Accepted Manuscript

Geological Society, London, Special Publications

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DOI: https://doi.org/10.1144/SP493-2018-45

Received 25 February 2018
Revised 2 November 2019
Accepted 24 February 2020

To cite this article, please follow the guidance at https://www.geolsoc.org.uk/~/media/Files/GSL/shared/pdfs/Publications/AuthorInfo_Text.pdf?la=en

Sandstone intrusions along different types of faults and their effect on fluid flow in siliciclastic reservoirs

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Abbreviated title: Sandstone intrusions along different types of faults

Abstract

The principle aim of this paper is to document well-preserved field examples of sandstone-filled faults in order to raise awareness of these poorly-understood structures, and discuss their potential as fault seals within injection-prone, multi-layered siliciclastic reservoirs. To achieve this goal, we have undertaken a detailed field survey in the Panoche and Tumey hills in Central California which has allowed us to recognise numerous faults filled by injected sand. In particular, sandstone-filled extensional, contractional and strike-slip faults are observed cutting the sandstone/mudstone successions. Sandstone-filled faults commonly display small offsets and apertures ranging from a few centimetres to some decimetres. Evidence of tectonic deformation is usually lacking, meaning that sand injection supported by overpressured fluids propped open the fault walls. In this paper we also describe the main mechanism leading to the emplacement of sand along a fault plane, and propose a predictive model of sandstone-filled fault distributions in different structural environments. Finally, we discuss the role of sandstone-filled faults, that although relatively small and not adding significant volume to the reservoirs, can markedly increase fluid transmissibility and thereby promote better reservoir connectivity.

One of the most important factors that helps trap hydrocarbons in multi-layered siliciclastic reservoirs is the occurrence of sealing faults (Allan 1989; Bouvier *et al*. 1989; Knipe 1992; Gibson 1994; Childs *et al.* 1997; Manzocchi *et al.* 1999; Fisher *et al.* 2001; Fisher & Knipe 2001; Bailey *et al.* 2002; Ainsworth 2006; Childs *et al.* 2007;

Jolley *et al.* 2007). However, it is also recognised that not all faults possess sealing properties and that some permeable faults cutting through the reservoir/cap-rock boundary may strongly compromise the integrity of the top-seal (Cartwright *et al*. 2007). Such faults may provide a conduit which links the reservoir rocks with other permeable units overlying the top-seal, or with the Earth's surface, thereby resulting in hydrocarbon leakage. The behaviour of a fault, either as a seal or a conduit, strictly depends on the structure of the fault zone and the juxtaposition of reservoir and non-reservoir lithologies (Caine *et al.* 1996; Storti *et al.* 2003). Understanding fault zone structure is therefore key to predicting connectivity and compartmentalization, together with hydrocarbon distribution within a reservoir. In fact, faults produce a series of fault rocks that control the flow properties and sealing capabilities (Yielding *et al*. 2010). In reservoirs comprising brittle rocks of either low porosity/permeability or high porosity/low permeability (i.e. carbonates), faults may provide significant connectivity and are often considered the most efficient pathways for fluid migration (Aydin 2000). In multi-layered siliciclastic reservoirs, where ductile mudstone intervals behave as low permeability membranes, connectivity is typically enhanced by the geometry and distribution of high-porosity/permeability lithologies such as sandstone, and faults can result in a general reduction in the fluid flow transmissibility (Watts 1987). This is due to a number of factors including the juxtaposition of permeable and impermeable strata, clay smearing produced during fault movement, the creation of fine-grained cataclasites along the fault zone (*sensu* Caine *et al*. 1996) and, diagenetic processes leading to the occlusion of pores (Watts 1987; Knipe 1992; Yielding *et al.* 1997).

A number of algorithms have been developed to predict the percentage of clay smear (and hence the sealing potential) in a fault zone that cuts through multi-layered siliciclastic reservoir rocks such as the Shale Gouge Ratio (SGR) (Yielding *et al.* 1997), the Clay Smear Potential (CSP) (Bouvier *et al.* 1989; Fulljames *et al.* 1997) and the Shale Smear Factor (SSF) (Lindsay *et al.* 1993). Implicit in the estimation of SGR, CSP and SSF is that reduction in grain size, and thus pore throat radius, reduces permeability. It is recognized that these algorithms are more applicable to rocks that consist of alternating lithified sandstone and plastic mudstone, and are not well suited for poorly consolidated strata that typically occur at shallow burial depths (Lewis *et al.* 2002). In fact, in this latter case, fault activity may lead to a transfer of sand from fault blocks into the fault core, thereby significantly increasing the porosity and permeability characteristics (Palladino *et al*. 2018).

In central California, examples of sandstone-filled extensional, contractional and strike-slip faults are observed in Mesozoic-Cenozoic sandstone/mudstone successions (Fig. 1). These faults provide valuable insights into the potential modification of reservoir seal integrity by fault-controlled sandstone intrusions. Although sandstone-filled faults do not add large volumes of sand to a reservoir, they are important as the occurrence of sand in fault zones significantly alters the fault permeability thereby conditioning fluid transmissibility. They must therefore be considered when designing models of fluid flow simulation in faulted sand injection-prone reservoirs. Here we address the role played by sandstone-filled faults on reservoir connectivity by investigating well-exposed outcrops in Central California.

Geological setting

The sedimentary sequence exposed in the Panoche and Tumey hills area of Central California is part of a NE-dipping Monocline Ridge which forms the northeastern side of the Tumey Hill Anticline (Dickinson 2002) (Fig. 1). It mainly consists of Cretaceous to Quaternary siliciclastic units deposited in different transitional to deep-water sedimentary environments varying from deltaic to the base of slope depositional settings (Moxon 1988; Johnson & Graham 2007). The succession includes two giant sand injection complexes, the Panoche Giant Injection Complex (PGIC) and the Tumey Giant Injection Complex (TGIC) hosted respectively within the Moreno Formation and Kreyenhagen Shale (Fig. 1). The PGIC is derived from the remobilization of turbidite channels that occur near the base of the Moreno Formation. Fluidized sand was injected upward through the stratigraphy giving rise to a strongly connected dyke and sill network (Vigorito *et al.* 2008; Hurst *et al*. 2011). At the top of the complex, sand extrudites testify to the localised flow of sand on a Danian paleo-sea floor (Vigorito & Hurst 2010). The TGIC formed by sand fluidization of turbidite channels occurring at different stratigraphic levels throughout the Kreyenhagen Shale (Zvirtes *et al*. 2019 this volume). The TGIC has a similar well-developed network of dykes and sills as the PGIC, but if extrudites were present they have been subsequently eroded. The age of the TGIC is therefore poorly constrained, although it should range between Middle Eocene and Late

Eocene/Early Oligocene (Zimmerman 1944). After emplacement of the TGIC, both complexes were subjected to deformation in different tectonic regimes, and younger generations of sandstone intrusions were emplaced along tectonic structures. Sandstone-filled faults described in this paper are ascribed to these younger suites of sandstone intrusions (Palladino *et al.* 2016, 2018).

