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Structural controls on polyphase hydrothermal dolomitization in the Kinta Valley, Malaysia: Paragenesis and regional tectono-magmatism

Ramkumar Mu [1, 2], Siddiqui Numair Ahmed [3, 4, *], Mathew Manoj [1, 5], Sautter Benjamin [3, 4], Hui Poon Xin [3], Nagarajan R. [6], Breitfeld H. Tim [7], Santosh M. [8, 9], Menier David [10], Poppelreiter Michael [1]

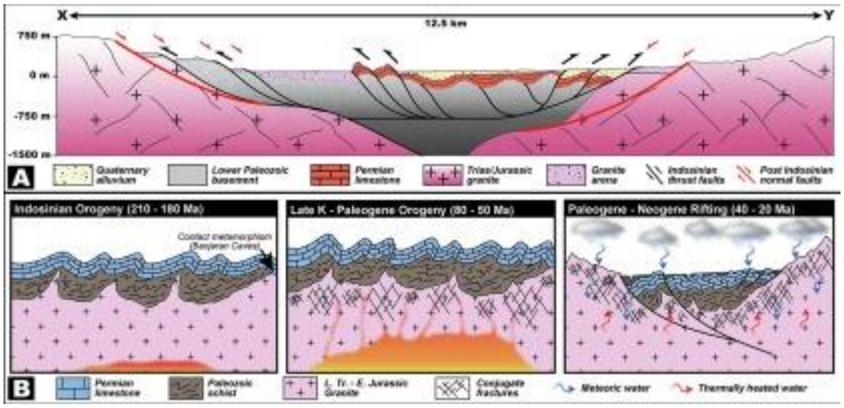
[1] Univ Teknol PETRONAS, South East Asia Carbonate Res Lab SEACaRL, Tronoh 31750, Perak, Malaysia.
[2] Periyar Univ, Dept Geol, Salem 636011, India.
[3] Univ Teknol PETRONAS, Dept Geosci, Tronoh 31750, Perak, Malaysia.
[4] Univ Teknol PETRONAS, Inst Hydrocarbon Recovery, Tronoh 31750, Perak, Malaysia.
[5] Univ Malaysia Terengganu, Inst Oceanog & Environm, Kuala Nerus 21030, Terengganu, Malaysia.
[6] Curtin Univ, Dept Appl Geol, Miri 98009, Sarawak, Malaysia.
[7] Royal Holloway Univ London, Dept Earth Sci, SE Asia Res Grp, Egham TW20 0EX, Surrey, England.
[8] China Univ Geosci, Beijing, Peoples R China.
[9] Univ Adelaide, Dept Earth Sci, Adelaide, SA 5005, Australia.
1 [0] Univ Bretagne Sud, Lab Geosci Ocean, UMR CNRS 6538, F-56017 Vannes, France.

* Corresponding author : Ahmed Siddiqui Numair : email address : numairpng@gmail.com

Abstract :

In the eastern side of the Malay Peninsula, thick successions of limestone formations preserve important records of the Mesozoic and Cenozoic tectonic events. Here we investigate the strata- and fracture-bound hydrothermal dolomites in the Palaeozoic carbonates of the Kinta Valley, western Peninsular Malaysia. Based on their textural and morphologic characteristics, structural relationships with the host rock, different facies types, and associations with hydrothermal calcite and low-grade metamorphic marble, we attempt to trace their polyphase origin and relationship with thereto-tectonic events of the region. A detailed evaluation of the nature of brecciation and crystallization of polyphase dolomites, dolomitic limestones, limestones and marble, under the influences of episodic faulting, is associated with the regional structural geology with emphasis on pre-existing fault reactivations, granitic emplacement and progressive thermal influence. Supply of Mg2+ from the host rock for dolomitization, limited and episodic influx of circulating fluids and cessation of thereto-tectonic evolution with progressive cooling are also inferred. Correlating the geological events in western Peninsular Malaysia with regional structural dynamics reveals that the major deformation episodes exerted first order controls on the loci of dolomite occurrences. The occurrence, geometry and structural relationships of the dolomites were controlled by successive magmatic events, whereas, the intensity of replacement dolomitization was controlled by host rock texture and varied bulk chemistry, together with the nature of circulating fluids.

Graphical abstract



Highlights

► The Palaeozoic carbonates strata- and fracture-bound hydrothermal dolomites in Kinta Valley, western Peninsular Malaysia. ► Enlisting of regional tectonic and magmatic events in chronological order with phases of dolomite formation. ► The control of dolomitization by texture and varied bulk chemistry, together with the nature of circulating fluids.

Keywords : Hydrothermal dolomite, Tectonics, Magmatism, Paragenesis, Structural evolution, Malaysia

1. Introduction

Understanding dolomitization and its controlling factors provide information on the evolution of basinal fluids, fluid-rock interactions during diagenesis, processes of mineralization, and aid in the prediction of possible presence of dolomitized bodies in the subsurface, reservoir location, geometry and continuity (e.g., Sun, 1995; Chen et al., 2004; Ronchi et al., 2012; Vandeginste et al., 2013). The key controls for the distribution of rock heterogeneities in fault-controlled or fault-associated dolostones that affect reservoir quality are still poorly constrained (e.g., Duggan et al., 2001; Martín-Martín et al., 2015).

The carbonates of equatorial humid-zones are different from those of subtropical arid-zones in terms of depositional and diagenetic characteristics (Wilson, 2002). The processes and controls on dolomitization, especially those of hydrothermal dolomites, and the structural tectonic evolution of Southeast Asia need systematic documentation and understanding (Carnell and Wilson, 2004).

Sundaland comprises of various continental blocks, fragments and suture zones associated with remnants of former oceanic basins (Fig. 1). Several episodes of deformation and associated thermal anomalies have affected the Malay Peninsula since its formation during the Sibumasu-East Malaya collision in the Lower to Middle Triassic (Metcalfe, 2013). Thick limestone successions were affected by Mesozoic and Cenozoic tectonic events. However, the timing, mechanisms and resultant changes in the rocks of the region are not yet fully understood (Morley, 2012; Sautter et al., 2017). Our study aims at interpreting the dolomitization in Palaeozoic carbonates in relation to the structural evolution and associated thermal events in the Kinta Valley located on the western side of the Malay Peninsula (Fig. 2). In this paper, we document the paragenetic sequence of hydrothermal dolomite and demonstrate how it was affected by regional tectonics and geodynamics.

2. Regional geological setting

Peninsular Malaysia (Fig. 2A) is located on the western part of Sundaland. Based on structural and geological differences, the region was divided into Western, Central and Eastern Belts, showing north-south trends (Fig. 2B) (Suntharalingam, 1968; Foo, 1983; Lee, 2009; Metcalfe, 2013). The Western Belt is located on the Sibumasu terrane, whereas, the Central and Eastern Belts are part of the East Malaya block (Metcalfe, 2013), intruded by arc-related plutons (Searle et al., 2012). The boundary between Sibumasu and East Malaya is represented by the Bentong-Raub Suture Zone (Harbury et al., 1990; Metcalfe, 1991; Hutchison, 1994), which represents the closure of the Paleo-Tethys in the Early to Middle Triassic (Hutchison, 1994; Metcalfe, 2000), an ancient ocean separating the two blocks and the Sukhothai Arc (Metcalfe, 2011a; Sevastjanova et al., 2011; Searle et al., 2012; Cottam et al., 2013).

The East Malaya Block, forming part of Indochina and Cathaysia, separated from Gondwana in the Early Paleozoic with the opening of the Paleo-Tethys. The Cathaysian fauna and flora indicate a warm-water equatorial climate since the Carboniferous (Metcalfe, 2011a). In contrast Sibumasu shows cold-water biotas and Gondwana affinity until the Permian (Metcalfe, 2011a) when it was separated from Gondwana with the opening of the Meso-Tethys (Wakita and Metcalfe, 2005). Collision of the two blocks was associated with subduction-related calc-alkaline magmatism in the Latest Permian to Triassic on both blocks (Searle et al., 2012). The complex subduction history is also accompanied by the separation of the intra-oceanic Sukhothai Arc from East Malaya and later collision before the amalgation of Sibumasu (Metcalfe, 2011a; Sevastjanova et al., 2011).

The collision of Sibumasu with East Malaya and the Sukhothai Arc resulted in crustal thickening, regional metamorphism (Searle et al., 2012) and emplacement of Late Triassic S-type granite in the Western Belt (Krähenbuhl, 1991; Searle et al., 2012; Ghani et al., 2013;

Ng et al., 2015a, b). These felsic granitoid intrusions are characterized by magma derivation by melting of deep crustal sources, suggesting an important orogenic thermal event (Metcalfe, 2000, 2013; Sautter et al., 2017).

In addition to the Permian-Triassic magmatism, some Late Cretaceous plutons from the Eastern Belt were previously reported (Garson et al., 1975; Bignell & Snelling 1977; Mitchell 1977; Beckinsale 1979; Cobbing et al. 1986, 1992; Searle et al., 2012). By the end of the Cretaceous, numerous isolated plutons were emplaced in this region and these are considered to be the causes of the poorly understood regional thermal anomalies of the Malay Peninsula (Ghani et al., 2013; Ng et al., 2015a, 2015b; Md. Ali et al., 2016). An intensive fracturing of the Western Belt Main Range granites together with large scale folding of the sedimentary units was followed later by an exhumation of the granite bodies during the late Early Cretaceous to Early Cenozoic (Krähenbuhl, 1991; Cottam et al., 2013; Md. Ali et al., 2016; François et al., 2017; Sautter et al., 2017). However, their causative mechanisms are not yet ascertained, but may be a response to the termination of subduction along the Sunda margin followed by collision of various micro-continental fragments with the southern margin of Sundaland (Hall, 2002, 2012; Clements et al., 2011; Cottam et al., 2013). Locally, ductile stretching lineations testify an early N-S extension in the Latest Cretaceous to Early Paleocene, prior to the widespread Late Paleogene rifting that occurred in entire Southeast Asia (Kawakami et al., 2014; Md. Ali et al., 2016; François et al., 2017; Sautter et al., 2017). Cottam et al. (2013) interpreted rapid exhumation of the plutons in the Late Eocene to Oligocene as a response to resumption of subduction along the Sunda margin ca. 45 Ma (Hall, 2012). These major tectono-magmatic events, their successive stages and resultant structural deformations are summarized in figure 2 at the scale of the Kinta Valley.

The Kinta Valley (Figs. 2A, 2B, 2C and 3), located in the Western Belt, is characterized by remnant limestone hills sandwiched between two granitic plutons: the Kledang Range in the west and the large Main Range Batholith in the east (Figs. 2B and 2C). The valley and its recent alluviums have been studied for over a century and a half (e.g., Rastall, 1927; Scrivenor, 1913, 1931; Jones, 1970; Newell, 1971; Lee, 2009), mainly for mining purposes, being one of the major tin fields in the world. However, a consensus on the lithostratigraphy, chronostratigraphy, depositional environments and thermal history of the older sedimentary sequences of this region is yet to be reached. The 700 m thick Kinta Limestone (Suntharalingam, 1968), deposited during the Silurian-Permian (Hassan et al., 2014), is a significant location where the typical cold water biota of Sibumasu until the Early Permian could be established and correlated with Gondwana (Shi and Waterhouse, 1991; Metcalfe, 2013; Hutchison, 2014).

The Kinta Limestone, also known as Kanthan Limestone (referring to limestone of the study area), was subjected to significant thermo-tectonic events (Metcalfe, 2013; Choong et al., 2014) mostly during emplacement of the Late Triassic to Early Jurassic granitic intrusions (Rastall, 1927; Richardson, 1946, 1947a, 1947b; Lee, 2009; Metcalfe, 2002, 2013). Additionally, there have been significant Middle to Late Cretaceous folding and faulting (Harbury et al., 1990; Krähenbuhl, 1991; Shuib, 2009) with most faults cutting across the Western Belt Main Range granites (Harun, 2002). Synchronous to this tectonic event, were emplaced several granitic bodies and the formation of the metamorphic Stong complex in the Central Belt (Singh et al., 1984; Ghani, 2009; Searle et al., 2012; Ng et al., 2015 a, 2015b). This Late Cretaceous thermal event has been interpreted as resulting in significant recrystallization and dolomitization of parts of the Kinta Limestone (Suntharalingam, 1968; Foo, 1983; Wong, 1991; Fontaine and Ibrahim, 1995; Lee, 2009). It has been previously suggested that migrating fluids in the Late Cretaceous resulted in major remagnetisation of Palaeozoic and Triassic rocks (Metcalfe, 1993, 2013; Richter et al., 1999). Other Palaeozoic rocks of the region are Ordovician to Devonian sandstones interbedded with shales and

Carboniferous black shale (Choong et al., 2014). An unconformity of Mississippian age is observed in the limestone unit (Metcalfe, 1983), that indicates a potential major rifting event with varying rates of uplift and subsidence along different fault blocks (Hassan et al., 2014). This event most likely refers to the rifting and separation of the Sibumasu continental terrane from Gondwana in the Palaeozoic (Metcalfe, 1999). Warm water flora and fauna were reported from the upper Early Permian suggesting the arrival of Sibumasu in low latitude regions and was correlated to Cathaysian biotas (Shi and Waterhouse, 1991; Metcalfe, 2013).

