An ontology-based knowledge model for the deep-marine clastic depositional system

Yuanwei Qu

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Supervisors: Ivar Midtkandal (UiO), Mara Abel (UFRGS)
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Preface:

This thesis is submitted to the Department of Geosciences, University of Oslo (UiO), for the Master of Geoscience program: Petroleum Geoscience. The research in this thesis was carried out in the autumn and spring of 2019 and 2020, respectively, as a 60 ECTS thesis of a total 120 ECTS Master of Science degree. The work of this thesis is based on the collaboration project *Digital Geosciences: Knowledge Management for Interoperability of Geoscientific Data* between the SIRIUS center at the University of Oslo and the Federal University of Rio Grande do Sul (UFRGS) in Brazil.

This thesis aims to establish a knowledge model for the description of the deep-marine depositional system based on well-founded ontologies, which shall make deep-marine sedimentological data communicable among different formats or databases, and provide a knowledge base for the future application of the computer-assisted geoscientific analysis. The thesis is supervised by Assoc Prof Ivar Midtkandal and Prof Mara Abel (UFRGS).

Yuanwei Qu

Oslo, Norway; June 15th, 2020

Acknowledgments

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Finally, I want to thank my family and my girlfriend for their long-lasting support and encouragement. 2020 is a special year, I wish everyone I know will keep healthy, nothing is more valuable than this.

Yuanwei Qu
Oslo, Norway; June 15th, 2020

Abstract

Over the last decades, a wide range of sedimentological studies has combined different scales of geological data to contribute to models of the deep-marine depositional system. With increasing demands for integration of geological data into computer-assisted decision-making and the development of the information technology, the geological data must be explicit with a common standard to support computer-assisted geoscientific analyses.

This thesis proposes an ontology-based knowledge model for a systematic description of deep-marine depositional occurrences in outcrop and subsurface records, with the intention of supporting computer analysis and interpretation. The model is founded on an extensive literature review that, among others, assembles the vocabulary applied in geological descriptions of the deep-marine depositional system. This review enables the knowledge model for the description of geological data in the deep-marine clastic depositional system, together with an ontological analysis of the vocabulary and associated definitions of different authors. The knowledge model is based on the specialization of the GeoCore Ontology (Garcia et al., 2020) that formalized the basic geological entities such as *Rock, Geological Object, Geological Structure,* and *Geological Process* after the top-level ontology: the Basic Formal Ontology (Arp et al., 2015).

This knowledge model considers a four-level hierarchy, and the key deep-marine architectural elements and deposits are defined as entities in the model. With the ontological analysis, each defined entity in this model has been demonstrated its essential identity and difference with other entities. Besides, this model defines the qualities that used to characterize the entities, the range of values of these qualities, and applies the focus on the formalization of the relationships among the entities. Furthermore, this thesis provides a new scope for geologists to explore and review the geological vocabulary and the data, especially in the deep-marine clastic depositional system. The new scope includes a separation of various time-related geological data, analyses and definitions of deep-marine deposits, the essence of lithofacies, and distinctions of relevant geological terms.

This tool gives geologists an ontological approach which provides a baseline for geologists to digitalize and formalize the geological knowledge in sedimentology. The model is tested with the description of the deep-marine depositional occurrences of the Niger delta basin in the offshore of West Africa, and the Ainsa-Jaca basin in Spain.

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1. Introduction

1.1 Motivation and objective

Sedimentology focuses on natural sediments, rocks that are constituted by these sediments, and the processes that natural sediments are involved in (Middleton, 2003). When geologists first started to observe sedimentary rocks, the study of sedimentology was involved. However, comparing with centuries history of geology, the time of sedimentology to be a widely accepted formal subject is less than a hundred years (Middleton, 2003). Since the 1950s, the term "sedimentology" has been regarded as the study of sedimentary rocks with an integration of results from different geologic sub-disciplines (e.g. petrology, paleontology) to get a full picture of sedimentary formations (Brouwer, 1962; Middleton, 2003).

The study of deep-marine sedimentology has been accelerated by the demand of the petroleum industry. As a result, a wide range of studies have been carried out by researchers, and many important deep-marine geological concepts such as the turbidite (Kuenen, 1957), the Bouma sequence (Bouma, 1962), the lobe model for the first ancient submarine fan (Mutti and Ghibaudo, 1972), the Lowe sequence (Lowe, 1982), and so on have been settled down. As the industrial exploration and academic research further develop, a large volume of geological data has been created in different scales of observation and interpretation for different usages and purposes. However, in comparison with other scientific subjects such as physics or mathematics, geology is a subject that often depends on the context with approximated descriptions of the research target (Garcia et al., 2020). The language used by geologists is a daily language to represents the geological concepts, rather than a language with strong restrictions and unitary meanings such as Mathematics or Physics.

With the development of computer technology, computer-assisted geoscientific analysis is becoming an increasingly important tool in both industrial and academic kinds of research. This requires that geological records, especially sedimentological analysis results must be translated into digital data, able to be stored and applied in computer applications. However, the different subfield backgrounds (sedimentology, structural geology, petrophysics, etc.), approaches to collect data, terminology, observation scale, and aims are producing geological data differently (Cullis et al., 2019). Such differences within a large volume of data lead to heterogeneities among geological data, and ambiguities among geologists and specialists from other relevant subjects (e.g. engineering, informatics). For example, in the study of Haughton et al. (2009), a debris flow is classified as a sediment gravity flow. In contrast, in the study of Posamentier and Martinsen (2011), a debris flow is classified as a mass-transport process. Following these two different definitions, even the sedimentological data that are collected from the same study area will not match to each other. Such knowledge heterogeneity has become a challenge that hinders the development of computer science applications (Abel et al., 2015).

Recently, geologists have looked for systematic ways of analyzing and capturing information about the deep-marine depositional system (Cullis et al.,2019) in order to store the digital data and establish a baseline for comparing and finding analogous occurrences. Databases have been built and applied to software, but many databases were prepared for particular usages and programs, the information is limited in the application or database, it is not easy to reuse databases for other researches or studies that have other goals.

In the current stage of information technology, Artificial intelligence has been considered the tool for the next generation of computer-assisted geoscientific analysis. This trending technology requires not only large quantities of data but also a robust knowledge base to allow computer applications to perform automated reasoning to identify the essential differences between different entities in the data. However, the various particular designed database with context-dependent geological descriptions and heterogeneity among geological data are hindering the development of this technology. Hence, increasing the interoperability of the geological data, making data processable, and building the sedimentological knowledge model are the new focal points. The ontology-based knowledge model is the first step to achieve these goals, to fill the gap in the scientific specter from natural variability to computer-based analysis. This will offer a problem-independent view to analyze the domain knowledge, characterize the most essential entities, and provide a homogenous data model for artificial intelligence.

Ontology engineering bases the construction of conceptual models, which analyze the commitment of the terminology together with the entities of reality that the terms represent. This analysis is supported by philosophical theories such as essence and identity, parts and wholes, unity and plurality, dependence, and qualities. This approach could produce models with better proximity to reality and reduces ambiguity. Presently, many knowledge models are built by ontology specialists, and cooperating with experts who have domain knowledge. Yet, due to the approximated natural language, ambiguities exist even between geologists who have different background knowledge. Therefore, building a knowledge model for deep-marine sedimentology is a collaboration between ontology specialists and geologists.

This thesis aims to build a knowledge model based on well-founded ontology from a geologist perspective to represent the entities in diverse geological studies, the qualities and relationships that support the occurrence interpretation. Such a knowledge model will reduce ambiguities within the deep-marine clastic depositional system domain, and assist geologists and other specialists to integrate geological data, illustrate the essential differences and relationships among geological entities. With fewer ambiguities in the deep-marine clastic depositional system, the computer application's interpretation and simulation could better support scientific researches in academia and industry. Besides, this knowledge model will bring a new scope for geologists to see the geology world and provide a baseline template for geologists, especially sedimentologists, to build an ontology-based knowledge model in their domains. Furthermore, the proposed knowledge model will use the published sedimentological data from the Niger delta basin (Zhang et al., 2015; Zhang et al., 2016; Zhang et al., 2018;) and the Ainsa-Jaca basin (Bell et al., 2018) to describe the geological entities and their relationships in these two study areas.

1.2 Research contributions and delimitations

The work of this thesis is based on the collaboration project *Digital Geosciences: Knowledge Management for Interoperability of Geoscientific Data* between SIRIUS at the University of Oslo and the Federal University of Rio Grande do Sul in Brazil. In the knowledge model, the Clastic Complex, and the relationship among the Clastic Unit, Depositional Unit, and Depositional System are inspired by suggestions from Mr. Fernando Cicconeto in the research group of the Federal University of Rio Grande do Sul, and developed as a joint work during the internship of the author in that university.

This thesis focuses on building good ontology content in the ontology-based knowledge model rather than on the computational tools and details of ontology implementations. Distribution and architecture of the deep-marine clastic depositional system depend on extrabasinal and intrabasinal factors (Arnott, 2010). Extrabasinal factors are outside of the system, which influences the allogenic processes, such as conditions in the provenance, global sea-level, type of the sediment feeding system, and storage capacity of shelf-edge. The type of gravity flow leave from shelf-edge is mainly depending on the extrabasinal factors (Sprague et al., 2005). While intrabasinal factors influence the autogenic processes, which are mainly related to seafloor physiography and topography. This work is mainly putting mind to the description of geological entities in the deep-marine clastic system, instead of these extra- and intrabasinal factors behind the architecture.

Besides, this knowledge model is limited to clastic rocks and disregards the composition of the clast, biochemical, or chemical rocks are excluded. Consequently, the model describes the “deep-marine clastic depositional system”, instead of the “deep-marine depositional system”.

2 Theoretical foundations

In this chapter, the theoretical foundations of the proposed ontology-based knowledge model of the deep-marine clastic depositional system will be introduced.

