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Conceptualizing fluid-rock interaction diagenetic models with focus on tectonic settings

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ABSTRACT

A new conceptual diagenetic model is proposed to better understand the relationship between multi-scale tectonic and the ensuing diagenetic processes, whereby the physio-chemical fluid-rock interaction processes are linked to tectonic controls, in terms of creation or destruction of accommodation space, the evolution of overburden and compaction, exhumation, as well as fracturing and creation of fluid flow pathways. In our research, key processes involved in diagenetic fluid-rock interactions have been applied to a recent multi-scale tectonically induced sedimentation model in order to define a linked diagenetic-tectonic cyclicity concept. We demonstrate the applicability of this concept in various tectonic and depositional systems with worldwide examples. Four distinct diagenetic fluid types modify the properties of sedimentary systems, which are basinal fluids, compactional fluids, meteoric fluids, and fault-associated fluids. The related, time-independent, diagenetic facies and their extent in the subsurface defined as diagenetic facies tracts include the modified rock affected by a singular diagenetic fluid or process. The proposed diagenetic facies tracts are the basinal diagenetic facies tract, compactional diagenetic facies tract, meteoric diagenetic facies tract and fracture-associated diagenetic facies tract. Their subsurface extent is controlled by the tectonic evolution, and we demonstrate that quantification and prediction is possible using a previously defined tectonic successions model. Each diagenetic facies tract is associated with a set of diagenetic processes and resulting products, that ultimately impact the pore space of the host rock and its flow properties. The combinations of several diagenetic tracts (into diagenetic facies tracts complexes) have been assessed, showing that the optimal situation for enhanced flow is the one that combines meteoric diagenetic facies tracts with fracture-associated diagenetic facies tracts, where karst dissolution together with fracturing are common. Contrastingly, quiescent tectonic settings with a typical burial history result in excessive cementation and therefore reduced flow. These attributes are critical for the large-scale screening and quantification of subsurface geo-resources, conventional and particularly important for the sustainable ones (e.g., geothermal energy) and geological storage (e.g., CO_2 or energy) that are associated with enhanced fluid-rock interaction processes.

1. Introduction

Diagenesis entails a sub-metamorphic group of processes that change the composition and texture of sedimentary rocks (Bathurst, 1975; Burley et al., 1985; Moore, 2001; Nader, 2017). These changes occur in the presence of fluids, during burial and/or exhumation, or by changes in the external or internal forcing of the sedimentary system (Moore, 2001; Nader, 2017). They involve physical, chemical, or biological processes working independently or in concert and are manifested by alterations in the ambient conditions in a specific depositional setting or during the subsequent burial or exhumation (Moore, 2001; Tucker, 1993). Within various marine or continental domains, these processes may include exposure to meteoric water or to extrinsic fluid circulation within developing fractures, or by changes of intrinsic fluid compositions (Al-Aasm et al., 2011; Nader, 2017; Swennen et al., 2012). In practice, diagenesis involves three main routes characterized by rock

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dissolution, cementation, or replacement with various mineral phases (Nader, 2017). We study the diagenetic processes by their products and by the tracers left in the rock, inferring the prevailing conditions, and forcing factors at the time of the transformation (Longman, 1980; Tucker, 1988).

Fluid-rock interactions are always driven by modifications in the physio-chemical conditions during the overall evolution of sedimentary basins, whether they are changes in the external factors, such as climate, burial and exhumation by tectonics, rate of sediment influx from the source area, or by changes in the internal factors, such as groundwater circulation, changes in the fluid overpressure and compaction, or the chemistry of circulating fluids (Moore, 2001; Worden and Burley, 2003a). Such modifications manifest themselves at multiple temporal scales, ranging from the hundreds of millions of years of plate tectonic cycles, to the shorter time scales at which we exploit subsurface geo-resources (Nader, 2017; Tucker, 1993). The latter can occur during fluid extraction or injection while exploiting the reservoirs for conventional or sustainable geo-resources and storage (e.g., CCS, energy) (Delerce et al., 2021; Gan et al., 2022). These changes also take place at multiple spatial scales, from the tens to hundreds of kilometres of an entire sedimentary basin, to the microscopic scale of pore networks where cementation and dissolution takes place (Nader, 2017; Swennen et al., 2012; Tucker, 1993). Furthermore, fluid-rock interactions often take place in an open system, in which fluid(s) can be externally injected or extracted at both the longer geological time scales, and at the shorter, societally relevant, reservoir exploitation time scales (Kazmierczak et al., 2022).

Previous studies have demonstrated that a key first-order control over diagenetic processes is provided by tectonics (Fontana et al., 2014; Nader et al., 2004; Roure et al., 2005; Siever, 1979), particularly in basins where sedimentation responds rapidly to the creation or destruction of accommodation space for reworked sediment by the activity of faults or deep-seated geodynamic processes, such as dynamic topography (e.g., Matenco and Haq, 2020; Rosenberg et al., 2018; van Unen et al., 2019). Furthermore, faults provide effective fluid flow pathways for the circulation of reactive extrinsic fluids (Frery et al., 2015; Nader et al., 2004; Swennen et al., 2012). Matenco and Haq (2020), among others, have also shown that tectonically induced sedimentation has a quasi-cyclic nature, where sedimentary sequences or successions can be described either using sequence-stratigraphic, sedimentologic or tectonic terminologies. In this framework, the genetic link between the overall multi-scale tectonic cycles and their external forcing on diagenetic processes is not well understood. Existing studies have focused either only on the response of sedimentation to tectonics (e.g., Matenco and Haq, 2020 and references therein) or only analyzing diagenesis in specific structural or tectonic settings that include extensional, continental exhumation, contractional or strike-slip settings (Roure et al., 2005; Shah et al., 2012; Vilasi et al., 2006).

Here we aim to advance our understanding of the relationship between multi-scale tectonic and diagenetic processes by defining a conceptual model where the physio-chemical fluid-rock interaction processes are linked genetically to tectonic controls, in terms of creation or destruction of accommodation space, the evolution of overburden and compaction, exhumation, as well as fracturing and creation of fluid flow pathways. Towards this objective, we will first review the processes involved in diagenetic fluid-rock interactions, followed by the application of a recently proposed model of tectonically controlled sedimentation (the tectonic successions of Matenco and Haq, 2020), to visualize linked diagenetic-tectonic cyclicity and derive a concept that could be applied to various tectonic and depositional systems. We specifically choose to first describe processes involved in diagenetic fluid-rock interactions in genetic areas and at times where tectonic processes are less active (such as over a passive continental margin) to quantify and describe at a second stage these processes in various tectonically active areas and regimes. We subsequently discuss consequences of our conceptualisation for passive continental margins.

2. Diagenetic fluids and processes

The generic “fluid-rock interaction” term is commonly understood to describe rock alterations induced by diagenetic processes, such as the appearance of new or modification of existing mineral phases (e.g., cementation, dolomitization), dissolution, mechanical and chemical compaction, or fracture mineralization (Tucker, 1988). From a geochemical perspective, fluid-rock interactions are defined as exchanges of isotopes and/or elements caused mainly by changes in temperatures and/or redox conditions, creating dissolution or precipitation by chemical or mechanical creep (diffusion, dislocation), exchange reactions, or their combination (Hurai et al., 2015). Such interactions may occur in both closed and open systems, and they are governed by the water/rock ratio (w/r), calculated from mass-balance equations (Hurai et al., 2015; Robinson, 1993).

Several types of diagenetic processes have been ascribed to specific depositional environments in sedimentary basins, defining diagenetic environments (Figs. 1, 2). In such environments, sediments are either produced in-situ, or they are derived from erosion and redeposited within a source to sink transportation system. The marine, buried under overburden and meteoric diagenetic environments in both carbonate and siliciclastic rocks develop in multiples scales in space in relationship to the time of diagenesis and are defined as early (eogenesis), intermediate (mesogenesis), or late (telogenesis) diagenesis (Moore, 2001; Tucker, 1990). These environments are characterized by specific fluid types (seawater, brine, meteoric−/fresh-water, or water derived from deeper levels), as well as specific physio-chemical conditions (Breesch et al., 2011; Moore, 2001). These factors determine which specific processes will prevail and what diagenetic phases and products will result (Nader, 2017).

A carbonate platform depositional setting has several diagenetic environments (Fig. 1). The marine diagenetic facies associations include the inner evaporative lagoon and its protected areas, the shoals and reefs as well as the distal open sea areas (Parker and Sellwood, 1994). The sediment types, fluid chemistry and overall physio-chemical conditions are different in each of these facies associations (Parker and Sellwood, 1994). The lack of water circulation in protected lagoons and excess evaporation lead to elevated salinities, sulphate mineral precipitation, micritization and dolomitization, while in the more permeable shoals and reefs water circulation is higher and cementation prevails (Tucker, 1990). In the deeper, open sea areas, the types of precipitating and accumulated minerals are governed by the seawater chemistry and depth, such as the aragonite compensation depth and calcite compensation depth (Fig. 1) (Moore, 2001). The most representative diagenetic phase of the marine carbonate environment is the fibrous aragonitic cement (Scholle and Ulmer-Scholle, 2003). The burial diagenetic environment is characterized by a varying degree of fluid mixing sourced from shallow, derived marine, meteoric and basinal brines, or more deeply derived (the so-called “mantle-charged”) fluids (Moore, 2001; Fig. 1). Sediments can also undergo mechanical and chemical compaction processes, resulting in additional dewatering and fluid circulations (Moore and Wade, 2013). Stylolites and sparry cements are the most common burial diagenetic phases (Scholle and Ulmer-Scholle, 2003). Organic-rich components generate hydrocarbon and associated gases through diagenesis, which impacts the overpressure, evolved fluid chemistry and basin-scale fluid-flow (Robinson, 1993; Roure et al., 2005). The meteoric diagenetic environment is observed in areas exhumed by tectonics or by sea-level fall (Tucker, 1993). This environment can be typically separated in two zones, vadose and phreatic (Fig. 1), with distinct physio-chemical conditions and flow dynamics (Longman, 1980). In the vadose zone, the sediments are not saturated with water, resulting in open karst systems with pervasive dissolution due to percolating waters (Fig. 1), and spelean cement phases (Ford and Williams, 2007). In the phreatic zone, the sediments are saturated with water, resulting in reduced water circulation outside the fault zones and mosaic calcite cement phases (Scholle and Ulmer-Scholle, 2003).