Consequent to the cessation of marine carbonate sedimentation, there was subsidence and emplacement of Triassic granites (Foo, 1983). No Mesozoic sediment was found in this region (Foo, 1983) except in the Northwestern corner of Malaysia where the Permian to Triassic accretionary prism-related Semanggol Formation has been described (Sashida et al., 1995; Metcalfe, 2000, 2013). Foo (1983) described the Kinta Limestone as generally pure but dolomitic in some places, pale colored and marbleized, and interbedded with subordinate schist and carbonaceous phyllites. The limestone sequences were folded during the Late Permian to Middle Triassic and heated by contact metamorphism with the emplacement of the post-collision Middle to Late Triassic to Early Jurassic Western Belt Main Range granites (Ros and Yeap, 2000; Searle et al., 2012; Sautter et al., 2017). At the contact with the granites, the limestone is marbleized (Choong et al., 2014). The subsequent Late Cretaceous thermal event may also be highlighted by voluminous acidic/felsic fluids clogging pre-existing fracture sets in the Main Range granitoids and along pluton margins (Sautter et al., 2017). Even though these dykes are not dated, they are temporarily constrained by relative chronology and indicate intense hydrothermal circulation by the end of the Mesozoic in the entire region.

3. Materials and methods

Initially, a combination of regional mapping (Figs. 2A and 2B) and analysis of SRTM (Shuttle Radar Topography Mission) 30 m Digital Elevation Models (SRTM data of 30 m resolution available at NASA website) of Peninsular Malaysia (Fig. 2C) was carried out. The use of this form of digital data is a distinctly pragmatic approach for studying and virtually "visiting" landscapes encompassing large areas where direct physical access may be limited due to hostile terrain and/ or thick vegetation cover (Menier et al., 2017; Mathew et al., 2016a; Mathew et al., 2016b). The aforementioned along with published data on regional geology and structural trends (Figs. 2B and 2D) were utilized to recognize and interpret structural anomalies and lineaments. This was followed by field campaigns to document structural information from selected outcrops and quarry sections (LaFarge Quarry at Gunung Kanthan formerly known as the Pan Malaysia Cement Quarry – Figs. 4 and 5) in the Late Devonian–Early Pennsylvanian limestone (Gebretsadik et al., 2015) of the Kinta Valley, accompanied by facies description at field and laboratory scale (Figs. 4 and 7). Documentation of depositional and tectonic structures (Figs. 4 and 5), together with dolomite occurrences, their compositional phases (Fig. 6), structural and textural features of the dolomites was correlated to the association with different lithofacies, their characteristics, and contact information including cross-cutting relationships (Figs. 4, 6 and 7). Samples were collected across the host rock, strata-bound and fracture-controlled dolomites, dolocalcites and marble (Fig. 4). Fifty-five polished thin sections were prepared from these samples and were stained with a mixture of Alizarin Red-S and potassium ferricyanide, following Adams et al. (1984) to distinguish calcite from dolomite and ferroan carbonate from non-ferroan carbonates. Detailed petrographic investigation was conducted under reflected and transmitted light to classify the textural and morphological types for each carbonate phase identified in the field (Fig. 7). All samples were analyzed for whole rock geochemistry and clay mineralogy by using X-ray diffraction, while major, trace, and rare earth element compositions were studied through X-ray fluorescence, Inductively Coupled Plasma-Mass Spectrometry, etc. The results of these data will be reported in a further section. However, inferences based on mineralogy and geochemistry are partially utilized in the present study in a supportive role. Petrographic details such as crystal morphology, size, and relationships with matrix, clasts and other cements were examined. Terminologies proposed by Sibley and Gregg (1987) were adopted for textural description of dolomite. Folk's (1962) size scale (< 30 μm - fine-crystalline, 30-150 μm - medium-crystalline, and > 150 μm - coarse-crystalline dolomite) were employed to subdivide the measured or estimated apparent maximum dimensions of the dolomite crystals and considered for characterizing them in terms of size distribution of each phase. Other petrographic characteristics such as cross cutting relationships, zoning, corrosion, regrowth, overgrowth, dissolution-precipitation and dissolution-replacement were also examined. These field and petrographic data were used to interpret different phases of dolomitization, to constrain the stages and phases of evolution and their paragenetic sequence. These were then integrated with regional structural trends and stages to evolve an idealistic model on which implications for the regional tectonic evolution were drawn.

4. Results

4.1. Facies characteristics

The Kinta Valley, located in the western part of Peninsular Malaysia (Fig. 2A), is 30 km long and 15 km wide in the southern part, whereas the width reaches less than 5 km in the northern part (Figs. 2B and 2C), exhibiting a 'V' shaped morphology. The LaFarge quarry is located at the northern tip of the Kinta Valley, less than 2 km away from the eastern flank of the Kledang Range. A quarry wall here shows excellently preserved structural characteristics (Figs. 4 and 5) and seven facies types including the host rock are identified (Figs. 4, 5 and 6). The dolomites show distinctly different structure- and strata-bound features (Fig. 4). While the strata-bound dolomite shows uniform textural characteristics, another facies occurs as fracture fill showing diverse size, morphology, composition and contact relationship, besides marble inclusions (Figs. 4 and 6). The facies types recognized in the field are also affirmed by microscopic (under reflected light; Fig. 6) and petrographic (under transmitted plane polarized light; Fig. 7) studies in the laboratory. The limestone facies forms the host rock, whereas, six types of dolomites, dolostones, etc., occur within major fractures (structure-controlled) and along the bedding planes (strata-bound). These are described herein.

4.1.1. Limestone host rock (F1)

The host rock is a thin-massive bedded, light to dark gray colored, calcareous mudstone (Fig. 4G (F1 and non-shaded region)). The beds are highly fractured (Fig. 4G (F1 and non-shaded region)) and show differential compaction that varies regionally. Orientations of these fractures vary from bedding parallel, tangent and perpendicular (Fig. 4D). Pale pink to dusky white colored, mm-few tens of cm wide calcite and dolostone veins with multiple orientations crosscut this facies. Stylolites of different nature, low amplitude stylolite (Fig. 7A) and tectonic stylolite (Fig. 7B) are associated in this facies, testifying compaction and tectonic compression.

4.1.2. Early replacement dolomite (F2)

This yellowish orange colored dolomite facies type (Fig. 6A (F2)) occurs along the walls of the closed fracture (Fig. 4G). This fracture has a shape resembling an inverted “V”, and is located adjacent to the host limestone facies (Fig. 4G (orange dashed lines, orange arrow)). This dolomite facies is massive and follows the shape of the fracture, while conforming to the bedding planes. The color, mineralogy and textural characteristics of this dolomite facies differentiate it from the host facies (F1 – host rock) and cement spars of the host rock. The cross-cutting relationship, morphology and textural characteristics of the spars affiliate this facies as the first stage of replacement dolomitization. The veins show transitional contact with host rock (F1), cut across the syn-depositional calcite cement and are cut by other dolomitic veins (Fig. 6A). Microscopically they are medium to coarse transitional planar-e (euhedral) and –s (subhedral) to non-planar-a (anhedral) dolomite crystals. The planar euhedral to subhedral dolomite crystals with idiotopic to hypidiotopic mosaics are 100-1000 µm sized, whereas, the non-planar anhedral dolomite crystals with xenotopic mosaic are 100-2000 µm sized (Fig. 7C). Few of the planar euhedral dolomite crystals have a cloudy core with a clear rim (Fig. 7D). These dolomites are associated with stylolites (Fig. 7E) and calcite veins of different compositions (Fig. 7F). Considering the thickness, quantum, occurrence and contact relationships, these are inferred to be of replacement in origin, formed during the first phase of dolomitization. The source of Mg^{2+} might be local in nature, drawn from the host rock in the immediate vicinity.

4.1.3. Sucrosic dolomite (F3)

Massive, reddish grey and white colored sucrosic dolomites with sugary texture (Fig. 6B) located at the core of the fracture and enclosed between both replacement dolomites (Fig. 4G (F3)). Millimeter-thick, multi-directional conjugate fractures and kinks are found within these sucrosic dolomites. They show sharp contact with replacement dolomites. Microscopically these are coarse to very coarse (200-2000 µm) planar-s to non-planar-a with hypidiotopic to xenotopic mosaics and medium to coarse (100-400 µm) planar-e dolomite crystals with idiotopic mosaics (Fig. 7G).

4.1.4. Metamorphosed dolomite (F4)

Metamorphosed dolomites are found within the early replacement dolomite facies (Fig. 4G (F4)), and are a relatively small, massive, pinkish orange and pseudomorph the early replacement dolomite facies (F2), maintaining sharp contact with early replacement dolomite (Fig. 6C). Minor fractures within the metamorphosed dolomite are filled with calcite veins (Fig. 6C).

4.1.5. Late replacement dolomite (F5)

White colored dolomite facies occurs in dense fractures that crosscut all other facies and located between the early replacement dolomite and sucrosic dolomite (Fig. 4G (F5)). This facies shows sharp contact with the early replacement dolomite (F2) (Fig. 6D). Its cross cutting relationship implies that this white dolomite facies (F5) postdates the yellowish orange dolomite (F2) filled fractures. The dolomites of this facies are coarse to very coarse (1000-2000 µm) planar-e and –s to non-planar-a dolomite crystals with idiotopic to hypidiotopic and xenotopic mosaics (Fig. 7H). Saddle dolomite crystals are also observed, ranging from 1000-2000 µm non-planar crystals, with scimitar-, or half-moon-like terminations pointing to pore spaces (Fig. 7I).

4.1.6. Brecciated limestone and dolostone (F6)

Brecciated limestone and dolostone are found near the foot of the fracture, within the first phase replacement dolomite facies (F2) (Fig. 4C). This facies was the result of brecciation of dark grey host limestone (F1) and early replacement dolomite (F2) followed by occlusion of open spaces created by white colored calcite cement (Fig. 6E). Breccia fragments consist of centimeter sized angular clasts of the host limestone and dolostone. Microscopically, these are planar subhedral dolomite crystals of various sizes, ranging from 50-500 µm (Fig. 7J). The dolomite crystals of this facies are cut through by various calcite veins of different compositions (Fig. 7K) and are tectonized (Fig. 7L).

4.1.7. Late stage calcite (F7)

Perfectly rhombohedral, transparent calcite crystals represent the last phase of the diagenetic history of partial to complete metamorphosed limestone (Fig. 6F). They occur as comparatively small, massive, dusky white to transparent, isolated chunks within apex of the fractures at the opposite quarry walls (Fig. 6F).

4.2. Regional structures

Several regional-scale fault patterns and fracture sets have been recognized by Shuib et al. (2009) and were suggested to postdate the thermal event of the emplacement of the post-collision S-type granites of the Main Range (Sautter et al., 2017). Major NW-SE trending faults including the Bok Bak Fault or the Bukit Tinggi/KL Fault, crosscut the Western Belt Main Range Province granites with a left lateral offset (Harun, 2002; Ghani, 2009; Sautter, 2017) and is poorly constrained to the Late Cretaceous. Along the Malay Peninsula, other major strike slip faults is thought to be active in the Late Cretaceous to Early Cenozoic (Morley, 2012). The NE-SW striking Ranong fault zone shows an early dextral transpressional deformation before 81 Ma (Watkinson, 2008, 2011). The Khlong Marui fault zone shows a major dextral shear that occurred between 59 and 49 Ma together with the Ranong fault (Watkinson, 2011; Kanjanapayont et al., 2012). The Klaeng fault zone east of Bangkok was active in the Eocene with a sinistral ductile shear (Kanjanapayont et al., 2013) whereas the Mae Ping and Three Pagodas faults were active as sinistral ductile shear zones between 40 and 30 Ma (Lacassin et al., 1997; Morley et al., 2007; Nantasin et al., 2012). Following the aforementioned studies, these NW-SE sinistral and NE-SW dextral faults were interpreted by Sautter et al. (2017) as conjugate strike slip faults testifying E-W shortening during the Late Cretaceous to Early Paleogene.

