Korean Jour. of Petrol. Geol., V. 3, No. 1, p. 16~27, 1995

Feldspar Diagenesis and Reservoir History of the Miocene Temblor Formation, Kettleman North Dome, California, U.S.A.

미국 캘리포니아주 케틀만 노스돔의 마이오세 템블러층에서 장석의 속성작용과 저류암의 발달사

Yong Il Lee(이용일)* and James R. Boles**

Abstract : The Early Miocene Temblor Formation forms an important sandstone reservoir at Kettleman North Dome oil field, California. Sandstones are mostly arkosic in composition except deepest sandstones containing much volcanic rock fragments. Arranged in paragenetic sequence prior to feldspar alteration, the Temblor sandstones contain cements of early calcite, dolomite, quartz, albite, mixed-layer chlorite/smectite (C/S) and smectite, and anhydrite. Diagenetic changes associated with feldspar are albitization of plagioclase, late calcite and laumontite cementation and grain replacement, plagioclase dissolution, and kaolinite cementation. Plagioclase albitization and late calcite and laumontite cementation in Temblor sandstones occurred at the time of maximum burial with temperatures up to 130℃. Volcanic plagioclases were selectively albitized. Most diagenetic changes are interpreted to have occurred before the major uplift which occurred within the last one million years ago. Since then to the time of hydrocarbon emplacement plagioclase dissolution and kaolinite cementation occurred. This reaction occurred in relatively closed system due to the occurrence of kaolinite next to the site of plagioclase dissolution. Unaltered part of volcanic plagioclase and plutonic plagioclase which escaped albitization during maximum burial were preferentially dissolved to make plagioclase porosity. Secondary porosity resulting from dissolution of plagioclase and carbonate and anhydrite cements was mainly produced by formation waters containing organic acids released during catagenesis of organic matter.

Key Words : San Joaquin basin, Temblor Formation, Sandstone diagenesis, Reservoir porosity, Burial history

요 약

전기마이오세의 템블러층은 캘리포니아의 케틀만노스돔 유전에서 중요한 사암의 저류층을 이루고 있다. 이 층의 사암은 대부분이 아코스의 성분을 가지나 최하부에는 많은 화산암의 암편이 함유되어 있다. 템블러층 사암에서 장석이 변질작용을 받기 이전에 일어난 속성작용의 단계를 순서대로 열거하면 초기의 방해석, 백운석, 석영, 알바이트, 녹니석과 스멕타이트의 혼합층 점토광물, 스멕타이트와 무수석고의 교질작용이 일어났다. 장석과 관련되어 일어난 속성작용으로는 사장석의 알바이트화작용, 후기의 방해석과 러몬타이트의 교질작용과 교대작용, 사장석의 용해, 카올리나이트의 교질작용이 있다. 사장석의 알바이트화작용과 후기의 방해석과 러몬타이트의 교질작용은 템블러층사암이 온도 약 130도 정도로 가장 깊이 매몰되었을때 일어났다. 사장석 중 화산기원의 사장석이 선택적으로 알바이트화작용을 받았다. 이 사암층에 일어난 대부분의 속성작용은 약 1백만년 전에 일어난 이 층의 융기 이전에 일어났다. 융기를 할 때부터 석유가 배태되기 이전에 사장석의 용해와 카올리나이트의 교질작용이 일어났다. 이 때의 속성작용은 카올리나이트가 사장석이 용해되는 장소 바로 옆에 일어난 점으로 미루어 볼 때 아마도 지구화학적으로 폐쇄된 환경에서 일어났음을 짐작할 수 있다. 이 층이 가장 깊이 매몰이 일어났을 당시 알바이트화작용을 겪지 않았던, 화산기원 사장석의 변질을 받지 않은 부분과 약간의 심성암 기원의 사장석이 선택적으로 용해되어 사장석의 용해공극을 형성하였다. 사장석의 용해작용과 탄산염과 무수석고 교질물의 용해작용이 일어나 이차공극이 형성되었는데, 이차공극은 유기물의 카타제네시스동안 발생한 유기산이 함유되어 있는 산성의 공극수에 의하여 형성된 것으로 해석된다.

주요어 : San Joaquin 분지, 템블러층, 사암의 속성작용, 저류암 공극률, 매몰역사

---

* Department of Geological Sciences, Seoul National University, Seoul 151-742, Korea (서울대학교 자연대학 지질과학과)
**Department of Geological Sciences, University of California, Santa Barbara, California 93106, U.S.A.

INTRODUCTION

Arkosic sandstone reservoirs containing abundant feldspars are known to contain enhanced secondary porosity from dissolution of feldspars (Bjϕrlykke, 1984). Reports document dissolution of feldspars through water-rock interaction from flushing by both formation waters during deep burial (Boles, 1982, 1992; Franks and Forester, 1984; Land, 1984; Lundegard and Land, 1986; Milliken *et al.*, 1989) and meteoric waters during shallow burial and/or uplift (Bjϕrlykke and Brensdal, 1986). The latter is well demonstrated in North Sea oil fields (Bjϕrlykke and Brensdal, 1986).

Even though significant amounts of hydrocarbon are being produced from the San Joaquin basin, California, few studies have been done on sandstone diagenesis except Boles (1984, 1987), Boles and Ramseyer (1987), and Schultz *et al.* (1989) on North Coles Levee field in the central basin, Hayes and Boles (1995) and Fischer *et al.* (1988) in the eastern flank, and Merino (1975a,b) and Tieh *et al.* (1986) in the western flank of the basin. At Kettleman North Dome (Fig. 1), Merino (1975a) described detailed 15 diagenetic minerals from the Miocene Temblor sandstones. He showed that in the deepest sandstones alteration of detrital minerals such as plagioclase, mafic minerals, quartz, etc. provided sufficient aluminum, silicon, and titanium, but insufficient sodium and calcium and excess potassium for late diagenetic mineral formation. Diagenetic minerals described by Merino (1975a) were recognized in this study and are considered in terms of the reservoir point of view. Porosity contribution from dissolution of plagioclase and some cement minerals was not discussed by Merino (1975a). Although the amount of cement dissolution is difficult to determine, plagioclase porosity constitutes up to 1/3 of the total point-count porosity of the reservoir.

Organic acids released to the pore water from the maturation of organic materials are known to enhance the solubility of aluminosilicates (Surdam *et al.*, 1984). Their role will be pronounced in the formation waters with low pH and when the alkalinity of the formation water is mainly contributed by organic acids instead of bicarbonate (Surdam *et al.*, 1984; Lundegard and Land, 1986; Harrison and Thyne, 1992; Reed and Hajash, 1992). Formation waters containing organic acids are mainly responsible for production of secondary porosity by dissolving carbonate cements and aluminosilicate minerals (e.g., Harrison and Thyne, 1992; Hamley and Nuccio, 1992; Chowdhury and Noble, 1992) The purpose of this study is to describe diagenesis paragenetically and to interpret reservoir history of the Miocene Temblor sandstones at Kettleman North Dome oil field as well as to compare and contrast them with other studies in the basin. The Temblor Formation at Kettlemen North Dome, San Joaquin Basin was chosen for this study because this formation produces both oil and gas, and because it has a relatively simple geologic history of subsidence to deep burial and uplift to the present. In addition to previous works, interpretation of porosity preservation and formation mechanism may provide more understanding of reservoir characteristics in the San Joaquin Basin.

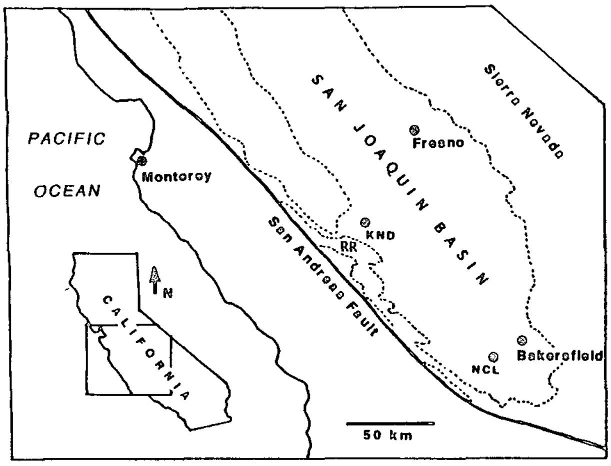

Fig. 1. Location map of the Kettleman North Dome in the San Joaquin basin, whose western boundary is marked by dotted lines (modified after Merino, 1975a).

