Dewatering textures in the world’s largest exposed injectite complex

Timothy J. Sherry\textsuperscript{1,2}, Christie D. Rowe\textsuperscript{1,2}, James D. Kirkpatrick\textsuperscript{1}, Emily E. Brodsky\textsuperscript{1}

Emily E. Brodsky, Earth and Planetary Sciences, University of California Santa Cruz, 1156 High St, Santa Cruz, CA 95064, USA (brodsky@es.ucsc.edu)

James D. Kirkpatrick, Earth and Planetary Sciences, University of California Santa Cruz, 1156 High St, Santa Cruz, CA 95064, USA (jkirkpat@ucsc.edu)

Christie D. Rowe, Earth and Planetary Sciences, McGill University, 3450 University St., Montréal, QC H3A 0E8, Canada (christie.rowe@mcgill.ca)

Timothy J. Sherry, Earth and Planetary Sciences, McGill University, 3450 University St., Montréal, QC H3A 0E8, Canada (timothy.sherry@mail.mcgill.ca)

\textsuperscript{1}Earth and Planetary Sciences, University of California Santa Cruz, 1156 High St, Santa Cruz, CA 95064, USA

\textsuperscript{2}now at: Earth and Planetary Sciences, McGill University, 3450 University St., Montréal, QC H3A 0E8, Canada
Abstract. Sandstone injectites form by up-section flow of a mobilized sand slurry through fractures in overlying rock. They act as reservoirs and high-permeability conduits through lower permeability rock in modern hydrocarbon systems. The Yellow Bank Creek Complex, Santa Cruz County, California is the largest known exposure of a sandstone injectite in the world. The complex contains granular textures that record processes of sand slurry flow, multiple pore fluids, and dewatering after emplacement. The injection was initially mobilized from a source at 1.3-1.6 km maximum depth containing both water and hydrocarbon supported slurries. The water-sand slurry reached emplacement depth first (390-480 m above the source), possibly due to lower fluid viscosity. As the sand slurry emplaced, the transition from slurry flow to pore water percolation occurred when the velocity reached $\sim 3$ cm/s. This transition resulted in preferred flow channels $\sim 6$ mm wide in which sand grains were weakly aligned (laminae). The hydrocarbon-sand slurry intruded the dewatering sands and locally deformed the laminae. Compaction of the injectite deposit and pore fluid escape, caused spaced compaction bands and dewatering pipes which created convolutions of the laminae. The hydrocarbon-rich sand slurry is preserved today as dolomite-cemented sand with abundant oil inclusions. The laminae in the complex are easily detected due to preferential limonite-cementation of the well-aligned sand laminae, and lack of cement in the alternating laminae. Subtle textures like these may develop during sand flow and be present but difficult to detect in other settings. They may explain permeability anisotropy in other sand deposits.
1. Introduction

Sand injectites form when a slurry of overpressured sand and fluid is mobilized and emplaced upsection through fractures in overlying low permeability hostrock. Injectites provide high-permeability conduits between reservoirs separated by low-permeability caprock, and are of significant interest during oil and gas exploration and development e.g. injectites seismically imaged in the North Sea oil fields [Cartwright et al., 2007; Hurst et al., 2003; Hurst and Cartwright, 2007; Huuse et al., 2010; Jonk et al., 2005]. Sand injectite complexes have been studied seismically [Cartwright et al., 2008], by analog experiment [Rodrigues et al., 2009; Ross et al., 2011] and in outcrop exposures [Hubbard et al., 2007; Minisini and Schwartz, 2006; Schwartz et al., 2003; Vigorito et al., 2008; Vigorito and Hurst, 2010]. These studies document the geometry of injectites and often interpret constraints on pressure and depth, and long-term permeability effects. However, few studies have directly investigated the dynamics of sand slurry flow and emplacement, as these processes are generally not thought to be preserved in the depositional record. Contributions have been made from studies of flow textures in injected sands, and scour features on the conduit walls [e.g. Kane, 2010] and mineral sorting by velocity gradients during injection [e.g. Kazerouni et al., 2011]. Mechanisms for triggering sand injections have also been studied, ranging from seismic waves [Levi et al., 2011], to diagenetic changes in pore pressure [Davies et al., 2006]. However, much remains to be learned about the dynamics of sand slurry flow and emplacement, as well as the dewatering processes which begin as the sand stops moving.
The Yellow Bank Creek Complex complex, Santa Cruz County, California is the world’s largest documented outcrop exposure by volume \cite{Thompson et al., 2007}. The largest of the sand injectites forms a thick sill exposed in \( \geq 10\) m high beach cliffs. This affords a unique opportunity to study the emplacement process of sand injectites, and to assess how much detail of granular flow dynamics may be preserved in the rock record.

A complex assemblage of textures are observed in the Yellow Bank Creek Complex, which have been the focus of two previous studies \cite{Scott et al., 2009; Thompson et al., 2007}. These previous works promote conflicting hypotheses as to the origins of the sand textures, and their implications. We employed field and microstructural studies to quantitatively describe the exposure- and grain-scale fabrics of the Yellow Bank Creek Complex, interpret the events of sand injection and emplacement, and resolve the remaining questions about the preserved textures. We relate these textures to the processes of sand flow, emplacement, jamming and dewatering. We then explore the implications of our results for the permeability structure of injected sands revealed in the laminae of the Yellow Bank Creek Complex.