The Western Belt Main Range province plutons show ubiquitous NW-SE and NE-SW to WNW-ESE and ENE-WSW oriented fracture-sets visible at the DEM-scale (Fig. 2D) as well as penetrative fractures at the outcrop-scale. These fractures are interpreted as conjugate set in the granitic plutons accommodating an E-W compression in the Malay Peninsula (Sautter et al., 2017). These and the fractures along the pluton margins are filled with felsic dykes of probable Cretaceous age in the Main Range Province (Sautter et al., 2017). Following this magmatic thermal event, a stage of regional extension affected both the onshore and offshore regions around the Malay Peninsula (Raj et al., 1998; Morley, 2012; Md. Ali et al., 2016; François et al., 2017). In the Kinta Valley, the western bounding fault, named the Kledang fault (Gobbett, 1971) has been formerly inferred as a strike-slip fault by the authors. Sautter et al. (2017) presented evidence for dextral shear in granitic gneiss along the eastern flank of the Kledang Range represented by enechelon quartz veins. This faulting was interpreted as Cenozoic in age, synchronous to the widespread rifting of the Oligocene basins offshore. Thus, three stages of tectono-thermal events namely, (1) Triassic emplacement of plutons, (2) (Late) Cretaceous faulting and folding with dyke intrusions, and (3) Cenozoic extension, strike-slip faulting and denudation, characterize the region.

4.3. Structural relationships between dolomite phases

Occurrence, morphology, structural relationship and distribution of the fracture patterns in the quarry walls and floor and outcrops in the vicinity were examined, revealing the following features. Frequent NW-SE and E-W oriented fractures filled with dolomites are exposed in the quarry walls (Fig. 4D) and are traceable across the mine floor and extend to the opposite wall of the quarry (Fig. 5D). Without exception, the polyphase dolomite-filled major fractures are all aligned perpendicular to the beddings of host rock. The fractures are all closed in nature and were not exposed to the paleosurface as they terminate below limestone beds. Reactivation of these fractures with slickensides (Fig. 4E) and cross-cutting veins of multiple generations of dolomite, dolocalcite and calcite (Figs. 4A, 4C, 7F and 7K), brecciation of host rock and previous generation dolomite (Figs. 4C, 6E and 7J), and the occurrences of brecciated marble clasts (Fig. 6C) indicative of thermal alteration were also observed. In addition to these major fractures, thinner and irregularly oriented fractures (Fig. 4B) also occur. In addition, millimeter-thick, multi-directional veins are present, which cut through all facies types (Figs. 4A and 6B). Evidence of ductile folds (Fig. 5B) as well as brittle deformation were also documented (faults and slickensides in the fracture-controlled dolostones facies - Fig. 4E). In summary, three distinct sets of fractures and veins cross-cut individual facies or all facies respectively. The oldest series of fractures are parallel, tangent or perpendicular to the bedding and form sets of NW-SE and E-W oriented fractures, which are dolomite-filled and cut through the thin massively bedded limestone host rock (Fig. 4D). Fractures from the second set are thinner and irregularly oriented (Fig. 4B). The last generation of fractures forms millimetre-thick, multi-directional veins that cut through all the facies types (Fig. 4A). The different sets of fractures and veins cutting through different facies reflect different onset timing for each generation of deformation event. Relative chronology of these fractures, thermal evidences and their relationship with regional tectonic events are presented in the discussion.

5. Discussion

Dolomitization is one of the most complex sedimentary diagenetic processes in carbonates and has been reported from different settings with distinct sedimentological and hydrological features (Malone et al., 1996). This process involves different mechanisms and various models have been proposed including evaporation (penecomtemporaneous, in hypersaline sabkha/supratidal), seepage-reflux, mixing-zone, burial and seawater (e.g., Tucker and Wright, 1990; Warren, 2000). Dolomitic formations take various morphologies and geometries. Those that formed during or soon after deposition resemble the geometries of original depositional strata (Vandeginste et al., 2013), whereas those formed in structurally controlled regions exhibit highly differing textural, porosity, and permeability characteristics (e.g., Davies and Smith, 2006; López-Horgue et al., 2010; Sharp et al., 2010). Documentation of these genetic and paragenetic conditions of dolomites are crucial in the fields of hydrocarbon exploration and production (Sun, 1995). The origins and spatial variability in reservoir quality of fault-associated dolomitized carbonates are poorly understood, even though they appear as one of the main players serving as proven hydrocarbon reservoirs in the subsurface (Machel, 2004; Wilson et al., 2007). Outcrop studies on distribution of dolomites, structural relationships, and linking them to large-scale structures, are essential in characterizing the spatial distribution of dolomite formations (Wilson et al., 2007; Vandeginste et al., 2013), and is one of the central themes of this study. In this section, we discuss the occurrences of polyphase dolomite, examine the strata and structural controls, interpret the paragenetic sequence and relate different phases with prevalent tectono-magmatic events to develop a realistic conceptual model.

5.1. Occurrences of dolomite and chronology of polyphase dolomitization

Among the natural outcrops and various quarry sections examined, the exposures at the LaFarge limestone quarry of the Kinta Valley stand out by its well-preserved sections, which exhibit a variety of characteristics and provide access to detailed examination. Based on contact relationships, form, geometry, distribution and other characteristics, it is evident in the study area that the dolomites belong to multiple generations that are strata-bound and structure-controlled, as evidenced from their occurrence within bedding planes of the host rock and within various cross-cutting fractures. Each generation of dolomite also exhibits varying color, form, texture, structural relationship, as observable in the field (Fig. 4G). Strata-bound dolomites of replacement origin are easily distinguished by their yellowish orange colour, shows uniform textural characteristics and occur in the vicinity of the fractures, but appear confined exclusively along the bedding planes of the host strata (Fig. 4G (F2)). The contact between the dolomite and host rock is transitional and becomes feeble-unrecognizable away from the bedding plane (Fig. 6A), suggestive of a replacement origin, influenced by dolomitizing fluid circulated along the bedding plane. Other than this, the dolomites occur in the LaFarge quarry as two separate fracture-bound segments, confined within two closed fractures on the same quarry wall, forming the shape of an inverted “V” at the outcrop scale (Fig. 4G (orange arrows)). Structure, geometry and lithological/petrographic associations of the dolomite are considered as important practical guides in investigating the genetic and paragenetic characteristics (e.g., Warren, 2000 and references therein). Most evident indications for fault and fracture control on dolomitization are based on field relations and geometry of the rock types in the outcrop. Field observations revealed that the LaFarge quarry dolomite is highly localized, occurring only within the fractures (e.g., Slater and Smith, 2012) and is absent away from the fractures (Fig. 4G), reflecting the structural controls on dolomitization. Various facies, each with distinct colour, morphology and composition, occurred within the fracture-bound dolomite s (Figs. 3 and 4). Sucrosic dolomite facies recognized by its reddish grey and white colour (Fig. 6B), formed within the strata-bound dolomite (Fig. 4G (F3)), has no definite shape and appears as fracture filling patchy dolomites. Its distinct colour and characteristic sugary texture implies variations of chemical compositions. Each structure-controlled dolomite phase/facies identified in the field based on colour, geometry, structural relationship, etc., also differ markedly from each other in terms of textural characteristics observed under the petrographic microscope. The medium to coarse and at times very coarse sized replacement dolomites (Fig. 7C) and sucrosic replacement dolomites show varied textures planar –e, -s and non-planar-a textures with hypidiotopic to xenotopic mosaics (Fig. 7G). Fracture-bound dolomites, another white coloured dolomite facies, that cross cut the strata-bound dolomites, follow the vertical orientation dip of the fractures (Figs. 4G (F5) and 6D). It was followed by metamorphosed dolomites that formed within the fracture-bound dolomites (Figs. 4G (F4) and 6C), followed by brecciation at the tips of the dolomite (Figs. 4G (F6) and 4C), which resulted in the formation of brecciated limestone and dolomites (Fig. 6C). Finally, late stage calcite crystallization occurred as perfectly rhombohedral transparent crystals within the fractures (Fig. 6F). Occurrences of dolomites were also observed outside of the periphery of the fractures. They occur as fracture-fill dolomites in minor fractures outside the periphery of the main fracture-sets. The fractures within the periphery are enlarged due to brecciation. Kinks were observed in these fracture-fill dolomites, indicating compaction postdating the formation of these dolomites (Fig. 4B).

The wide variety in appearance, morphologies, composition and nature of dolomite facies, together with successive generations of fractures and veins, suggesting multiple origins for each facies and multiple processes such as replacement, brecciation, metamorphism and crystallization have taken place in the diagenetic history, each structurally affected the previously formed ones, perhaps as a result of prevalent increase in tectono-magmatic intensity (discussed in a later section).

5.2. Hydrothermal origin

Dolomite occurrences in various settings are interpreted to be of hydrothermal origin (Malone et al., 1996) and different models have been suggested to explain their formation (Beales and Hardy, 1980; Cervato, 1990; Cooper and Tindall, 1994; Duggan et al., 2001; Davies and Smith, 2006; Di Cuia et al., 2011; Banerjee, 2016). Some of these models are critically reviewed in other studies (Hardie, 1987; Braithwaite, 1991; Machel, 2008; Gregg et al., 2015). Hydrothermal dolomites (HTD) are characteristic of definitive geometry and formed within zones of elevated temperature, where relatively permeable pathways are available, for instance faults, thrust planes, or areas beneath impermeable seals (Warren, 2000). In contrast, near-surface dolomitization usually results in a more extensive, laterally widespread dolomite (Slater and Smith, 2012). Dolomites of the study area occur exclusively within in closed fractures (Fig. 4G) of the host rock, which had no connectivity with the paleosurface. This indicates structural control on dolomitization, and also that the dolomitizing fluids must have come from beneath, consistent with the description of a focused outflow of thermally charged waters resulting in the formation of hydrothermal dolomites (Warren, 2000; Davies and Smith, 2006) and/or calcite and dolomite (Slater and Smith, 2012). Enlarging the scale, regional structural trends (fault geometry) and fault-controlled/hydrothermal dolomites are closely associated; striking patterns of dolomite distribution showing strong structural control are reported in many previous studies (e.g. Mountjoy and Halim-Dihardja, 1991; Newman and Mitra, 1994; Duggan et al., 2001; Shah et al., 2010; Slater and Smith, 2012; Martín-Martín et al., 2015).

The compilation of data from structural, petrographic and geochemical analyses makes a strong argument for dolomitization by relatively hot fluids that have travelled upward from depth through faults and fractures (hydrothermal origin). Hydrothermal dolomites are characterized as dolomites formed at a higher than ambient temperature in relative to the host rock (Machel and Lonne, 2002), whereby 5-10°C is considered significant in relative to surrounding environment (White, 1957). Hydrothermal dolomites usually have depleted $\delta^{18}O$ values, with the range -2‰ to -20‰ (Smith, 2004). Kinta Valley dolomites show depletion of $\delta^{18}O$ values, with the range of -18.4‰ to -16.37‰ (Shukri, 2010), which falls within the range of other globally comparable dolomites of hydrothermal origin, testifying its formation in elevated temperatures.

Petrographic evidences also support a hydrothermal origin for the dolomitization. Non-planar textures were observed microscopically in all the studied dolomite varieties (Figs. 7C, 7G and 7H). Non-planar textures are common in dolomites formed at high temperature, above 50°C (Gregg and Sibley, 1984), whereas dolomite crystals formed at high temperatures, exceeding a critical roughening temperature, will have non-planar faces (Warren, 2000). Given cognizance to these, except the strata-bound dolomites, all other dolomite phases of the study area are interpreted to have formed under the influence of hydrothermal fluids.