GEOLOGIC BACKGROUND

Kettleman North Dome oil field in the western San Joaquin basin, California is the northernmost of the Kettleman Hills consisting of three anticlinal structures (Fig. 1). Kettleman North Dome is about 28 km long and 8 km wide. Kettleman North Dome field comprises sediments ranging in age from Recent through Upper Cretaceous. Production is obtained from, in descending order, the Temblor (lower to middle Miocene), Vaqueros (lower Miocene), Kreyenhagen (Oligocene to Eocene), and Upper and Lower McAdams (Eocene) formations (Sullivan, 1966). The midpoint depth of reservoir ranges from 2,060 m to 3,450 m below sea level (Kharaka and Berry, 1974). Kettleman North Dome is a steeply and doubly plunging asymmetrical anticline with a steeper limb on the southwest flank. Based on the relative thickness of the units affected by the folding, Harding (1976) determined that the fold was formed approximately within the last one million years. At Kettleman North Dome about 600 m to 1,000 m of sediments have been removed by erosion (Merino, 1975a).

The Temblor Formation is the main oil and gas producing zone in the field. The Temblor is 300-680 m thick (Merino, 1975a) and is subdivided into five zones; namely, Zone I through Zone V, which are separated by at least 15 m thck impervious shales (Fig. 2). Zones I, II, and V were deposited in shallow marine to deltaic setting, Zone III in submarine fan, and Zone IV in deltaic setting (Kuespert, 1985). Reservoir pressure is slightly higher than the hydrostatic values

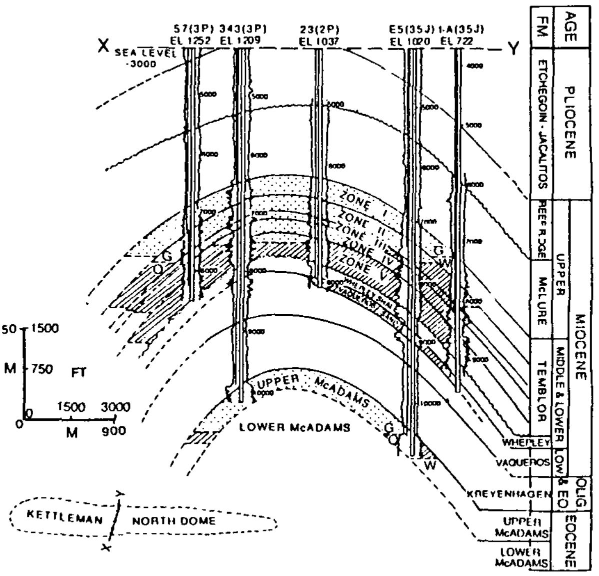

Fig. 2. Cross section X-Y of Kettleman North Dome oil field (modified after Sullivan, 1966).

Table 1. Location of Temblor sandstone core samples at Kettleman North Dome field.

Well number	Well location			Core interval studied, ft (m)	Number of thin sections	Temblor zone
	section	township	range			
56	8	22	18	8312-9747 (2533-3249)	5	I to V
58	17	22	18	6400-7030 (1951-2143)	4	I to IV
61	20	22	18	7070-7663 (2155-2336)	3	III to V
55	20	22	18	7136-8131 (2175-2478)	4	I to III,V
V21	17	22	18	6578-7291 (2005-2222)	3	I,II,IV
8	8	22	18	7893 (2406)	1	V
F1	35	21	17	6888-7253 (2099-2211)	2	I,II
H1	29	21	17	7428-8275 (2264-2522)	9	I to IV
V38	34	21	17	7480-7490 (2280-2283)	2	V

(Kharaka and Berry, 1974).

PETROLOGY

A total of 33 Temblor sandstone core samples were collected from 9 wells (Table 1). Sandstones are mostly medium to coarse grained. The average porosity is 15% in uncemented sandstones. Compositional variation was determined by counting average 600 points per thin section. The main framework grains consist of quartz (39.7%), plagioclase (10.9%), potassium feldspar (11.0%), and rock fragments (14.5%), primarily of volcanic origin. The ratio of plagioclase to potassium feldspar ranges from 0.1 to 3.4 with an average of 1.0. Volcanic rock fragments are main lithic component and constitute generally less than 15% of the rock in Temblor Zones I to IV, but occurs up to 45% in Temblor Zone V (Fig. 3).

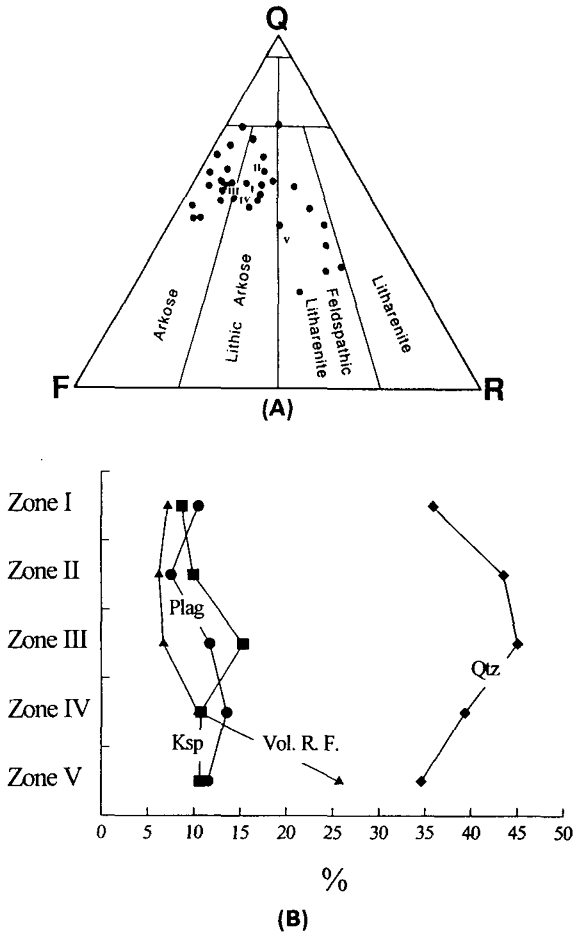

Fig. 3. (A) Classification of the Temblor sandstones at Kettleman North Dome. Letters I to V represent the average sandstone composition in each zone. (B) Zonal distribution of framework grains in the Temblor sandstones.

DIAGENETIC FEATURES

The major downhole diagenetic features observed in the Temblor Formation at Kettleman North Dome are 1) early calcite cement, 2) dolomite cement, 3) quartz cement, 4) albite cement, 5) authigenic clay minerals, 6) anhydrite cement, 7) late calcite cement and grain replacement, 8) albitization of plagioclase, 9) laumontite cement and replacement, and 10) plagioclase dissolution. K-feldspar overgrowth and pyrite are minor diagenetic minerals. The timing of these events relative to burial history will be shown in a later section of this paper. Most of the diagenetic features in the Temblor are typical of arkosic sandstones. In addition to these chemical diagenesis, physical compaction features are commonly observed.