Sandstone-filled faults

Details of faults, as well as the inner fault zone architecture (Caine *et al*. 1996), are generally not imaged on seismic sections as they are below the limits of seismic resolution, and general insights are therefore drawn from outcrop analogues. Fault zones developing in under-compacted multi-layered siliciclastic deposits generally consist of a mix of smeared clay and sand grains (Gibson 1998; Bense *et al.* 2003). In particular, sand can be incorporated along fault zones due to: i) shearing processes resulting in deformed ribbons parallel to the fault plane; ii) dragging and rotation of sandstone beds along a fault until they become parallel to the fault plane; iii) injection processes resulting in fluidized sand being intruded directly along the fault zone (Lewis *et al.* 2002). According to these authors, in the first two cases, the incorporation of sand into the fault zone implies deformation and the consequent development of fault-parallel anisotropy as well as shear bands, multiple slip surfaces and alternating shale/sand stripes. In the third case however, the sand is injected under pressure into pre-existing or newly-formed fault surfaces by fluid overpressure. Fault-parallel anisotropies are related to lamination and banding created by differences in grain alignment and reorganisation occurring as a result of the fluid movement.

In the next sections we describe three representative and very well-preserved examples of reverse, normal and strike slip sandstone-filled faults from Central California. Although these structures formed in different tectonic contexts, they display some common characteristics, which in the multi-layered siliciclastic successions generally lead to increasing permeability and connectivity of the hydrocarbon system.

Examples of sandstone-filled faults

Sandstone-filled faults associated with contractional tectonics

In the Monocline Ridge area, a sandstone-filled thrust cutting through the Kreyenhagen Shale outcrop (TGIC) consists of an E-W striking blind thrust with up to 15 cm displacement that dies out towards the fault tip (Figs. 1, 2a). The fault-related fold shows an asymmetric geometry with an overturned forelimb indicating northwards-directed vergence (Fig. 2b). The sandstone filling the thrust plane is well-sorted, medium grained, and structureless or poorly laminated. Even though the whole thrust is entirely filled by injected sand, the sandstone thickness varies laterally from a few millimetres to several centimetres. In particular, thick sandstone intrusions occur in the fold hinge in saddle reef cavities, or along releasing steps created during thrust movement. Sandstone-filled thrust faults are attributed to Eocene to Oligocene contractional deformation (Palladino *et al.* 2016).

Sandstone-filled faults associated with extensional tectonics

Sandstone-filled normal faults are common in the study area. The example shown in Fig. 3 is from Tumey Gulch (Fig. 1) where a fault array offsetting the Moreno Formation crops out. These structures cut through different sandstone units, which include both depositional units (thin-bedded turbidites) and sandstone intrusions belonging to the earlier PGIC (Fig. 3a, b). Normal fault kinematics can be deduced by offset marker beds and by the dragging of sandstone along fault planes. Dip-slip striations are recognized discontinuously along the fault walls. They probably formed during the early stage of the fault formation and were partially removed by the arrival of the injected sand. Fault offsets range from 10 to 15 cm, and fault apertures range from 2 to 10 cm, with infill commonly consisting of structureless or poorly laminated sand. Sandstone-filled normal faults developed in this area are attributed to outer arc extension of folds formed during the Eocene (Palladino *et al.* 2016).

Sandstone-filled faults associated with strike-slip tectonics

Sandstone-filled strike-slip faults that cut through the Moreno and Kreyenhagen Shale formations are less common than those showing extensional and contractional kinematics. A well-preserved example from Silver Creek (Fig. 1) consists of a NW-SE trending left-lateral strike-slip fault that displays clear cross-cutting relationships with an older generation of vertical dikes belonging to the PGIC. Fault kinematics, depicted by the offset of pre-existing vertical sandstone intrusions, is best appreciated in plan-view (Fig. 4a, b). Strike-parallel striations are locally preserved along the fault walls. The average fault offset is 30 cm while the aperture is 15 cm. The sand fills the entire length of the described fault and maintains a constant thickness. Internal structures include fault parallel banding. Local releasing steps, consistent with left lateral movement of the fault, are also present. The age of this fault is uncertain, although given its orientation and position, it may be linked to the San Andreas Fault System which shows an average azimuth N324° (Aydin & Page 1984).

Basic conditions and mechanism for sand emplacement along a fault plane

In order for fluidized sand to be injected along a fault plane, two essential preconditions must be met in the faulted sequence: i) high pore-fluid pressure (*Pf*) and ii) occurrence of poorly-consolidated sandstone. The first precondition is encountered in siliciclastic-filled sedimentary basins, formed of sandstone bodies alternating with mudstones, where overpressure development is related to sealing mechanisms, rapid deposition of the sedimentary column, tectonic loading, diagenesis, and rapid migration of hydrocarbon gas (Osborne & Swarbrick 1997). Deep-water marine turbiditic successions are considered to be the most commonly-fluidised strata (Jolly & Lonergan 2002).

The second precondition typically occurs in sedimentary basins that were never deeply buried (less than 1 km) or thermally altered (less than 60ºC) so that the sandstone has not been subjected to significant diagenetic alteration. Other conditions linked to the average net to gross ratio, the thickness and spacing of the sandstone units are described by Lewis *et al.* (2002), who suggest that environments characterized by high net to gross ratio and thick sandstone layers are most prone to develop sandstone-filled faults.

