Hydrothermal alteration of dolostones in the Lower Ordovician, Tarim Basin, NW China: Multiple constraints from petrology, isotope geochemistry and fluid inclusion microthermometry

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Abstract

Massive dolostones pervasively occur in the Lower Paleozoic strata in Tarim Basin, NW China. This study focuses on the hydrothermally-altered dolostones in the Lower Ordovician at Sancha, Bachu County where the hydrothermally-altered dolostones, marbles and diabase intrusions co-occur within a large-scale, NW trending strike-slip fault zone. Within this zone, the intrusive diabases mostly occur along the master border faults to the east and west, respectively. The limestones that got in contact with the intrusions commonly were marbleized and the antecedent dolostones were subject to intense hydrothermal alteration, particularly along fractured portions. Based on field investigations and petrographic examinations on the hydrothermally-altered dolostones, five distinctive fabrics of matrix and cement dolomites are distinguished. Two episodes of vein-filling calcites postdate the hydrothermally-precipitated saddle dolomites. Integrated isotopic geochemistry (C, O and Sr) and fluid inclusion microthermometry suggest that dolomite recrystallization and precipitation were associated with the hydrothermal activity induced by fracturing/faulting and intrusive magmatism. Cameca SIMS U-Pb isotope dating of zircon grains from the diabases yields an age of 290.5 ± 2.9 Ma in the Early Permian, which reconciles the relative timing revealed by the paragenetic history. The magmatic emplacement was thus linked to the large igneous province (LIP) of Early Permian in Tarim Basin. In this case, the widespread magmatic activities could have caused the thermal anomaly and fracturing in the strata that were penetrated by the intrusions, enhancing the thermal diffusion and hydrothermal fluid migration (although minor volumes of thermal fluids from the basic magmas) through the fracture/fault systems, thereby resulting in contact metamorphism (or marbleization), recrystallization of matrix dolomites and dolomite precipitation commonly in primary dolostone successions. This study provides a useful analogue to understand the dolomitization and relevant issues for the deeply-buried dolostones associated with tectono-magmatism within the Tarim Basin and elsewhere.

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1. Introduction

The origin of ancient massive dolostones has been a matter of disputes for more than a hundred years, despite numerous models of dolomitization have been proposed to explain the widespread dolostones in stratigraphic columns (Land, 1980, 1985; Morrow, 1982, 1998; Asquith and Gibson, 1985; Hardie, 1987; Tucker and Wright, 1990; Warren, 2000; Davies and Smith, 2006). In recent decades, hydrothermal dolomitization has drawn much more attentions than ever before and is becoming a new bandwagon (Davies and Smith, 2006). Despite hydrothermal dolomitization (or alteration) could occur in absence of magmatic (or volcanic) activity, some studies have testified the close relationship of hydrothermal dolomitization with tectono-magmatic activity in some cases (Cervato, 1990; Wilson et al., 1990; Spencer-Cervato and Mullis, 1992; Nader et al., 2004).
Tarim Basin is a large complex sedimentary basin that suffered multiphase tectonic activities (including volcanism) and deformation in NW China (Kang and Kang, 1994; Jia, 1997). Dolostones occur pervasively in the Lower Paleozoic, particularly in the deeply buried (>4000 m) Cambrian and Lower Ordovician strata which experienced complex multiphase diagenetic processes. In recent years, the interests for exploring the deeply buried massive dolostones as the potential reservoir have been greatly sparked, so to the origins of these dolostones. Although many studies have been carried out on the Early Paleozoic dolostones in Tarim Basin which have generally been interpreted as a product of multiple mechanisms of dolomitization (Gu, 2000; Qian and You, 2006; Wu et al., 2008; Zhang et al., 2008b), only a few researches put the emphasis on the hydrothermal (or diagenetic) dolostones (Zhang et al., 2009; Zhu et al., 2010; Jiao et al., 2011). However, the relationships between the postdepositional dolomitization and tectonic events (i.e., magmatism) were poorly constrained in general.

In order to elucidate the mechanism of tectonically- or hydrothermally-altered dolostones and their linkage to the tectonic event and hydrothermal (or magmatic) anomaly in Tarim Basin, a well-exposed outcrop section at Sancha, Bachu County along the cliff of Keping (or Kalpin) uplift (Fig. 1) is selected along which hydrothermally-altered dolostones and marbles of Lower Ordovician, and diabase intrusions co-occur within a strike-slip fault zone (Fig. 2), providing a unique example to explore the relations of postdepositional dolomitization to tectonic and magmatic activities.

2. Geological setting and stratigraphy

During the Cambrian and Ordovician periods, the study area was located on a stable shallow marine carbonate platform on which very thick carbonate sediments, up to 2000 m, were deposited (Gu, 2000; Cai et al., 2001; Zheng et al., 2007). In the carbonate successions, dolostones predominate over the Cambrian and Lower Ordovician. Carbonate deposition was terminated near the end of Ordovician and replaced by siliciclastic deposition and subsequent burial persisted due to continuous subsidence of basin floor. During the Permian time, intense volcanic activity (large-scale basalt eruptions and igneous emplacements) took place extensively in Tarim block, which is considered as a large igneous province (LIP) as a result of southward convergent subduction of Middle Tianshan arc to the north (Chen et al., 1997; Tang et al., 2004). Near the end of Permian, in virtue of further amalgamation between the island arc of Middle Tianshan and Tarim plate (Jia, 1997), Tarim block experienced an extensive uplift and subsequent exhumation and erosion, particularly along the northwestern flank of Tarim block where the studied section was located. As a result, the Mesozoic sequences were mostly absent or missed along the northwestern flank of the basin although present locally (Jia, 1997). Since the Cenozoic, higher positive relief along the northwestern flank was reinforced due to the collision from the Indian plate farther south and Asian plate, forming a series of NEE-striking, imbricated overthrust nappes, including the Keping uplift, along the northwestern flank of Tarim block (Tapponnier and Molnar, 1977; Burchfiel et al., 1999). On the contrary, the vast areas of plate interior were subject to an accelerating subsidence and plunged downwards to depths, forming the widespread negative relief of Tarim Basin surrounded by numerous uplifts (or mountains) as seen today (Fig. 1A; Shu et al., 2004; Tang et al., 2004).

