outcrop of Mesa Rica and Romeroville Sandstone formations (Holbrook,2001) (Fig.20). This assumption will illustrate valley trends of each individual generation instead of illustrating one major integrated trend of all valleys. Another advantage of applying this assumption is that it provides more details of valleys within the main drainage system which can be used to recognize valley-fill deposits from interfluves. Sand-bodies within the J and D Sandstone valley-fills can be distinguished from interfluves that separate each valley from the other and also can show the valley-fill distribution within the drainage which gives more precise estimation for future exploration and drilling locations within the main drainage. The intersection of valleys within the J and D Sandstone are observed in both J Sandstone isopach map (Fig.8) and Huntsman isopach map (Fig.9) and are illustrated by dashed lines. In the J Sandstone isopach map, valley intersections of the J Sandstone are demonstrated by the intersection of the thick trends of the western source (in the western side of the study area) with valleys that have northwestern source.

In the Huntsman isopach map, valley intersections of the D Sandstone are demonstrated by the intersections of the thin trends of Huntsman Shale (where the D Sandstone is thick). Valleys from eastern, western and southern sources in the study area intersected with each other in South-central part of study area. The high angle of the intersections in both isopach maps is an indication that these valleys are from different generations that cut-cross each other.

These intersections of different valley generations of the J and D Sandstone can be explained by using the Buffer and Buttress model. Valleys were formed as result of repetitive series of cut (incision) and fill (aggradation) (Holbrook, 2001) within a vertical stable buffer zone. In both isopach maps, the J and D Sandstone valleys cut and fill into the Skull Creek Shale and Huntsman Shale respectively. As valleys were almost filled, valleys topped, and their channels started to avulse to a new direction (Holbrook, 2001). This process resulted in a new valley generation will incise and aggrade in a new location intersecting with the older valley (Holbrook, 2001).

4.4 Paleogeography of the J and D Sandstones

Distribution and paleogeography of the Dakota Group strata in the study area are analyzed using the two isopach maps and well-log cross-sections of the Huntsman Shale, D and J sandstone units. Depositional models that developed here are derived from depositional models of Weimer (1988) and Weimer (1992) for the J “Muddy” sandstone in northern Denver and Sonnenberg (1987) for the D sandstone in western and central Denver Basin , and outcrop interpretations for Dakota Group age equivalents in southeastern Colorado and northern Oklahoma that were studied by Holbrook (2001) , Holbrook (2006) and Oboh-Ikuenobe et al. (2008), and Buffer and Buttress model that was proposed by Holbrook (2006) . The large study area does not permit the illustration of the details of the smaller scale features of each individual delta (e.g. shape and type), but does illustrate the major drainage trends.

During Cretaceous, the North America continent witnessed a series of flooding events from two separated seas located in northern and southern parts of the continent. The Tethys was a warm and saline sea that was located in the southern North America continent, whereas the Boreal was less saline, cooler water sea that located in northern part of the continent (Kauffman,1977;Plint and Wadsworth,2003) (Fig.21). These two seas were possibly connected and separated many times before they became a fully connected seaway (the Western Interior Seaway, Fig.1) in Late Cretaceous (Oboh-Ikuenobe et al. ,2008) as will be further discussed in this section.

The Boreal and Tethys seas were connected in the early part of Late Albian (Kauffman,1977; Oboh-Ikuenobe et al. ,2008) when the Skull Creek Shale was deposited. During the very late part of Albian, sea level dropped in the Western Interior Seaway and these two seas were separated allowing large areas of Skull Creek on both the Seaway shores to be subaerially exposed to erosion (SB3) (Fig.21, A). In Buffer and Buttress model, sea-level drop will pull the buttress (i.e. sea-level) back which will lead to lengthen the profile (Fig.18,D) and increasing the distance that rivers can drain. Rivers and their associated deltas drained the exposed areas and incised into the underlying marine shale (Skull Creek) to reach the new base level between the Buffer zone. In the study area, deltas prograded eastward and southeastward from western and northwestern sources. This interpretation is based on valley trends in both isopach map (Fig.8) and cross-sections which both show that the majority of valleys trends are west-east and southeast-northwest. This interpretation of valley trends matches with Weimer (1992) (Fig.22), Dolson (1991), and Porter and Sonnenberg (1994) (Fig.23) interpretation of the J “Muddy” Sandstone paleogeographic trend in northern Denver Basin. There are indications of an eastern delta source outside the study area presented by the thickening in the J sandstone northeastward and the presence of number of tributaries in the southeastern part of the study area in the J Sandstone isopach map. Some of the valleys in the study area were cut-cross by younger valley generations as previously discussed. These younger generations either cut and fill the older valley or just joined the older generation path as they met in the center of study area. This cross-cut relationship is illustrated in isopach map where two thick trend valleys cross-cut each other.

