Genesis and characterization of dolomite,
Arab-D Reservoir, Ghawar field, Saudi Arabia

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ABSTRACT

This study reports the results of an investigation into the nature, origin and significance of linear dolomite trends across the Arab-D reservoir in Ghawar field. In the course of this study, three distinct types of dolomite were identified based on petrographic and geochemical criteria: fabric-preserving (FP), non-fabric-preserving (NFP) and baroque dolomite. Fabric-preserving (FP) dolomite is very finely crystalline dolomite in which details of the original limestone fabric are usually well preserved. Beds of FP dolomite typically occur as thin, sheet-like or stratigraphic layers that are always intimately associated with the overlying anhydrite. This dolomite is interpreted to have formed very early in the diagenetic history of the sediment, by dense, highly evaporated magnesium-rich brines associated with the overlying anhydrite. In contrast, NFP dolomite is a medium crystalline, non-baroque dolomite in which all traces of the original limestone fabric have been obliterated. This dolomite also typically occurs as stratigraphic beds, although it is not restricted to the uppermost part of the Arab-D but occurs throughout the reservoir. The NFP dolomite is the most common type present in the reservoir, and is interpreted on the basis of its general geochemical similarity to the FP dolomites to have mostly formed from hypersaline fluids, although some NFP dolomite is thought to represent a transitional form with the third dolomite type, baroque dolomite. Strontium isotopic ratios suggest that both the FP and most of the NFP dolomite formed very early, at or shortly after deposition of the original sediment. The third type of dolomite, baroque, is a coarsely crystalline dolomite with “saddle-shaped” crystals displaying undulose extinction in thin section. It is rare in the reservoir and appears to be limited to wells that contain abnormally thick sections of dolomite; in extreme cases, baroque dolomite is vertically pervasive. Geochemically, baroque dolomite is distinctive with high iron and very low oxygen isotopic compositions, and is interpreted to have formed from high temperature fluids during burial diagenesis. These fluids are suggested to have ascended up into the reservoir from depth along a fault/facture system, relatively late in the diagenetic history of the rock.

INTRODUCTION

It has long been recognized that the Arab-D reservoir in Ghawar field (Figure 1) contains a significant amount of dolomite rock (defined in this study as carbonate rocks that are composed of more than 75% of the mineral dolomite (Powers, 1962), and that the occurrence of dolomite is highly variable. Arab-D dolomites typically have pore systems and reservoir characteristics that are fundamentally different from those of nearby limestones, and thus represent a distinct petrophysical and fluid-flow unit in the reservoir.

Primarily, dolomite occurs in two broad categories in the Arab-D (Figure 2), as either stratigraphic or non-stratigraphic dolomite (Mitchell et al., 1988). Stratigraphic dolomites are thin, lenticular or sheet-like beds that typically range in thickness from one to 15 ft, and usually occur within fairly well-defined stratigraphic intervals within the Arab-D. The thickest stratigraphic dolomites tend to occur in the middle of the Arab-D reservoir in the uppermost portion of Zone 2B (Figures 1 and 2), while the most continuous dolomite bed is found at the top of Zone 3A. These dolomites can be quite areally extensive, covering tens of square kilometers. Other stratigraphic dolomites in the Arab-D can rapidly change in character, as shown in Figure 2, where in the distance of less than two kilometers several dolomite beds either disappear or significantly change in thickness. Vertical transitions from limestone to dolomite are typically gradational in character, usually occurring over a vertical distance of one to two feet.
**Figure 1:** Basemap showing the various operational areas of Ghawar field, and a schematic display of the reservoir zonation naming scheme used in Ghawar.
In contrast, non-stratigraphic dolomite is vertically pervasive in nature, with thick sections of it cross-cutting stratigraphic reservoir zones (Figure 2). These dolomites occur when normally dolomite-free parts of the section contain significant amounts of dolomite, and typically crosscut other stratigraphic dolomites and often occupy most of Zone 2 and parts of Zone 3. These intervals of non-stratigraphic dolomite typically have a very limited areal extent, generally extending for only one to two kilometers. In many cases, these thick dolomites are encountered in only one well. Vertical transitions from limestone to dolomite for this non-stratigraphic dolomite are typically quite abrupt.

The present study began several years ago following some recent mapping of the dolomite distribution within the Arab-D in Ghawar and Abqaiq fields (Figures 3 and 4). This mapping (reported most recently in Cantrell et al., 2001) revealed that dolomites were not distributed randomly throughout the reservoir, but that several parallel linear trends of high dolomite content occurred across most of Ghawar and Abqaiq. These trends have a dominant NE-SW orientation, although a less well-pronounced NW-SE trend also occurs, and they generally intersect those areas of vertically pervasive dolomite. The main NE-SW orientation was especially surprising in that it is oblique to the overall structural orientation of Ghawar (which generally strikes NNE-SSW), and almost exactly perpendicular to the depositional strike.

Figure 2: Cross sections contrast the lateral persistence and continuity of stratigraphic dolomites (above) with vertically pervasive, non-stratigraphic dolomite (below).
From a reservoir management perspective, it is important to understand the occurrence and distribution of dolomite in the reservoir. Dolomite in the Arab-D has a pronounced impact on reservoir quality, in a number of ways. At times, dolomite is responsible for producing zones of extremely high permeability and high fluid flow (‘super-k’) in the reservoir, while at other times these rocks act as permeability barriers or baffles. In addition, dolomite typically has a higher grain density and acoustic velocity than limestone, which affects the response of most porosity wireline logging tools to dolomite rocks. Dolomite also reacts more slowly to the presence of acids than does limestone, resulting in uneven responses to acidization treatments. Surface chemistry differences may also result in dolomite and limestone differing in their wettability and adsorption characteristics within a reservoir. Finally, limestone and dolomite differ greatly in their strength and ductility. Abundant experimental (Handin et al., 1963; Hugman and Friedman, 1979) and field (Stearns, 1967) data suggest that dolomite is generally stronger and more brittle than limestone at the same burial depth. The preferential development of fractures in dolomite beds often enhances their permeability (without greatly affecting their porosity) and potentially influences the overall quality of the reservoir.

The primary objectives of this study were: (1) to document the nature of the dolomites in the Arab-D both on and off the dolomite trends; and (2) to define the major factors that lead to the formation of the dolomites along these trends.

The presence of such pronounced linear trends in the distribution of dolomites strongly suggests that some structural element is responsible for controlling their orientation. Initially we speculated that some form of fracturing and/or faulting may have directly or indirectly influenced the location and orientation of the dolomite trends. For example, fracture-related dolomitization has been previously reported in the literature (the Albion-Scio Trend of Michigan; Taylor and Sibley, 1986). In that case, it was postulated that fractures allowed fluids to move vertically upward from depth into the reservoir, and preferentially dolomitize the limestone along the fracture trends. If a similar scenario existed in the Arab-D, it could have important reservoir management implications because the fractures that were responsible for forming the linear dolomite trends may still be open and have some influence on present-day reservoir fluid flow. These fractures – if they actually exist and are still open – would also be likely areas of possible vertical communication with the underlying Hanifa Formation.