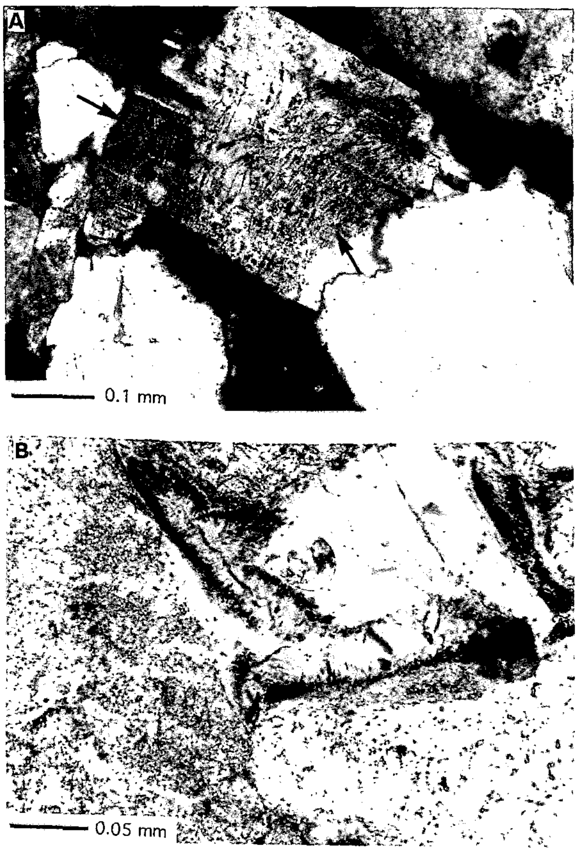

Fig. 4. (A) Stressed albitization (arrows) of plagioclase grain where it is in contact with pointed tips of quartz grains. Sample 3-58, 2131.2 m. Crossed nicols. (B) The spalled C/S cements off the grain are shown in pore. The circular object with high relief is an artifact. Sample 3C-H1, 2460.7 m. Plane light.

Compaction

Evidence for physical compaction is observed in biotite and muscovite crushed between resistant grains and in fractured quartz and feldspar grains. In some cases, relatively soft grains such as brachiopod shells, phosphorous shells, glauconite, and volcanic rock fragments are also distorted and pressure-dissolved by compaction. Also observed is the stressed plagioclase showing strain haloes of stress-induced albitization (Boles, 1984) when plagioclase is in contact with pointed tips of quartz and potassium feldspar grains (Fig. 4A). In some samples the collapsed grain molds rimmed with mixed-layer chlorite/smectite cements are observed. Some mixed-layer chlorite/smectite rim cements were spalled off from the host grain by compaction (Fig. 4B). Calcite pore-fill cements show twinning resulted from loading.

Samples containing abundant late calcite cements have the pre-cement volume of 25% in the Temblor indicating that in uncemented samples about one third of original depositional porosity (38%, Zieglar and Spotts, 1978) had been reduced by compaction during burial.

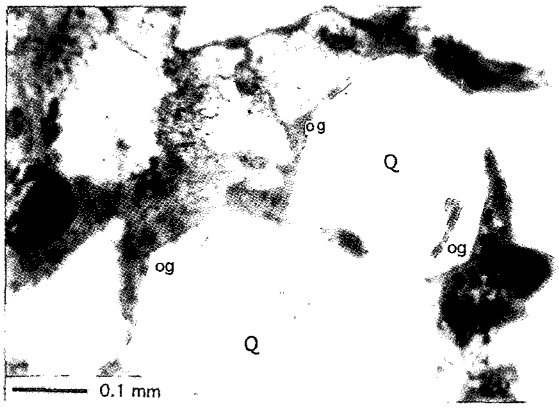

Fig. 5. Euhedral quartz overgrowths (og) on detrital quartz grains (Q). Thin dusty lines separate quartz grain and overgrowth. When they are not present, quartz overgrowth is identified by straight crystal boundary. Sample 2-55, 2219.2 m. Plane light.

Diagenesis Prior To Feldspar Alteration

Early Calcite Cement : Micritic early calcite cement comprises 39% of the rock, which is the evidence for an early origin. When examined under cathodoluminescence early calcite cement shows dark to brown dull luminescence with thin dull luminescent rims. Based on sparse oxygen and carbon isotopic composition and trace element composition the early calcite is interpreted to have precipitated from mixed marine-meteoric fluids near the sediment-sea water interface (Lee and Boles, 1995).

Dolomite Cement : Dolomite comprises up to 30% in Temblor sandstones at Kettleman North Dome. It occurs as small euhedral rhombohedral crystals (0.02 to 0.1 mm) attached to detrital grains and euhedral to subhedral pore-filling crystals. Some dolomite rhombs show diamond-shaped hollow shell due to dissolution of the center zone, which is revealed in the trace element composition that the cores are slightly enriched in Ca compared with the rim zones (Lee and Boles, 1995). The dolomite cement precipitated from mixed marine-meteoric fluids during shallow burial as inferred from oxygen isotopic and trace element composition (Lee and Boles, 1985).

Quartz Cement : Quartz cement (Fig. 5) as overgrowths on detrital quartz grains is a common diagenetic mineral, although it rarely exceeds 3% of rock. Minor meniscus-type quartz cement is also observed. Quartz overgrowth occurs more commonly in clear sandstones. Its formation postdates the early micritic calcite cement and fracture development, but predates the late sparry calcite.

Albite Cement : Although occurring in minor amount, diagenetic albite cement occurs as overgrowths on and as healing fractures in plagioclase grains (Fig. 6). In most cases, albite overgrowth does not show albite twinning and exti-

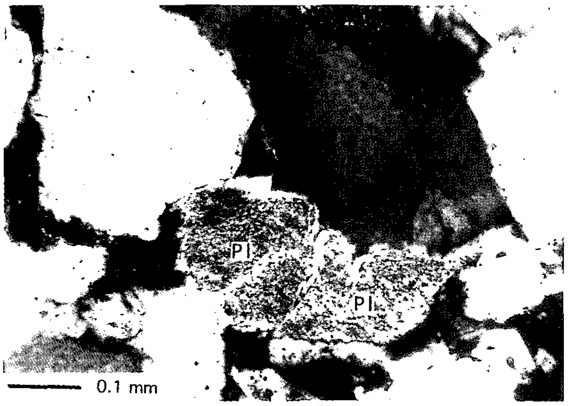

Fig. 6. Euhedral albite overgrowths on detrital plagioclase (Pl) are inclusion-free and show euhedral shape. Also shown is albite cement healing fractures in plagioclase. Light grain in the upper left is quartz with overgrowths. Sample 5-55, 2478.3 m. Crossed nicols.

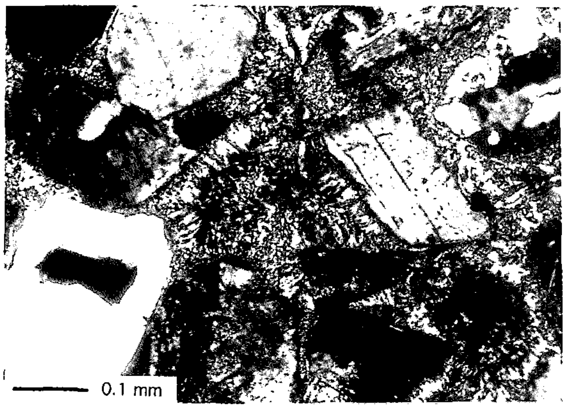

Fig. 7. Oriented pore-lining C/S clay partially occludes porosity, reducing reservoir quality. Note that clay platelets are oriented perpendicular to pore wall. Sample 3C-H1, 2460.7 m. Crossed nicols.

nction is somewhat different from the host grain because of the chemical difference. When albite overgrowth is in contact with quartz overgrowth, they seem to be coeval indicated by the presence of compromise crystal boundary between them. The fracture-filling albite is water-clear and shows a seam along its center (Fig. 9-B). Albite cement formation postdates the early calcite cement and fracturing of grains, but predates the late calcite cement.

Mixed-layer Chlorite/Smectite and Smectite : Authigenic clay minerals formed prior to feldspar diagenesis in the Temblor sandstone at Kettleman North Dome include mixed-layer chlorite/smectite (C/S) and smectite. The C/S clays occur abundantly as a coating on many detrital grains and a fibrous pore-filling cement (Fig. 7). The C/S clay occurs up to 50 mm thick and shows greenish brown color. The C/S clays are regularly interstratified with 50 to 60 percent smectite layers. The abundance of the C/S clays is closely related to the abundance of volcanic rock fragments. Thus Zone V with >40% volcanic rock fragments has much C/S clay cements (up to 9%). The smectite clays refer to both smectite and mixed-layer illite/smectite with more than 80 percent expandability. This clay also forms as a coating on grains and a pore-filling cement. Petrographic evidence indicates that the C/S and smectite clays postdate quartz and albite overgrowths as shown by no C/S and/or smectite rim or coating between host grain and overgrowths, but predate late calcite cement. In places, the clay cement arrested development of quartz overgrowths.