2. Geologic Setting

The Monterey Formation was deposited on the California coast in a northward-migrating transtensional basin along the San Andreas Fault system during the late Miocene \cite{Graham and Williams, 1985}, (Figure 1A). The formation is regionally important as the reservoir and source rock for the Monterey Formation oils \cite{Graham and Williams, 1985}. The upper part of the formation is predominantly thin bedded diatomaceous mudstone \cite{Bramlette, 1946}. However, in Monterey and Santa Cruz Counties, discontinuous well-sorted Santa Margarita Formation sands, are interfingered in lenses near the top of
the Monterey Formation [Bramlette, 1946]. Above the Santa Margarita Formation, the Monterey Formation is locally known as the Santa Cruz mudstone [Boehm and Moore, 2002] (Figure 1B).

Sandstone injectites, sourced from the Santa Margarita sands, occur in the upper Monterey Formation, injecting upsection [Stanley, 1990; Bramlette, 1946]. The injectites form dikes, sills, large amorphous bodies, and locally, appear to have been shallowly emplaced, some of which may have reached the paleo-sea floor as extrudites [Boehm and Moore, 2002]. Some of the sandstone injectites are tar-saturated, or cemented with dolomite containing bitumen [Stanley and Lillis, 2000]. Injectite ages may be constrained as the Santa Margarita Formation sands were deposited in the upper Miocene based on the ages of invertebrate fossils [Addicott, 1972] and vertebrate fossils [Phillips, 1981], and the unconformity separating the Santa Cruz Mudstone from the overlying Purisima Formation of late Miocene to late Pliocene based on fossil ages [Clark, 1981].

Abundant evidence for fluid migration within the Monterey Formation and Santa Margarita sands has led to several theories for the driving forces causing the injectites. Boehm and Moore [2002] argued that the position of the injectite complex toward the thin edge of a westward-deepening basin would have generated artesianal fluid overpressures as pore waters escaped up-dip from the more deeply buried strata to the west. Silica diagenesis in the diatomaceous Monterey Formation may have caused injectite formation by facilitating the reduction of porosity, increasing pore fluid pressure during opal de-watering [Davies et al., 2008], and embrittlement of the mudstones [Gross, 1995]. Numerous authors have suggested seismic shaking may be a proximal trigger of the fluidization and injection of sand, especially given the basin’s close proximity to both the San Andreas and San Gre-
gorio fault systems, which were active in this area during the late Miocene when these formations were deposited [Stanley and Lillis, 2000; Boehm and Moore, 2002; Thompson et al., 2007].

The majority of the sand injectites in the area can be classified as single and cluster dikes, or sills, a few centimeters wide and several meters long. Injectite orientations suggest that the tectonic stresses affecting the region in the late Miocene were similar to today [Boehm and Moore, 2002].

At Yellow Bank Beach, locally known as Panther Beach (located in Coast Dairies State Park, 10 km north of the Santa Cruz city limits), a unique, large-scale injection is exposed. The injection has a sill-like, tabular shape, and Thompson et al. [2007] estimated its total volume at $8.4 \times 10^6 m^3$. The complex contains both hydrocarbon-saturated and hydrocarbon-poor injectites [Boehm and Moore, 2002]. The Yellow Bank Creek Complex has attracted broad interest due to its size and the complexity of its internal fabrics [Aiello, 2005; Scott et al., 2009; Thompson et al., 2007]. The maximum burial depth of the Santa Cruz mudstone host rock to the injectite is well constrained. Apatite fission track studies by Thompson et al. [2007] and estimates of burial temperature from silica diagenesis by El-Sabbagh and Garrison [1990] suggest the formation reached depths and temperatures of 1.3 - 1.6 km and 45 - 50$^\circ$C. Observations of this and other nearby sand injectites suggest that the long outcrop length in horizontal beach exposure is due to the intrusion of a sill, subparallel to the paleo-seafloor, sourced from a wide dike of sand that migrated vertically up-section [Phillips, 1990].
3. Previous work

Previous studies of the Yellow Bank Creek Complex described the complex fabrics which characterize this outcrop. These fabrics are described in detail in following sections. Sand cemented with dark gray, hydrocarbon-rich dolomite forms rounded and columnar shapes with sharp boundaries. The sand around these dolomite-cemented areas is weakly cemented. Limonite cement stains alternating laminae (≈5-10 mm thick), which are locally organized into zones 10-20 cm thick called layers by Thompson et al. [2007] or bands by Scott et al. [2009]. The thin laminae are ubiquitous and usually sub-horizontal, while the coarser bands vary in orientation, cut margins between laminated and dolomite sands, and are well developed only near the edges and base of the injectite [Thompson et al., 2007]. Clasts of the mudstone host rock are included in the injectite, and are particularly abundant near the edges.

The origins of the fabrics and different cements in the Yellow Bank Creek Complex are ambiguous. Previous authors have presented two different interpretations. Based on outcrop observations, Thompson et al. [2007] argued that the 10-cm bands were flow bands formed during sand injection, and the rhythmic limonite cementation was Liesegang banding formed during groundwater flow through the injectite long after emplacement. However, they also noted that the relative chronology of the two fabrics is sometimes ambiguous. Dolomite cement is interpreted to have formed by bacterial action when either oil displaced pore water in the sands, without disrupting the surrounding granular structure, or during the intrusion of an oil supported slurry into previously emplaced water-saturated sands [Thompson et al., 2007]. Scott et al. [2009] described the same fabrics, but used qualitative microstructural observations to develop a different interpretation of their ori-
gins. Based on the evidence for corrosion of the mudstone host rock, *Scott et al.* [2009] argue convincingly that the sand was injected as a high velocity turbulent flow, and the preserved laminae and layering record late-emplacement processes. They report that the mm-scale laminae are defined by a difference in grain packing (porosity), and therefore argue that the iron oxide cement overprints on a primary grain fabric formed during injection of the sand, not by Liesegang instabilities as suggested by *Thompson et al.* [2007]. *Scott et al.* [2009] suggest that the 10-20 cm banding was formed by shearing within the sand body while in a semi-consolidated state.