**Objectives and Initial Hypothesis**

The presence of such pronounced linear trends in the distribution of dolomites strongly suggests that some structural element is responsible for controlling their orientation. Initially we speculated that some form of fracturing and/or faulting may have directly or indirectly influenced the location and orientation of the dolomite trends. For example, fracture-related dolomitization has been previously reported in the literature (the Albion-Scio Trend of Michigan; Taylor and Sibley, 1986). In that case, it was postulated that fractures allowed fluids to move vertically upward from depth into the reservoir, and preferentially dolomitize the limestone along the fracture trends. If a similar scenario existed in the Arab-D, it could have important reservoir management implications because the fractures that were responsible for forming the linear dolomite trends may still be open and have some influence on present-day reservoir fluid flow. These fractures – if they actually exist and are still open – would also be likely areas of possible vertical communication with the underlying Hanifa Formation.
Some preliminary evidence supported the hypothesis of fracture-controlled dolomitization in the Arab-D. While fracturing is generally rare throughout most of the Arab-D, it can be locally common, and faulting within the reservoir has been identified seismically although fault cuts observed in Arab-D core are rare. Faulting does occur in the Permian Khuff Formation below the Arab-D (I. Al-Jallal, Saudi Aramco, personal communication), and within this interval there is abundant evidence of diagenesis by high temperature, mineral-laden fluids. Sphalerite (ZnS), pyrite (FeS₂), barite (BaSO₄), celestite (SrSO₄), and Mn-rich calcite all occur as cements in this formation and are clear evidence for diagenesis by hot, mineral-rich fluids. Finally, fractures filled by sphalerite and dolomite (Figure 5a) have been observed in the Fadhilli Reservoir approximately 1,000 feet below the Arab-D in northern Ghawar (B.H. Walthall, Saudi Aramco, personal communication, and confirmed by us on a sample provided by him), again indicating that hot, mineral-rich fluids were present. Therefore, it seemed feasible that dolomitization by high temperature, mineral-rich fluids from depth could have occurred along zones of fractures in the Arab-D, giving rise to the observed high dolomite trends.

Method of Study

A two-part approach was used to study the questions raised by the dolomite distribution: (1) document (using petrographic and geochemical techniques) the character of the dolomite along the trends to see if these dolomites are different from off-trend dolomites, and determine if there is any evidence to indicate dolomite formation by high temperature fluids; and (2) document any direct evidence, from descriptions of fractures observed in core, that might indicate a fracture system associated with the NE-SW oriented dolomite trends.

Figure 5a: This limestone from approximately 1,000 feet below the Arab-D in ‘Ain Dar contains a near-vertical fracture that is filled by both sphalerite (S) and dolomite (D). The occurrence of these minerals is clear evidence for hot, geothermal fluids at depth. Slabbed core photograph, ANDR well, core depth=8,367 feet. Core is approximately 3 inches in diameter.

Figure 5b: Dolomites in Zone 1 are typically fabric-preserving (FP) in nature. In this FP dolomite, minute details of the precursor limestone fabric– such as relict grains, pore types and cements– are clearly visible even though completely replaced by dolomite. These dolomites have porosity/permeability characteristics that are more typical of limestones than of dolomites. Plane-polarized light, well BB, core depth=7,649.5 feet.

Figure 5c: Detail of the previous photograph. Relict grains – such as ooids (OO), probable dasycladacean green algae (D) and probable bivalves (B) – are identifiable, as is relict isopachous bladed cement (arrows). Pore types include relict interparticle (BP) and moldic (MO). Plane-polarized light, well BB, core depth=7,649.5 feet.
Petrographic techniques used in this study included standard plain light petrography as well as cathodoluminescence and blue-light fluorescence petrography. Geochemical techniques included analysis of stable oxygen, carbon, and strontium isotopic ratios, analysis of elemental compositions by electron microprobe, and fluid inclusions studies. Finally, core descriptions were analyzed for evidence of a fracture system in the Arab-D.

Background and Regional Geology

The Arab Formation was deposited during the Upper Jurassic in the shallow Tethys Sea on a broad, relatively stable shelf or platform. This broad shelf lay between 10-15 degrees south latitude, and was bounded to the north by the Basrah Basin and to the south by the Rub‘Al-Khali Basin. To the west lay the Arabian Shield, while the Qatar-Surmeh High was located to the east. The overall abundance of grain-rich, mud-poor sediments suggests that generally high energy conditions prevailed across much of this shelf area. Overall, the paleoclimate was probably hot and arid, much like today’s climate on the Arabian Peninsula. The geology of this area during the Kimmeridgian-Tithonian has been previously summarized in detail (Al-Husseini, 1997; Alshalharan and Magara, 1995; Grabowski and Norton, 1995; Cecca et al., 1993; Fourcade et al., 1993; Mitchell et al., 1988; Le Nindre et al., 1987; Al-Sharhan and Kendall, 1986; Ayres et al., 1982; Murris, 1980; Wilson, 1975; Powers, 1962), and will not be reviewed further here.

It should be noted that research is currently underway within Saudi Aramco to define a sequence stratigraphic architecture for the Arab-D (and preliminary results are summarized in Handford et al., 2002 and Handford et al., 2003), but no consensus stratal framework has as yet been finalized for this interval. As a result, all discussion of stratigraphic framework in this study utilizes the lithostratigraphic zonation scheme defined in Figure 1.

RESULTS

The results of this study are discussed in terms of three major areas of effort: petrography, geochemistry and fracture evaluation. These efforts were all directed at characterizing the nature and origin of the dolomite.

Petrography

Arab-D dolomites were studied using three different petrographic techniques: plane-polarized light, blue-light fluorescence and cathodoluminescence petrography. While many past studies have used plane light petrography to examine Arab-D dolomites (Mitchell et al., 1988; Meyer and Price, 1993; Meyer et al., 2000; Broomhall and Allen, 1987), this study is the first to use these last two techniques to systematically examine Arab-D dolomites. Literally thousands of samples from across the field were examined for this study; a map showing the location of wells from which samples were examined petrographically (as well as sampled for geochemistry) is given in Figure 18. Based on these petrographic studies, at least three different types of dolomite are recognized in the Arab-D.

The first type of dolomite is a fabric-preserving (FP) variety that typically exists in Zone 1 in Ghawar and Abqaiq (Figure 5b and c, Figure 6). FP dolomite generally occurs as laterally discontinuous sheet-like or stratigraphic layers of five feet or less in thickness. The FP dolomite is always intimately associated with the Arab-D Anhydrite (Figure 6a), occurring either as interbeds within the Anhydrite itself or within the transition zone (Zone 1) between the overlying Anhydrite and the underlying limestones of the Arab-D reservoir.