Following the sea level drop, sea level started to rise and the incised valleys that have not yet been filled by rivers and streams began to be filled with fluvial and estuarine deposits of the J Sandstone unit in down-dip to a certain distance towards up-dip. Sea level rise (i.e. buttress rise) will increase the buffer zone from down-dip to a certain distance in up-dip (Fig.18, B) where buttress shift effect is neglected. Further up-dip, incision and aggradation of valleys within the thick buffer zone happen freely without the influence of marine transgression and they are mainly influenced by climate variation and/or subsidence (Holbrook, 2001). Then sea level continued rising, shifting shoreline landward and allowing waves to scour and erode (i.e. TSE2) the top of the valley-fills (the J Sandstone) in areas down-dip to some distance towards up-dip where marine water overrun the valleys and waves influence is intense. In southeastern outcrops, TSE2 is absent as wave influence is neglected up-dip away from shoreline where sea level rise only caused aggradation (Fig.12). In these up-dip areas, maximum regressive surface (MRS) or transgressive surface (TS) can be found and it is correlative to TSE2. The TSE2 can be a composite surface near the shoreline where waves and tides erode the maximum regression surface and formed a complex surface of the TSE2 and maximum regressive surface on its position.

As sea transgression proceeded marine shale of Huntsman Shale deposited on the top of the maximum regressive surface and/or TSE2 surface at the top of the J sandstone. The general increasing in Huntsman Shale thickness in the center and towards the northern and southwestern parts of study area indicates that position of deep basin is somewhere northern and southwestern the study area and illustrates that sea transgression was mainly from northwest to south as Martin (1965) demonstrated and from south to north as Oboh-Ikuenobe et al.(2008) demonstrated. During this transgression, a possible shallow marine connection between the Boreal and Tethys seas occurred allowing the two seas water to mix (Oboh-Ikuenobe et al. ,2008) (Fig.21, C) . This connection was favored because of the presence of mixed assemblage of dinoflagellates, acritarchs, and agglutinated Foraminifera from both seas in the subsurface Huntsman Shale and upper part of Dry Creek Canyon Formation (Oboh-Ikuenobe et al., 2008; Ludvigson et al., 2010). This presence of fossil assemblage supports and further argues that these two units (subsurface Huntsman Shale and surface Dry Creek Canyon Formation) correlates and are time equivalents as discussed earlier.

In early-late Cretaceous, and following Huntsman Shale deposition, sea level dropped again exposing large, low relief areas of the basin to be subaerially eroded (i.e. SB4) and drained by rivers and deltas (Fig.21, D). The same concept of Buffer and Buttress as the J sandstone is applied here, sea-level drop will pull the buttress to the back which will lengthen the profile (Fig.18,D) and increase the distance that rivers drained. Rivers feeding and later deltas incised partially into the Huntsman Shale and/or fully through and into the uppermost part of the J Sandstone in certain locations of the study area (zero value in isopach map) (Fig.9). By analyzing valley trends in Huntsman isopach map (Fig.9), these deltas were mainly prograded from the east and northeast with minor progradation from west and south in the study area. Valleys apparent in isopach maps are located where Huntsman thickness is zero or very thin as the D Sandstone valleys totally incised through Huntsman shale, or into large portion of Huntsman thickness. In southeastern outcrop, these valleys are 1-2 km wide which implies that what is presented in the isopach map is general trend of multiple valleys nested together as one or more wide valleys. Terraces within valleys in eastern and western parts (T in Fig.9) of the study area represent a relative lowering in base level (Holbrook,2001) which led to deeper valley incision by rivers to reach the new base level leaving high, relatively flat areas in both sides of the newly incised valley. Intersections of valleys are also presented in the D Sandstone valleys especially in the southern study area. By examining the intersections pattern of valleys in isopach map; it is obviously that they formed as result of intersection between the southern deltas and the eastern and western ones in succession such that older valleys incised and filled before being incised by younger valleys as discussed previously. It is very difficult to determine which of these valley intersections is younger or older from borehole data as the valley contacts can not be seen without seismic data.

Sea level rose again and the incised valleys down-dip that were still not filled by river sediments were filled with fluvial and estuarine deposits of the D Sandstone unit to a point up-dip where marine transgression influence is neglected, whereas up-dip valleys cut and fill within the thick Buffer zone under the influence of climate and subsidence only (Holbrook,2001). Again, and as the case in the J Sandstone, sea level rise (i.e. buttress rise) will increase the thickness of the buffer zone from down-dip to a certain distance in up-dip (Fig.18,B) where buttress shift effect is neglected (Holbrook,2006).

Sea level rise continued and waves started to erode the top of the D Sandstone valley-fills (i.e. TSE3). Then these valley-fill deposits were capped by transgressive marine shale deposits of Graneros Shale. This transgression continued and a full connection between the Boreal and Tethys seas was established in Middle Cenomanian and lasted to the end of the Cretaceous period (Kauffman,1977; Oboh-Ikuenobe et al., 2008).

