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Sand injectites in the West Crocker Formation, Kota Kinabalu, Sabah

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Abstract: Sand injectites are common in the turbidite sequences of the West Crocker Formation (Eocene-Oligocene) but their occurrences have never been reported. This paper describes sand injectites and related deformational structures from outcrops of West Crocker around Kota Kinabalu, Sabah. The injectites range in scale from millimetres to metres, occurring in the interbedded sandstone-mudstone facies. They are usually found in thickly-bedded massive sandstone facies that comprise mainly Bouma Ta/Tb divisions. This facies type is characterized by dewatering features such as dish and pipe structures and represents parts of the sedimentary system that are prone to overpressure buildup. The injectites are thought to have been formed by the sudden release of overpressure in the water-charged turbiditic sediment at shallow burial depths, possibly triggered by seismic shock or gravitationally induced failure/slumping up-dip of the depositional site. The injectites occur in various forms, including dykes, sills and pipes; the latter representing major conduits for vertical fluid movement and sediment remobilization through the turbidite sequences. The common occurrence of injectites in the West Crocker Formation suggests that they may also be present in the Neogene deepwater sequences offshore West Sabah. Outcrop studies on these features may help predict their presence and distribution in the subsurface and assess their possible impact on reservoir distribution, heterogeneity and connectivity.

Keywords: Sand injectites, turbidites, overpressure, West Crocker Formation, Sabah

INTRODUCTION

Deep marine turbidite sequences commonly exhibit features related to dewatering and compaction, such as dish structures, dewatering pipes, and sand injectites. Such features are also quite common in the West Crocker Formation, the Eocene-Oligocene flysch deposits that crop out in the Kota Kinabalu region in West Sabah, Malaysia. Whereas dish and pipe structures have been described as a characteristic feature of these turbidite deposits, sand injectites have so far not been given the attention they deserve. This paper describes some sand injectites or "intrusions" observed in several outcrop localities around the city of Kota Kinabalu (Figure 1). These soft-sediment deformational features have been widely documented from other deep-marine depositional systems and occur in various forms and sizes from micro to macro (seismic) scales (Figure 2). The term "injectites" was introduced by the petroleum industry in the 1980s as these features began to be recognized in the subsurface as important elements of deepwater sedimentary systems (Shanmugam, 2006). In the same context, "injectites" is used in this paper as a general term for sand-filled intrusive bodies occurring within the turbiditic sandstone-mudstone facies.

Similar structures have been referred to in older literature as "sand dykes", "clastic dykes" or "Neptunian dykes"; the latter may have a different origin than the former two as it refers to passive filling of open fractures or fissures (Maltman, 1994, p. 28). Hence, injectites are considered as one of the earliest described deformational sedimentary structures, dating back to early 1800s (e.g., Diller, 1890; Demoulin, 1978). Although during the early days they were only of academic interest, by early 2000s sand injectites were recognized as potential hydrocarbon traps (coined "intrusive traps") and soon developed into a hydrocarbon play concept (Hurst *et al*., 2005; Hurst & Cartwright, 2004). In 2007 the American Association of Petroleum Geologists (AAPG) published a special volume dedicated to sand injectites, underlining their importance in hydrocarbon exploration and production (Hurst & Cartwright, 2007). Sand injectites may be important also in the search for economic mineral deposits (e.g., Chi *et al*., 2007).

Figure 3 illustrates some of the different geometries of sand injectites and their main mode of occurrence. A sudden release of overpressure, possibly triggered by an earthquake or catastrophic failure on the shelf or slope (e.g., slumping or mass movement), may cause the intrusion of unconsolidated sand from a parent sand body upwards through the sedimentary layers, forming various sand-filled sand bodies such as dykes (generally discordant to the paleo-horizontal or bedding) and sills (concordant with bedding) (Figure 3a). Some of these features may terminate at an edifice on the paleo-sea floor, but may be quickly removed by subsequent turbidite flows. Repetitive injection-depositional events may result in a complex tiering of sand injectites which may have a significant impact on reservoir heterogeneity and connectivity (Figure 3b). In extreme cases of sand injectites, such as in the North Sea, 80% of sandstone volume could be the result of post-depositional remobilization, including sand injection (Andresen *et al*., 2019). For this reason, injectites have generated a lot of interest in the oil industry within the last decade or so, due to their potential impact on reservoir distribution and connectivity in deepwater depositional systems (e.g. Grippa *et al*., 2019).

Several authors (e.g. Shanmugam, 2006; Hurst *et al*., 2011) discussed the criteria for identifying injectites in cores and seismic although no signal criterion is diagnostic. Some injectites may resemble other common features of deep marine sedimentary systems, such as slumps and debris flow deposits. Studying injectites in outcrops is useful for their recognition in the subsurface. The outcrops of deep-marine turbidites of the West Crocker Formation in Kota Kinabalu provide us with the opportunity to study these interesting enigmatic features.

GEOLOGICAL SETTING

The study area around Kota Kinabalu, West Sabah, is geologically within the Tertiary NW Borneo Basin that underlies Sarawak, Brunei and Sabah at the southern margin

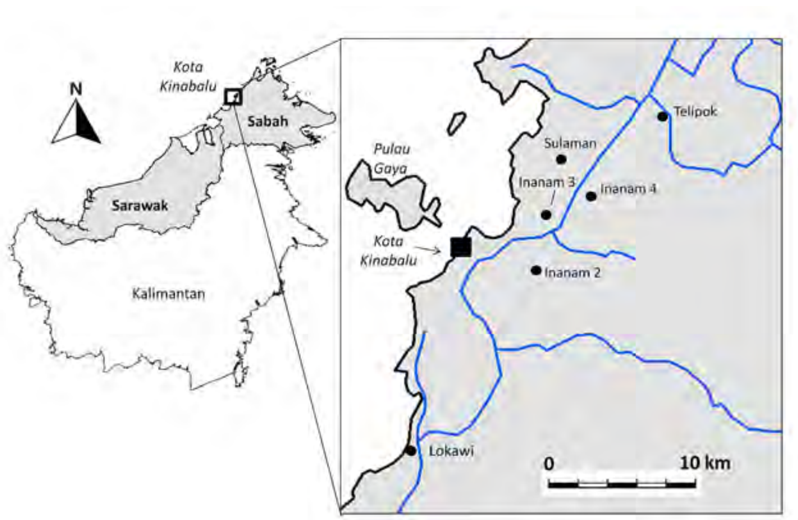

Figure 1: Map of the study area around the city of Kota Kinabalu, West Sabah (Malaysia) in northern Borneo. Outcrop localities referred to in the text are marked in solid circles.

Figure 2: Location of known clastic intrusions (injectites) in the world; representing outcrops, mines and subsurface occurrences, shown as red dots (modified from Braccini *et al*., 2008). The location for the subject of this paper, Sabah, is added.

of the South China Sea (Figure 1). The West Crocker Formation crops out extensively in the western coastal zone and foothills of the Crocker Range in western Sabah, and is considered by many workers as forming part of a late Cretaceous-Eocene accretionary prism that was formed by subduction of the proto-South China Sea oceanic crust underneath Sabah (Hazebroek & Tan, 1993) (Figure 4). The uplifted accretionary prism represents an oroclinal fold-and-thrust belt that spans the entire island of Borneo, from west Kalimantan to Sabah (Moss *et al*., 1998; Hutchison,

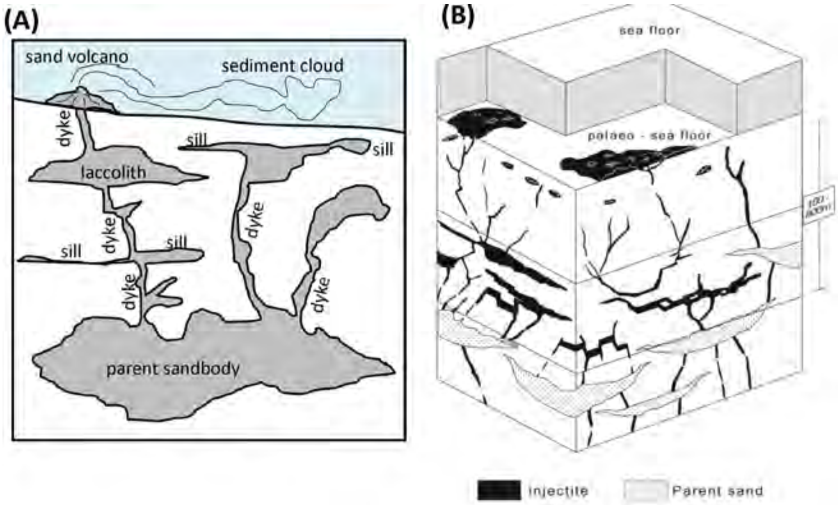

Figure 3: Main types of clastic injectites
(A) 2D illustration of seabed and subsurface with overpressured turbidite sandbody and different types of sand injectites intruded into overlying sediment and extruded onto the sea floor. Modified from Cossey *et al*. (2013).
(B) 3D illustration of several layers of turbidite deposits affected by injectites, forming an injectite complex showing extensive sand-mud interface. Host to parent and injectite sand (unornamented) is mud. Modified from Parnell *et al*. (2013).