This study focuses on the stratigraphic formations of the Lower and Middle Ordovician, including the Yingshan, Yijianfang, Qiaerbake and Lianglitag Formations in ascending order (Fig. 1B). The Yingshan Formation, about 200 m thick, is composed of two parts:

**Figure 1.** (A) Simplified geological map in the Bachu and Keping Counties, NW Tarim Basin. Inset map shows the main tectonic units in Tarim Basin in which inset square is the area of A. Stratigraphic system: Z – Sinian (Neoproterozoic), c – Cambrian, O – Ordovician, S – Silurian, D – Devonian, C – Carboniferous, P – Permian, Q – Quaternary. Note the studied area (within the dashed circle). (B) Stratigraphic and lithologic succession of the Ordovician strata in studied area (modified from Zhou et al., 2001).
the lower grey thin-bedded, finely to medium crystalline dolostones intercalated with bioclastic limestones, and the upper grey medium- to thick-bedded grainy limestones. The overlying Yijianfang Formation, about 60 m thick, is dominated by grey thick-bedded to massive bioclastic limestones of marginal reef or shoal deposits that is capped by an unconformity surface (Xiong et al., 2006). The Qiaerbake Formation, generally about 20 m thick, is characterized by red argillaceous bioclastic limestones yielding pelagic and nektonic fauna (Zhao et al., 1999; Zhou et al., 2001; Wang et al., 2006; Xiong et al., 2006), and unconformably lies on the Yijianfang Formation. The uppermost Lianglitag Formation, about 50 m thick, is mainly composed of dark grey medium-bedded micritic limestones with a few bioclastic grains.

### 3. Research methods

Detailed field outcrop investigations, descriptions and sampling upon the selected Sancha section in the Bachu County were firstly carried out (Figs. 1A and 2). Then, detailed petrographic studies were conducted on hand specimens and thin sections that were stained with Alizarin Red-S and potassium ferricyanide (Dickson, 1965) to distinguish calcite from dolomite and ferroan carbonate. Afterwards, cathodoluminescence (CL) microscopy was performed on a RELIOTRON III stage from RELION Industries. CL observations were performed at 5—8 kV with a gun current of about 300—500 μA.

Different types of dolomite and calcite were sampled using a dental drill for carbon and oxygen isotope analysis (n = 31) and strontium isotope analysis (n = 25), which were performed at the Institute of Geology and Geophysics, Chinese Academy of Sciences. For C and O isotope analysis, about 20 mg of calcite and dolomite powders were reacted with anhydrous phosphoric acid at 25 °C for 24 h and for 72 h, respectively. The extracted CO2-gases were analysed with a Finnigan MAT-252 mass spectrometer. The δ13C and δ18O values are reported in per mille relative to the Vienna PeeDee Belemnite (VPDB) standard. Precision was better than ±0.1‰ for both δ13C and δ18O. For strontium isotope analysis of carbonates, 30—50 mg of sample powders were dissolved in 2.5N HCl, and the strontium was then extracted using the conventional cation exchange procedures. The 87Sr/86Sr ratios were measured on a Finnigan MAT-262 mass spectrometer and corrected relative to the NBS987 standard. The analytical mean error (2σ) is ±1.2 × 10−5 for 87Sr/86Sr ratios. For 87Sr/86Sr analysis of basic rocks, about 100 mg of sample powders were dissolved using a mixed acid of 3 ml anhydrous HF and 0.5 ml HClO4 on a hotplate at 120 °C for more than one week. After the samples were completely dissolved, the solutions were dried on the hotplate at 180 °C to remove the HF and HClO4. The strontium was then extracted following the same procedures as for carbonates. The 87Sr/86Sr ratios were measured on a GV Isoprobe-T mass spectrometer and corrected relative to the NBS987 standard. The analytical mean error (2σ) is ±0.6 × 10−5 for 87Sr/86Sr ratios.

Fluid inclusion analysis was carried out on double-polished thin sections on a Linkam THM600 heating—freezing stage that was calibrated using the Fluid synthetic standard. The accuracy of final melting temperature of ice (Tm) and Tl values is within 0.5 and 2.5 °C respectively. Salinities were calculated from final ice melting temperatures using the equation of Bodnar (1993) in terms of the H2O–NaCl system: wt% NaCl = 1.78 × Tm − 0.0442 × (Tm)2 + 0.000557 × (Tm)3.

Zircons were separated from diabase samples using standard gravitational separation techniques. Representative grains were hand-picked under a binocular microscope. Zircon grains, together with a zircon U—Pb standard TEM (417 Ma, Black et al., 2004), were cast in epoxy mounts, which were then polished to section the crystals in half for analysis. Internal structures were examined and imaged using cathodoluminescence prior to SIMS analyses. Only elongate euhedral zircon crystals of volcanic origin are further selected for age determination. Measurements of U, Th and Pb as...
well as U–Pb isotopic determination were performed using a CAMECA IMS 1280 large-radius SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences. Every three runs of age dating were monitored by a TEM run. Measured 206Pb was applied for the common lead correction. The errors for individual analyses are quoted at the 1σ level, whereas the errors for weighted mean ages are quoted at 2σ (95% confidence level). Detailed analytical procedures are referred to Li et al. (2009).

4. Description of outcrop section

The studied outcrop is located within a ~ 3 km-wide fault zone trending in NW–SE, which cross-cuts the strata from Ordovician to Carboniferous along the cliff of NNE-striking Keping uplift at San-cha, northwest of Bachu County (Fig. 1A). It is apparent that the western wall rocks moved farther south relative to the eastern wall rocks, showing sinistral strike slips (or displacements) along the border master faults (Fig. 2). Within the border faults, the carbonate rocks were commonly subject to intense brecciation, grinding, slight mylonitization and/or hornfelsization (Fig. 3A–D). A large-scale drag recumbent fold (anticline) was induced by the opposite displacement (or slip) of wall rocks beyond the fault borders (Fig. 2). From the core to the apex surface, Yingshan and Yijianfang Formations crop out in order, but lower stratigraphic successions are truncated by the western border fault. Diabases occurred as laccoliths, sills, dikes/veins and irregular forms and mostly intruded into the upper part of Yingshan Formation near the border faults. The carbonates that were directly in contact with these diabases commonly suffered contact metamorphism (marbleization) (Fig. 3E), palpably in a zone of 2.5 km, commonly suffering relatively weak recrystallization (Fig. 2). In the faulted zone, there are two stages of crosscutting fractures (Fig. 5E). After later documentation) or other inclusions, i.e., clay minerals and/or bitumen (or pyrobitumen) (Fig. 7A, B). The dolomite crystals show planar, subhedral (or euhedral) appearance, and generally have cloudy cores with clear rims. Under cross-polarized light, the Cd1 dolomite crystals display a dull-red colour at cores and a very dull-red colour or non-luminescence towards the outer thin rims.

