An Ontological Model for Turbidite Channel Migration

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Abstract. *Geology interpretation applies abductive reasoning to determine, from the actual existent rock units, the processes that create these occurrences. In particular, modelling the sedimentary processes of erosion and deposition, are of crucial importance for understanding the spatial distribution of the rock bodies that configure actual petroleum reservoir. This paper proposes an ontological model for turbidite channel migration, which is an important event in the formation of turbidite systems, a common type of reservoir. The proposed model is based on the Unified Foundational Ontology and presents both a high level description of the event as well as details its main composing events, namely erosion, transportation and deposition of sediments.*

1. Introduction

Ontologies can be regarded as explicit specifications of conceptualizations (Gruber, 1993). In a practical sense, an ontology formally describes the concepts of a given domain and the relationships among them. Such concepts may represent both things that *exist* (usually called *objects*) as well as things that *happen* (usually called *events*). In spite of that, there is a somewhat widespread view that objects are ontologically prior to events[1], according to which objects are all that exists and events exist just as the distribution of matter and objects in space and time (Galton, Mizoguchi, 2009). Nevertheless, from chemical reactions to business transactions, it seems that great part of our reality is fundamentally dependent on events (Casati, Varzi, 2015). Therefore, a thorough ontological treatment of this dynamic aspect of reality would surely enhance our means of representing the world. An example of domain that would take advantage of good ontological analysis of perdurants is Geology.

Geology is the domain that studies the Earth and the rocks that compose it. Since geologists cannot observe their whole subject of study, they heavily rely on the understanding of the geological processes that form rocks, since it can support the interpretation of the environment which is under analysis. With that, they can analyze samples of rock and other indirect measures from some geological target of investigation and infer the processes that led it to its current state. Then, considering that the other geological objects which are present in the same environment may have been affected by the same processes, this approach can provide a glimpse of the conditions of these other objects.

The understanding of geological processes is particularly important for the comprehension of sedimentary deposits, such as turbidites - a frequent type of clastic

[1] We use here the terms process, event, occurrent and perdurant interchangeably along the text keeping the same meaning.

deposit on the continental slope (McHargue et al., 2011) associated to the occurence of hydrocarbon reservoirs in several parts of the world. These deposits are formed as a result of turbidity currents, which are dense sediment gravity flows that happen when the accumulation of sediments in the border of the continental platform achieves its equilibrium limit and suddenly fall down. Due to their strength, such currents dig deep channels in the border of the slope, transporting and depositing large volume of coarse-grained clastic sediments from continental slope into deep ocean. Besides creating new turbidite channels, subsequent flows can also reshape previously formed channels and deposits, by means of the deposition of new sediment as well the erosion and reallocation of already deposited sediment. Fig. 1 shows a schematic representation of a turbidity current.

According to (McHargue et al., 2011), despite the abundance of turbidites and the many years of study of such deposit type, their characterization and predictability is still a big challenge for industry, due to the three-dimensional complexity and diversity of channel systems.

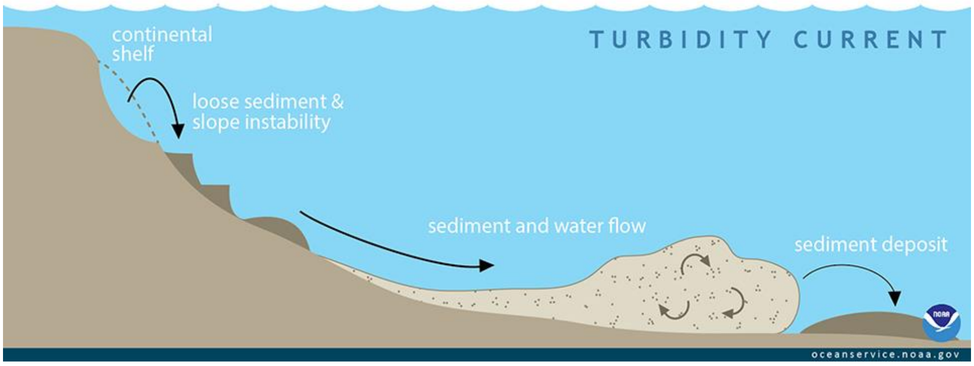

Figure 1. A turbidity current carrying the sediments towards the distal part of the area. (source National Ocean Service, USA).