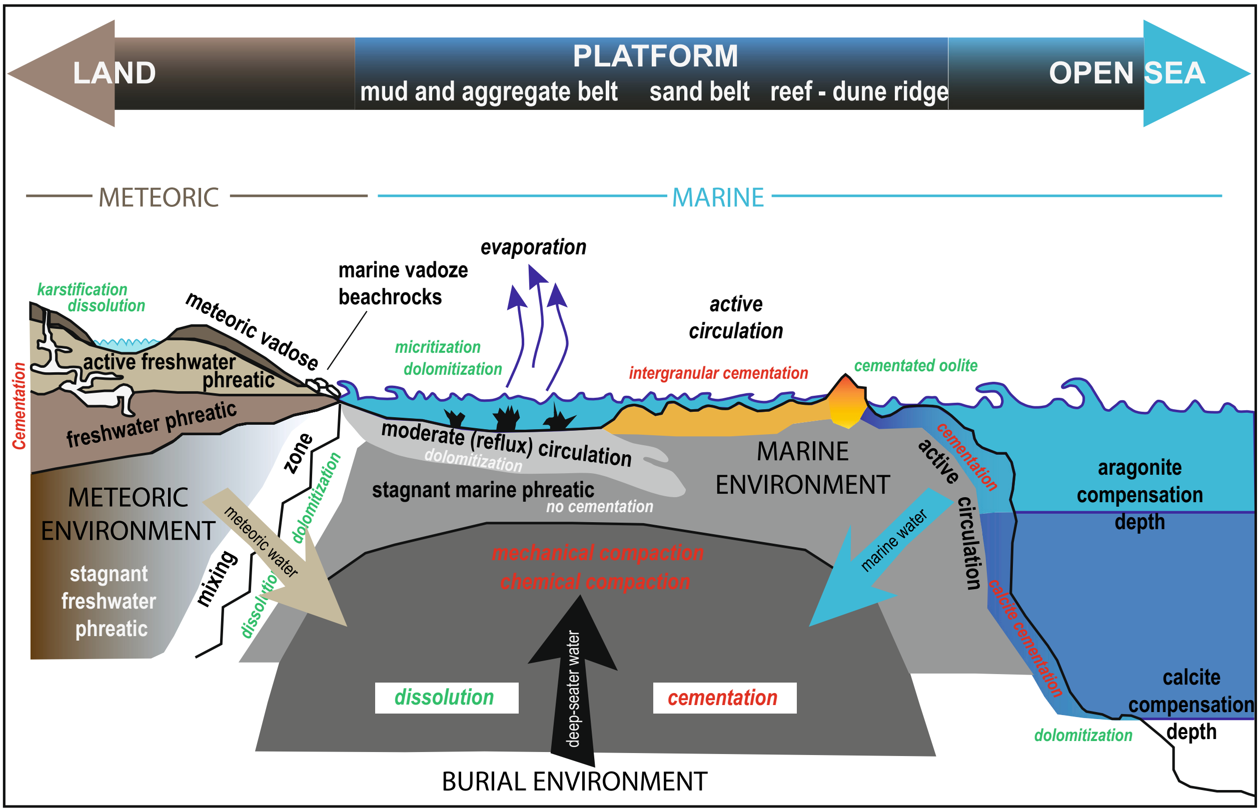


Fig. 1. Schematic representation of major diagenetic environments and its associated processes and products in carbonate depositional settings (modified from Longman, 1980; Parker and Sellwood, 1994). In this situation, significant are the diagenetic environments associated with marine, burial and meteoric fluids. The diagenetic processes are illustrated with green when they increase the bulk porosity and with red when they decrease the bulk porosity). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The diagenesis of siliciclastic sediments (Fig. 2) is significantly different when compared with carbonates, owing to their different processes of deposition and mineralogical composition (Burley et al., 1985; Worden and Burley, 2003a). While carbonates often form in-situ within their environment of deposition, siliciclastic sediments are produced as a result of weathering and erosion of exhumed basement and sediments, as well as the fluvial and aeolian transport before the eventual deposition in marine or continental basins (Burley et al., 1985). Therefore, the impacts of early diagenesis, which is influenced by climatic conditions and their transport to the main depocenter, is significant (Bertier et al., 2008; Worden, 2003). For instance, in humid and arid climates, aluminosilicate source sediments are weathered into gibbsite, kaolinite and smectites (Fig. 2), whereas a larger variety of clay minerals occurs in cooler and temperate climates (Worden and Burley, 2003). Environments of early diagenesis (fluvial and alluvial) are characterized during warm and dry climatic conditions by the development of calcretes, dolocretes, and gypcretes closer to the main sink area (Fig. 2). The salinity of water increases downstream with further evaporation and weathering of detrital grains (Fig. 2). This leads also to higher Mg/Ca ratios during early calcite precipitation (Worden and Burley, 2003). Under humid, temperate climatic conditions, fresh and oxidized water prevails in the fluvial diagenetic environments, resulting in lower salinity, pH and Fe-content (Fig. 2). Hence, kaolinite and minor carbonate minerals dominate the sand infill of the fluvial channels where freshwater percolates (Bertier et al., 2008; Worden and Burley, 2003). Smectite or ‘green-clays’ (i.e., Fe-rich smectite) and silica cement are found in stagnant water bodies, where increasing silica and potassium concentrations prevail (Leckie and Cheel, 1990). The organic-rich silt and detrital clay in abandoned channels with vegetation cover lead to the formation of peat followed by bleaching of sands, and precipitation of kaolinite and siderite nodules (Boles and Franks, 1979; Worden and Burley, 2003). In marine environments with continuous burial (Fig. 2), such sediments that became saturated with seawater, are subjected to bacterial mediated processes (e.g., iron and sulphate reduction, methanogenesis and decarboxylation) resulting in the precipitation of calcite, glauconite, pyrite, dolomite and ankerite, as well as hydrocarbon generation (Odin and Matter, 1981; Worden and Burley, 2003). During burial diagenesis, porewater is released from sediments due to mechanical and chemical compaction processes, which start at 1–2 km burial depths and temperatures between 30 and 70 °C (Morad et al., 2000). Reactive fluids that are responsible for the related dissolution and cementation are the by-products of the dehydration of clays, gypsum and organic matter (Morad et al., 2000). Fluids are released from buried sediments and flow along high permeability pathways (Fig. 2). Further burial results in increasing temperatures causing petroleum generation and migration as well as overpressure build-up (Benchilla et al., 2003; Robinson, 1993). After burial, sediments may be exhumed into the (near-)surface environment, whereby mixing of influx of meteoric water with the formation basinal water results in cementation, and a decrease in the bulk rock porosity (Morad, 1998; Worden and Burley, 2003).

The configuration of diagenetic environments is variable with time and can overlap, resulting in mixing zones, affected by a larger range of fluids and prevailing conditions (Figs. 1 and 2). A continuous evolution from marine to burial and meteoric diagenetic environments may not always occur, and depends on the external forcing factors, such as tectonics and sea-level variations, which modify their boundaries and the overburden (Nader, 2017). Consequently, one depositional facies may witness several diagenetic environments that change their charged fluids with time (Moore, 2001; Morad et al., 2000; Tucker, 1990). These evolving environments from the original to the diagenetic ones make the characterization of diagenetic cycles in sedimentary basins quite challenging (Muchez et al., 2000; Roure et al., 2005), and individual studies

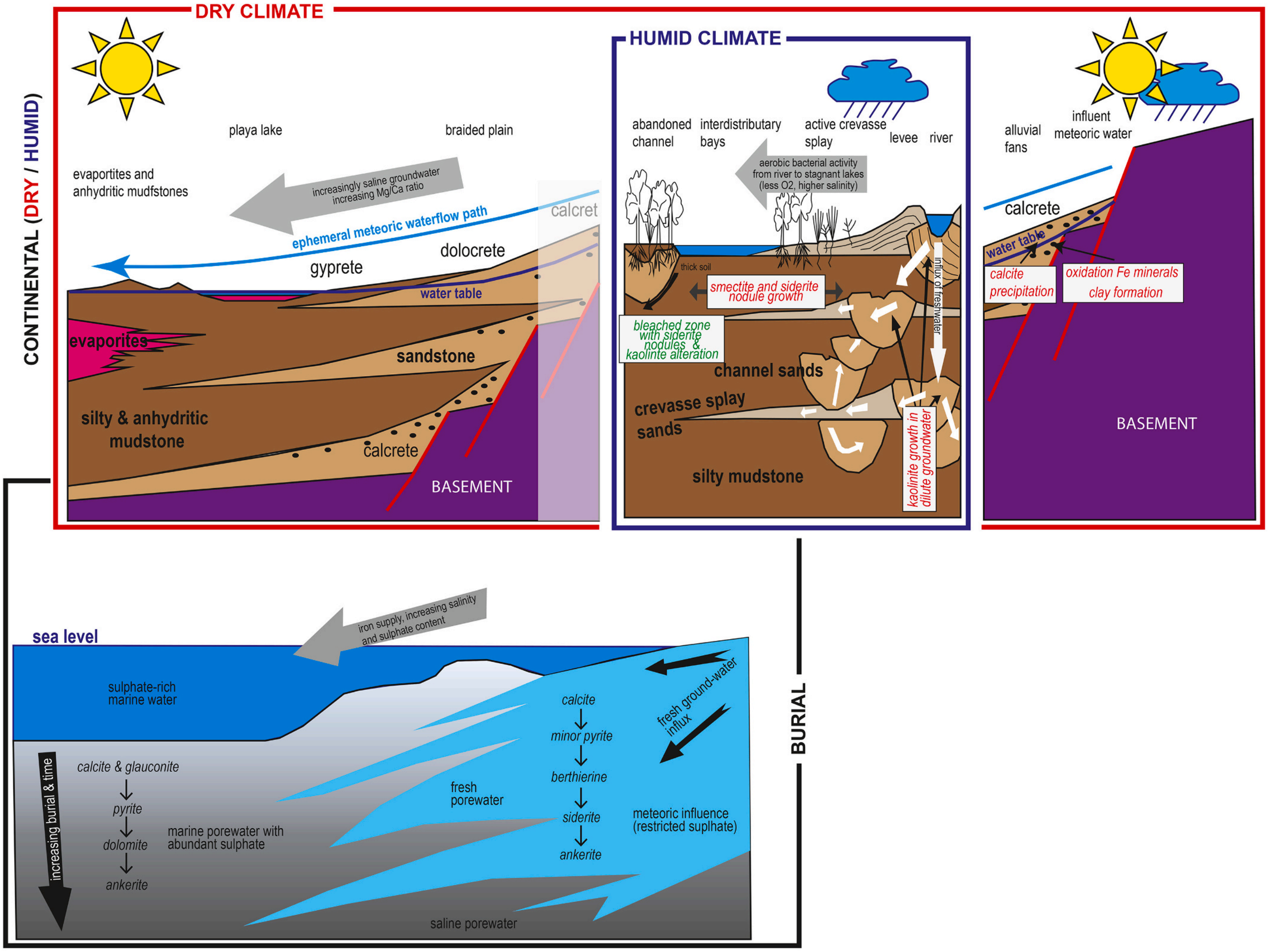


Fig. 2. Schematic representation of major siliciclastic diagenetic environments, related processes and products in continental settings under dry/arid and humid climatic conditions (adapted from Worden and Burley, 2003). Diagenetic products in burial environments with marine or continental lacustrine are also shown. These are illustrated with green when they increase the bulk rock porosity and with red when they decrease the bulk rock porosity). The major diagenetic environments are those associated with evolving meteoric and fresh water that is influenced by climatic conditions, mineralogy of the sediments, and increasing burial and temperatures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are often based on specific regional settings, rather than a widely applicable genetic model.

Any diagenetic environment can be spatially or temporally defined as being influenced by a combination multiple types of fluids (Fig. 3). Fluids intrinsic to the sedimentary basin are basin fluids derived from the marine environment and compaction fluids generated by their expulsion from the underlying sediments (Fig. 3). Extrinsic fluids have an external source and invade the sediments by mixing with or displacing the intrinsic fluids (Nader, 2017). The extrinsic fluids can be classed as meteoric fluids that invade from above (topography-driven, Roure et al., 2005) and fracture-associated fluids (often termed as “hydrothermal” due to their higher temperatures) invading from the underburden (Fig. 3).

The basin fluids (Fig. 3) are derived from evolved sea water that interacts with sediments to induce cementation and mineral replacement. Typical products of the interaction with carbonate sediments in marine domains are isopachous fibrous aragonitic cement crystals forming continuous rims around grains or botryoidal fan-shaped structures composed of fibrous crystals (Moore, 2001; Scholle and Ulmer-Scholle, 2003). Basin fluids transform ooids composed of aragonite minerals into stable calcite-phases associated with variable contents of magnesium. The transformation of calcite into dolomite (i.e.,

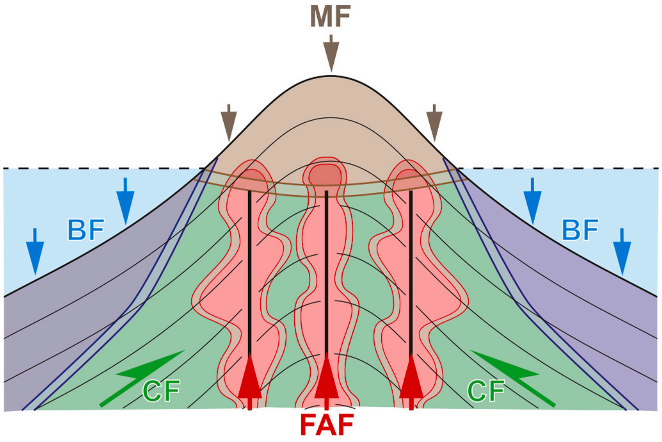


Fig. 3. Schematic illustration showing the typical diagenetic environments and the associated fluid types. FAF: fault-associated fluids, CF: compaction fluids, BF: basin fluids, MF: Meteoric fluids.

dolomitization) takes place by continuous pumping of Mg-rich water, often in association with sulphate precipitation in evaporitic marine environments (Bathurst, 1975; Machel, 2004). Such reactions create a neomorphic increase in crystal size (Nader et al., 2004; Scholle and Ulmer-Scholle, 2003). The overall impact of these processes on the bulk porosity of sediments is usually negative, with a general decreasing trend with increasing interaction time with evolved basin fluids (Nader, 2017). In clastic depositional environments, the interaction of reducing organic matter, oxidizing inorganic fluids and reactive mineral phases, mainly sulphates and iron oxides, result in alteration of sediments and the precipitation of pyrite, carbonates, glauconite, illite and smectite (Hesse, 1986; Irwin et al., 1977; Tucker, 1990).

The compaction (or burial) fluids (Fig. 3) are pre-existing fluids in sediments characterized by normal burial temperatures and normal or over-pressured conditions (Moore, 2001). Mechanical and chemical compaction of sediments lead to dewatering (or fluid extrusion) as well as fluid and heat transfer (Rowan et al., 2002; Tucker, 1990). In these conditions, pressure dissolution, such as stylolites formation, and cementation occurs (Morad et al., 2018). In open systems, the fluids and chemical species may travel far away from the site of dewatering and pressure dissolution, being characterized by a large variety of chemistry, salinity, and temperatures (Ferket et al., 2000; Roure et al., 2005). These fluids disperse through more permeable rock facies (Fontana et al., 2014). Once oversaturated with respect to specific mineral species and through interaction with the host rocks, several diagenetic processes may occur in terms of dissolution, cementation, or mineral replacement (Moore and Wade, 2013; Nader, 2017). The flow patterns follow the margins of the sedimentary system under burial, mostly along active faults and permeable facies (Guilhaumou et al., 2000; Roure et al., 2005). Typical examples are burial dolomitization, which increases the bulk porosity of the carbonate mass-rock, or hypogene dissolution, often associated with hydrocarbon generation, which creates large karstic networks in carbonate and leaching in siliciclastic sediments (Palmer, 2007; Robinson, 1993; Swennen et al., 2012; Swennen et al., 2000). Massive cementation may occur creating poikilotopic sparry calcite cements filling all existing pore-space (Scholle and Ulmer-Scholle, 2003), leading to decrease in porosity. However, in the prevailing burial conditions, this process may also lead to overpressure, fracturing and fluid escape (Moore, 2001).

The major processes known to dominate during the burial of clastic sediments are associated with the progressive increase in overburden and temperatures (Morad et al., 2000). At burial depths equivalent to temperatures of 70–90 °C, smectite is progressively replaced by illite (Boles and Franks, 1979). K-feldspar dissolution occurs at depths of 1.5 km (50 °C), becoming more extensive at 2.5 km to 4.5 km (150 °C; Worden and Burley, 2003). At depths equivalent to temperatures greater than 70 °C, and mostly above 130 °C, the reaction of kaolinite with K-feldspar produces illite and quartz (Bjørkum and Gjelsvik, 1988). Quartz cement precipitates at temperatures exceeding 70–80 °C and prevails at temperatures higher than 80–100 °C (Giles et al., 2000). Fe-rich clays (berthierine) convert into grain-coating chlorite at burial >3 km and temperatures higher than 90–100 °C (Ehrenberg, 1993). Ferroan dolomitic cements (and other carbonate cements) precipitate at temperatures greater than 100 °C, under varying diagenetic conditions, and are prone to recrystallization with increasing temperatures (Morad, 1998). Gypsum dehydrates to form anhydrite at depths between 1.5 and 4 km (50–120 °C) depending on salinity, pressure, and thermal gradients (Hardie, 1967). The remaining early diagenetic kaolinite is affected by pervasive dissolution and reprecipitation (as dickite) at burial depths of 3–4.5 km, temperatures between 90 °C and 130 °C (Ehrenberg, 1993). Kaolinite can be also replaced by chlorite (Aagaard et al., 2000).

Meteoric fluids (Fig. 3) are under-saturated when compared with the marine environment, with a chemistry that often fluctuates, particularly in lacustrine settings (Tucker, 1990). The difference in chemistry results often in massive dissolution, particularly relevant in carbonate systems, where the term karstification is used to define dissolution large vugs, channels and caverns (Choquette and Pray, 1970). A relatively minor cementation is observed in meteoric phreatic settings, observed by mosaic equant calcite cement, where saturated meteoric water continuously circulates through the recharge (Scholle and Ulmer-Scholle, 2003). Meteoric fluids also affect clastic sediments, resulting in the oxidation of reduced ferroan cements (Fe-calcite/dolomite, ankerite, siderite), the dissolution of feldspars and chert (Shanmugam and Higgins, 1988), and alteration of feldspars to clay minerals (Emery et al., 1990). Such meteoric processes only affect the first tens of meters below the siliciclastic host-rock surface (Emery et al., 1990; Worden and Burley, 2003), and the associated dissolution features are referred to as “pseudokarst” (Palmer, 2007). The typical processes of carbonate meteoric diagenesis, namely extensive karst dissolution, do not occur in siliciclastic host-rocks (Worden and Burley, 2003).