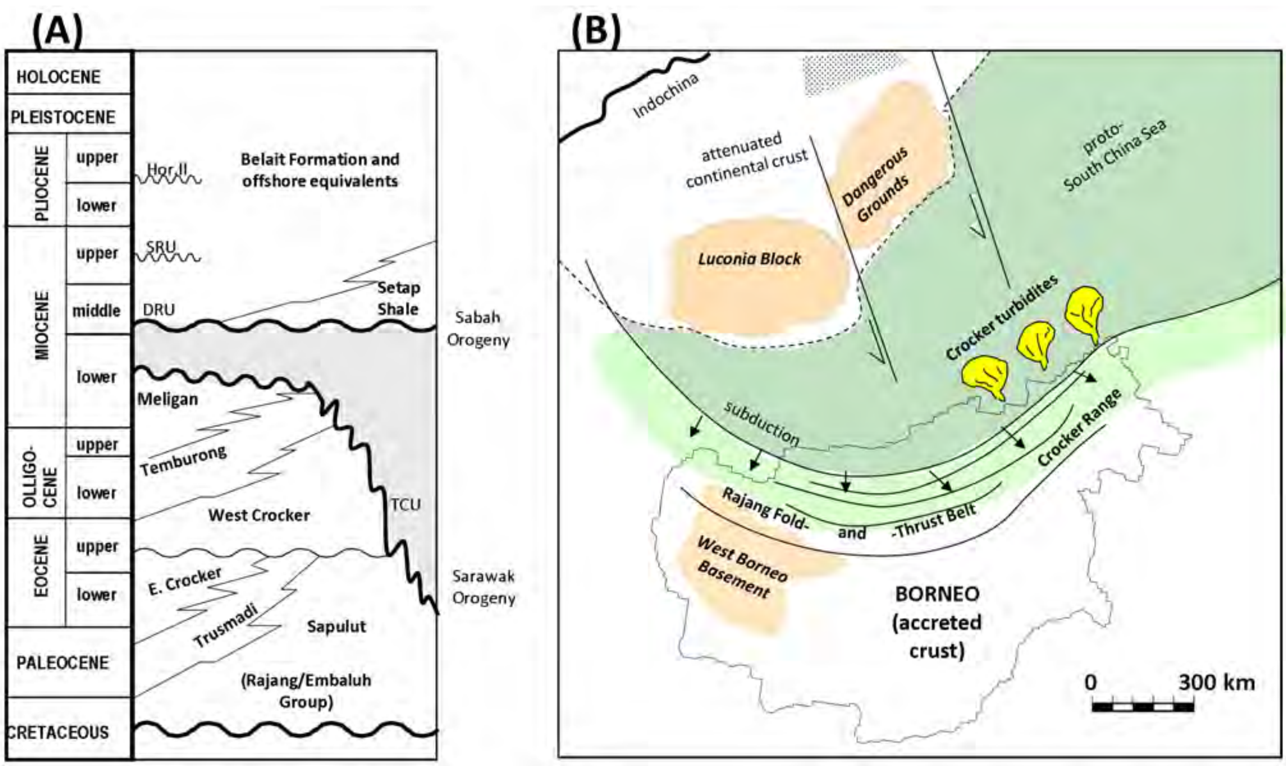

Figure 4: Regional geological and tectonic framework of the study area. (A) Stratigraphic summary of the Western Sabah region, based on various sources, including van Borren *et al*. (1996), Cullen *et al*. (2012), Leong (1999), Hutchison (1996), Hall *et al*. (2008), and Lunt & Madon (2017). The Top-Crocker Unconformity (TCU) was introduced by Hall *et al*. (2008) as the regional base-Miocene angular unconformity that marks the peneplanation of uplifted Crocker accretionary prism, hence the name. The Deep Regional Unconformity (DRU), of Middle Miocene age, is the regional angular unconformity at the base of shallow marine sequences in the offshore NW Sabah but has been shown to merge with the TCU landwards (Levell, 1987; Cullen, 2010). The DRU and TCU are therefore shown here as a composite unconformity. (B) Schematic paleogeography of the NW Sabah basin during the deposition of the West Crocker Formation (~Late Eocene). Present-day outline of Borneo is shown for reference.

1996, 2010). The eroded fold-and-thrust belt, of which the West Crocker is part, essentially forms the basement to the NW Sabah basin. Overlying the West Crocker, with great unconformity, is a >12 km thick Middle Miocene and younger shelf-slope systems of the present day NW Sabah hydrocarbon-bearing basin.

The West Crocker Formation has been described invariably as "flysch", "turbidite", "submarine fan", and/or "mass-flow" deposits (e.g., Stauffer, 1967; Tongkul, 1989; Hutchison, 2005; Crevello *et al*., 2007a). Its precise age is uncertain but more recent paleontological work indicates Upper Eocene to Oligocene age (Lambiase *et al.,* 2008; Cullen, 2010; Cullen *et al*., 2012). It comprises predominantly unmetamorphosed deep-marine sediments of generally high sand-shale ratios (70-80%, Madon *et al*., 2010) and an estimated total thickness of more than 6000 m (Lee *et al*., 2004). Sedimentological studies by the present author indicate that the turbiditic sediments of West Crocker Formation generally lack major erosional scours and are characterized by sheet-like geometries with flat bases and tops (Madon *et al*., 2010). Other authors have offered slightly differing interpretations: unconfined basin-floor fan (Crevello *et al*., 2000), slope aprons (William *et al*., 2003; Lambiase *et al*., 2008), and a single large submarine fan (Jackson *et al*., 2009; Zakaria *et al*., 2013).

OCCURRENCES OF SAND INJECTITES

The sand injectites were observed in several exposures of West Crocker Formation around Kota Kinabalu, labelled herein as Telipok, Sulaman, Inanam 2, Inanam 3, Inanam 4, and Lokawi (Figure 1). Representative sedimentary logs from some of the outcrops are shown in Figure 5. The turbiditic sequences generally comprise a sand-rich succession characterized by mostly fine-grained, very thick- to medium-bedded sandstones interbedded with mudstone and mud-rich slump intervals. Some of the thicker amalgamated sandstone beds may exceed 30 m in thickness. Many are massive and exhibit erosive bases and faint parallel lamination, often with dewatering features such as dish and pipe structures, characteristic of the Bouma Ta/Tb divisions. The thinly bedded turbidites (<1 m) show graded bedding with commonly recognised Bouma Ta-Tb-Tc-Td divisions. Many sandstone beds have well-developed sole marks, which include flute moulds, current lineations, as well as load and flame structures.

The turbidite sandstones generally have sheet-like geometry and appear to be laterally continuous at the scale of the outcrops. The sequences show repetitive coarsening-upward cycles of about 15-25 m thick, which may represent progradational fan lobes, probably in the middle to lower fan region. Fining-upward units, with very thick massive sandstone at the base, may be interpreted as channel-fill deposits in the upper fan or slope region, resulting from the basin-ward advance of the depositional lobes over the fan complex. The sandy nature of the sequences meant that trace fossils are often easily found within the thicker shale intervals, which could represent the inter-fan lobe or overbank areas, or off-fan basin plain mudstones.

Sand dykes and sills

The injectites show a variety of geometries and features, as illustrated in the sketches in Figure 6. They range in scale from a few millimeters to several centimetres (Figures 6a, 6b), but in some cases may be several meters in dimensions (Figure 6c). Field photographs of the injectites are shown in Figures 7 to 16. The injectites occur at boundaries between mudstone and sandstone, usually in the thick massive sandstone facies characterized by Bouma Ta/Tb division. The structures are mostly linear to curvilinear features, a few cm wide and tens of cm long. They are often recognizable on the surfaces of the sandstone-mudstone outcrops by their distinct, sharp boundaries, either sand against sand (Figures 7a-c) or sand against mud (Figure 8).