4. Field observations

The striking outcrop appearance of the Yellow Bank Creek Complex is due to the juxtaposition of different granular fabrics and two types of boldly colored mineral cements (Figure 2A). We give morphological descriptions of these features to establish terminology, document the crosscutting relationships between various features, and present quantitative observations of fabrics on outcrop to thin-section scale. The injectite outcrops along ∼170m of beach cliffs that are ∼10 m high.

Laminae

The most ubiquitous fabric of the injectite is the ∼6 mm thick laminae (Figure 2, 5, 3) [previously described by *Scott et al.*, 2009; *Thompson et al.*, 2007]. This fabric is defined by thin, alternating laminae of iron oxide-cemented and uncemented sand. The laminae are always locally parallel and consistent in thickness. Limonite cemented laminae are typically thinner than the uncemented laminae in between. The laminae are wavy and undulating on wavelengths of a few centimeters to 10s meters (Figure 2). They are
pervasive throughout the outcrop of the large sand injectite, but are absent from the
thinner (≤1 m) sand dikes in the area, which are massive or show wall-parallel grain size
gradients [Thompson et al., 2007]. The laminae thickness across the entire outcrop is
∼ 5.7 ± 1\(mm(1\sigma); N = 697\). Limonite-cemented laminae are more erosion resistant than
uncemented laminae and subtly stand out as positive erosional features.

The dolomite-cemented sand does not contain the limonite cements which elsewhere de-
fine and emphasize the laminae. In some areas, the dolomite-cemented columns sharply
cut across laminae (Figure 3), while in others, the laminae are curved toward small
dolomite cemented bodies (Figure 2B). In either case, the laminae are deformed by the
dolomite-cemented sand bodies.

Mudstone Clasts

Clasts of Santa Cruz Mudstone are observed within the both dolomite-cemented and
laminated sands (Figure 2C, D). These were described by Scott et al. [2009] and by
Thompson et al. [2007] as sedimentary xenoliths. The mudstone host rock is strongly
bedded, contributing to an abundance of elongated clast shapes (Figure 2C) with some
larger clasts containing intact bedding planes. We measured clast long and short axes on
the outcrop surface (Figure 4). The clasts range in size from sand-sized grains to ∼70
cm, but most of the observed clasts are a few centimeters. As reported by Scott et al.
[2009], the clasts are more abundant close to the injectite margins. The observation that
many clasts are rounded, saturated with hydrocarbons, and have dolomite sand rims (e.g.
Figure 2D) supports the hypothesis that the mudstone clasts were not all locally derived,
as the exposed wall rock to the injection is relatively hydrocarbon-poor. This supports
Scott et al. [2009]'s interpretation of significant vertical transport of the clasts during rapid upward injection of the sand slurry.

We compared the clast size and orientation of the long axis of the elongate mudstone clasts to the orientation of the laminae around each clast to determine whether the clasts and the laminae were locally parallel (Figure 4). Of the 27 elongate clasts, 50% have their long axis aligned within 10° to the local laminae. The other 50% have long axis at an angle of 10-50° to the laminae. Mudstone clast rake on the outcrop surface has a wide distribution of angles for any given location along the exposure. Mudstone clasts are sub-horizontal (mean apparent plunge of long axis = 17°±17°, N=82). There is no apparent relationship between clast size, aspect ratio, and orientation relative to local laminae. The laminae wrap around the mudstone clasts, never terminating against them.

**Dolomite cemented sand**

The most noticeable feature of the injectite in outcrop is the contrast between the laminated orange-yellow sand and the lava lamp-like, circular, elongate blue-gray blobs and columns of hydrocarbon-rich dolomite cement (Figure 2, 3). The contacts between regions of different cement are smoothly curved and sharp. Dolomite cemented bodies strongly resemble bubbles in shape, have consistent sense and radius of curvature, and are aligned in vertical columns or trains (Figure 2A, B, 3). There is a rim of maroon-colored hematite cement ~2 cm thick forming a cortex around the margins of dolomite-cemented regions (Figure 2B). The laminae are crosscut by or deformed by contacts between laminated and dolomite-cemented sand (Figure 2B, 3).
**Banding**

Six to thirteen cm-spaced *bands* deform both laminated and dolomite cemented sand across the outcrop. The bands are most strongly expressed in laminated sand as ~1-2 cm wide layers where the laminae are more closely spaced (Figure 5A). These bands are more erosion-resistant due to a concentration of limonite cement and stand out from the outcrop surface. The laminae locally deflect to become more parallel and planar in the bands, relative to the general wavy style (Figure 5A). This foliation was called “layers” by Thompson *et al.* [2007] and “bands” by Scott *et al.* [2009]. The banding also occurs in the dolomite-cemented sandstone, where bands preferentially weather back creating aligned indentations in the outcrop surface (Figure 2E). In some areas, bands cut across the boundaries between laminated sand and dolomite-cemented sand (Figures 2A, E).

The bands are locally planar, but undulate on wavelengths of several meters. They are strongly developed in some parts of the injectite (Figure 5A), and weak or absent in other parts (Figure 5B). They are generally subhorizontal or gently dipping but steepen dramatically at the northern end of the outcrop in the proximity of a fault. Thompson *et al.* [2007] proposed that bands generally follow the roughness of the floor of the injectite, but we could not confirm this as the floor is not locally exposed.