Faults and fracture zones play a specific role in facilitating the circulation of fluids (Fig. 3) and their mixing in the host sediments (Davies and Smith, 2006; Frery et al., 2015; Vandeginste et al., 2012). Fluids are generated during burial through several processes, such as smectite to illite reactions, source-rock maturation (producing hydrocarbon, water, CO_2, H_2S, or N_2), and gypsum dehydration (Robinson, 1993; Worden and Burley, 2003). Deeper fluids with higher temperature escape towards the surface using the faults and fractures systems, bringing extrinsic chemical species, and creating similar or different types of fluid-rock interactions when compared with burial compaction fluids (Tucker, 1990). For instance, an influx of low salinity water may result in dissolution of feldspars and carbonates in sandstones, whereas an influx of high salinity water may result in precipitation of authigenic cements (Bertier et al., 2008; Worden and Burley, 2003). The characteristics of the fault-associated fluids are based on their circulation along the fractures and their pumping mechanisms (by overburden or deeper seated, such as true hydrothermal, deeper derived or generated by an increase in the heat-flux). The flow takes place throughout the fracture’s active life (Davies and Smith, 2006; Frery et al., 2015; Roure et al., 2005; Vilasi et al., 2009). This is very well illustrated with crack-seal veins, formed by repeated fracturing and sealing (Passchier and Trouw, 2005), by cementation, localization inside the vein (syntaxial veins), or at the vein-host rock interfaces (anti-axial veins; Fontana et al., 2014). In general, according to our observation, while the matrix porosity is reduced, the permeability is enhanced along faults, as long as they remain active.

3. Multi-scale tectonic-diagenetic tracts and their composite diagenetic facies complexes

The infill of sedimentary basins is primarily controlled by the interplay of the rate of changing the accommodation space and the rate of sediment supply (Schlager, 1993). On passive continental margins sediment progradation and its associated facies distribution occurs when the rate of creating accommodation is lower than that of sediment supply, while retrogradation or back-stepping occurs when the rate of creating accommodation space is higher and aggradation or building-up stratal architecture when creating accommodation space and sediment supply are equal (Matenco and Haq, 2020). In a sequence-stratigraphic analysis, such sedimentary architectures and facies successions are associated with the dynamics of shoreline movement that are controlled by sea-level fluctuations (Catuneanu et al., 2009; Vail et al., 1977).

Tectonically induced sediment infilling of basins has been conceptualized in the past where faults play an important role in the sedimentation dynamics (Martins-Neto and Catuneanu, 2010; Ravnas and Steel, 1998). More recently, Matenco and Haq (2020) proposed a first principal description of tectonic successions nomenclature that relates to the observed facies resulting from the changes in the rates of creation of accommodation space and sediment supply in response to specific tectonic movements (Fig. 4). This model is applicable both at lower-order and higher-order scales in fault-bounded sedimentary basins. The basin infill is composed of alternating sourceward-shifting facies

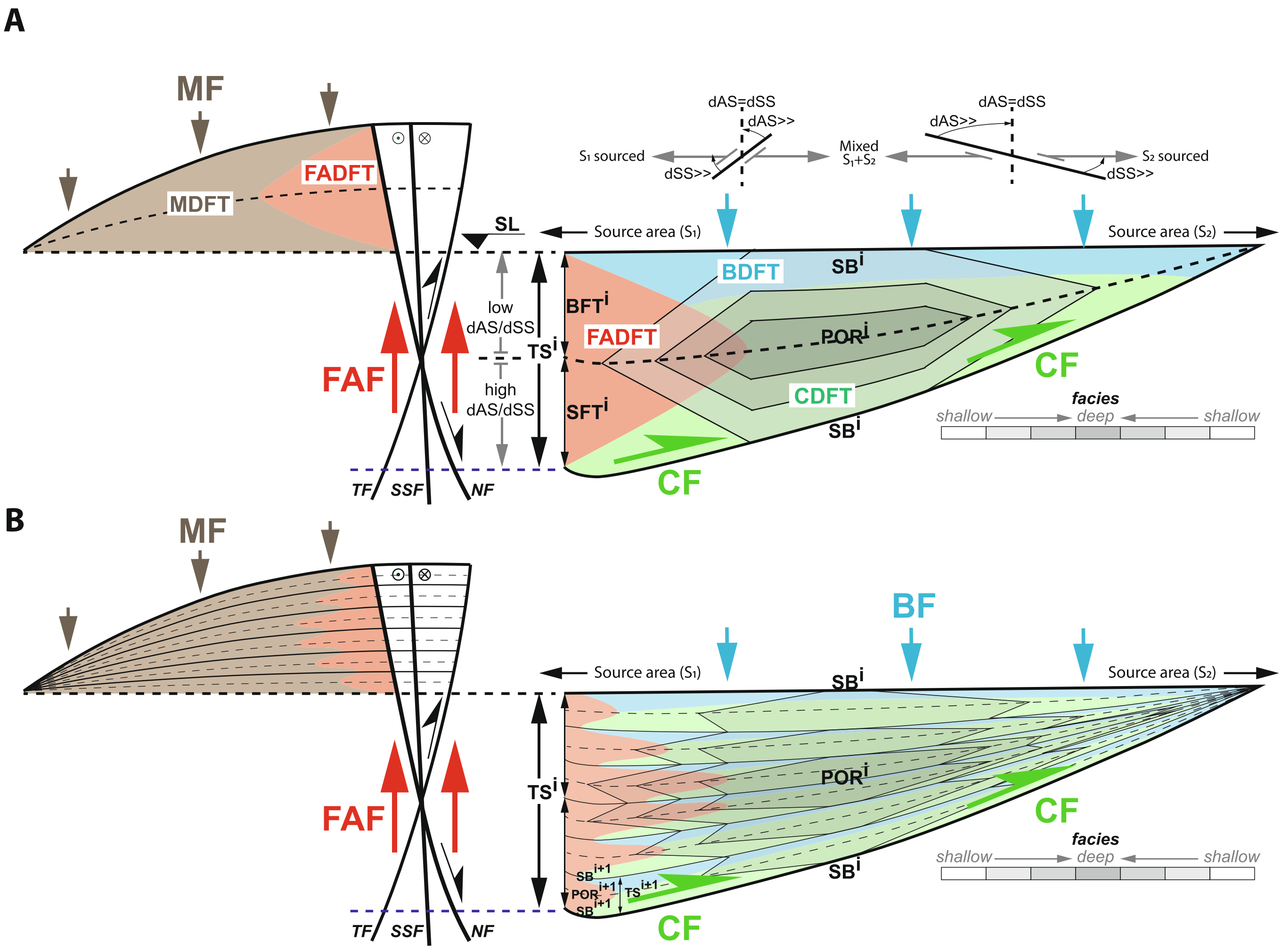


Fig. 4. Conceptualization of time-independent diagenetic facies tracts within the framework of tectonic successions as defined by Matenco and Haq (2020). Tectonic successions (TS) have been defined as lower-order (i) and higher-order (i + 1) packages of sediments in fault-bounded sedimentary basins that are composed of a sourceward-shifting facies tract (SFT) and a basinward-shifting facies tract (BFT). These facies tracts are separated at a point of reversal (POR), which is the position where the rate of sediment supply (δSS) exceeds the rate of creation of depositional space (δAS).The black lines in the middle indicate the type of faults, normal (NF), thrust (TF) and strike-slip (SSF), offsets that create the wedge-shaped depositional accommodation space in the hanging-wall, footwall or transtensive compartment of the fault, respectively. The opposite compartment records uplift that may exhume rocks to sub-aerial conditions (as sketched in the figure) or remain in sub-aqueous conditions (not sketched in the figure). S1 and S2 are the source areas of sediment supply, SL denotes sea-level, SB are succession boundaries, δSS is the rate of sediment supply, δAS is the rate of creation/destruction of the accommodation space. The direction of migration diagenetic fluids is illustrated with arrows (FAF: fault-associated fluids, CF: compaction fluids, BF: basin fluids, MF: Meteoric fluids). Similar colours illustrate diagenetic facies tracts (FADFT: fault associated diagenetic facies tract, BDFT: basin diagenetic facies tract, CDFT: compaction diagenetic facies tract, MDFT: meteoric diagenetic facies tract).

tracts and basinward-shifting facies tracts. Here, we extend this model by including uplift motions along faults and the prevailing type of diagenetic fluids mentioned above (Fig. 3), as well as their impacts on the flow properties.

For tectonic successions affected by diagenetic processes, one can conceptualize the resulting products as time-independent diagenetic facies and their total geographic extent as diagenetic facies tracts (Fig. 4a). A diagenetic facies tract defines the modified rock affected by a specific diagenetic fluid and/or process. Since tectonic facies tracts are also essentially time independent (i.e., fault-associated sedimentation can have a singular or similar origin at variable time scales), by analogy individual diagenetic facies tracts can also be considered time-independent. But there is one clear distinction of the latter from the former: over the longer time scales, sediment undergoing diagenesis can be multiple times affected by multiple types of fluids, up to a period of several millions of years. Such a diagenetically transformed body of rock, affected by multiple phases of alteration, is better termed as a diagenetic facies complex. We envision that such diagenetic facies complexes to be composed of individual diagenetic facies tracts.

The basinal diagenetic facies tract (BDFT) groups together all diagenetic products generated by marine water interaction (after infiltration) with the underlying sediments (Figs. 1, 2). Similarly, the compaction diagenetic facies tract (CDFT) groups all diagenetic products formed by interaction between fluids released during burial and compaction with the sediments (Figs. 1, 2). CDFT is dominant in the lower part of the overburden where the burial load is greater, while in the upper part they dynamically interact with basinal fluids (Fig. 4). The meteoric diagenetic facies tract (MDFT) comprises all diagenetic products created by the interaction of meteoric fluids infiltering the underlying sediments, whether by dissolution or precipitation (Figs. 1, 2). The fault-associated diagenetic facies tract (FADFT) contains the diagenetic products associated with fluid migration along faults. On the fault section that creates accommodation space (the down-throw side in Fig. 4), the fault-associated fluids dynamically interact with the basin and compaction fluids. On the fault section that is uplifting, the interaction can be dual. If the uplift creates sub-aerial exposure, then fault-associated fluids interact with the meteoric fluids (see Fig. 4A). But if the uplifted part remains sub-aqueous (not shown in Fig. 4), the fault-associated fluids interact with the compaction and basinal fluids in the significantly thinner sediments deposited on this fault compartment (for instance in a wedge-top basin). In the lower part of the tectonic succession the burial is deeper and can release more compaction fluids, while in the upper part of the succession, the infiltration of basinal fluids is higher given the higher permeability of less consolidated sediments. The overall geometry of the FADFT is further dependent on the interplay between the rate of slip along faults, where a higher rate releases more fault-associated fluids, as well as on the permeability of sedimentary facies invaded by fault-associated fluids. We have simplified our concept to illustrate the spatial coincidence between the maximum width of the zone invaded by fault-fluids with the point of reversal (Fig. 4A). However, in the original concept of Matenco and Haq (2020), the point of reversal marks the change where the rate of sediment supply exceeds the creation of accommodation space and is not necessarily the moment of maximum rate of slip along the faults. The change from slow to rapid filling of accommodation due to increased sediment supply at the point of reversal also implies that the rock permeability may be lowest near the basin centre at this time, which may limit the width of the of the zone invaded by fault-associated fluids. Thus, it is likely that the maximum width of this zone of fluid invasion does not coincide with the point of reversal and may be located more in the domain of the sourceward shifting facies tract (Fig. 4A). This is also where the rate of slip along faults maximizes, being modulated by the distribution of permeability towards the basin centre. The same logic applies to the uplifted faulted compartment, although the tectonic succession model does not provide a separate facies tract distribution on this side of the fault. In this case the maximum width of the zone invaded by fault-associated fluids would likely correspond to the moment when the rate of slip along fault maximizes.

Even though tectonic successions are considered to be time-independent, we can still envisage different orders of successions developing at different time scales. For instance, if we group two different orders of successions (a lower order *i* and a higher order $i+1$), then the superposition of higher-order cycles will create repetitive diagenetic facies tracts in the basin infill (Fig. 4B). Because the lower-order tectonic succession also has at the maximum rate of slip along the controlling fault, the resulting geometry will show a maximum width of the zone invaded by fault-associated fluids at or below the point of reversal (of the lower order tectonic succession). However, our concept (Fig. 4B) does not include intermediate or later diagenetic changes created by the subsequent burial of the high-order tectonic

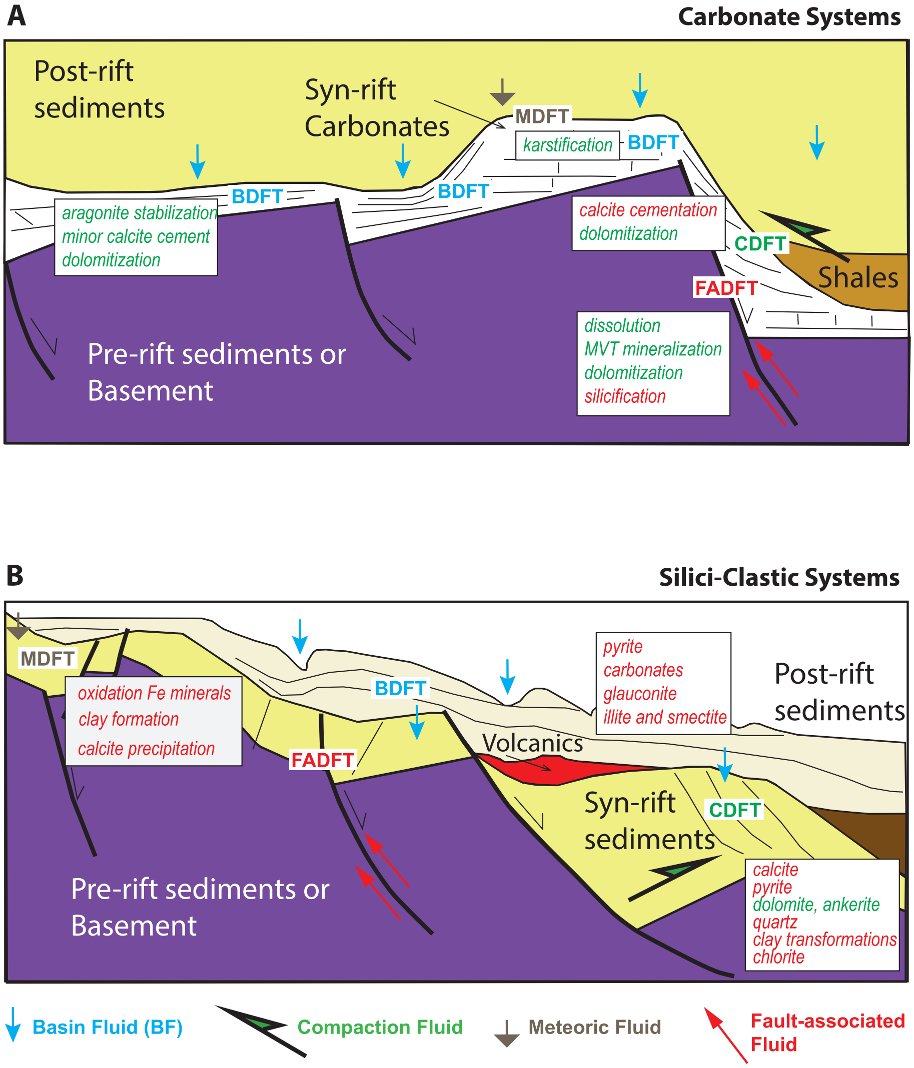


Fig. 5. Simplified illustrations of tectono-stratigraphic configurations in extensional basins with carbonate and siliciclastic sediment infilling (A and B, respectively). In both settings, the sediments are mainly dominated by basin fluids and the corresponding BDFT diagenetic facies tract. Compaction fluids prevail in the deeper, overburdened parts resulting in CDFT. At times of relative sea-level drop and/or subaerial exposure, meteoric fluids reach the sediments and establish zones of MDFT. The FADFT are along major faults, where the fault-associated fluids dominate. The associated diagenetic products are also shown in the figure. Modified from Kombrink (2008) for (A) and Nonn et al. (2019) for (B).

successions, which will be discussed in later sections.