5. Petrography of dolomites

5.1. Replacement dolomite

5.1.1. Fine- to medium-crystalline, planar-e dolomite (Rd1)

The Rd1 dolomite is light grey to beige in hand samples. Dolomite crystals, 50–200 μm in size, generally have curved crystal surface and are tightly packed. Vague low-amplitude stylolites occur in the crystal mosaic (Fig. 6B). Intercrystalline pores are present locally and remain open. Some crystals were subject to silicification but still retained the shape of dolomite crystal. This kind of dolomite crystal generally shows a sharp extinction under cross-polarized light, and displays dull red luminescence in cores and thin bright red rims under CL. Volumetrically, Rd2 dolomites make up about 2–3% of the total dolomite volume.

5.1.2. Fine- to medium-crystalline, non-planar-s dolomite (Rd2)

The Rd2 dolomite is light grey to beige in hand samples. Dolomite crystals, 50–200 μm in size, generally have curved crystal surface and are tightly packed. Vague low-amplitude stylolites occur in the crystal mosaic (Fig. 6B). Intercrystalline pores are present locally and remain open. Some crystals were subject to silicification but still retained the shape of dolomite crystal. This kind of dolomite crystal generally shows a sharp extinction under cross-polarized light, and displays dull red luminescence in cores and thin bright red rims under CL. Volumetrically, Rd2 dolomites make up about 2–3% of the total dolomite volume.

5.1.3. Medium- to coarse-crystalline, non-planar-a dolomite (Rd3)

This type of dolomite is light to dark grey in hand specimen. It is commonly fabric-destructive with extremely rare relics of precursor components or earlier sedimentary textures (oidoidal and skeletal ghosts). The dolomite crystals (100–500 μm) are non-planar, anhedral, and commonly interlocking with curved intercrystalline surfaces, so that rare intercrystalline pores are preserved (Fig. 6C, D) in which the pores are locally occluded by quartz, clay mineral or pyrite (Fig. 6E). In general, almost all crystals have a cloudy appearance in the presence of abundant inclusions with a thin, inclusion-free rim. The Rd3 dolomites generally display undulose extinction under cross-polarized light and dull red with light-coloured red blotches under CL light (Fig. 6D). High-amplitude stylolites are present in the host matrix locally and often charged by bitumen/organic materials (Fig. 6F). It is the most abundant component, accounting for more than 90% of dolostones.

5.2. Cement dolomite

5.2.1. Medium to coarse crystalline, planar-s dolomite cement (Cd1)

This type of dolomite, generally 200–500 μm in size, exclusively occurs as the initial cement that lines the walls of fractures/veins or dissolution vugs in the host of Rd3 dolomites, in which residual porosity could have been preserved towards the pore centre or alternatively was filled by later dolomite and calcite crystals (see later documentation) or other inclusions, i.e., clay minerals and/or bitumen (or pyrobitumen) (Fig. 7A, B). The dolomite crystals show planar, subhedral (or euhedral) appearance, and generally have cloudy cores with clear rims. Under cross-polarized light, the Cd1 dolomite crystals display a sharp extinction or weak undulose extinction. Under CL, the crystals exhibit none to very dull-red colour in the cores and brighter luminescence in the outer thin rims. Volumetrically, Cd1 dolomite cement is rare, only accounting for about 1% or less of all dolostones.

5.2.2. Coarse- to very coarse-crystalline, non-planar saddle dolomite cement (Cd2)

The Cd2 dolomite cement is milky white or pink in hand specimen (Fig. 5A–C), and ranges from 250 μm to 2 mm in size, with scimitar-, or half-moon-like terminations (Fig. 7C–E). It occurs as void- and fracture-fillings which partially or completely occludes...
the vugs, veins or fractures (Fig. 7C–F). Although Cd2 dolomites mostly occur as the initial generation of cements, in rare cases, they postdate Cd1 dolomites, showing two stages of dolomite precipitation from Cd1 to Cd2 (Fig. 7E). Under cross-polarized light, Cd2 dolomite cements commonly have curved or lobate crystals and display undulose extinction. Under CL, they exhibit zonation of alternated dark red and bright red bands (Fig. 7E). Cd2 crystals become coarsening and curving towards the pore centre. The residual pore spaces are either open or filled by later quartz or calcite crystals (Fig. 7C–F). A sharp transition commonly occurs between cement dolomites and later quartz/calcite crystals (Fig. 7C, D, F), however, in rare cases, corrosive micro-reliefs are present between them (Fig. 7E, F). Volumetrically, they are relatively minor, accounting for about 5% of dolostones.

Figure 3. (A, B) Field photos showing intense brecciation, grinding and/or mylonitization along the eastern (A) and western (B) border faults. Hammer for scale (35 cm). (C) Field photo showing intense hornfelsization of marbles along the eastern border fault. Note the calcite porphyroblasts in the fine-grained calcite matrix. Scale in centimetre. (D) Photomicrograph showing the calcite porphyroblast in the fine-grained calcite matrix. Cross-polarized. (E) Field photo showing the intrusive diabase and contact metamorphism of carbonates (marble and dolomite marble) along the eastern border fault (see Fig. 2 for location). Standing person for scale (1.75 m).
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Figure 4. (A) Zircon U–Pb concordia plot of 17 analyses (spots) for the diabase at Sancha, Bachu County, NW Tarim Basin (refer to Fig. 2 for location). (B) Mean age plot (1σ error) of zircons. Analyses with 1σ error ellipses are plotted as radiogenic ratios after common Pb corrections, using measured 204Pb. Weighted mean 206Pb/238U dates (290.5 ± 2.9 Ma) at a 95% confidence level for the main group of zircon grains show the best estimated age for the dated sample. MSWD = Mean square of weighted deviates.