**Convolutions**

The laminae locally show regularly spaced upward undulations creating antiformal deflections (Figure 2F, 5). These were described as “convolute lamination” by Thompson *et al.* [2007] and as “pipes” by Scott *et al.* [2009]. The lower edge of each feature is emergent and the amplitude of deflection increases upward (Figure 5B). As noted by Scott *et al.* [2009], the center of each feature is massive (i.e. the laminae are “washed-out” in
the middle, Figure 5A). The upper terminations of the features are sharp, with a sudden transition from a strongly deflected lamination to smooth, parallel laminae. The tops are either concentric (i.e. center of Figure 5A) or flattened to a rectangular shape against the overlying band (i.e. right side of center band, Figure 5A). These shapes are accommodated by changes in the spacing, and size of the laminae, similar to the bands described above. Each individual lamination is continuous across the convolution feature (i.e. the number of laminae on each side of the center “washout” is typically the same).

Where the banding is strongly developed, the antiformal convolutions are limited in axial trace length (or vertical “reach”) to the distance between two adjacent bands (Figure 5A). In this case, the convolutions are closely and regularly spaced, similar in amplitude, and recur within each space between bands. The axial planes are not always normal to the bands, as in Figure 2F, where axial trace is near parallel (upper left to lower right in photo) to banding. Convolutions are sometimes cut or confined by dolomite cemented sandstone bodies (Figure 2F). Where banding is absent, the vertical reach of the convolutions is not limited and has a vertical extent of \( \sim 0.5 - 1.5 \) m or greater (Figure 5B). Upward deflections of laminae were observed below mudstone clasts (Figure 2C).

Summary of cross-cutting relations

Below we review the individual features of the Yellow Bank Creek Complex in chronologic order, highlighting crosscutting relationships.

- Mudstone clasts are included within both laminated and dolomite-cemented sandstones.
Laminae (~6 mm thick sub-horizontal alternating layers of limonite cemented and
uncemented sand) are pervasive throughout the injectite except in dolomite-cemented
areas. Laminae wrap concentrically around mudstone clasts.

- Column or bubble-shaped dolomite-cemented sandstone bodies cut and deform lam-
inae.

- Banding (spaced compaction bands expressed by decreasing spacing of the laminae)
and convolutions (antiformal undulations of laminae) formed roughly simultaneously, per-
haps with banding initiating prior to convolutions. Convolutions terminate against band-
ing where both features are present. Isolated convolutions occur where banding is not
expressed. Convolutions are sometimes confined between two dolomite-cemented sand-
stone bodies.

5. Microstructural observations

Laminae were described by Thompson et al. [2007] and interpreted as Liesgang banding,
or concentric oscillations in cementation within homogeneous rock. Scott et al. [2009]
argued that fluctuations in packing density of the sand grains are responsible for the
laminae, and the iron-oxides preferentially precipitated in the lower-porosity bands. To
test these hypotheses, we have used image analysis of photomicrographs to quantify the
grain size distribution, packing density, and grain inclination patterns, for comparison
between the two laminae types: uncemented vs. limonite cemented.

Thin sections were prepared from oriented samples in which the two laminae could be
easily distinguished. Photomicrographs at 1.6x magnification were taken of representative
areas of the samples in both plane-polarized and cross-polarized light with the edge of the
photomicrographs parallel to the laminae in the section. From these photomicrographs, sub-areas of limonite cemented and uncemented areas were selected from within the laminae for image analysis (Figure 6). Grains and impressions in the epoxy showing where grains were plucked during polishing were selected manually from each sub-area. The resulting grain maps were analyzed following the method of Björk et al. [2009]. Grains were automatically detected in the image by specifying the grayscale value used to construct the grain maps. Each grain was assigned a unique identity and the area was calculated from the number of pixels comprising each grain. Two-dimensional porosity (apparent porosity) was calculated by subtracting the sum of pixels within detected grains from the total pixels in the image. Pore space and mineral cements (dolomite or limonite) were therefore combined to represent primary porosity. An ellipse of equal area to each grain and with the long axis orientation specified by the second moment of the grain pixel distribution was assigned to each grain (Figure 6). The angle between the long axis of each grain and the local surface of the limonite-cemented laminae was measured (orientation in x-z plane, Fig. 6). Inclinations counter-clockwise from horizontal are positive, and clockwise from horizontal are negative. The aspect ratio of grains was calculated from the long and short axes of the best fit ellipses. The aspect ratio seen in the 2D section is a function of the true aspect ratio of the grain, as well as the orientation of the grain within the plane of the laminae (x-y plane, Fig. 6).

Analysis of eight sub-areas from within the limonite-stained laminae yields a mean apparent porosity of 51.3 ± 2.8% (1σ) with porosity values ranging from 57% to 48%. Eight sub-areas from within uncemented laminae define a mean apparent porosity of 47.8 ± 3.0% (1σ) with porosity values ranging from 51% to 43%. Kolmogrov-Smirnov
tests with a 5% (p-value = 0.05) significance threshold were performed to compare distributions between laminae types. The Kolmogorov-Smirnov test showed the porosities of the limonite-cemented and uncemented laminae are indistinguishable (p-value = 0.18). The sand is composed of quartz, lithics, plagioclase feldspar, glauconite, carbonate fragments, and mud pelloids. We detected no grain compositional difference between limonite-cemented and non-cemented layers consistent with the previous work of Scott et al. [2009] and Thompson et al. [1999]. The apparent porosity values are derived from 2D section through the sandstone. The high apparent porosity values are reasonable as 3D porosity is on the same order of magnitude but slightly lower than apparent 2D porosity in typical sands [Long et al., 2009; Keehm et al., 2004].

A total of 1354 grains were counted in selected regions within the limonite laminae and 1356 grains in the non-cemented laminae. The minimum apparent 2D grain diameter detected by our method is $2.6 \times 10^{-2}$ mm and the maximum is 0.54 mm. Apparent grain diameter is a proxy for grain size (Figure 7a).