4. Tectonic diagenetic facies tracts in tectonic settings

4.1. Extensional basins

Extensional basins result from lithospheric stretching by divergent tectonic movements, often reactivating older suture zones (e.g., Manatschal et al., 2015; Balázs et al., 2017). They are observed in continental rift settings (e.g., East African Rift) or back-arc regions (e.g., the Mediterranean, Southeast Asia; Chorowicz, 2005; Faccenna et al., 2013; Pubellier and Morley, 2014; Heron et al., 2016 and references therein). In such systems, the organisation of normal faults may result in the formation of quasi-symmetrical half grabens with changing kinematics along their strike, where the localization of deformation is often controlled by the inherited rheology of continental plates (e.g., van Wijk et al., 2008; Corti, 2009).

In extensional basins, the carbonate buildups are often found on the uplifted parts of the normal faults, where carbonate bio-constructors thrive (Fig. 5A), while the fine carbonate sediments settle in the fault-controlled local depocenter (on downthrown parts). The siliciclastics fill the extensional depocenters, on the downthrown parts of the normal faults featuring downlap and pinching out geometries (Fig. 5B). In such configurations, both clastic and carbonate sediments will be diagenetically influenced mainly by basinal fluids, particularly in the upper part of the overburden, resulting in basin diagenetic facies tracts (BDFT). The compactional fluids and associated diagenetic tracts (i.e., CDFT) prevail in the lower part of the overburden where the burial load is higher (i.e., higher accommodation and stratigraphic thickness). The fault-associated fluids would be obviously focused in fault zones, resulting in the occurrence of fault-associated diagenetic facies tracts (FADFT). Surface-exposed areas due to relative sea-level drop and/or uplift along faults, as well as carbonate over-production (exceeding sea-level rise) may also be affected by meteoric fluids and the associated diagenetic facies tracts (MDFT). Normal faults in extensional basins control the stratigraphic architecture and the geometries of structures, which influence the vertical and lateral fluid flow and heat transfer. This influence was previously demonstrated for instance in the GPF Ardèche scientific project developed in the Southeastern Basin of France (Guilhaumou Touray et al., 1996; Pagel et al., 1997). In this project, two scientific wells (BA-1 and MM-1) were drilled and cored on both sides of the Uzer normal fault, allowing the quantification of the fault influence on fluid flow and thermal evolution through analyses of organic matter (maturation), clay minerals, fluid inclusions and apatite fission tracks as well as burial and thermal modelling (Guilhaumou Touray et al., 1996; Pagel et al., 1997; Roure et al., 2005).

Early diagenetic processes affect carbonate and siliciclastic sediments at the time of deposition and during shallow burial (Tucker, 1990; Worden and Burley, 2003). For carbonates, the stabilization of aragonite sediments (to calcite), and the minor eogenetic cementation prevail in the marine environment, while meteoric fluids result in dissolution and paleokarst horizons (Fig. 5A). For the siliciclastics, the weathering of the detrital components and some early cementations occur depending on the climatic conditions and the depth from sediment surface (Fig. 2). Late diagenetic processes include smectite-illite transformations (Fig. 5B), which are variable as a function of a decreasing amount of smectite with increasing depth (Pagel et al., 1997). Dissolution (hypogenic karstification), dolomitization and mineralization (e.g., Mississippi Valley Type, MVT) in carbonates have also been recorded in extensional basins along active or re-activated faults and through fault-associated fluid circulations (Muchez et al., 2000; Rowan et al., 2002; Vandeginste et al., 2007).

One illustrative example of hydrothermal fluid flow along major normal faults that bring deep-seated fluids to shallower rock formations is the dolomitization observed along the Cantabrian Fault in Spain (Shah et al., 2010; Swennen et al., 2012). Here, the fault-associated fluids produced a series of diagenetic phases, including multiple fault-related dolomites and late diagenetic calcite cement (Nader et al., 2012; Swennen et al., 2012). These diagenetic phases can be classed as FADFT. One other example is the Dinantian carbonate platforms of the Netherlands, which have been associated with extensive normal faulting during rifting (Geluk, 2007). The tilted fault block system that originated from the reactivation of weak Caledonian structures created heavily asymmetric half-graben structures in which the footwall highs were suitable for shallow carbonate build-ups, whereas the hanging wall blocks were filled by deep water deposits (Fig. 6; Geluk, 2007). During the deposition of the carbonate build-ups (before burial), early marine cementation (fibrous calcite; C1a, Fig. 6A) corresponding to BDFT in our interpretation, was followed by meteoric dissolution and cementation upon subaerial exposure (dogtooth calcite; C1b, Fig. 6B) – MDFT (Modderman, 2021). During the later burial, a phase of equant calcite (C2; Fig. 6C) occluded the primary porosity after further possible meteoric dissolution (Fig. 6D) that could still relate to MDFT in our interpretation. Increasing burial upon the Early Numerian deposition of shales covering the carbonates led to compaction stylolites, burial diagenesis and fracturing. These are represented by veins with ferroan calcite and dolomite filling cross-cutting stylolites and older phases (Fig. 6E,F). Such diagenetic phases have been interpreted to relate to extrinsic fluid-flow that might be a mix of compaction and fracture-associated fluids (Rosenberg et al., 2018), corresponding to CDFT and FADFT in our interpretation.

4.2. Contractional basins

Most contractional basins reside in orogenic areas where the depositional space is created by tectonic loading during thrust and nappe emplacement associated with the growth of mountain ranges (van Unen et al., 2019). It has long been recognized that such loading results in creation of significant depositional space due to the flexure of oceanic and continental lithosphere undergoing subduction, forming accretionary wedges and forearc, back-arc foreland or foredeep basins, influenced by many forcing factors (Beaumont, 1981; Cloetingh et al., 2015). The resulting kinematic evolution in contractional basins also involves the fluids that often migrate together with the deformation from internal to external parts (Roure et al., 2005). Fluid-flow and subsequent fluid-rock interactions are intimately related to the structural deformation of orogens and fold and thrust belts (Benchilla et al., 2003; Guilhaumou et al., 2000; Swennen et al., 2003). For instance, the uplifted orogens become subaerially exposed and are influenced by meteoric fluids and associated telogenesis, while in the subsiding basins, where additional depositional space is created, basinal fluids prevails in the upper part and compaction fluids in the lower, deeper parts (Fig. 7). Fault-associated fluids are focused on the active thrust faults cross-cutting the previously mentioned domains (Fig. 7).

Major thrust faults in contractional orogens are the preferred pathways for deep-seated, fault-associated fluids that often result in pervasive dissolution, dolomitization (in carbonates), Mississippi Valley Type (MVT) mineralization, and eventual emplacement of hydrocarbons that may also include corrosive organic acids (Fig. 7, Roure et al., 2005; Vandeginste et al., 2005). The higher temperature, deep-seated fluids displace and mix with cooler formation fluids to produce significant dissolution, that can be further enhanced in the presence of organic acids (Robinson, 1993; Tucker, 1990). The resulting diagenetic events/phases are interpreted as FADFT. Compactional fluids circulate in the same direction as the deformation, from the deeper to shallower parts of the basins during deformation (Fig. 7). The resulting CDFT can include dissolution, dolomitization as well as calcite and dolomite equant mosaic cementation in carbonates and quartz cementation in sandstones (Roure et al., 2005). Karstification and associated diagenesis characterize the subaerially exposed domains that are interpreted as MDFT, while typical basinal diagenesis, such as isopachous, syntaxial overgrowth, equant calcite cementation, create BDFT in the basin (Fig. 7;

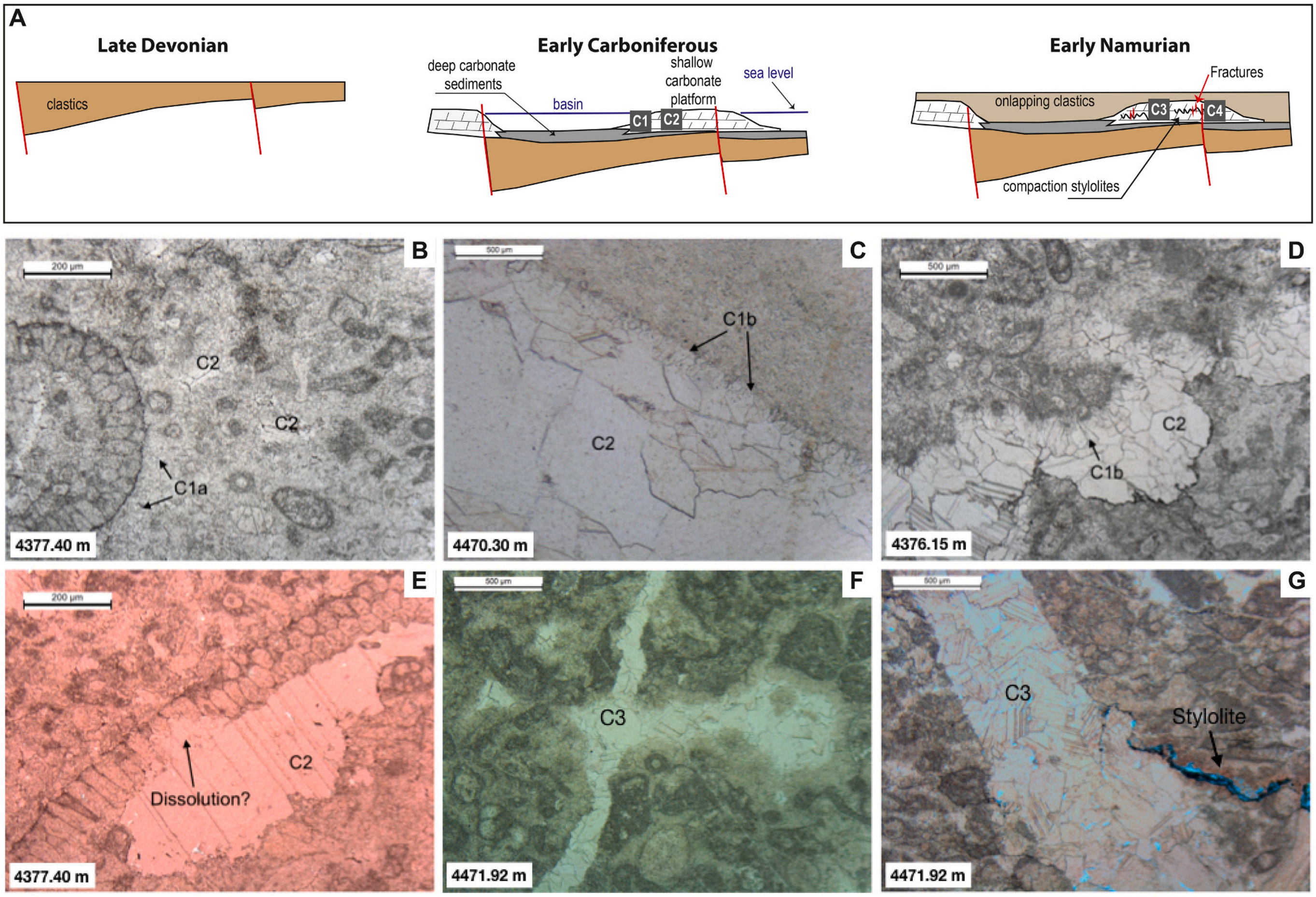


Fig. 6. (A) Schematic representation depicting the development of the Dinantian carbonate platforms on the upthrown parts of extensional faults in the Early Carboniferous. (B-G) Plane polarized light (PPL) photomicrographs showing the types of calcite cements observed in LTG-01well intercepting Dinantian carbonate of in the Luttelgeest structure (the Netherlands): B) Fine crystalline, fibrous calcite cement (C1a) of early marine diagenetic origin; C) limpid dogtooth calcite of early meteoric diagenetic origin (C1b); D, E) equant calcite that replaces aragonitic components and occludes primary and dissolution pores during shallow burial (C2); F, G) calcite spar that cemented within the first phase of fracturing, post-dating interpreted compaction stylolites. Depths of the thin sections are shown in the corners of the photographs. Photomicrograph D is red due to staining. Photomicrographs from Modderman (2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