2.1 What is Ontology and an ontology

Traditionally, the Ontology is a philosophical term and is the basic branch of metaphysics. Philosophical Ontology is the study of describing the existence of natural beings in reality, which can trace back to the time of Aristotle (Guarino et al., 2009). For computer science, an ontology is a computational artifact designed to formally and explicitly model the concepts in a domain to solve a specific task and represented in a specific language (Guarino et al., 2009). Ontology engineering bases the construction of conceptual models, which analyze the commitment of the terminology together with the entities of reality that the terms represent. (Mizoguchi and Ikeda, 1998). Studer et al. (1998) defined “an ontology is a formal, explicit specification of a shared conceptualization”.

A conceptual model is formed after the conceptualization, and the conceptualization is an abstract entity that exists in a human’s mind, in other words, conceptualization is a specific view of the given domain that a person or group of people wish to represent for some purpose (Guarino et al., 2009). Thus, a conceptual model (mental model) is someone’s conceptualizations of reality, not representing reality itself. For geologists, the reality that they observe is not as same as what reality that camera captured, due to their understanding of the Earth. For example, Figure 2.1 (Jee et al., 2014) is showing three images of a geological body (fold), A is the photograph captured by a camera, B is a sketch of the outcrop drawn by a person without geoscience training, and C is the sketch drawn by a geology student. There are some differences among A, B, and C, comparing with the camera and the person without geoscience training, the geology student abstracts the geological relevant entities from the outcrop, and leaves out geological irrelevant entities, instead of a copy of the photograph of the whole outcrop. And this geological sketch is intelligible for the geological community, it is because the geological language behind this sketch, the conceptualization in the geology student’s mind and the external representation are shared among the community with the same meaning.

Therefore, the conceptualizations and models are abstract entities that only exist in the mind of an individual or a group of people and represents by the language (symbol) (Guarino et al., 2009). Ullmann (1972) illustrated the relations between the object, the symbolic representation (language), and the conceptualization known as Ullmann’s triangle (Figure.2.2). The dashed line between the symbol and the thing in the Ullmann’s triangle signals that the relation between the language and the reality can only through a conceptualization (Baldinger, 1980). These relations are extended by Guizzardi (2005), the abstraction is added between the conceptualization and the mode. In his model, both conceptualization and abstraction belong to the mental world, while language and model belong to reality, and the new relations are shown in Figure 2.3. The abstraction corresponds to the capture of the part of the reality, which based on a given conceptualization, and the model is the representation in the reality of the abstraction.

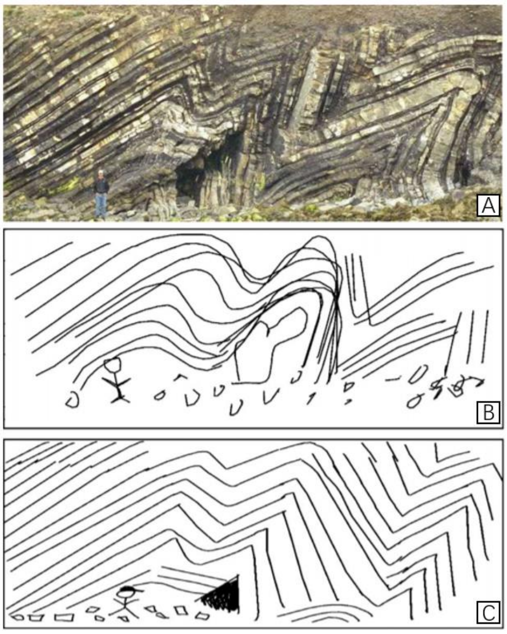


Figure 2.1 The images of a folded outcrop in reality. A is the photograph of the outcrop, B is a sketch drawn by a person without geoscience training, and C is the sketch drawn by a geology student (Jee et al., 2014).

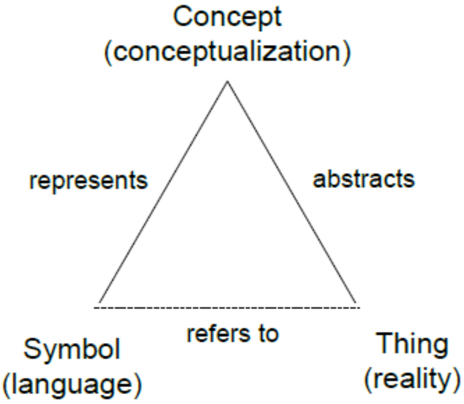


Figure 2.2 Ullmann's triangle illustrates the relations between a concept in mind and the thing in reality, and the concept is represented by the symbol (Guizzardi, 2005; Ullmann, 1972).

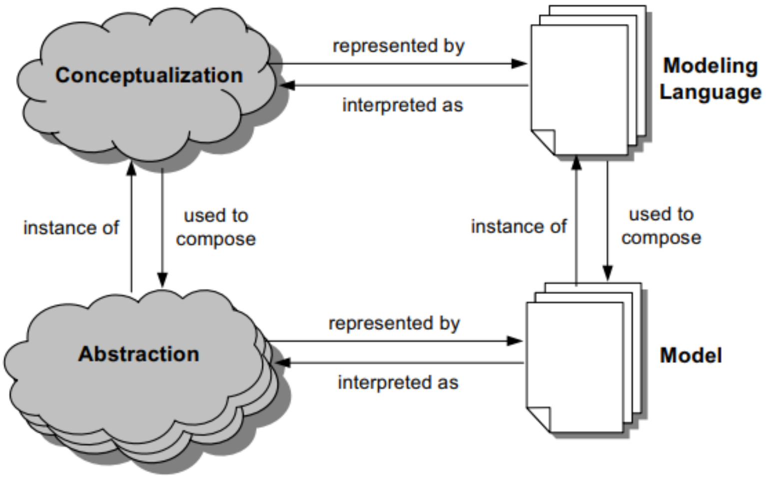


Figure 2.3 The relationships among conceptualization, abstraction, modeling language, and model (Guizzardi, 2007).

An ontology is about shared conceptualizations and their corresponding representations (Werlang, 2015). In recent years, with the development of Artificial Intelligence and Information Technology, the knowledge-based system provided by knowledge engineering became essential to solve complex problems. Here, knowledge includes domain information and how that information is applied to solve problems. The purpose of knowledge engineering is to extract and model knowledge, formalize it, be able to read it by computers, and understand by people (Studer et al., 1998). Scholars in the fields of Informatics have begun to use the concept of ontology in knowledge engineering, that is, the basic elements in the ontology: concepts and the connection between concepts, as a model of knowledge to describe the real world. As a result, more and more knowledge models are in form of ontologies. The term ontology changed from a philosophical uncountable noun to a countable noun (Guarino et al., 2009). That is to say, an ontology becomes a computational artifact, which is an explicit specification of a conceptualization, and is used as a tool to model the system structure and comprise a taxonomy as a proper part (Gruber, 1993; Guarino et al., 2009). The definition of ontologies has become more detailed and specific along with the development of ontologies. An ontology was first defined by Gruber in 1993 as an “explicit specification of a conceptualization”, while Borst (1997) defines as a “formal specification of a shared conceptualization”. Based on the previous two definitions, Studer et al. (1998) concluded that “an ontology is a formal, explicit specification of a shared conceptualization”.

For an ontology, it has to be machine-readable, which means AI can follow this to perform the reasoning, and this is represented by term *formal*. In other words, the language used in building a specific geology domain needs to be logical, it has to clarify the concepts and the relationships of all entities in a structured model. In an ontology, the world represented by an individual (conceptualized knowledge) should be agreed by a community (Guarino et al., 2009). When a geologist draws a set of compact parallel lines to represent the parallel laminations, it will be accepted by the rest of geologists, and this is *shared*. Besides, the knowledge in an ontology has to be explicitly constrained, this is defined as *explicit* (Guarino et al., 2009). For example, relations between the parallel laminations and their forming processes are causal and a constrain is that parallel laminations cannot cause themselves.

The classification of ontologies is mainly based on the degree of dependency and the purpose of using (Guarino, 1998). Three types of ontologies are worth to be mentioned, in order to provide a better understanding of the discussion throughout this thesis:

Top-level ontologies: a type of ontology describes the broad view of the most common entities and relations that are domain independent. The goal of a top-level ontology is to provide a highly general system of meta-types to classify the concepts of the world, which integrate information across different domains (Arp et al., 2015).

Domain ontologies: a type of ontology focuses the integrating of knowledge information within a specific domain (such as Sedimentology, Structural geology, or Mineralogy). To achieve this goal, a domain ontology needs to cover the vocabulary of the specific domain and represent the entities and their relations in a formal way (Arp et al., 2015).

Core ontologies: a type of ontology lies between the Top-level ontologies and Domain ontologies. The Top-level ontologies provide a basic framework to formalize the knowledge in different sub-domains, and the core ontologies (e.g. GeoCore Ontology) define the main concepts of a target domain (such as Sedimentology in Geology or Cell biology in Biology) (Oberle, 2006).

2.2 Study domain: the deep-marine clastic depositional system

The deep-marine depositional system has become a popular sedimentological topic since the middle of the twentieth century. Before that time, the understanding of the deep-marine depositional system was started from the submarine canyons, relative subjects such as turbidity current and mass-transport deposits were recognized afterward (Garcia et al., 2015). After that, the deep-marine reservoirs have gradually shown an enormous hydrocarbon potential, and the industry needs to have a well understanding of these reservoir properties.