Mean uncemented and limonite-cemented apparent grain diameter are 0.17 mm ± 0.07 (1σ) and 0.17 mm ± 0.08 (1σ), respectively. The two sets of grain size measurements have similar distributions (p-value=0.87). Therefore, we observe no differentiation in grain size between uncemented and limonite-cemented laminae.

Apparent grain aspect ratios, defined by the ratio of the major and minor axes of the equivalent area ellipse, were analyzed (Figure 7B). Apparent aspect ratios in both limonite-cemented and non-cemented laminae fall mostly between one and two. Mean aspect ratios for non-limonite and limonite-cemented datasets are 1.77 ± 0.6 (1σ) and 1.81 ± 0.70 (1σ). The Kolmogorov-Smirnov test confirmed a small, but significant difference
between sand grains in uncemented laminae and sand grains in the limonite-cemented laminae (p-value = 0.0014).

The inclination of grains to the lamination were compared between the two populations (Figure 7C). Mean inclination angles for limonite-cemented and uncemented populations are $1.85 \pm 46.7^\circ$ (1σ) and $0.7 \pm 47.6^\circ$ (1σ). There is no difference in the populations (p-value=0.63).

The analysis of the microstructure of the sand demonstrates that subtle differences exist between the layers at the grain scale. They are indistinguishable when compared in terms of apparent porosity, grain size, and inclination of sand grains to the laminae. The only subtle but significant difference is found in the apparent aspect ratio.

6. Discussion

A sand injectite such as the Yellow Bank Creek Complex, which is mobilized as a slurry, must go through two transitions in flow regime as the flow stops. First, the velocity of the turbulent slurry will slow down as it rises through cracks and relieves the driving pressure. The Reynolds number will consequentially drop and the flow will transition from turbulent to laminar flow. Second, at the time of emplacement, the flow will transition from a “single-phase” fluid where sand and pore fluid are moving at approximately the same velocity, to a “jammed” state, in which the pore fluid velocity has dropped sufficiently that grains are no longer suspended, come into contact, and geometrically lock. At this point, the jamming transition, the sand grains will stop moving and the pore fluid will flow through pore spaces, exerting a slight flow pressure on the grains.

Below, we review the relative timing of development of each of the textural features described in the previous sections and then discuss the mechanisms by which they formed.
We incorporate our new data, expanding upon the generalized emplacement interpretations by Thompson et al. [2007] and Scott et al. [2009] to establish the emplacement history and relate the textural features to flow dynamics.

6.1. Injection Initiation

Prior to injection, lithified Santa Cruz mudstone overlay the Santa Margarita Formation whose pore fluids consisted of both aqueous and hydrocarbon phases. These were likely spatially separated, creating a two phase reservoir containing a region of water saturated sand and a region of oil sand [local outcrop examples of fluid phase boundaries were described by Phillips, 1990] (right side Figure 8A). Overpressures occur when the pore fluid pressure exceeds the hydrostatic pressure [Jolly and Lonergan, 2002]. A trigger event, likely seismic shaking, combined with the pressure gradient created by the opening of fractures in the overlying mudstone, fluidized the sands [Jolly and Lonergan, 2002] and drove the fluid-sand slurries into the fractures.

Under the same driving force, differing viscosities of the aqueous and hydrocarbon fluids would result in different flow rates, separating the injecting slurry into two phases [Jonk, 2010] (left side Figure 8A). At some depth below the sea floor, the injecting sand dike diverted laterally, parallel to bedding, forming the large sill-like body observed at Yellow Bank Beach. This may correlate to the stage when the fluid pressure in the flowing slurry dropped below the tensile strength of the host mudstone, so that further upward flow by fracture growth through the wall rock was inhibited and bedding plane weaknesses were exploited.

Jolly and Lonergan [2002] explored the distance from source bed that a dike transitions to a sill. A first order approximation of the maximum depth at which an injection complex
forms may be made using Equation 9 of \textit{Jolly and Lonergan} [2002], therefore the maximum
distance the injectite exposure at Yellow Bank Creek Complex lies above the source bed
may be constrained. Assuming that the maximum burial depth is the depth at which
injection was triggered, and that the injection was triggered by burial-driven overpressure
in the source sand bodies, the length of the feeder dike, \(H\), between sill and source bed is
given by:

\[
H = \frac{z(1 - K)\rho_s}{\rho_s - \rho_w}
\]

where \(z\) is the source bed depth (Figure 8A), \(K = \sigma_H/\sigma_V\) (ratio of principal vertical
and horizontal stresses for hydrostatic and uniaxial vertical stress conditions), \(\rho_s\) is the
density of host rock, and \(\rho_w\) is the fluid density. \textit{Thompson et al.} [1999] defined maximum
burial depth from vitrinite reflectance data of Santa Cruz Mudstone near the complex and
apatite fission-track analyses of injectite sandstone (1.3 - 1.6 km assuming a geothermal
gradient of \(\sim 30^\circ C/km\)). Mudstone hostrock density is approximated at \(\rho_s=2000\ kg/m^3\)
and we use water as the pore fluid with \(\rho_w = 1000\ kg/m^3\). Under hydrostatic and uniaxial
vertical conditions the ratio of principal vertical and horizontal stress, \(K\), is derived from
the ratio of horizontal and vertical effective stresses at a typical fluid pressure gradient and
for a given vertical stress is estimated as 0.85, for a fine grained mudstone similar to the
Santa Cruz mudstone host rock \textit{[Jolly and Lonergan, 2002]}. Thus, the maximum vertical
length of the feeder dike from source bed to injectite \((H)\) is 390 - 480 m, at emplacement
level just over a kilometer below paleo seafloor. This is a minimum estimate for \(H\) (and
places a maximum constraint estimate for depth below sea floor), because this construction
assumes no tectonic stress and no external trigger (such as seismic activity). Conversely,
if the pore pressure in the Santa Cruz mudstone increased with depth at a higher rate
than a typical basin, this would reduce the differential stress in the system, increasing the $K$ value, resulting in a smaller feeder dike length $H$ [Jolly and Lonergan, 2002; Hillis, 2001]. Boehm and Moore [2002] observed sandstone extrudites (dikes that penetrated the paleosea floor) near the injectite complex, so emplacement of nearby injectites was shallower than this estimate. This may suggest seismic triggering or other factors which caused the injection to form at shallower depths than required to force initiation by burial overpressures.