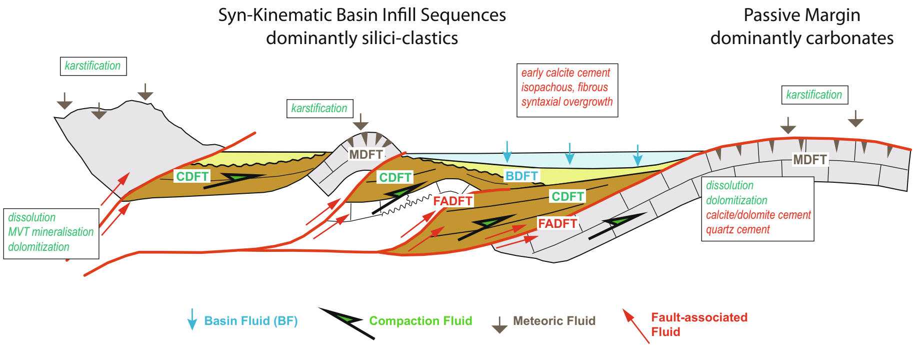
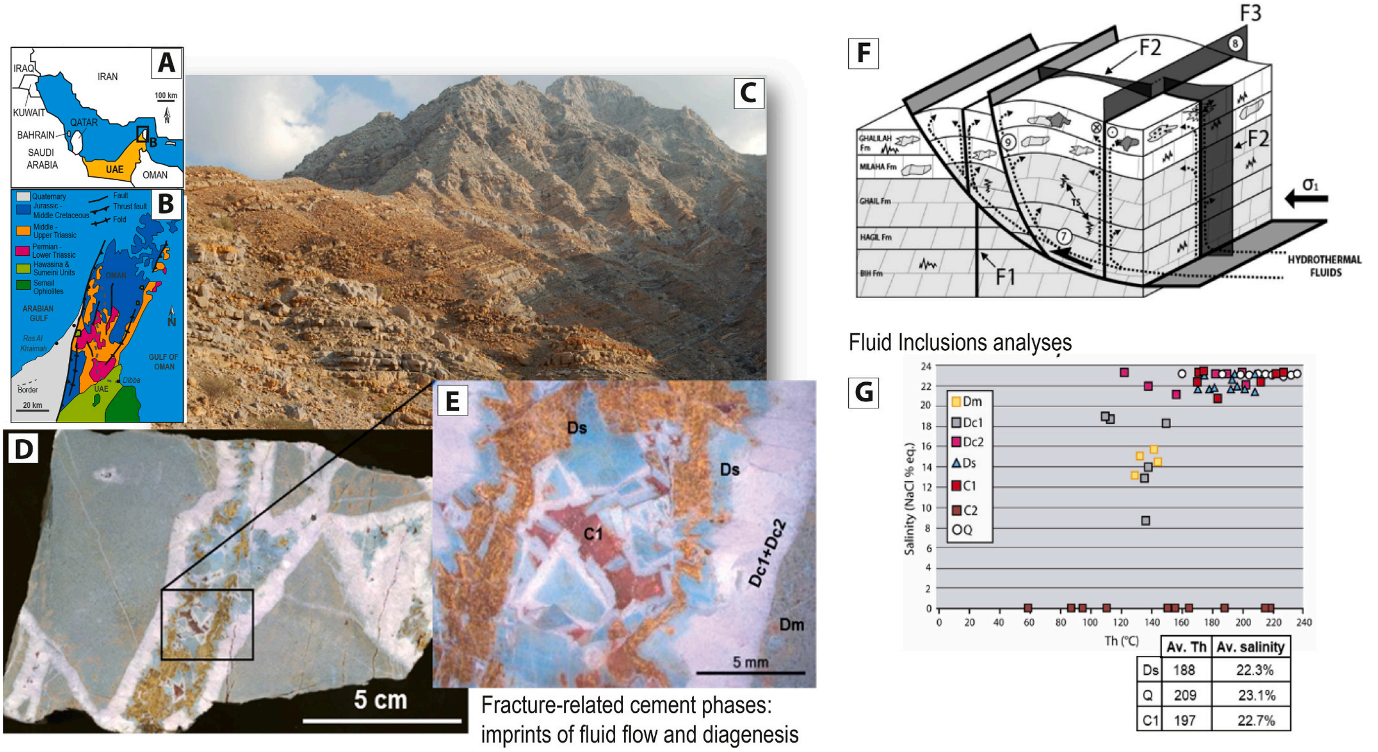


Fig. 7. Conceptual illustration of contractional basins and *syn*-kinematic siliciclastic deposition associated with the evolution of a foreland fold-and-thrust belt (modified from Roure et al., 2005) with the schematic representation of diagenetic fluid flow. The syn-kinematic evolution is mainly associated with circulation of compactional fluids and fault-associated fluids that takes place in the direction of deformation from the hinterland towards the foreland. The uplifted and subaerially exposed hinterland, forebulge and hanging-walls are influenced by meteoric fluids, while basin fluids prevail in depositional domains. The locations of the associated diagenetic facies tracts (MDFT, BDFT, CDFT and FADFT) are indicated. We refer to the related diagenetic facies tracts discussed in the main text.

Moore, 2001).

The Middle East region includes some of the best examples of the impact of the deformation in fold-thrust belts and nappe stacking on fluid-flow and diagenesis (Breesch et al., 2009; Fontana et al., 2014). In Ras Al Khaimah (United Arab Emirates) pervasive late stage dolomitization and later calcification and calcite precipitation occurred along major thrust faults at the time of nappe stacking during Zagros fold and thrust emplacement (e.g., Roure et al., 2005; Fontana et al., 2014;



	Av. Th	Av. salinity
Ds	188	22.3%
Q	209	23.1%
C1	197	22.7%

Fig. 8. FADFT characteristics across a fold and thrust belt deformation in the United Arab Emirates (modified from Fontana et al., 2014): (A) Location map of the investigated area in the northern UAE; (B) Simplified geological map of the Musandam Peninsula; (C) Panoramic view of Wadi Sha'am fault; (D, E) Photomicrographs of stained slab featuring a fracture infilled with various phases of dolomites, calcite and quartz; (F) Conceptual model of structural deformation, fluid flow and diagenesis; and (G) Results of fluid inclusions analysis on the featured diagenetic phases showing their estimated temperature of homogenization (Th) and salinity (NaCl %eq.).

Fig. 8). The conceptualized model (Fig. 8F) is envisaged to include multiple episodes of fracturing, circulation of fracture-associated fluids, and diagenesis at high temperatures and salinity, conformable with excessive burial conditions, which have been confirmed by petrographic, geochemical, and fluid inclusions analyses (Fontana et al., 2014). The interpreted FADFT include several dolomitic phases (matrix-dolomitization and cement infill), as well as high temperature calcite and quartz cements (Fig. 8). Fluorite and MVT as well as associated karst dissolution and hydrocarbon trapping have been observed in worldwide inverted contractional basins, such as in the foreland fold and thrust belts of Sulaiman and North Khirthar ranges at the western margin of the Indo-Pakistan plate (Guilhaumou et al., 2000; Benchilla et al., 2003), the circum-Mediterranean domain such as in Tunisia (Benchilla et al., 2003) or the Illinois Basin, USA (Rowan et al., 2002). The analyses of fluid inclusions (hydrocarbon and aqueous inclusions), particularly in fluorite and orebodies, coupled to absolute dating and thermal/fluid flow models have demonstrated the significance of resulting quantitative constraints to basin modelling (Benchilla et al., 2003; Ferket et al., 2000; Rowan et al., 2002).

Numerical modelling of coupled fluid flow and structural deformation in fold and thrust belts has been performed in various regions, such as the Albanides (Vilasi et al., 2009), or the Dinarides (Nader et al., 2023). The evolution of calculated water saturation (in %) with time across the 2D model allows the determination of principal fluid migration pathways during the fold and thrust deformation (Fig. 9). The flow directions, that are indicated in Fig. 9, can be regrouped by the specific diagenetic fluids (Fig. 9) and related diagenetic facies tracts (MDFT, BDFT, CDFT, and FADFT). The FADFT include at least two episodes of overpressure and hydro-fracturing associated with high temperature calcite and dolomite cementations (Vilasi et al., 2009). Crack and seal veins were also found and interpreted as multiple phase fracturing and cementation during structural deformation (Nader et al., 2023; Vilasi et al., 2009). Another important structural feature known to affect contractional basins are layer parallel shortening stylolites that in our models are associated with CDFT. Previous studies have shown that the formation of these stylolites could reset the paleomagnetic signatures of carbonates in foreland basins (e.g., Robion et al., 2004). These studies have applied the anisotropy of magnetic susceptibility on layer parallel shortening stylolites to demonstrate a resetting of the Paleozoic reservoir original magnetic poles to *syn*-kinematic Cretaceous-Paleocene ones in the Eastern Canadian Cordillera. Other techniques have been applied, and still need to be improved, to provide accurate thermo-barometers. For example, Ferket et al. (2000) and Gonzalez et al. (2012) have coupled petrography and analyses of fluid inclusions to thermal/basin fluid flow models to quantify erosion and burial, and to date diagenetic events during contraction of the Cordoba Platform in Mexico.

4.3. *Strike-slip basins*

Strike-slip basins form along major transcurrent boundaries, where major displacements occur in the horizontal plane due to either right or left- lateral movements (Matenco and Haq, 2020). In these tectonic settings, depositional space is created along releasing bends, when horizontal offsets are transferred between two or more strike-slip faults (pull-apart basins), or through a combination of these mechanisms (e.g., van Wijk et al., 2017). Many such basins are known to be associated with major strike-slip offsets that display tens to hundreds of km of horizontal displacement. Well-known examples are along the San Andreas Fault system in western United States, the North Anatolian Fault in northern Turkey, the Levant (Dead-Sea) fracture in the Eastern Mediterranean, the Alpine Fault of New Zealand, and the Cerna-Timok Fault system of the Carpathians (Okay et al., 2000; Barnes et al., 2005; McLaughlin and Nilsen, 2006; Schmid et al., 2008). Previous studies have conceptualized the expected extensional (transtensional) structures in a right-lateral

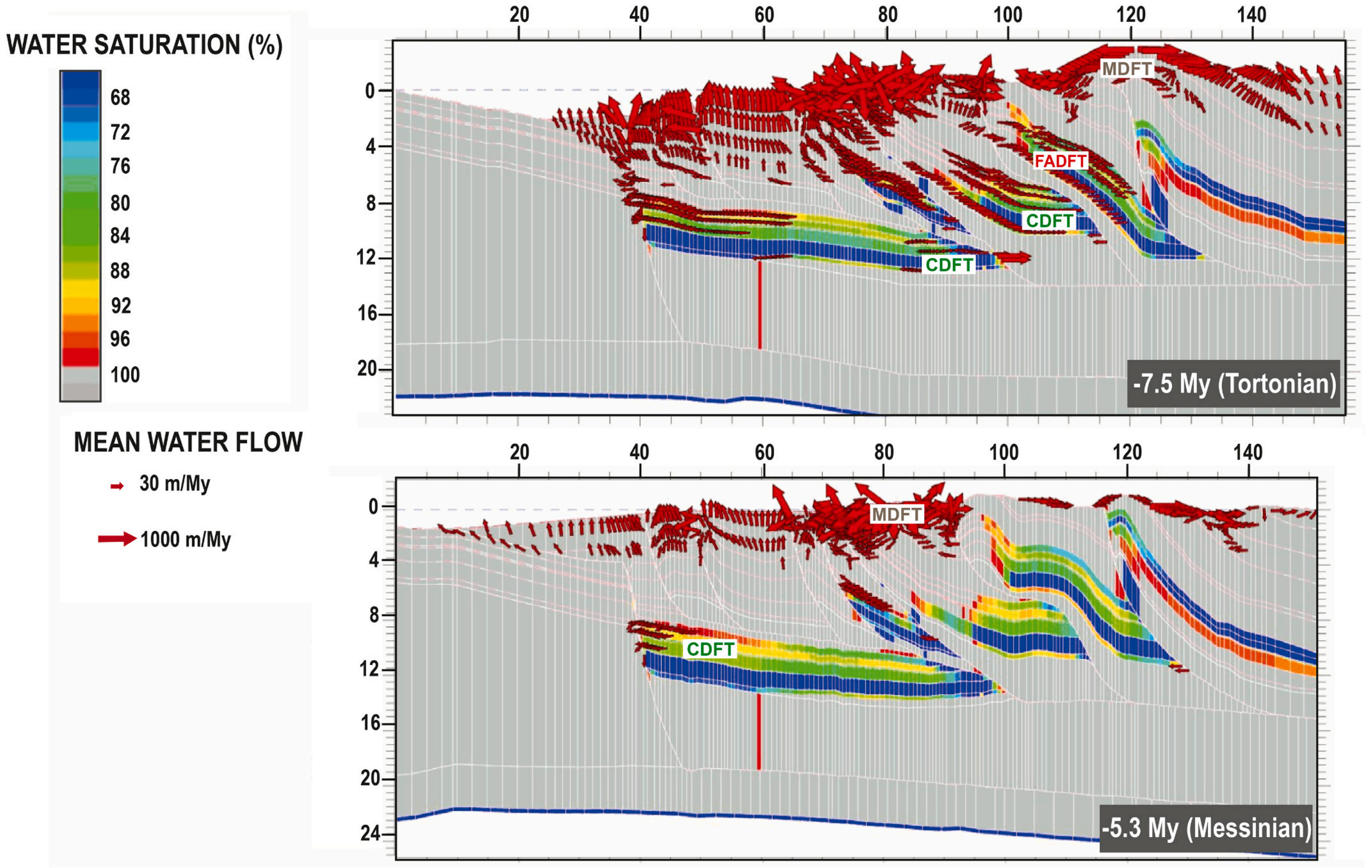


Fig. 9. Coupled model of kinematic evolution and fluid flow across the Albanides fold and thrust belt (from Vilasi et al., 2009), showing the related diagenetic facies tracts as well. Tortonian to Messinian water migration pathways are illustrated by red arrows. The water flow is expressed in m/My. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

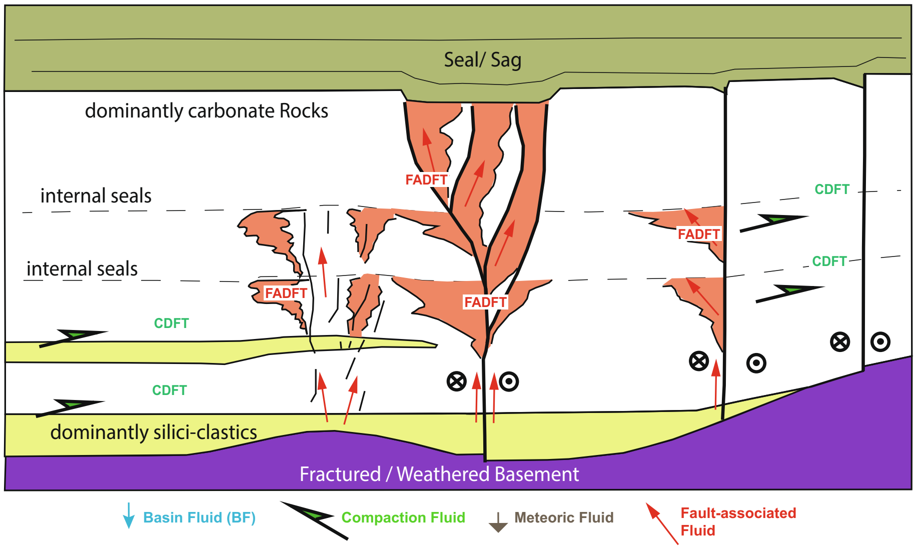


Fig. 10. Simplified illustration of strike-slip tectonic settings, indicating fault-associated fluids and compactional fluids circulation patterns, which result in FADFT and CDFT, respectively (modified from Davies and Smith, 2006).