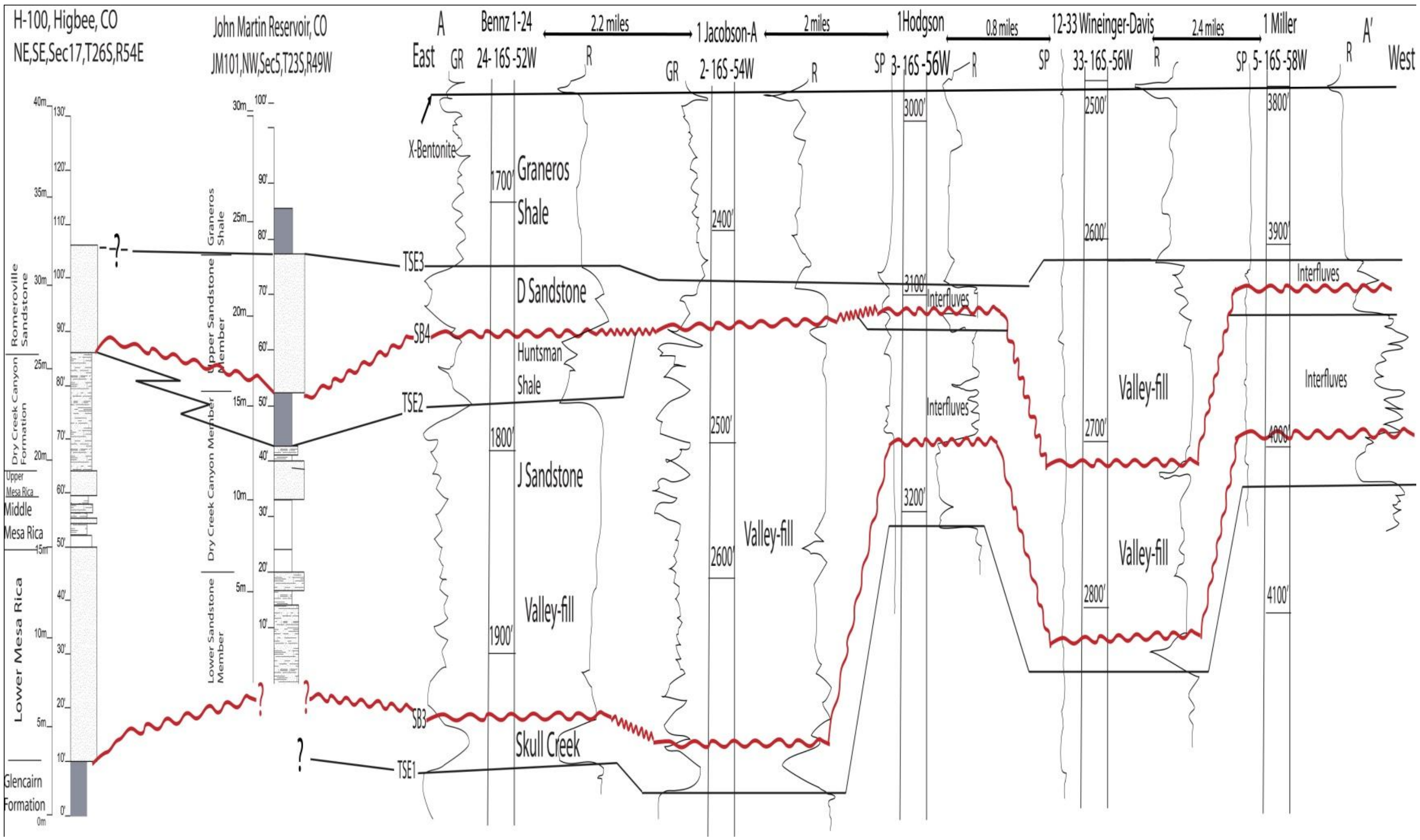

Fig.16: Correlation of subsurface Dakota Group E-W cross-section with surface measured sections in outcrops (JM-101) and (H-100) in southeastern Colorado.