6.2. Preservation of flow characteristics in observed fabrics

During sand emplacement, the system must have transitioned from a flowing to geometrically locked grain geometry [the jamming transition; sensu Corwin et al., 2005]. In the case of the Yellow Bank Creek Complex, the transition occurred when a sand-water mobile slurry (Figure 8B) decreased in fluid velocity until the grains made contact and locked into a network of framework sand grains with fluid flowing through the pores (Figure 8C). The Yellow Bank Creek Complex contains multiple fabrics, most of which we interpret to have formed either at or after, the jamming transition between granular flow and pore fluid diffusion during dewatering.

We observed high apparent porosity in the laminated sandstone. Thompson et al. [2007] also observed high apparent porosity, and explained this observation by post-emplacement grain dissolution. The pore spaces in our samples are significantly smaller than grains (Figure 6) so we consider this explanation unlikely although we can not rule out the possibility that some fine fraction was dissolved subsequent to emplacement. Scott et al. [2009] measured porosity of the laminated sandstones (mean: 29%), and found lower porosity than our estimates (48% and 51%). Scott et al. [2009]'s measurements were
performed on cemented samples, which under-represent the primary porosity of the sand. They also suggest that porosity at the time of consolidation must have been at least 46%, where 54% is the approximate maximum granular concentration for fluidization. Based on this data and the preservation of the delicate laminae and other grain structures, our data are reasonable estimates for the original porosity of the sand just after the jamming transition. [Blower et al., 2003] showed that for spherical bubbles (we may consider bubbles analogous to grains), size following a power law distribution 2D grainsizes will underestimate 3D grainsizes. Therefore, our 2D porosity values are overestimates of 3D porosity.

6.2.1. Mudstone clasts aligned to local flow lines during emplacement

Wall rock clasts were ripped from the walls during turbulent, high velocity flow [Scott et al., 2009; Thompson et al., 2007] and can be treated as large, elongate grains in a viscous flow. Previous authors have used Stokes settling velocity calculations to bound the minimum upward sand velocity, with the caveat that the density and viscosity of the sand slurry during flow are not preserved so must be estimated. Scott et al. [2009] used the largest clast observed in the outcrop to bound the minimum emplacement velocity at \( \sim 2-10 \) m/s. Duranti and Hurst [2004] fixed the slurry density at 1900 kg/m\(^3\) to calculate a minimum emplacement velocity of 0.23 - 0.37 m/s. Scott et al. [2009] calculated Reynolds numbers for three models of differing estimated fluid densities (from estimated packing densities), differing fluid viscosities, and differing estimated minimum settling velocities. Scott et al. [2009] used fluid viscosity values ranging from \( \sim 0.001 - 0.26 \) Pas. These viscosity values are near that of water [Kestin et al., 1978] and too low for a granular slurry viscosity as demonstrated by Major and Pierson [1992]. Recalculating Reynolds
number values for Scott et al. [2009]'s three models using a slurry viscosity of 10 Pas. 

[Major and Pierson, 1992] yields Reynolds numbers of $\sim 3 - 7 \times 10^3$. These Reynolds numbers still lie within the turbulent regime, but are three orders of magnitude below values calculated by Scott et al. [2009], placing the flow regime much closer to laminar flow.

The flowing slurry transitioned to laminar flow as the velocity decreased. The entrained mudstone clasts, which rotated randomly in the turbulent regime, likely aligned to flow lines when the transition to laminar flow occurred. Mudstone clasts are gently dipping $(17^\circ \pm 17^\circ, N=82)$ on the outcrop surface, consistent with rotating toward flow lines as the injectite sill flowed horizontally along bedding. Studies of phenocrysts transported in viscous flows have been shown to develop a characteristic alignment parallel with flow direction [Yamato et al., 2012] and sorting of grains by density and shape according to velocity profiles [Geoffroy et al., 2002]. Therefore, we hypothesize that local mudstone clast alignment is the best preserved record of last direction of sand slurry flow during injectite emplacement. We use this alignment as a tentative marker of flow direction, to which we can then compare the other granular features. There can have been almost no relative motion between wall rock clasts and the sand encasing them following emplacement. Any relative rotation would have destroyed laminae microstructures, and this is not observed, so we can assume the orientation we observe is primary (Figure 2C).

6.2.2. Laminae created by pore fluid percolation

Our observations of cross-cutting relationships confirm that the limonite-cemented and uncemented laminations are a primary fabric defined by small grain-scale differences [cf. Scott et al. [2009]]. The field observations of cross-cutting relationships show that the
laminae are the earliest-formed fabric in the injectite. They formed prior to large-scale
dewatering, as they are deformed by compaction banding and convolute structures (dis-
cussed below). The limonite cementation exploited this earlier primary fabric. In contrast
to Scott et al. [2009] we did not detect any packing difference between the laminae types.
The only grain-scale difference we detected is a distinction in the apparent aspect ratio
of grains. The apparent aspect ratio seen in the 2D thin section is a function of the true
aspect ratio and the angle of the grain long axis to the plane of the thin section (rotation
about the z-axis, Figure 6). Since the grain size distributions are the same, this suggests
the grains were not sorted to form the laminae. We infer that the difference between
limonite-cemented and uncemented laminae reflects a difference in the degree of align-
ment, or lineation, of grains within the plane of the laminations, although this distinction
can not be directly measured in our 2D sections.