The whole deep-marine depositional system is mainly generated by sediment gravity flows such as turbidity current, debris flow, and co-genetic flow, which transport sediments downwards, erode different scales of channels from the slope to the basin floor or abyssal plain, and form lobes in the distal part of the system (Garcia et al., 2015). Different gravity flow types with their own attributes and deposits are illustrated in Figure 2.4. Some minor gravity-driven processes also play a role in the system, such as slump, slide, and creep, which could form mass-transport deposits (MTD) on the basin floor (Shanmugam, 2006). Sediments in the system are mainly delivered by fluvial and longshore-drift processes, they can either be transported directly over the shelf-edge and turn into sediment-gravity flows or accumulate on the shelf-edge. Once the sediments on the shelf-edge are over the storage capacity, a gravity-driven process is triggered. A general illustration of the whole system overview is shown in

Figure 2.5. In Figure 2.5, the most important architectural elements in the deep-marine depositional system are submarine valleys (canyons and slope valley), channels, lobes, overbank deposits (levee and crevasse splay), and mass-transport complex. Due to the potential of good reservoir quality and the distinct geometry, channels and lobes are the most popular elements that geologists focusing on. It is worth mentioning that geologists use the term deep-marine to describe the origin of the deposition, therefore the reservoir doesn't need to locate in the deep-marine environment at the present time (Shanmugam, 2006).

In some deep-marine depositional studies, researchers might use “deep-water” to describe their study targets, however, these two terms are not having an equal meaning. The “deep” of the deep-marine is refer to seawater depth over 200m, in other words, it is the bathyal water depth. According to Shanmugam (2006), the term deep-water is used for both marine and lacustrine settings. Therefore, for research projects that only focusing on the marine setting, the term deep- marine should be used, instead of deep-water.

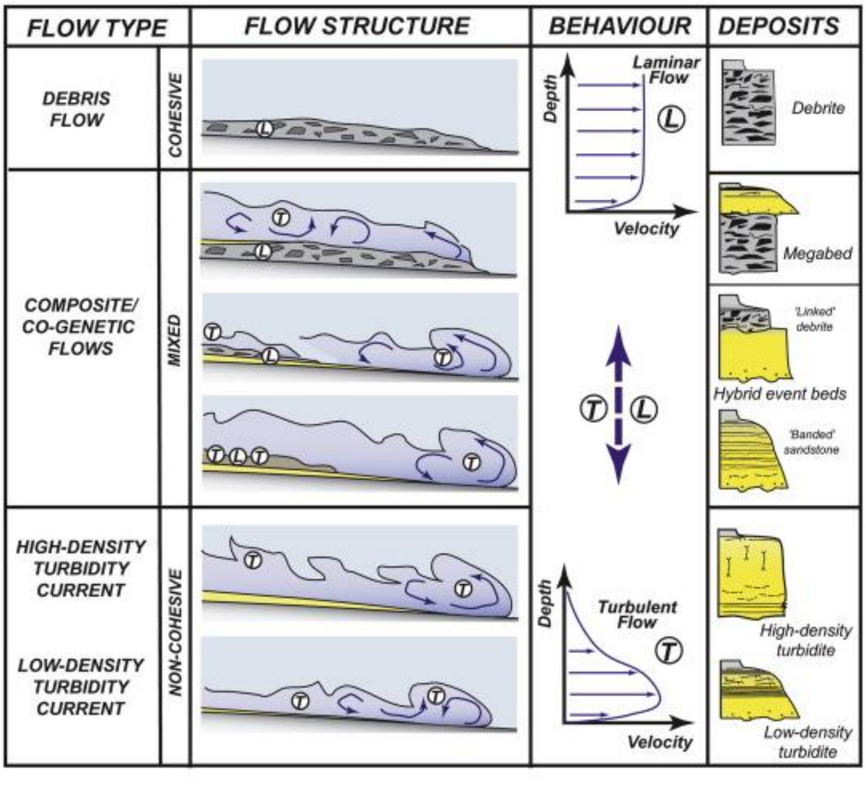


Figure 2.4. A classification scheme of main gravity flow types, with their flow structures, behaviors, and beds of deposits (Haughton et al., 2009).

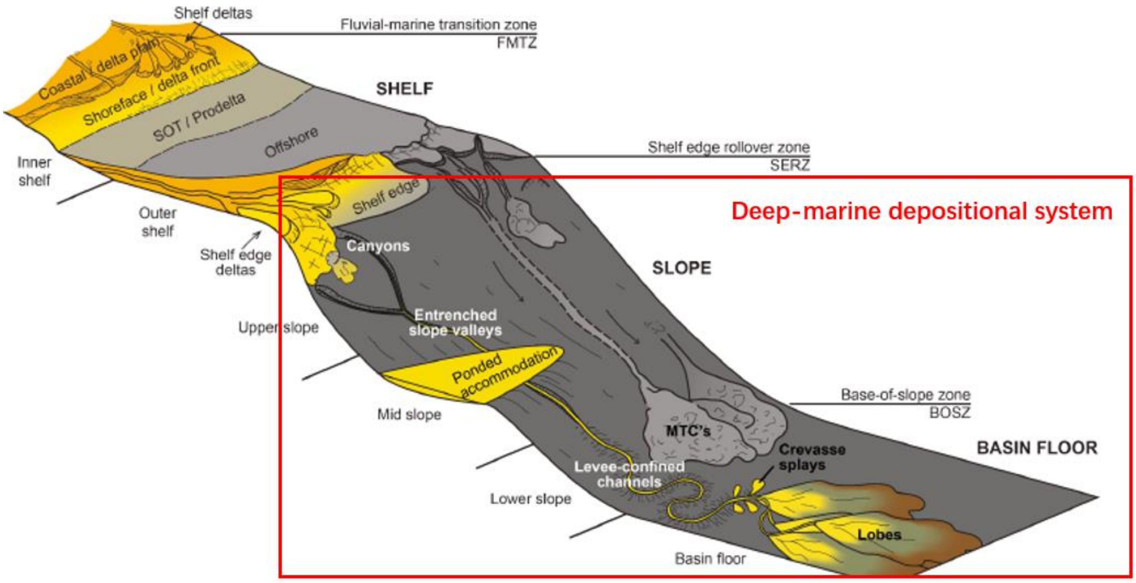


Figure 2.5 The general overview of the deep-marine depositional system, it starts from the shelf edge and ends at the basin floor (in the red box) (Poyatos-Moré et al., 2016).

Terms such as turbidite systems and submarine fan systems are both frequently used by some researchers to refer to the deep-marine clastic depositional system (Garcia et al., 2015). However, both terms are ambiguous to people who are not familiar with sedimentology. Semantically speaking, a turbidite system sounds like a system that only focusing on the depositional system generated by turbidity current, and the submarine fan system is more likely to define a system of a fan or lobe-shaped deposits. However, is it usual to see other types of gravity flows and their deposits in the system, and the fan-shaped deposits are not the only type of architectural elements in the system. Therefore, the term deep-marine clastic depositional system is more suitable for this study domain.

2.3 The methodology of the OntoClean

Starting from Aristotle, many philosophers have been trying to model the world formally and logically. And OntoClean methodology is based on the conceptual analysis and techniques from previous philosophers to address problems in an information system - to formalize the quality of taxonomic relationships in the ontology modeling. In other words, the OntoClean gives guidance during the ontology modeling when entities need to be characterized by their properties, classes, and subsumptions (Guarino and Welty, 2009).

The clarification of terms is necessary and essential in ontology modeling. Scientists sometimes borrow terms from different fields and use those terms in other fields. Thus, the meaning of the terms will be ambiguous. People who have different knowledge backgrounds will have a different understanding of the same term. The OntoClean first clear the two terms: *property* and *class*. The *property (universal)* is the intentional meaning of the expression that describes a specific maximal state of affairs, it is essential for an entity to be an instance of a particular *class* (Guarino and Welty, 2009). While the *class* is a set of entities that show the corresponding *property* in a particular world and each *property* has a corresponding class, entities that are the members of a class will be called instances (Guarino and Welty, 2009). For example, a clastic sedimentary rock and a chemical sedimentary rock are sharing the same property – "being a sedimentary rock", so there are two instances of a class – sedimentary rock. Based on this example, it is clear for geologists that both of these sedimentary rocks are two classes. The way geologists characterize clastic sedimentary rocks is mainly based on the grain size. Under this classification, if the grain size of the rock sample is medium (1/16 – 2 mm), it is a sandstone; if the grain size is from 1/16 - 1/256 mm, then it is siltstone. Sometimes in the field, due to the lack of high accuracy tools, the boundary between sandstone and siltstone can be a blur. In the view of the OntoClean, both sandstone and siltstone are sharing a common property – "being a clastic sedimentary rock". The main difference between them is the value of grain size, and both sandstone and siltstone can be further subdivided based on the value of the grain size.

The OntoClean also introduces basic notions to characterize properties, which are called *metaproperties.* The essence of a property in its instances is described by *rigidity.* If a property is essential to all possible entities that exhibit it, thus this property is rigid (Guarino and Welty, 2009). For example, the property – "being formed by accumulation or deposition of deposits" is essential to all kinds of sedimentary rock. Thus, this property is rigid. On the contrary, an anti-rigid property is a property that is not essential to all entities that exhibit it. In the case of sedimentary rock, the property - "being overbank deposits" is not essential for all sedimentary rocks that are overbank deposits. A semi-rigid property is essential to some entities that exhibit it and not essential to others. Back to the sedimentary rock case, for example, the property "being fine" (1/16 - 1/256 mm) grain size is essential to siltstone, but not essential to conglomerate or other sedimentary rocks.

It is natural for geologists to recognize a satellite photo of the Nile delta that was taken 20 years ago, and a satellite digital photo of the Nile delta that was taken recently are the satellite photos of the same entity: the Nile delta. This is because of the metaproperty – *identity*, it is a criteria that allow people to recognize two or more entities as being the same or not regardless the time and space. The identity criteria of a property can be *carried* (inherited along a subsumption hierarchy) or can be *supplied* by itself (Guarino and Welty, 2009). In geology, "being a sedimentary rock" supplying the identity criteria, and "being an overbank deposit" carrying identity criteria from "being a sedimentary rock".