Petrographically, FP dolomite is very finely-crystalline, containing cloudy crystals that range in size from approximately 10 to 50 microns (Figure 5c). These crystals appear non-luminescent when examined under cathodoluminescence, yet fluoresce strongly under blue-light fluorescence (Figure 6c). FP dolomite is formed by replacement of a precursor limestone grainstone in which most of the fabric details have been perfectly preserved; depositional grains, cements and pores are all readily identifiable. Pore types present are predominantly relict interparticle and relict moldic pores, and are more typical of Arab-D limestones than of other Arab-D dolomites.
The second variety of Arab-D dolomite is the non-fabric-preserving (NFP) variety that is the most volumetrically significant type present in the reservoir (Figure 7 and Figure 8a). Similar to the FP dolomite, this dolomite typically occurs as stratigraphically-concordant beds that may be up to 15 feet thick. However, while NFP dolomite is usually restricted to certain well-defined stratigraphic intervals within the section, it occurs throughout the Arab-D, especially in Zone 2B and Zone 3A. NFP dolomite is generally rare in Zone 2A and negligible in Zone 3B. Beds of NFP dolomite can be quite widespread, extending areally for tens of square kilometers (Figure 2).

Petrographically, the NFP dolomite is much coarser than the FP dolomite, with average crystal sizes generally ranging from 50 to greater than 150 microns (Figure 7a and b). These anhedral to euhedral crystals locally display internal zoning (Figure 7c, Figure 8a), in which cloudy, inclusion-rich areas alternate with clear, limpid areas. This zoning may be simple, with crystals that only have cloudy centers and clear rims, or it may be quite complex, with crystals containing several alternating zones of clear and cloudy dolomite. Under cathodoluminescence, crystals appear non-luminescent, although they fluoresce weakly under blue-light fluorescence (Figure 8a). In contrast with the FP dolomite, the NFP-type dolomite typically shows no traces of the original limestone fabric, producing instead a crystalline fabric that may be either sucrosic or mosaic, depending on whether or not intercrystalline porosity is present. Dolomite with abundant intercrystalline porosity, or sucrosic dolomite (having a “sugary” texture), has a fabric of loosely-connected dolomite rhombs and typically is an excellent reservoir rock (Figure 7a) that is locally responsible for high flow zones (or “super-k”) in the reservoir. In contrast, dolomite with little or no intercrystalline porosity, or mosaic dolomite, has a fabric of tightly packed, anhedral dolomite rhombs and generally is a poor reservoir rock (Figure 7b). Local variability between these two end members is common, and can occur on a centimeter scale.

Figure 6a: FP dolomites are always associated with anhydrite, occurring either immediately below or interbedded with anhydrite. Here, anhydrite (A) occurs as a cement that fills relict interparticle (BP) and moldic (MO) pores. Plane-polarized light, well O, core depth=6,534.3 feet.

Figure 6b: Even though completely replaced by dolomite, details of a hardground in the precursor limestone have been preserved. Differences in degree of cementation above and below this surface are clearly visible. Relict moldic (MO) and interparticle (BP) pores are present. Plane-polarized light, well C, core depth=6,823.9 feet.

Figure 6c: Under blue light, the FP dolomite fluoresces strongly. Here, a relict gastropod (G) occurs and is partially cemented by non-fluorescent (dark) anhydrite (A). Remaining porosity is filled by fluorescent epoxy (arrows). Blue light fluorescence, well O, core depth=6,534.1 feet.
Finally, a third type of dolomite, baroque dolomite (Figure 8b and c, Figure 9), was identified during the course of this study. This dolomite is also non-fabric-preserving, although locally some hints of the original limestone fabric are preserved. Overall, baroque dolomite is rare in the Arab-D, and was observed to occur in abundance in only one of the study wells, in which baroque dolomite is estimated to be at least 67 feet thick. Other wells locally contain baroque dolomite, but never in great abundance and usually in association with other NFP dolomite. In most wells where baroque dolomite occurs, anomalously thick sections of dolomite are present, and may consist of admixtures of both baroque and NFP dolomite. In these wells, dolomitization is vertically pervasive with dolomite occurring in portions of the section that are normally dolomite-free. Vertically pervasive or non-stratigraphic dolomite also cross-cuts other stratigraphic dolomites and often occupies most of Zone 2 and parts of Zone 3. While these non-stratigraphic dolomites may be very thick vertically, they tend to be restricted areally. Non-stratigraphic dolomites typically occur along the linear trends of abnormally thick dolomite that were discussed in the Introduction (Figures 3 and 4).

Petrographically, baroque dolomite tends to be coarsely crystalline, with crystals generally ranging in size from 100 to 700 microns (Figure 9a). These crystals appear ‘saddle-shaped’ and display a sweeping or undulose extinction in thin section (Figure 8b and c); they also commonly display a bluish hue when stained with Potassium Ferrocyanide in thin section, suggesting that they contain elevated amounts of iron. Under cathodoluminescence, baroque dolomite has a variable or patchy luminescence (Figure 9b) with areas of bright luminescence alternating with areas of dull or no luminescence; such patchy luminescence probably results from variable (but relatively high) amounts of iron and manganese in these crystals (Nickel, 1978; Pierson, 1981). Baroque dolomite crystals fluoresce weakly under blue-light fluorescence (Figure 9c).
Arab-D Reservoir, Ghawar field, Saudi Arabia

Four geochemical techniques were employed to assess the nature and time of formation for the three types of Arab-D dolomite. They included: (1) stable carbon and oxygen isotope ratios, (2) elemental compositions, (3) stable strontium isotope ratios, and (4) fluid inclusions. None of these techniques alone provides a completely definitive conclusion as to the origin of Arab-D dolomites. However, each technique yields information that, in conjunction with other data, allows interpretation of the manner and time at which each of the three dolomite types formed.

Carbon and Oxygen Isotope Geochemistry

Stable carbon and oxygen isotope analyses were conducted on 164 samples from 28 Ghawar and Abqaiq wells; results of these analyses are shown in Figure 10. Also shown for comparison in Figure 10 is the presumed isotopic composition of Jurassic seawater (Lohmann, 1988). All laboratory analyses were conducted by Exxon using standard techniques (McCrea, 1950). Values are reported relative to the PDB standard in parts per thousand (‰) in the conventional notation.

Carbon isotope values in Arab-D dolomites occur within a fairly restricted range, generally between 2 and 4‰ PDB (Figure 10). Generally in sedimentary rocks, the presence or absence of organically-derived carbon has a major influence over the \( \delta^{13}C \) composition of the sediment. Organic carbon is typically greatly depleted in \(^{13}C \) compared to oxidized carbon. Since the overall sensitivity of \( \delta^{13}C \) values to
temperature is small, δ¹³C values can be used to monitor the impact and relative importance of this reduced organic carbon in the solutions from which the dolomites formed (Anderson and Arthur, 1983). The δ¹³C/δ¹²C ratios that were determined during the course of this study represent oxidized, relatively positive (enriched in ¹³C relative to ¹²C) values that show little evidence to support organic carbon (or reactions involving organic carbon) as an important component in the fluids responsible for dolomitization. Note also that these ratios are generally in agreement with the interpreted δ¹³C composition of Jurassic seawater (Lohmann, 1988).