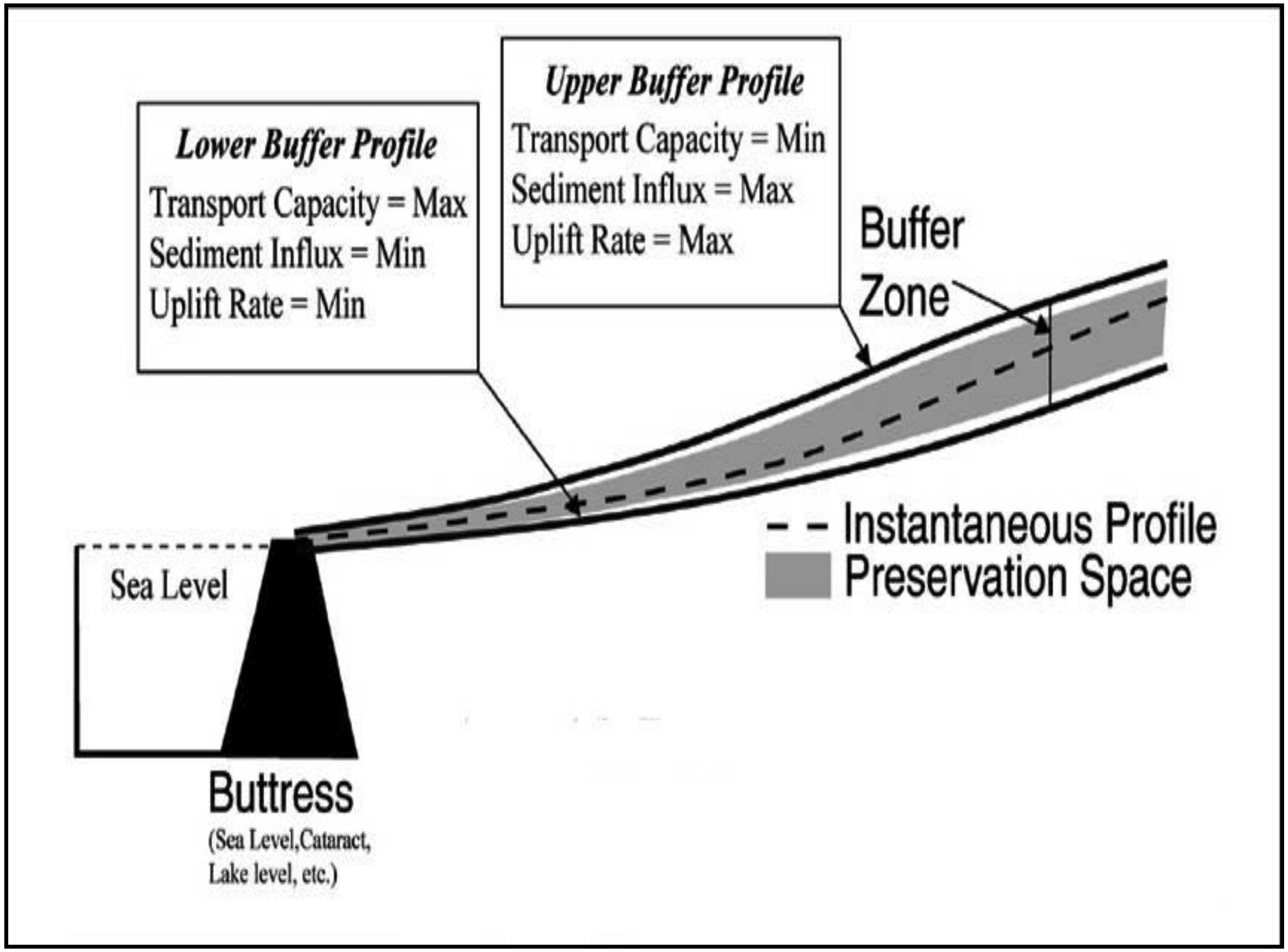

Fig. 17: Buffer and Buttress model showing the location of Buffer upper and lower zone limits and Buttress. (Holbrook, 2006)