In order to help in achieving a better understanding of turbidite deposits, this paper proposes an ontological model for the process of lateral migration of turbidite channels (i.e., the erosion of sediments from the lateral bank of the channel followed by the transport and deposit of the sediment further ahead on the channel). The model is based on the Unified Foundational Ontology (UFO) (Guizzardi, 2005) and may help in developing a geological model of the sedimentation-erosion process of the lateral migration process, which can further feed the flow model of reservoirs.

Thus, the model makes explicit (a) the pre-conditions and the results of the lateral migration process, (b) the stages of this process, (c) the required conditions to the occurrence of each of the stages, (d) the objects that participate in them, and (e) which role they play in the process.

The remaining of the paper is organized as follows: section 2 presents an overview of UFO, section 3 provides a summary of the turbidite domain, section 4 presents and discusses the proposed model, and section 5 brings our final remarks.

2. The Unified Foundational Ontology (UFO)

UFO is a philosophically and cognitively well-founded foundational ontology (Guizzardi et al., 2013), which provides a set of meta-types described in terms of well-defined meta-properties (such as rigidity, provision of identity criterion, relational dependence). One of its major benefits is that, by offering such meta-properties, it gives us a systematic and rigorous way to analyze the universals (i.e. a notion roughly equivalent to that of concept or class) of a domain. It can be done by identifying which combination of meta-properties the universal presents and then selecting the corresponding meta-type into which the universal should be classified. UFO divides universals into two broad categories: endurant universals and perdurant universals.

Endurant universals gather individuals that are in time (i.e. they are wholly present whenever they are present). A person, a rock, and a pen are examples of endurant individuals. Endurant universals are further divided into *objects* (i.e. existentially independent endurants, e.g., book, water) and *moments* (i.e. that only exist in other individuals, e.g., weight, color) (Guizzardi, 2005).

Perdurant universals (hereafter referred to as *event universals*) comprise individuals that happen in time (i.e. they extend in time accumulating temporal parts) and that are existentially dependent on the objects that participate in them. Instances of such universals are regarded as transformations of the state of affairs from one *situation* to another (Guizzardi et al., 2013). Examples of event individuals include the fall of an apple from a tree (that would be existentially dependent on the apple) or a game of chess (dependent on the players and the chess set).

Situation universals comprise particular configurations of a part of reality that can be understood as a whole. A traffic jam and a weather station deployed on a given area are examples of situations. A situation instance may be related to an event instance either being its *pre-state* (i.e. situation that triggers the occurrence of an event, e.g. some water exposed to below freezing temperature triggers a freezing event) or its *post-state* (i.e. situation that is brought about as a result of the occurrence of the event, e.g. a wet soil after a rain). There is a unique particular situation that triggers a particular event occurrence, as well as there is a unique maximal situation that is brought about by such occurrence.

Events may be composed by other events. A particular way of partitioning a complex event is separating each part of it that is existentially dependent on each of its participants. Each of such parts would be a *participation* (i.e. an event exclusively dependent on a single object). Each participation induces one or more *processual roles* over its participant object, representing the role the object plays in the event it participates in (i.e. the way its participation influences the event) (Guizzardi et al., 2013).

3. Turbidite Channel Lateral Migration

Turbidite channels are conduits on the underwater surface that are dug by turbidity currents. These channels are formed by delineated by sediment volumes that act as border walls of the channel confining the currents that flow on it. Such sediment volumes are called banks and may be of two types: inner banks or outer banks. Inner banks are convex-shaped banks that form the inner side of the curves of some channel whereas outer banks are concave-shaped banks that form the outer side of the curves of some channel. The shape of a turbidite channel is given by the shapes of its composing banks and both turbidite channels and banks are characterized by their sinuosity, which roughly corresponds to how curved the channel/bank is.

The lateral migration of the turbidite channel is an event that reshapes the architecture of a channel and increases its sinuosity by transferring sediment among its banks. Thus, this event can be decomposed in three other events: erosion, transportation, and deposition of sediments.