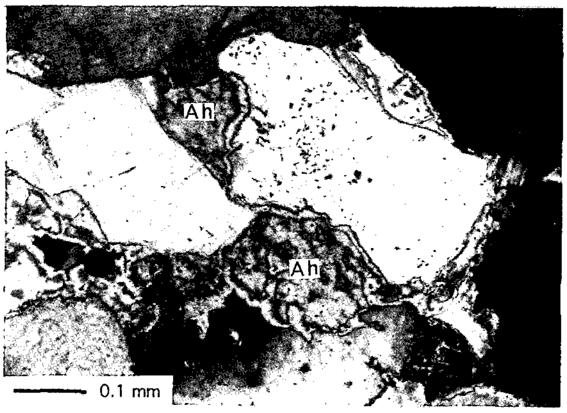

Fig. 8. Pore-filling anhydrite (Ah) cement. Some grain margins show ragged texture suggesting either some grain dissolution before anhydrite cementation or partial replacement of grains by anhydrite cement. Sample 5-55, 2478.3 m. Crossed nicols.

Anhydrite Cement : Poikilotopic to sparry anhydrite cement occurs up to 12% of the rock, mostly in Temblor Zone V sandstones (Fig. 8). It also replaces some detrital grain margins. Anhydrite cement clearly postdates quartz and albite overgrowths and the C/S. Some quartz overgrowths are corroded by anhydrite cement. When both anhydrite and late calcite cements are present, detrital grains show point contacts in anhydrite cemented zone whereas late calcite occurs in more densely packed zone and in crushed biotite flakes indicating that anhydrite cement precipitated prior to late calcite cement. Dissolution features of anhydrite cement are commonly observed.

Anhydrite cement has never recorded from other areas of the San Joaquin basin. This cement may be common in the western part of the basin or only recorded in the Kettleman North Dome. At present the source of Ca and S is not clearly identified.

Feldspar Diagenesis

Diagenetic changes associated with plagioclase alteration in the Temblor sandstones are plagioclase albitization, late calcite and laumontite cementation and grain replacement, plagioclase dissolution, and kaolinite cementation.

Albitization of Plagioclase : Albitized plagioclase (Fig. 9A) is common in Temblor sandstone at Kettleman North Dome (Table 2). Microprobe analysis on plagioclase shows a wide range of albite composition from 42 to 99 mole percent. The presence of albitized plagioclase in samples heavily cemented by early carbonates (1-55 and 2B-H1) indicates that some albitized plagioclases are of a detrital origin. Albitization in the core of plagioclase with fresh rim, extensive albitization near both sides of the fractures (Fig. 9B), and concentrically zoned distribution of dusty inclusions (Fig. 4A) at stressed contact with potassium feldspar and quartz grains are textural criteria for in situ albitization of plagioclase. The stress-induced albitization of plagioclase occurred after fracture development in grains and albite fracture-fill. As summarized in Table 2, albite ranges from 17 to 35% of all plagioclases. In addition, multiple point analyses of single plagioclases reveal that partially albitized plagioclases occur up to 28% of all plagioclases. The composition of unaltered plagioclases shows wide range from Ab_{31} to Ab_{87}.

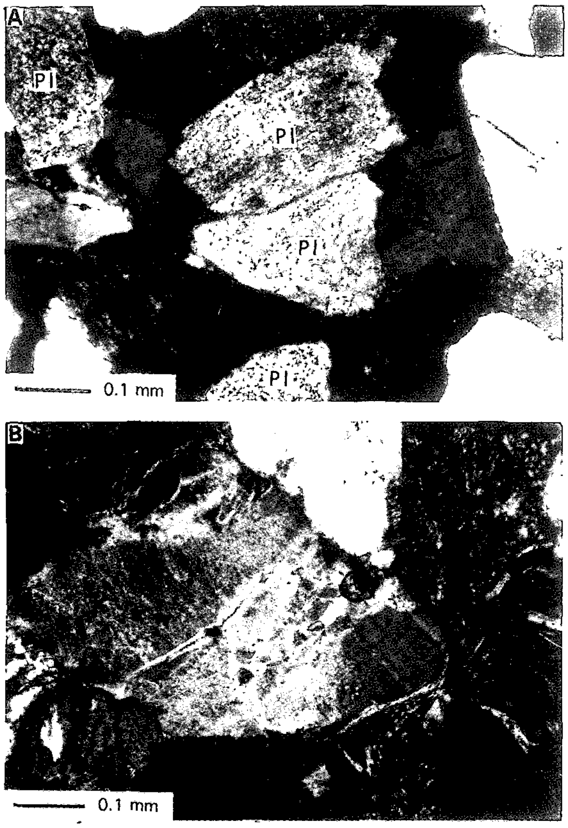

Fig. 9. Albitized plagioclase grains. (A) Completely albitized plagioclase grains (Pl) in Temblor Zone V. Note that plagioclase looks turbid because of abundant vacuoles. Sample 5-56, 2970.9 m. Crossed nicols. (B) Plagioclase albitization is well developed near both sides of fracture. Clear albite fracture-fill with a seam along its center. Sample 4-H1, 2522.2 m. Crossed nicols.

Table 2. Plagioclase composition, porosity, and formation water oxygen isotope data of Temblor sandstones.

	Zone I	Zone II	Zone III	Zone V
Sample	1-55,	2B-H1, 2D-H1, 2-55	3-58	5-8, 5-55, 5-61, 5-56, 5A-V38, 5B-V38
N*	19	69	18	76
$Ab_{>90}$	32%	17%	17%	35%
plagio. ϕ	1.6%	2.3%	4.7%	7.1%
$\delta^{18}O_w$**	3.9‰	2.8‰	1.8‰	0.2‰

*total number of point analysis by microprobe. **data are from *Kharaka et al.* (1973).

Late Calcite Cement and Replacement : Late calcite cement is observed after the precipitation of quartz and albite overgrowths (Fig. 10A) and occurs mainly as pore filling. The late calcite usually forms poikilotopic texture and its volume ranges up to 24% of the rock. Some framework grains, mostly plagioclase, are replaced by calcite, too. Calcite replacement usually occurs in compacted rocks, in which grains show long to concavo-convex contacts. Although rare, the late calcite also filled cleavage spaces of crushed biotite flakes formed due to compaction (Fig. 10B) indicating a relatively late origin. Under the luminoscope late calcite shows homogeneous dull orange luminescence. Light oxygen iso-

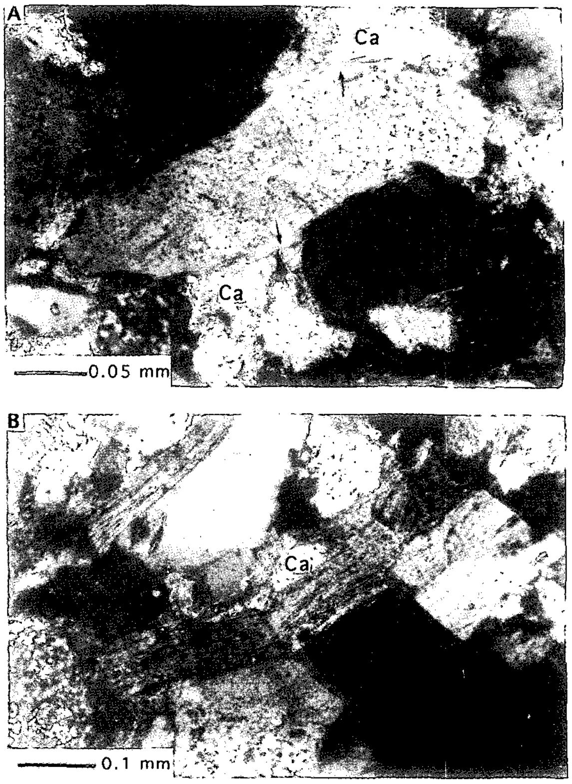

Fig. 10. Late calcite cement. (A) Calcite (Ca) pore-fill cement after quartz overgrowths (arrows). Sample 1-58, 1950.7 m. Crossed nicols. (B) Calcite (Ca) fills cleavage space in the crushed biotite flakes. Sample 5-55, 2478.3 m. Crossed nicols.

topic composition (−8.8 and −13.5‰ PDB) and trace element composition suggest that late calcite precipitated from evolved marine fluids during deep burial (70-120℃; Lee and Boles, 1995).

