

PS Fault-Controlled Dolomitization of Upper Cretaceous Reservoirs, Zagros Basin, Kurdistan Region of Iraq: Implications for Hydrocarbon Migration and Degradation*

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Abstract

The close association between oil seepages with fault- and fracture-bounded dolomitized limestones as well as vug/gash-lining saddle dolomite and/or calcite is widespread in Cretaceous carbonate successions of the Kurdistan Region of Iraq. This integrated field, petrographic, chemical, stable C, O and Sr isotopes, and fluid inclusion investigations aims to link these diagenetic alterations to the origin and geochemical evolution of fluids and oil migration in the Upper Cretaceous Bekhme carbonates. Flux of hydrothermal fluids, which is suggested to have occurred during the Zagros Orogeny, resulted in dolomitization and cementation of vugs by saddle dolomite, coarse-crystalline equant calcite and anhydrite. The saddle dolomite and host dolostones have similar stable isotopic composition and formed prior to oil migration from hot (81-115 °C) basinal NaCl-MgCl₂-H₂O brines with salinities of 18-22 wt.% NaCl eq. The equant calcite, which surrounds saddle dolomite, has precipitated during oil migration from cooler (60-110 °C NaCl-CaCl₂-H₂O brines (14-18 wt.% NaCl eq). The yellowish fluorescence color of oil inclusions in the equant calcite indicates that the oil had API gravity of 15-25° composition, which is lighter than present-day oil in the reservoirs (API of 10-17°). This difference in oil composition is attributed to oil degradation by the flux of meteoric water, which is evidenced by the low $\delta^{13}\text{C}$ values (-8.5‰ to -3.9‰) as well as by nil salinity and low temperature in fluid inclusions of late columnar calcite cement. This study demonstrates that linking fluid flux history and related diagenesis to the tectonic evolution of the basin provides important clues to the timing of oil migration, degradation and reservoir evolution.

Fault-controlled dolomitization of Upper Cretaceous reservoirs, Zagros Basin, Kurdistan Region of Iraq: implications for hydrocarbon migration and degradation

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Introduction

The flux of hydrothermal fluids into cooler strata is envisaged to occur along deeply-seated faults in sedimentary basins (Packard et al., 2001; Lavoie and Chi, 2006; Shah et al., 2010; Dewitt et al., 2012, Corbella et al., 2014). The upward flux of these fluids has been attributed to strain cycling during basin deformation (Sibson et al., 1985) and/or through the sudden release of overpressure fluids (Muir-Wood, 1994). Thus, these fluids are characterized by higher temperatures and pressures than in those in the limestones (Davies and Smith, 2006). The general petrographic, geochemical and micro-thermometric characteristics of the resulting hydrothermal dolostones and associated saddle dolomite cement have been constrained in the literature (e.g. Lavoie and Morin, 2004). However, the links between the flux and evolution of these dolomitizing fluids and hydrocarbon migration are not equally well constrained.

The aim of the paper is to use integrated field, petrographic, chemical, stable isotopic and fluid inclusions investigations to decipher the diagenetic conditions of dolomitization and cementation by saddle dolomite and calcite in the outcropped Upper Cretaceous carbonates of the Bekhme Formation, Kurdistan region, Iraq (Fig. 1). Ultimately, the constrained diagenetic alterations will be linked to the origin and flux of fluids, including oil, during tectonic evolution of the Zagros fold-thrust belt.

Samples and method

Fifty three samples covering the diverse textural and occurrence habits of carbonate cements and host dolostones were collected from the type locality of the Bekhme Formation (Bellen et al., 1959) in the High Folded Zone of Kurdistan region (Fig. 1). Thin sections were prepared for all samples and examined using petrographic microscope, ultraviolet (UV), cathodoluminescence (CL) and backscattered electron (BSE) microscopy. Carbon, oxygen and strontium isotopes and rare earth elements (REE) element ratios of different carbonate materials were measured. Fluid-inclusion microthermometry was performed on coarse crystalline saddle dolomite and calcite in vugs and host dolostones. Both homogenization (T_h) and final ice melting temperatures (T_{mice}) were measured. Principal biomarkers such as alkanes (isoprenoids), steranes, terpanes and aromatic hydrocarbon have been fractioned in a tar sample using the SARA method (Bennett and Larter, 2000).

Outcrop observations

The dolostone succession contains vugs and tension gashes, which are filled with carbonate and anhydrite cements and bitumen. The vugs are circular to irregular in shape, whereas the tension gashes are elongated parallel to each other and aligned perpendicular to the thrust surface .

The vugs and gashes display variable degrees of interconnectivity (Fig. 3B). Saddle dolomite crystals consistently line the gashes and vugs walls; the intercrystalline space in saddle dolomite is filled with bitumen (Fig. 3C). In some cases, the vugs coalesce with each other being separated by very thin line of host dolostone (Fig. 3D). Coarse-crystalline (1-8 cm across) equant calcite covers the saddle dolomite crystals (Fig. 3E). Locally, saddle dolomite lines brownish-stained zones or patches within the host dolostones, which might enclose vugs (Fig. 3F).