The occurrence of saddle dolomites was commonly used in studies of the western Canada sedimentary basin as evidence of interaction of high-temperature hydrothermal fluids with host limestones associated with tectonic influences (Al-Aasm, 2003). As observed elsewhere (e.g., Duggan et al., 2001; Wilson et al., 2007; Lapponi et al., 2011; Ronchi et al., 2012), the highly localized, patchy, irregularly shaped dolomites (Fig. 4G) and fracture, fracture-within-fracture natures and confinement of dolomites of the study area within these fractures (Fig. 4G) strongly imply their causative mechanism being related to faulting events. The close geometry of the fracture and their non-exposure to paleo-surfaces implies dolomitization by deeper crustal fluids, i.e., the role of hydrothermal fluids. The availability of hydrothermal fluids for dolomitization is also testified by the occurrences of high temperature products such as low-grade metamorphosed limestones/dolomites and tin mineralization in the Kinta Valley region. According to Mitchell (1977, 1979, 1981) and Hutchison (1989) the Western Belt Main Range granites are highly radioactive with U contents up to 37000 ppm in the zircons.

Hydrological factors constrain the evolution of natural dolomites and the presence of a fluid capable of supplying and maintaining sufficient volumes of magnesium to generate and sustain supersaturation is a must for crystals to precipitate and re-equilibrate in dolomitization (Warren, 2000). Unlike large-scale dolomitization processes which require large volumes of magnesium supply to completely replace the host limestone (Machel, 2004; Davies and Smith, 2006), localized hydrothermal dolomitization (such in the study area) only requires much lower volumes of magnesium supply. Different sources of magnesium are suggested to act as potential dolomitizing fluids, such as seawater, continental waters, evolved basinal brines, mixing of hypersaline brine with seawater, mixing of seawater with meteoric water, or cooled basinal brines (Warren, 2000; Davies and Smith, 2006). Basinal brines or mixing of basinal brines with other source are usually the dolomitizing agent in hydrothermal dolomites. Given cognizance to these, in addition to the occurrence of limited extent of strata-bound replacement dolomite, followed by fracture-controlled, limited extents of polyphase dolomites and also the presence of hydrothermal calcite as the last phase of paragenetic sequence, it is inferred that the most probable sources of magnesium for the replacement of the Kinta Valley dolomites are locally drawn from the host rock (Kinta Limestone) in the immediate vicinity. The carrier of magnesium is most likely circulating hot basinal waters, which become hydrothermal when they transfer upward into cooler areas during tectonic activities, and are capable of mineralizing and precipitating/replacing dolomites (Hardie, 1991). The basinal waters rise upwards and outwards along bedding planes, faults or other permeable paths as their buoyancy is heightened when they get heated during hydrothermal circulation (Freeze and Cherry, 1979). The most plausible pathways for hydrothermal fluids circulation are smaller and distant vents connected to hydrothermal vents. Thermal convection during magmatic activities episodically heated up deep seated basinal brine. The heated brines channelled from distant hydrothermal vents and then travelled up along available migration conduits during tectonic fracturing events. By fluid-rock interaction, the heated basinal fluids could extract magnesium from the precursor host rock along its way. Where magmatic activities are active and temperature differentials exist, circulatory systems are formed, that supply fluids and temperature for replacement and or hydrothermal crystallization of dolomite.

Another possible source of magnesium is dewatering and leaching of surrounding siliciclastics due to compaction. However, given the dominance of carbonate mudstone host rock with thickness of more than 700 m, the occurrence of dolomites that are fracture-controlled and limited in extend, the closed nature of fractures, and interpretation of thermally convected fluids as the source for dolomitizing fluids, an origin by compaction of siliciclastics seems unlikely. Evolved formation water is commonly suggested as dolomitizing fluids (e.g., Malone et al., 1996, Martín-Martín et al., 2015). However, formation water is most unlikely, in this case, from analytical data and based on the geochemistry of the dolomites. From the geochemical data we also infer that the limestones are of marine origin, but the elemental compositions of the dolomites do not match with that of seawater and the dolomites do not behave geochemically the same way as that of the host limestones (our unpublished data). Hence, the dolomitizing fluid must be non-marine.

5.3. Polyphase dolomitization and paragenetic sequence

From the field and petrographic data, it is inferred that initially, the calcitic phases of the host limestone (F1) got replaced when the dolomitizing fluids travelled along the bedding planes. High intensity of replacement along the bedding planes was observed and is commonly reported in grain-dominated lithologies (e.g., Davies and Smith, 2006; Wilson et al., 2007). Away from the bedding planes the intensity of replacement waned, as it was observed elsewhere (Laubach et al., 2009), signifying the influence of fluid-rock access (Dewit et al., 2014). The hot fluids, possessing heat energy, penetrated through the permeable beds and portions of host rock, defined by favorable textural class, and continued to dolomitize the host limestone, and eventually resulted in a strata-bound dolostone (F2) (e.g., Lapponi et al., 2011). There were successive fracturing events, accompanied by thermal events which heated up the deep seated basinal brines. These hot fluids were forced up along the fractures by resultant pressure of the active faulting events.

The relationship between brittle deformation and/or dolomite recrystallization during fracturing is well-noted (Newman and Mitra, 1994), especially the close relationship between multiple phases of fracturing and dolomitization (Mountjoy and Halim-Dihardja, 1991; Newman and Mitra, 1994; Duggan et al., 2001; Warren, 2000; Chen et al., 2004). Dolostones found in the study area show a polyphase origin, with multiple generations of dolomite and calcite, implying a series of fluid pulses expelled from beneath the closed fractures. Multiple fluid pulses accompanied by changing and evolving fluid chemistry and temperature may re-equilibrate the dolomites many times during the dolomitization history. Subsequently, early stage dolomites were subjected to evolution or re-equilibration into new forms as conditions continued to change (Warren, 2000). The dolomites of the Kinta Valley are interpreted, based on field and petrographic observations, as polyphase dolomites-dolostones-dolocalcites-calcites which formed at different times within each fracture probably by differing diagenetic fluids. Thus, several diagenetic phases can be reconstructed by field and petrographic evidences and be placed in a paragenetic sequence, linking it to tectonic and hydrothermal activities, and fluid flow events.

Dolomitization at the studied outcrop begins with initial compaction of the host rock (F1), as evident in the association of the low-amplitude stylolites (Fig. 7A) with fracture-filling replacement dolomites. This compaction of the host rock resulted in the dewatering of limestone, probably releasing interstitial water trapped within the pore system, which then evolved with the Mg^{2+} expelled from the limestone host rock, and became supersaturated with magnesium ions, followed by initiation of replacement dolomitization *enroute*, affecting only the susceptible grains, matrix and cement of the host rock. The dolomites formed along dissolution seams (Fig. 7E) may reflect a localized source of Mg^{2+} ions for dolomite cementation (Carnell and Wilson, 2004; Machel, 2004). Ubiquitous presence of thin fractures aligned parallel to beddings (which in turn could also have served as conduits for circulation of dolomitizing fluids) (Figs. 4G and 5A) indicate compressional regime across the bedding, probably due to weak upwarping associated with ascendance of distal magmatic activity. This could have happened during or immediately post-dating the Permian-Triassic Sibumasu-East Malaya collision, or during the mid-Late Cretaceous folding and faulting of the Malay Peninsula. However, this cannot be determined with certainty based on the available data. On an additional note, as the extent/volume of Late Cretaceous granites are less and appear only in the Eastern and Central Belts, dyke intrusion and resultant thermal contribution could be speculated.

The second phase of dolomitization starts with a tectonic event (structural extension, probably Late Cretaceous or Early Cenozoic faulting) and followed by a first brecciation which formed collapse breccia of the host limestone and replacement dolomites (F6) filling the fractures (Fig. 4C). It was followed by hydrothermal activity, where thermally supercharged fluids heated up by ascending magma from beneath dissolved the calcareous mudstone and became enriched in magnesium. The fractures formed as a result of this tectonic event acted as major feeder systems for hot fluids, as evident by the localized nature of the dolostones within closed fractures (Fig. 4G). This event had precipitated dolocalcite along the walls of fractures where nucleation sites for precipitation are available. Hence dolocalcite is found at the tips of the fractures and various textural types of this facies are distributed laterally. This diagenetic fluid continued to dolomitize the host limestone along the walls of the fracture, forming the early fracture-bound replacement dolomites (F2). The hydrothermal fluids resultant from the hydrothermal activity of this stage migrated upward along existing fractures, consuming any remaining magnesium available along the way, and penetrated into the most permeable strata, developing the strata-bound replacement dolomite (F2). Synchronously to this replacement dolomites formation, the dolostones were brecciated forming both hydrothermal and collapse breccia (F6), as both appear related to tectonic and hydrothermal activity of this phase. The dolomite crystals are cut through by calcite veins (Fig. 7K) reflecting later fracturing followed by calcite cementation. The dolomite crystals are also severely sheared and tectonized (Fig. 7L), which evidences a regional tectonic event. Euhedral to subhedral dolomite crystals (Fig. 7C) are formed during this stage, implying a relatively lower temperature of dolomite formation. Sparry planar dolomites dominated by cloudy centers with clear rims (Fig. 7D) also reflect a lower temperature dolomite formation (Warren, 2000). The cloudy centers could be inclusions of low-Mg calcite precursors or voids created by Mg-calcite dissolution, or by fluid-filled micro-cavities, or/and incorporation of impurities (Warren, 2000; López-Quirós et al., 2016). Drousy dolomites are typically the result of quick crystallization near or at surface conditions (Tucker and Wright, 1990). On the other hand, the clear rims reflect precipitation from solutions undersaturated with respect to low-Mg calcite or variations in crystal growth rate or changes in dissolution/precipitation of the outer portion of precursor crystals (Warren, 2000). Calcite cementation along fractures formed within the dolomites took place in this phase, at a later time. The fracture-filling calcite could be formed by the same diagenetic fluid as the dolomites, but at different temperatures. Transition from dolomite to calcite saturation in the fluid could be a result from a temperature drop (Carpenter, 1980) as well as exhaustion of Mg^{2+} ions in the circulating fluid and locally sourced Mg^{2+}. This could be correlated with tectonic events in Late Triassic to Early Jurassic where there was regional transpression and associated metamorphism.

The third phase of dolomitization resulted in the formation of sucrosic dolomites (F3) implying a similar reactivated tectonic cycle of the fracture system and then influx of hydrothermal fluids followed by resultant cross cutting of early formed fracture-fills and precipitation of dolomites. Formation of dolomite crystals with relatively coarser and sucrosic fabric could be due to relatively low Mg/Ca ratio and limited availability of burial-derived dolomitizing fluids (Warren, 2000) and slower crystal growth rate. These sucrosic dolomite crystals appear fractured and filled with calcite (Fig. 7G) implying later minor fracturing events and depletion of Mg^{2+} in addition to local sourcing and limited availability of magnesium ions. This could also signify limited availability of fluids and higher difference of bulk chemistry of circulating waters and host rock wherein the circulating fluids reach supersaturation owing to higher reactivity (Ramkumar, 2007, 2008; Ramkumar et al. 2006, 2013) after the formation of sucrosic dolomites. The fracture-filling calcite is inferred to have formed from the same diagenetic, but Mg^{2+} depleted fluids at a later time and comparatively lower temperature. This could have taken place during Cretaceous where NW-SE and NE-SW faults were activated and associated to a thermal event producing acidic dykes that filled fractures and fractures along the Main Range pluton edges (Sautter et al. 2017).

The fourth phase is also a result of reactivation of the fracture system, followed by expulsion of hydrothermal fluids from beneath. The hydrothermal fluids resultant of this local deformation event migrated up along existing fractures, consuming any remaining magnesium available along the way, penetrated through resultant fractures created into permeable strata and dolomitized it. This dolomitizing fluid appear again of varied chemistry and resulted also in the development of late fracture-bound replacement dolomite (F5). The larger crystal size and irregular outline of the dolomite crystals (Fig. 7H) reflects a higher temperature which leads to a more advanced stage of recrystallization. Some of the anhedral dolomite crystals are recrystallized dolomites of the earlier relatively lower temperature dolomites. Anhedral to subhedral dolomite crystals characterize the final dolomitization phase (Warren, 2000). This late stage recrystallization enables the dolomites to reorganize structurally and compositionally to more stable forms, transforming themselves toward enhanced stoichiometry (Warren, 2000). The presence of saddle dolomites (Fig. 7I) is also indicative of interaction of high temperature (above 80ºC, see Machel, 2004) hydrothermal fluids with host carbonates (Al-Aasm, 2003; and references therein). This highly thermogenic phase has most probably also led to the formation of marble (F4) that followed second stage of brecciation and collapse of the early formed fracture fills. This phase could be coeval with Late Cretaceous tectonic events where major dextral slip faults were reactivated and major thermo-tectonic event across Malay Peninsula, marking the most extensive thermogenic phase.