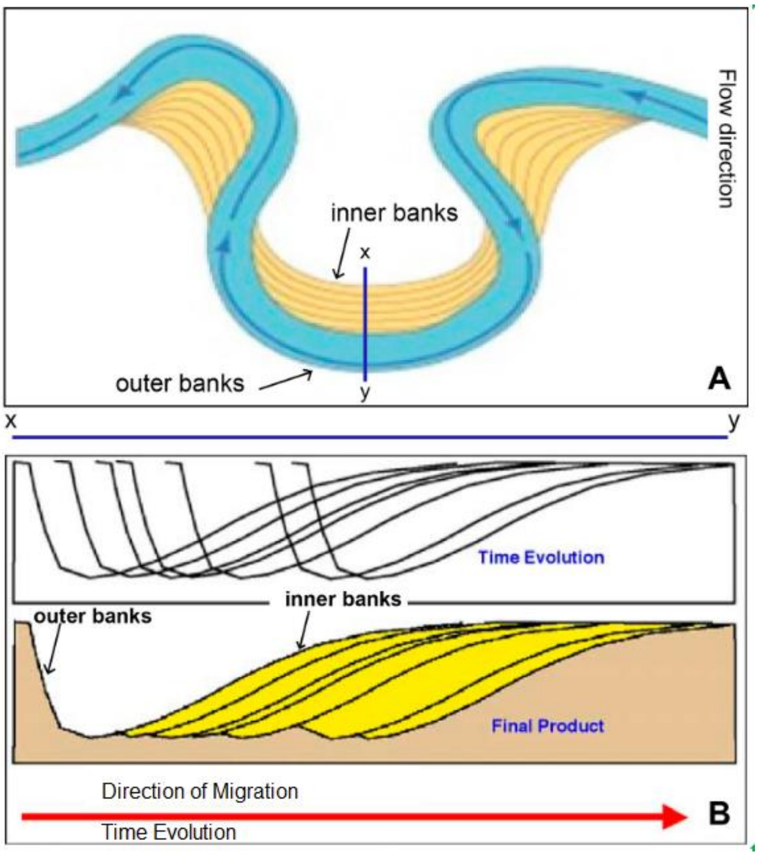

Figure 2: A) Schematic illustration of sediment flow through a turbidite channel. The cross-sectional view (x-y) illustrates the vertical view of turbidite channel that is presented in (B), (Modified from Posamentier & Walker, 2006). B) Depositional model of the turbite channel migration that results from systematic erosion of the outer banks and deposition along inner banks. (Modified from Abreu et al., 2003).

First, in the event of *erosion*, unconsolidated material that is located in some outer bank of the channel is eroded by the flowing water, due to its high energy in that point of the channel. The *transportation* process drags the eroded sediment downstream until the water loses the necessary energy to transport it, which happens when reaching some inner bank of the channel. At this moment, we have the *deposition* of the heavier sediments on the reached inner bank, while the lighter portion may remain in suspension, being carried by the water to some place ahead on the channel. Fig. 2A shows a sinuous channel, indicating both inner and outer banks. Fig. 2B shows the lateral profile of the channel depicted in Fig. 2A, depicting the inner and outer banks from another perspective and presenting the temporal evolution of the sediments deposits on the inner bank.

4. An Ontological Model for Turbidite Channel Lateral Migration

This section presents the proposed ontological model for the event of turbidite channel lateral migration. It first presents a high-level model of the event, describing it in terms of its pre-state and post-state situations, its continuant participants, and the processual roles they play. Then it enumerates the stages that compose the migration event, which are further detailed one at a time.

There are basically four types of continuants involved in a turbidite channel migration event: the turbidite channel, its composing banks, water, and sediment, which are shown in Fig. 3. ***Turbidite channel*** is a channel on the underwater surface that are formed by turbidity currents and whose shape is delineated by that of its composing ***banks*** (i.e., the sediment mass that forms the border walls of the channel). Both turbidity channels and banks are characterized by their ***sinuosity*** (i.e., how curved they are). Depending on their shape, banks are further divided into ***inner banks*** (i.e., convex-shaped banks that form the inner side of the curves of some channel) and ***outer banks*** (i.e., concave-shaped banks that form the outer side of the curves os some channel).