When exposed on the upper bedding surfaces of sandstones, the sand injectites appear to emanate from the sandstone bed upwards into the adjacent clay stone (Figures 8a, b). They may have branches or splits, and appear to form part of a larger network of sand-filled fractures, with criss-crossing patterns and "T-junctions" (Figure 7b). They intrude into claystone at high angle and are probably oriented perpendicular to the bedding (therefore may be regarded as "dykes"). The dykes penetrate some distance into the claystone and in places spread laterally, parallel to the bedding of the claystone (as in Figure 7c). These features may therefore be referred to as "sills". Some sand injections are observed in bioturbated sandstones (Figure 8c) and slumped mudstones (Figure 8d). In thick shale/mudstone intervals, the sand injectites are deformed along with the enclosing mudstones as a result of post-depositional tectonic event, as seen in the examples from Lokawi (Figure 8d).

Sand dykes also appear to have been emplaced preferentially along a network of fractures as seen in several places, for example at Inanam 4 (Figure 9a). At that outcrop, the sand injectites which originate in the thick massive sandstone and penetrate upwards into the overlying mudstone are aligned in a specific orientation, as seen both in bed-parallel and bed-normal perspectives (Figures 9b, 9c). The sand injectites, with varying widths up to several cm, can be seen clearly penetrating into the overlying mudstone at an oblique angle to the bedding. On the bedding surface, the injectites appear as curvilinear features oriented in a particular direction, presumably along the maximum horizontal stress direction at the time the injection took place. Although the orientations of the fracture networks were not measured, studies at other outcrops have shown that injection structures are aligned along paleo-stress directions (e.g., Monnier *et al*., 2015).

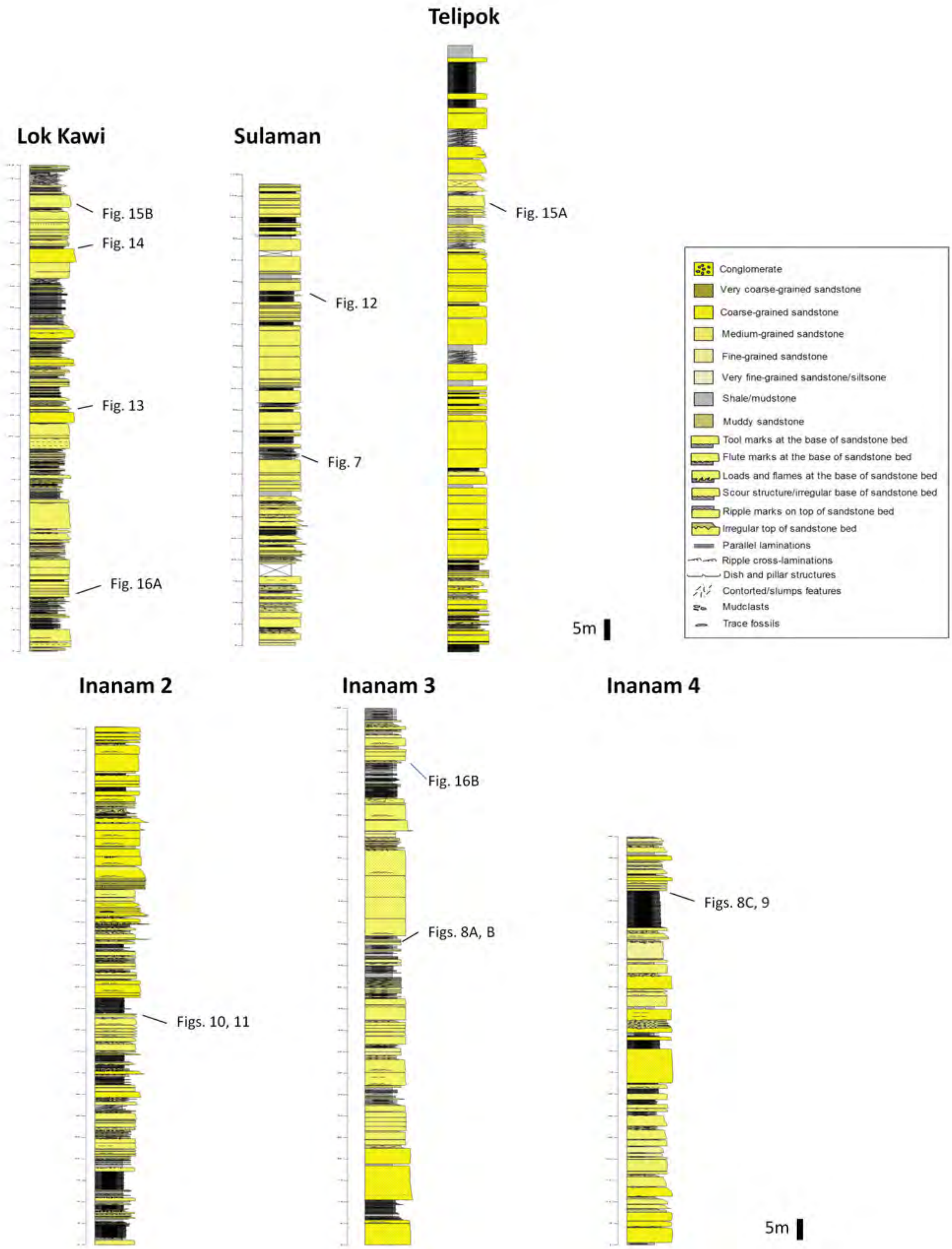

Figure 5: Sedimentological logs of the outcrops at the localities shown in Figure 1 where the injectites described in this paper were observed. The respective Figure numbers indicate the approximate location of the occurrences within the outcrop sequence.

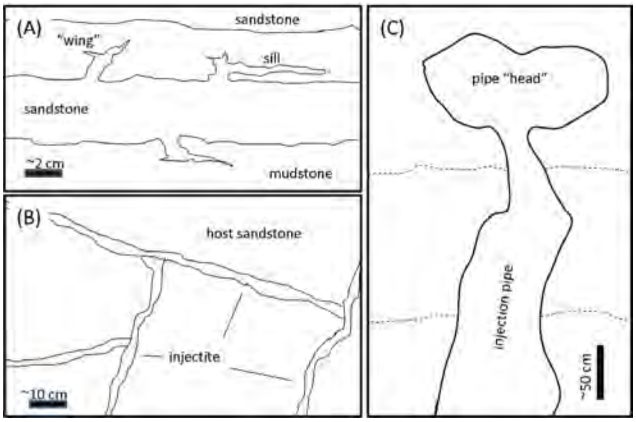

Figure 6: Sketch of the main features of the injectites from field observations at the outcrop localities shown in Figure 1.
(A) Small-scale sand injectites developed in thinly bedded turbidite facies. Injectites penetrate upwards or downwards into the adjacent mudstones and may spread laterally to form sills and wing-like features.
(B) Linear to curvilinear sand injectites interpreted to have been emplaced into the sandstone along discrete fracture network.
(C) Large injection pipe structure piercing through three thickly bedded massive sandstone beds, terminating in a cloud-shape pipe "head" or "laccolith". Dashed horizontal lines mark the amalgamation surfaces in the stacked sandstone beds.