In addition, a series of mm-thick calcite veins are present in all the lithologies and postdate all different phases of dolomitization. During this fifth phase, the same cycle of fracturing, influx of hydrothermal fluid and crystallization is suggested to be repeated; however, instead of dolomite, large chunks of cm-scale transparent calcites were emplaced at the apex of the fracture. This could represent an exhaustion of Mg^{2+}. The transparency, perfect rhombic morphology and large crystal size of this calcite phase highlight the intensity and rate of crystallization, as well as the relative tectonic quiescence that followed. This phase could point towards Cenozoic whence there were normal faulting and major wrench faulting, associated with thermal events in the Paleogene and followed by tectonic quiescence in the Neogene.

From these inferences on paragenetic sequences, it is envisaged that the different onsets of dolomitization and hydrothermal activities were directly related to either faulting or reactivation of pre-existent fault/fracture systems, which in turn were influenced by progressively intensified magmatic events. The multiple phases of fracturing and dolomitization are a function of accumulation and release of stress, and thermal events, induced by regional tectonic events. Based on these inferences, an idealistic model for the development of strata-bound and polyphase fracture-controlled dolomite has been constructed and presented in figure 8. It is presumed that drawing the link between each diagenetic event, local and regional events, or thermo-tectonic events can be inferred and the understanding on the regional tectonic history can be enhanced.

5.4. Regional tectono-thermal implications

Having established the polyphase origin of dolomites, involvement of episodic tectonism and progressively intensified hydrothermal activity as a result of magmatism, it becomes pertinent to examine the causative events and their chronology. First premise made in this discussion is, as demonstrated in other documented fault-related dolostones, fault controlled hydrothermal dolomites in the study area are directly impacted by regional tectonic events (Malone et al., 1996). Second premise is that, the hydrothermal dolomite formation takes place in an extensional regime where there is elevated heat flow during the events (Davies and Smith, 2006). These two assumptions are consistent with the geological setting of the Kinta Valley (Fig. 3A) where reactivation of faults and extensional events occurred from the Paleozoic to the Recent (Sautter et al., 2017). The valley consists of Lower Paleozoic Kinta Limestone (being the calcareous mudstone host rock) that was affected by Sibumasu-East Malaya collision that induced multiple thrust faults later probably reactivated as normal faulting in the Cenozoic (Sautter et al., 2017). The Late Triassic and Late Cretaceous granitic batholithic emplacements (Rastall, 1927; Richardson, 1946, 1947a, 1947b; Lee, 2009; Ghani, 2009; Metcalfe, 2002, 2013; Searle et al., 2012; Ng et al., 2015a, 2015b; Sautter et al., 2017) generated tremendous crustal fluids amounts circulating through these thrust faults among other compressive fabrics (Sautter et al., 2017). Plumes of hydrothermal waters gain more heat as magmatic activities are enhanced. This assumption calls for progressive increase of temperature and resulted in the subsequent formation of various dolomite phases. Occurrence of polyphase dolomites warrants repetitive influx of thermally charged basinal brines from distant hydrothermal vents, which moved up along the fractures during reactivation of faults and repetition of the same fluid-rock interaction with continued sourcing of magnesium from the precursor host rock along its way. After each fluid-rock interaction, Mg content in the precursor host rock might have been more and more depleted. At the final stage where the Mg is exhausted, late stage calcite crystallization occurred, postdating the dolomitization. Thus, these two major inferences, i.e., faulting/reactivation of faults and distal magmatic events warrant the regional tectono-magmatic events.

The form, occurrence, structural and textural characteristics reflect multiple, yet localized hydrothermal upwelling systems from distal, major subcrustal magmatic events, connected to crustal weak planes such as faults and fractures capable of limiting the dolomitization process (e.g. Warren and Kempton, 1997). In other words, a conduit to supply a focused outflow of hydrothermal waters and episodic pulses of fluids to precipitate polyphase dolomites is required. As could be envisaged from figures 2C and 3, channelling conduits were available, with the presence of numerous faults and fractures in the study area. The permeable faults and fractures allowed dolomitization of the adjacent host limestones. Considering the structural setting of the Kinta Valley, the facies and other characteristics of dolostones and their hydrothermal nature, the most plausible mechanism is inferred to be thermal convection (e.g., Martín-Martín, 2015). Thermal convection is an efficient dolomitizing mechanism, that could supply higher fluid and heat flow rates for dolomitization than other mechanisms (Davies and Smith, 2006; Gasparrini et al., 2006).

During the Late Permian-Early Triassic, thin skinned deformation of the Malay Peninsula was initiated by collisions of Sibumasu with the Sukhothai Arc and between the Sukhothai Arc with Indochina (East Malaya), and proceeded until the end of the Triassic, where subduction halted and Western Belt Main Range S-Type granitoids were generated by crustal thickening and slab break off (Metcalfe, 1998, 2002, 2013; Searle et al., 2012). Major N-S trending faults are suggested to be due to oblique amalgamation of Sibumasu and the Sukhotai Arc during Permian-Triassic (Metcalfe, 2013). In this backdrop, the first post-collisional event from Late Triassic to Early Jurassic was regional transpression resulting in dextral transpressive deformation and metamorphism (Shuib, 2009). NNW-SSE major dextral faults of the Malay Peninsula region are suggested to be Late Triassic-Jurassic, and have caused the opening of the Jurassic-Cretaceous continental pull-apart basins in East Peninsular Malaysia and considered to be the result of a second post-collisional event (Shuib, 2009; Metcalfe, 2013). During Cretaceous, NW–SE and NE–SW faults were activated probably linked to the collision of Burma arc with East Asian Continent (Krähenbuhl, 1991) or collision of microcontinental fragments derived from Australia with the Sunda margin (Hall, 2012). A third post-collision event took place during the Late Cretaceous where the preexistent major dextral strike slip faults further reactivated with a sinistral sense of shear; coeval with emplacement of youngest granitic intrusion in the Central and Eastern Belts, e.g. Stong magmatic complex (Harun, 2002; Hutchison and Tan, 2009; Shuib, 2009; Metcalfe, 2013; Md. Ali et al., 2016; François et al., 2017). It was also a time of significant thermo-tectonic event across the Malay Peninsula, which includes folding and faulting at a crustal scale (Shuib, 2009; Morley, 2012; Md. Ali et al., 2016; Sautter et al., 2017) that lasted until Early Paleogene.

The Cenozoic Period witnessed normal faulting, and major wrench faulting (Morley, 2011; Pubellier and Morley, 2014; Sautter et al., 2017). Resumption of subduction in SE Asia around 45 Ma (Hall, 2002, 2012) resulted in exhumation of the Malay Peninsula along large-scale north-east – south-west to north-south trending major structures (Cottam et al., 2013). Metamorphism and transpression in Thailand and Indochina is reported by e.g. Searle et al. (2007), Morley (2004, 2012) in the Eocene. Large Cenozoic half grabens are present in the offshore regions whereas onshore Cenozoic deposits are limited to isolated continental basins that are associated with regional fault zones (Kuala Lumpur and Bok Bak fault zones), implying transtensional wrench conditions have been episodically active till then (Tjia, 2010). From the Cretaceous to the Paleogene, deformation and exhumation of the entire Peninsula is inferred from field and low temperature thermochronology studies (Krähenbuhl, 1991; Shuib, 2009; Cottam et al., 2013). Regionally, there were episodes of extensive basin development and regional development of rift basins in South East Asia from the Late Eocene and onwards (Hall and Morley, 2004). Renewed wrench faulting took place along several pull-apart boundaries in the Eocene (Tjia, 1996). Sundaland is considered to have achieved tectonic stability at the end of the Neogene, although there were occasional crustal movements (Tjia, 2010) and its western margin is still active with the pull-apart opening of the Andaman Sea since the Late Miocene (Curray, 2005; Morley, 2016).

Based on the above discussion on tectonic and magmatic events of the region, we arrive at the following inferences.

For hydrothermal dolomite to form, release of pressurized fluids trapped at depth is needed. Hence the necessary elements for the process to take place are faulting and fracturing (Davies and Smith, 2006). Thus, the timing of hydrothermal alteration is closely linked to the timing of fault movement. Slater and Smith (2012) proposed that the episodic fluid flow may be caused by the cyclic increase in pressure before a fracturing event. According to Sibson (1994), this seismic pumping mechanism could take tens-to-many thousands of years and an immediate decrease in pressure which in turn may take only a few seconds. The fluid flow is then blocked by growth of crystals along open fractures that occlude the pore-fracture network (Slater and Smith, 2012). The fractures remain blocked until the next buildup of pressure reactivates the fault or create a new one (Slater and Smith, 2012) and the post-seismic adjustment may last for days to years (Sibson, 1994). As a result of each of this pressure build-up, fluid influx and resultant precipitation events, a phase of dolomite and/ or calcite precipitated. Prevalence of multiple events might have resulted in the formation of polyphase dolomite-dolocalcite-calcite. Sources for the heat flow, which resulted in hydrothermalism, are interpreted to be the emplacement of granite plutons after the Sibumasu-East Malaya collision, metamorphism associated with transpression, Cretaceous magmatic thermal event associated with acidic dykes and Cenozoic lithospheric thinning inducing mantle upwelling. The heat and fluid flow convection were likely enhanced by local structures associated with the regional fault system (Fig. 2D). Searle et al. (2012) correlated the heat source of the batholiths along the Western Belt Main Range of Peninsular Malaysia and associated pervasive mineralization to the mantle with possible relation to injection of mantle derived melts at the base of the crust. Matsubayashi and Uyeda (1979) proposed possibility of regional extensional tectonics behind the Andaman-Sunda arcs to explain the unusual high heat flow in the region. The occurrences of brecciated marble clasts within the fractures that are related to the phase-4 of fracturing brecciation, formation of marble clasts and dolomitization, and regional marble occurrences encircling the Paleozoic carbonates, is interpreted to be related to the polyphase dolomitization with the Late Cretaceous tectono-magmatic event. These speculations, together with the highly radioactive uranium contents of zircons contained within these granites and their close association with hydrothermal activity and resulting tin mineralization within the Kinta Valley unequivocally permits to interpret post-Late Triassic heat source for the various dolomitization phases of the present study. However, it is also presumable that the heat source for this event could be due to the youngest granite intrusion similar to the Stong Complex. Reactivation of pre-existing faults might have allowed higher temperature fluids to travel from greater depths upward. Notwithstanding the chronological resolution, the idealistic model presented in the figure 8 illustrate the role of tectono-magmatic chronology of events.

6. Conclusions

The 700 m thick, Kinta Limestone, was subjected to significant thermo-tectonic events since Late Triassic to Late Cretaceous. Analysis of the regional structural trends, logging of outcrops and quarry sections, followed by documentation of fracture patterns, classification of dolomite, dolomitic-limestones, limestones, together with contact relationships, form, geometry, morphology, texture, etc., revealed multiple episodes of strata- and structure-controlled hydrothermal crystallization in response to Late Triassic-Late Cretaceous tectono-thermal events in the study area. Limited nature of the circulated fluid, highly differed bulk chemistry between host rock and circulating fluid, gradual ascendance of magmatic heat source, subcrustal and distal nature of the magma were interpreted to have caused polyphase dolomites. A final tectonic quiescence after crystallization of perfectly rhombohedral calcite is also interpreted. Enlisting of regional tectonic and magmatic events in chronological order and incorporating the phases of dolomite formation resulted in construction of a six-stage idealistic model. With this model, we have demonstrated the synchronized tectono-magmatic events that initiated redistribution of interstitial water and magmatic heat, and precipitation of multiple generations of dolomite-dolocalcite-calcite that exhibit individual sets of geometry, form, texture, facies and structural relationships unique to each of the tectono-magmatic event, active tectonism and tectonic quiescence. This study has also demonstrated a methodology for linking local-regional tectono-magmatic events through systematic documentation of facies, texture and structural relationships of rock types in the field and laboratory.

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LIST OF FIGURES AND CAPTIONS

Fig. 1. Regional tectonic and structural framework. Continental blocks, terranes and fragments, and principal sutures of west Sundaland. Red box indicates the Kinta Valley study zone.