The mechanism leading to the emplacement of sand along a fault plane is dependent on the behaviour of the overpressured fluids circulating along the fault. This behaviour is still a poorly understood phenomenon, although some indications are provided by various theoretical and observational studies. Models show that fluids moving along faults may intermittently propagate as upwards- or laterally-directed pulses, shock waves or ‘burps’ at a rate of m/yr to km/yr (Rice 1992; Nur & Walder 1992; Roberts & Nunn 1995; Losh *et al.* 1999; Finkbeiner *et al.* 2001; Revil &

Cathles 2002; Miller *et al.* 2004; Haney *et al.* 2005). Although these fluid velocities are considered geologically fast, even higher velocities, of the order of cm/s, are needed for sand to be fluidised and injected and for sandstone intrusions to be emplaced. Previous studies demonstrate that if the pore-fluid movement reaches the minimum fluidization velocity, it imposes a drag force that is able to mobilize sand grains (Lowe 1975). For well-sorted, fine-grained sands, similar to those included in the Moreno and Kreyenhagen Shale formations, the calculated minimum fluidization velocity is estimated to be as low as 0.01 m s^{-1} (Duranti & Hurst 2004). Therefore, sandstone-filled faults described in this study provide evidence for high-velocity fluids flowing along fault zones. As the ascent of fluidized sand occurs along all types of faults, even compressional faults where the adverse orientation of principal stresses should impede fluid flow and sand fluidisation, we believe that the migration of the fluidised sand must occur within an open, obstacle-free conduit (the fault plane). This condition is encountered only for supra-lithostatic pore pressures which are able to prop open the fault.

A model for fluid transport along a fault plane that could account for rapid fluid flow which is able to cause prolonged dilation of the fault and to remobilize the sand was proposed by Sibson (1990). According to this model, upward or lateral fluid transport occurs along a fault which cuts through a rock sequence composed of different lithologies that form pressure cells each characterized by different *Pf* (Fig. 5). This situation is commonly observed for sedimentary sequences composed of alternating sandstone and mudstone, where there is a general increase in *Pf* with depth. Considering a simple case where two sandstone bodies are separated by a low permeability mudstone (Fig. 5a), the pre-faulting *Pf* profile will follow the hydrostatic gradient in the uppermost sand body and rapidly increase through the mudstone horizon. Then, it will continue to increase (even if less rapidly) in the lowermost sandstone body, following a supra-hydrostatic path. When faulting occurs in such a succession (Fig. 5b), it produces an abrupt *Pf* disturbance, and the fault turns into a lower-pressured zone recalling fluids from the lowermost, but higher-pressured, sand body thereby establishing an upward-directed pressure gradient. During the early stage of faulting, elevated *Pf* will dilate the fault plane thus creating space and causing high velocity flow that triggers sand fluidization and transport along the fault plane. This mechanism is identical to sand injection into hydraulic fractures in mudstone, the mechanism by which most sandstone intrusions form (Vigorito & Hurst 2010). Following the upward discharge of fluid, the pore pressure profile in the mudstone and the lowermost sandstone will tend to equilibrate (Fig. 5b). According to Sibson (1990), if the fault is resealed the system can be recharged and the processes can be cyclically repeated with the fault acting as a valve (the fault valve mechanism). In sand injection complexes it appears that fluids continue to dilate fractures after sand is no longer fluidised, and in some cases provide nucleation sites for the formation of mineral veins (Cobbold *et al.* 2013).

Impact of sandstone-filled faults on fluid flow

In hydrocarbon exploration, the sealing potential of a fault is one of the crucial factors to take into account when predicting fluid migration scenarios and estimating hydrocarbon volumes in faulted siliciclastic reservoirs. Therefore, a good understanding of fault behaviour allows the geological risk to be assigned, for example if a fault is leaking or sealing.

Faults may act both as conduits or barriers to hydrocarbon migration by favouring, stopping or diverting the migration pathway over geological timescales (Allan 1989; Caine *et al.* 1996; Fisher & Knipe 2001). Whilst faults acting as barriers commonly play an important role in trapping hydrocarbons, they may however also compartmentalize reservoirs, making hydrocarbon recovery challenging (Corrigan 1993). Faults acting as conduits may cause leakage, and thereby limit or prevent hydrocarbon accumulation (Cartwright *et al.* 2007). The behaviour of faults as conduits or barriers in poorly consolidated siliciclastic successions depends on the net to gross characteristics of the deformed successions, fault rock typology created during deformation (cataclasite, clay smear, etc.), the magnitude of the fault throw and fault activity (active or dormant faults). For faults that do not contain sandstone intrusions, two possible scenarios are possible in terms of fluid migration:

i) For faults affecting sedimentary successions characterized by high net to gross values, there is a high probability that once offset reservoir units are still in contact, even after large amounts of fault throw (Harding & Tuminas 1989; Knott 1993). This potentially ensures cross-fault fluid transfer. However, the occurrence of fault gouge can still favour along-fault fluid flow. This is because fault gouge which mainly consists of a mixture of sand grains and mudstone-derived clasts, can acquire important shear-related, fault-parallel physical anisotropies, which can focus fluid movement along the direction of anisotropy. These fault-parallel barriers, represented by shear bands and smeared clay, generally form an obstacle for cross-fault fluid movement thus favouring along-fault fluid transfer (Arch & Maltman 1990). Large amounts of permeable sandy clasts, floating in an impermeable fault gouge material, ripped up from the fault walls, contribute to an increase in total permeability of the fault. In this latter case, connectivity is effective only if the clasts are still partially in contact with the wall rocks (Fredman *et al.* 2007).

ii) In the case of faults affecting sedimentary successions characterized by low net to gross ratios, tectonic structures tend to develop clay smear or juxtapose reservoir and sealing units therefore resulting in a general lowering of the fault permeability (Fig. 8b). Sandy clasts ripped from the fault walls may eventually be surrounded by an impermeable matrix. In this situation, both cross-fault and along-fault fluid flow becomes markedly reduced.

When mineralogically-mature sand is injected into faults, according to the process described above, the fault permeability may improve dramatically. In an environment prone to sand remobilization, sandstone-filled faults represent an additional route for fluid migration. This is particularly likely to be the case in low net to gross sedimentary successions, as sandstone-filled faults are able to connect otherwise isolated reservoir lithologies located at different stratigraphic levels. This behaviour explains unexpectedly high levels of hydrocarbon reservoir connectivity within thick inter-reservoir seal units (Briedis *et al.* 2007) and improved connectivity in less mudstone-rich reservoirs where intra-reservoir mudstone seals are present (Guargena *et al.* 2007; Satur & Hurst 2007). They only contain faint fault-parallel anisotropy represented by banding acquired during the sand emplacement which does not represent a major obstacle for fluid migration.