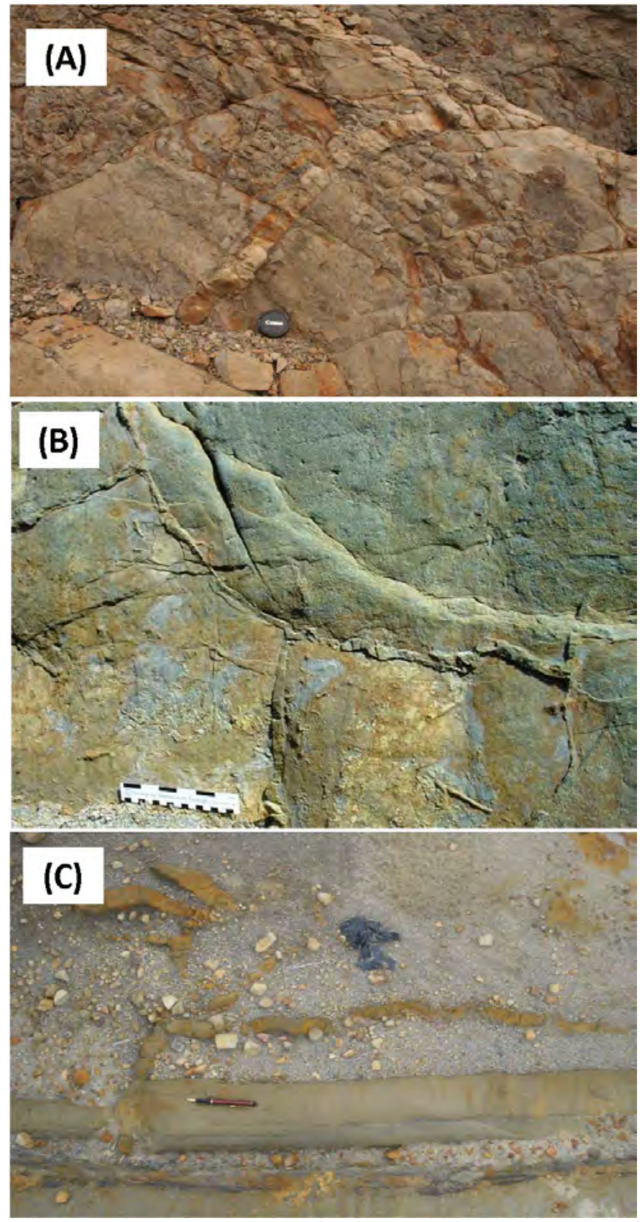

Figure 7: Examples of sand injectites from the Sulaman locality. They appear as linear or curvilinear sand-filled intrusions into sandstone (A, B) or into mudstone (C). In (A) the injectite is clearly intruded into the surrounding sandstone which appear to be of same material as the injectite but is clearly recognisable due to the sharp boundaries and that the injectite is fragmented into smaller segments. In (B) the injectites observed on bedding surfaces form angular network of fractures through which overpressured sand may have been injected. (C) Small-scale injectites emanating from the sandstone bed at the bottom and spreading laterally along the bedding in the mudstone.

Similarly, at Inanam 2 (Figure 1 for locality), an exposed bedding surface of a massive sandstone bed (> 2 m thick) with well-preserved ripple marks contain numerous sand-filled fractures that interpreted as sand injectites (Figure 10). The sand dykes penetrate vertically into the overlying mudstone interval which is even thicker (ca. 4 m). It appears that a pre-requisite for the formation of sand injectites is a thick massive sandstone bed (> 1-2 m thick) overlain by an equally thick mudstone unit. One particular sand dyke could be traced from the sandstone bedding surface through a couple of thin sandstone beds and into the overlying mudstone interval (Figure 10b). The sand dyke, only a few cm thick, has a complex morphology, zigzagging through and cutting across the thin sand layers of the heterolithic mudstone interval (Figure 11a). As in the example in Figure 8d, sand injectites totally encased in mudstone intervals tend to be prone to soft-sediment deformation or slumping. The sand dykes appear to have been deformed (folded) by subsequent (post-depositional) tectonic deformation that affected the entire sequence. In another instance, as the Inanam 2 (Figure 11b), a sand dyke appears to have been injected vertically upward into overlying claystone and then horizontally along the bedding plane of the claystone to form a sill.

At Sulaman 2 locality (Figure 12a) interesting geometries of the injectites structures were observed in a 2-m thick shale-rich section sandwiched between a 0.5 m thick massive sandstone beds (characterized by Bouma Ta/Tb divisions). Within the thick shale is discrete sandbody which appears to be isolated and discontinuous, "floating" in the mudstone interval. It is not clear if this is a major sand injectite body or a transported sandstone block (part of mass-transport complex) incorporated in the mudstone interval as a slump unit. The injection structures are mm- to

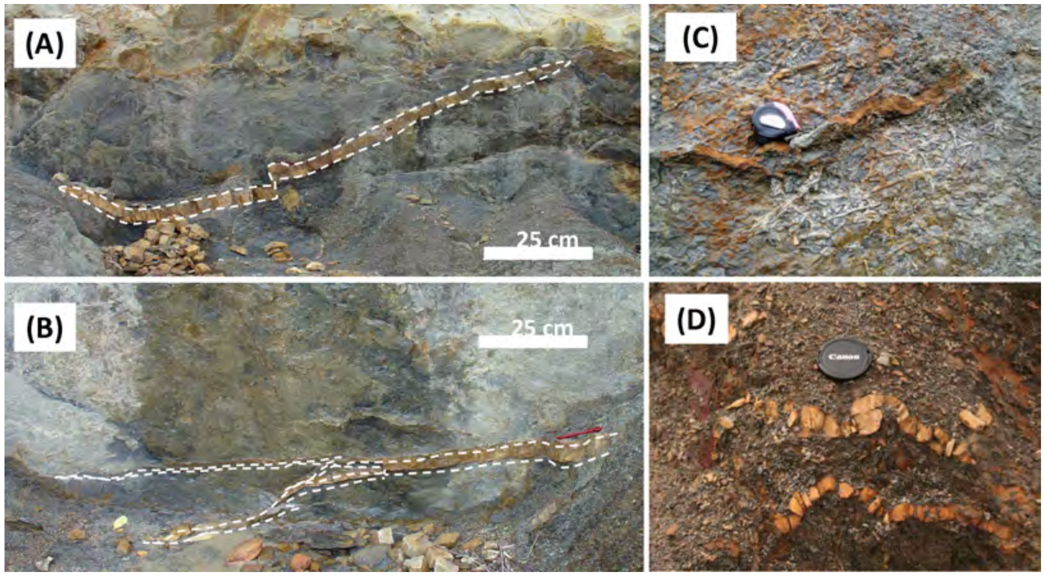

Figure 8: (A) Sand-filled fracture forming an injection structure seen from under a steeply dipping, thick massive turbidite sandstone bed. Way-up is into the plane of the photograph. What has been weathered out is claystone, hence the sand appears to have been injected downwards into the claystone from the overlying sandstone bed. Locality: Inanam 3. (B) Another injectite in claystone at the same locality: Inanam 3. (C) Sand injectite amongst burrowed claystone. The injectite clearly formed after the burrowing. Locality: Inanam 4. (D) Sandstone injections totally encased in claystone within a thick mudstone interval between massive sandstone beds. The sand dykes appear to have been deformed (folded) by subsequent (post-depositional) tectonic deformation that affected the sequence, particularly the muddy intervals like this one. Locality: Lokawi.

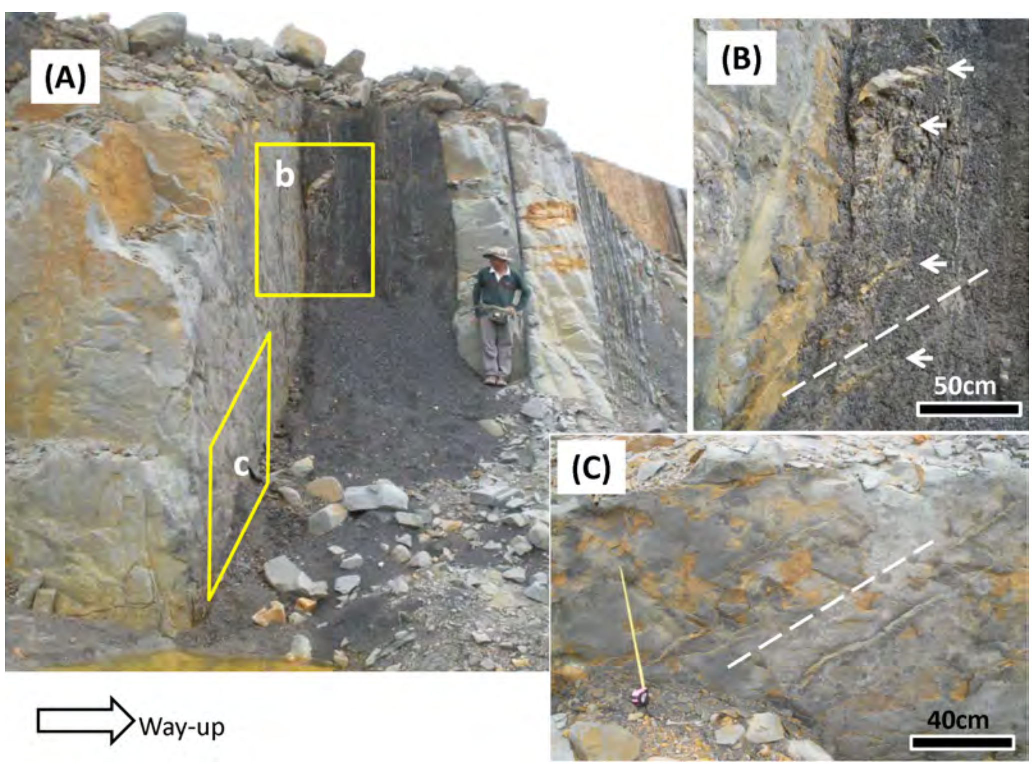

Figure 9: Inanam 4 outcrop (Locality in Figure 1) where sand injections are observed to be aligned in a specific orientation.
(A) Outcrop of thick massive sand with ripple-marked top surface overlain by a 2 m-thick shale/mudstone, which is in turn overlain by medium-bedded turbiditic sandstone bed (geologist for scale ~ 1.6 m). (B) Close-up of area in (A) where several sand injectites can be seen penetrating into the overlying mudstone at an oblique angle to the bedding (arrows). Dashed white line represents the general orientation of the sand injections. (C) When viewed perpendicular to bedding surface the injectites appear as curvilinear features oriented in a particular direction (dashed white line).