In addition to filling the vugs and gashes, tar has also been formed along thrust plane (Fig. 4A). The upper and lower walls of these thrust planes are lined with large (about 3-5 cm long) columnar-shaped calcite crystals, which are oriented perpendicular to the fracture surfaces (Fig. 4B). The columnar calcite crystals from opposite directions are touching each other or separated by a thin layer of host dolostone.

Petrography

The dolostones are composed of interlocked, subhedral and euhedral rhombic crystals (100-700 μ m across), which lack intercrystalline porosity (Fig. 5A) and display turbid cores and clear rims (Fig. 5B). Partly to severely dolomitized peloidal limestones (Figs. 5C and D) occur as scattered patches (1-4 cm across). Such limestones contain variable amounts of scattered moldic pores and inter- and intragranular isopachous, columnar and equant dolomite crystals, which are typical shapes of calcite cements in limestones (Fig. 5C).

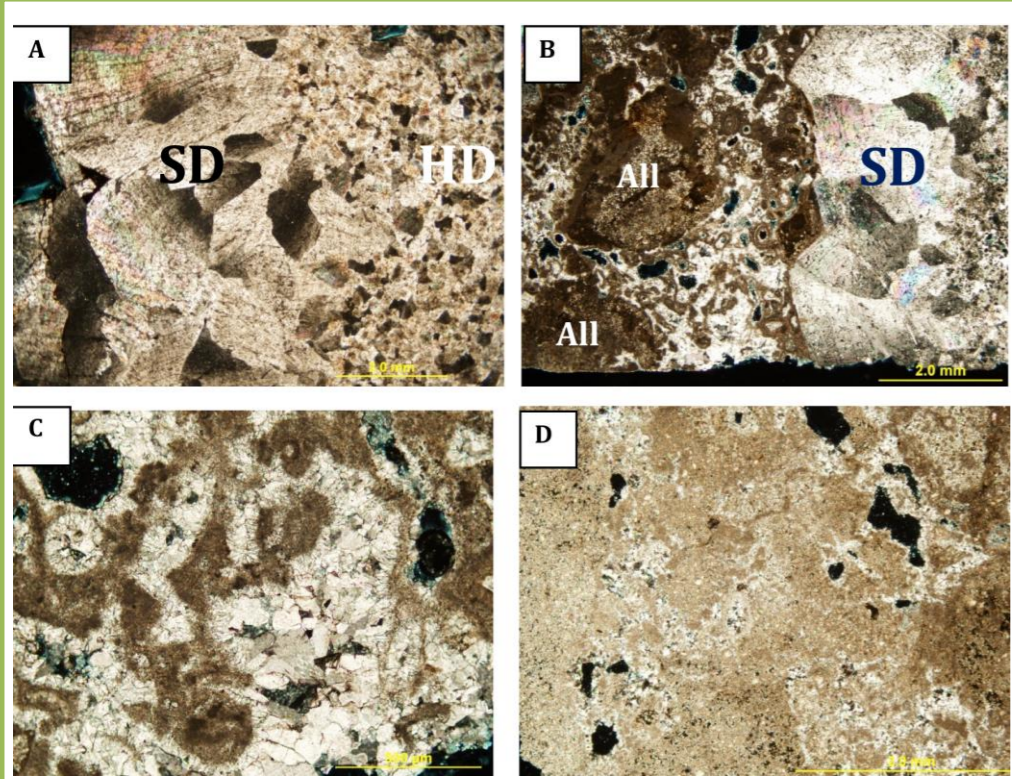


Fig. 5. Optical photomicrographs (XPL) showing: (A) Saddle dolomite crystals (SD) arranged vertically on the host dolostone (HD) and extending into a vug. Dolomite in the host dolostones has mainly rhombic shape and display an inclusion-free rim. (B) Saddle dolomite (SD) filling a vug in a dolostone, which is composed of dolomitized allochems (All) and dolomitized calcite cement. (C) Close up view of the dolomitized scalenohedral calcite cement and dolomitized peloids (brownish). (D) Compacted and dolomitized peloids with scattered small vugs (black).

Carbon, oxygen and strontium isotope

The fracture- and vug-filling saddle dolomite cement has a relatively narrow ranges of $\delta^{18}O_{VPDB}$ values (-9.53‰ to -7.48‰), $\delta^{13}C_{VPDB}$ values (+1.64‰ to +2.68‰) and Sr isotopic ratios of 0.70774-0.70780. The host dolostones have overall comparable $\delta^{18}O_{VPDB}$ (-9.72‰ to -6.34‰), $\delta^{13}C_{VPDB}$ (+0.82‰ to +2.26‰) (Fig. 6) and Sr isotopic ratios (0.70764-0.70779) to the saddle dolomite. The fracture/vug-filling equant calcite cement, which engulfs and hence postdates saddle dolomite, displays wide ranges of $\delta^{13}C_{VPDB}$ (-10.49‰ to +2.06‰) and $\delta^{18}O_{VPDB}$ (-19.19‰ to -4.71‰) and Sr isotopic ratios (0.70773-0.70796). The columnar calcite, which lines fractures along the thrust zones and associated with thick bitumen, has consistently negative $\delta^{13}C_{VPDB}$ (-8.53‰ to -3.93‰) and very low $\delta^{18}O_{VPDB}$ (-22.23‰ to -15.12‰) and non-radiogenic Sr isotopic ratios (0.70771-0.70772). There is a trend of negative correlation between the carbon and oxygen isotope compositions of the entire data set, which includes various types of calcite and dolomite (Fig. 6). However, this negative correlation is linked primarily to the isotopic compositions of equant and columnar calcite cements. A cross plot of the oxygen and Sr-isotopes display a very weak trend of positive correlation (Fig. 7).