A heap of rocks can divide into two heaps of rocks, while one compass can not separate into two compasses, this is peoples' common sense. The metaproperty behind this sense is *unity.* Unity refers to the conditions that able to hold all the parts that form an entire certain entity. Thus, the property – "being a trilobite" holds unity criteria, because all trilobites should have the same unifying relation among different parts of their bodies. However, some properties are not having unity criteria, based on the integrality of their instances, two new unity types: *no unity* and *anti-unity* are introduced (Guarino and Welty, 2009). No unity is referring to those properties whose instances are necessarily to be whole, it is called no unity. For example, the property – "being a geological tool" holds no unity, because different tools have to be whole and have different unifying relations. While anti-unity is the instances of the property are not necessarily to be whole. Therefore, the property for example– "being the amount of natural gas" holds anti-unity, since the amount of natural gas is not necessarily to be whole.

An important aspect among properties is *subsumption*, which is a relation between two properties where, if p subsume q, then all entities of q are also entities of p (Guarino and Welty, 2009). For example, p is a sedimentary rock, and q is sandstone. All entities of sandstone are also entities of sedimentary rock. Sandstone is a sedimentary rock. Sedimentary rock holds anti-unity, and sandstone holds anti-unity. Therefore, we have a sedimentary rock subsume sandstone. Another example is a sedimentary rock (p) and a channel element (q), the relation between them is not subsumption. This is because the sedimentary rock has anti-unity, while the channel element has unity (channel has its own geometry). The relation between sedimentary rocks and channel infills should be channel infills are constituted by sedimentary rocks.

Rigidity	Referring to the essence of a property in its instances: (1) a property is rigid if it is essential to all its possible instances; (2) a property is anti-rigid if it is not essential to all its possible instances; and (3) a property is semi-rigid if it is essential to some instances and not essential for others.
Supplying identity	Supplying the identity that holds for all directly subsuming properties.
Carrying identity	Not supplying identity, while being subsumed by a property.
Unity	To recognize the parts forming an individual or the special continuity of an individual.

Table 1. The summary of metaproperties in OntoClean methodology, concluded from Guarino and Welty (2009)

2.4 The Basic Formal Ontology

There are several top-level ontologies in the present field, such as the Basic Formal Ontology (BFO), the Unified Foundational Ontology (UFO) (Guizzardi, 2005), and the Yet Another More Advanced Top-Level Ontology (YAMATO) (Mizoguchi, 2010). The complete view of the BFO was introduced by Arp et al. (2015), it is designed to help the integration of scientific research data. All entities are divided into two categories: Continuant entities (enduring objects) and Occurrent entities (perduring objects), thus it can deal with both static and dynamic entities in reality. The UFO is first proposed by Guizzardi (2005), the main purpose of it is to offer a groundwork for conceptual modeling (business modeling is included), and detailed in metadata type. While the YAMATO is focusing on characterizing quality, quantity, attribute, and property, which is provided by Mizoguchi (2010).

In this thesis, the ontology-based knowledge model is mainly based on the Basic Formal Ontology. Comparing with other two top-level ontologies, the main benefits of using BFO as top-level ontology is that BFO is designed to be small and for scientific use (Arp et al., 2015). The small size of BFO makes it able to represent the most common and general concepts in different specific domains and provides a starting point for work by those with specialist knowledge. Besides, the BFO offers a concentrated illustration of how to use its abstract concepts during the conceptual modeling of a domain. What's more, the BFO has been accepted as an industrial standard top-level ontology. Thus, the knowledge model based on the BFO should be easy to present in the Geology domain and have fewer obstacles to apply in the industry.

2.4.1 Continuant

The *continuant* entities will be continuously existed in time, have no temporal parts, and preserve their identity through changes (Arp et al., 2015). In geology, for example, a sandstone is a continuant entity, it will exist as a sandstone as long as it exists and not undergo other geological processes (e.g. metamorphism).

Based on the existential dependence, the *continuant* is further divided into: *independent continuant, generically dependent continuant*, and *specifically dependent continuant* (Figure 2.6). The *independent continuants* are supplying an identity principle, this principle defines what keep them being the same in time and space, while *dependent continuants* are not supplying this principle (Guarino and Welty, 2009). For example, the sedimentary rock is an *independent continuant*, this rock cannot stop to be sedimentary rock unless it undergoes other geological processes. Meanwhile, in the case of “the sedimentary rock with the brownish-yellow color”, the entity the brownish-yellow color is an instance of the *dependent continuant* because the color of this sedimentary rock cannot exist without this sedimentary rock. Thus, the sedimentary rock here is a bearer of the color. The separation of the *generically dependent continuant* and the *specifically dependent continuant* is mainly based on their ability of migration among their bearers (Arp et al., 2015). Back to the sedimentary rock as an example, here a sedimentary rock has a yellow color and a hummocky cross-stratification. According to the terminology defined in the BFO, in order to exist, a *specifically dependent continuant* has its existence on some specific independent bearers. The yellow colour of the sedimentary rock has to depend on the specific sedimentary rock (which the color describes) to exist. However, the hummocky cross-stratification is different, this sedimentary structure describes a specific internal structure of sedimentary rocks, and it not only can be identified in different sedimentary rocks but also can be described by drawing on the paper or PC. Based on the BFO definition, a generically dependent continuant is defined as a continuant that is dependent on one or other independent continuants that can serve as its bearer, and it can migrate between bearers. In this case, the yellow color of this sedimentary rock is an instance of the *specifically dependent continuant*, and the hummocky cross-stratification of this sedimentary rock is an instance of the *generically dependent continuant*.

Independent continuants are classified into *material entities* and *immaterial entities*. The former one is constituted by matter in reality while the latter one is not. *Material entities* are differentiated among *objects, object aggregates*, and *fiat object parts*. An *object* is a self-connected and unified material entity with three dimensions of spatial extension (Arp et al., 2015). An *object aggregate* is an aggregate of more than one *objects,* and a *fiat object part* is a part of an *object*. Within the *immaterial entities*, a continuant *fiat boundary* is a one, two or three-dimensional boundary of some *material entity* that exists exactly where that *object* meets its surroundings, a *site* is bounded by *material entities* and *objects* can be contained. A *spatial region* is a part of space (zero, one, two or three dimensions) that *objects* are contained (Arp et al., 2015). For example, a geology hammer is an *object,* a heap of geology hammers in a box is an *object aggregate,* the handle of a geology hammer is a *fiat object part,* the box that contains hammers is a *site,* each hammer occupies a *spatial region,* and each hammer has its own continuant *fiat boundary.*

The BFO separates *specifically dependent continuant* into the *quality* and the *realizable entity*. A *quality* inheres in an entity and fully exhibited or realized in that entity (Arp et al., 2015). Comparing with a *quality*, a *realizable entity* needs a process to be realized. For example, for a geology student who has black hair, people can realize the color of his hair without any process, while in order to realize he is a student, this student should show his registration in an education institute. *Relational quality* is a special type of *quality*, which is a *quality* among more than one *independent continuant* (e.g. a marriage relation). The *realizable entity* is differentiated into *role* and *disposition*. Comparing with the *role*, without a *disposition* the bearer could change physically (e.g. the Uranium-235 has a *disposition* to decay, if it stops to decay, then it is not the U-235 anymore. While a geology student is a *role*, a person can stop to be a geology student at any time he wants). And the *function* is a special kind of *disposition*, which inhere in a bearer in virtue of how it came into being (e.g. the function of the pump is to pump water/liquid).

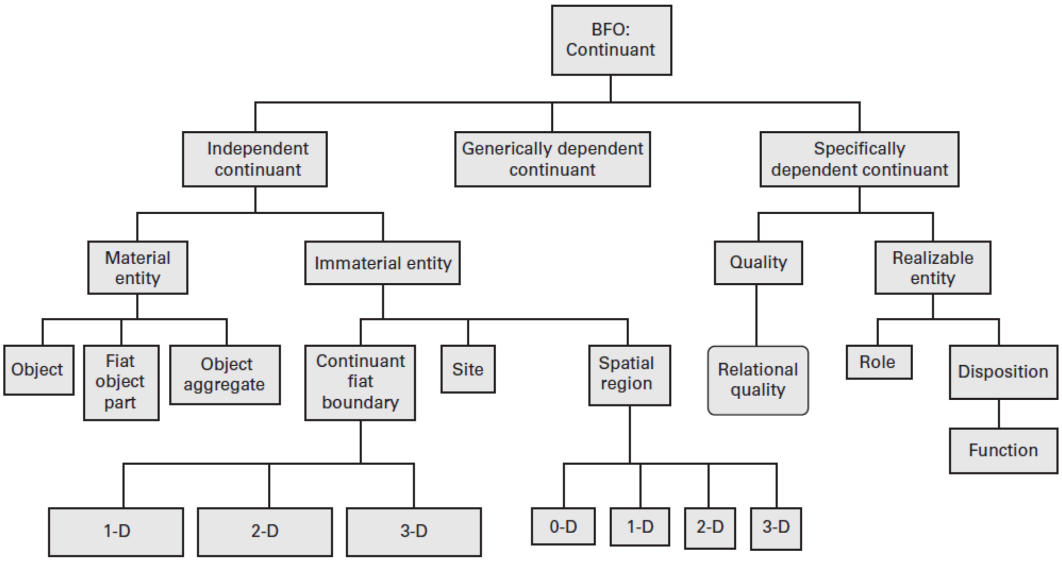


Figure 2.6 The subsumption relationships of BFO continuants (Arp et al., 2015).

2.4.2 Occurrent

The *occurrent* entities have temporal parts, unfold themselves phase by phase, and exist only in a period (Arp et al., 2015). In geology, all the geological events and processes are *occurrents*. The turbidite is the geologic deposit of a turbidity current, which is a *continuant* in the BFO. While a turbidity current is an *occurrent* in the BFO since it starts and ends at specific points of the time.