During sand injection, the movement of fluidized sand inevitably produces an abrasive effect on fault walls, which has the potential to “clean” them by removing smeared clay-rich fault gouge and fine grained cataclastic material. In the case of sandstone-filled faults in high net to gross sedimentary successions, both cross-fault and along-fault fluid flow transmissibility are strongly enhanced by the occurrence of sand instead of fault gouge material. Hydrocarbons will be free to move across the fault plane from the hanging-wall to the footwall and vice versa without any appreciable hindrance. Upward, along-fault fluid flow movement is enhanced in the direction of the maximum hydraulic gradient. In the case of sandstone-filled faults cutting through low net to gross sedimentary successions, along-fault fluid flow transmissibility will be considerably improved allowing the fault to hydraulically link isolated reservoir units.

Predicting orientation and geometry of sandstone-filled faults in different geodynamic settings

Since sandstone intrusions occurring within tectonically-active basins tend to be emplaced along newly-formed, structural discontinuities (Winslow 1983; Palladino *et al.* 2016, 2018), it is possible to develop predictive models for their distribution (Fig. 6). In particular, as the development of horizontal or vertical tectonic discontinuities are determined by the orientation of the regional stress field (Anderson 1951), different sandstone intrusion geometries represented by high/low angle dykes or sills are potentially predictable.

In extensional regimes (Fig. 6), the vertical orientation of the maximum principal stress promotes the development of high angle dykes which are intruded along steeply dipping conjugate shear faults and near-vertical tension fractures, whereas the formation of concurrent sills is prevented because of the adverse orientation of the maximum principal stress (σ_1). Normal faults commonly occur in areas subjected to regional extensional tectonics, or locally are associated with contractional and strike-slip structures in different tectonic settings (Fossen 2016). Some outcrop examples of sandstone-filled extensional faults are documented (Taylor 1982; Davison 1987; Audemard & de Santis 1991; Ribeiro & Terrinha 2007; Montenat 1991, 2007; Ravier *et al.* 2015; Palladino *et al*., 2018) and similar features were reproduced in laboratory experiments (Galland *et al*. 2006). Sandstone intrusions associated with normal faults have often been recognized in the subsurface by means of seismic profiles and cores (Dixon 1995; Lonergan and Cartwright 1999; Shoulders *et al.* 2007; Koša 2007; Bureau *et al.* 2013). Sandstone-filled normal faults in extensional regimes commonly strike parallel to the maximum horizontal stress. Resultant sandstone intrusions are arranged as parallel arrays, or form conjugate, conical-shaped, injections (Palladino *et al.* 2018). Sandstone-filled normal faults sometimes also occur in association with contractional folds as a result of outer arc extension (Palladino *et al.* 2016). In this case, they have a radial arrangement with the strike oriented parallel to the fold axis.

In contractional regimes (Fig. 6), the horizontal orientation of the maximum principal stress (σ_1) allows the development of both sills and dykes since low-angle shear faults and near-horizontal tension fractures develop. Sandstone intrusions occurring in the hanging-wall of major thrusts were first documented in southern Chile by Winslow (1983). Laboratory experiments investigating pluton emplacement demonstrate that when contractional deformation is applied to multi-layered sequences, flat-lying sills and low- to high-angle dykes propagate along the basal detachment surface and develop almost simultaneously (Galland *et al.* 2003). These experimental results prove to be valid for sandstone intrusions along contractional faults, as is widely confirmed by outcrop observations (Taylor 1982; Di Tullio & Byrne 1990; Ujiie 1997; Waldron & Gagnon 2011; Palladino *et al.* 2016). In contractional regimes, vertical sandstone dykes may form swarms striking parallel to the maximum principal stress (σ_1). It follows that in contractional tectonic settings the simultaneous emplacement of both high- and low-angle dykes and sills is possible. Complete and incomplete saucer-shaped intrusions, corresponding with double- or single-vergent thrusts, respectively are also an expected geometry (not to be confused with intrusions having similar geometry described by Jackson et al. (2011) in extensional tectonic settings).

In strike-slip regimes (Fig. 6) sandstone intrusions may occur along the major fault plane itself, or along different cavities originating on the fault plane as well as *en echelon* fracture arrays or, in association with fault bends. In the latter case, releasing bends are the best suited locations to host sandstone intrusions. Outcrop evidence of sandstone intrusions related to strike-slip tectonics are rare within the literature (e.g. Macdonald & Flecker 2007). Sandstone-filled strike slip faults are expected in zones of active strike-slip tectonics, or in the footwall of thrusts where they form conjugate sets of vertical faults with the axis of maximum compressive stress (σ_1) oriented parallel to the bisector. Sandstone intrusions associated with strike-slip faults generally form near-vertical sandstone dykes.

Discussion and implications for reservoir modelling

Modelling sandstone-filled faults when evaluating fault seal potential is particularly challenging due to the paucity of published subsurface and outcrop datasets. However, greater attention should be given to these structures especially when considering intrusive-prone successions, (i.e. alternating mudstones and poorly-lithified sandstone successions), that could give rise to intrusive reservoirs. As pointed out by Lewis *et al.* (2002), fault seal analysis methods are often applied to multi-layered-siliciclastic reservoirs without considering the possible occurrence of sandstone along fault planes which would significantly improve fault permeability and reservoir connectivity in general. Ignoring this could lead to overestimation of the sealing potential of the system. Conversely, failure to recognise sandstone-filled faults, which add new sand to the system, can lead to the underestimation of the total volume of hydrocarbon present in a reservoir.

Sandstone-filled faults in the subsurface are only rarely described in borehole cores (Dixon *et al.* 1995; Kosă 2007) although some seismic-based studies may enhance the understanding of their geometry/volume (Dixon 1995; Shoulders *et al.* 2007; Bureau *et al.* 2013). The main reason for this is that during faulting the amount of sand remobilized is a tiny volume when compared with the huge volumes of sand that are mobilised during the formation of giant sand injection complexes (Vigorito *et al.* 2008). Consequently, sandstone intrusions along faults are commonly too narrow and too steep to be detected in seismic data (Grippa *et al*. 2019). Based on our outcrop observations, sandstone-filled faults can form closely-spaced fault arrays (Fig. 3), sometimes cross-cutting, and often resulting in a dense network of sandstone intrusions associated with inferred high permeability. Sandstone intruded along faults can either be uniformly distributed within the fault zone, or form porous and permeable sand lenses within the less permeable fault rock.