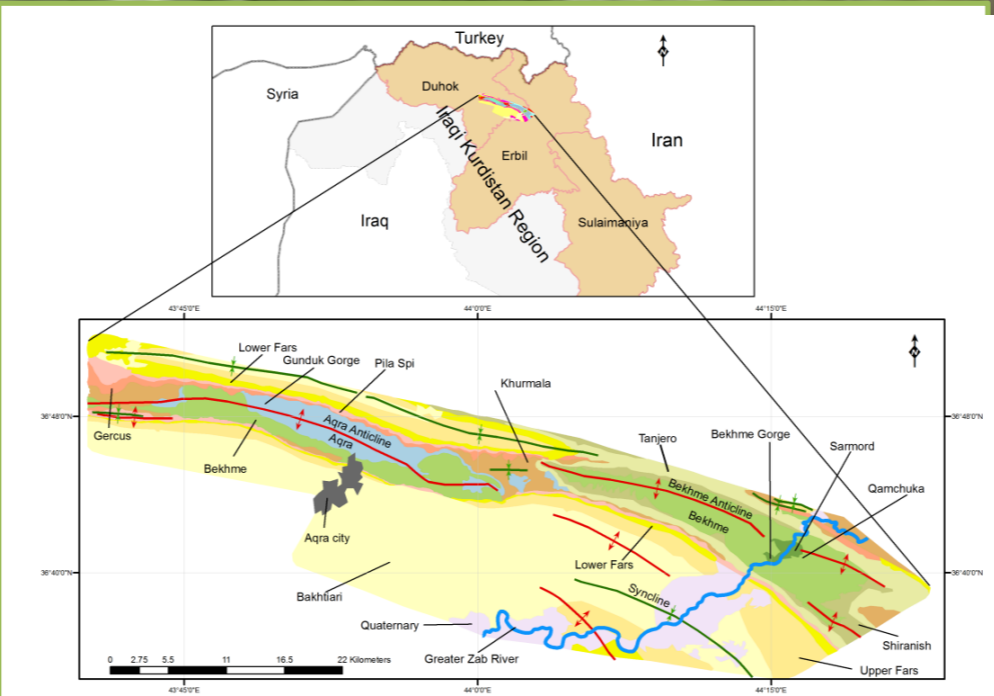


Fig. 1. The outcropped Upper Cretaceous carbonates of the Bekhme Formation, Kurdistan Region, Iraq

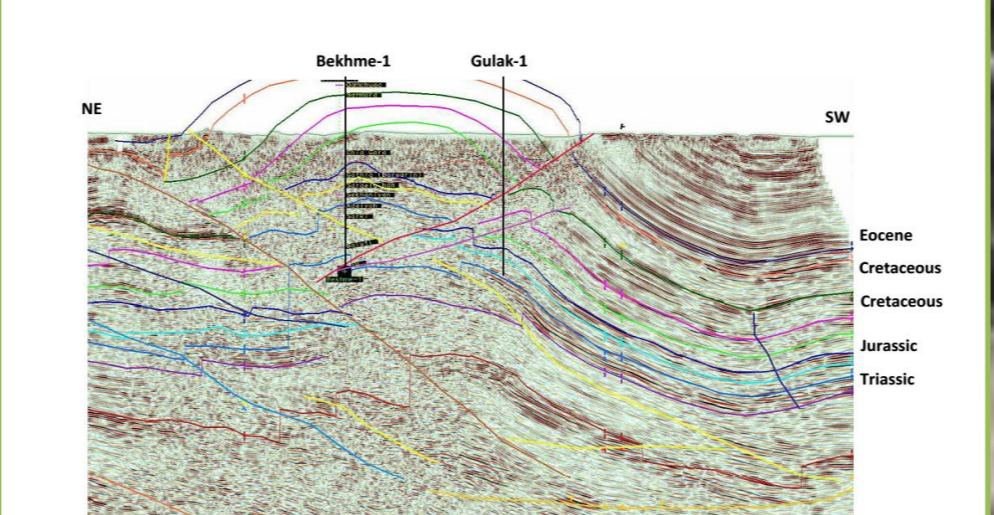


Fig. 2. An interpreted 2D seismic line showing the main subsurface features of the Bekhme anticline. The two wells drilled in the core and fore-limb areas of the anticline have been used to identify some of the reflectors. Note the “main” fore- and back-thrusts which seem to intersect at a relatively shallow level and less constrained deeper thrusts accommodating the shortening.