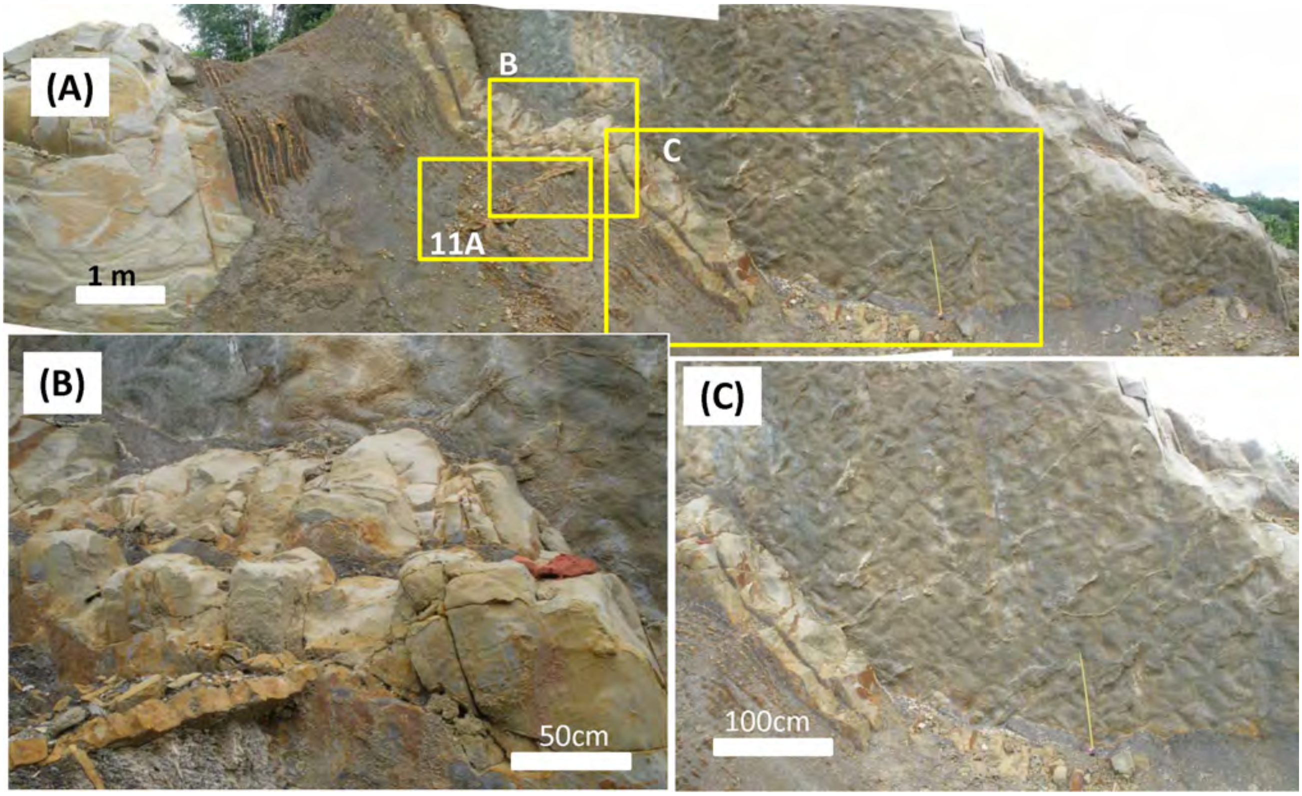

Figure 10: Locality: Inanam 2. (A) Mosaic of the entire outcrop, way-up to the left, starting from thick massive sandstone with rippled top surface [a close-up shown in (C)] showing numerous linear sand injectites coming out from the bedding surface, penetrating into the overlying thin sandstone beds (shown in B) and further upward into the 2 m-thick mudstone interval above it [close-up shown in Figure 11A]. Rectangles represent zoom-in photos shown in (B), (C) and Figure 11A.

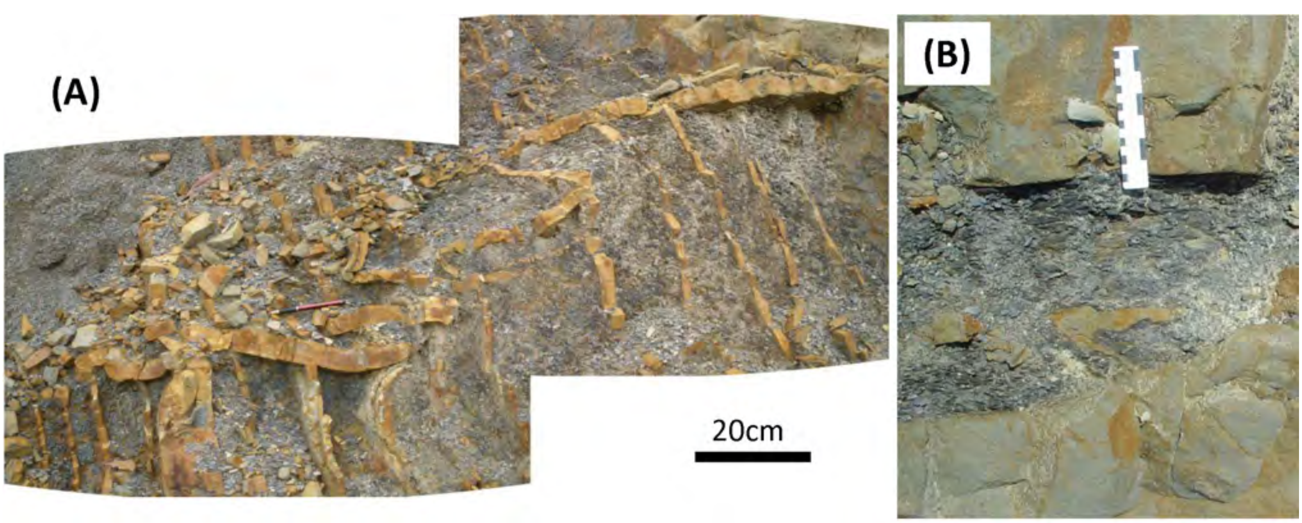

Figure 11: (A) Close-up of rectangle in Figure 10A, from Inanam 2 locality, in which a sand dyke a few mm thick originating from the thick massive sandstone shown in Figure 10A, is seen crossing the thick shale interval with twists and turns while cutting through all the thin sand layers in the thick mudstone unit. (B) Example of a sand injectite intruding upwards into shale above before moving laterally along bedding plane in the claystone. Locality: Inanam 2.