Fig. 2. Regional geological setting, structural trends and location of the study area. A: Simplified topographic map showing regional setting and location of the Kinta Valley in western Malaysia. **B:** Geological provinces of western Malaysia, divided into Western, Central and Eastern belts. **C:** Geological map showing the sprawl of the Kinta valley, regional geology and location of the study area, sandwiched between two granitic plutons. **D:** Digital Elevation Model (DEM) of the region manifesting landscape and regional structural trends of the Kinta Valley and adjoining regions.

Fig. 3. Major tectono-magmatic events in and around Kinta Valley in the western belt, Western Malaysia. A: Cross section across the profile indicated in figure 1C. **B:** Sketches of the regional tectono-magmatic events, successive stages and resultant structural deformations.

Fig. 4. LaFarge quarry face exposing strata-bound and fault-related dolomite phases and host limestones, and well preserved structural characteristics. A: Millimeter-thick,

multi-directional veins cut through all the facies types, representing the last generation of fractures. **B**: Second set of thinner and irregularly oriented fractures. **C:** Brecciated limestone and dolostone found at the foot of the fracture. **D**: First set of fractures characterized by bedding parallel, tangent and perpendicular NW-SE and E-W oriented dolomite-filled fractures cutting through the limestone host rock. **E**: Slickensides in the fracture-controlled dolostone reflecting brittle deformation. **F**: NW-SE oriented dolomite-filled fractures exposed on the smaller inverted "V" fracture in the mine wall. **G**: Lafarge quarry face exposing strata-bound and fault-related dolomite phases and host limestones, each with distinct texture, form, geometry, morphology and associated fracture patterns and orientations.

Fig. 5. Field-scale structures and fracture patterns on the quarry wall opposite the wall depicted in A: Evidence of fluid movements and brittle deformations such as thin-bedding parallel fractures and slickensides highlighted with distinct coloration. Occurrence of this bedding parallel fracture is observed on the opposite mine wall located away from the fracture shown in figure 3. Continuation of the fracture shown in figure 3 is traceable through the mine floor to this location. Red box area showing a ductile deformation characterized by folding. **B**: Close-up view of the ductile deformation shown in the previous photo. Boudins (?) indicated by red arrow are visible as manifested by thickening and thinning of beds and folding. **C**: Brittle deformations observed on another section of this same mine wall, characterized by thin fractures (indicated by red lines) and breccia (indicated by red arrow). **D**: Structural characteristics are characterized by fractures (indicated by red lines), displacements (indicated by yellow lines) and folds (indicated by orange lines).

Fig. 6. Dolomite and calcite facies types. A: Early replacement dolomite (F2). Dolomites (F2) and host limestones (F1) are easily distinguished by the color differences between yellowish orange (dolomites) and light to dark grey color (limestone host rock). The contact between limestone host rock (F1) and dolomite (F2) is gradual. **B:** Sucrosic dolomite (F3)

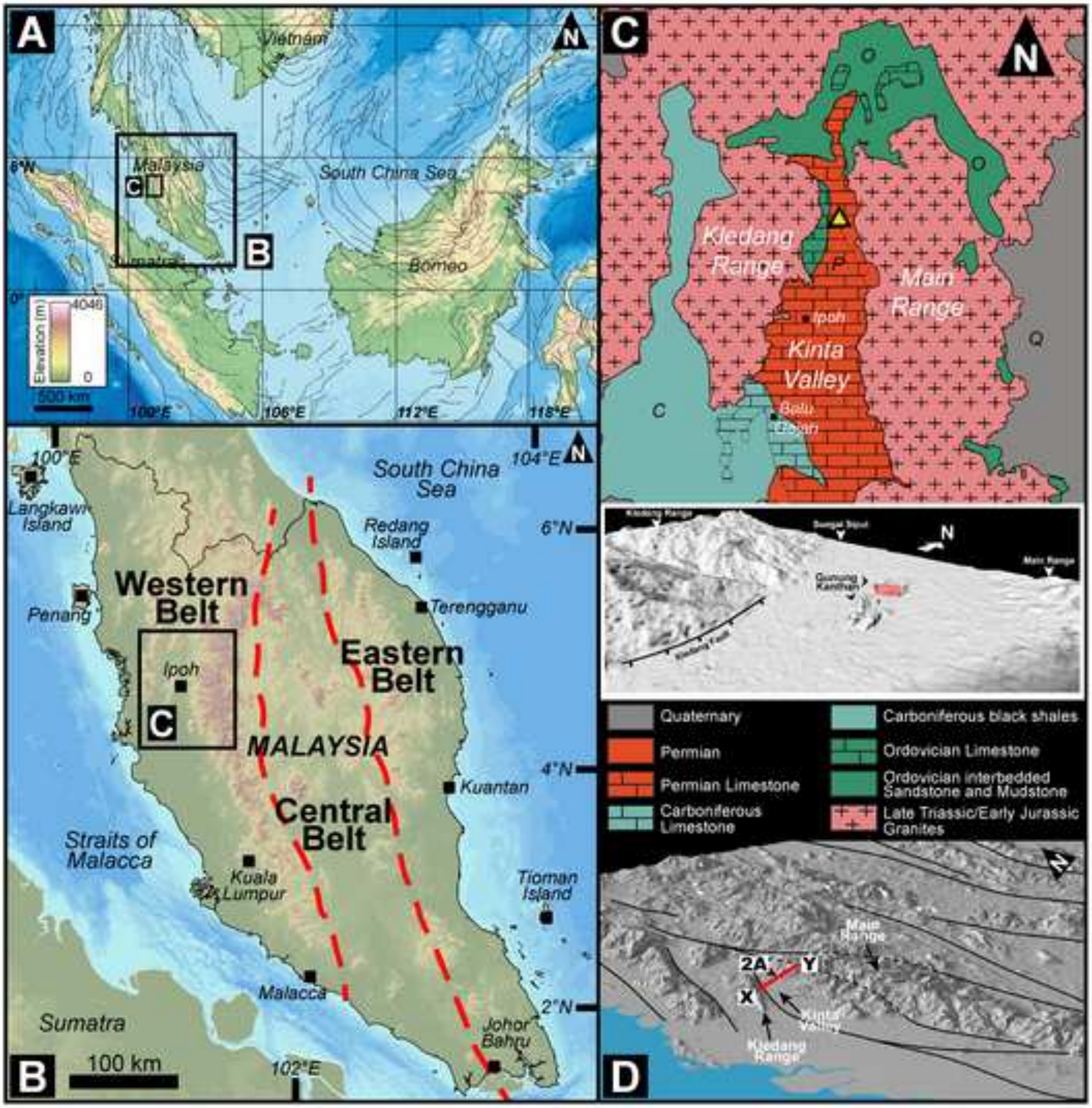
exhibits a sugary texture, associated with multi-directional conjugate cracks and kinks. **C**: Sharp contact between metamorphosed dolomite (F4) and early replacement dolomite (F2), and minor fractures filled with calcite veins. **D:** Late replacement dolomite (F5) characterized by its white color appearance associated with a dense fracture network. **E:** Brecciated limestone (F1) and early replacement dolomite (F2). Angular clasts of breccia fragments are cemented by white colored calcite. **F:** Perfectly developed, transparent rhombohedral calcite crystals of the last phase of the diagenetic history.

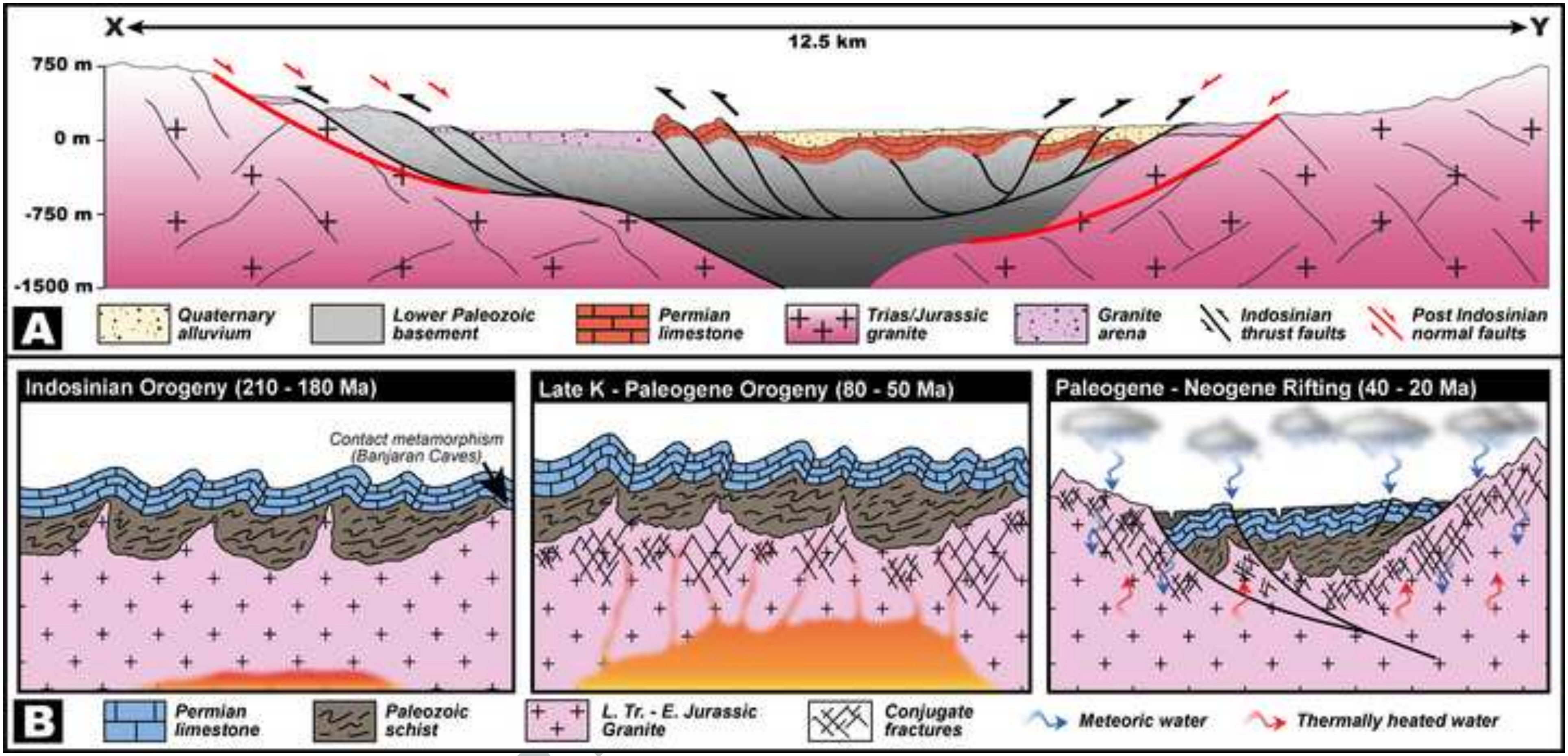
Fig. 7. Photomicrographs showing textural characteristics and relationships of the various facies types found in the quarry wall (all microphotographs are taken under polarized light. Scale bar is in the photograph itself). **A**: Association of low amplitude stylolites in host rock limestone (F1) reflects compaction in the host rock which resulted in dewatering of limestones and evolved into dolomitizing fluids together with Mg ions. **B**: Occurrence of tectonic stylolites in limestone facies (F1) indicates occasions of tectonic compression, testifies the happenings of tectonic events. **C**: Microscopic texture of early replacement dolomites (F2) showing 100-1000 µm sized planar euhedral to subhedral dolomite crystals with idiotopic to hypidiotopic mosaics and non-planar anhedral dolomite crystals with xenotopic mosaic are 100-2000 µm sized. **D**: Few of the planar euhedral dolomite crystals of early replacement dolomites (F2) have a cloudy core with a clear rim. **E**: Formation of early replacement dolomites (F2) along stylolites may indicate a localized source of Mg ions for dolomite cementation. **F**: Association of early replacement dolomites (F2) with calcite veins of varied compositions as evident in different colors in stained calcite veins. **G**: Microscopic texture of sucrosic dolomites (F3) showing coarse to very coarse (200-2000 µm) planar-s to non-planar-a with hypidiotopic to xenotopic mosaics and medium to coarse (100-400 µm) planar-e dolomite crystals with idiotopic mosaics. **H**: Microscopic texture of late replacement dolomite (F5) exhibits coarse to very coarse (1000-2000 µm) planar-e and –s to non-planar-a