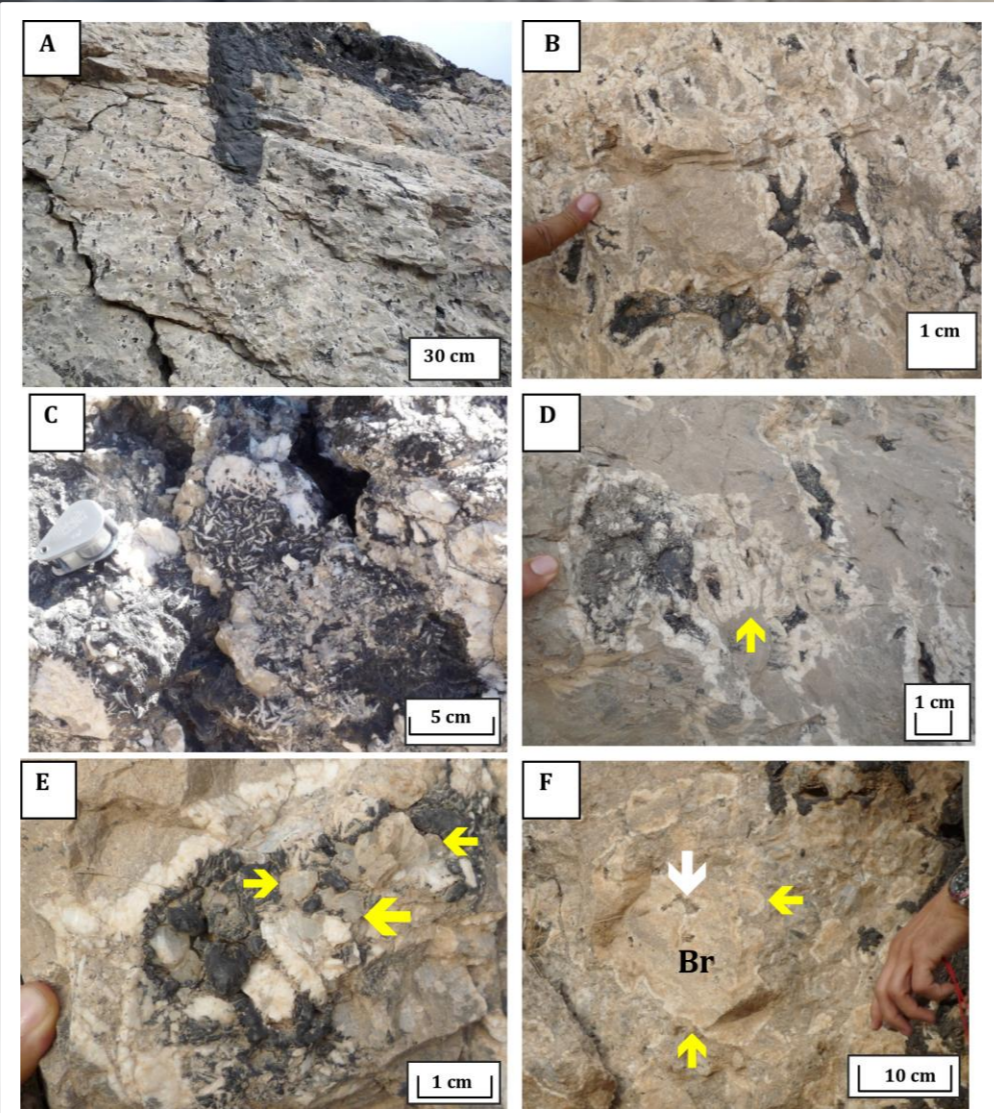


Fig. 3. Field photographs showing: (A) Parallel-aligned tension gashes filled with saddle dolomite, calcite and bitumen. The gashes are arranged perpendicular to the thrust plane. Note the thick bitumen seepage from the thrust plane at top of the photograph. (B) Close up view of the tension gashes showing that the saddle dolomite (whitish) lines the gashes and related vugs, which are filled with bitumen (black). (C) Top view of a vug lined by saddle dolomite, which is engulfed by coarse-crystalline equant calcite which engulfs saddle dolomite (arrow); note that bitumen (black) fills the intercrystalline space between saddle dolomite. (D) Saddle dolomite lines and nearly completely fills some of the narrow, parallel-aligned tension gashes (arrows). (E) A vug lined by saddle dolomite and partly filled by calcite; calcite covers and engulfs saddle dolomite (arrows); not that bitumen covers saddle dolomite, whereas the calcite covers bitumen. (F) A brownish-stained area (Br), which is composed of rhombic and saddle dolomite and lined by saddle dolomite (yellow arrows). Note the presence of a small vug, which is partly filled with saddle dolomite in the middle of the brownish area (white arrow).