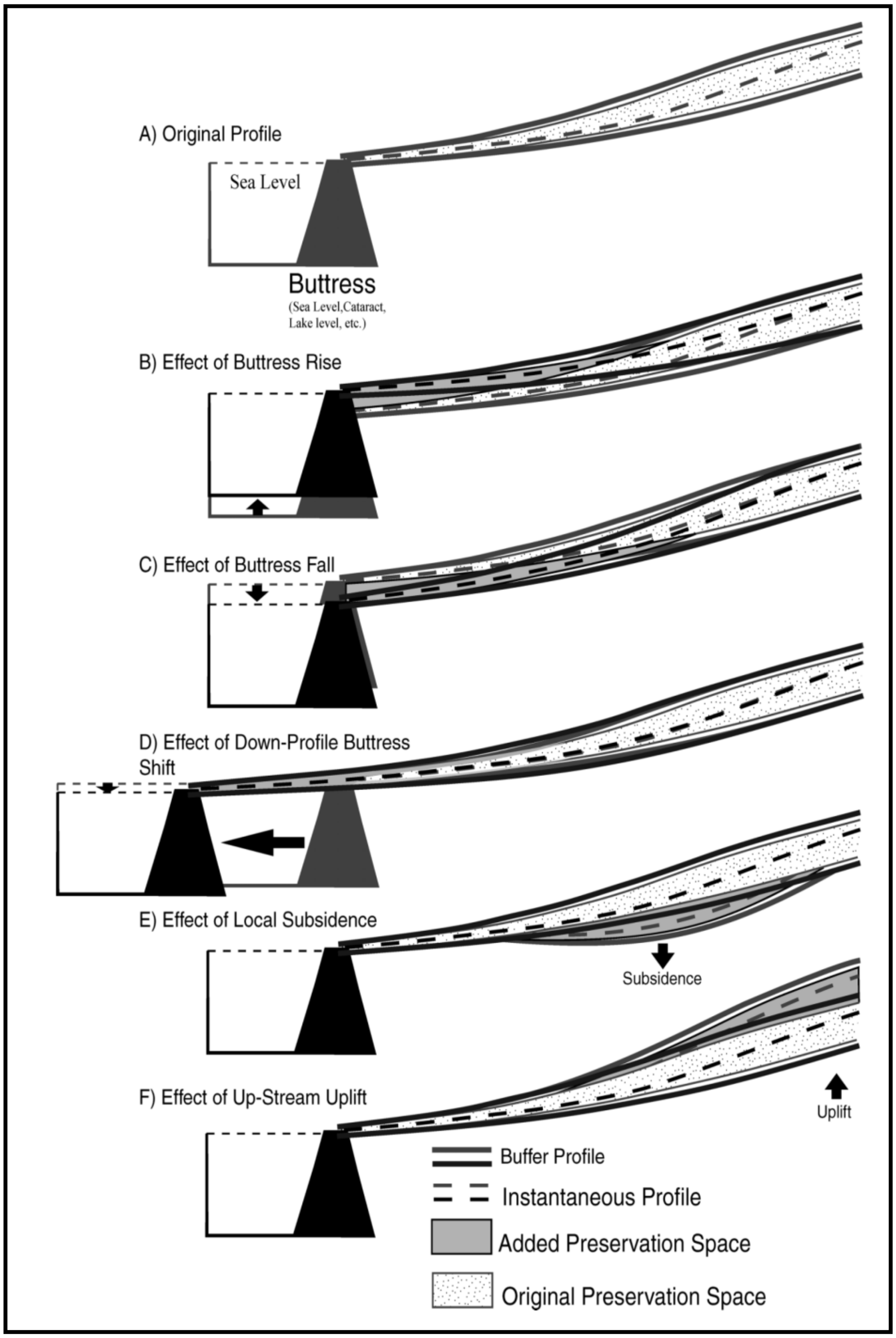

Fig.18: Buffer zone response to Buttress change in Buffer and Buttress model. (Holbrook,2006)

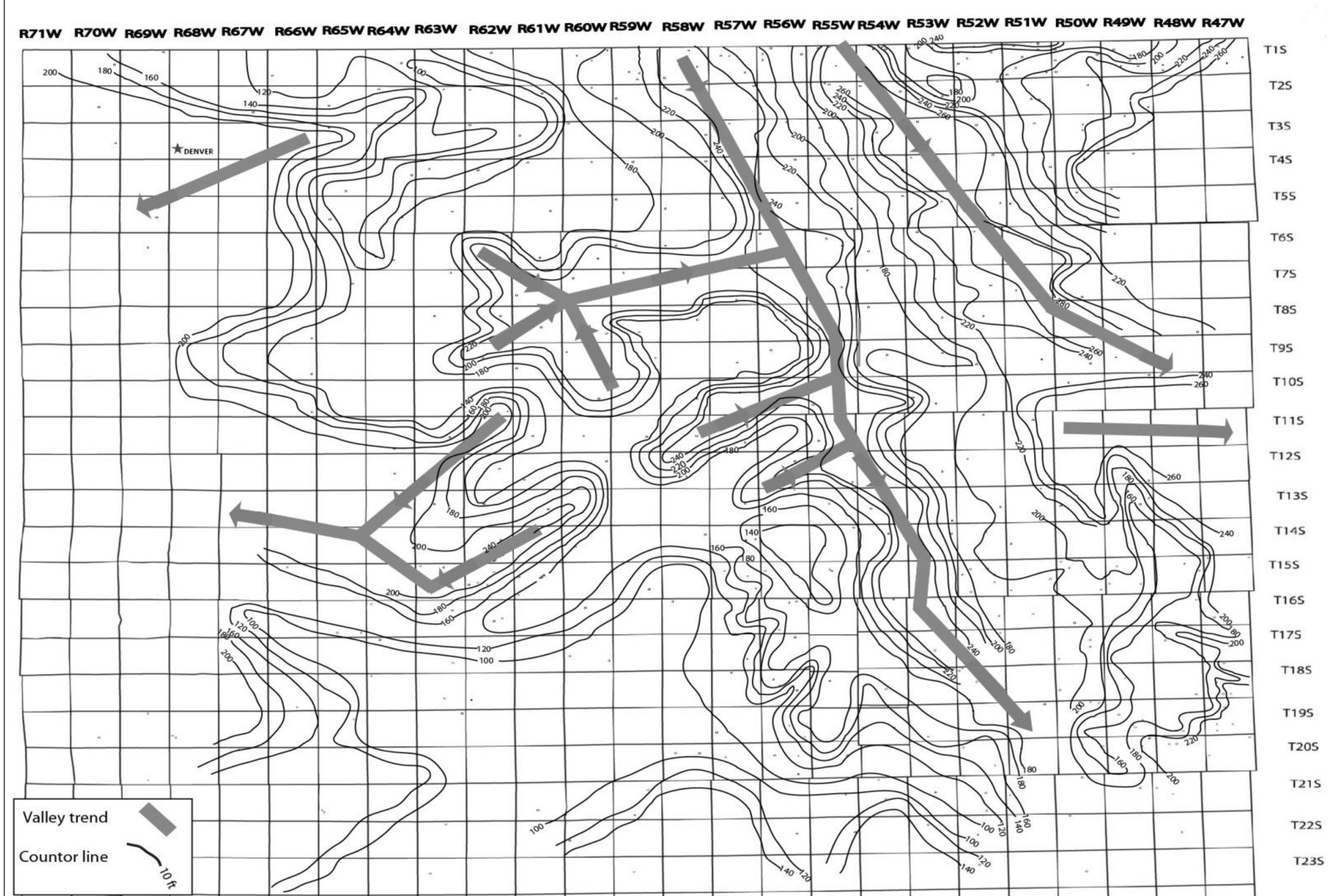

Fig.19: Isopach map of Dakota Group strata with same data as Fig.8 with the assumption that valleys are synchronous (do not cross-cut each other). This map was constructed to be compared with Fig.8 where valleys are asynchronous