In contrast, the δ¹⁸O of the Arab-D displays a wide range of values, from approximately 0 to -9‰ PDB (Figure 10). The δ¹⁸O of dolomite is primarily a function of the isotopic ratio of the water and the temperature at which the mineral formed (Epstein, 1959). Seawater has a narrow composition near zero ‰ Standard Mean Ocean Water (SMOW), while evaporation (especially of seawater) produces water enriched in ¹⁸O (Anderson and Arthur, 1983). In modern settings in which such evaporated water occurs, δ¹⁸O values of 3 to 4‰ SMOW have been documented (Land, 1980; McKenzie et al., 1980; Truesdell, 1974; Lloyd, 1966). In contrast, meteoric water is relatively depleted in ¹⁸O (more negative δ¹⁸O values); depending on such variables as latitude, altitude and temperature (Anderson and Arthur, 1983), δ¹⁸O values for precipitation can range from 0 to -24‰ SMOW or less (Yurtsever, 1975). Typically, high temperature fluids also produce carbonates with depleted oxygen isotopic ratios. Since Arab-D dolomites show such a wide range of δ¹⁸O values, and values which broadly depart from that of the interpreted δ¹⁸O composition of Jurassic seawater, it is likely that more than one type of fluid and/or fluids of different temperatures were involved in their formation.
Elemental Compositions of Arab-D Samples

Electron microprobe (EMP) analyses of Arab-D dolomites revealed that baroque dolomite is compositionally distinct from other types of dolomite in the Arab-D. While both the FP dolomite and the NFP dolomite are typically stoichiometric in composition and are low in iron (Fe) and manganese (Mn) – generally near or below instrument detection levels – baroque dolomite is non-stoichiometric and contains high Fe (2 to 4 weight% FeCO₃) and variable but generally elevated Mn (0.2 to 0.3 weight% MnCO₃). This variability in Mn concentration is probably responsible for the variable or patchy cathodoluminescence noted in the baroque dolomite. In comparison with the baroque dolomite compositions, other Arab-D dolomites typically contain less than 300 ppm Fe and Mn levels that are at or below the detection limits of the EMP.

Strontium Isotope Geochemistry

Strontium (Sr) isotope analyses were conducted on 35 Arab-D rock samples from 13 Ghawar and Abqaiq Arab-D wells. All strontium isotope analyses were conducted by Kruegar Enterprises, Inc., Geochron Laboratories Division using standard techniques (Burke et al., 1982). Precision of these analyses is estimated to be ±0.00005.

Of the three different types of Arab-D dolomite, only baroque dolomite displays Sr ratios that are significantly distinct from other Arab-D dolomites, with an average ^{87}Sr/^{86}Sr isotopic ratio of 0.70712. In contrast, the average ^{87}Sr/^{86}Sr isotope ratio for other, non-baroque Arab-D dolomite is 0.70683 (differences of 0.0001 are significant). A breakdown of these analyses by reservoir zone appears in Table 1.

The utility of Sr isotope ratios for age dating has been demonstrated by previous researchers (McArthur et al., 2001; Hess et al., 1986; DePaolo, 1986; DePaolo and Ingram, 1985; Burke et al., 1982). These studies have shown that the Sr isotope ratio of ocean water is relatively constant world-wide at any one point in time, but that this ratio has varied in a systematic manner throughout much of geologic history. Since marine carbonates will have the same ^{87}Sr/^{86}Sr ratio as the seawater in which they formed, these fluctuations of seawater ^{87}Sr/^{86}Sr that are recorded in carbonate sediments can be used as a stratigraphic correlation tool for dating the age of a sediment. Later diagenesis can alter the Sr isotope ratio (Veizer and Compston, 1974), depending on the ^{87}Sr/^{86}Sr ratio of the solution which is influencing the carbonate.
Two-phase aqueous fluid inclusions were examined in seven dolomite samples from five Ghawar Arab-D wells; results from six of these samples are listed in Table 2 below and in Figures 15a and b. A seventh sample was also examined (well O, 6,534.3), but proved to contain no fluid inclusions. In each of these six samples, many fluid inclusions were recorded, and the temperature of homogenization (Th), melting point depression temperature (Tmp) and calculated fluid salinity for each Tmp value are given. All analyses were done by T. James Reynolds of Fluid Inc.

Analysis of fluid inclusions can indicate the minimum temperature at which the crystal containing the inclusions formed (the homogenization temperature), as well as the salinity of the fluid contained in the inclusion, which, by inference, is the original fluid from which the crystal formed. All but one of the Arab-D samples (an FP dolomite from Zone 1) had abundant fluid inclusions that contained very high salinity fluids (average salinity = 20.9 weight% NaCl equivalent). These fluid inclusions also had relatively high homogenization temperatures (average temperature of homogenization 97.4 degrees C).

Compilation of Fracture Observations from Core Descriptions

Finally, we also conducted a survey of all available Arab-D core descriptions to check for previously reported direct observations of fractures reported in core. The data used in this survey was compiled from different sources of core description information (compiled from both Saudi Aramco and Exxon core descriptions), each of which recorded fracture information with varying degrees of detail. Several types of information were compiled, including (1) the fracture depth, (2) whether or not the fracture is open or closed, (3) the fracture orientation or dip and (4) the lithology (limestone or dolomite) of the fractured interval. Figure 19 shows the locations of the wells used in this survey.

### Table 1:
Summary of average $\delta^{18}$O/$\delta^{16}$O isotope ratios in 35 Arab-D dolomite samples. Most of these samples display values that are fairly similar and which all fall at or shortly after the time of Arab-D deposition on McArthur et al.’s (2001) ocean water curve. In contrast, baroque dolomite $\delta^{18}$O ratios are higher than those found in other types of dolomite and, as a consequence, plot at a later time.

| Reservoir Zone/ Dolomite Type | Number of samples | Mean Sr Ratio | 1 Standard Deviation |
|------------------------------|------------------|--------------|---------------------|
| Anhydrite (FP)               | 1                | 0.70693      | NA                  |
| Zone 1 (FP)                  | 8                | 0.70680      | 0.00016             |
| Upper Arab-D (NFP)           | 12               | 0.70683      | 0.00023             |
| Lower Arab-D (NFP)           | 11               | 0.70681      | 0.00026             |
| Baroque Dolomite             | 3                | 0.70712      | 0.00006             |

### Table 2:
This table lists average values for homogenization temperature (Th), melting point depression temperature (Tmp) and calculated fluid inclusion salinity for 6 Arab-D dolomite samples. Two samples are baroque dolomites, well V, 7,221,3 and well X, 7,227,2. All temperatures are in degrees Centigrade, and salinities are in parts per million (ppm) NaCl equivalents.

| Well | Sample Depth | Dolomite Type | Th (°C) | Tmp (°C) | Fluid Salinity (ppm NaCl equiv.) |
|------|--------------|---------------|---------|----------|-----------------------------------|
| O    | 6,607.2      | NFP           | 85.2    | -19.3    | 221,667                           |
| C    | 6,950.2      | NFP           | 114.1   | -16.0    | 196,667                           |
| T    | 6,966.1      | NFP           | 97.2    | -16.6    | 198,000                           |
| V    | 7,221.3      | Baroque       | 97.5    | -15.4    | 194,615                           |
| X    | 7,227.2      | Baroque       | 107.4   | -20.3    | 230,000                           |
| X    | 7,249.9      | NFP           | 95.7    | -19.5    | 222,727                           |