The limonite, precipitated from fresh pore water at a later stage after uplift of the
marine section, is preferentially concentrated in alternating laminae. Limonite occurs in
the laminae with slightly higher apparent aspect ratio (consistent with stronger shape
lineation.) We suggest this reflects a difference in the permeability of the laminae during
ground water flow.

We propose that a permeability difference between otherwise similar laminae was es-
lished by a percolating fluid rearranging grains immediately following jamming of the
granular slurry (Figure 8B, C). The apparent 2D porosity (~50%) is similar to the critical
packing densities reported for ellipsoidal grains [Garboczi et al., 1995; Saar and Manga,
2002]. Near the critical porosity small variations in porosity or pore geometry give rise
to large permeability variations, even with identical grain populations. Permeability is a
function of the porosity, as well as geometric details controlling the pore geometry and
connectivity, such as grain shape, aspect ratio and orientation. In granular material, when
the porosity approaches a critical value, parameters that are dependent on porosity, such
as permeability, exhibit power law changes in response to small porosity variations. This
is the percolation threshold.

We therefore suggest that at the percolation threshold, the pore fluid rearranged grains
in such a way to cause the slight alignment contrast between higher and lower permeability
laminae. This formed a feedback whereby the flow through relatively high permeability
layers was promoted, enhancing the permeability difference. Pore fluid drained prefer-
tentially into and along the higher permeability layers (Figure 8C). These were the same
layers that were later cemented with limonite, possibly because of preferred groundwater
flow along them.

Previous authors who have studied the Yellow Bank Creek Complex have not suggested
a mechanism for setting a critical length scale (laminae thickness, 5.7 ± 1 mm). Therefore,
we propose a new mechanism, which is consistent with the absence of grain sorting, and
can explain the critical length scale observed in outcrop.

We propose that the uniform thickness of the laminae reflects a characteristic length
scale for the process controlling the permeability instability. The length scale was estab-
lished by the relative contribution of pore fluid advection along the laminae and diffusion
across the laminae. We use the length scale to estimate the pore fluid flow velocity from
the Péclet number, \( P \). The Péclet number is described as

\[
P = \frac{UL}{D}
\]  

(2)
where \( U \) is the fluid velocity (m/s), \( L \) is the critical length scale (m, 1/2 laminae length for a relative permeability channel with two walls), and \( D \) is the diffusivity (m\(^2\)/s, along dewatering pathways as indicated in Figure 8C). The system is at the dewatering threshold when advection rate and diffusion rate are balanced, i.e. \( P = 1 \). Using the average half length scale of laminae (\( \sim 3 \) mm) and assuming a hydraulic diffusivity of \( 10^{-4} \) m\(^2\)/s for the sand [Iverson and Vallance, 2001], we estimate a fluid velocity value of \( \sim 3 \) cm/s, an order of magnitude lower than the peak emplacement velocity estimated by Scott et al. [2009].

6.2.3. Banding and Convolutions

After the jamming of the sand grains and formation of the laminae, compaction commenced and the pore water escaped from the injectite. Two classes of features were formed, simultaneously, by dewatering: 6 - 13 cm banding, which crosscuts both the dolomite-cemented and laminated sands, and convolute structures, which are observed primarily in the laminated sand.

The bands represent a spaced compaction fabric, which is primarily horizontal but undulates, possibly in response to topography on the floor of the injectite. Olsson et al. [2002] showed that compaction bands form perpendicular to the maximum strain direction, locally reducing permeability. Multiple localization fronts can create trapped fluid in higher porosity zones resulting in an increased pore pressure. Olsson et al. [2002] argue that this increased pore pressure will locally decrease the effective mean stress driving compaction and can slow or stop the compaction process. In the Yellow Bank Creek Complex, the increased pore pressure between compaction bands was released by localized fluid venting in pipes which deformed or destroyed laminae, forming the convolute structures. These
strongly resemble fumarolic pipes formed in compacting ash flows, where material is also well mixed and microstructure destroyed along the upward flow path [Nermoen et al., 2010].

In areas of the injectite where compaction bands are weakly expressed or absent, convolute structures grew much taller and are widely spaced (Figure 5B). These may have facilitated the draining of larger volumes of water. In the southern part of the outcrop, where dolomite-cemented sand forms vertical columns (Figure 3), tall, isolated convolutions are more abundant. This may record vertical motion of the sand during upward emplacement. Where compaction bands are strongly developed, short, closely spaced convolutions formed. Each space between bands formed its own discrete set of convolutions. Toward the northern part of the outcrop, where the subhorizontal compaction bands are strongly developed, the convolutions are short and closely spaced, and lean toward the north, as do the “fingers” of oil sand injected into the wet sand (Figure 3A). This may record a component of subhorizontal flow during injection of the sill, and the continued lateral momentum during initial dewatering and compaction. Convolutions and areas of wiped-out laminae are also found immediately below mudstone clasts. This may indicate that fluid pressure was elevated due to the mudstone clast blocking upward fluid escape.

7. Summary and Conclusion

The Yellow Bank Creek Complex is a natural example of the subsurface mass movement of a sand slurry and preserves textures that provide insight into the dynamics of injection in the rock record. Numerous textural features are evident in the exposure of the injectite. From field and microstructural observations we show that many of these textures are
formed during the jamming transition and dewatering of the mobilized sands. We conclude that injectite formation involved the following processes:

- Pore-fluid pressure exceeded the lithostatic pressure and combined with a trigger event, likely seismic shaking, fluidized and emplaced the granular slurry upsection in two separate phases (aqueous and hydrocarbon) through fractures in the mudstone hostrock.