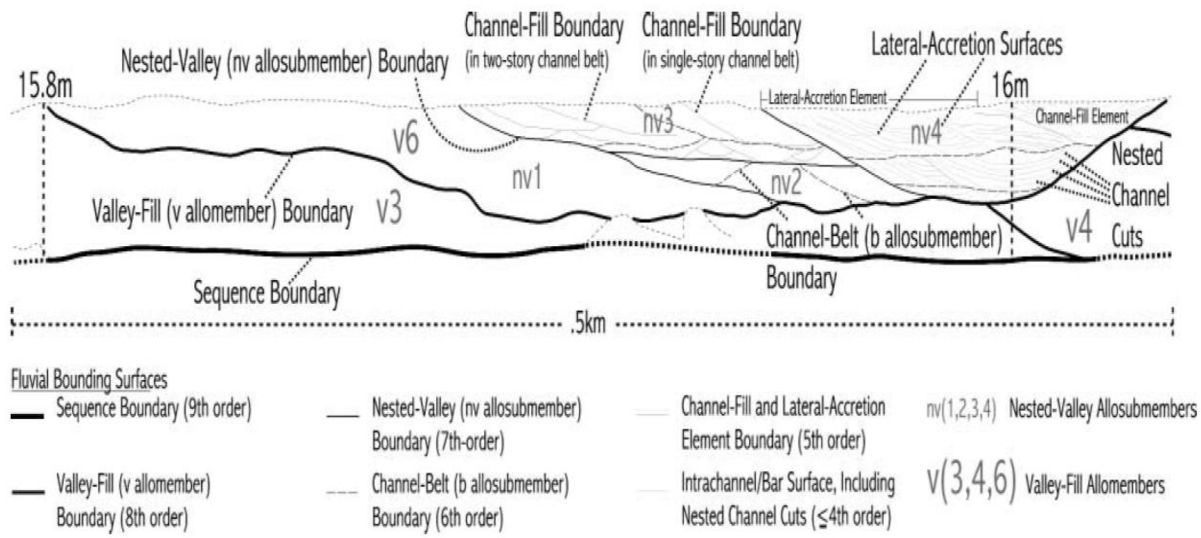

Fig. 20: Outcrop cross-section of Romeroville Sandstone from Huerfano Canyon southeastern Colorado showing intersections of different valley generations. (Holbrook,2001)