In the *occurrent* hierarchy (Figure2.7), a *Process* is an entity that exists in time by occurring or happening, it has *temporal parts* and depends on at least one *material entity* (Arp et al., 2015). And a *process* may have other *processes* as parts. For example, the geological event that generated the Helvetiafjellet Formation in Svalbard is a *process*, and every single layer of the Helvetiafjellet Formation is generated by a single *process*. The *history* a subtype of the *process*, it is a unique process that is associated with exactly one material entity. It is the sum of all processes taking place in the spatiotemporal region occupied by the *material entity* (Arp et al., 2015). Therefore, a *history* of the Helvetiafjellet Formation is the sum of all *processes* that occurred from the start of the formation to nowadays.

Each *process* has its own starting and ending point in time, these points are the boundary of the process and separate this process from other ones (Arp et al., 2015). In the BFO, this boundary is called a *process boundary*. For example, a turbidity current is a *process*, the starting point is when the current is generated and the ending point is when the current loses its energy, and all sediments it is carried are all deposited. And these two points of time formed the *process boundary* of the turbidity current. An *occurrent* needs to happen and locate in time and space, and this time and space is called the *spatiotemporal region* in the BFO. The *spatiotemporal* *region* for the Helvetiafjellet Formation is the Svalbard region in the time from ca. 129.4 to 125 Ma (the time period of Barremian), and the Helvetiafjellet Formation is represented this specific *spatiotemporal region*. Comparing with the *spatiotemporal region*, a *temporal region* in the BFO is a part of the time in which an occurrent happens. A *temporal region* can be zero-dimensional or one-dimensional. A zero-dimensional *temporal region* is a point of the time, while the one-dimensional *temporal region* is an interval (Arp et al., 2015). The hierarchy of BFO occurrents is shown in Figure 2.7.

Here are classification examples of *occurrents* in the deep-marine depositional system:

- One gravity flow through the whole deep-marine depositional system (starts from the shelf-edge and end at the basin floor) is a *process*.
- A single sediment gravity flow erodes the slope and forms the channel is a *process*.
- The start and end of the deposition of a depositional system is *process boundary*.
- The start and end of single gravity sediment flow in a whole depositional system is *process boundary*.
- The points in time at which the gravity flows leave from the shelf-edge and stop on the basin floor two *zero-dimensional temporal regions*.
- The time taken by one sediment gravity flow from the start to the end is a *one-dimensional temporal region.*
- Any slice of spacetime during the deposition of the depositional system is a *spatiotemporal region.*

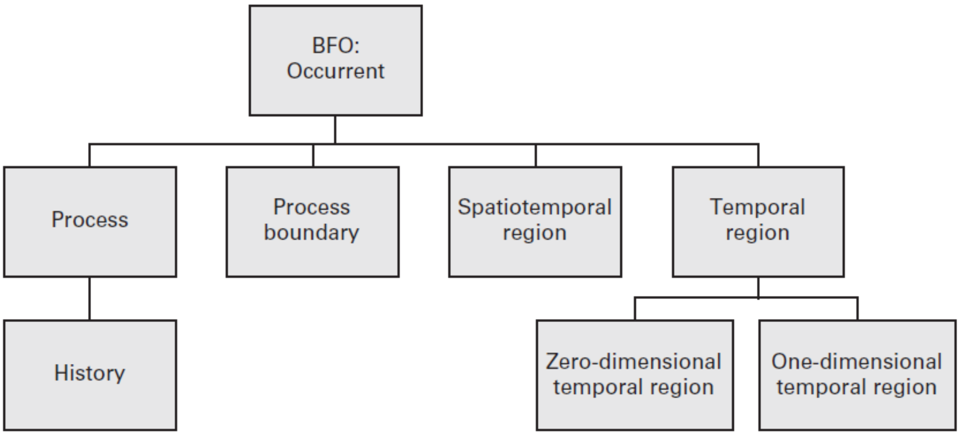


Figure 2.7 The subsumption relationships of BFO occurrents (Arp et al., 2015).

2.5 The GeoCore Ontology

The domain of geology is broad, it has various subjects as its branches, some were developed over a long time and some were only born for a few decades. And the vocabulary in geology is often ambiguous, the meaning behind it usually depends on the background context. Therefore, in order to build a specific domain ontology-based knowledge model, for example, a deep-marine depositional environment model, it required not only a top-level ontology to provide a structured system to classify the concepts in general (for example the BFO), but also a core ontology to offer a more specific and formalized framework to keep the information integration in the same way within different subfield domain. In this thesis, the GeoCore Ontology is used as a core ontology to provide a framework for modeling geology knowledge, while the subfield domain is the deep-marine clastic depositional system in sedimentology. The goal of the GeoCore Ontology (Garcia et al., 2020) is to define a limited set of general concepts within the geology field. By using the foundation of the BFO and concepts of the GeoCore as a backbone, it will be easier for geoscientists to build specialized ontology-based knowledge models and have control of the integration baseline.

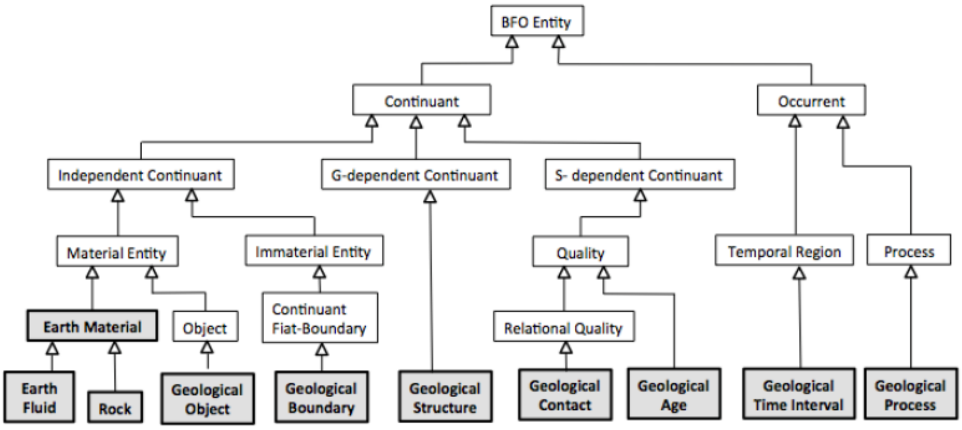


Figure 2.8 The overview of Geocore ontology and relations of subsumption (Garcia et al., 2020)

Based on the entities in the BFO, the GeoCore is focusing on the relations of main geological concepts and their own definitions. The GeoCore illustrated the very general geological terms: *earth material, geological object, geological boundary, geological structure, geological contact, geological age, geological time interval*, and *geological process*, and their subsumption relations, which are illustrated in Figure 2.8 (Garcia et al., 2020). These terms are key concepts in the model, and they provide a guideline for users especially geologists to handle the knowledge model, and provide a baseline for different geology subfields in a common framework. Thus, based on these limited terms and depends on the specialized geological domain, users can expand the vocabulary and categories to fit their specialized domain knowledge models.

In the GeoCore, the term *earth material* is a newly added term which subsumed by the *material entity* in the BFO. An *earth material* is a natural amount of matter that is generated by a *geological process*, which subsumes terms *earth fluid* and *rock* (Garcia et al., 2020). An *earth material* is rigid, supplies its own identity criteria, but has no unity criteria (Garcia et al., 2020). The *earth material* is not subsumed by the *object*, either by *object aggregate*. It is clearly not an *object*, because it has no unity criteria. An *object aggregate* is made up of a collection of *objects* and whose parts are exactly exhausted by the *objects* that form this collection (Arp et al., 2015). Under this definition, a group of sand grains is an *object aggregate*. However, it is clear for geologists that a group of sand grains is different from a sandstone. Therefore, in order to integrate geological knowledge more easily, the term *earth material* is applied here. A *rock* is a solid and consolidated *earth material* made of mineral and solid mineraloid (e.g. a portion of sandstone), and an *earth fluid* is a fluid *earth material*, such as water, oil, and gas (Garcia et al., 2020).

Entities in geology that are formed by at least one *geological process*, comprised of some *earth material*, and supply its own identity criteria, hold rigidity and unity criteria are called the *geological object* in the GeoCore (Garcia et al., 2020). Hence, *geological objects* vary from one single rock to a basin. In this thesis, *geological objects* are all formed under the deep-marine clastic depositional system.

In geology, terms like “surface” or “boundary” are often used as a discontinuity to separate two or more geological bodies. While in the view of the BFO or the GeoCore model, the “boundary” in geology should be separated into two terms: the *geological boundary* and the *geological contact*. The *geological boundary* is a *continuant fiat boundary* in the BFO, it is a physical discontinuity of any nature, located on the external surface of a *geological object* (Garcia et al., 2020).

In a 2D or 3D view of sedimentology, normally will geologists first notice a geobody is by distinguishing the *geological boundary*, then identify the sediment infills. The boundary belongs to its own object, in order to connect two *geological objects*, the term *geological contact* was applied here, which is a *relational quality* that relates two *geological objects* whose *geological boundaries* are adjacent to each other (Garcia et al., 2020). Here is an example: geologists usually use erosion surface as a discontinuity to separate a channel body and the background sediments on an outcrop. And this scenario is illustrated in Figure 2.9A, the yellow color body represents the channel infill and the brown color body represents the background sediments. The view under the ontology-based knowledge model is shown in Figure 2.9B, which is a zoom-in view of Figure 2.9 A. In Figure 2.9 B, two *geological boundaries* belong to their own *geological objects* (channel infills and background deposits), and they are adjacent to each other by the *geological contact* (white color band). This contact is not visually and physically exist, but it is necessary for two objects to connect each other.