Including sandstone-filled faults when modelling hydrocarbon reservoirs formed by sandstone intrusions entails the following advantages: i) unlike modelling ‘ordinary’ faults, which commonly involves a number of uncertain factors which are directly linked with the fault rock properties as well as the structure (usually strongly anisotropic), composition (consisting of a sand-mudstone mixing) and rheology of the fault gouge (Hesthammer & Fossen 2000), modelling sandstone-filled faults importantly reduces the uncertainties since injected sandstones generally consists of clean and well-sorted sand that, based on core data generally have porosities of 30-40% and permeabilities of more than 1 Darcy (Duranti *et al*. 2002; Briedis *et al*. 2007); ii) fault zones are often free of gouge material (Palladino *et al*. 2018), as this is removed during the sand injection; iii) the concept that fluidized sand is forcibly injected along tectonic discontinuities strongly helps in predicting the distribution of sand injections in a reservoir subject to tectonic stress.

Conclusion

In this paper we use well-preserved outcrops from Central California to discuss the fluid flow importance of normal, strike-slip and contractional sandstone-filled faults, affecting multi-layered, siliciclastic reservoirs. Occurrence of these structures shows that sand remobilization is particularly active along fault zones where high-velocity fluids are capable of fluidizing and remobilizing poorly lithified parent sandstone.

Using the case study examples, we have also shown that sandstone-filled faults common in sand-injection -prone reservoirs, add a new factor in modelling poorly consolidated siliciclastic reservoirs. In particular, sandstone-filled faults, which tend to form in groups rather than occurring as isolated structures, act as conduits for fluid migration and reduce reservoir compartmentalization.

Sandstone-filled faults are relatively straightforward to model in terms of permeability and porosity, as the injected material generally consists of well-sorted clean sand. Sandstone emplacement produces an abrasive effect along fault walls thereby potentially removing the low permeability fault gouge represented by fine-grained sand or clay smear. Sandstone-filled fault orientation is also predictable, as it is controlled by the local tectonic stress field. Consideration of sandstone-filled faults may enhance our understanding of the recovery of oil from newly discovered or mature sand-injection prone reservoirs, such as those in the North Sea, which show dimensions and architectural characteristics very similar to the injection complexes exposed in California. Further advances in understanding the role of sandstone-filled faults in reservoir fluid flow transmissibility must necessarily start from the study of well-exposed outcrop analogues and then be applied to the evaluation of subsurface data.

Acknowledgements

We are very grateful to companies sponsoring Phase 3 of the Sand Injection Research Group (SIRG). We acknowledge the continuing help provided by the Bureau of Land Management (BLM) in California.

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Figure captions

Fig. 1. Geological map (modified from Bartow 1996) of the western margin of the San Joaquin Valley in California (see inset map for general location). Outcrop locations and places referred to in the text are also shown. The stratigraphic position of the Panoche Giant Injection Complex (PGIC) and the Tumey Giant injection Complex (TGIC) is also reported. SAFZ-San Andreas Fault Zone.

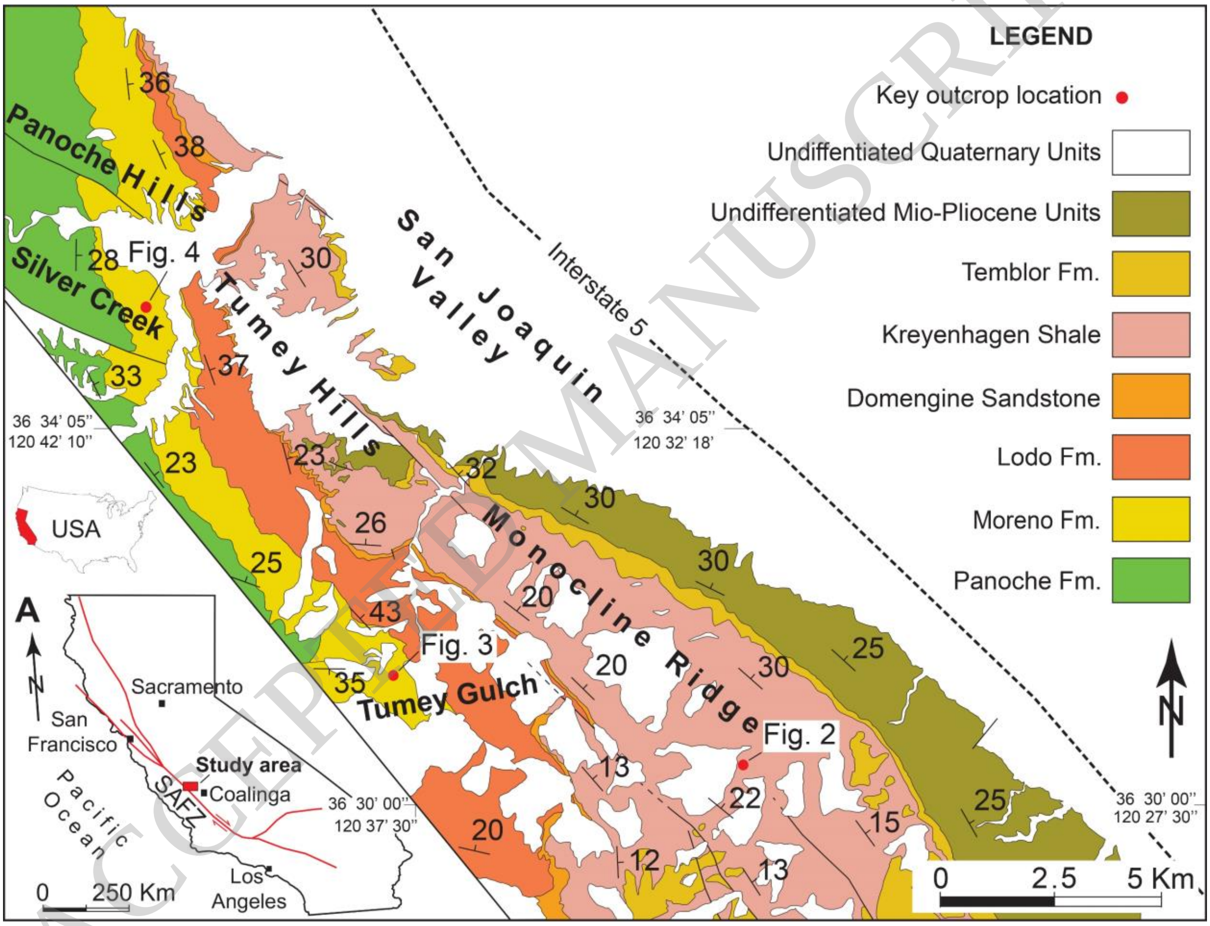
Fig. 2. Sandstone-filled faults associated with contractional tectonics: (**a**) photograph and (**b**) associated line drawing of a meso-scale blind sandstone-filled thrust cutting through the Kreyenhagen Shale at Monocline Ridge. Note the occurrence of sand throughout the entire fault plane and within saddle reef and releasing step cavities (modified from Palladino *et al*. 2016).