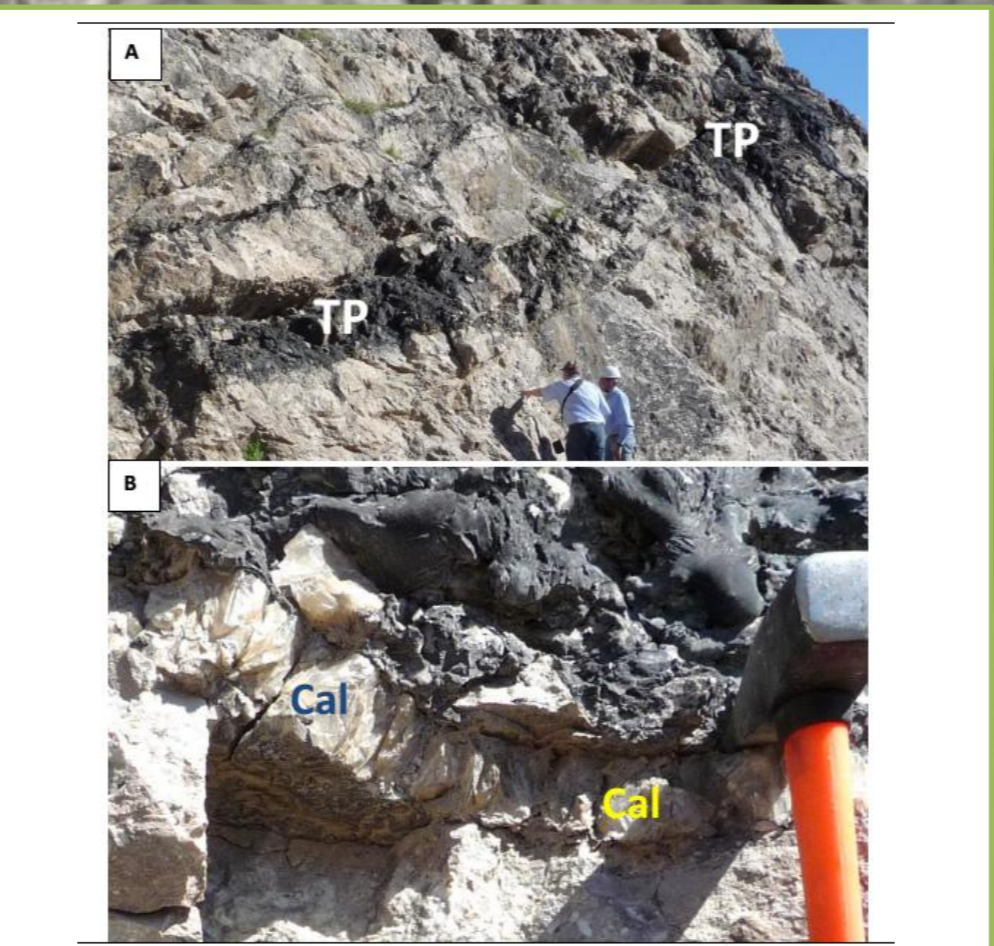


Fig. 4. Field photographs showing: (A) Bitumen (black) occurring along a thrust surface (TP). (B) Columnar calcite crystals (Cal), which are arranged perpendicular to the fracture walls/thrust surface, are covered by bitumen seepage (black).

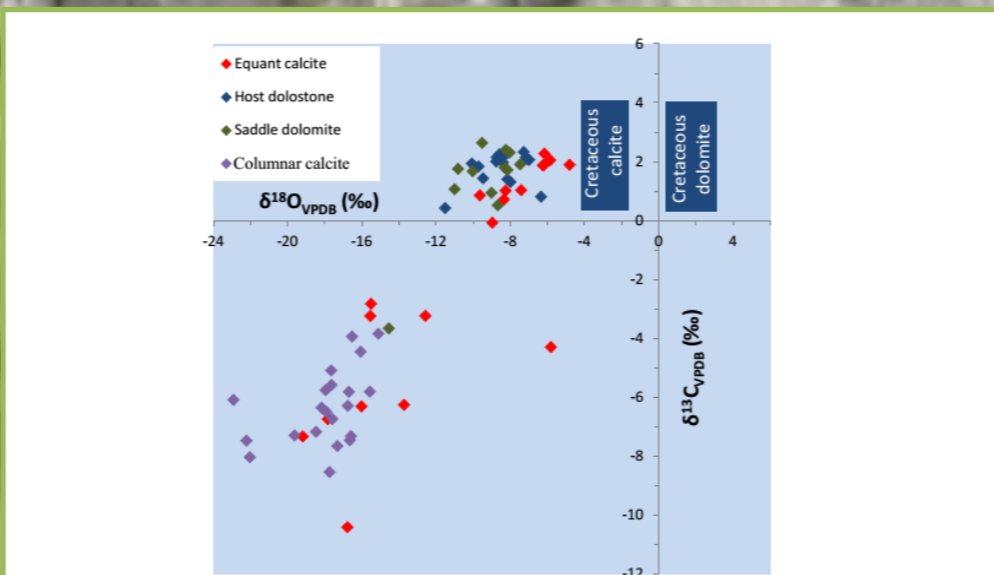


Fig. 6. Cross plot showing negative correlations between carbon versus oxygen isotope data of both calcite and dolomite. Note that the dolostones, saddle dolomite and large number of equant calcite have carbon isotopic values similar to Cretaceous seawater. Conversely, the columnar calcite and large number of equant calcite have both carbon and oxygen values, which are far less than those expected for calcite and dolomite precipitated from Cretaceous seawater.