Figure 5. (A) Field photo showing grey massive dolostone composed mainly of coarse crystalline matrix Rd3 dolomites, and cut by fractures filled with minor saddle dolomite (Cd2) and later coarse calcite (Cc) cements. Scale in centimetre. (B) Field photo showing highly fractured massive dolostone in which the matrix dolomites were subject to stronger recrystallization, and fractures were nearly completely occluded by saddle dolomite (Cd2) and/or later-stage megacalcite (Cc) cements. (C) Field photo showing the intensively recrystallized massive dolostones (matrix dolomites) cut by two later-stage crosscutting fractures: the early one (1) plugged by Cd2 dolomite and calcite cements which correspond to those in (A) and (B), the later one (2) filled by calcite cement. (D) Field photo showing two-stage crosscutting fractures (1, 2) filled by megacalcite crystals in the highly brecciated marbles along western border fault. 1 – the earlier one, 2 – the later one. Hammer for scale (35 cm). (E) Massive dolostone cut by two later-stage fractures: the earlier one (2) filled by calcite cement, the later one (3) without infills. Hammer for scale.
5.3. Late-stage quartz and calcite cements

There are minor late-stage quartz and calcite cements occurring as void and fracture infills and postdating dolomite cements in the hydrothermally-altered dolostones. Minor quartz crystals are found locally either lining the cement dolomites or corroding them (Fig. 7F). Late-stage calcite crystals are the most common void- and fracture-fillings postdating all types of dolomite, and consist of coarse equant to columnar megacrystals up to several centimetres in size (Fig. 7C, D, F). Two stages of calcite cements are recognized in terms of their crosscutting relationships (Fig. 5C, D). Under CL, the earlier calcite cements exhibit non-luminescence and/or dark orange luminescence. However, the later type yields bright yellow luminescence. Although being widely distributed, they are more abundant in the highly-fractured sectors, especially for the earlier type, and volumetrically of minor importance (1–5%).

5.4. Paragenetic sequence

The carbonates from the Lower Ordovician Yingshan Formation in Tarim Basin have a complex diagenetic history from the early primary deposition through deep burial. The paragenetic sequence shown in Figure 8 is recognized based on detailed field investigations, conventional and cathodoluminescence microscopic examinations. The early and intermediate stages of diagenesis are defined relative to stylolite formation (Qing and Mountjoy, 1989, 1994; Chen et al., 2004). Micrites and allochemical grains could be deposited in a wide spectrum of marine environments. The fibrous and blade calcite cements in the interparticle or shelter pores in carbonate rocks from grainstone to wackestone are generally considered to be formed in syndepositional to very early diageneric conditions (e.g. Tucker and Wright, 1990). They all can be truncated by low-amplitude stylolite which probably formed at
depths of about 500–1000 m (Dunnington, 1967; Lind, 1993; Nicolaides and Wallace, 1997; Duggan et al., 2001). The earliest replacement dolomites (Rd1 dolomites) occurred as rhombs scattering in the matrix of wackestone/mudstone along the low-amplitude stylolites (Fig. 6A). Due to lack of sufficient evidence, the precise timing of Rd2 dolomite formation cannot be definitely determined. The presence of low-amplitude stylolite in Rd2 dolomites (Fig. 6B) indicates they, at least, partially overlap with Rd1 dolomites. However, the tightly-packed, curved crystal mosaic of both Rd2 and Rd3 dolomites (Fig. 6B–F) points to a higher formation temperature at deeper burial depths (Gregg and Sibley, 1984; Gregg and Shelton, 1990; Montanéz and Read, 1992; Chen et al., 2004). The dominant occurrence of high-amplitude stylolites in Rd3 dolomites suggests a deeper burial depth, at least for some of Rd3 dolomites, with respect to Rd2 dolomites. These facts indicate that Rd2 and Rd3 dolomites could have formed from intermediate to deep depths, likely prior to hydrocarbon migration as shown by the presence of bitumen along high-amplitude stylolites and/or in intercrystal pores in Rd3 dolomite mosaic (Fig. 6F).

The rare preservation of transition from Cd1 to Cd2 dolomites indicates Cd1 dolomites predated the latter. The presence of both Cd1 and Cd2 dolomites as cements along the edges of vugs, veins and/or fractures that crosscut all matrix dolomites suggests the cement dolomites (Cd1, Cd2) postdated matrix dolomites (Fig. 5). Although rare in amount, quartz crystals precipitated immediately after cement dolomites (Fig. 7F). The extensive occurrence of coarse to very coarse calcite crystals in the residual pore spaces left by cement dolomites within voids and fractures points to the later precipitation of the calcite crystals (Fig. 7C, D, F). Two stages of later precipitation of the calcite crystals...
calcite cements are revealed as indicated by two sets of crosscutting calcite-filled veins and fractures. The earlier one was more intensely fractured and commonly filled by calcite megacrystals in both dolostones (Fig. 5C) and marbles (Fig. 5D). Locally, the latest calcite-filled voids and fractures are cut by fractures without infills (Fig. 5E).

6. Isotope geochemistry and fluid inclusion microthermometry

6.1. Oxygen and carbon isotopes

Thirty-one outcrop samples of different types of dolomite and calcite were drilled for oxygen and carbon isotope analyses (Table 2; Fig. 9). The Rd1 and Cd1 dolomites are too small to sample for isotopic analysis. The δ18O and δ13C values of matrix dolomites (Rd2, Rd3) are overlapping, and vary from −8.80 to −5.83‰ VPDB (average −7.15‰) and from −1.76 to −0.74‰ VPDB (average −1.18‰), respectively, generally falling within the range of the original Ordovician seawater values (Burke et al., 1982; Qing and Veizer, 1994; Veizer et al., 1999).