The concept of ***water*** refers to specific, maximally connected portions of the homonymous chemical substance. For the purposes of this work, we highlighted the ***kinetic energy*** attribute of water as a way to statically represent its "moving state" (as a disposition that leads to some moving event). Regarding this attribute, we subdivided the concept of *water* into ***moving water*** (i.e., water with some kinetic energy) and ***still water*** (i.e., water with no kinetic energy). On top of that, we further divided the concept of moving water into ***high energy water*** and ***low energy water***, according to the amount of kinetic energy it has, which would lead to faster or slower water flow. Finally, ***sediment*** represents specific, maximally connected portions of material that typically composes the underwater surface (including structures such as channels and banks), that may be of various types (e.g. sands constituted by diverse chemical substances).

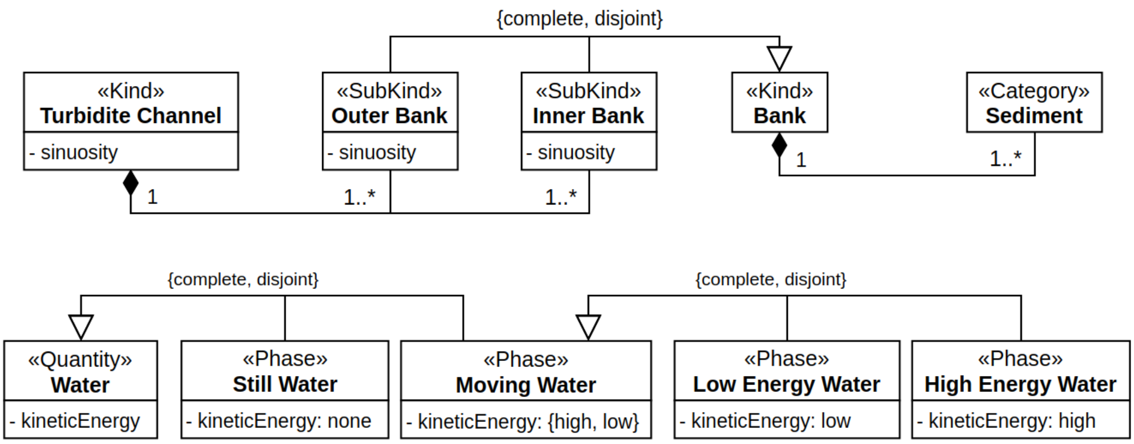

Figure 3 - Continuants that participate in lateral migration events.

4.1. Turbidite Channel Lateral Migration: High-Level Model

Turbidity channel migration is the event in which some portion of moving water that fills a channel reshapes it by reallocating the sediment that composes its banks, increasing the sinuosity of the channel. Thus, it is an event that is triggered by a pre-state situation of water flowing through channel and brings about a situation of channel with increased sinuosity, in which the same initial turbidite channel has a more sinuous shape. We represented the pre-state situation by means of the dynamic fill material relation (i.e., UFO's Relator), which relates some turbidite channel (that plays the role of confining channel) to the moving water that is running through it (that assumes the role of water stream). The water participates as the channel sculptor and the channel participates, during most of the process, as the shape-changing channel, and as the resulting reshaped channel at the end of the event. Channel sinuosity increases during the process. This is the high-level description of the lateral migration event that is presented in Fig. 4.

Since it is not an instantaneous, atomic event, we can go on in our analysis, breaking it into its main stages, which can give us a better understanding of the way the process occurs. We are considering that any transference of sediment between any two banks of a turbidity channel changes its shape, by increasing the sinuosity of the involved banks. Thus, any such transference can be regarded as an event of lateral migration of the channel. Based on that, we can analyze how this transference takes place.

Within the pre-state situation of a turbidite channel migration event (i.e., the *water flowing through channel* situation), we can focalize a partial, local ***strong flow over outer bank*** situation, encompassing a portion of the water stream that is abrading an outer bank of the channel. This situation triggers the first stage of the channel migration: the event of ***erosion of outer bank***, which represents the extraction of sediment from an outer bank and its transference to the water stream. Such event brings about an ***erosion result*** situation, which is composed by two smaller situations: the ***outer bank in new shape***, that composes the post-situation of the whole turbidite channel migration event and comprises an eroded and more sinuous outer bank, and the ***loaded flow*** situation, which includes some moving water containing the eroded sediments.