(dextral) wrench fault systems together with the associated preferred sites for hydrothermal fluid flow along faults (Fig. 10, Davies and Smith, 2006). Such deep-seated fault-associated fluids, whose ambient temperature is higher than the overlying host-rock, may ascend along strike-slip faults and invade overlying permeable facies. Away from the strike-slip faults, compaction fluids may also prevail due to burial conditions when they exist.

Specific cases have been documented worldwide, such as in Jurassic rocks of the Levant Lebanese region, where faults, volcanic rocks, as well as dolomites have been mapped crosscutting into the Jurassic carbonate rock bodies (Nader et al., 2004, Fig. 11A, B). Here, volcanism- and fault-associated fluids were interpreted to ascend from deeper strata, resulting

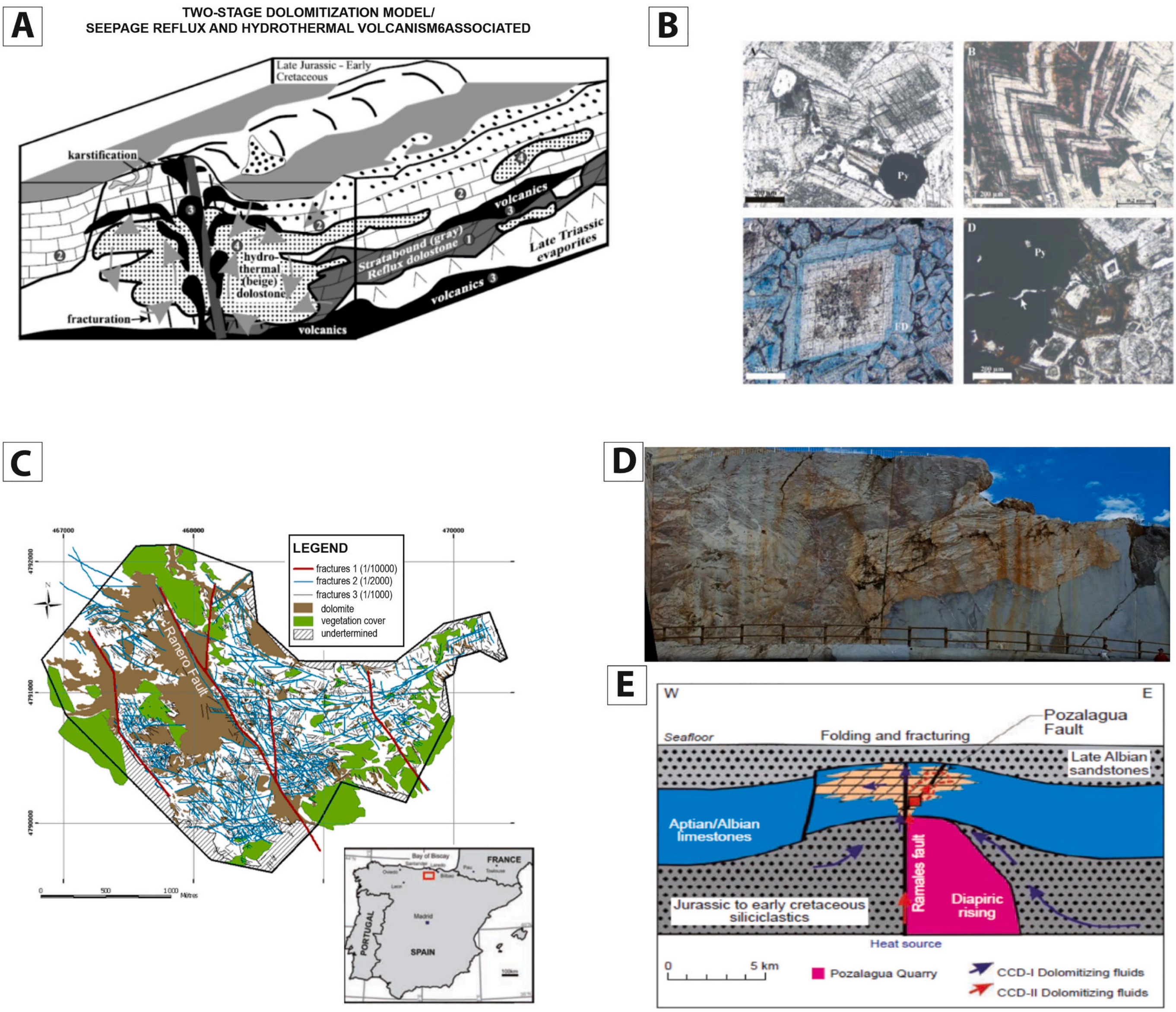


Fig. 11. Characteristics of dolomitization along strike-slip faults: (A) Conceptual model of seepage reflux and later hydrothermal volcanism-associated dolomitization stages in a Lebanon case study (after Nader et al., 2004); (B) Photomicrographs showing the petrographic characteristics of the HTD with non-ferroan and ferroan phases (after Nader et al., 2004); (C) Satellite map of faults, fractures and dolomite occurrences along the Ranero Fault (location is indicated with the index map of Spain (after Shah et al., 2012); (D) photographs of the major fault plane and associated dolomite in Ranero quarry (Nader et al., 2012); (E) Conceptual model of the fault-associated dolomitizing fluids circulation and dolomite bodies emplacement (after Nader et al., 2012). The strike-slip fault was interpreted to be associated with diapiric salt uplift.

in pervasive discordant FADFT dolomitization. Similar mechanisms have been reported from the Ranero Fault system in Cantabria, northern Spain, where the previous normal faults have been reactivated by strike-slip movements, bringing deep-seated remineralizing and dolomitizing fluids to the overlying strata in the late diagenetic stages (Shah et al., 2012; Nader et al., 2012; Fig. 11C, D, E). The FADFT along the Ranero Fault (and other similar faults) consist pre-dominantly of high temperature dolomites, MVT deposits and calcite (Shah et al., 2012; Swennen et al., 2012). Salt diapir structures may occur in various tectonic settings, involving different diagenetic fluids and facies tracts (e.g., Guilhaumou et al., 2000). Such fluids ascend at the boundary of the salt, reacting with the salt and resulting in series of diagenetic processes including dolomitization along their pathways (Al-Aasm and Abdallah, 2006), hence interpreted as FADFT. Meteoric, freshwater flowing from adjacent aquifers have to escape upward when they reach the salt diapir (Al-Aasm and Abdallah, 2006), resulting in MDFT dissolution.

5. Inferences on the diagenesis on passive continental margins

Because tectonics decreases during the evolution of a passive continental margin, the classical sequence stratigraphy using sea-level variations and the dependency of sedimentation to the position of the shoreline (Tucker, 1993; Sarg, 1988) is better suited to describe diagenetic environments, where the spatial and temporal distributions of the diagenetic processes and associated phases can be better predicted (Moore and Wade, 2013). One relevant example is the Late Jurassic carbonate successions of the Middle East, known as the Arab Formation, which were deposited on a distally steepened ramp consisting of a mudflat area, a lagoon, an offshore break with shelf margin carbonates, and a slope (Nader et al., 2012). Based on a large dataset of petrographic, geochemical and petrophysical analyses, Morad et al. (2012) proposed a generalized conceptual model for the spatial and temporal distributions of diagenetic alterations and related porosity and permeability within a typical stratigraphic sequence (bounded by surfaces of subaerial exposure; Fig. 12). In these settings, during sea-level rise the transgressive system tract and the highstand system tract grainstones and packstones are affected by marine/basinal fluids resulting in circum-granular isopachous, syntaxial overgrowth and equant calcite cements principally in the shelf margin carbonates, preserving their reservoir quality through prevention of extensive burial compaction (average porosity of 23 % with permeability about 263 mD; Fig. 12). Because of their preserved porosity, these facies can be subjected to consequent burial diagenesis by means of basinal brines and compaction fluids circulations and interactions, whereby coarse-crystalline rhombic dolomites replace the calcite grains, while anhydrite may get dissolved (porosity ranging between 13 and 29 % with permeability around 5000 mD; Fig. 12). Similarly extensive dolomitization also occurs in the mud-supported transgressive system tract sediments below the maximum flooding surface, resulting in fine-crystalline, tightly interlocked dolostones, which are often characterized by low permeability (Tucker, 1993; Morad et al., 2000).

The shelf margin carbonates can be interpreted, therefore, as a basinal diagenetic facies tract (BDFT), that may undergo dolomitization due to the circulation of evolved seawater (basinal fluids, BDFT) and later burial compaction fluids (CDFT). The transgressive system tract and the maximum flooding surface are characterized by low rates of sedimentation relative to sea-level rise and long residence time of sediments on the basin floor with prevailing marine fluids. The mud-supported sedimentary facies of these system tracts may also be partially to completely dolomitized (Morad et al., 2012). These are also classified as BDFT, nevertheless, and they have lower permeability values compared to the above-mentioned shelf margin highstand BDFT, mainly due to the finer dolomite crystals (overprinting the matrix mud-dominated sediments) and the inter-crystalline porosity reducing cements.

During a relative sea-level fall, the exposed mudflat is affected by evaporation leading to the precipitation of anhydrite and gypsum from increasingly saline pore water (modified basinal fluids). This also leads to concurrent dolomitization of the mud-dominated facies mainly in the upper parts of the highstand system tract (average porosity of 17 % and permeability 1.4 mD; Fig. 12). Here dolomitization may improve the flow properties, when, due to later subaerial exposure, episodes with meteoric fluids prevail and result in intense dissolution of the evaporite cements leaving the dolomite crystals with considerable inter-crystalline porosity (Morad et al., 2012). At the same time, the lagoon becomes smaller and completely isolated from the open sea, resulting in increased evaporation and salinity. The lagoon brines would seep into the underlying highstand system tract and transgressive system tract packstones, grainstones (shoal) as well as the lowstand system tract grainstones, leading to further dolomitization, which has been conceptualized as the seepage reflux dolomitization model (Machel, 2004). The lowstand system tract grainstones that are deposited on the fore-shoal during sea-level fall are affected by meteoric-water percolation below SB (during subaerial exposure), which results in pervasive dissolution and cementation.

The lowstand wedge grainstones with important moldic porosity and enhanced permeability (due to dissolution by meteoric water) are interpreted in our conceptualisation as a meteoric diagenetic facies tract (MDFT). Where sedimentation rates are higher than the relative sea-level rise, particularly close to the sequence boundaries and within the highstand system tract (Sarg, 1988), the above cited BDFT (with possible CDFT) might be subaerially exposed and overprinted by meteoric fluids (Tucker, 1993; Modderman, 2021), resulting in the emplacement of a meteoric diagenetic facies tract (MDFT) that is expressed by dissolution and equant calcite cementation (Morad et al., 2012).

6. Discussion

6.1. Variability of diagenetic mechanisms controlling the geometry of different diagenetic facies tracts

The position and geometry of the diagenetic facies tracts are intrinsically related to the tectonic successions and diagenetic environments (Fig. 3). They further rely on the mechanisms or processes of diagenesis that are in turn governed by diagenetic fluid types, the prevailing physio-chemical conditions, and the fluid circulation patterns that are dependent on the permeability of the host rocks. Some of the best examples to illustrate how fluid flow patterns relate to the produced geometries of the diagenetic facies tracts are the dolomitization (mineral replacement) and karstification (dissolution) processes in carbonate rocks and smectite-illite reactions (mineral transformation) in

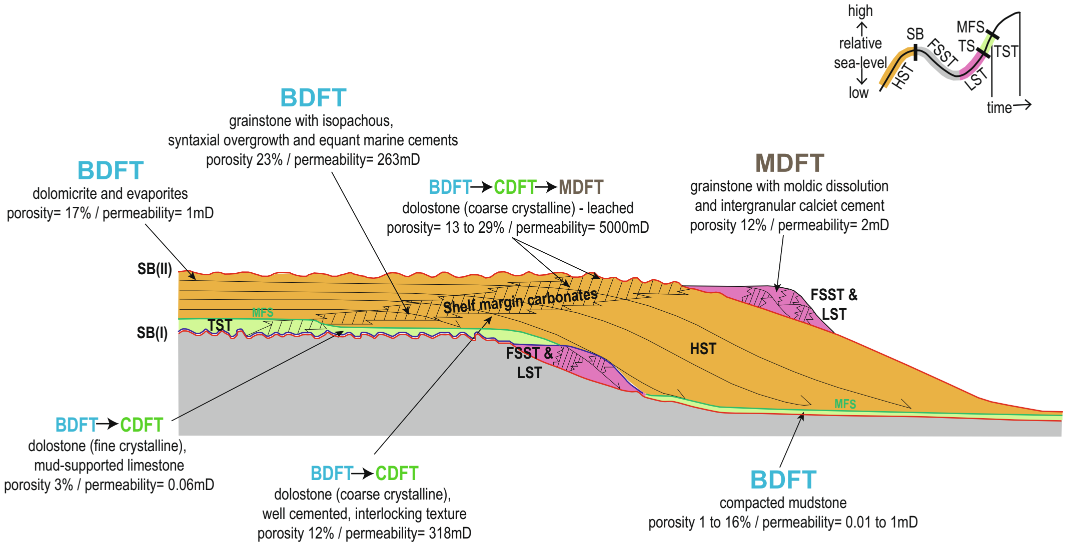


Fig. 12. Conceptual sequence stratigraphy model of passive margin platform carbonate sedimentary systems and early diagenesis, mostly related to BDFT, CDFT and MDFT (example from Middle East Jurassic carbonates, modified after Morad et al., 2012). Early diagenetic processes of BDFT and MDFT characterize the various systems tracts and key sequence-stratigraphic surfaces, impacting the rock facies and corresponding flow properties (porosity and permeability). The diagenetic facies tracts complexes, such as the BDFT followed by CDFT and MDFT, are also indicated. The porosity and permeability average values are based on core analyses (from Morad et al., 2012).

siliciclastics.