- Clasts of mudstone were entrained in the granular slurry, the long axis of which likely aligned with laminar flow paths as slurry velocity waned.

- The granular slurry velocity dropped and could no longer suspend grains, creating a jammed granular framework. At this percolation threshold (estimated 3 cm/s) slight differences in grain organization can lead to exponential variations in permeability. Pore waters reorganized grains creating a primary fabric composed of alternating laminae of more and less well aligned grains.

- The higher viscosity of hydrocarbon slurry allowed it to continue to flow beyond aqueous slurry dewatering, intruding the recently injected sand, cross-cutting and deforming the laminae microtextures.

- Compaction of the system occurred creating compaction bands and convolute dewatering structures.

- Later, two separate cements were formed: dolomitization of the hydrocarbon sands, and limonite preferentially precipitated in high permeability laminae in the aqueous sand.

The conditions of “jamming” of this sand injectite during emplacement are preserved in the spacing of the laminae, controlled by the velocity of the pore fluid at the moment of grain lock-up. This transient condition created a fabric which persists in the sandstone and affects pore water flow as evidenced by the differential cementation of alternating...
laminae. In the Yellow Bank Creek Complex, these laminae are highlighted by limonite cement, but without differential cementation they are very difficult to distinguish by microstructural observations alone and it is unlikely that they would be detected. We speculate that similar textures may be present in other sand deposits emplaced by granular flow processes, and may have noticeable effects on permeability anisotropy.

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Monterey Formation:
• Diatomaceous shales, locally porcelainite
• \( \leq 800 \) m thick in Santa Cruz County
• Variable degree of silica cementation; clay-rich beds are weakly cemented.

Santa Cruz Mudstone
• Diatomaceous shales, locally porcelainite
• Carbonate seep deposits and nodules
• Sandstone dikes and sills locally abundant

Purisima Formation
• Yellow gray lithic wackes, conglomerates
• Shell beds, channel facies and debris flows

Santa Margarita Formation
• Quartzose to feldspathic arenites
• Locally glauconitic. Locally fossiliferous.
• Locally hydrocarbon-rich

Figure 1. A: Regional map showing location of Yellow Bank Beach relative to San Andreas and San Gregorio fault systems. B: Regional stratigraphy modified from Clark [1981]; Scott et al. [2009]; Stanley and Lillis [2000]; Thompson et al. [2007].
Figure 2. A: Overview of the Yellow Bank Creek Complex outcrop. Undulating roof of injectite is exposed (ceiling is host rock Santa Cruz Mudstone). Small sand dyke injects from top of injectite at center toward upper left of photo. Majority of exposed sand injectite is laminated with limonite cement (appears yellow in photo). Dolomite-cemented, bitumen-rich sandstone is exposed at beach level and forms rounded columns and bubble shapes leading to “lava lamp”-like appearance. Locations of photos B, E, F, and Figure 3A are indicated. B: Relationship between dolomite-cemented and laminated sandstone. Rounded body of dolomite-cemented sandstone distorts laminae in laminated sand (dashed white lines trace deformed laminae). C: Limonite-cemented laminae distorted around a mudstone clast within sand injectite. Dashed white lines trace laminae. D: Largest exposed mudstone clast in the injectite. Clast has rim of dolomite-cemented sandstone which is surrounded by limonite-cemented laminae. E: Banding cutting across contacts between dolomite-cemented and laminated sand. F: Steeply dipping laminae between bands of dolomite-cemented sand. Convolute structures (black arrows) deform laminae with antiforms pointing laterally toward upper left of photo.
Figure 3. Dolomite-cemented sandstone columns crosscutting laminae. Hammer for scale.

Figure 4. Geometry of the mudstone clasts. Horizontal axis: Aspect ratio of mudstone clast. Vertical axis: local angle between the long axis of the mudstone clast and the laminae in the surrounding sand. Symbol size scaled by equivalent diameter. None of these three measurements co-vary. N=27.
Figure 5. A: Outcrop photo showing relationship between laminae, bands and convolutions. Sub-horizontal, \( \approx 6 \) mm laminae (orange lines in cartoon) are differentially limonite-cemented. Closer spacing of limonite-cemented laminae in spaced surfaces create \( \approx 10 \) cm banding (brown arrows). Antiformal undulations of the laminae create convolutions (blue arrows) which are confined between bands. B: In other areas along outcrop where banding is not present laminae are deformed as convolution structures where axial reach is not limited into banding. We interpret these relationships to show that laminae predate both banding and convolutions.
Figure 6. From photomicrographs of limonite-cemented (A) and uncemented (B) laminae, subareas were defined which lie completely within a single lamination. Grains in the subareas were outlined in Adobe Illustrator to facilitate analysis. Using the method of Björk et al. [2009], best fit ellipses were applied to grains and the inclination angle between long axis and horizontal was measured (sign conventions are shown). Angles were measured from top edge of the subset area, parallel to laminae.
Figure 7. Histograms showing apparent grain diameter, grain aspect ratios, and grain inclination for limonite-cemented and uncemented laminae. All data are normalized to the total number of grains counted in each type of laminae.
Figure 8. A. Cartoon illustrating Equation 1. Cartoons illustrating transition from granular flow (B) to porefluid flow (C) at threshold velocity. Blue arrows show pore fluid flow paths, yellow arrows show granular transport path. Red arrows show general transport direction in B and pore fluid escape direction in C.