Laumontite Cement and Replacement : Abundant laumontite pore-fill cement and replacement of plagioclase grains (Fig. 11) occur in one Temblor Zone V sandstone (5-61) comprising 12% of the rock. Another sample from Temblor Zone III also contains trace amount of laumontite replacement of plagioclase grains. Some laumontite cements are in optical continuity with the ones which replaced plagioclase across the C/S rim-cemented grain boundaries (Fig. 11) indicating that laumontite precipitation postdates the C/S clays. The limited occurrence of laumontites suggests that these components have not been transferred greater than a zone and also shows influence of volcanic protolith on their occurrence. The laumontite-bearing sandstone contains the most abundant amount (56.3% of the rock) of combined plagioclase and volcanic rock fragment among the Temblor sandstones. Plagioclases in the sandstone containing laumontite are almost completely albitized suggestive of causal relationship between these two components.

Plagioclase Dissolution : Plagioclase is selectively dissolved partially to completely leaving a skeletal framework when incomplete (Fig. 12). Plagioclase dissolution commonly occurred along cleavages, twinning planes, and fractures. Early-formed fracture-fill albite usually is stable with respect to the dissolution and forms a skeletal framework after plagioclase dissolution. Plagioclase with stress-induced albitization shows dissolution features indicating the stress-induced albitization predated plagioclase dissolution. Plagioclase dissolution ranges from 0.3 to 8.5% of the rock based on point counting. The amount of plagioclase porosity increases from Zone I to Zone V (Table 2). The large amount of plagioclase porosity in Zone V may be related to the abundance of volcanic plagioclases (Fig. 3B). K-feldspar is not affected by dissolution except when it is fractured.

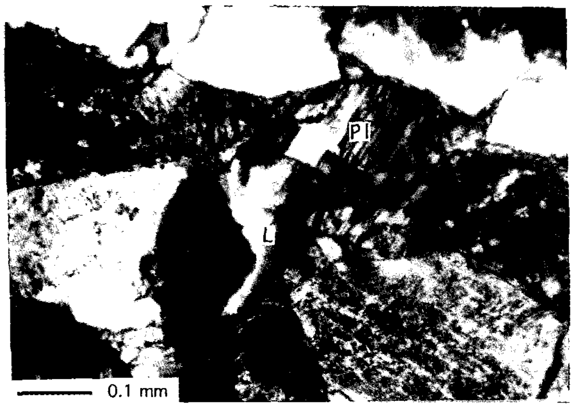

Fig. 11. Laumontite (L) pore-fill cement and replacement of plagioclase grain (Pl). Note optical continuity of laumontite cement to replacement across the original plagioclase grain boundary delineated by the C/S clay. Sample 5-61, 2335.7 m. Crossed nicols.

Plagioclase porosity is not observed when the rock is completely or extensively cemented by calcite, dolomite, and anhydrite indicating dissolution postdates most diagenetic changes in the Temblor sandstones at Kettleman North Dome. Distribution of plagioclase porosity has no relation to oil and gas cap zones (Table 3).

Kaolinite Cement : Authigenic kaolinite cement occurs in minor amount in Temblor sandstones at Kettleman North Dome. It occurs as clusters of interstitial crystals (Fig. 13). Kaolinite is commonly associated with plagioclase dissolution and postdates the C/S clay. When kaolinite occurs intergrown with or in other clays, its identification under petrographic microscope is very difficult, but X-ray diffraction analysis of clay separates (<2μm) clearly reveals its presence.

BURIAL HISTORY

A burial history diagram (Fig. 14) for the Temblor Formation has been constructed using the program SINWELL (Nigrini *et al*., 1989) with data from well E72-3P near the northern crest assuming a constant geothermal gradient.

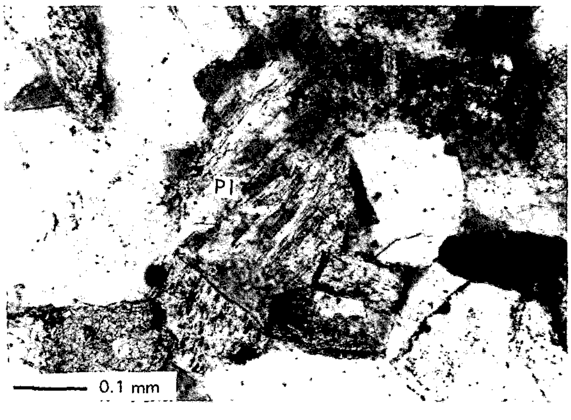

Fig. 12. Plagioclase (Pl) dissolution resulted in plagioclase porosity shown in gray. Sample 2-V21, 2130.6 m. Plane light.

Table 3. Distribution of plagioclase porosity in the Temblor sandstones.

Gas cap		Oil zone	
sample	plagio. ϕ (%)	sample	plagio. ϕ (%)
1-58	1.7	2C-H1	4.0
1-V21	0.3	2D-H1	1.7
1-F1	4.3	3-61	4.2
2-58	0.3	3-55	1.6
2-V21	2.5	3A-H1	2.5
2-55	2.2	3B-H1	0.2
3-58	2.1	4-V21	5.6

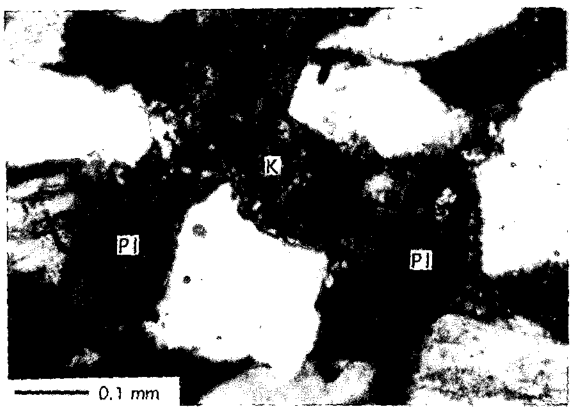

Fig. 13. Kaolinite (K) pore-filling cement. Note ragged texture on plagioclase (Pl) suggesting kaolinite has filled pore space after some plagioclase dissolution. Sample 4-56, 2761.5 m. Crossed nicols.

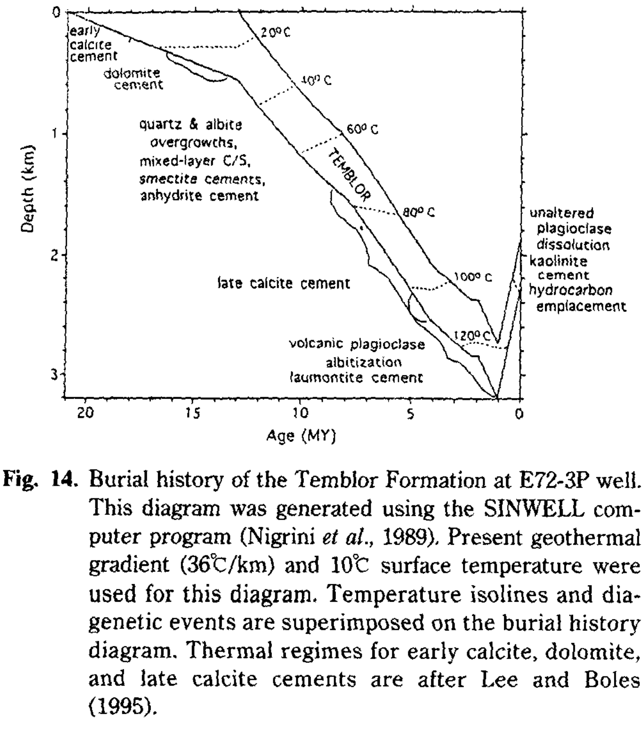

Fig. 14. Burial history of the Temblor Formation at E72-3P well. This diagram was generated using the SINWELL computer program (Nigrini *et al.*, 1989). Present geothermal gradient (36℃/km) and 10℃ surface temperature were used for this diagram. Temperature isolines and diagenetic events are superimposed on the burial history diagram. Thermal regimes for early calcite, dolomite, and late calcite cements are after Lee and Boles (1995).