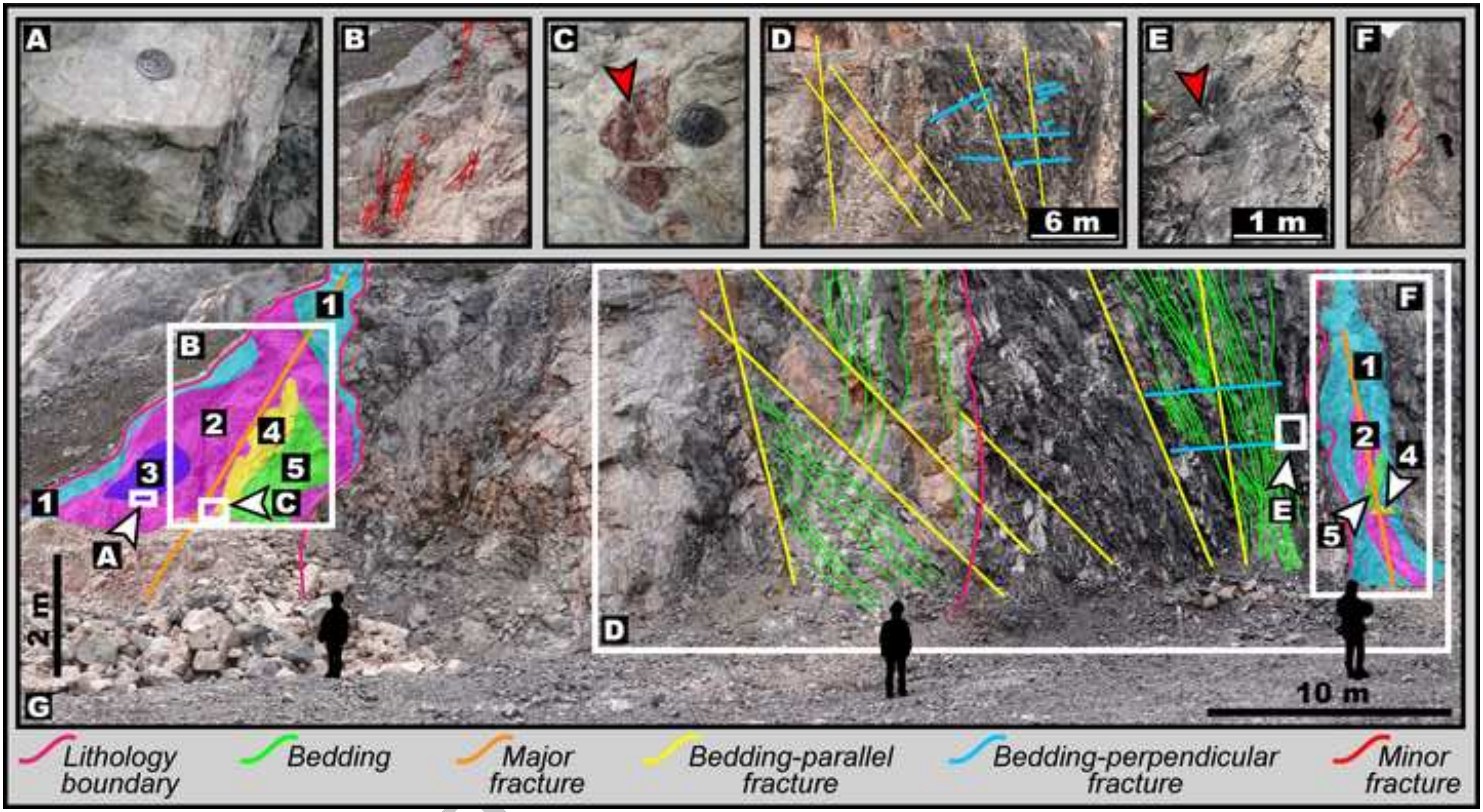
dolomite crystals with idiotopic to hypidiotopic and xenotopic mosaics. **I**: Occurrence of saddle dolomites in late replacement dolomite facies (F5) characterized by large crystal size (coarse to very coarse), curved crystal faces, and scimitar-like terminations pointing to pore spaces. **J**: Microscopic view of brecciated limestone and dolostone (F6) showing planar subhedral dolomite crystals of various sizes, ranging from 50-500 µm. **K**: The brecciated dolomites in F6 facies are cut through by calcite veins. **L**: Dolomite crystals being severely sheared and tectonized again reflects the recurrence of tectonic events.

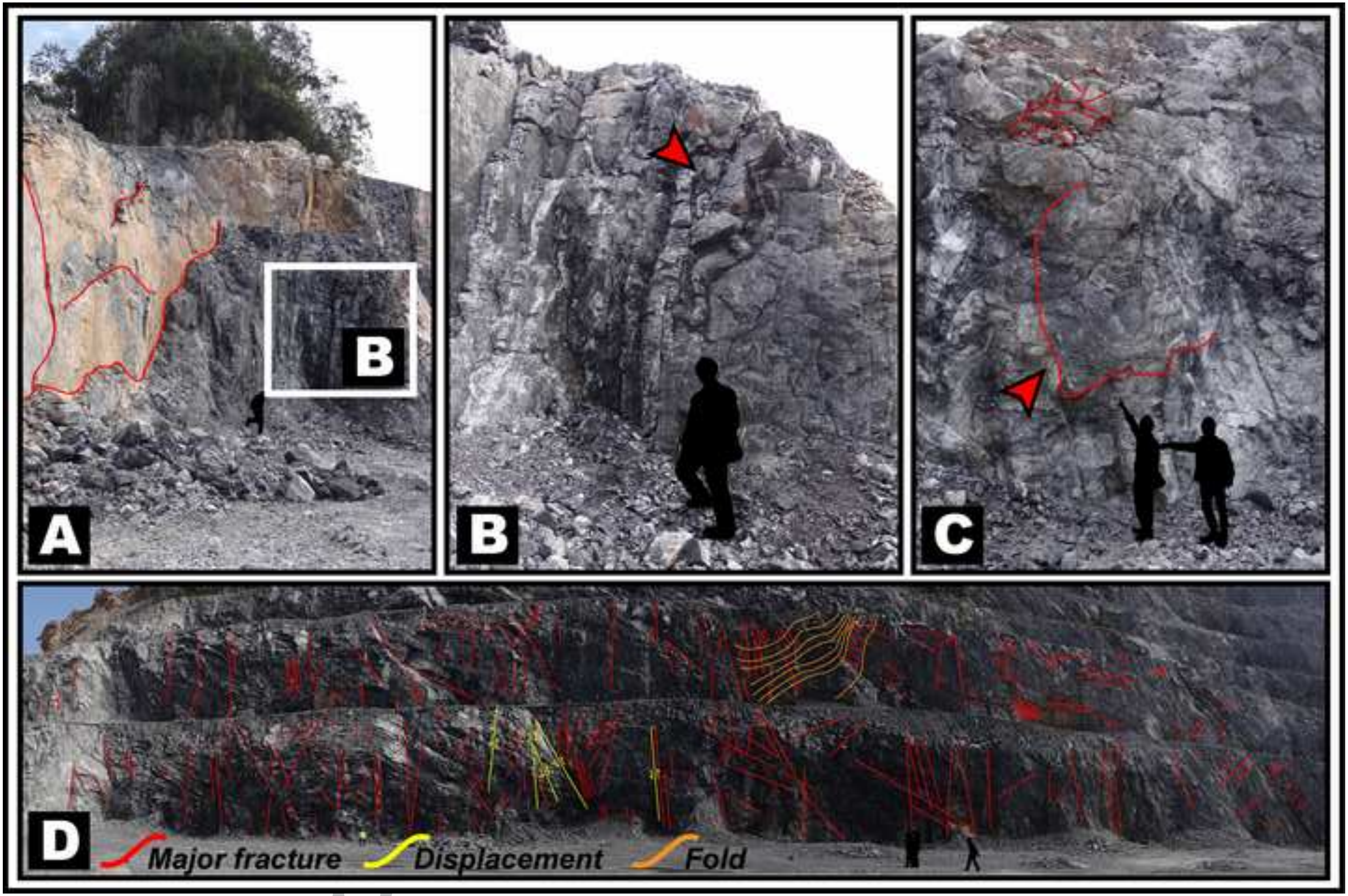
Fig. 8. Polyphase strata and fracture bound dolomitization. A: Deposition and early phase lithification of very thick (> 700 m) carbonate mudstones of the Paleozoic Kinta Limestone. After lithification, the carbonates endured distal orogeny and magmatic source, leading to slight bedding-parallel fractures and influx of hydrothermal fluids along bedding due to regional upwarp-dewatering of sedimentary rocks with pressure from below and restriction by basin margin faults and formation of strata-bound replacement dolomite. This strata-bound dolomitization might have formed during Permian-Triassic or Early Jurassic. **B:** Ascendance of magma and increase of pressure from below, formation of closed fractures that terminate below the surface, influx of hydrothermal fluid, first stage brecciation, and formation of fracture-controlled dolomite phase 2. This event might be related to Late Triassic to Early Jurassic regional transpression and associated metamorphism .**C:** Ascendance of magma and increase of pressure from below, formation of closed fractures that terminate below the surface, influx of hydrothermal fluid, and formation of fracture-controlled dolomite phase 3. Progressive increase in heat flow might be due to proximity of magma. **D:** Ascendance of magma and increase of pressure from below, formation of closed fracture that terminate below the surface, influx of hydrothermal fluid, and formation of fracture-controlled dolomite phase 4 and marble. Subcrustal magma might have got emplaced into batholiths. **E:** Ascendance of magma and increase of pressure from below, formation of

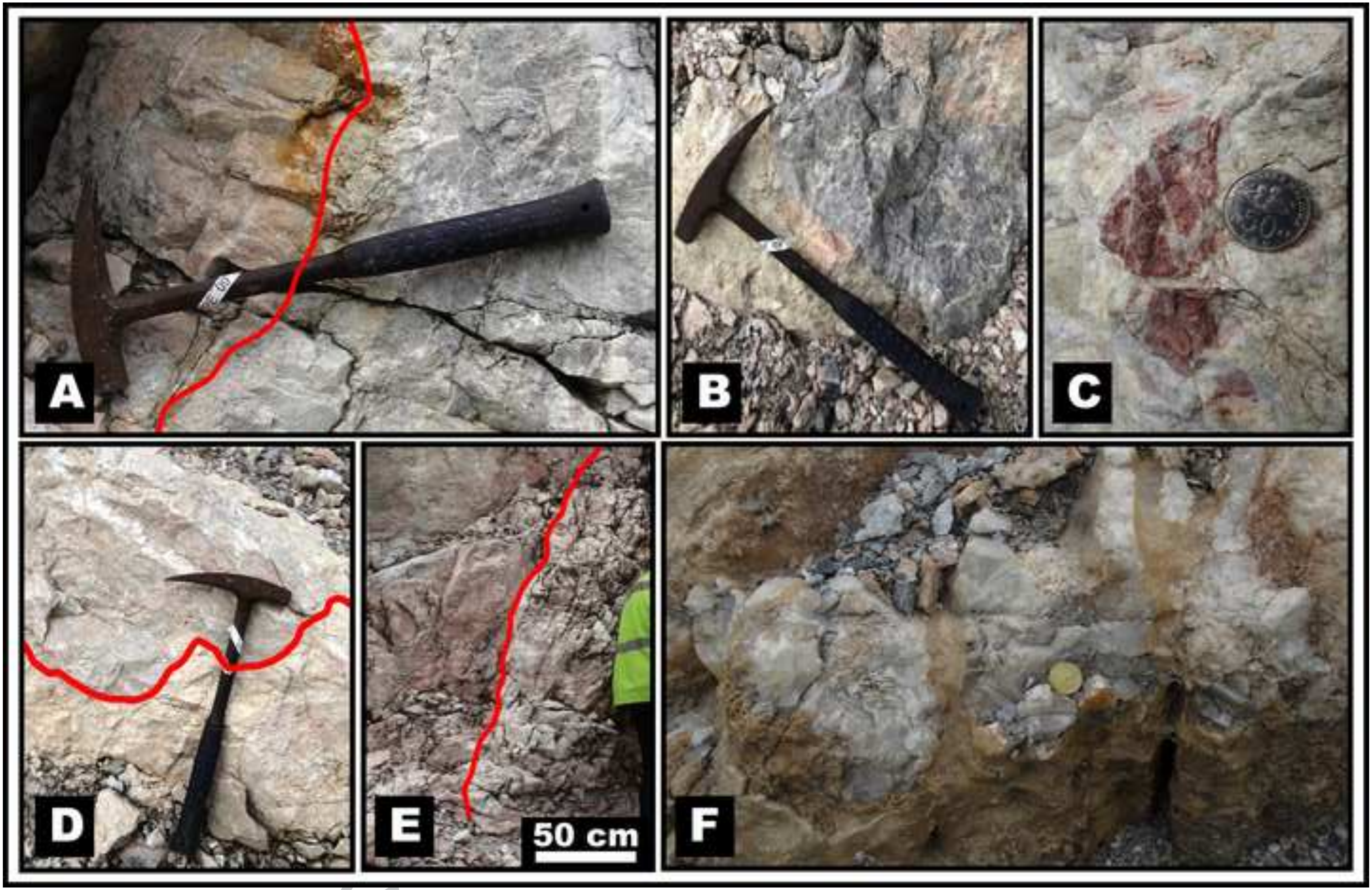
closed fractures that terminated below the surface, influx of hydrothermal fluid, second stage brecciation, and formation of fracture-controlled calcite. Heat conductance and pressure by mantle upwelling due to regional uplift and exhumation in Late Cretaceous might have significantly influenced this phase. Also, tectonic quiescence soon after this event is reflected in the larger, clear, perfectly rhombohedral calcite crystal clusters. **F:** This phase is probably of Cenozoic age (normal faulting and strike-slip faulting), leading to younger faulting events, topographic evolution, and exhumation of overburden and exposure of the buried carbonate mudstones to atmospheric elements.