In terms of BDFT in carbonates, the variable geometry of dolomite bodies has been associated with different types of dolomitizing fluid circulations and diagenetic processes that are principally based on field occurrences and case studies (Nader et al., 2013). The process of dolomitization demonstrates the role of the controlling factors, such the diagenetic fluid typology and flow circulation, on the positioning and geometry of diagenetic facies tracts (DFTs). Nader et al. (2013) presented some of these models and associated them to their tectono-stratigraphic positioning, geometries, and dolomitizing fluids circulation. The dense brines in lagoons under evaporative conditions flow downwards in the relatively permeable facies resulting in tongue shaped dolomitization bodies, with decreasing dolomite content with depth. The resulting strata-bound architecture of dolomite consists of laterally extensive dolostone layers with enhanced flow properties, intercalated with low-permeability non-dolomitized limestone layers (Fig. 13). This dolomitization process by means of evolved seawater during shallow burial is interpreted here as BDFT. Typical BDFT in siliciclastic sediments include a broad variety of cements (and associated sediment alterations) such as pyrite, carbonates, glauconites, smectite and illite. These are the result of the interaction of reducing organic matter and oxidizing inorganic solutes and minerals, such as sulphates and iron oxides. The sequence of minerals mentioned here varies for BDFT in typical marine settings compared to the BDFT in meteoric influenced domains (Fig. 2). The presence of smectite and K-feldspar in the sediments prior to considerable burial will control the smectite-illite reactions which lead to major impacts on the rock-fluid systems.

Further burial and sediment compaction release mineralizing fluids that flow or escape through faults and fractures zones as well as relatively permeable strata in the nearby carbonate rocks, resulting in CDFT (Fig. 13). The resulting dolomite geometries consist of large, vertically extensive bodies that are located at the margins of the compacted basinal sediments, closer to the fluid sources. Some compaction fluids may flow upwards and invade host rocks at lower temperatures, with different fluids, such as meteoric or basinal. In such situations, pervasive dissolution has been observed together with dolomitization. Clayey sediments in the deeper parts of the basins contain a variety of chemical species that can be charged in the compaction fluids, leading to a broad range of precipitating minerals in the host rocks, such as MVT, ferroan calcite and dolomite, quartz. Compaction through burial of siliciclastic sediments at increasingly elevated temperatures (50 °C – 90 °C) leads to K-feldspar dissolution, gypsum dehydration and the replacement of smectite by illite with the release of considerable amounts of reactive fluids, corresponding to the CDFT. Beyond 70 °C burial or in the case of temperatures anomalies exceeding 130 °C, illite and quartz are formed, filling the remaining porosity (Bjørkum, 1988). At even higher temperatures (of burial), Fe-rich clays (berthierine) transform into grain-coating chlorite, and ferroan dolomites precipitate.

In the case of the fault-associated diagenetic facies tracts (FADFT), the geometries of dolomite bodies created by hydrothermal fluids is controlled by the *syn*-kinematic evolution of the faulting (Fig. 10). The dolomitizing fluids, ascending along deep-rooted faults and fracture zones displace and/or mix with formation waters that are generally colder, resulting in pervasive dissolution (e.g., hypogenic karstification), dolomitization and mineralization. The fluid-flow pattern follows the fracture zones vertically and laterally in permeable strata. This often results in dolomite bodies with a cedar tree geometry (Fig. 13). Faults and fracture zones are pathways for the circulation of fluids, also in siliciclastic sediments. Fluids are generated during burial of siliciclastics through several processes, such as the above described smectite to illite reactions. For instance, an influx of low salinity water may result in dissolution of feldspars and carbonates in sandstones, whereas an influx of high salinity water may result in precipitation of authigenic cements. For the fluids related to the generation, expulsion and trapping of hydrocarbons, CO$_2$ and hydrogen in association with faults and fractures must also be taken into account. Bleaching in sandstone due to CO$_2$-rich fluids migration along faults has been well documented in the Little Grand Wash and Salt Wash faults in the Paradox Basin (Utah, USA) that are world class examples of fault-related natural CO$_2$ leakage systems from depth to surface (Frery et al., 2017; Frery et al., 2015; Pevear et al., 1997). These faults, located at the front of the Sevier Fold-and-Thrust Belt are partially exhumed, and well exposed, demonstrating the link

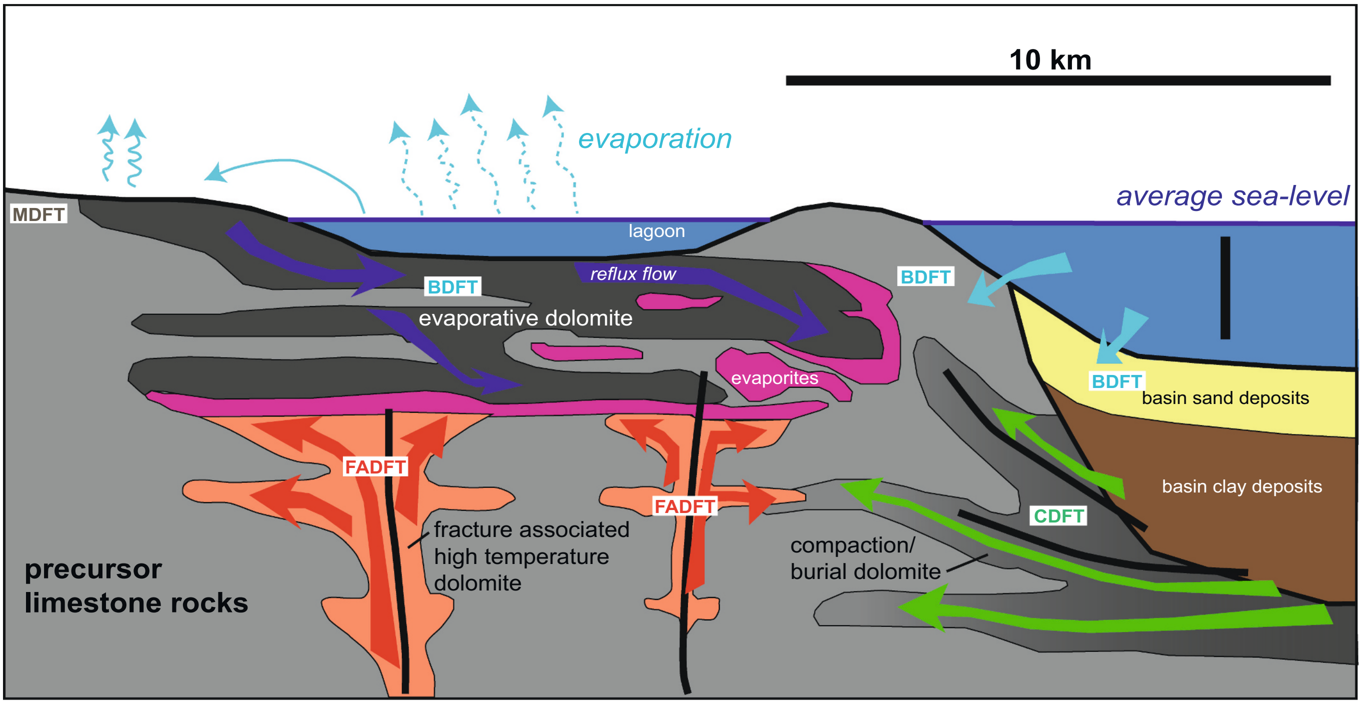


Fig. 13. Schematic illustration of some of the major dolomitization processes of marine platform carbonates, their fluid flow patterns (arrows) and geometry of the resulting geo-bodies. Evaporative dolomitization is mainly associated with BDFT, burial and compaction dolomitization with CDFT, and fracture-associated high temperature dolomite with FADFT (after Nader et al., 2013).

between the fault paleo- and modern activity and associated the fluid flow history leading to bleaching of red-coloured sandstones and gypsum mineralization (Frery et al., 2015), corresponding to FADFT.

The meteoric diagenetic facies tracts (MDFT) are well developed particularly in carbonates. Karstification processes affect subaerially exposed and uplifted carbonate and evaporite rock masses through dissolution by meteoric fluids (Fig. 14). While most karstification occurs at and below exposure surfaces, the meteoric fluids can flow deeper in the subsurface and reach burial conditions. Some of the deepest explored karst systems exceed 2 km in vertical depth and hundreds of kilometres of cave passages. The MDFT location and geometry depend on the specific diagenetic mechanisms that prevail in the vadose and phreatic sections of the subsurface (Fig. 14). The vadose section is characterized by an upper zone of pervasive dissolution, leaving empty, vuggy to cavernous porosity in the rock mass. Such a dissolution mechanism is controlled by the infiltration/circulation of meteoric fluids that are under-saturated with respect to carbonate and evaporite minerals. The meteoric waters may incorporate CO_2 that is produced in the soil cover, increasing their potential for dissolution. The CO_2 is incorporated in the water as an aqueous species, percolating in thin fractures and channels. As water reaches larger, empty vugs and caverns, the CO_2 (aqueous) degasses while the water becomes oversaturated with dissolved calcite, resulting in calcite cementation. This process occurs in the lower precipitation zone of the vadose section, where meniscus and pendant cements occur, as well as all forms of speleothems (e.g., stalactite, stalagmite), slightly decreasing the overall porosity. The water table usually limits the base of the vadose section, overlying the phreatic section where all voids are filled with water (Fig. 14). The phreatic section is in turn subdivided into three zones. The upper one is where dissolution by undersaturated water prevails. Moldic and vuggy dissolution types are most common in this zone together with the stabilization of aragonitic and high-Mg calcitic sediments through replacement with the more stable low-Mg calcite. The underlying stagnant zone characterize the area where no or little water movement occurs, hence minimal diagenesis and no impact on porosity. In contrast, active water circulations characterize the deepest precipitation zone, where the fluids are oversaturated with calcite resulting in rapid, pervasive cementation that is expressed as isopchous bladed, interlocking equant mosaic, and syntaxial overgrowth cement types and fabrics. Thus, the overall porosity is generally greatly reduced. This zone is very close to the burial domain resulting in cements reflecting both meteoric fluid origin and burial thermal conditions, such as the drusy, equant mosaic calcite.

The MDFT also exist in the siliciclastic domains, though no typical classification is known to occur. The oxidation of reduced ferroan cements (Fe-calcite/dolomite, ankerite, siderite), dissolution of feldspars and chert (Shanmugam and Higgins, 1988), as well as alteration of feldspar minerals to clay minerals (Emery et al., 1990) are the result of the interaction of meteoric water and siliciclastics.

6.2. *Non-diagenetic factors controlling the geometry of diagenetic facies tracts*

The fault-associated diagenetic system tracts (FADFT) succinctly illustrate the controls of both fracturing and original sedimentary facies on the resulting geometries. The major deep-rooted faults and fracture zones will convey fluids when they are tectonically active, bringing fluids from the deeper parts of the crust towards the surface. At the same time, such fluids may laterally invade those strata that are relatively permeable adjacent to the fault. The resultant geometries may be in the form of vertical strata-discordant bodies, lateral strata-concordant bodies, and/or a mixture of both forming cedar tress shaped edifices.

The geometries of the produced diagenetic facies tracts may therefore be controlled as well by factors such as sedimentary facies and fracturing, that are not diagenetic (i.e., associated with fluid-rock interactions). The original sedimentary (depositional) facies are characterized by specific porosity types and suites of minerals that control the flow of diagenetic fluids and their chemical reactivity with the host rock. Irrespective of the nature of the diagenetic fluids, their flow pattern and residence time are influenced by the porosity and permeability properties of the host rocks. The reactivity of the minerals composing the host rock to the circulating fluids may lead to diagenetic processes such as dissolution, precipitation, and mineral replacement. If the fluids are undersaturated with respect to certain minerals, the latter will be dissolved and the fluids will evolve towards oversaturation, leading to the reprecipitation of the same minerals downflow (in an open system). If the fluids are oversaturated with respect to the existing minerals or some other, non-existing minerals in the host rock, cementation and/or mineral replacement (e.g., dolomitization, silicification) may occur. Note that in many cases the diagenetic fluids are mixtures of intrinsic (formational) and extrinsic fluids, invoking a dynamic chemical evolution rather than simple replacement of one fluid by another.

The mechanical evolution of the host rocks during burial and tectonic deformation, also play an important role in flow properties. The behaviour of the rocks with overburden and tectonic stresses, as well as pore overpressures, may also play a role. The sediments may be compacted during burial or tectonic deformation, first by mechanical rearrangement and packing of the constituting grains, then by pressure dissolution resulting in stylolites (flow barriers during burial). If the interstitial formation waters are not released (e.g., in closed systems),

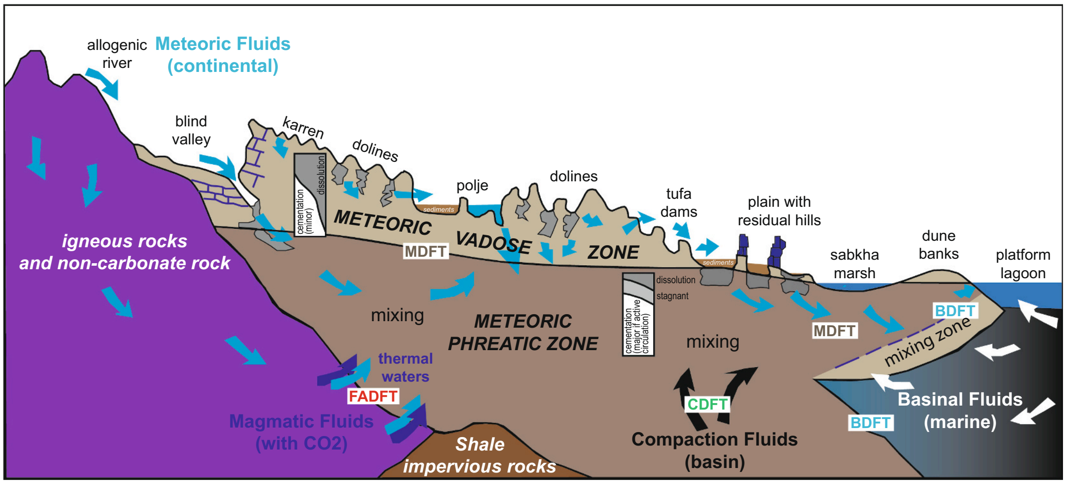


Fig. 14. Schematic illustration of meteoric karstification processes, their fluid flow patterns and geometry of resultant MDFT as well as the mixing realms with the other types of fluids and associated diagenetic facies tracts (modified from Ford and Williams, 2007).

the pore overpressure withstand compaction, stabilizing the pore-space during burial or tectonic deformation. If the pore pressure becomes higher than the ambient overburden pressure, hydrofracturing often takes place. When faults and fractures are active, the associated flow is optimal, since the fluids do not have enough time to precipitate cement, and even if they do, the cement crystals can be washed away or the fracture will reopen after cementation (e.g., crack and seal veins/ fractures).