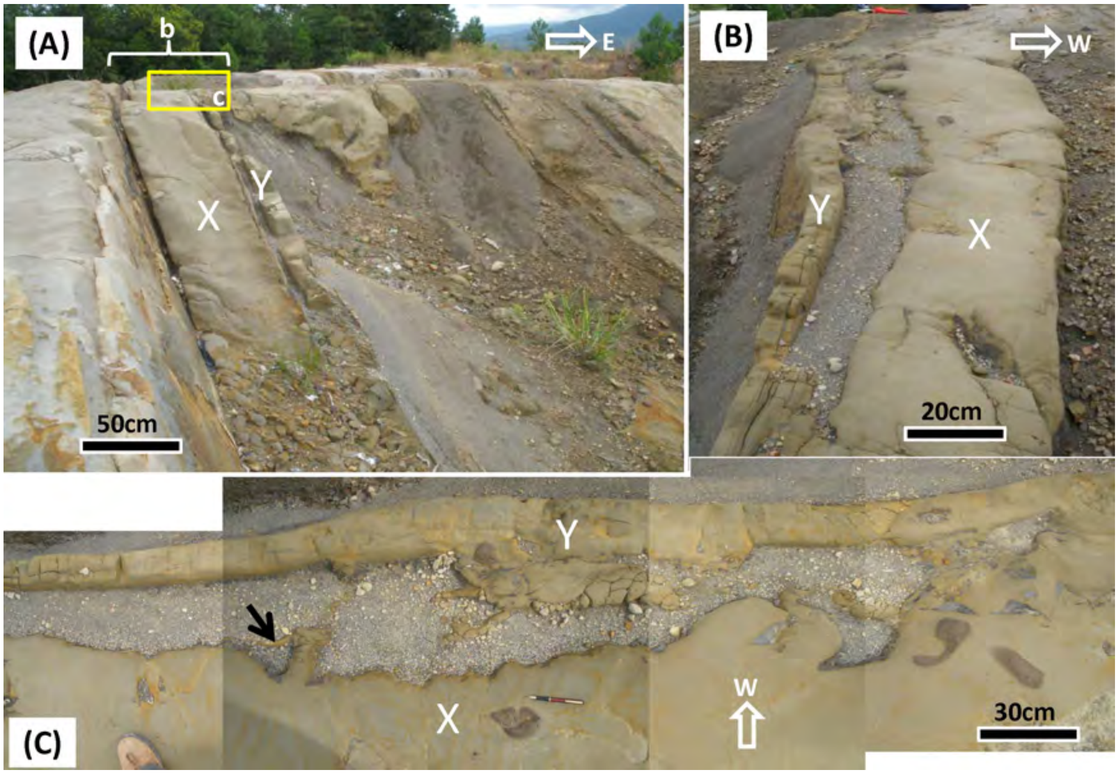

Figure 12: Locality: Sulaman (see Figure 1). Thick mudstone interval of about 2 m thick sandwiched between thick-bedded massive sandstone (at left and right of photograph; way-up to the right or East, viewed towards North). In the middle of the mudstone is an irregular sandbody which could represent an isolated body of sand injectite. Note sandbodies labelled X and Y for reference in (B) and (C). Other annotations: b is the section in (B) viewed from opposite direction towards South. Here the two sandbodies X and Y are identified for reference. (C) View of a part of (B) from above, i.e. perpendicular to bedding; injectites are observed to emanate from sand X (arrow, left of photograph) and, in places, connects with sand Y (to extreme right of photograph).

cm-scale features emanating from the lower sheeted massive sandstone and display the typical "flame" and "wing"-like geometries (Figures 12b, c). Some of these injectites join up with the bed-parallel sandbody in the middle of the shale interval, which suggests that the lenticular sandbody could well be a large sand injection structure. From these examples (Figure 12c) it seems that sills can have irregular shapes and varying thickness along their lengths as they penetrate through the host sandstone. In some places there are more irregular "flame-like" injectites emanating from the sandstone bed tops. In some cases, sand injectites can attain complex shapes as they penetrate into the host sandstone, developing branches and "wings" (Figures 13a, b). Besides these, there are also small mm-scale sand injectites commonly occurring at the interface between sandstone (Ta/Tb/Tc) and heterolithic mudstone (Td/Te) facies (Figure 13c).

Injection pipes and "blow-out" structures

Besides sand dykes and sills described above, there are larger-scale features (>10-20 cm wide and elongated perpendicular to bedding) which could be interpreted as injection "pipes". Two examples of these types of injectites were observed; one at Lokawi (Figure 14) and another at Telipok (Figure 15b). At Lokawi, on open ground excavated for building construction, steeply dipping massive sandstone beds are exposed to reveal a major sand injection structure a few metres long (Figures 14a, b). The presence of amalgamation surfaces between the thick massive sandstone beds suggests that the injectite had pierced through at least three sandstone beds stacked on top of one another (Figure 14c, cf. sketch in Figure 6). The piercement terminates in the third sandstone bed as a domal structure with rounded edges, a "laccolith", to borrow the term from igneous petrology (as also used by Kane, 2010; Figure 14b). The structure appears to be narrow and probably tubular or pipe-like in longitudinal section, and perhaps circular in cross section, through which the overpressure in the parent sediment is released by remobilization of the fluidized sediment into overlying sediments. This type of injectite is analogous to piercement structures normally associated with salt or shale diapirism.

It is observed (see Figure 14b) that the piercement or pipe structure terminated to form the "laccolith" within a sandstone bed after passing through at least two other

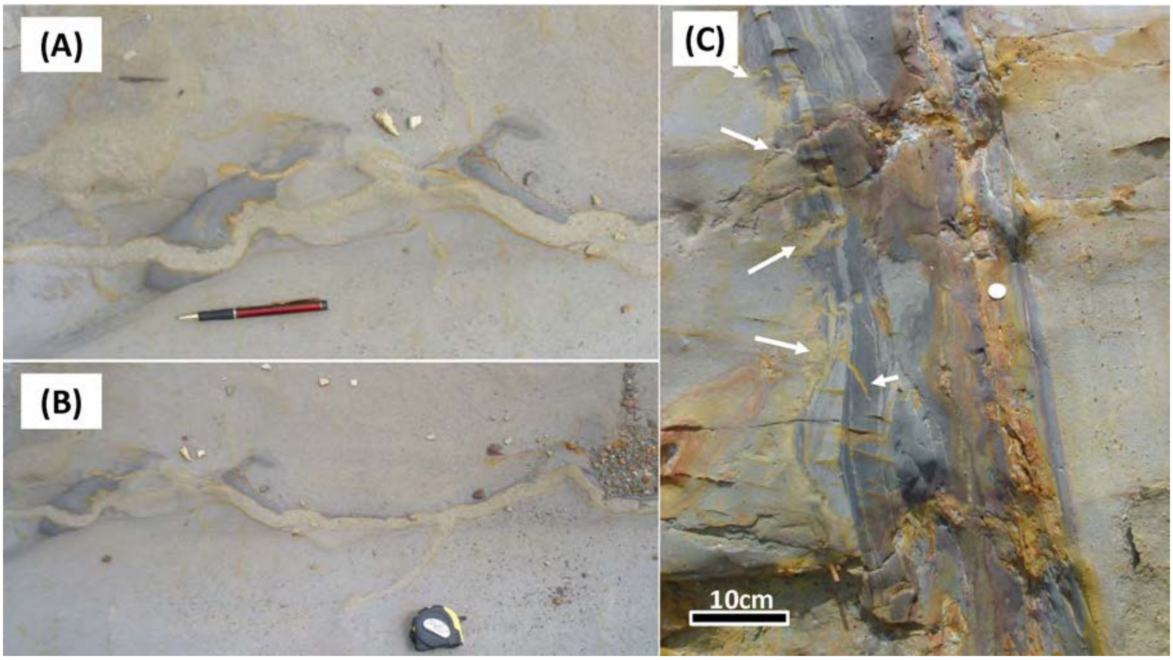

Figure 13: Complex shapes of sandstone sills with branches, "flames" and "wings". (A) and (B) are cm-scale injectites in massive sandstone beds. (C) mm-scale injectites at the top of massive sandstone boundary with mudstone, indicated by white arrows. Locality: Lokawi (see Figure 1 for location).