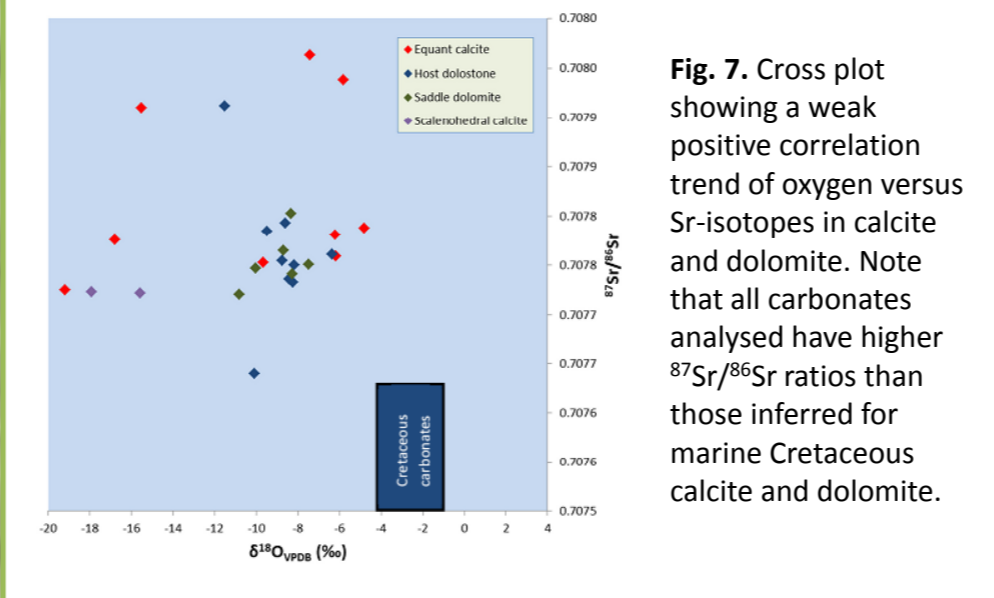


Fig. 7. Cross plot showing a weak positive correlation trend of oxygen versus Sr-isotopes in calcite and dolomite. Note that all carbonates analysed have higher $^{87}Sr/^{86}Sr$ ratios than those inferred for marine Cretaceous calcite and dolomite.

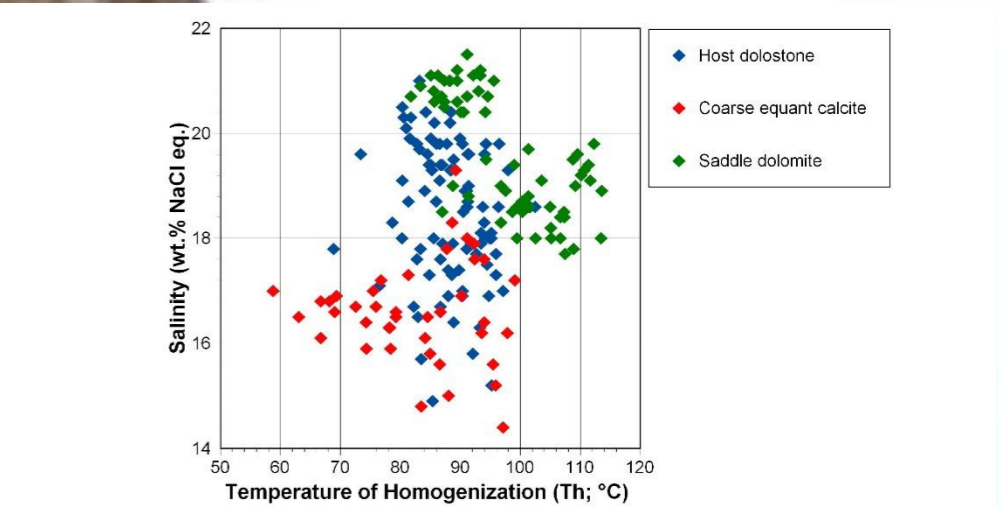


Fig. 8. Cross plot of homogenization temperatures (T_h) vs salinity plot in the calcite and dolomite showing that precipitation occurred from fluids with wide ranges of salinity but relatively narrow overlapping temperature ranges. Overall, the equant calcite has precipitated at lower temperatures than the host dolostones and, particularly compared to the saddle dolomite. See text for further explanation.