Fluid Inclusion Studies

Two-phase aqueous fluid inclusions were examined in seven dolomite samples from five Ghawar Arab-D wells; results from six of these samples are listed in Table 2 below and in Figures 15a and b. A seventh sample was also examined (well O, 6,534.3), but proved to contain no fluid inclusions. In each of these six samples, many fluid inclusions were recorded, and the temperature of homogenization (Th), melting point depression temperature (Tmp) and calculated fluid salinity for each Tmp value are given. All analyses were done by T. James Reynolds of Fluid Inc.
DISCUSSION AND SYNTHESIS

Petrography

Because of its intimate association with the overlying Arab-D Anhydrite, the cloudy, finely-crystalline, FP dolomite is interpreted to have formed very early or penecontemporaneously in the diagenetic history of the sediment, by dense, evaporated Mg-rich brines associated with the overlying evaporites. The interpretation of a very early time of formation for this FP dolomite is in agreement with many previous studies of fabric-preserving or mimetic dolomites (Dawans and Swart, 1988; Pleydell et al., 1990; Land, 1991; Kimbell, 1993; and others); previous workers have suggested that this FP texture will not form if the precursor limestone has already stabilized to low-Mg calcite (Sibley, 1982, 1991). The dense brines responsible for forming this FP dolomite are thought to be derived from connate fluids within the overlying evaporitic section which became concentrated by evaporation and sufficiently dense to sink downward and dolomitize the underlying lime sediments in close association (Adams and Rhodes, 1960). These fluids are potent dolomitizing agents primarily because of the high Mg/Ca ratios produced by evaporation and by the precipitation of gypsum (CaSO4), which reduces the total Ca+2 of the water. For example, in modern sabkha environments along the Arabian Gulf, Mg/Ca ratios in excess of 12 have been reported (Patterson and Kinsman, 1982). Dolomite formed in this manner has been documented on the sabkhas of Abu Dhabi (Butler, 1969) and on the supratidal flats of Bonaire (Deffeyes et al., 1965) and Andros Island (Shinn et al., 1965).

NFP dolomite has a different, and more complex, origin than that of the FP dolomites. While petrography alone cannot determine the timing or the exact mechanism of formation of this type of dolomite, most previous workers have taken the lack of original fabric detail in other NFP dolomites to suggest that the precursor limestone must have been 100% low-Mg calcite at the time of dolomitization (Dawans and Swart, 1988; Fouke, 1994; Vahrenkamp and Swart, 1994). We therefore suggest that this NFP dolomite formed somewhat later than did the FP dolomite, after stabilization of the original sediment to low-Mg calcite had occurred. Additional geochemical evidence for the timing and nature of the fluids responsible for the formation of these dolomites will be presented later.

Since baroque crystals display a distinct style of dolomitization, this type of dolomite probably formed by a different mechanism than those responsible for the other Arab-D dolomites. Conventionally, baroque dolomite is thought to form relatively late in the diagenetic history of a rock from high temperature fluids during deeper burial diagenesis (Folk and Assereto, 1974; Radke and Mathis, 1980). Typically, such dolomite is the last dolomite phase to form, and is usually trace element-rich (especially in iron). Therefore, baroque dolomite in the Arab-D is interpreted to have formed from metal-rich hot fluids and is thought to be the last type of dolomite to have formed.

Based on petrography, then, three different types of Arab-D dolomite can be recognized: FP dolomite, a common NFP dolomite, and rare baroque dolomite. While petrography alone cannot precisely constrain the time of formation of these three phases, the general sequence of diagenetic events can be deduced. In such a paragenesis of Arab-D dolomite phases, the FP dolomite formed very early, almost penecontemporaneously with deposition, while the common NFP dolomite formed somewhat later (but still relatively early in the history of the rock). Baroque dolomite was probably the last phase to form, during later burial diagenesis.

Geochemistry

Carbon and Oxygen Isotope Geochemistry

The δ13C and δ18O ratios for all dolomite samples examined in this study generally fall into two categories, baroque dolomite and non-baroque dolomite (Figure 10). Baroque samples occur as a distinct field that has more negative δ18O values (average = -7.37‰). In contrast, the other dolomites analyzed display significantly more positive isotopic ratios, with an average δ18O composition of -2.58‰. Two samples that were petrographically identified as calcitized dolomites, or ‘dedolomites’, have values that do not fall within either of these two categories, with more negative oxygen and carbon values. Dedolomites represent a case of very special chemical and diagenetic conditions in which a limestone was first dolomitized and then converted back to calcite, and are very rare overall in the Arab-D.
Such a clear difference in isotopic composition between baroque dolomite and other types of Arab-D dolomite underlines the petrographic distinctiveness of the baroque dolomite. Isotopically negative $\delta^{18}O$ values in dolomites can be produced in two ways; either from isotopically heavy water at elevated temperatures or from water containing a large component of isotopically light meteoric water (Land, 1983; Horton, 1985). Since baroque dolomite is typically associated with hot fluids, and since petrographic evidence of meteoric fluids is rare in the Arab-D (Mitchell et al., 1988), baroque dolomite in the Arab-D is interpreted to have formed from isotopically heavy water at elevated temperatures.

Non-baroque Arab-D dolomites are typically more stratigraphic in nature and their oxygen isotopic values should be considered within a stratigraphic framework (Figure 11). The $\delta^{18}O$ values for FP dolomites in Zone 1 and in the Arab-D Anhydrite occur within fairly narrow fields that have similar ranges and averages. Dolomites from other zones (Zones 2 and 3) display a wider range of values that broadly overlaps the FP dolomite field. Within this wide range of values, samples from the lower Arab-D (Zone 3) tend to have more negative $\delta^{18}O$ values than do the upper Arab-D (Zones 2) samples.

The dolomites that occur in Zone 1 and in the Arab-D Anhydrite typically are the FP dolomites that, on the basis of their petrography and regional association with the overlying anhydrite, are interpreted to have formed via dolomitization by hypersaline brines. Even though modern dolomites formed by this mechanism typically have $\delta^{18}O$ values of about 2‰ or greater (Warren, 1988; Mazzullo et al., 1987; Carballo et al., 1987; Pierre et al., 1984; Kinsman and Patterson, 1973), Arab-D evaporite-associated dolomites have much lighter oxygen isotope values, with averages ranging from -1.3 to -2.9‰ PDB. There are two reasons for this discrepancy between Arab-D dolomites and their modern-day analogs that presently exist along the Trucial Coast; (1) ancient seawater probably had a lighter isotopic composition than does modern seawater (Veizer, 1983; Lohmann, 1988), and (2) diagenesis generally causes a negative shift in oxygen isotope ratios in carbonate sediments through time.