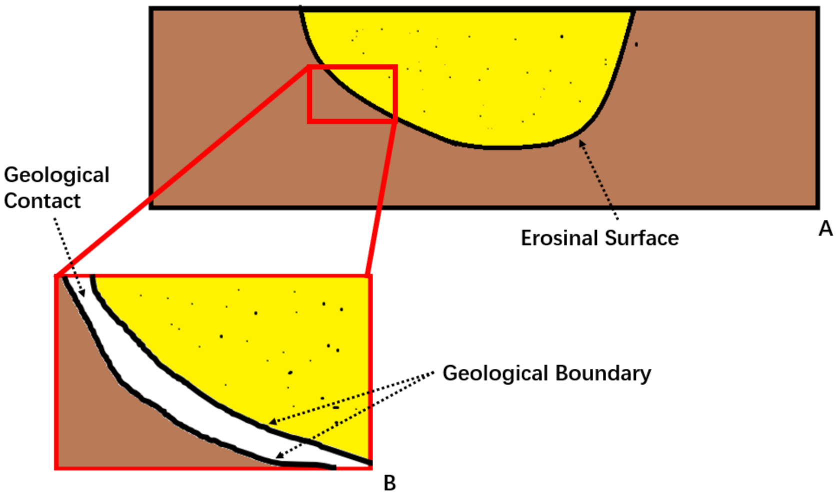


Figure 2.9 Example of Geological Boundary and Geological Contact of a channel cross-section. The zoom view represents the ontological view of the erosional surface. The white void of the geological contact does not exist in reality, it's an illustration.

Geological structures of a rock represent records of what happened to the rock in the past. In GeoCore, a *geological structure* is defined as a *generically dependent continuant* that describes the internal distribution of a *geological object* (Garcia et al., 2020). In other words, it is a record of the configuration and the mutual relationships of its bearers' different parts (Garcia et al., 2020). In sedimentology, structures such as ripple marks, soft-sediment deformation structures, and cross-stratification structures are common to be found in the deep-marine clastic depositional system.

A *rock* is generated by some specific processes, and in the GeoCore these processes which form, shape, and modify the compositions, and their distributions of rocks are called *geological processes* (Garcia et al., 2020). The *geological process* is a *process* in the BFO since it is clear that the *geological process* has a start and end point in time and space. A *geological time interval* is a *temporal region* in the BFO, which can represent a geological period and one or more *geological processes* (Garcia et al., 2020). Instances of the *geological time interval* can be varied into a period of the formation of a sandstone, the formation period of the Helvetiafjellet Formation, the time period of the Cambrian, or the time period of the Cenozoic. An age in geology is to describe the time period from the rock that has been formed to nowadays. The age is different from the *geological time interval* because it is not describing the period of processes. In Geocore the age is called the *geological age* which is subsumed by the *quality*, relevant to some *geological time intervals*, and a *geological object* is the bearer of *geological age*. For example, the Helvetiafjellet Formation formed mainly in Barremian. The value of the *geological age* of it is ca. 129 Ma and the forming time from start to the end of Barremian is an instance of the *geological time interval*.

2.6 The Information Artifact Ontology

The Information Artifact Ontology (IAO) is aiming to represent the *information content entities* (ICEs) and was created by Smith and Ceusters (2015). This ontology is a domain-neutral ontology, which means it needs to embed in a larger ontology framework to be used. In this section, the Information Artifact Ontology is embedded in the top-level ontology: the Basic Formal Ontology which has been introduced in section 2.4. Under the scope of the Basic Formal Ontology, a hammer is an *object*, this is because a hammer is a material continuant that its existence is not depending on others, it cannot cease to be a hammer and its parts are indivisible (one hammer cannot divide into two hammers). And a photograph is also an *object* since it follows the definitions above. However, a photograph is different comparing with other *objects*. Photography not only supplies its own identity but also allows people to recognize other identities from it. For example, a photograph of the geologist Tom who is standing in front of an outcrop. Tom's colleagues can tell this photograph is a photograph, not a book nor a map, because of the identity of the photograph. And they can tell the person is their colleague: the geologist Tom, because the person in the photograph has the identity "being Tom" and they know that Tom has a *role* "being a geologist". The information content is not limited in the photograph, it can be the content in a notebook, light signal from a traffic sign, well-log data, or seismic data. How to model the information contents and the relation between information contents and the entities in the reality is the case that the Information Artifact Ontology is aiming to model. The information content that the Information Artifact Ontology is dealing with is not limited in the photograph, it can also represent entities such as files, documents, emails, and digital images.

The most important term in the Information Artifact Ontology is the *information content entity*, which defined as: a *generically dependent entity* that is dependent on some *material entity*, and it retains a relation of *aboutness* to some entities in the reality (Smith and Ceusters, 2015). The relation *aboutness* was first described by Yablo (2014) refers to the meaning of ' denotation' or ' reference', which is not only the linguistic expression but also includes the relationship of cognitive and intentional directedness related to the capturing of information. The *aboutness* is expressed as *is about* in the Information Artifact Ontology, which is the relation between an *information content entity* and the associated some portions of reality (Smith and Ceusters, 2015). The bearer of the information in IAO is called *information artifact*, in the sense of the BFO, an *artifact* is a *material entity* that created, modified or selected by some agent to realize a certain *function* or *role*, and the *artifact* could be an *object* or *fiat object part* (For example a compass, or the needle of a compass) (Smith and Ceusters, 2015). While an *information artifact* is an *artifact* whose *function* is to bear information (For example, a hard drive, a textbook, a student card, or a digital image format) (Smith and Ceusters, 2015). The term *information quality entity* is the carrier of the information, which is a *quality* that is the concretization of an *information content entity* and allows the *information content entity* to be readable or interpretable (Smith et al., 2013). The relationships among *information artifact*, *information content entity*, and *information quality entity* are embedded into the Basic Formal Ontology and showing in Figure 2.10.

Seismic data can be a good example to be modeled, it plays a vital role in the petroleum exploration and production industry, which provides an indirect method to observe the subsurface area of the Earth. In the IAO sense, for a seismic data, the *information artifact* is the drive that store the seismic data file (e.g. SEG-Y); the *information content entity* is the seismic information content which constituted by seismic reflectors, captured by some receivers that register the variances of seismic waves; the *information quality entity* is the concretization of the seismic information that store in a drive. The seismic information content is about a particular subsurface area of the Earth in reality.

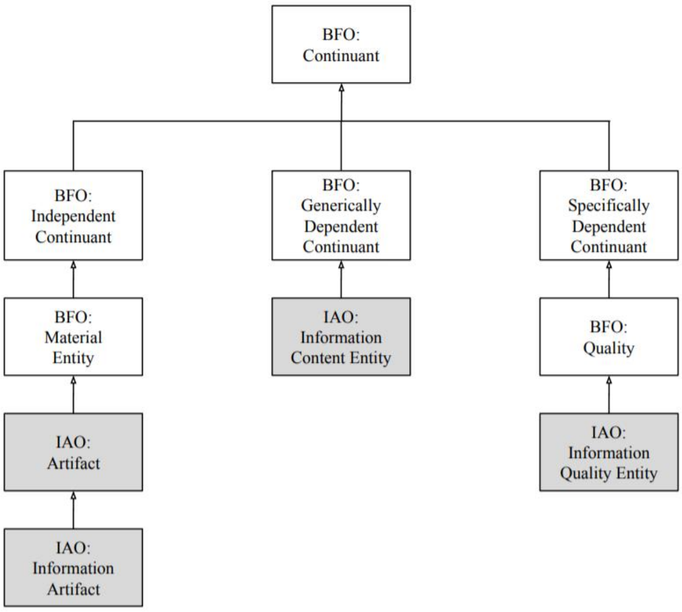


Figure 2.10: The IAO continuants are under the BFO framework (Smith and Ceusters, 2015).

3 Related works

Having the motivation to assist solving the problem of knowledge heterogeneity that related to different geological settings, data collecting approaches, observation scales, terminology, and hierarchical classifications, Cullis et al. (2019) presented a relational database, which could support the comparative analyses of the deep-marine depositional system. The research group was first focused on the hierarchical classification of channels and lobes in the deep-marine clastic depositional system (Cullis et al., 2018), and aims to conclude a hierarchical classification that could reconcile the various existing classification schemes. Authors have studied a large variety of hierarchical classifications that were established by different geologists (Abreu et al., 2003; Gardner and Borer, 2000; Mayall et al., 2006; McHargue et al., 2011; Mutti and Normark, 1987; Pickering et al., 1995; Pickering and Cantalejo, 2015; Sprague et al., 2005; Terlaky et al., 2016), which are designed to assist the identification and description complex and various elements with different orders in the deep-marine depositional system. Through different studies, authors are trying to have comparative analyses and build a comparison of classifications. However, due to the numerous classification criteria, inconsistencies, and geological backgrounds, the variations hinder the research group to conclude a unified hierarchical classification that could adjust current schemes.

Resting on a large amount of research data, the research group moves forward from the hierarchical classification to the relational database that could integrate and store sedimentological data to a common standard from different studies with various approaches and scales. In order to record the data of architectural attributes, facies characteristics, spatial and hierarchical organizations, the relational database classify data into three types of entities: geological unit, spatial relationship, and associated metadata (Cullis et al., 2018). The geological units are entities such as sedimentary packages or geomorphological surfaces; the spatial relation is the spatial transition between geological entities; the associated metadata is the types of the original data. In Cullis et al. (2019), authors are emphasizing element, facies of the geological unit, spatial relationship. An element is a geological unit, which represents specific processes happening in a particular deep-marine sub-environment and characterized by distinct architectural or geomorphology, and every single element contain a facies. While facies is defined as the smallest unit characterized in the database and recognized by changes of lithology, grading style, sedimentary structure, etc. In the spatial relationship, the relations between different elements are called element transitions or channel networks; the relations between facies are stored as facies transitions. Due to the difficulty of a standard hierarchical classification presented by Cullis et al. (2018), the research group focused on hierarchical parent-child relationships between elements with different hierarchical orders.