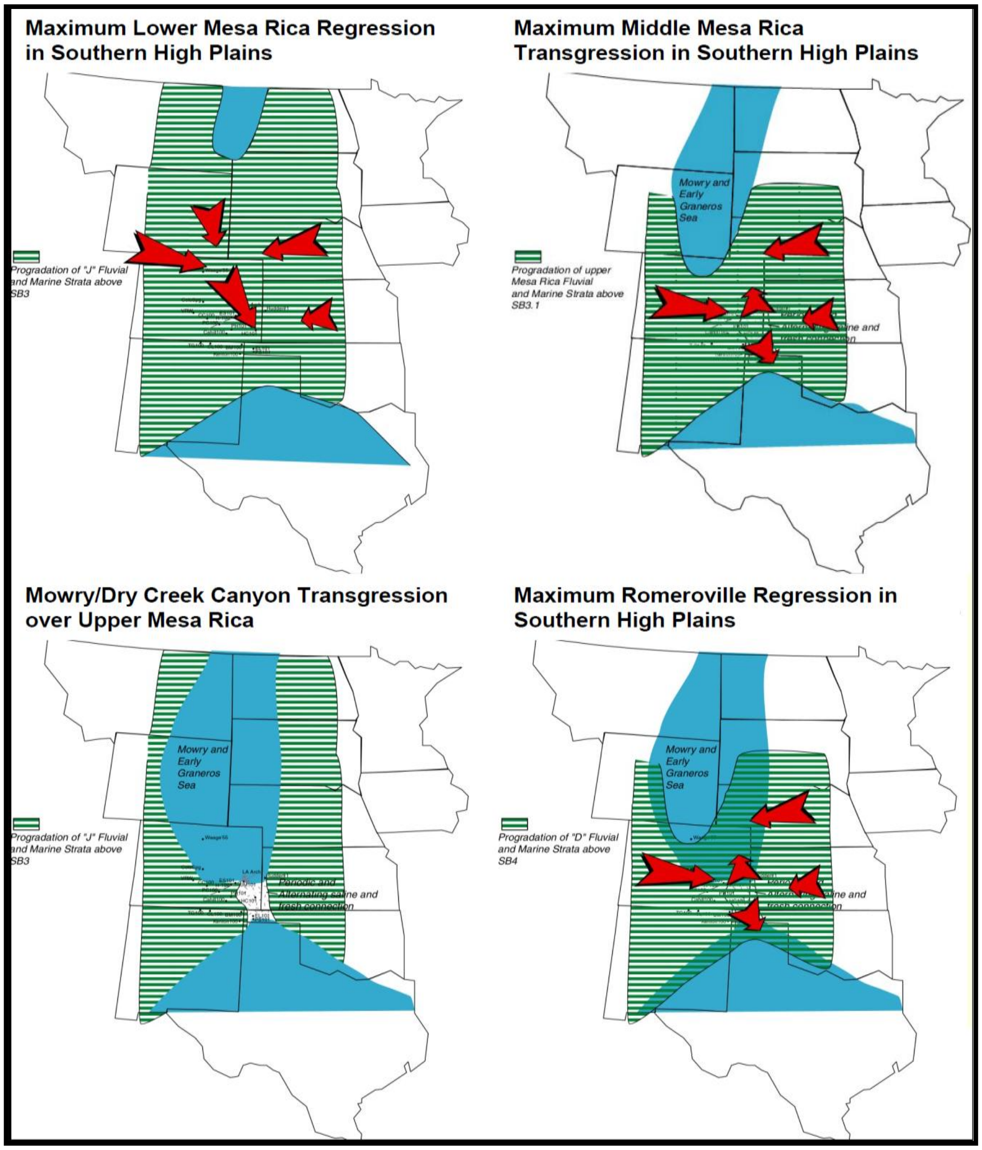

Fig. 21: proposed maximum regression and transgression limits and possible two seas connection during Dakota Group strata deposition. From (Holbrook, personal communications).

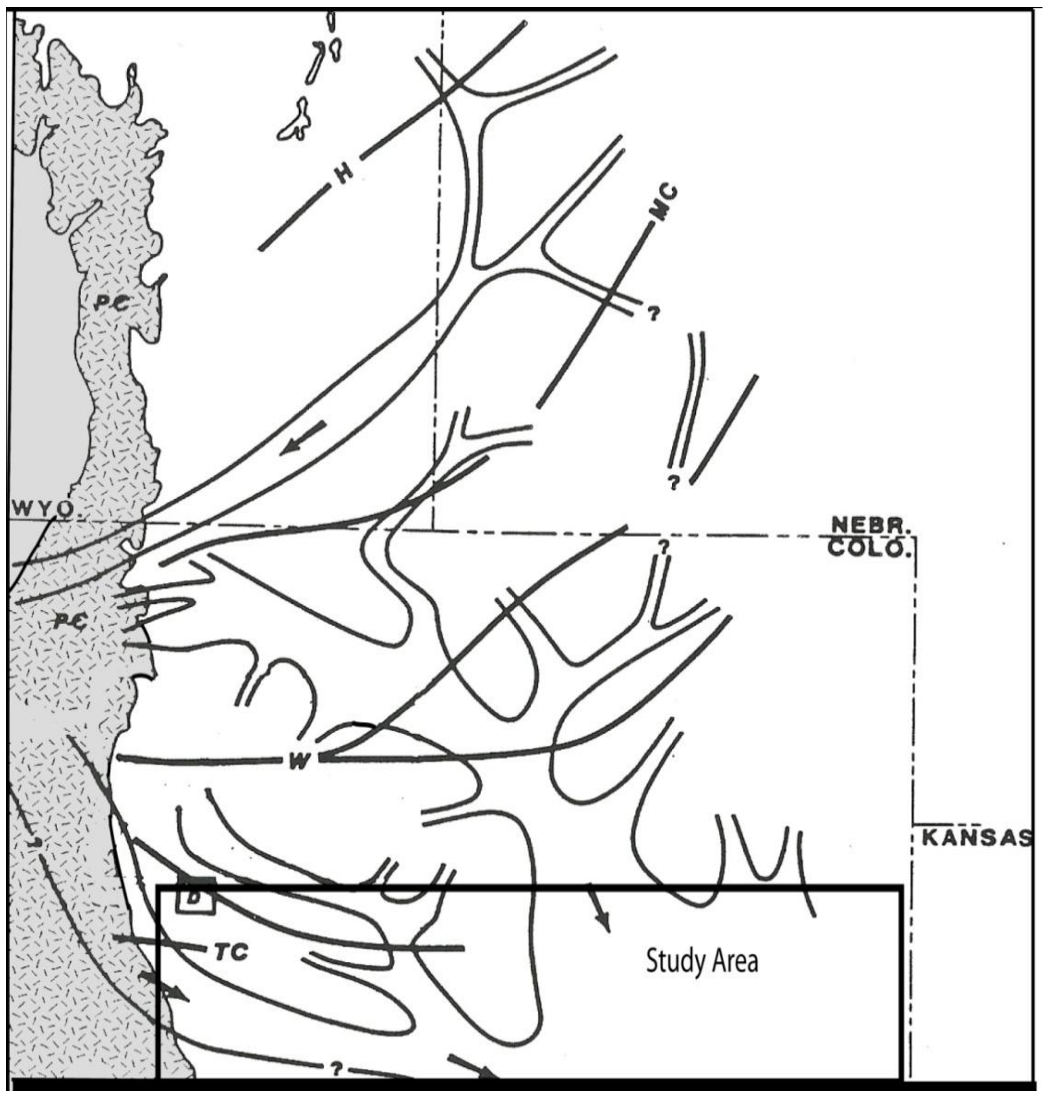

Fig. 22: Paleovalley trends in northern Denver Basin interpreted by Weimer (1992) . Modified from (Weimer, 1992)