The isotopic values of Cd2 dolomite cements tend to be lower than those of matrix dolomite, although there is a large overlap between them (Fig. 9). The δ18O and δ13C values of Cd2 dolomite cements in the veins/fractures and vugs/voids are generally identical, and vary from −10.24 to −5.88‰VPDB (average −8.13‰) and from −1.18 to −0.86‰ VPDB (average −1.29‰), respectively. The δ18O and δ13C values of later calcite cements are distinctly lower than those of all types of dolomites (Table 2; Fig. 9). Stage-1 calcite samples yield δ18O values from −13.49 to −9.26‰ VPDB (average −11.43‰), and δ13C values from −3.75 to −2.38‰VPDB (average −2.81‰), respectively. Two-stage-2 samples yield δ18O values from −13.01 to −12.76‰ VPDB (average −12.88‰), and δ13C values from −2.85 to −1.64‰ VPDB (average −2.24‰).

6.2. Strontium isotopes

Five basic intrusive rocks (diabase and gabbro) and twenty-five carbonate samples were assigned for Sr isotope analysis (Table 2; Fig. 10). The 87Sr/86Sr ratios of basic magmatic intrusions are the lowest and vary in a very narrow range between 0.7072 and 0.7075. The 87Sr/86Sr ratios of matrix dolomites (Rd2, Rd3) range between 0.7051 and 0.7094, showing a large overlap with those of Ordovician seawater (Burke et al., 1982; Veizer et al., 1999). As for Cd2 dolomite cements, their 87Sr/86Sr ratios, although largely overlapped with those of matrix dolomites, vary in a wider range between 0.7088 and 0.7097, and some are even lower than those of matrix dolomites. Furthermore, the 87Sr/86Sr ratios of stage-1 dolomite cements are distinctly lower than those of all other dolomite cements.
calcite cements vary from 0.7090 to 0.7094, fully falling within the range of matrix dolomites. In comparison, the 87Sr/86Sr ratios of Stage-2 calcite crystals are higher, although still in the range as stated above.

6.3. Microthermometry of fluid inclusions

Two-phase (liquid—vapour) primary aqueous fluid inclusions from marble, dolomite and calcite crystals were chosen to measure the homogenization temperature (T_h) and ice melting temperature (T_m) (Fig. 11). Fluid inclusions in all samples are very small (3–6 μm) and some have negative crystal shapes but most have irregular to elongated shapes. The fluid inclusions measured are considered to be primary by the criteria of Goldstein and Reynolds (1994). Unfortunately the fluid inclusions in the Rd3 dolomite are too small to measure.

The marble sampled near the magmatic intrusions has the highest T_h values from 177.9 to 240.7 °C (average 219.6 °C) and T_m values from −24.7 to −11.8 °C (average −19.4 °C) (Table 3; Fig. 11A). Salinities, estimated from T_m values, vary from 15.8 to 25.4 wt% NaCl equivalent (average 21.8%) (Table 3; Fig. 11C). The Cd2 dolomite cements yield T_h values from 98.5 to 131.4 °C (average 115.7 °C) and T_m values from −24.9 to −3.3 °C (average −18.2 °C) (Table 3; Fig. 11B). Calculated salinities vary from 5.4 to 25.5 wt % NaCl equivalent (average 20.3%) (Table 3; Fig. 11D).

In this study, only stage-1 calcite megacrystals are available for microthermometry of fluid inclusion, and yield a wide spectrum of T_h values (82.7–154.1 °C, average 116.4 °C). These data, however, apparently cluster on two groups: group one, clustering between 80 and 110 °C, derives from the fracture-filling calcite in hydrothermally-altered dolostones away from the intrusions, and group two, clustering between 140 and 160 °C, derives from the calcite near the intrusive bodies along the border master faults (Table 3; Fig. 11B). However, the T_m values from different localities are generally consistent, varying from −15.0 to −5.8 °C (average −8.5 °C) (Table 3). Accordingly the salinities vary from 8.9 to 18.6 wt % NaCl equivalent (average 12.0%) (Table 3; Fig. 11D).

7. Discussion

7.1. Origins of matrix dolomites

Within the Ordovician successions at Sancha section in Bachu County, replacive dolomites occur as medium- to coarse-crystalline, non-planar matrix mosaics, particularly in the lower part of Yingshan Formation. The Rd1 dolomites are rare and mainly distributed in the ooidal–peloid wackestones/mudstones. The occurrence of Rd1 dolomites in association with low-amplitude stylolites and their subhedral to euhedral crystal behaviour (Fig. 6A) suggest that they were formed through pressure dissolution in a shallow burial condition and the temperature was lower than the critical roughening threshold temperature for dolomite (Gregg and Sibley, 1984). Assuming a normal geothermal gradient of 30 °C/km and a surface temperature of 20–25 °C (Pang et al., 1996; Qiu et al., 1997; Li et al., 2005), the Rd1 dolomites are estimated to be formed at burial depths of about 500–1000 m which could have been reached from terminal Late Ordovician to Early Silurian (Fig. 12; Ye, 1994). Thus, the main source of dolomitizing fluids was likely derived from modified seawaters or remnant connate seawaters preserved in Ordovician strata.

The curved crystal surfaces and packed mosaic of Rd2 dolomites (Fig. 6B) indicate a rise in formation temperature (or burial depth) above roughening temperature (Gregg and Sibley, 1984). However, their co-occurrence with the low-amplitude stylolite implies that formation in a relative shallow burial depth, likely overlapping with or slightly deeper than the formation depth of Rd1 dolomites. The δ18O values (−6.54 to −5.83 ‰) of Rd2 dolomites generally fall within the range of the Ordovician seawater, providing an additional constraint on the nature of the dolomitizing fluids. Moreover, the large overlap of 87Sr/86Sr ratios of Rd2 dolomites with the Ordovician seawater (Burke et al., 1982; Qing et al., 1998; Veizer et al., 1999; Shields et al., 2003; Table 2; Fig. 10) also suggests that the dolomitizing fluids may have derived from the connate seawater likely preserved in the formations; the slight increase in 87Sr/86Sr ratio from one sample was likely induced by enhanced water–rock interaction by which the terrigenous influx was enhanced as well.