Boundary ages were sourced from Wooding *et al*. (1940) and Sullivan (1966). The Temblor underwent subsidence until middle Pleistocene when the uplift of Kettleman North Dome occurred at about 1 Ma ago (Harding, 1976). Bottomhole temperature measured in the Temblor Zone V reservoir is about 100℃ (B. Bilodean, Chevron, personal communication, 1992). The geothermal gradient in the northern center of the field is calculated from the bottomhole temperatures measured in 1985, to be 36℃/km to 3 km assuming 10℃ surface temperature. This geothermal gradient is similar to gradients in the southern San Joaquin basin (Boles and Ramseyer, 1987). Assuming maximum erosion of 1000 m due to uplift (Merino, 1975a), the maximum burial temperature of the Temblor Zone V is about 130℃ (~1 m. y.b.p.). During early stages of Temblor deposition, the paleo-heatflow may have been lower than the present value suggesting the paleogeothermal gradient was lower than at present. Heasler and Surdam (1985) have modeled that paleo-heatflow has nearly doubled since Temblor deposition times. Thus, initial geothermal gradient was probably considered lower than the present values. However, the maximum burial of the Temblor sandstone had occurred around 1 Ma before the onset of uplift, which suggests that maximum temperatures calculated using the present geothermal gradient is a reasonable estimate. The paragenetic sequence of diagenetic events is superimposed on the burial history diagram in Fig. 14.

POROSITY IN TEMBLOR RESERVOIRS

Both intergranualr and intragranular porosities occur in Temblor sandstones. Intergranular porosity is of two types; depositional and secondary. The secondary porosity is inferred by the presence of plagioclase porosity and of the etched crystal boundary of calcite, anhydrite, and quartz overgrowths in open pore space. However, the volume of intergranular porosity of secondary origin is difficult to estimate in case of cements. Intragranular porosity is the plagioclase porosity. Since dissolution of both plagioclase and carbonate cements in the Temblor reservoirs might have been caused by acidic waters concurrently, only plagioclase dissolution will be discussed here.

Although it is difficult to date the timing of plagioclase dissolution and kaolinite precipitation, petrographic evidence clearly reveals that this event occurred after late calcite precipitation and albitization of plagioclase. Since hydrocarbons are trapped in the structure, they must have migrated after the structural development at Kettleman North Dome within the last one million years. The reservoir porosity should have been preserved and formed before or immediately after structure formation.

Plagioclase dissolution due to meteoric water invasion during and after uplift is unlikely considering from the present formation water chemistry. The present Temblor formation waters were interpreted by Kharaka and Berry (1974) and Kharaka *et al.* (1973) to be meteoric water modified by shale membrane hyperfiltration primarily based on low deuterium composition of the waters. These "meteoric" waters have anomalous high salinities up to 41,000 mg/l (Kharaka and Berry, 1974, table 3). However, San Joaquin basin formation waters possessing similar low deuterium values as well as oxygen isotopic compositions and salinities to those of the Kettleman North Dome oil field are interpreted as the diagenetically modified sea water by Fisher and Boles (1990). We believe the meteoric origin of the present Temblor formation waters is questionable due to high salinities and rather interpret they are diagenetically modified connate waters (Lee and Boles, 1995).

According to the reconstruction of Temblor sandstones before structure development, the maximum temperature of the Temblor Zone V is estimated about 130℃ (Fig. 14). Among plagioclases of different origins volcanic plagioclases are more susceptible to albitization in diagenetic fluids than plutonic ones (Ramseyer *et al.*, 1992). The plagioclase albitization reaction is known to occur between 120℃ and 160℃ in the San Joaquin basin (Boles and Ramseyer, 1988). In Temblor sandstones plagioclases seem to be mixtures of both volcanic and plutonic origins due to the presence of significant amount of K-feldspar and volcanic rock fragment (Fig. 3B). Hence burial of Temblor sandstones to 130℃ might have caused volcanic plagioclases to react preferentially to albitization process along fractures and at the stressed contacts. The occurrence of albitized plagioclase in Temblor Zone I suggests that plagioclase albitization reaction occurred at temperatures below the lower window, probably around 100℃. Even lower temperature for plagioclase albitization was suggested by kinetic modeling (Ben Baccar *et al.*, 1993). Apparently plutonic plagioclases did not undergo albitization during maximum burial because they were not bathed in a thermal fluid of appropriate temperatures. Due to the albitization reaction volcanic plagioclase became altered partially to completely, whereas plutonic plagioclase remained unaltered and later became the target of attack by acidic pore waters. Sometime after albitization of plagioclases up to present day plagioclase dissolution (porosity) developed.

The plagioclase albitization and dissolution in the Temblor is supported by higher Ca/Na ratios in formation waters (Fig. 15). Similar observation was reported from formation waters in the southern San Joaquin basin (Fisher and Boles, 1990). Also, $\delta^{18}O$ composition of the Temblor formation waters becomes lighter stratigraphically from +3.9‰ in Zone I to +0.2‰ in Zone V (Table 2; Kharaka *et al.*, 1973). Partly, this is explained by albitization of plagioclase because the albite is replacing a feldspar formed at high temperatures (Fisher and Boles, 1990). Based on the chemistry and isotopic composition of the formation waters the *in situ* albitization and dissolution of plagioclase was more active in Zone V sandstones (Table 2), which also indicates lack of fluid mobility between zones in Temblor reservoirs.

Plagioclase dissolution post-dating plagioclase albitization indicates that this diagenetic change occurred during and after structural development. Because meteoric influence on plagioclase dissolution has been ruled out by the formation water geochemistry, no appropriate hydrologic flow regime is suggested for plagioclase dissolution during uplift of Temblor sandstones. Also, the fact that precipitation of kaolinite occurred next to the site of plagioclase dissolution instead of some distance away from it indicates local conservation of Al inspite of some mass transfer reported in the Gulf Coast by Moncure *et al.* (1984). The present Temblor reservoir temperature ranges from 85 to 100℃ (Fig. 14) suggesting plagioclase dissolution at temperatures close to this range. Similar temperature range for plagioclase dissolution was reported in the southern San Joaquin basin (Boles, 1987, 1992). Then, it is interesting to note that the dissolution of plagioclase grains as well as of calcite and anhydrite cements in Temblor sandstones occurred between 85 to 100℃ and this temperature range corresponds closely with a marked increase in organic acids in pore waters of the San Joaquin basin (Carothers and Kharaka, 1978). These organic acids are known to have the capability to dissolve aluminosilicates (Surdam *et al.*, 1984). The overlap of the large presence in organic acids in pore waters with the apparent timing of plagioclase, calcite, and anhydrite dissolution at Temblor sandstones shows the probable influence of kerogen maturation on porosity enhancement.

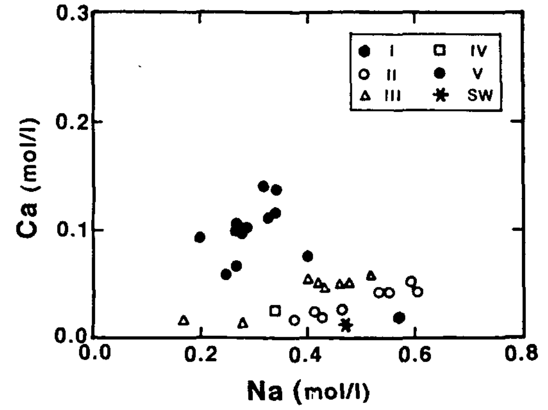

Fig. 15. Plot of Ca vs. Na concentration for the Temblor formation waters at Kettleman North Dome. All Na/Ca ratios are above the evolution value of sea water caused by albitization of plagioclase. The theoretical pathway of sea water may follow Na/Ca ratio from 46 to 22 at 120℃ (Helgeson, 1972). The present formation water contains more Ca than the predicted amount, probably caused by dissolution of plagioclase after albitization reaction. SW: sea water. Data from Merino (1975b).