In contrast with present-day seawater (which has a typical composition of 0‰ SMOW), Jurassic seawater had an isotopic composition of approximately -1‰ SMOW (Veizer et al., 1986). At least since the Triassic, the $\delta^{18}O$ of ocean seawater is usually assumed to have been the same in the past as it is at present (Veizer, 1983). The only deviations from this trend occurred as a result of intervening interglacial periods, during which time most major continental glaciers melted. Since these glaciers contained very light precipitated water ($\delta^{18}O$ of less than -25‰ SMOW, according to Dansgaard et al., 1969 and Johnson et al., 1972), the $\delta^{18}O$ of seawater during these interglacial periods was shifted toward lighter (or more negative) values. Most researchers feel that this shift in $\delta^{18}O$ was on the order of -1.2‰ SMOW (Savin and Yeh, 1981). The upper Jurassic was a time of eustatic sea-level highstand (Vail et al., 1977), when most major glaciers had

![Figure 11: $\delta^{18}O$ vs $\delta^{13}C$ cross-plot for all non-baroque dolomite samples illustrates the variability in these samples when grouped by reservoir zone. All values listed are relative to the PDB standard.](http://pubs.geoscienceworld.org/geoarabia/article-pdf/9/2/11/5441540/cantrell.pdf)
melted. As a result, Jurassic seawater probably had a much lighter composition than it does today, and probably had $\delta^{18}O$ values of at least -1‰ SMOW. Evaporation, then, would not have produced waters that have $\delta^{18}O$ values as heavy as those that are present today along the Trucial Coast. We estimate evaporated Jurassic seawater to have had $\delta^{18}O$ of approximately 1-2‰ SMOW. The dolomites formed by these evaporated, hypersaline waters in the Arab-D, therefore, would have initial oxygen isotope ratios that were much lighter by some 1-2‰ than those in their modern-day analogs.

There is also some evidence that, through time, diagenesis causes a regular change in $\delta^{18}O$ ratios in carbonate sediments as they are buried (Land, 1980). In general, there is a gradual depletion in $^{18}O$ through time, probably as a result of recrystallization in which early-formed, calcium-rich and metastable dolomite recrystallizes to more stable forms during burial (Hardie, 1987). During this recrystallization process, $^{18}O$ is preferentially transferred to pore fluids, leaving the dolomite with relatively low $\delta^{18}O$ values. Assuming an average geothermal gradient of 36°C/1,000 meters (or 2°F/100 feet) for Ghawar and a present-day depth of burial of about 1980 meters (or 6,500 feet), $\delta^{18}O$ values for Arab-D dolomites have probably shifted -2 to -3‰ PDB on average from their initial value (Figure 12).

Actual analytical values from Arab-D evaporite-associated dolomite average -2.08‰ PDB, and are similar to that expected, given both the initially lighter composition of seawater and the effects of diagenesis.

Once the oxygen isotopic composition of the fluid responsible for dolomitization is estimated, and knowing the $\delta^{18}O$ of the dolomite, it then becomes possible to estimate the temperature at which dolomitization occurred. Figure 13 from Land (1983) describes how this can be done. For the Zone 1 FP dolomites, one can estimate the $\delta^{18}O$ of the water to have been approximately 1.5‰ SMOW. Using -2.08 as an average value for $\delta^{18}O$ of the dolomite then yields a temperature of about 50°C for the dolomitizing fluids (Figure 13 (Land, 1983)). This value agrees well with a very early, shallow burial origin for this dolomite. While $\delta^{18}O$ compositions vary somewhat for other NFP Arab-D dolomites (ranging from about -0.7‰ to about -5‰ $\delta^{18}O$), interpreted temperatures of dolomitization for these dolomites still generally suggest relatively low temperatures of formation, yielding temperatures of around 45°C to 65°C. While this range of estimated temperatures does suggest that no one single mechanism or episode of dolomitization can account for all dolomite types in the Arab-D, it does confirm a generally shallow burial temperature for most dolomite types observed.

As noted previously, stratigraphic NFP dolomite from lower zones in Ghawar (Zones 2 and 3) has $\delta^{18}O$ values that basically overlap or bracket those from Zone 1 and the Anhydrite. As a result, dolomitization in these lower zones probably also involves hypersaline brines, although not in exactly the same manner as in the FP dolomites in Zone 1. Unlike the FP type, dolomite in Zones 2 and 3 is non-fabric-preserving in character and, because of this difference in style of dolomitization, it is interpreted to have formed by a different mechanism and probably slightly later than the very early FP dolomite. Since the temperature of the fluids responsible for the dolomites in the lower zones was apparently similar to that of the fluids in Zone 1 (ranging from about 45°C to 65°C), depth of burial when dolomitization occurred was probably minor. Thus, these lower non-fabric-preserving dolomites are probably only slightly younger than are the Zone 1 dolomites, and probably formed during deposition of the overlying Arab-D Anhydrite.
Finally, it should be noted that geochemical differences exist even within these NFP dolomites found in Zones 2 and 3. Overall, Zone 3 dolomites have slightly lighter oxygen isotopic compositions than do the Zone 2 dolomites, even though the overall population of dolomites in Zone 3 basically overlaps the Zone 2 (and even Zone 1 FP) dolomites to some extent. In addition, and as previously reported in another study (Cantrell et al., 2001; Swart et al., in preparation), these NFP dolomites can be further differentiated on the basis of both their geochemistry and porosity content. Previous geochemical analyses had indicated that some sucrosic (or “super-k”) NFP dolomite has a much lighter (more negative) oxygen and carbon isotopic signature than do mosaic (or “non-super-k”) NFP dolomites, even though these two dolomite fabrics appear petrographically similar (other than the fact that the sucrosic dolomite has abundant intercrystalline porosity while the mosaic dolomite does not). Typically, oxygen isotope values for the sucrosic (“super-k”) NFP dolomites typically ranged from -3.5 to -5‰ \( \delta^{18}O \) and carbon values range from 1.8 to 2.8‰ \( \delta^{13}C \), while the mosaic (“non-super-k”) NFP dolomites had \( \delta^{18}O \) values of -2.5 to 0‰ and \( \delta^{13}C \) values of 2.5 to 3.3‰. These results suggest that the sucrosic NFP dolomites are isotopically intermediate in composition between the baroque dolomites and the other (generally mosaic) NFP dolomites. As a result, these sucrosic NFP dolomites are interpreted to represent a transitional phase between baroque dolomite and other NFP dolomites.

Overall, then, stable isotope geochemistry supports conclusions made from petrography and serve to further clarify the timing of dolomitization. These analyses indicate that: (1) baroque dolomite represents a distinct dolomite phase formed from higher temperature fluids; (2) the FP dolomite in Zone 1 formed very early, from highly evaporated hypersaline waters at approximately 50°C; (3) most of the mosaic NFP dolomite in Zones 2 and 3 also formed fairly early, from hypersaline fluids of about the same temperature as that for the FP dolomite. Also, as previously reported (Cantrell et al., 2001; Swart et al., in preparation) some of the sucrosic NFP dolomite probably represents a transitional phase between baroque dolomite and other (generally mosaic) NFP dolomite.