6.3. Genetic implications for complex diagenetic processes in tectonic settings

Our objective here has been to provide a succinct model of diagenesis that is largely time independent and widely applicable, with focus on

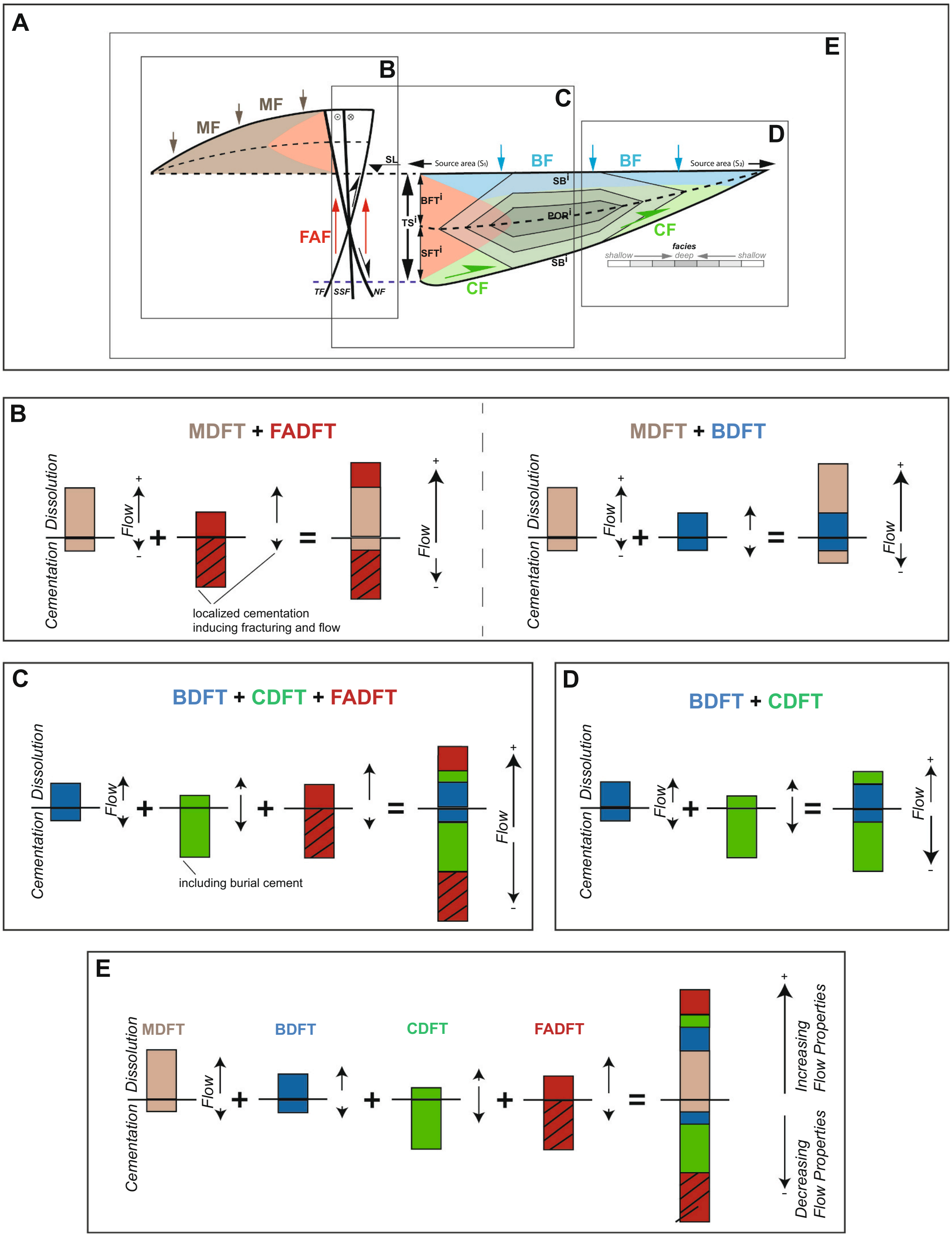


Fig. 15. Visualization of the interaction of various diagenetic fluid types and associated diagenetic facies tracts across tectonic successions following the conceptual definition of Fig. 4. (A) Index figure showing the locations and interactions of the diagenetic facies tracts in the subsequent B-E figures with respect to the tectonic successions framework; (B) Impacts of MDFT and FADFT in the uplifted parts of tectonic successions, and alternitavely, MDFT and BDFT in the downthrown parts; (C) Impacts of FADFT together with BDFT and CDFT in the subsided parts of tectonic successions; (D) Impacts of BDFT and CDFT in typically basinal settings; E) Cumulative impacts of all diagenetic facies tracts. The histograms have three relative size grades (minimum, moderate, maximum) and represent the amplitude of effect on the diagenetic facies tracts in terms of dissolution/cementation. The arrows indicate the positive or negative vectors with their respective effects on flow properties: enhanced (+) or reduced (−). The cementation component of FADFT is considered to be localized around and within faults and fracture zones, resulting in a lesser (−) impact on the corresponding flow vector.

their impact to tectonically active areas (Fig. 15). All presented diagenetic facies tracts and their associated processes are focused on the alteration of the pore space and the associated permeability in rocks. Simply stated such alteration can be visualized as the process of cementation (mineral precipitation) as a vector to reducing the pore space and associated permeability (working against keeping or enlarging the original depositional pore space). Conversely, dissolution can be considered as a process that increases the pore space and associated permeability (Fig. 15). For example, the meteoric fluids in MDFT, through interactions with host rocks, result in major dissolution (karstification) on the detriment of the cementation process which remains minimal (e.g., pendent, meniscus, spelean calcite cement). By comparing the amplitude of these processes and their effects, the MDFT is suggested to be generally associated with increasing – rather than decreasing – porosity. Following the same analysis for the basin fluids in the BDFT, the compactional fluids and frault-associated fluids, significant cementation and therefore decrease in porosity takes place at the expenses of dissolution. In these two latter diagenetic tracts, mineral replacement (e.g., dolomitization, silicification) is common and can be envisaged as in-situ dissolution and precipitation.

For the meteoric fluids and MDFT, the maximum dissolution that is accompanied by minor cementation results in overall enhanced flow properties (shown by the maximal (+) arrow and minimal (−) arrow in Fig. 15). Basin fluids and BDFT show moderately increased flow properties due to the dissolution and stabilization of aragonite and H—Mg calcite. Basin fluids cementation and mineral replacement result in slightly reduced flow properties. Hence, the overall effects tend towards moderate enhancement of flow properties. The CDFT shows relative decrease in flow properties due to excessive cementation. High rates of localized cementation (in and along fractures and faults) are observed in the FADFT but the overall flow properties are believed to increase due to the local characteristic of such cementation and coupled fracturing effects (Fig. 15). In both latter cases, relatively lesser amount of dissolution is expected based on the destabilization of host rock minerals upon interactions with the extrinsic compaction and fault-associated fluids.

Our model allows the addition of the effects of diagenetic processes on increase or decrease of porosity and the resulting flow properties or permeability. By adding the simplified effects for the various diagenetic tracts (processes and flow properties), one can discern indication about the overall imprints of dissolution/cementation and relative amounts of increase/decrease of flow properties (Fig. 15). A global diagenetic facies complex that includes all facies tracts, will result in almost similar amounts of dissolution and cementation. The cumulative effect is, nevertheless, believed to enhance the flow properties since some of the cementation is localized in and along fractures and do not affect the reservoir rocks. This observation stems from the fact that the scales of each tract are not taken into account in our model. For example, the FADFT is very much limited in volume when compared to BDFT, and therefore the cementation effect on permeability has been given a lower weight. According to our model (Fig. 4), some overlap between diagenetic tracts can occur, such as, MDFT and FADFT, or MDFT and BDFT, FADFT, BDFT and CDFT, or even BDFT and CDFT. The cumulative diagenetic effects of these diagenetic facies complexes show that the meteoric and fracture-associated fluids (alone or combined) have the best impact in terms of increasing flow properties, when added to the other diagenetic facies tracts (Fig. 15). This is contrasted with a complex that includes BDFT and CDFT, where cementation is more pervasive, resulting in decrease in flow properties. The FADFT-BDFT-CDFT complex results in slightly increasing flow properties, though overall cementation appears to be larger than dissolution. This is explained by the effect of fracturing that is associated with the FADFT.

The proposed diagenetic conceptual model can also be used to predict the major diagenetic tracts and their impacts on flow properties in the three principal tectonic settings - extensional, thrusting/contractional and strike-slip basins – as well as basins that are controlled by sagging, high sediment supply and eustatic variations (Fig. 16). In the unexhumed basins that are tectonically controlled or not (e.g., extensional, sag basins), the shallow marine domain will be affected by basinal fluids and therefore the BDFT dominates. At depth, due to the increasing overburden, compactional fluids result in the enhancement of the CDFT (relative impacts on porosity and flow dynamics, Fig. 16). The BDFT-CDFT complex diagenetic facies tracts can also occur, resulting in overall reduced flow properties. In the contractional settings, the uplifted part of the basin will be affected by meteoric fluids, resulting in a prominent MDFT, while the subsiding part will be like the other settings, though sediments may be thrusted deeper and hence affected more by compactional fluids. The FADFT will prevail along faults in all settings and may as well overlap with the other diagenetic facies tracts forming complexes. The overall flow properties are generally enhanced where FADFT overlaps with the other diagenetic facies tracts (Fig. 16).

7. Conclusions

Based on observations of diagenesis in various sedimentary systems and tectonic settings, we have proposed a conceptual diagenetic model where the physio-chemical fluid-rock interaction processes are linked to tectonic controls, in terms of creation or destruction of accommodation space, the evolution of overburden and compaction, exhumation, as well as fracturing and creation of fluid flow pathways. Our model helps in further understanding the relationship between multi-scale tectonic and diagenetic processes. We first reviewed the processes involved in diagenetic fluid-rock interaction, then we applied them to a recent

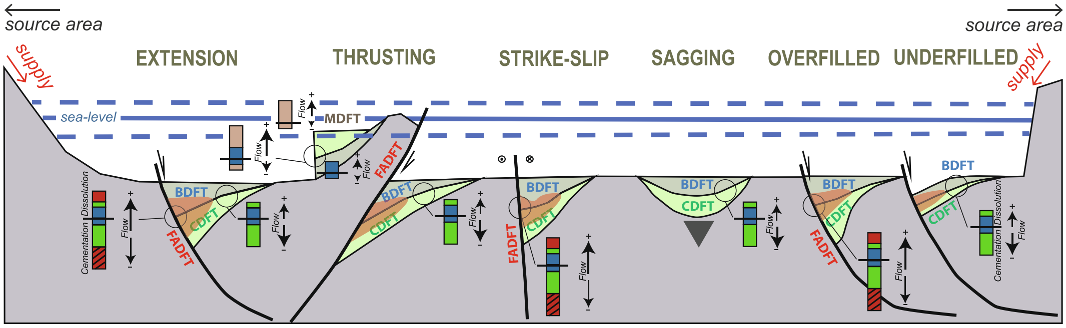


Fig. 16. Conceptualization of the diagenetic facies tracts (BDFT, CDFT, MDFT, FADFT) and their impacts in the key tectonic settings including extensional, contractional and strike-slip basins as well as basins where tectonics have a less dominant control, whereby sagging, high sediment supply (overfilled basins), and high eustatic variations (underfilled basins) prevail. The cumulative impacts of the diagenetic facies tracts on dissolution/cementation (increase/porosity decrease) and flow properties (enhanced/reduced) are indicated by the histograms representation and arrows, respectively. The sizes of the rectangles in the negative and positive domains include the effects of mineral replacement. The three grades approach is also maintained here, with positive and negative arrows representing increasing or decreasing overall flow properties. Note that only the dominant diagenetic facies tract is represented, and the colour convention respects the definition in Fig. 15.

multi-scale tectonically induced sedimentation model and defined a linked diagenetic-tectonic cyclicity concept. We demonstrated the applicability of this concept in various tectonic and depositional systems from examples in different parts of the world.

Four distinct diagenetic fluids are involved in the attribution of specific diagenetic facies tract, which are basinal fluids, compactional fluids, meteoric fluids, and fault-associated fluids. The related, time-independent, diagenetic facies and their total geographic extent defined as the diagenetic facies tracts include the modified rock affected by a singular diagenetic fluid and/or process. Therefore, the proposed diagenetic facies tracts are basinal diagenetic facies tract (BFDT), compactional diagenetic facies tract (CDFT), meteoric diagenetic facies tract (MDFT), and fracture-associated diagenetic facies tract (FADFT). The diagenetic facies complexes are composed of several individual diagenetic facies tracts, where the sediments/rocks may have been affected by multiple diagenetic fluids during their paragenesis.

Each diagenetic facies tract is associated with a set of diagenetic processes and resulting products that ultimately impact the pore space of the host rock and its flow properties. These latter attributes are critical for sustainable usage of the subsurface for energy needs (e.g., geothermal energy) and for mitigating climate change (e.g., geological storage of CO$_2$ or energy). In practice, older systems will tend to be more challenging to interpret due to the complexity caused by multiple series of diagenetic episodes, under differing physio-chemical conditions. Thus, we suggest a simplified approach for obtaining an understanding of the impacts of the diagenetic processes in each diagenetic facies tract. This is based on considering the diagenetic processes in terms of two main pore-space changing pathways: dissolution (enhancement of pore spaces) or cementation (reduction of pore spaces). This approach can be extended to understanding the overall flow properties of the host rock, which we illustrate in our model distinguishing two end-member domains, i.e., flow enhancing or reducing. Based on the known diagenetic processes prevailing in each diagenetic facies, such as karstification in MDFT, mineral stabilization in BDFT, cementation in CDFT, fracturing and cementation/mineral replacement in FADFT, one can infer the major imprints on porosity and flow properties. In the case of diagenetic facies complexes, where the host rock is affected by multiple diagenetic environments and facies tracts, the cementation/dissolution and flow properties vectors can overlap to produce cumulative results. The optimal situation in terms a best-case scenario for enhanced porosity and flow is the one that combines MDFT and FADFT, where karst dissolution, together with fracturing prevail. The more quiescent tectonic settings with a typical burial history result in decreased porosity and flow potentials due to excessive cementation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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