The loaded flow situation leads to the second stage: the event of ***sediment transportation to inner bank***, that represents the movement of the sediment-loaded water until it reaches an inner bank. This transportation event brings about a ***loaded weak flow on inner bank*** situation, which triggers the last stage of the migration event: the ***sediment deposition onto inner bank***. This depositional event results in an ***inner bank with new sediment*** situation, that comprises an inner bank with newly deposited sediment and, consequently, with an altered, more sinuous shape. Given such shape modification, this situation is also a part of the post-state of the turbidite channel migration event as a whole.

It is important to note that events of migration of turbidite channel are not restricted to a single sequences of erosion-transportation-deposition events. Considering the whole extension of the channel and the whole body of water flowing through it, there may be several outer banks suffering the erosive pressure of the water flow, which will lead to several independent chains of erosion-transportation-deposition events that will compose an overall turbidite channel migration event. This possibility is represented by the *1..** cardinalities on the composition relations between the pre/post-state situations and their component situations and on the composition relations between the *turbidite channel migration* event and its component stages. In the following, we detail such stages.

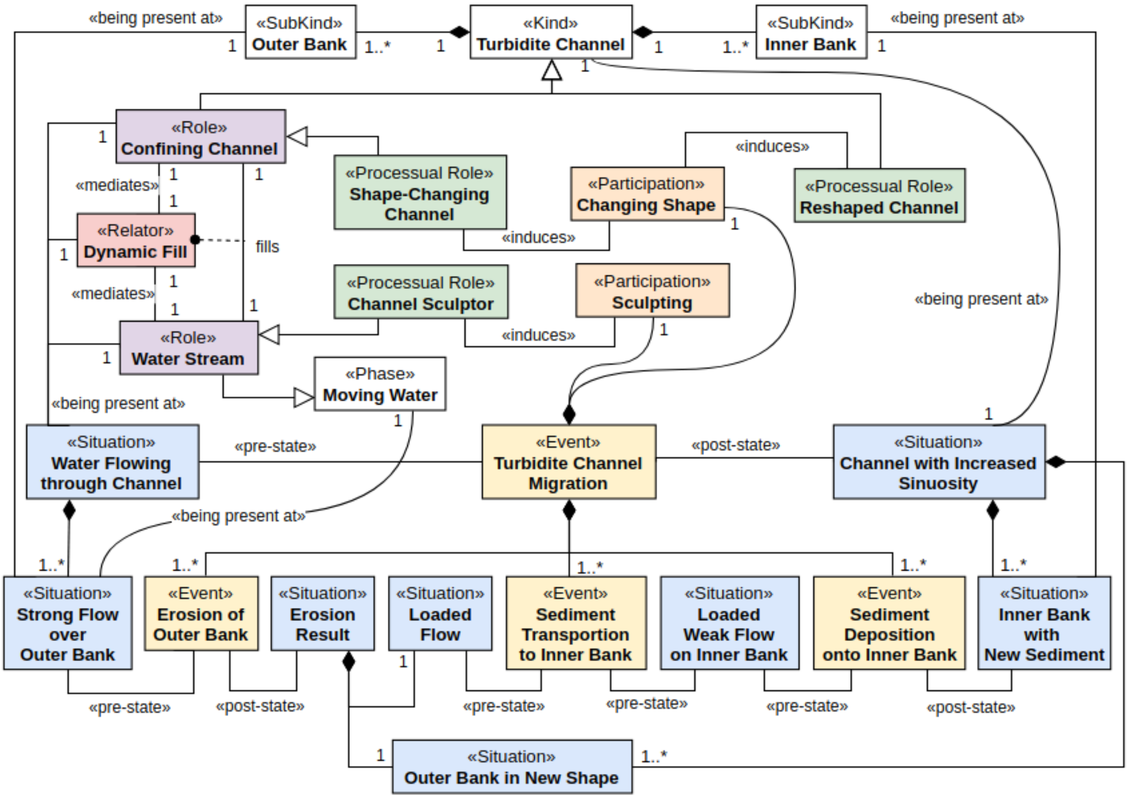

Figure 4 - Turbidity Channel Migration Ontological Model.