The tightly-packed non-planar, coarser crystal behaviour of Rd3 dolomites (Fig. 6C, D) suggests that they were formed at higher temperatures apparently above the roughening temperature due to rapid disorder crystal growth (Gregg and Sibley, 1984; Gregg and Shelton, 1990; Montañez and Read, 1992; Chen et al., 2004). This scenario could have occurred in so far as the carbonate sediments were progressively buried to depths greater than 1000 m, i.e., from the Early Silurian to latest Permian as stated above (Fig. 12; Ye, 1994).
Figure 11. Histogram showing distributions of fluid inclusion homogenization temperatures ($T_h$) in marble, Cd2 dolomite cements and stage-1 calcite cements. (A) Homogenization temperatures of fluid inclusions in marble. (B) Homogenization temperatures of fluid inclusions in Cd2 dolomite cements and stage-1 calcite cements. (C) Cross-plot of salinity (NaCl wt% equivalent) and homogenization temperatures of fluid inclusions from marble. (D) Cross-plot of salinity and homogenization temperatures of fluid inclusions from Cd2 dolomite and stage-1 calcite cements.

Table 3
Fluid inclusion data of marble, Cd2 dolomites and late-stage calcite in Bachu County.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral type</th>
<th>No. of inclusions</th>
<th>$T_h$ ($^\circ$C)</th>
<th>$T_m$ ($^\circ$C)</th>
<th>Salinity (wt% NaCl eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>Max.</td>
<td>Mean</td>
</tr>
<tr>
<td>09sc-26</td>
<td>Marble</td>
<td>9</td>
<td>177.9</td>
<td>240.7</td>
<td>219.6</td>
</tr>
<tr>
<td>09sc-76</td>
<td>Vuggy Cd2 dolomite</td>
<td>2</td>
<td>107.5</td>
<td>108.8</td>
<td>108.2</td>
</tr>
<tr>
<td>09sc-88</td>
<td>Vein Cd2 dolomite</td>
<td>1</td>
<td>124.4</td>
<td>124.4</td>
<td>124.4</td>
</tr>
<tr>
<td>09sc-90</td>
<td>Vein Cd2 dolomite</td>
<td>4</td>
<td>113.1</td>
<td>131.4</td>
<td>122.4</td>
</tr>
<tr>
<td>09sc-96</td>
<td>Vein Cd2 dolomite</td>
<td>3</td>
<td>98.5</td>
<td>141.5</td>
<td>109.0</td>
</tr>
<tr>
<td>09sc-59</td>
<td>Late-stage calcite</td>
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<td>144.2</td>
<td>144.2</td>
<td>144.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>147.8</td>
<td>154.1</td>
<td>151.0</td>
</tr>
<tr>
<td>09sc-87</td>
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<td>92.8</td>
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<td></td>
<td>4</td>
<td>95.8</td>
<td>130.3</td>
<td>109.9</td>
</tr>
</tbody>
</table>

Figure 12. Burial history of Lower Ordovician carbonates on the Keping uplift, Tarim Basin (modified from Ye, 1994) and presumable major diagenetic processes (or events).
Under this circumstance, the dolomite crystals could have grown over the precursor dolomite nucleus as overgrowths and finally obliterated the primary dolomite texture through progressive burial, compaction and dissolution within the strata with few exogenous Mg supply (Machel, 1997, 2004). The large overlaps of isotopic ($\delta^{18}$O, $\delta^{13}$C, and $^{87}$Sr/$^{86}$Sr) values between Rd3 dolomite and earlier dolomite (Rd2) (Figs. 9 and 10) indicate that Rd3 dolomite was mainly formed in a modified conenate seawater or formation saline fluid system, rather than in a complete different fluid system circulated well by large-scale fluid migration. This can account well for the widespread dolostones exclusively composed of matrix dolomite in the lower part of Yingshan Formation and likely those further underneath (e.g., Camhian). However, the apparent coarsening of matrix dolomites (Rd3 and even Cd2 saddle dolomite) in the highly fractured dolostone section in the uppermost dolostones of the Yingshan Formation (Fig. 5A–C) was likely influenced by hydrothermal recrystallization or overgrowth (also see later documentation). This can be corroborated by the widespread presence of irregular overgrowth rims over the matrix dolomites as show by the bright red CL luminescent colour same as the latest overgrowth band of saddle dolomite cements in vugs and fractures (Figs. 6D and 7D, E), attesting to the product of hydrothermal fluids. In this case, the previous matrix dolomite crystals could have apparently increased in size (due to recrystallization), subsequently resulting in substantial decrease in intercrystalline porosity and thereby the mosaic fabrics. Similar cases have been documented by numerous researchers (Montanè and Read, 1992; Reinhold, 1998; Yoo et al., 2000; Coniglio et al., 2003; Chen et al., 2004; Fu et al., 2006; Lonnee and Machel, 2006; Kirmaci, 2008). In a rare case, the matrix dolomites could have even evolved into saddle dolomite behaviours showing undolose extinction inasmuch as stronger hydrothermal activity.

### 7.2. Origins of cement dolomites and calcites

As described above, two types of cement dolomites are recognized in study area: planar-s (Cd1) and non-planar saddle dolomite (Cd2). Their predominant occurrence as cements or infills of fractures/veins and associated vugs (Figs. 5A–C and 7) indicates their precipitation was closely associated with fracturing, or tectonic activity to a broader sense. Under this circumstance, the hydrothermal fluids at depths could have readily been channelled and migrated upwards along faults and/or fractures. In view of enormously thick dolostones underlain by the Yingshan Formation, the fluid dissolution on these rocks must have been enhanced so that dissolved Mg ions could have progressively increased in the fluids through entrainment during the course of fluid migration. As Mg concentrations of hydrothermal fluids reached the saturation with respect to the dolomite, dolomite crystals could have precipitated from the high-temperature fluids and grew on the dolomite substrates along fractures and voids. Apparent coarsening and curving of Cd2 crystals relative to Cd1 dolomites point towards a higher formation temperature and Mg inputs. Simultaneously, the hydrothermal fluids could have also caused crystal coarsening (or recrystallization) of matrix dolomites as observed in the host dolostones adjacent to the fracture conduits (Fig. 6B–D), likely through thermal baking and fluid diffusion.