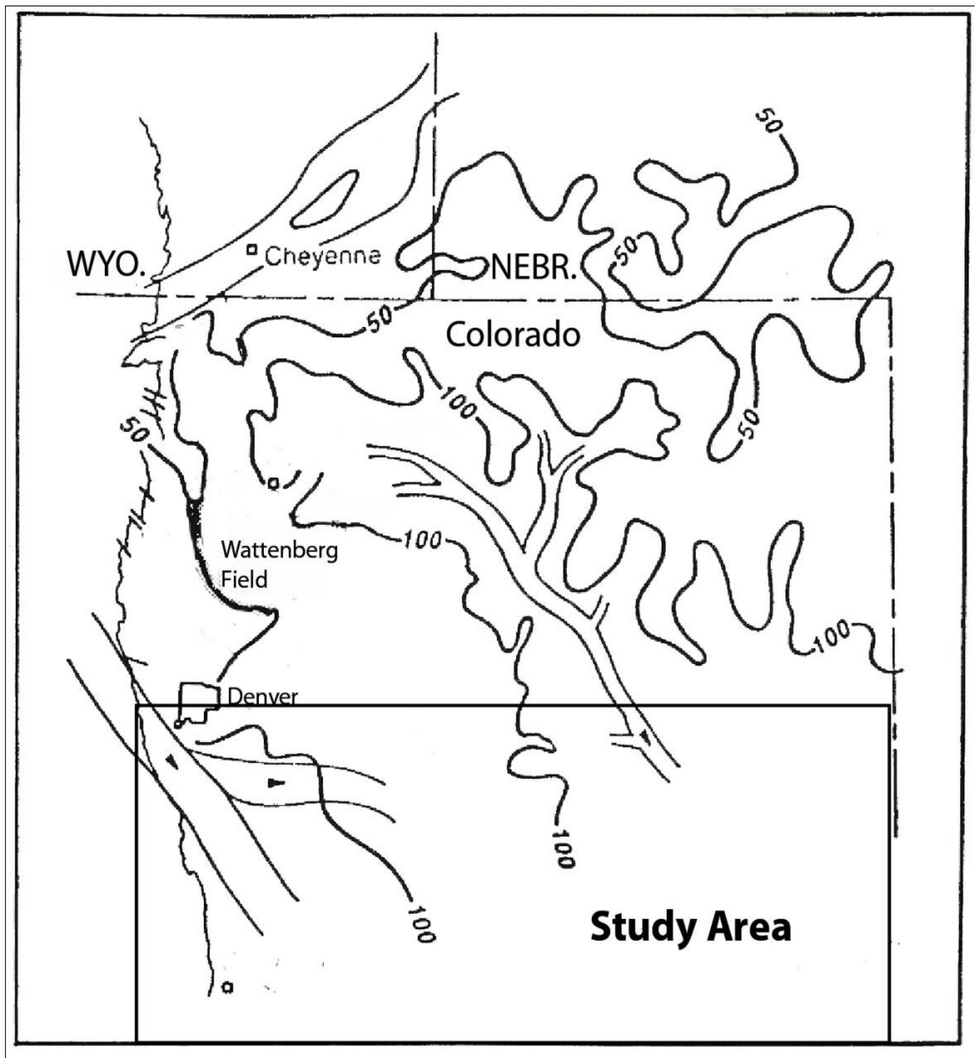

Fig. 23: Isopach map of the J"Muddy" Sandstone showing valley trends in northern Denver Basin interpreted Sonnenberg .
Modified from (Porter and Sonenberg,1994)

CHAPTER 5

CONCLUSION

This study was an attempt to correlate subsurface Dakota Group strata in the Denver Basin with their surface equivalents in outcrops of southeastern Colorado using well-logs and measured outcrop sections. Sequence stratigraphic surfaces within subsurface Dakota Group strata in well-logs were correlated throughout southern Denver Basin and then were correlated to their age-equivalents in southeastern outcrops. Also, a paleogeographic model was proposed using the Buffer and Buttress model of olbrook (2006). The main important outcomes of this study are:

1. The subsurface J Sandstone, Huntsman Shale, and the D Sandstone of subsurface Dakota Group and their sequence stratigraphic surfaces (SB3, SB4, TSE3, TSE2) are correlated to their age-equivalents of the Mesa Rica Sandstone, Dry Creek Canyon Formation and Romeroville Sandstone of surface Dakota Group respectively in southeastern outcrops.
2. Similarity in facies, trends and the presence of mixed assemblage of dinoflagellates, acritarchs, and agglutinated Foraminifera from both Boreal and Tethys seas in the subsurface Huntsman Shale and upper part of Dry Creek Canyon Formation confirm that they are correlated and extend the Huntsman Shale from subsurface to outcrop.
3. Valleys of the J and D Sandstone within the study area identified in the isopach maps and cross-sections are asynchronous where younger valley generations cut and fill the older valleys at the same stratigraphic level rather than synchronous prior researchers propose for these and similar strata.

4. Deposition, distribution and valley trend variations of the J and D Sandstone in Denver Basin can be better explained by using the Buffer and Buttress model that was proposed by Holbrook (2006) in both down-dip and up-dip.

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