4.2. First Stage: Erosion of Outer Bank

Erosion of outer bank (Fig. 5) represents the process of dragging sediment out of the bank. This event is the result of the manifestation of two complementary dispositions: the disposition of pulling sediment out from a bank that inheres in *high energy water*, and the disposition of deposited sediment of being carried out when touched by some high energy water. Thus, the event is triggered by a ***strong flow over an outer bank*** situation, which gathers all the required conditions for the referred disposition manifestation, and brings about an ***erosion result*** situation.

A ***strong flow over an outer bank*** situation involves a ***frictional contact*** relation between some *high energy water* (which plays the role of ***frictioning water***), the *outer bank* that is in contact with the water (which plays the role of ***frictionally pressed outer bank***), and the portion of deposited sediment over which the water is exerting pressure (which plays the role of ***unstable sediment***). With that, the outer bank participates as the ***erosion patient*** of the event, the water participates as the ***erosive agent***, and the sediment participates as the ***frictioned sediment***.

The ***erosion result*** situation is composed by an ***outer bank in new shape* situation** and a ***loaded flow*** situation. The first one corresponds to the state of the *outer bank* after losing part of its sediment and, consequently, becoming more sinuous. With that, the outer bank also participates in the event as ***eroded bank***.

The other (i.e., *loaded flow*) refers to the state of the remaining participants, including the same portion of moving water that was present in the pre-state of the event, but now loaded with the eroded sediment. To represent that, we included the ***traction*** relator (i.e., the relation between flowing water and some heavy sediment that it is transporting), which relates some ***tractive water*** (i.e., the water that carries the sediment) to its ***drawn sediment*** (i.e., the sediment that is being carried by the water). Due to that, besides being the *erosive agent* of the event, the water also participates in the event as ***sediment receiver***, and the sediment also participates as ***removed sediment***.

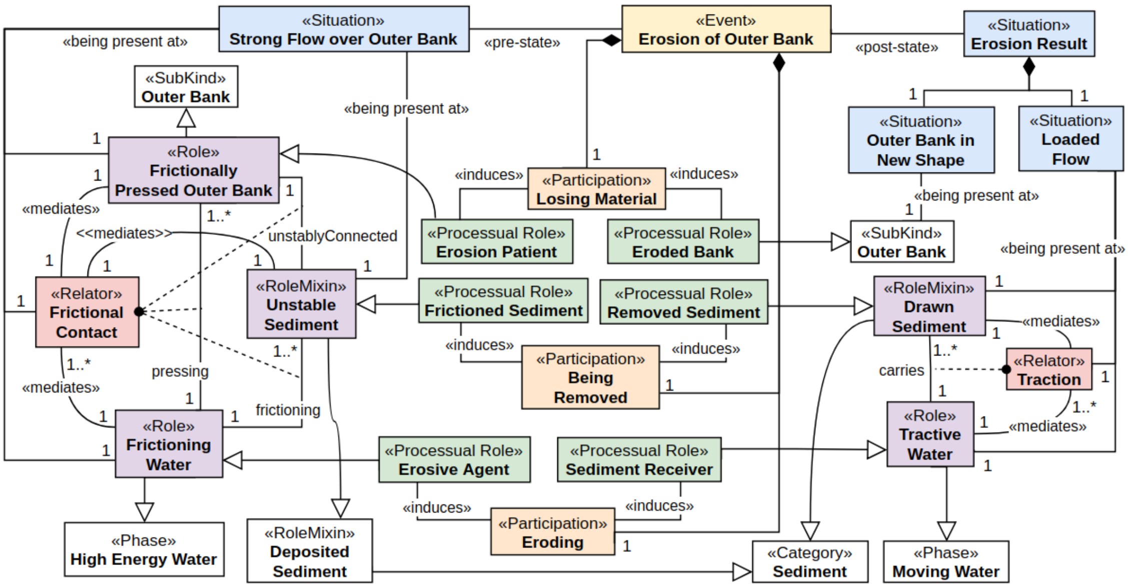

Figure 5 - Outer Bank Erosion Event.