It should be noted at this point that we do not feel that any of the dolomites identified in this study formed via a mixing-zone mechanism, for the following reasons:

- There is overall very little evidence to suggest that significant meteoric diagenesis occurred in these sediments. While dissolution of metastable components is common (which by itself is not unequivocal evidence of meteoric diagenesis – see Melim et al., 2002), there are virtually no other criteria present (freshwater cement fabrics or well-developed rooted intervals, for example) that would suggest that a large, active freshwater lens formed and influenced the diagenesis of this interval.
- Evaporites occur locally throughout the Arab-D, and a relatively pure 100-150 feet thick evaporate unit caps the Arab-D carbonate; the abundance of evaporites in the section strongly suggests that not only was the climate fairly arid during Arab-D time (and further supporting the difficulty of forming an extensive freshwater lens that could have promoted meteoric diagenesis), there was as well an ample source for the hypersaline fluids interpreted to have dolomitized much of the Arab-D.
• There are no documented modern occurrences of dolomite forming in modern mixing-zones and
significant controversy still remains regarding the kinetic and thermodynamic viability of
mixing-zone dolomitization in general (Machel and Mountjoy, 1986; Hardie, 1987; Purser et al., 1994;
Budd, 1997).

**Strontium Isotope Geochemistry**

Based on the Sr isotope ratios, non-baroque dolomites from the Arab-D all formed at or very shortly
after the time of deposition of the Arab-D (Upper Jurassic/Kimmeridgian time, Figure 14). This conclusion
agrees with the conclusions from petrography and oxygen isotopes, that both the FP and the NFP
dolomites formed at or shortly after deposition. Also, since the Sr isotope values all fall on the Phanerozoic
ocean water curve (see Figure 14), these non-baroque dolomites must have formed from a fluid derived
from seawater. The deep-burial origin of the fluids responsible for baroque dolomitization probably
invalidates Sr isotope use for dating their formation.

**Fluid Inclusion Studies**

The high temperatures observed in the fluid inclusions in the dolomite samples examined were
unexpected in light of the fact that all the other geochemical evidence suggested that most Arab-D
dolomite formed at or shortly after deposition, at minor burial depths where temperatures are low. No
major differences in temperature or salinity exist between the fluid inclusions in baroque and other
types of inclusion-rich dolomite in the Arab-D. The temperatures and fluid salinities of these inclusions
are essentially identical to present-day reservoir conditions (Table 2, Figure 15), and the same zones also
contain secondary hydrocarbon inclusions. These hydrocarbon inclusions occur in variable sizes and

![Figure 14: (a) Plot displaying the marine 87Sr/86Sr record for the Permian through Neogene (from McArthur et al., 2001). Data and curve with 95% confidence bounds for area outlined in the box above are shown in Figure 14b below.](image_url)

![Figure 14: (b) Detail view of the marine 87Sr/86Sr record, with the distribution of average 87Sr/86Sr ratios for both the FP and NFP dolomites displayed (in stippled box). 87Sr/86Sr ratios for most Arab-D dolomites fall on or near the marine 87Sr/86Sr ratio for Arab-D time.](image_url)
have variable liquid to vapor ratios, all suggesting that these inclusions do not represent primary fluids that were present as the crystal grew. Furthermore, dolomites precipitated from fluids of these temperatures would have unusually light isotopic compositions; note also that fluid inclusions in the baroque samples contain essentially identical salinities and homogenization temperatures to those observed in the NFP dolomites. These inclusions probably formed by later fracturing of the crystal, thereby allowing fluids to migrate into it. Such fractures could then heal completely and leave no visible trace of ever having been open (Goldstein, 1986).

Only one FP dolomite sample was analyzed and found to contain no visible fluid inclusions. This sample had abundant solid inclusions (composed mostly of calcite and organic material), which gave it a characteristically cloudy appearance. The fact that this FP dolomite was the only Arab-D sample to contain no fluid inclusions further underlines the distinctiveness of the FP from other types of dolomite.

**Compilation of Fracture Observations from Core Descriptions**

On the basis of this core-based fracture characterization database compiled for this study, we can make several conclusions about the nature of fracturing and its relationship to dolomite in the Arab-D.

First, fracturing is rare overall in Ghawar; of the 185 wells examined for fractures (either direct observations of cores or a review of core descriptions) as part of this study, 46 percent contained no fractures at all. Second, fracture densities are higher in dolomites than in limestones (Figure 16a). While most of the fractures observed in Arab-D cores occur in limestones, limestones are much more abundant in the reservoir than are dolomites. Therefore, when these results are normalized in terms of fractures per 100 feet of core, higher fracture densities actually occurred in the dolomites. Average fracture densities in

![Figure 15: (a) Plot displaying the distribution of all homogenization temperatures which were derived from analysis of two-phase fluid inclusions in 6 Arab-D dolomite samples. Mean homogenization temperature is 97.4 degrees Celsius.](image)

![Figure 15: (b) Plot displaying the distribution of all fluid inclusion salinities which were derived from analysis of fluid inclusions in 6 Arab-D dolomite samples. Mean salinity is 208,900 ppm NaCl equivalent.](image)
dolomites are 8.3 fractures/100 feet, as compared to 3.1 fractures/100 feet for limestones. This observation agrees with known geomechanical data on the more brittle nature of dolomite.

Third, fracturing generally increases with depth in the Arab-D (Figure 16b). Analysis of the core description information revealed that both the fracture frequency and fracture density generally increase with reservoir depth. This trend is consistent with the increasing abundance of low porosity, fine-grained rocks with depth in the Arab-D and again agrees with geomechanical theory. Theory suggests that finer grained, lower porosity rock is more brittle and thus, more likely to fracture. Therefore, Zone 3 mudstones and wackestones should be and are more fractured than the packstones and grainstones of Zone 2. Zone 1 is an exception to the general trend in that fracture densities are higher there than in the underlying Zone 2. This probably occurs because Zone 1 is more dolomitic and thus more fracture-prone than the less dolomitic Zone 2 rocks. Also, Zone 1 contains abundant anhydrite which may have resulted in the carbonates in this zone being subjected to unusual stresses during their burial history.

Fourth, most Arab-D fractures are at least partially open (Figure 16c). According to core description information, about 61 percent of the total reported fractures are open to some degree. However, while the overwhelming majority of the fractures in dolomites and fractured intervals of unknown lithology are open, most of the fractures in limestones are closed. Core descriptions generally describe fractures as being either (1) completely cemented and now impermeable, (2) partially cemented but with some preserved porosity, (3) completely open or (4) tar-plugged to varying degrees. In all but the first case, fractures were categorized as open in this survey. Most of these open fractures have apertures to the order of 0.5 mm or less.

Finally, most Arab-D fractures are typically steeply dipping, high-angle fractures (Figure 16d). Of all the fractures that have orientation information recorded, 90 percent have dips of 70 to 90 degrees from the horizontal.

Unfortunately, core coverage and available descriptions of fractures in the Arab-D is inadequate for any quantitative areal assessment of fracture density across the field, and its relationship to the dolomite trends. While these data suggest that the dolomites are more fracture-prone than limestones, and that these fractures have a higher probability of remaining open, we could demonstrate no conclusive genetic link between fracturing and dolomitization.