The large overlap of $\delta^{18}$O and $\delta^{13}$C values between Cd2 and matrix dolomites indicates that the hydrothermal fluids responsible for Cd2 dolomite precipitation apparently inherited the signatures of formation waters stored in the underlying host dolostones that penetrated by the hydrothermal fluids, in agreement with the interpretation aforementioned. However, the lower $^{87}$Sr/$^{86}$Sr ratios in some Cd2 dolomites than those of matrix dolomites, although largely overlapped with each other (Fig. 10), indicate more or less additions (introduction) of less radiogenic strontium sourced from basic magmatic fluids into the dolomitizing fluids. This situation is thus reasonably linked to the extensive basic magmatic emplacement and/or eruption as evidenced by numerous diabasic intrusions within the fault zone (Fig. 2), which yield fairly low $^{87}$Sr/$^{86}$Sr ratios (Fig. 10). The inputs of magmatic fluids with poor-radiogenic strontium into the formation waters could have apparently led to a drawdown of $^{87}$Sr/$^{86}$Sr ratios in the hydrothermal fluids from which dolomite precipitated. In addition, the decreasing $T_h$ temperatures from marbles in the intrusion contact zones to cement dolomites in fractured dolostones away (Fig. 11) also point to the involvement of magmatic hydrothermal fluids. However, in view of the low fluid content related to the basic magmas (Le Maitre, 1976; Gaetani et al., 1993), large-scale, magmatic-driven hydrothermal fluid migration may have not taken place as evidenced by the relatively low abundance of hydrothermally-altered dolostones. In this case, magmatic emplacement may have mainly provided the heat source and resulted in thermal baking (or metamorphism) upon the rocks around the intrusions as seen the extensive marbles within the contact zones (Figs. 2 and 3E), although minor amounts of magmatic fluids could have been channelled away through faults/fractures as documented above.

It should be noted that, although the $T_h$ temperatures of saddle dolomites roughly fall within the range of formation temperatures (110–145 °C) at burial depths of 3–4 km during the Permian (Fig. 12; Ye, 1994), yet the real trapping temperatures should be much higher if pressure correction was made (Goldstein and Reynolds, 1994). Assuming that fluid inclusions were trapped under lithostatic pressure with an average rock density of 2.65 g/cm$^3$ (cf. Asquith and Gibson, 1985; Chen et al., 2004) at burial depths of 3–4 km at Sancha during the Permian time, pressure corrections were made from the intersection of trapping pressure (i.e. lithostatic pressure) and established isochores for measured fluid inclusions using the FLINCOR program (Brown, 1989). As a result, true $T_i$ values were 137–172 °C at a burial depth of 3 km, about 20–55 °C higher than the normal burial temperature. At the burial depth of 4 km, $T_i$ values were 150–185.6 °C, about 5–40 °C higher than the normal burial temperature. Therefore, these data suggest that the saddle dolomite cements at Sancha precipitated in close relation to the hydrothermal activity (Machel and Lonnee, 2002); this scenario is particularly unequivocal at burial depth of about 3 km during the Early Permian (Fig. 12; also see later documentation). In addition, at Keping, about 80 km NE of study area, more detailed $T_h$ measurements on the overgrowth zones of saddle dolomites in the uppermost Cambrian show the peak $T_h$ values in the CL brightest zones range between 147 and 165 °C (Dong et al., 2013), which are apparently higher than the burial temperature during the Early Permian even though they are not corrected in terms of burial pressure.

As documented above, dolomite precipitation terminated and was succeeded by two generations of calcite inclusions, indicating apparent variations in fluid composition, i.e. Mg depletion. Apparent decreases in $\delta^{18}$O values of later calcite crystals (Fig. 9) suggest they could have precipitated from either higher-temperature or diluted fluids (Land, 1980; Azmy et al., 1998). However, the decreased $T_i$ values and salinity levels of these calcite cements (Fig. 11B, D) favour a diluted fluid in which they precipitated. This condition could have resulted from increased meteoric influx which could in turn have been induced by regional uplift of the formations. On the other hand, the higher $T_h$ values of later calcite crystals around the intrusions along the master fault (Fig. 11) also implicate the magmatic hydrothermal influences on the carbonates, although magmatism waned during the calcite precipitation with some meteoric waters circulated downward and mixed.
7.3. Structural style and fluid pathway

The structural style is a crucial element controlling attributes of fluid conduit systems and volumes of fluid migration. In general, the tensional structure styles provide open fractures and/or faults through which fluids are readily channelled, they are thus the most favourable fluid conduits (Connolly and Cosgrove, 1999; Lewis and Couples, 1999; Davies and Smith, 2006). The occurrence of the hydrothermally-influenced dolostones in a specific site within the fault zone (Fig. 2) indicates a similar structural condition under which they were formed.

As documented earlier, the magmatic intrusions preferentially occurred along the master border faults to both the east and west (Fig. 2), implying that the border faults were deep-seated and likely activated simultaneously with the magmatic emplacement at least at the initial stage, although they could have reactivated lately. It was the deep-seated faults that provided a favourable site for magmas to intrude upwards and emplace into the overlying strata through fractures and/or interbedding surfaces. The presence of horizontal displacement beyond the border faults (Fig. 2), mylonitization along the border faults (Fig. 3A) and large-scale drag fold within the fault zone (Fig. 2) points to the transpressional strike-slip faulting. As described above, hydrothermal-influenced dolomites preferentially took place in the fractured dolostones within the hinge zone of the drag anticline (Fig. 2) within which a tensional stress field could have been induced so that the hydrothermal fluids were readily introduced to cause recrystallization and codolomitization of dolomites. This scenario indicates the secondary tensional stress-field regime within an overall compressional state could be the favourable site for hydrothermal dolomitization (or modification).

7.4. Timing of hydrothermal activity

Timing of hydrothermal dolomitization is crucial for understanding the basinal-scale, tectonically-controlled fluid processes and dolomitizing mechanisms, but is very difficult to constrain in the absence of reliable direct geochronological dating methodology for carbonates. Therefore, in most cases, the relative timing of dolomitization becomes the exclusive scale available to constrain the dolomitizing processes (Wilson et al., 1990; Braithwaite and Rizzi, 1997; Reinhold, 1998; Kirmaci and Akdag, 2005; Davies and Smith, 2006; Gasparrini et al., 2006; Kirmaci, 2008; Touir et al., 2009). As mentioned in the previous documentations, the Rd3 dolomite was formed at a burial depth probably greater than 1500 m, approximately during the Middle–Late Devonian, calculated by using a normal geothermal gradient (Fig. 12; Ye, 1994). Paragenetic sequence shows that cement dolomites, notably the Cd2 dolomite cements, although postdated the Rd3 dolomites (Fig. 5A–C), predated later two-stage fracture- or vein-filling calcite crystals (Fig. 5C, D), which were further followed by the latest fractures without filling (Fig. 5E). Hence, the timing of saddle dolomite cementation should be later than Devonian.