4.3. Second Stage: Sediment Transport to Inner Bank

The movement of the eroded sediment towards an inner bank is represented by the ***sediment transportation to inner bank*** (Fig. 6) event. It is triggered by some ***loaded flow*** situation and happens as a series of successive manifestations of two complementary dispositions: the disposition that a moving water has of carrying a mass load proportional to its kinetic energy, and the corresponding disposition of the sediment of being carried by some fluid with enough kinetic energy. The event ends when the loaded water reaches an inner bank.

For the dynamics of fluids that run through channels, the flowing water loses energy and gets slower when reaching an inner bank. As a result, the post-state of this event is a ***loaded weak flow over inner bank*** situation. This situation includes an ***obstacle contact*** relator, representing the relationship between the inner bank (that plays the role of ***obstacle inner bank***), the loaded water that is being slowed down by the inner bank (that plays the role of ***obstacled loaded water***), and the sediment that is in traction (that plays the role of ***obstacled sediment***).

Given this description, the water participates as the ***vehicle*** for the sediment, the sediment participates as the ***transported load*** during most of the event and as the **blocked load** at the end of the event, and the inner bank participates as the ***arriving point*** of the transportation.

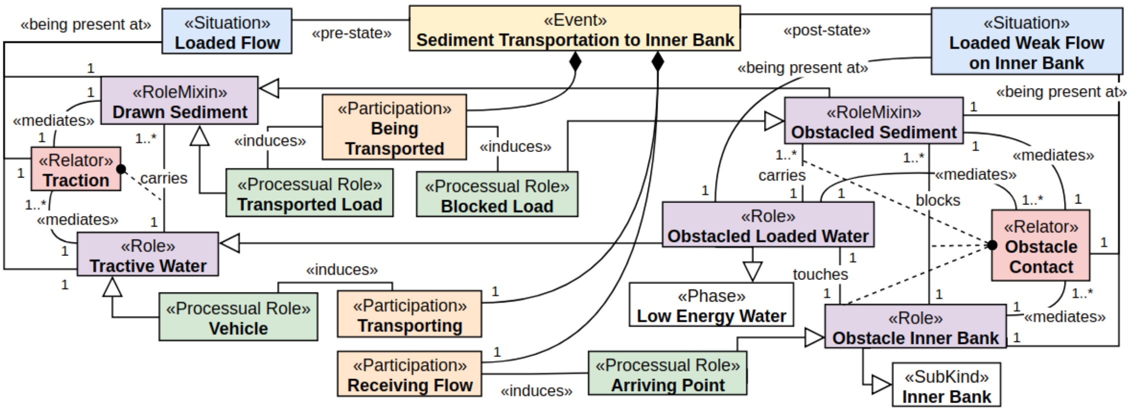

Figure 6 - Sediment Transport to Inner Bank Event.

4.4. Third Stage: Sediment Deposition onto Inner Bank

The event of *sediment transport to inner bank* ends in a situation with some slow moving, loaded water that is being obstacled by an inner bank - which is exactly the situation that triggers the event of ***sediment deposition onto inner bank*** (Fig. 7). However, it raises the question of why such a situation leads to an event of deposition and not to a different event of transportation (e.g., deviating from the inner bank).

As mentioned before, the event of transportation is composed by successive activations of the disposition that a moving water has of carrying a load proportional to its kinetic energy and the complementary disposition that the sediment has of being carried by a sufficiently strong water flow. Therefore, although the end mark of such directed transport event is the arrival of the loaded water at some inner bank, it coincides with the instant in which the conditions that cause the activation of the referred dispositions cease to exist. In other words, given their shape and inner bank position, inner banks have the disposition of hinder the water flow. With that, when the loaded water reaches an inner bank, there is a decrease in the kinetic energy of the water that prevents it from pushing the sediment forward to the next position. Moreover, the presence of some obstacle also prevents the sediment from occupying the next position ahead. It is this presence of such diverse conditions that changes the behavior of the involved continuants and triggers the event of *sediment deposition onto inner bank.*

Thus, whereas the *obstacle inner bank* simply participated as the arriving point in the transportation event, in the deposition event it participates as the ***obstacle*** that causes the ceasing of the conditions of activation of the dispositions of the moving water and the drawn sediment. First it slows water down, reducing its kinetic so that it is no longer sufficient to keep sediment in traction. Along with that, it blocks the sediment, making it even harder to be carried by the water. Then, water loses its load (participating as ***unloading vehicle***) and the drawn sediment is deposited on the inner bank (participating as ***captured sediment***), and, with that, the inner bank also participates as ***depositing place***.