Plagioclase dissolution is not restricted to oil zone as observed at North Coles Levee (Boles, 1991), but occurs equally in both oil and gas zones (Table 3). This means that a) plagioclase porosity is pre-oil and gas emplacement or that b) communication exists between oil and gas zones or that c) development of gas zone was late after development of plagioclase porosity. Two hypotheses can account for the dissolution of plagioclase. The first is that organic acids migrated prior to the migration of the present Temblor hydrocarbons might have caused the plagioclase dissolution (i.e., Crossey *et al.*, 1986; Surdam *et al.*, 1984, 1989). This is supported by no obvious differences in diagenesis between present gas, oil, and water zones indicating no further significant diagenesis has occurred since hydrocarbon emplacement.

Second, plagioclase dissolution and kaolinite precipitation are related to the organic acids derived from oils. This mechanism was advocated from the Miocene Stevens sandstones at North Coles Levee by Boles (1991, 1992), who reports that plagioclase dissolution and kaolinite precipitation are found in oil zones but not in the gas zone. Organic acids are recognized as a dominant alkalinity component in the San Joaquin basin formation waters (Carothers and Kharaka, 1978; MacGowan and Surdam, 1990; Fisher and Boles, 1990). They are also present as a chief alkalinity contributor in the Kettleman North Dome formation waters in the form of acetate and propionatae ions (Willey *et al.*, 1975). If plagioclase dissolution had been caused by organic acids in the present formation waters, then this event is very late and is still occurring today. This hypothesis may explain kaolinite precipitation proximal to plagioclase dissolution sites. However, experimental study shows that the organic acids are effective in modifying stability of aluminosilicates only when the pH of the fluid is very low (<5) and thus is acidic (Surdam *et al.*, 1984; Harrison and Thyne, 1992). The measured pH of the Temblor formation waters at Kettleman North Dome is nearly neutral (6.3-7.9) at surface temperature (Kharaka and Berry, 1974), and the calculated pH at 100℃ is alkaline ranging from 8.1 to 8.7 with the assumption that biocarbonate is the main alkalinity component (Merino, 1975b), although this value may be too high for the reservoir conditions. Therefore, the role of organic acids in the present formation waters contributing to the solubility of aluminosilicates is difficult to assess and hence interpretation of plagioclase dissolution by the organic acids after hydrocarbon emplacement is ambiguous.

SUMMARY

1. The Temblor Formation (early Miocene) at Kettleman North Dome is an arkosic hydrocarbon reservoir with abundant volcanic rock fragments in the deepest Temblor (Zone V) sandstones. The point-counted reservoir porosity averages about 15%.

2. Diagenetic changes in the Temblor include compaction, cementation, and alteration of grains. Micritic calcite and dolomite cements formed early during shallow burial, which were followed by fracturing of grains, quartz and albite cements, clay (C/S and smectite) cements, anhydrite cement, late calcite cement and replacement, and by plagioclase albitization with progressive burial. The Zone V sandstones also contains laumontite cement and replacement after plagioclase due to original compositional difference. Plagioclase dissolution and kaolinite cementation as well as some cement dissolution are the latest diagenetic changes in Temblor sandstones. Relatively closed system is inferred for plagioclase dissolution and kaolinite precipitation.

3. Most diagenetic changes seem to have occurred before the uplift of the Temblor to form the present anticlinal structure. Albitization of plagioclase and associated calcite and laumontite cementation and/or replacement in Temblor sandstones were the highest temperature (130℃) diagenetic events occurred at the time of maximum burial. Volcanic plagioclases were preferentially albitized, whereas unaltered part of the volcanic plagioclase as well as plutonic plagioclase was dissolved later forming plagioclase porosity.

4. Secondary porosity was formed by dissolution of plagioclase and some carbonate and anhydrite cements after structural development but prior to hydrocarbon emplacement. Organic acids influx during kerogen maturation is interpreted to be responsible for secondary porosity formation.

ACKNOWLEDGEMENTS

The Temblor core samples from Kettleman North Dome oil field were kindly provided from Chevron Oil Field Research Company (COFRC) and California State University, Bakersfield. X-ray diffraction and part of microprobe analyses were done by E. Mountcastle. Stable isotopes were analyzed by COFRC and Pat Dobson at Unocal. Y.I. Lee was supported by the fellowship from the former Ministry of Energy and Resources, Korea while at UCSB. J. Boles acknowleges grants from Lawrence Livermore National Laboratory (8960-20), Petroleum Research Fund (18438-AC2), and National Science Foundation (EAR-17013). The manuscript has benefitted from careful reviews by Prof. S. Koh and Dr. J. D. Son.

References

Ben Baccar, M., Fritz, B., and Made, B., 1993, Diagenetic albitization of K-feldspar and plagioclase in sandstone reservoirs: thermodynamic and kinetic modeling. *Journal of Sedimentary Petrology*, 63, 1100-1109.

Bjφrlykke, K., 1984, Formation of sedondary porosity: how important is it?. In: D.A. McDonald and R.C. Surdam (Editors), Clastic Diagenesis. *American Association of Petroleum Geologists Memoir* 37, 277-286.

Bjφrlykke, K. and Brendsdal, A.,1986, Diagenesis of the Brent Sandstone in the Statfjord field, North Sea. In: D.L. Gautier (Editor), Roles of Organic Matter in Sediment Diagenesis. *Society of Economic Paleontologists and Mineralogists Special Publication* 38, 157-167.

Boles, J.R., 1982, Active albitization of plagioclase, Gulf Coast Tertiary. *American Journal of Science*, 282, 165-180.

Boles, J.R., 1984, Secondary porosity reactions in the Stevens sandstone, San Joaquin Valley, California. In: D.A. McDonald and R. C. Surdam (Editors), Clastic Diagenesis. *American Association of Petroleum Geologists Memoir* 37, 217-224.

Boles, J.R., 1987, Six million year diagenetic history, North Coles Levee, San Joaquin Basin, California. In: J.D. Marshall (Editor), Diagenesis of Sedimentary Sequences. *Geological Society of London Special Publication* 36, 191-200.

Boles, J.R., 1991, Plagioclase dissolution related to oil residence time, North Coles Levee Field, California (abs.). *American Association of Petroleum Geologists Bulletin*, 75, 544.

Boles, J.R., 1992, Evidence for oil-derived organic acids in reservoirs. In: Y.K. Kharaka and A.S. Maest (Editors), *Proceedings of the 7th International Symposium on Water-Rock Interaction*. 311-314.

Boles, J.R. and Ramseyer, K., 1988, Albitization of plagioclase and vitrinite reflectance as paleothermal indicators, San Joaquin Basin, California. In: S.A. Grahamn (Editor), Studies of the Geology of the San Joaquin Basin. *Pacific Section of Society of Economic Paleontologists and Mineralogists*, 60, 129-139.

Carothers, W.W. and Kharaka, Y.K., 1978, Aliphatic acid anions in oil-field waters-implications for origin of natural gas. *American Association of Petroleum Geologists Bulletin*, 62, 2441-2453.

Chowdhyry, A.H. and Noble, J.P.A., 1992, Porosity evolution in the Albert Formation of the Stoney Creek oil and gas field, Moncton Subbasin, New Brunswick, Canada. *American Association of Petroleum Geologists Bulletin*, 76, 1325-1343.

Crossey, L.J., Surdam, R.C., and Lahann, R., 1986, Application of organic/inorganic diagenesis to porosity prediction. In: D.L. Gautier (Editor), Roles of Organic Matter in Sediment Diagenesis. *Society of Economic Paleontologists and Mineralogists Special Publication* 38, 147-155.

Fisher, J.B. and Boles, J.R., 1990, Water-rock interaction in Tertiary sandstones, San Joaquin Basin, California, U.S.A.: Diagenetic controls on water composition. *Chemical Geology*, 82, 83-101.