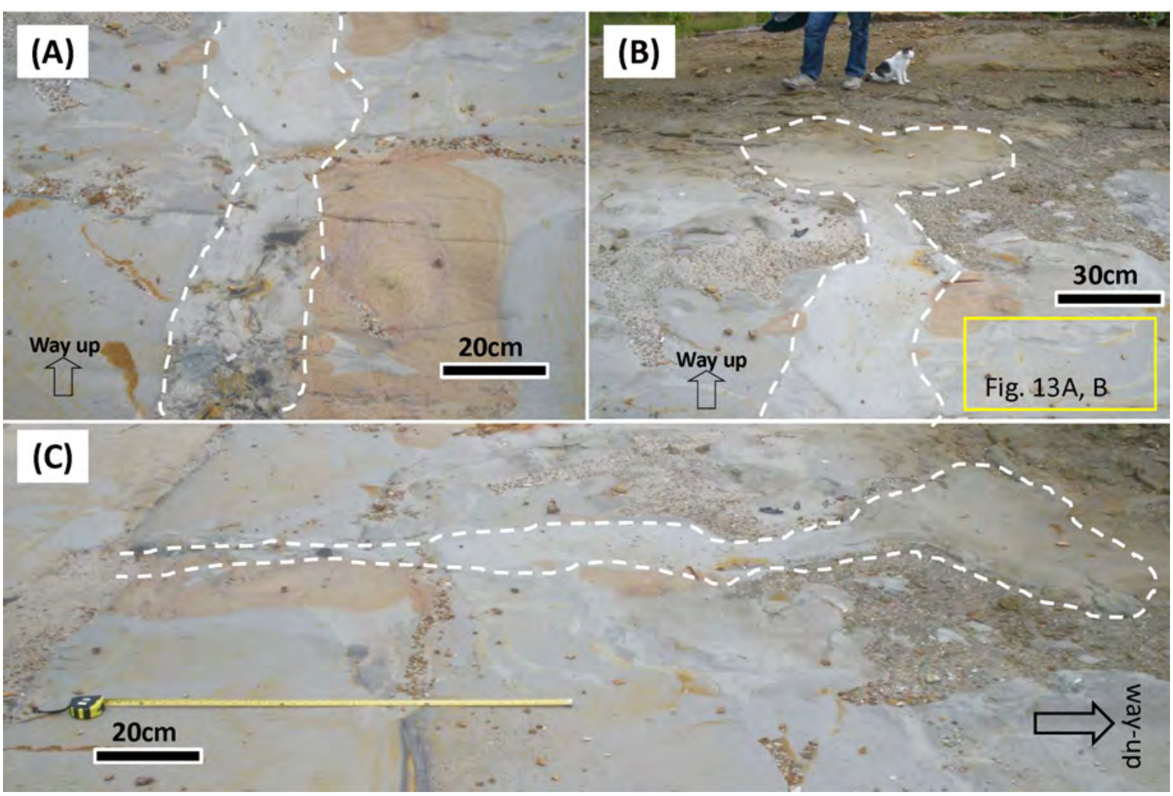

Figure 14: Metre-scale injection structure at Lokawi locality (see Figure 1 for location) where ground clearing exposed a horizontal section of steeply dipping massive sandstone beds. (A) Dashed white line shows the outline of a vertical injection pipe, 10-20 cm wide, cutting through several amalgamated massive sandstone beds. (B) The pipe structure terminates with a mushroom-shaped "head" (dashed white outline). Rectangle outline at bottom right represents the region where cm-scale injectites are observed (shown in Figure 13A, B). (C) side view of the pipe structure (white dashed line) from the bottom (left) to the terminus (right). Scale ruler is 1 m.

beds, probably because the energy due to overpressure had dissipated by the time it reaches that point. Had the pipe or piercement structure reached the sea floor, it would have resulted in a "blow-out", thus producing a seabed expression such as a pockmark or sand volcano (Figure 3). Fluid escape pipes have been described from seismic reflection data to have terminations at the seabed as pockmarks or palaeo-pockmarks (Cartwright & Santamarina, 2015). An example of a "blow-out" structure was found at Lokawi (location in Figure 1) where a conical shape vertical pipe, narrow at the base and widens towards the top of the bed, may represent a sediment blow-out at the seabed due to explosive release of overpressure from the underlying sediment.

A smaller pipe structure was found at Telipok (locality in Figure1) and is shown in Figure 15a. In this example, a massive sandstone bed about 30 cm thick contains a vertical pipe structure measuring 20 cm at the base narrowing to about 6 cm at the top of the bed. Within it are vertical "flow-lines" through which remobilized sediment and fluid may have passed through to an edifice above, which is unlikely to be preserved as it would have been eroded away by the succeeding turbidity currents.

It should be mentioned that although most injectites are made up of sand, there are instances of clay injectites into sands these appear to be minor. Two examples are shown in Figure 16. One is from Lokawi locality where clay injectites occur at the base of a massive sandstone bed and appears to be aligned to a particular fracture orientation (Figure 16a). Another example is from Inanam 2 where a 30 cm thick turbidite sandstone (Bouma Tb/Tc divisions) is cut by numerous bedding normal clay-filled fractures (Figure 16b). The upward tapering geometry of some of the clay-filled fractures indicates that the clay was injected upwards from the underlying mudstone.

ORIGIN OF THE INJECTITES

As in other deep marine depositional systems, clastic injectites are a common feature of the turbidite sequences in the West Crocker Formation. The injectites described from the study area in Kota Kinabalu are similar to other injectites reported elsewhere. Examples of upward, downward, as well as lateral injectites have been observed. Injectites can be formed by sand injected into sand, sand into mud or mud into sand. Sand injectites are the product of sediment remobilization and fluid/gas movements in the basin (van Rensbergen *et al*., 2003; Hurst *et al*., 2011). They occur in a variety of shapes and sizes and are thought to occur at relatively shallow burial depths of less than 1000 m generally (Jolly & Lonergan, 2002).This is apparently also the depth at which mechanical compaction of sediment is overtaken by chemical compaction processes which include quartz cementation (overgrowth), grain-to-grain dissolution and clay transformation (e.g., Houseknecht, 1987). It has been long established that at these relatively shallow burial

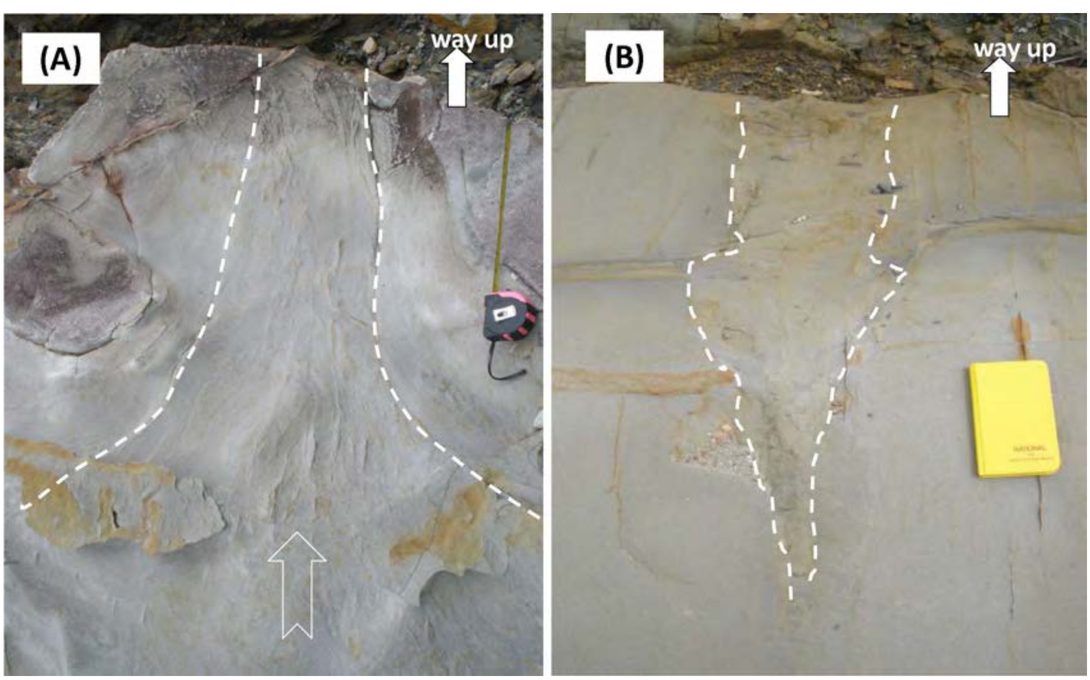

Figure 15: Examples of small-scale injection pipes and possible blow-out structure. (A) Funnel-shaped water-escape pipe clearly visible in this outcrop at Telipok (see Figure. 1 for location). The edges of the structure marked with white dashed line. Also clearly visible are the internal "flow-lines" along which the water-charged sediment may have been squeezed upwards into the overlying bed (arrow). (B) This funnel-shaped structure cuts through several massive sand beds, becomes wider upwards, possible representing a "blow-out" structure due to sudden overpressure release and collapse of the surrounding walls, as indicated by the disrupted or chaotic fill of the funnel. Locality: Lokawi.