MODEL OF DOLOMITIZATION

The dolomites of the Arab-D in Ghawar field present two distinct aspects that must be explained in any dolomitization model. The first aspect involves the petrographic and geochemical variability of the dolomite (to describe the nature of the fluids responsible for dolomitization), while the other is the three-dimensional distribution of the dolomites – and especially the trends of high dolomite – in the reservoir. We propose a multi-genetic model of dolomitization to explain these two aspects of Arab-D dolomites.

Figure 17 shows a diagrammatic representation of the major phases of dolomitization we envision. Results of this study identified three different types of dolomite in the Arab-D (FP, NFP and baroque). As discussed previously and as suggested by their Sr isotope ages, we believe that most Arab-D dolomite formed early. The FP dolomites of Zone 1 formed very shortly after deposition from highly evaporated pore fluids from overlying evaporites. These dolomites may even be penecontemporaneous (?) with evaporite deposition, since there is evidence to suggest that these originally lime sediments had not yet undergone significant mineralogic stabilization. Since FP dolomites formed in direct association with the dynamics involved with evaporite deposition, they are unrelated to the dolomite trends. Most of the NFP dolomites formed slightly later (but still early, as suggested by their Sr isotope ages), by dense, saline waters moving downward from the overlying evaporites. These dolomites would also be generally unrelated to the trends of high dolomite. The third type of dolomite, baroque dolomite, occurs superimposed on these other pre-existing types of dolomite and formed from hot, mineral-laden fluids from depth sometime later during burial. It is this last dolomite type that is most closely associated with the dolomite trends. Also, as previously reported (Cantrell et al., 2001; Swart et al., in preparation), some of the sucrosic NFP dolomite was probably genetically related to the baroque dolomite, and so is also interpreted to be related to the dolomites trends.
We propose that the dolomite trends were formed primarily by a system of faults and/or fractures that developed after Arab-D deposition and allowed upward migration of hydrothermal fluids into the reservoir and dolomitization along these fault/fracture trends. It is this fracture-related dolomite (the baroque dolomite identified in this study as well some of the previously reported sucrosic NFP dolomite) that formed the non-stratigraphic (and in some cases vertically pervasive) dolomitization that comprises the previously mapped trends of high dolomite. We suggest that, once these vertical fracture systems were open, fluids would have moved upward into the reservoir and preferentially invaded the more permeable beds of the upper Arab-D (Zone 2) and thus would not have involved the lower Arab-D (Zone 3) except in the immediate vicinity of a fracture or fault. These hot fluids would have produced vertically pervasive “chimneys” of baroque dolomite in the immediate vicinity of the fracture/fault that sourced these fluids, but as these fluids moved out into the more permeable strata of the upper Arab-D they would have cooled somewhat, but would still have been capable of producing the sucrosic NFP dolomite with a relatively light (negative) isotopic signature. We suggest that it is these zones of relatively light NFP dolomite, together with vertically pervasive intervals of baroque dolomite, that form the linear trends of high dolomite observed in maps of overall dolomite content in the Arab-D. While baroque dolomites form the “heart” of these fracture-related dolomite trends, the chance of intersecting these intervals of baroque dolomite (which we would interpret to have very limited areal extent) with vertical wells is very low. Instead, we suggest that zones of high dolomite would extend much further areally than would the interval of baroque dolomite, and it is these zones of high dolomite (characterized by relatively low isotope values and perhaps by “super-k”) that are more likely to be sampled by vertical wells.

This model of dolomitization explains the petrographic, geochemical and three-dimensional distribution of the Arab-D dolomite, and supports our initial hypothesis that the dolomitization of NE-SW dolomite trends originated from hydrothermal fluids that moved upward from depth along fractured zones into the reservoir. The alignment of these dolomite trends across all of Ghawar strongly suggests that the NE-SW orientation is not random, but is the result of some type of field-wide structural control over dolomite occurrence.

Figure 16: (a) This comparison of fracture densities in Arab-D dolomites and limestones illustrates how, in terms of number of fractures per 100 feet of core, dolomites are typically more heavily fractured than limestones. Figure 16: (b) Fracture density (in terms of number of fractures per 100 feet of Arab-D core) generally increases with depth, although the very thin Zone 1 at the top of the reservoir has slightly higher fracture density than does Zone 2.

Figure 16: (c) Based on all available core description information, slightly more fractures in limestones are closed than open, while most fractures in dolomites and in rocks of unknown lithology are open. Figure 16: (d) Most Arab-D fractures are steeply dipping to vertical (70 to 90 degrees from horizontal).
We propose that the origin of these dolomite trends lies within the structural growth history of the field. Some amount of structural relief is known to have been present during the deposition of the Arab-D (R.M. Hagerty, Exxon, personal communication). This relief resulted from early basement block faulting that continued to exert an influence on depositional and structural elements through the Tertiary. In the arching and extension that accompanied this early structural growth, we suggest that a series of NE-SW and NW-SE trending normal faults developed after Arab-D deposition. These trends are seen repeatedly in other structural elements across the field. For example, the northern boundaries of ‘Ain Dar and Shedgum have a NW-SE orientation, as does the southernmost boundary of Haradh. Other eastern and western boundaries of Ghawar locally have a preferred NE-SW orientation. In addition, a probable dog-leg or “trap door” fault pattern that crosses ‘Ain Dar and Shedgum has a pronounced NE-SW orientation (T. P. Harding, Exxon, personal communication) that parallels the high dolomite trends. Finally, NE-SW trending extension joints occur on outcrop in Tertiary sediments in this area (Hancock et al., 1984). The consistency of these orientations suggests that all of these structural elements are products of the same structural regime.

We suggest that these NE-SW and NW-SE trending normal faults at depth were active after deposition of Arab-D carbonates (probably occurred during the Cretaceous when major structural relief was developed in Ghawar) and allowed hydrothermal fluids to rise to the Arab-D and form baroque dolomites. These local pathways for vertical fluid movements would most likely lie along the NE-SW dolomite trends, and would typically be quite narrow in scale and difficult to detect with current well spacing and core control from vertical wells.

Attempts to directly identify and characterize these postulated faults and/or fracture zones in seismic data, and correlate them with the observed high dolomite trends, have unfortunately been unsuccessful to date, for a number of reasons. Most observed faults at the Arab-D level tend to have very short throw vertically and so are only marginally visible in seismic. In addition, the quality of the seismic data is often compromised by such issues as surface-related problems, multiples problems, and evaporites in the section, with the resulting data generally being of fairly poor quality – with insufficient resolution to identify the structural features (faults and fracture trends) that we have called upon to explain the high dolomite trends in the Arab-D. Seismic characterization of faults and fracture trends in the Arab-D reservoir is an area of on-going research at Saudi Aramco and our belief is that future developments will result in an improved ability to image these postulated faults and/or fracture zones in the future.

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Figure 18: Location of wells examined petrographically and sampled for geochemistry.

Figure 19: Location of all cores and core descriptions examined for fracture characterization information.
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