Through the study of different cases, the relational database could assist researchers in both pure and applied science to have quantitative comparative analyses and characterization of the deep-marine depositional system, which would also support the reservoir prediction and exploration.

A knowledge conceptual model for the information implement is vital, which shall assist the development of the computer system to access and analyze the geoscience data. Having realized the need for geology to be more formalized to apply to information implements, Richard (2006) has developed a conceptual model. This conceptual model is built for the basic description of entities in the geoscience domain to supply a foundation for the development of the computer implement. Based on the conceptual model from the North America Geological-Map Data Model (NADM, 2004), and presented as Unified Modeling Language for a wider application range, this model defined three essential concepts to the geoscience: Earth material, Geologic Unit, and Geologic Structure as the baseline for building the model.

Modifying and evolving from Richard's conceptual model, the Commission for the Management and Application of Geoscience Information (CGI) has provided the GeoSciML model to supply an open-source standard data structure for the digital geoscientific information exchange, which could reduce the obstruction caused by different local formats of geological data from the world (CGI, 2017). When geoscientists sharing different databases, the GeoSciML allows users to transfer their data to the GeoSciML structure and keep their internal database types, which shall largely increase the efficiency of data transferring across borders (CGI, 2017).

4 The ontology-based knowledge model

The ontology-based knowledge model for the deep-marine clastic depositional system is presented in this chapter. This model includes continuants and occurrents that are defined in this domain, with their relationships. The index table of all definitions is available in Appendix. As the modeling suggestions and principles are given by Smith (2006), the ontology-based knowledge model of the deep-marine clastic depositional system shall follow these rules:

1. All new definitions are enumerated, in bold, and with definition number (e.g. Def.1, Def.2).
2. Definitions in the model that are taken from previous works are in italic, and with their origin. The words in a relationship are linked by "-" instead of space.
3. Definitions in this work shall keep simple, and stay close to the terms that have established meanings.
4. Definitions shall follow the principle of intelligibility to reduce errors in human use.
5. All entities in the model are universals instead of instances
6. Definitions are singular nouns.
7. As one step forward for the sedimentology community, this work has open access.

4.1 Clarification of important definitions

Definitions of entities and relations between entities that are taken from theoretical foundations, which will be used in the ontology-based knowledge model are clarified in this section first.

4.1.1 Clarification of terms

In this subsection, all terms from the Basic Formal Ontology (BFO) are defined by Arp et al. (2015), all terms from the GeoCore Ontology (GeoCore) are defined by Garcia et al. (2020), and all terms from Information Artifact Ontology (IAO) are defined by Smith and Ceusters (2015).

- Entity: everything that exists (Arp et al., 2015).
- Relation: the manner in which two or more entities are associated or connected together (Arp et al., 2015).
- Concept: mental abstraction of a portion of the reality (Guarino et al., 2009).
- Universal: A mind-independent, repeatable feature of reality that exists only as instantiated in a respective instance and is also dependent upon an instance for its existence (Arp et al., 2015).
- Instance: an individual denizen of reality (Arp et al., 2015).
- Property: the meaning of the expression that characterizes entities (e.g. being an apple or

being a rock) (Guarino and Welty, 2009).

- Class: a set of entities that exhibit a property in common (Guarino and Welty, 2009).
- Domain: a delineated portion of reality corresponding to a scientific discipline (Arp et al., 2015).
- Continuant (BFO): An entity that continues through time, one of the highest universals in BFO.
- Independent continuant (BFO): A continuant entity that is the bearer of qualities and a participant in processes.
- Specifically dependent continuant (BFO): A continuant entity that depends on precisely one independent continuant for its existence.
- Generically dependent continuant (BFO): A continuant that is dependent on one or other independent continuants and can migrate from one bearer to another through a process of copying.
- Quality (BFO): A specifically dependent continuant that, if it inheres in an entity at all, is fully exhibited, manifested, or realized in that entity.
- Relational Quality (BFO): A quality that inheres in two or more independent continuants.
- Object Aggregate (BFO): A material entity that has as parts (exactly) two or more objects that are separate from each other in the sense that they share no parts in common.
- Fiat Object Part (BFO): A material entity that is a proper part of some larger object, but is not demarcated from the remainder of this object by any physical discontinuities (thus, it is not itself an object).
- Site (BFO): An immaterial entity in which objects such as molecules of air or organisms can be contained.
- Spatial Region (BFO): A continuant entity that is a part of space. When an object moves from one place to another, it occupies a continuous series of different three-dimensional spatial regions at different times.
- Function (BFO): A realizable entity whose realization is an end- or goal-directed activity of its bearer that exists in the bearer in virtue of its having a certain physical makeup as a result of either natural selection (in the case of biological entities) or intentional design (in the case of artifacts).
- Occurrent (BFO): An entity that unfolds itself in time.
- Process (BFO): An occurrent entity that exists in time by occurring or happening, has temporal parts, and always depends on at least one independent continuant as a participant.
- Temporal Region (BFO): An occurrent entity that is a part of the time.
- Rock (GeoCore): Rock is a solid consolidated Earth Material, made of polycrystalline, monocrystalline or amorphous mineral matter or material of biological origin. Rock is

defined at a scale of observation that is such that it can be considered homogeneous even when it is constituted by an aggregate of particles.

- Earth Fluid (GeoCore): An Earth Material that represents a volume of fluid.
- Water: an Earth Fluid that has chemical compound H_2O.
- Geological Object (GeoCore): a rigid entity that provides its own identity criteria and holds the unity criteria. A Geological Object is generated by at least one Geological Process.
- Geological Structure (GeoCore): a Generically Dependent Continuant which describes the internal arrangement of a Geological Object
- Geological Contact (GeoCore): a Relational Quality which relates two Geological Objects having the same dimension (1D, 2D, or 3D), whose external boundaries are adjacent to each other.
- Geological Process (GeoCore): a physical, chemical, or biological process or series of processes that generate, destroy, or modify the shape, the composition, or the arrangement of at least one Geological Object.
- Geological Time Interval (GeoCore): a Temporal Region of finite or zero-dimension within the geological time. A Geological Time Interval may be occupied by one or several Geological Processes.
- Geological Age (GeoCore): the Geological Age is a Quality of Geological Object related to a Geological Time Interval during which some Geological Process operated. The age of a Geological Object is the age of the process that generated this object.
- Mineral: a mineral is a Geological Object, it is a solid chemical compound that occurs naturally (Garcia et al., 2019; Wenk and Bulach, 2004).
- Grain: a Grain is constituted by a small individuated portion of Mineral (Garcia et al., 2019).
- Collection of Grains: a Collection of Grains has Grain as its member (Garcia et al., 2019).
- Information Content Entity (IAO): a Generically Dependent Continuant which is depends-on some Material Entity, and stands in is-about a relation to some Entity.
- Artifact (IAO): a Material Entity created or modified or selected by some agent to realize a certain Function or Role.
- Information Artifact (IAO): an Artifact whose function is to bear an Information Quality Entity.
- Information Quality Entity (IAO): a Quality that is the concretization of some Information Content Entity.

4.1.2 Clarification of relations

The knowledge model is based on the BFO, the GeoCore, and the IAO, and both the GeoCore and IAO are also using the BFO as the top-level ontology. Therefore, most relations that are presented in this subsection are derived from or relevant to the BFO, which was introduced by Arp et al. (2015).

- Is-a: a subsumption relation between two universals, it used to form the backbone taxonomic hierarchy of an ontology. If A is-a B, then all entities of A are also entities of B (Guarino and Welty, 2009).
- Constituted-by: a relation between some material entity and the material that it is made of (Evnine, 2011). Both material entity and the material are occupying the same space.
- Constitutes-: a relation between the material and some material entity that it is made of (inverse of constituted-by) (Evnine, 2011). Both material entity and the material are occupying the same space.
- Has-part: the parthood relation between a whole and its part.
    - Composed-of: a parthood relation between a whole (object) and its part (object), discontinuities are distinct between its parts (Garcia et al., 2020).
    - Has-member: a parthood relation between a collection (object aggregate) and an item (object).
    - Has-temporal-part: a parthood relation between a whole (process) and its part (process).
- Part-of: the parthood relation between a part and its whole (inverse of has-part).
    - Compose-: a parthood relation between a part (object) and its whole (object), discontinuities are distinct between its parts (Garcia et al., 2020).
    - Member-of: a parthood relation between an item (object) and a collection (object aggregate) (inverse of has-member).
    - Temporal-part-of: a parthood relation between a part (process) and its whole (process).
- Bearer-of: a relation between an independent continuant (the bearer) and a specifically dependent continuant, in which the dependent continuant specifically depends on the bearer for its existence.
    - Has-function: a relation between an independent continuant (the bearer) and a function, in which the function specifically dependents on the bearer for its existence.
    - Has-quality: a relation between an independent continuant (the bearer) and a quality, in which the quality specifically dependents on the bearer for its existence.
- Has-relational-quality: a relation between two or more independent continuants (the bearers) and a relational quality.