The event of *sediment deposition onto inner bank* brings about an ***inner bank with new sediment***, which gathers an inner bank with some deposited sediment (which is represented by the ***deposition*** relator, and its relata - ***deposited sediment*** and ***deposition bank***). This completes the reallocation of sediment of the banks of the channel. Moreover, the sum of modifications on the outer and inner banks involved in the three presented represent a modification on the overall shape of the channel as a whole. This combination of sediment reallocation and channel reshaping qualifies the sequence of such stages as a *turbidite channel lateral migration* event.

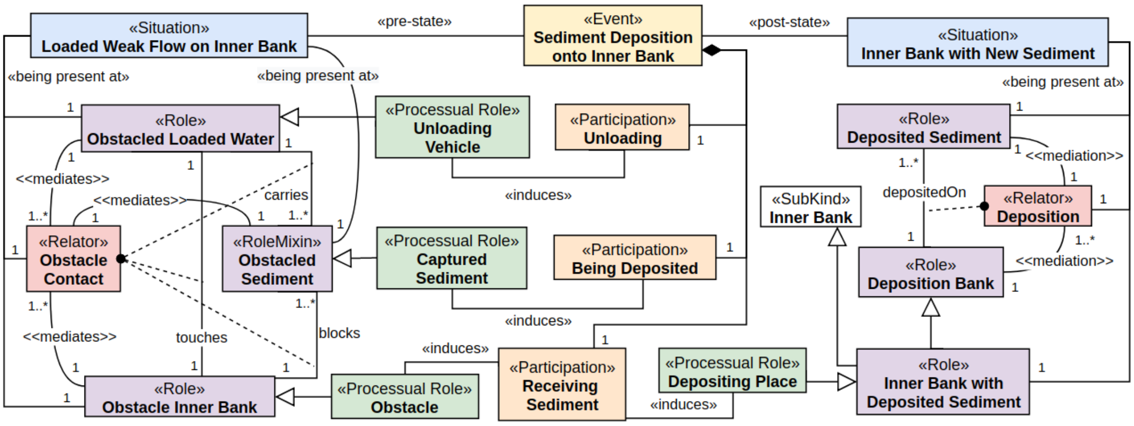

Figure 7 - Sediment Deposition onto Inner Bank Event.

5. Concluding Remarks

This paper presented an ontological model for turbidite lateral channel migration, which was developed based on the Unified Foundational Ontology. It provides a general, high level description of the event as well as details its three main stages - i.e. erosion of sediment from an outer bank, sediment transportation, and sediment deposition onto an inner bank. The model makes explicit the pre and post conditions of the lateral migration event, as well as the pre and post conditions of each of its stages. It also exposes the specific contributions of the participants to the overall event and its stages, as well as their arrangement in the situations that precede and follow each of the events.

With the conceptual formalization of this important process in the formation of turbidite systems we aim to contribute to a better comprehension of its effects over the final configuration of turbidite deposits, enhancing its predictability. Aligned with that, our model may provide a conceptual framework to guide simulation efforts and to contextualize their findings, since it indicates which are the main objects involved in the development of the event, makes explicit which are their noteworthy attributes and interactions, and establishes how these elements must be arranged to trigger each of the described events and how they are left after the each event happens. This can provide basis for further definition of the physical quantities involved (e.g. the model indicates the general disposition of high energy water of eroding sediments from outer banks, which may be further quantified to establish the energy level required to erode different types of sediment).

As future work, we intend to model the other events that occur inside turbidite channels (e.g. aggradation, flow stripping) and those events that comprise the whole turbidite channel system. We believe that fully modeling the events related to turbidite systems can greatly improve the understanding of such a complex systems and support the building of more accurate 3D models of this type of sedimentary deposit.

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