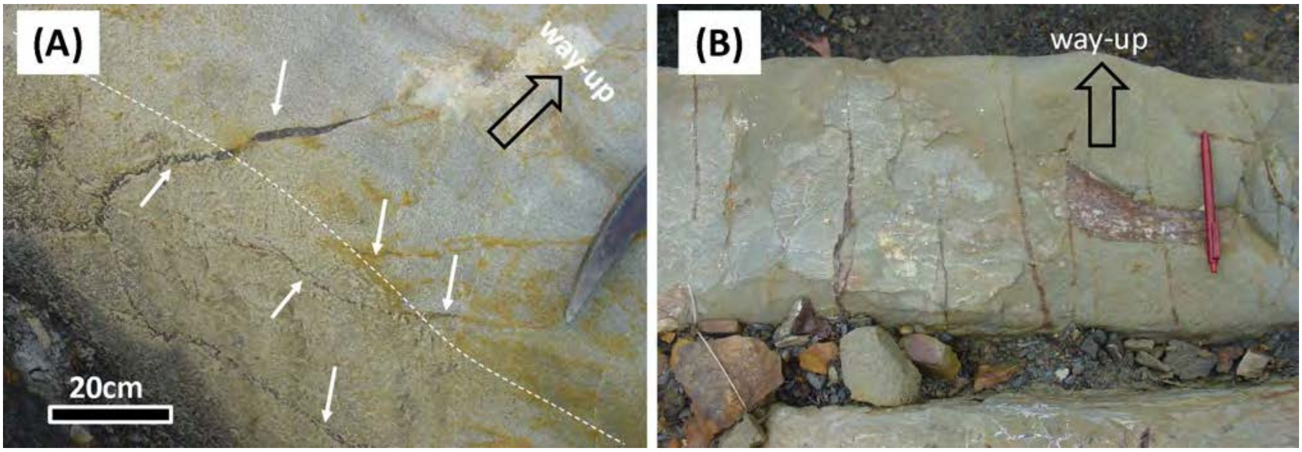

Figure 16: Examples of clay-filled fractures which may be interpreted as clay injectites. (A) Clay-filled injectites (white arrows) seen at the base of massive sandstone. The injectites seem to be aligned in a specific orientation. Locality: Lokawi. (B) Clay-filled fractures traversing a thin sandstone bed. Note the fractures appear to originate at the base of the sandstone bed and thins towards the top of the bed. Locality: Inanam 2.

depths that water-laden sediment is most prone to sediment remobilization due to overpressure buildup as a result of rapid sedimentation and burial (Figure 3).

Based on current understanding in the literature (e.g., Hurst *et al*., 2011; Cossey *et al*., 2013) the main mechanisms of generating sand injectites are overpressuring and rapid release of large volume of fluids through the sedimentary column. They could be triggered either by high-magnitude seismic/earthquake event or a mass-wasting or slumping generated up-dip of the depositional site, which causes instability in the overpressured sands below. Sand injectites may indicate overpressuring in the sediments due to rapid overburden accumulation, which resulted initially in fracturing of the claystone immediately above. The liquefied sand is injected upwards and then spreads laterally, and as the overpressure dissipated the injection terminates. The linear sand dykes along fracture networks indicate brittle deformation of partially consolidated sediments at relative shallow depths of about 1000 m below the sea floor where stress is built up to critical levels causing hydraulic fracturing.

There are many examples in the literature of injectites caused by overpressured deepwater sediments, such as in the Pliocene basin-floor fan sedimentation in the Bay of Bengal (offshore northwest Myanmar) (Yang & Kim, 2014) and in the Qiongdongnan Basin where overpressure had caused hydrofracturing of turbidite sediments and generation of injectites (Shi *et al*., 2013). Injectites are probably not caused by overpressure alone but may be triggered by sudden loading of water-saturated turbidites, e.g. slumping, such as in the Lower Devonian Muth Formation barrier island sandstones in NW Himalayas (Draganits *et al*., 2003) and in the Shwe gas field offshore Myanmar (Yang & Kim, 2014) and due to rapid differential loading of turbidite sediment (Andresen *et al*., 2019). Fractures orientation, as observed in West Crocker, appears to be controlled by the prevailing stress orientations, which is also well-documented in other basins (Monnier *et al*., 2015). Besides overpressures, other contributing causes of sand injection include regional tectonic stresses, lateral fluid pressure transfer, and overpressures related to petroleum fluid migration (Lonergan *et al*., 2000; Jolley & Lonergan, 2002; Huuse *et al*., 2010; Cossey *et al*., 2013).

IMPLICATIONS FOR HYDROCARBON RESERVOIRS, TRAPS AND SEALS

Injectites have been observed in core, outcrop and seismic, in many basins particularly in the North Sea (e.g., Dixon *et al*., 1995; Safronova *et al*., 2012). While the injectites described from the West Crocker Formation are relatively small in scale, in some parts of the world they can be very large. In the Vocontian Basin (SE France) injectites can be up to 10 m thick and several km long (Parize *et al*., 2003). In some basins, large injectite complexes can be several kilometers in dimension and may form potential reservoir drilling targets, such as in North Sea and Barents Sea, where hydrocarbons are produced from large-scale injectite complexes (Safronova *et al*., 2012; Andresen *et al*., 2019). Examples of hydrocarbon production from injectites or injectite-related sandstones are in Alba Field, North Sea (Lonergan *et al*., 2007) and Volund Field (de Boer *et al*., 2007). More recent exploration for sand injectite plays has proven to be successful particularly in the North Sea, with discoveries such as the Agar and Plantain fields in the UK North Sea and the Frosk and Froskelår Main fields in the Norwegian side of the Viking Graben[1].

[1] Revival of the injectite play. Expronews, February 13, 2019. https://expronews.com/2019/02/13/revival-of-the-injectite-play/ Accessed 14 May 2019.

Depending on the scale and distribution of these features, the presence of sand injectites in a reservoir system may have important implications on oil development and production, as these structures may provide reservoir continuity between otherwise discrete or discontinuous sand bodies in the turbidite systems. If their presence is overlooked their impact on reservoir connectivity could be underestimated. As injectites are mainly post-depositional structures, they may pierce through sands that were deposited in different parts of the submarine fan complex and are otherwise unlikely to be connected or juxtaposed.

Besides their potential significance to hydrocarbon reservoir potential and connectivity, sand injectites may, however, pose a risk to trap seals and seal integrity (Hurst & Cartwright, 2007). The fact that they intrude into adjacent shale or mudstones through fractures, possibly by hydraulic fracturing due to overpressure, they also act as conduits for the escape of fluids, including migrating hydrocarbons. It is generally agreed that sand injectites form during shallow burial (<400 m) due to overpressure arising from rapid burial of deep marine sands (Jonk *et al*., 2005), but the relative timing of injectite generation and petroleum migration may determine if injectites impact on petroleum migration and seals.

In offshore West Sabah and adjacent Brunei, large-scale fluid escape pipes have been identified on multi-channel seismic reflection data and were interpreted as being associated with gas hydrates escape (Laird & Morley, 2011; Paganoni *et al*., 2016, 2018; McGiveron & Jong, 2016, 2018). Fluid-escape features on the seafloor in modern deep marine environments are widespread globally, and some are known to be associated with injectites within turbiditic sediments (Somoza *et al*., 2014; Cartwright & Santamarina, 2015). Hence, these features may be a common feature of the turbidite sequences offshore West Sabah but have not yet been recognized. The author has personally observed some small-scale injectites in the core samples in some deepwater wells from offshore Sabah. It is hoped that the origin and potential impact of these features on the petroleum reservoir and seal properties be assessed and documented, and the results published.

Sandstone dykes, however, are generally difficult to detect in seismic as they are often steeper than 45°, which have resulted in their presence being grossly underestimated (e.g., Grippa *et al*., 2019). Outcrop analogs such as the West Crocker turbidites, however, may provide useful insight into their geometry, orientation and distribution so that their presence and possible implications to reservoir connectivity and heterogeneity can be better anticipated and assessed. Furthermore, since the preferred orientation of sand dykes appears to be controlled by the prevailing stress regime, their recognition in core and outcrop may provide valuable information on the changes in regional stress patterns over time. The study on injectites in the Danian-aged deepwater slope-channel complexes in Death Valley, California, by Scott *et al*. (2013) is an example of the value of outcrop analogs in understanding the impact of injectites in the subsurface. Such a study could be replicated in the West Crocker Formation, wherein the injectites and related structures could help us understand the processes that might impact reservoir properties and connectivity in the subsurface turbidite reservoir systems in offshore West Sabah.

CONCLUSION

1. Sand injectites occur widely in the West Crocker Formation turbidite sequences, as observed in several outcrops in the Kota Kinabalu area. They occur in a range of sizes from mm to cm scale, and more rarely metre-scale. The main morphological types of injectites include dykes, sills and pipes.

2. Based on literature review, the injectites are interpreted as the result of critical overpressure buildup in the unconsolidated deep-marine turbidite sands causing upward injection of fluidized sediments through the overburden at relatively shallow burial depths. The sudden release of overpressure could be triggered by earthquakes or by slumping in an up-dip area of the sedimentary system.

3. To date, there are no reports yet of any occurrence of sand injectites in the hydrocarbon-bearing Neogene turbidite sequences of offshore West Sabah. Injectites in the West Crocker Formation outcrops provide analogs for their recognition and identification in the subsurface turbidite sequences in offshore West Sabah and elsewhere.

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