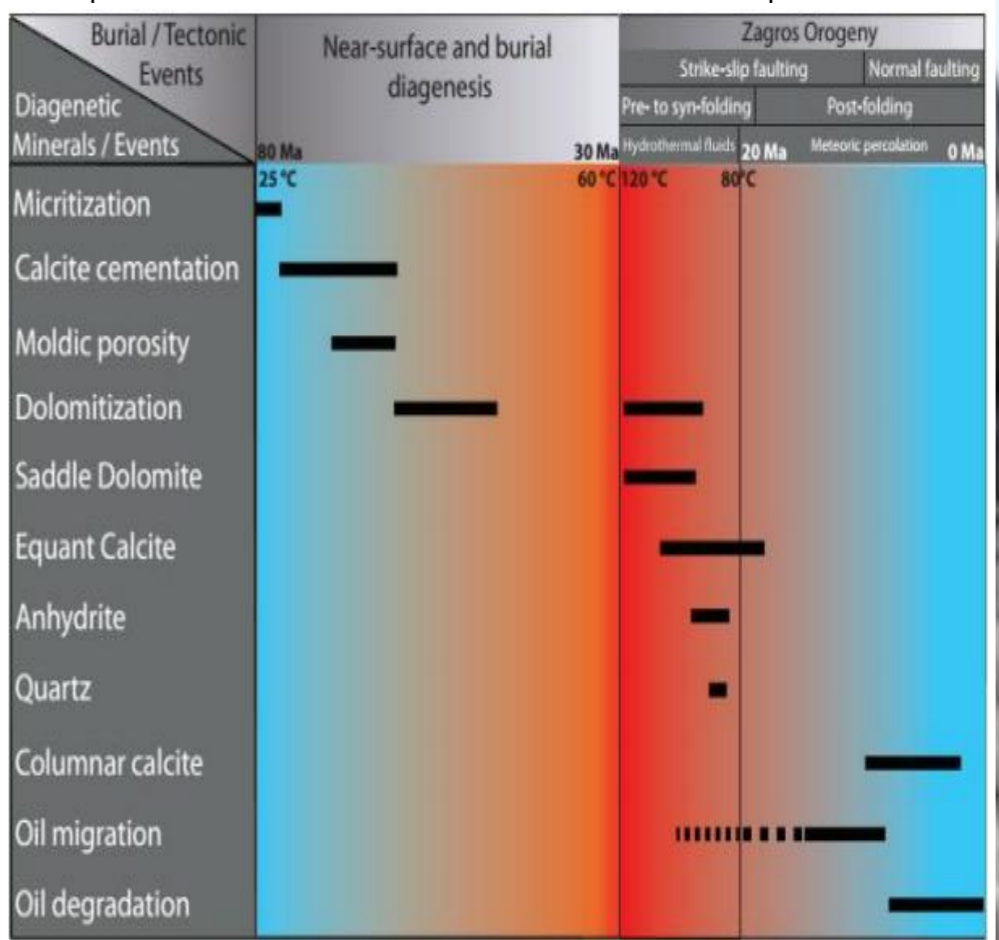


Fig. 9. General paragenetic sequence reconstructed for Bekhme Formation. Two main diagenetic products, events of hydrothermal flow, oil migration and degradations have been inferred.

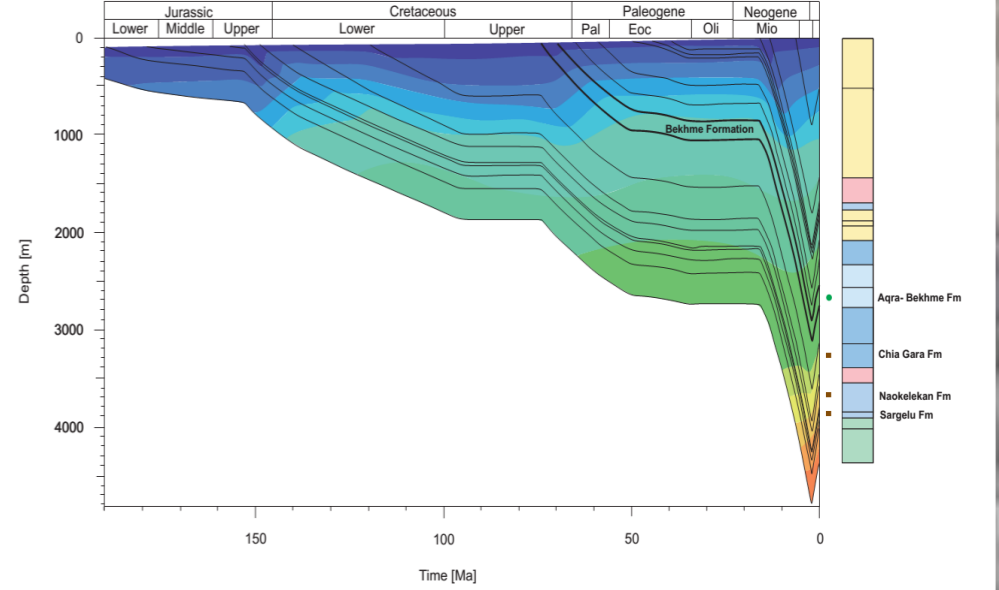


Fig. 10. Burial-thermal history curve of the Upper Cretaceous Bekhme Formation. Note an uplift event at the end of Miocene.