Franks, S.G. and Forester, R.W., 1984, Relationships among secondary porosity, pore-fluid geochemistry and carbon dioxide, Texas Gulf Coast. In: D.A. McDonald and R. C. Surdam (Editors), Clastic Diagenesis. *American Association of Petroleum Geologists Memoir* 37, 63-80.

Hamsley, P.L. and Nuccio, V.F., 1992, Upper Cretaceous Shannon Sandstone reservoirs, Power River Basin, Wyoming: Evidence for organic acid diagenesis?. *American Association of Petroleum Geologists Bulletin*, 92, 781-791.

Harding, T.P., 1976, Tectonic significance and hydrocarbon trapping consequences of sequential folding synchronous with San Andreas faulting, San Joaquin Valley, California. *American Association of Petroleum Geologists Bulletin*, 60, 356-378.

Harrison, W.J. and Thyne, G.D., 1992, Predictions of diagenetic reactions in the presence of organic acids. *Geochimica et Cosmochimica Acta*, 56, 565-586.

Hayes, M.J. and Boles, J.R., 1995, Evidence for meteoric recharge in the San Joaquin basin, California provided by isotope and trace element chemistry of calcite. *Jouranl of Marine and Petroleum Geology*, in press.

Helgeson, H.C., 1972, Chemical interaction of feldspars and aqueous solutions. In: W.S. Mackenzie and J. Zussman (Editors), The Feldspars. *Proceedings NATO Advanced Study Institute, Manchester, Manchester University Press*, 184-217.

Kharaka, Y.K. and Berry, F.A.F.,1974, The influence of geological membranes on the geochemistry of subsurface waters from Miocene sediments at Kettleman North Dome in California. *Water Resource Research*, 10, 313-327.

Kharaka, Y.K., Berry, F.A.F., and Friedman, I., 1973, Isotopic composition of oil-field brines from Kettleman North Dome, California, and their geologic implications. *Geochimica et Cosmochimica Acta*, 37, 1899-1908.

Kharaka, Y.K., Law, L.M., Carothers, W.W., and Goerlitz, D.F., 1986, Role of organic species dissolved in formation waters from sedimentary basins in mineral diagenesis. In: D.L. Gautier (Editor), Roles of Organic Matter in Sediment Diagenesis. *Society of Economic Paleontologists and Mineralogists Special Publication* 38, 111-122.

Kuespert, J., 1985, Depositional environments and sedimentary history of the Miocene Temblor Formation and associated Oligo-Miocene units in the vicinity of Kettleman North Dome, San Joaquin Valley, California. In: S.A. Grahamn (Editor), Geology of the Temblor Formations, western San Joaquin Basin, California. *Pacific Section of Society of Economic Paleontologists and Mineralogists*, 44, 53-67.

Land, L.S., 1984, Frio sandstone diagenesis, Texas Gulf Coast: a regional isotopic study. In: D.A. McDonald and R. C. Surdam (Editors), Clastic Diagenesis. *American Association of Petroleum Geologists Memoir* 37, 47-62.

Lee, Y.I. and Boles, J.R., 1995, Depositional control on diagenetic carbonate in the San Joaquin Basin, California. *Society for Sedimentary Geology Special Publication*, in press.

Lundegard, P.D. and Land, L.S., 1986, Carbon dioxide and organic acids: Their role in porosity enhancement and cementation, Paleogene of the Texas Gulf Coast. In: D.L. Gautier (Editor), Roles of Organic Matter in Sediment Diagenesis. *Society of Economic Paleontologists and Mineralogists Special Publication* 38, 129-146.

MacGowan, D.B. and Surdam, R.C., 1990, Carboxylic acid anions in formation waters, San Joaquin Basin and Louisiana Gulf Coast, U.S.A.- implications for clastic diagenesis. *Applied Geochemistry*, 5, 687-701.

Merino, E., 1975a, Diagenesis in Tertiary sandstones from Kettleman North Dome, California-I. Diagenetic mineralogy. *Journal of Sedimentary Petrology*, 45, 320-336.

Merino, E., 1975b, Diagenesis in Tertiary sandstones from Kettleman North Dome, California-II. Interstitial solutions: distribution of aqueous species at 100℃ and chemical relation to the diagenetic mineralogy. *Geochimica et Cosmochimica Acta*, 39, 1629-1645.

Milliken, K.L., McBride, E.F., and Land, L.S. 1989, Numerical assessment of dissolution versus replacement in the subsurface destruction of detrital feldspars, Oligocene Frio Formation, south Texas. *Journal of Sedimentary Petrology*, 59, 740-757.

Moncure, G., Lahann, R., and Siebert, R., 1984, Origin of secondary porosity and cement distribution in a sandstone/shale sequence from the Frio Formation (Oligocene). In: D.A. McDonald and R. C. Surdam (Editors), Clastic Diagenesis. *American Association of Petroleum Geologists Memoir* 37, 151-163.

Nigrini, A., Palciauskas, V.V., Crowe, J., Wood, M.F., and Peoples, C.J., 1989, SINWELL: an interactive single well source-rock maturation modeling program for the PC. *Cheveron Oil Field Research Company*.

Ramseyer, K., Boles, J.R., and Lichtner, P.C., 1992, Mechanism of plagiocalse albitization. *Journal of Sedimentary Petrology*, 62, 349-356.

Reed, C.L. and Hajash, A., Jr., 1992, Dissolution of granitic sand by pH-buffered carboxylic acids: A flow-through experimental study at 100℃ and 345 bars. *American Association of Petroleum Geologists Bulletin*, 76, 1402-1416.

Schmidt, V. and McDonald, D.A. 1979a, The role of secondary porosity in the course of sandstone diagenesis. In: P.A. Scholle and P.R Schluger (Editors), Aspects of Diagenesis. *Society of Economic Paleontologists and Mineralogists Special Publication* 26, 175-207.

Schmidt, V. and McDonald, D.A., 1979b, Texture and recognition of secondary porosity in sandstones. In: P.A. Scholle and P.R Schluger (Editors), Aspects of Diagenesis. *Society of Economic Paleontologists and Mineralogists Special Publication* 26, 209-225.

Schultz, J.L., Boles, J.R., and Tilton, G.R., 1989, Tracking calcium in the San Joaquin Basin, California: a strontium isotopic study of carbonate cements at North Coles Levee. *Geochim. Cosmochim. Acta*, 53, 1991-1999.

Surdam, R.C., Boese, S.W., and Crossey, L.J. 1984, The chemistry of secondary porosity. In: D.A. McDonald and R. C. Surdam (Editors), Clastic Diagenesis. *American Association of Petroleum Geologists Memoir* 37, 127-149.

Surdam, R.C., Crossey, L.J., Hagan, E.S., and Heasler, H.P., 1989, Organic-inorganic interactions and sandstone diagenesis. *American Association of Petroleum Geologists Bulletin*, 73, 1-23.

Sullivan, J.C., 1966, Kettleman North Dome oil field. *Summary of Operations, California Oil Fields*, 52, 5-21.

Tieh, T.T., Berg, R.R., Popp, R.K., Brasher, J.E., and Pike, J.D., 1986, Deposition and diagenesis of Upper Miocene arkoses, Yowlumne and Rio Viejo fields, Kern County, California. *American Association of Petroleum Geologists Bulletin*, 70, 953-969.

Willey, L.M., Kharaka, Y.K., Presser, T.S., Rapp, J.B., and Barnes, I., 1975, Short chain aliphatic acid anions in oil field waters and their contribution to the measured alkalinity. *Geochimica et Cosmochimica Acta*, 39, 1707-1711.

Woodring, W.P., Stewart, R., and Richards, R.W., 1940, Geology of the Kettleman Hills oil field, California. *U. S. Geological Survey Professional Paper* 195, 170p.

Zieglar. D.L. and Spotts, J.H., 1978, Reservoir and source bed history in the Great Valley, California. *American Association of Petroleum Geologists Bulletin*, 62, 813-826.

Manuscript received May 14, 1995.