Fig. 3. Sandstone-filled faults associated with extensional tectonics: (**a**) photograph and (**b**) associated line drawing of closely-spaced swarms of sandstone-filled normal faults cutting through the Moreno Formation at Tumey Gulch. Note post-emplacement deformation processes represented by vertical fault segmentation and anomalous fault planes curvatures (modified from Palladino *et al*. 2018).

Fig. 4. Sandstone-filled faults associated with strike-slip tectonics: (**a**) plan-view photograph and (**b**) associated line drawing of meso-scale sandstone-filled left-lateral strike-slip faults at Silver Creek. The photograph has been obtained using close photogrammetry techniques.

Fig. 5. Simplified geological model and associated fluid flow profiles consisting of two sandstone bodies separated by a low permeability mudstone (modified from Sibson 1990). (**a**) Pre-faulting stage: the low permeability mudstone forms a barrier separating hydrostatic and suprahydrostatic fluid pressure regimes. (**b**) Faulting stage: hydrostatic and suprahydrostatic pressure cells are juxtaposed along the fault. This generates an upward directed pressure gradient capable of fluidizing and remobilizing the sand which is forcibly injected along the fault plane.

Fig. 6. Cartoon illustrating the conceptual model of sandstone-filled fault orientation predicted for different tectonic regimes (see text for explanation).