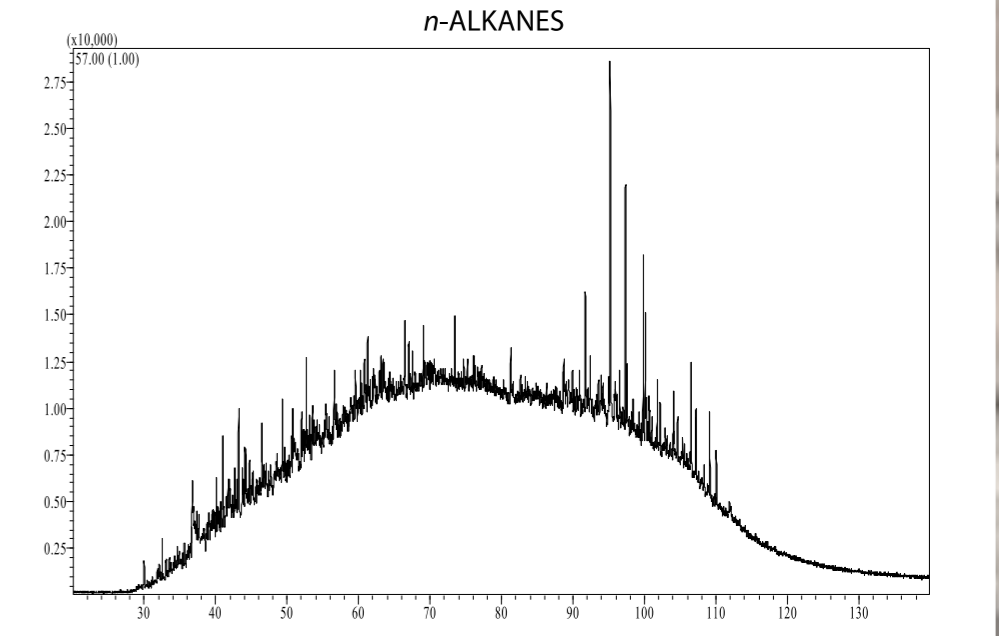


Fig. 11. The mass chromatograms of TIC (total ion current) and ion m/z 57 show an UCM hump (Unresolved Complex Mixture). The shape of the UCM hump clearly shows biodegradation process. The prominent peaks shown in the chromatogram represent terpane biomarkers.

Discussion

The Field observations and petrographic examinations coupled with isotope analyses and fluid-inclusion microthermometry allow constraining the paragenetic sequence of diagenetic events (Fig. 9). Over-dolomitization, which has presumably resulted from repeated flux of fluids, is evidenced by the presence of clear dolomite rims around the previously formed, replacive dolomite crystals and nil porosity of the dolostones. Recrystallization is evidenced by the presence of coarser crystals, some of which with saddle dolomite habit, engulfing discrete or scattered patches of fine-crystalline dolomite. Over-dolomitization and recrystallization have likely obliterated isotopic signatures of earlier dolomitization events (Lonnee and Machel, 2006).

The precise timing of formation of tension gashes and vugs and dolomitization/over-dolomitization of the limestones is uncertain. However, the forceful flux of over-pressured, CO_2 -saturated (i.e. under-saturated with respect to carbonates) hydrothermal fluids through more brittle, tight dolostones (Gilhooly and Weissenberger, 2000; Davies and Smith, 2006) may account for the brecciation (i.e. cemented fractures engulfing floating fragments of the host carbonate) and simultaneous formation of dissolution vugs (Qing and Mountjoy, 1994; Katz et al., 2006; Dravis and Muir, 2014). The saddle dolomite and host dolostones have similar stable isotopic composition and precipitated, prior to oil migration, from hot (81-115°C) basinal $NaCl-MgCl_2-H_2O$ brines with salinities of 18-22 wt.% NaCl eq. The equant calcite has precipitated during oil migration from cooler (60-110°C) $NaCl-CaCl_2-H_2O$ brines (14-18 wt.% NaCl eq). The fluorescence color of oil inclusions indicates that the oil had 15-25 °API composition, which is lighter than present-day oil in the reservoirs. C_{15+} n -Alkanes, Isoprenoids, Terpanes, Tri-aromatic steroids GC-Mass spectra show advanced biodegradation. This difference in oil composition is attributed to oil degradation by the flux of meteoric water, which is evidenced by the low $\delta^{13}C$ values (-8.53‰ to -3.93‰) as well as by nil salinity and low-temperature in fluid inclusions of late equant calcite cement.

Conclusions

- Dolomitization, formation of tension gashes, vugs, brecciation and partial cementation by saddle dolomite and later by equant calcite and anhydrite are attributed to the flux of over-pressured basinal fluids into Cretaceous carbonates of the Bekhme Formation along deeply rooted faults. The flux is suggested to have taken place during development of Bekhme anticline and associated thrusts during the Zagros Orogeny.
- Dolomitization and cementation of the tension gashes and vugs by saddle dolomite pre-date oil migration and reservoir filling, whereas cementation by equant calcite and by anhydrite post-date oil migration.
- Dolostones exhibit good reservoir quality owing to the development of interconnected tension gashes and vugs, whereas the host dolostones exhibit very low porosity. The partly cemented gashes are arranged perpendicular to the thrust faults.
- Depressurization of the basin during uplift was accompanied by the downwards flux of fresh meteoric water, which resulted in the precipitation of columnar calcite. The flux of meteoric waters has caused oil degradation from initial 15-25 °API, which have been entrapped as inclusions in hydrothermal carbonate cements, to the present-day 10-17 °API.