Numerous studies show that Tarim block, particularly the northwestern flank where Keping uplift is located, suffered extensive magmatic emplacement and volcanic eruption in the early Permian (Yang et al., 2007; Zhang et al., 2008a, 2010; Tian

Figure 13. Conceptual model showing the relationship of hydrothermal dolomitization (or alteration) in the Lower Ordovician carbonates to the tectonism and magmatism during the Permian at Sancha, Bachu County, NW Tarim Basin. The basic (diabase) magmatic emplacement into the Lower Ordovician carbonates predominantly provided the abnormal heat source, resulting in contact metamorphism (marbleization) with minor hydrothermal fluids. These igneous-originated fluids could have been channelled through the fracture system induced by simultaneous structural activity and migrated into the primary massive dolostone strata, leading to hydrothermal alteration (or recrystallization) and dolomite precipitation there. A – Yingshan Formation, B – Yujianfang Formation, C – Querhbake Formation, D – Lianglitag Formation.
et al., 2010; Yu et al., 2011) and subsequent large-scale uplift in the Late Permian–Early Triassic in the course of amalgamation (or Tianshan orogeny) between Tarim and Siberia plates (Jia, 1997). Since Paleogene, the northwestern flank further uplifted due to overthrusting from the northwest, resulting in complete exhumation and erosion of Paleozoic rocks from the Neogene (Tappponnier and Molnar, 1977; Burchfiel et al., 1999). Assuming that the latest non-filled fractures formed in response to the latest episode of tectonic activity in Tarim block, the earlier two sets of cross-cutting fractures filled with calcites were thus formed accordingly in responses to the two earlier episodes of tectonic uplifting during the Late Permian–Early Triassic and Paleogene, respectively as documented above (Fig. 12). Under this circumstance, the tectonically-controlled hydrothermal process (or alteration upon dolostones and precipitation of dolomites) was reasonably constrained within the Early Permian, and was linked to the extensive magmatic emplacement and volcanic eruption on Tarim plate (Yang et al., 2007; Zhang et al., 2008a; 2010; Tian et al., 2010; Yu et al., 2011).

As documented earlier, compared to the matrix dolomites, the presence of lower 87Sr/86Sr ratios in some cement dolomites confirms the causal linkage of the cement dolomite precipitation with the basic magmatic emplacement nearby, reconciling well the above scenario inferred from relative timing of major tectonic episodes. Most importantly, high-resolution U–Pb zircon dating of the diabase yields a direct age of 290.5 ± 2.9 Ma, definitely falling within the Early Permian (Fig. 4), indicating the magmatic emplacement at study area was a part of the Permian large igneous province (LIP) in Tarim block (Yang et al., 2007; Zhang et al., 2008a; Tian et al., 2010; Yu et al., 2011). In this case, the basic magmatism could have contributed the abnormal heat source, and minor hydrothermal fluids, leading to thermal baking (or marbleization) in carbonates surrounding the intrusions and possible small-scale fluid circulation away from the magmas into the host carbonates where fracture or fault conduits were available. When the thermal fluids were circulated into the dolostone host, hydrothermal alterations (crystallization, precipitation) could have occurred as documented above (Fig. 13; cf. Machel, 2004; Lonnee and Machel, 2006).

8. Conclusion

This study presents an example of hydrothermal dolomitization (or alteration) in the Lower Ordovician (Yingshan Formation) controlled by tectonism at Sancha, Bachu County, NW Tarim Basin. Hydrothermally-altered dolostones mainly take place in the fractured antecedent dolostones along the hinge zone of a secondary recumbent fold away from the diabasic intrusions within a transpressional strike-slip fault zone.

Three types of matrix dolomites and two types of cement dolomites are distinguished from hydrothermally-altered dolostones. Matrix dolomites include (1) fine- to medium-crystalline, planar-e, floating dolomite (Rd1), (2) fine- to medium-crystalline, non-planar-s dolomite (Rd2), and (3) medium- to coarse-crystalline, non-planar-a dolomite (Rd3). Cement dolomites include (1) medium- to coarse-crystalline, planar-s dolomite (Cd1), and (2) coarse- to very coarse-crystalline, non-planar saddle dolomite (Cd2). Dolomitization predated two stages of later calcite cements in fractures/veins, or vugs.

Matrix dolomites could have formed by replacement and recrystallization respectively from shallow to deep burial conditions. Cement dolomites, however, precipitated from higher-temperature hydrothermal fluids when the Mg concentration was saturated with respect to dolomite through fluid cannibalization and migration from underlying dolostones with extra addition of magmatic fluids in the course of extensive basic magmatic emplacement during the Early Permian. However, carbonates that were in contact directly with the intrusive diabases underwent strong thermal baking (or marbleization).

Hydrothermal dolomitization (or alteration) preferentially occurred in the tensional field, i.e., along the hinge zone of the recumbent anticline where the fluids were readily introduced. The hydrothermal fluids could have resulted in initial dolomite dissolution, then precipitation and simultaneous recrystallization of host matrix dolomites.

Hydrothermally-related dolomite precipitation was terminated as the Mg concentration in the hydrothermal fluids dropped to which was undersaturated with respect to the dolomite with increasing influx of meteoric waters in the context of waning magmatism and progressive uplift of the target dolostones likely from the Late Permian to Early Triassic.

This study illustrates that the intense tectonic and associated magmatic activities during the Early Permian in Tarim block could have played a role in carbonate alterations mainly through providing heat source and minor fluid flux. In general, marbleization predominated over the carbonates in contact with the magmatic intrusions. Hydrothermal dolomitization (or alteration) could have occurred in antecedent dolostones that suffered tectonic fracturing or faulting.

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