LEGEND
Key outcrop location ●
Undiffentiated Quaternary Units
Undifferentiated Mio-Pliocene Units
Temblor Fm.
Kreyenhagen Shale
Domengine Sandstone
Lodo Fm.
Moreno Fm.
Panoche Fm.
N
0
2.5
5 Km
Panoche Hills
Silver Creek
Tumey Hills
Tumey Gulch
San Joaquin Valley
Monocline Ridge
Interstate 5
Fig. 4
Fig. 3
Fig. 2
36
38
28
30
33
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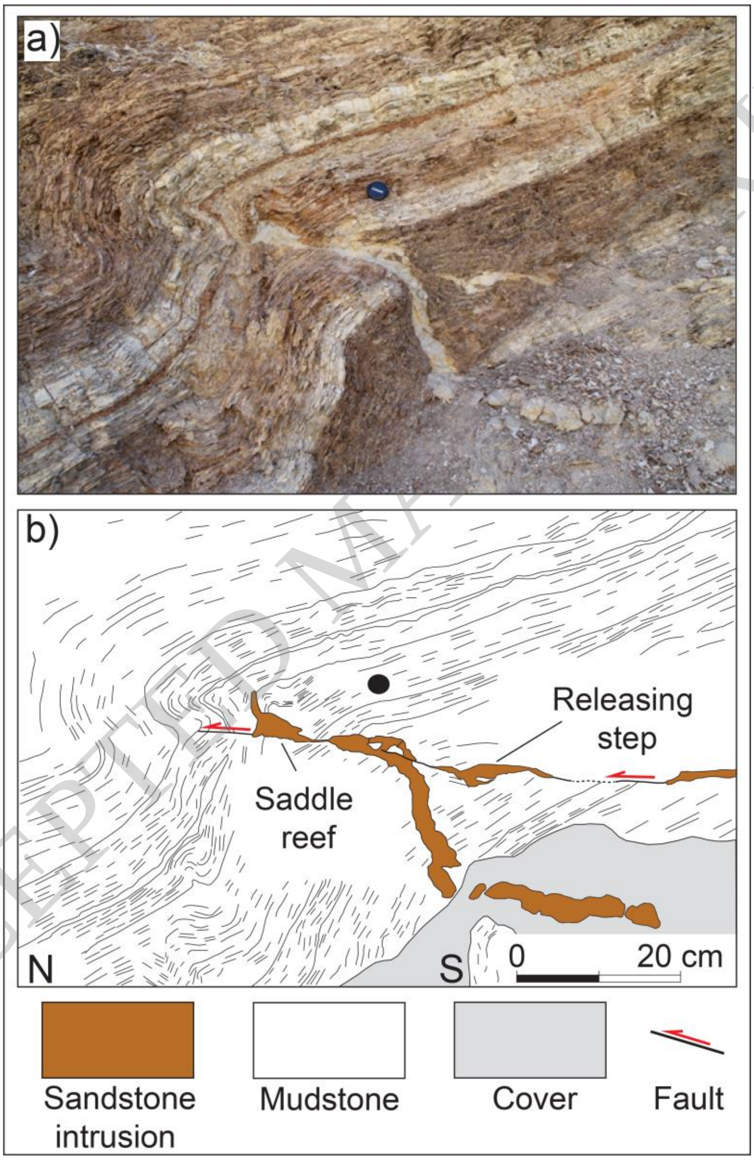
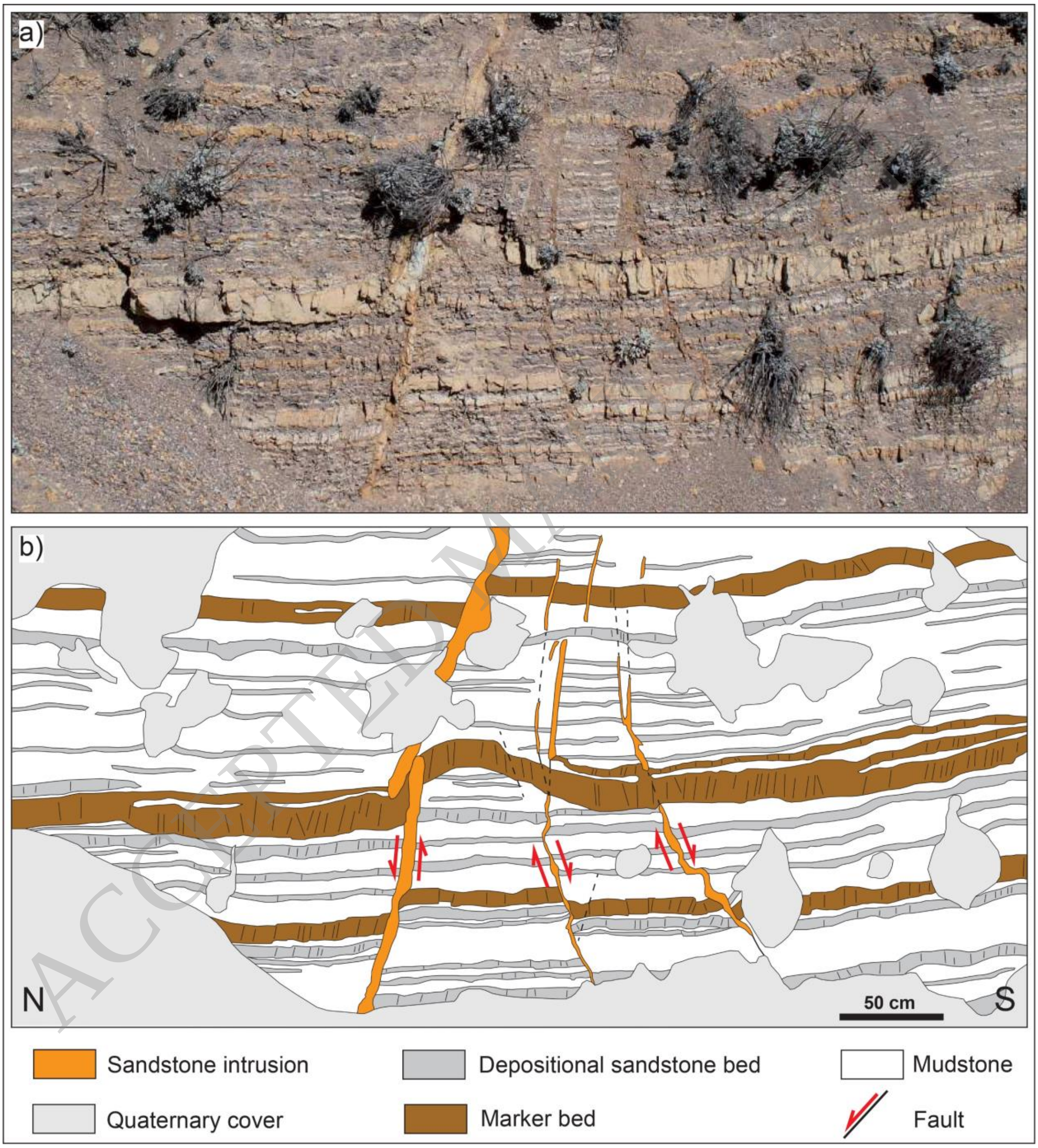
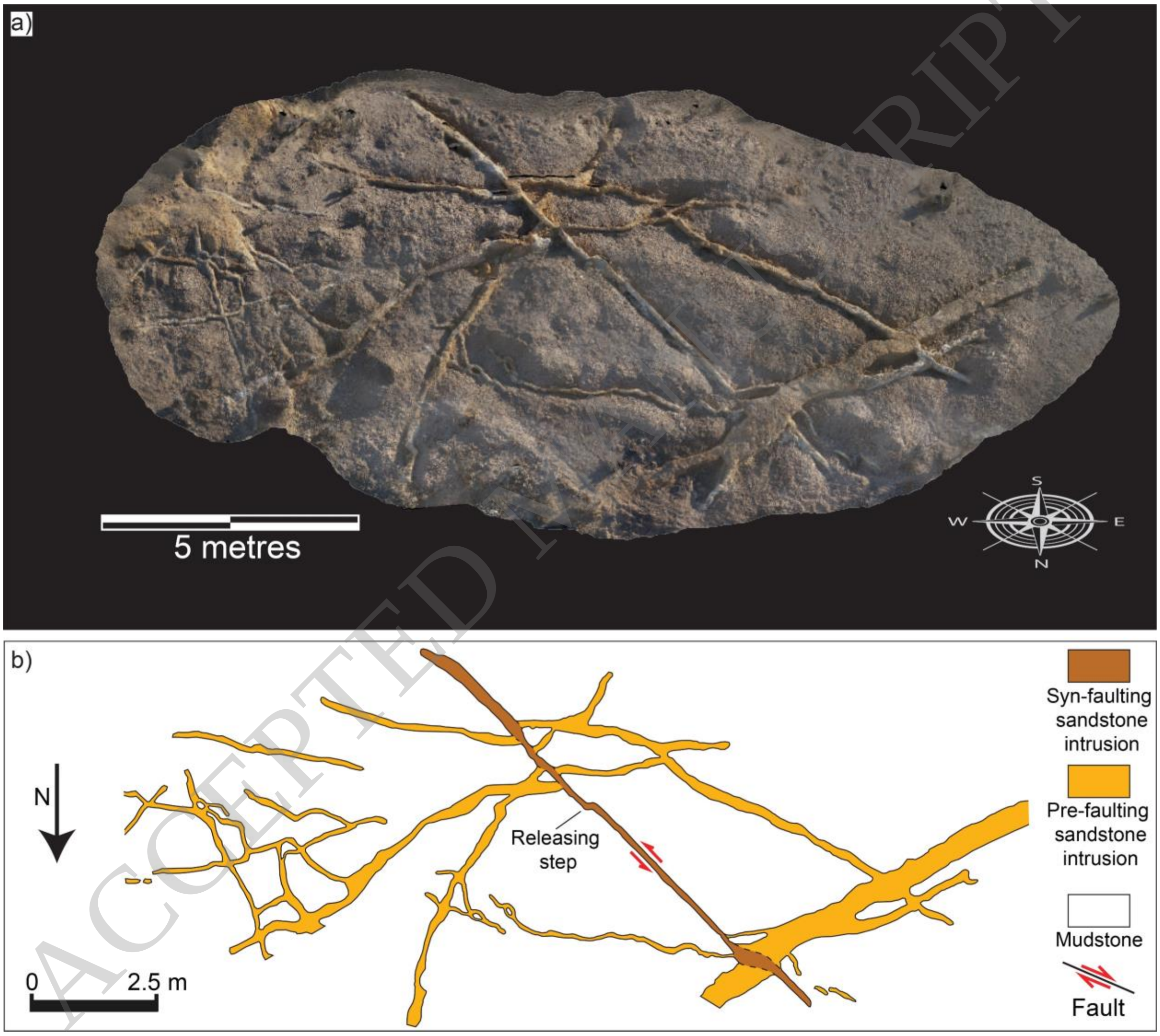
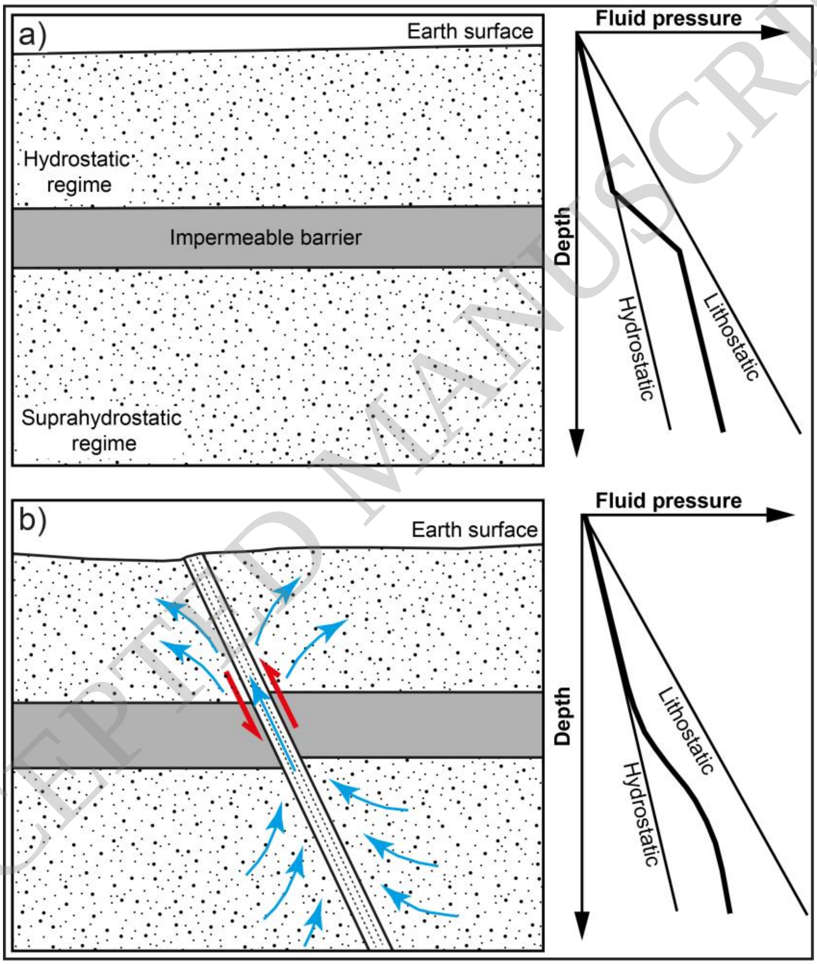
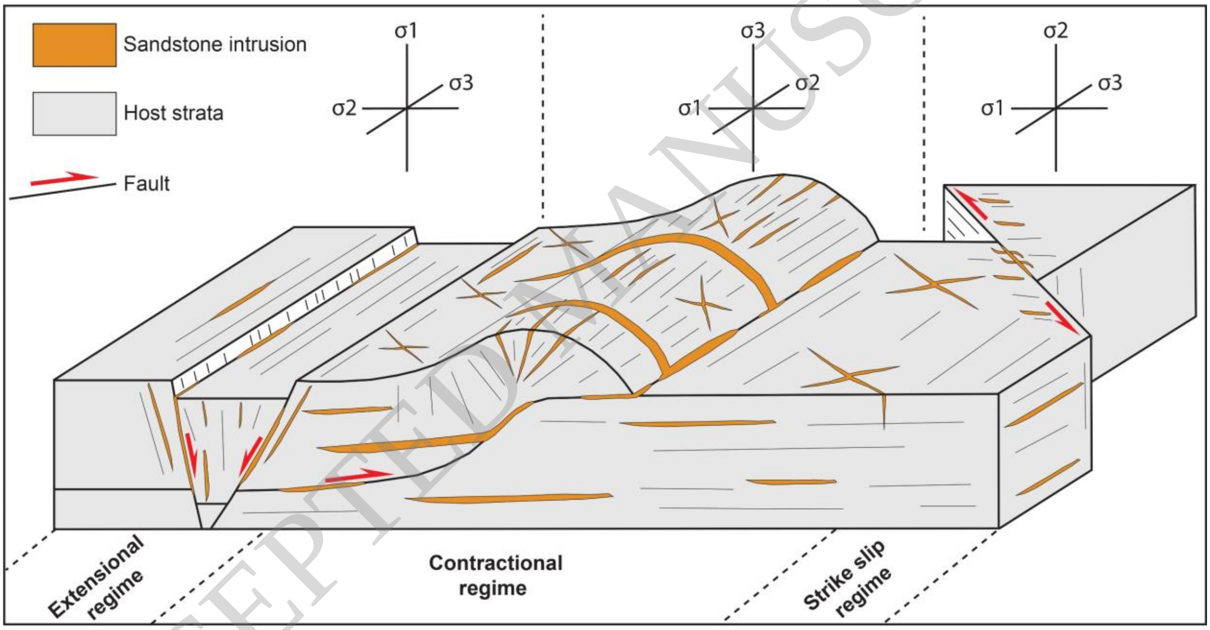
23
23
26
32
30
30
25
20
43
35
20
30
25
13
22
25
15
20
12
13
36 34' 05''
120 42' 10''
36 34' 05''
120 32' 18'
36 30' 00''
120 37' 30''
36 30' 00''
120 27' 30''
USA
A
N
Sacramento
San Francisco
Study area
Coalinga
SAFZ
Pacific Ocean
Los Angeles
0
250 Km


a)
b)
Releasing step
Saddle reef
N
S
0
20 cm
Sandstone intrusion
Mudstone
Cover
Fault


a)
b)
N
S
50 cm
Sandstone intrusion
Quaternary cover
Depositional sandstone bed
Marker bed
Mudstone
Fault


a)
5 metres
S
W
E
N
b)
N
0
2.5 m
Releasing
step
Syn-faulting
sandstone
intrusion
Pre-faulting
sandstone
intrusion
Mudstone
Fault


a)
Earth surface
Hydrostatic regime
Impermeable barrier
Suprahydrostatic regime
Fluid pressure
Depth
Hydrostatic
Lithostatic
b)
Earth surface
Fluid pressure
Depth
Lithostatic
Hydrostatic


Sandstone intrusion
Host strata
Fault
σ1
σ2
σ3
σ3
σ1
σ2
σ2
σ1
σ3
Extensional regime
Contractional regime
Strike slip regime