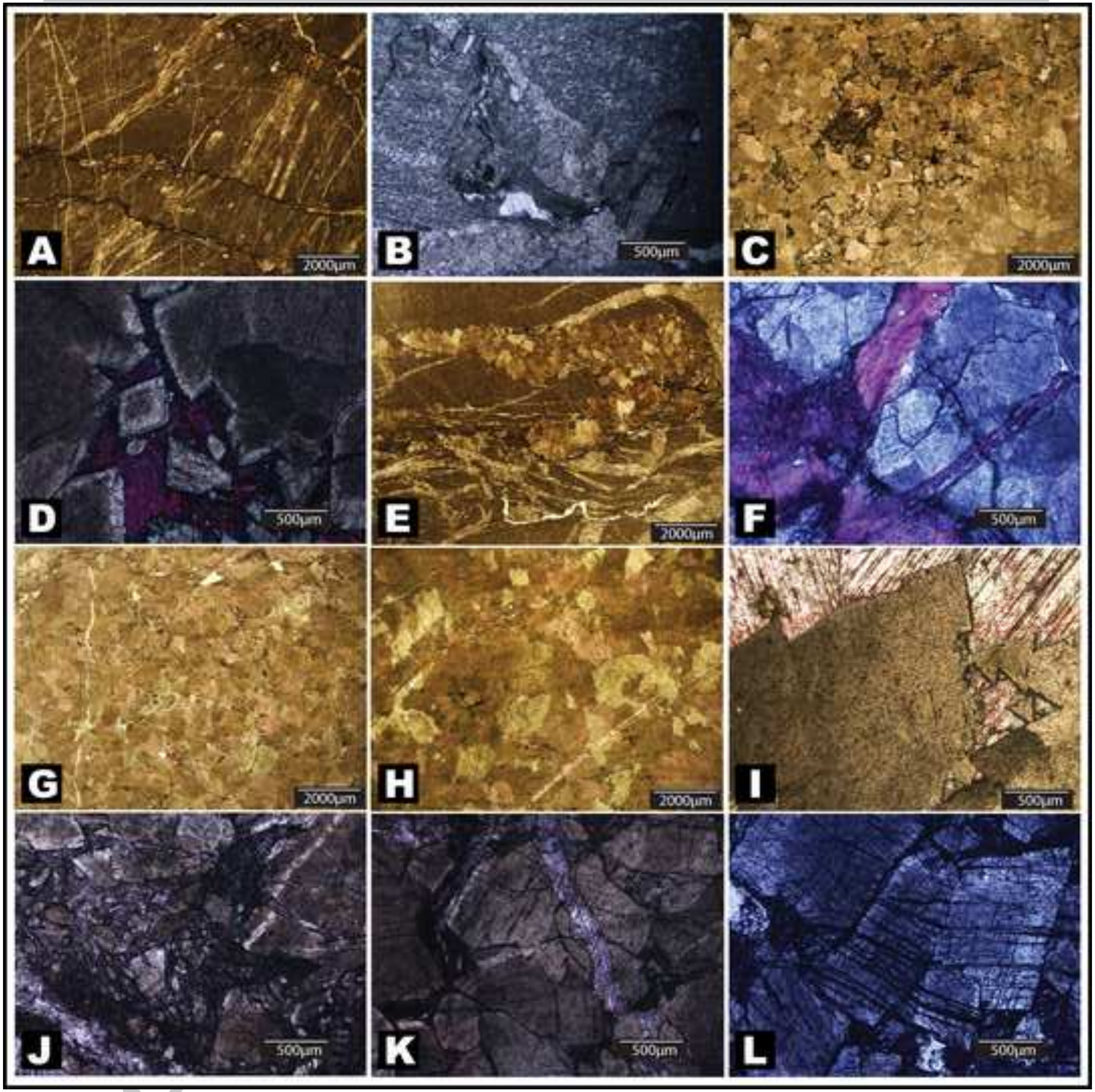

A
Vietnam
Malaysia
South China Sea
Sumatra
Borneo
Elevation (m)
4046
0
500 km
100°E
106°E
112°E
118°E
B
C
Western Belt
Eastern Belt
Central Belt
MALAYSIA
South China Sea
Langkawi Island
Penang
Ipoh
Redang Island
Terengganu
Kuantan
Straits of Malacca
Kuala Lumpur
Tioman Island
Malacca
Sumatra
Johor Bahru
100 km
100°E
104°E
102°E
6°N
4°N
2°N
Kledang Range
Main Range
Kinta Valley
Ipoh
Batu Gajah
Q
C
P
Quaternary
Permian
Permian Limestone
Carboniferous Limestone
Carboniferous black shales
Ordovician Limestone
Ordovician interbedded Sandstone and Mudstone
Late Triassic/Early Jurassic Granites
Main Range
2A
X
Y
Kinta Valley
Kledang Range
D

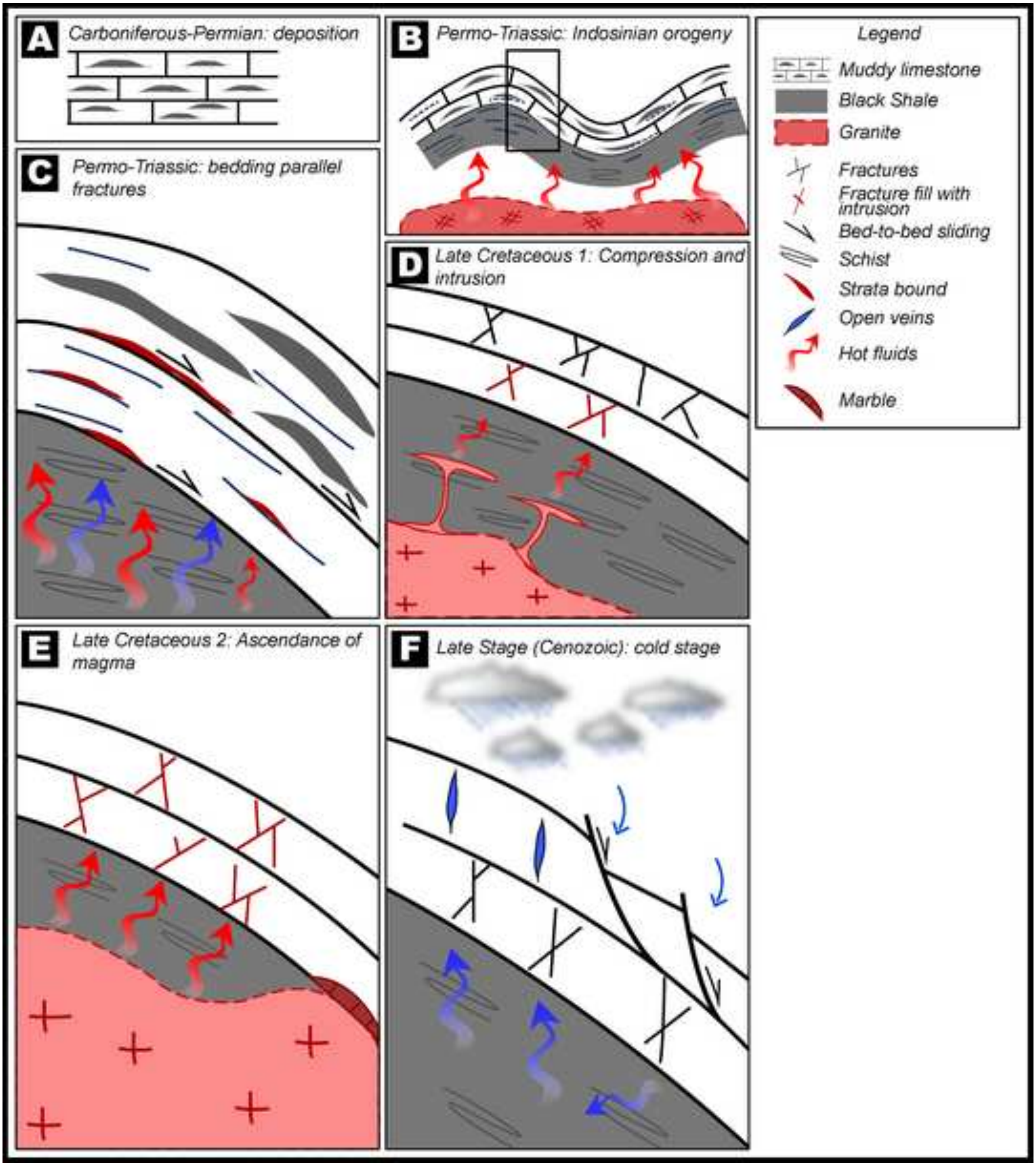

X
Y
12.5 km
750 m
0 m
-750 m
-1500 m
A
Quaternary alluvium
Lower Paleozoic basement
Permian limestone
Trias/Jurassic granite
Granite arena
Indosinian thrust faults
Post Indosinian normal faults
Indosinian Orogeny (210 - 180 Ma)
Contact metamorphism (Banjaran Caves)
Late K - Paleogene Orogeny (80 - 50 Ma)
Paleogene - Neogene Rifting (40 - 20 Ma)
B
Permian limestone
Paleozoic schist
L. Tr. - E. Jurassic Granite
Conjugate fractures
Meteoric water
Thermally heated water


A
B
C
D
E
F
6 m
1 m
G
2 m
10 m
1
2
3
4
5
Lithology boundary
Bedding
Major fracture
Bedding-parallel fracture
Bedding-perpendicular fracture
Minor fracture


A
B
B
C
D
Major fracture
Displacement
Fold


A
B
C
D
E
50 cm
F


A
2000µm
B
500µm
C
2000µm
D
500µm
E
2000µm
F
500µm
G
2000µm
H
2000µm
I
500µm
J
500µm
K
500µm
L
500µm


A
Carboniferous-Permian: deposition
B
Permo-Triassic: Indosinian orogeny
Legend
Muddy limestone
Black Shale
Granite
Fractures
Fracture fill with intrusion
Bed-to-bed sliding
Schist
Strata bound
Open veins
Hot fluids
Marble
C
Permo-Triassic: bedding parallel fractures
D
Late Cretaceous 1: Compression and intrusion
E
Late Cretaceous 2: Ascendance of magma
F
Late Stage (Cenozoic): cold stage

Highlights

- The Palaeozoic carbonates strata- and fracture-bound hydrothermal dolomites in Kinta Valley, western Peninsular Malaysia.
- Enlisting of regional tectonic and magmatic events in chronological order with phases of dolomite formation.
- The control of dolomitization by texture and varied bulk chemistry, together with the nature of circulating fluids.

Graphical abstract