- Inheres-in: a relation between a specifically dependent continuant and an independent continuant (the bearer), in which the dependent continuant specifically depends on the bearer for its existence (inverse of bear-of).
  - Function-of: a relation between a function and an independent continuant (the bearer), in which the function specifically dependents on the bearer for its existence.
  - Quality-of: a relation between a quality and an independent continuant (the bearer), in which the quality specifically depends on the bearer for its existence.
- Inheres-between: a relation between a relational quality and two or more independent continuants (inverse of has-relational-quality).
- Concretizes-: a relation between a specifically dependent continuant and a generically dependent continuant, in which the generically dependent continuant depends on some independent continuant in virtue of the fact that the specifically dependent continuant also depends on that same independent continuant. Multiple specifically dependent continuants can concretize the same generically dependent continuant.
- Is-concretized-as: a relation between a generically dependent continuant and one or more specifically dependent continuants, in which the generically dependent continuant depends on some independent continuant in virtue of the fact that the specifically dependent continuant also depends on that same independent continuant. A generically dependent continuant may be concretized as multiple specifically dependent continuants (inverse of concretizes).
- Dependent-on: a relation between a generically dependent continuant and an independent continuant, in which the generically dependent continuant depends on one or more independent continuant bearer instances.
- Bounded-by: a relation between a site and its surrounding material entity.
- Bounds-: a relation between the material entity and the site that surrounding by it (inverse of bounded-by).
- Has-participant: a relation between a process and a continuant, in which the continuant is somehow involved in the process.
  - To-generates: a relation between a process and a continuant, in which the process generates the continuant.
- Participates-in: a relation between a continuant and a process, in which the continuant is somehow involved in the process (inverse of has-participant).
  - Generated by: a relation between a continuant and a process, in which the continuant was generated by the process (inverse of generates-).
- Occurs-during: a relation between a process and a 2D temporal region, in which the process takes place exactly in the 2D temporal region.
- Located-in: a relation between two independent continuants, the target (material entity)

and the location (site), in which the target is entirely within the location.

- Adjacent-to: a relation between two independent continuants that these two entities are next to each other.
- Occurs-in: a relation between a process and an independent continuant, in which the process takes place entirely within the independent continuant.
- Is-about: a relation between an Information Artifact Entity and an Independent Continuant in reality (Smith and Ceusters, 2015).

4.2 The knowledge model for the general clastic depositional system

In this section, all defined entities are not limited in the deep-marine clastic depositional system, they should also be able to apply on any kind of clastic depositional system such as aeolian, shallow water, fluvial and deltaic depositional system. It is a knowledge model of continuants and occurrents, which describe the entities that exist and occur in the time. In this model, the property of an entity is considered as the meaning of the expression of an entity, for example, the property of sedimentary rock (entity) is “being a sedimentary rock”.

4.2.1 Continuants of the general clastic depositional system

The taxonomy of continuants is presented in Figure 4.1. Some continuants that are defined in the BFO are not presented in the knowledge model and Figure 4.1, such as Spatial Region, and Role. This does not mean they don’t fit this model. In contrast, some of them are basic concepts that are no need to further define or discuss. For example, each Independent Continuant will occupy a region of space, and this region is the term Spatial Region. This definition is clear and does not need to further discuss.

(Def.1) Sedimentary Object is-a *Geological Object (GeoCore)* which is constituted-by some **Sedimentary Rock (Def.7)** and generated-by some **Sedimentary Process (Def.36)**. It supplies its own identity criteria, it holds unity criteria for all its instances and is rigid, since it is not possible for a Sedimentary Object to stop being a Sedimentary Object.

Note: Instances of the Sedimentary Object are separated by the abrupt change of lithology, rock textures, sedimentary structures or erosional surfaces in the field, and seismic reflection amplitude, continuity, and frequency in the seismic data. Each Sedimentary Object is bounded by its own Geological Boundary and has Geological Contact with other adjacent instances of the Sedimentary Object. Two instances of the Sedimentary Object are the same if they share the same Geological Boundary.

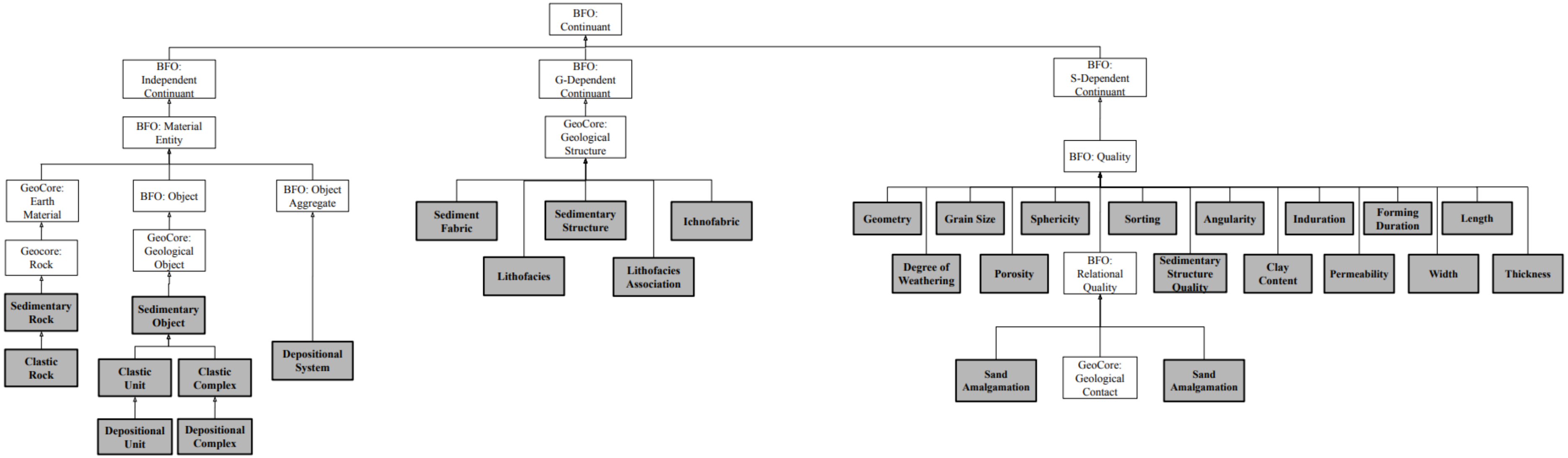


Figure 4.1 Hierarchical taxonomy of the continuants in the general clastic depositional system and their relation

(Def.2) Clastic Unit is-a **Sedimentary Object (Def.1)** which is constituted-by some **Clastic Rock (Def.8)** and generated-by some **Mechanical Process (Def.38)**. The **Clastic Unit (Def.2)** supplies its own identity criteria, it holds unity criteria for all its instances, and is rigid, since it is not possible for a **Clastic Unit (Def.2)** to stop being a **Clastic Unit (Def.2)**. The **Clastic Unit (Def.2)** can be considered homogeneous even, though it is constituted-by some **Clastic Rock (Def.8).**

(Def.3) Clastic Complex is-a *Geological Object (GeoCore)* which is composed-of more than one **Clastic Units (Def 2.)**. It carries identity criteria from **Clastic Units (Def 2.)**, holds unity and rigidity criteria for all its instances.

(Def.4) Depositional Unit is-a **Clastic Unit (Def.2)** which is member-of a **Depositional System (Def.6)**. It carries identity because being a member of a **Depositional System (Def.6)** will not change its identity criteria; it holds unity because the **Clastic Unit (Def.2)** is indivisible; it is anti-rigid because, without the “member-of” relation, a **Depositional Unit (Def.4)** is just a **Clastic Unit (Def.2)** that formed by some **Sedimentary Process (Def.36)**.

(Def.5) Depositional Complex is-a **Clastic Complex (Def.3)** which is composed-of more than one **Depositional Unit (Def.4)**. It carries identity criteria, holds unity, and anti-rigidity.

(Def. 6) Depositional System is-an *Object Aggregate (BFO)* which is a three dimensional aggregate of some **Depositional Unit (Def.4)** and has-member some generically-related **Depositional Unit (Def.4)**. The **Depositional System (Def.6)** supplies its own identity criteria because it is not just a collection of **Depositional Unit (Def.4)**, it also a particular *Spatial Region (BFO)* which is a geographical location and extension. It holds unity criteria and is rigid.

Note: the Depositional system links in a particular geographical region and environmental setting, which means it occupies a three-dimensional spatial region in reality (Galloway, 1998).

(Def.7) Sedimentary Rock is-a *Rock (GeoCore)* which is constituted-by a *Collection of Grains* and is generated-by one or more **Sedimentary Process (Def.36)**. It supplies its own identity criteria, holds anti-unity for being an amount of matter, and is rigid for being unable to cease being a **Sedimentary Rock (Def.7)**.

(Def.8) Clastic Rock is-a **Sedimentary Rock (Def.7)** which is constituted by a *Collection of Grains* form pre-existing *Rock (GeoCore) and* generated-by one or more **Mechanical Process (Def.38)**. It supplies its own identity criteria, holds anti-unity for being a *Collection of Grains*, and is rigid for being unable to cease being a clastic rock.

For geologists, specific types of clastic rocks such as sandstone, siltstone, and mudstone are classified by their grain size. For example, sandstone is a clastic rock constituted by sand-sized grains, and they have a specific range of grain size values. In this ontology-based knowledge model, these differences are caused by the **Clastic Rock (Def.8)** has-qualify **Grain Size (Def.19)** in different values.

(Def. 9) Conglomerate/Breccia is-a **Clastic Rock (Def.8)** which is constituted-by a *Collection of Grains,* and major *Grain* are mainly larger than 2mm in diameter (bear **Grain Size (Def.19)** in positive real number value larger than 2mm). The difference between Conglomerate and Breccia is defined by two *Quality (BFO)*: **Angularity (Def.21)** and **Sphericity (Def.22).**

(Def.10) Sandstone is-a **Clastic Rock (Def.8)** which is constituted-by a *Collection of Grains,* and major *Grain* are mainly between 0.06 and 2mm in diameter (bear **Grain Size (Def.19)** in positive real number value between 0.06 and 2mm).

(Def.12) Siltstone is-a **Mudstone (Def.14)** which is constituted-by a *Collection of Grains,* and major *Grain* are mainly between 0.004 and 0.06mm in diameter (bear **Grain Size (Def.19)** in positive real number value between 0.004 and 2mm).

(Def.13) Claystone is-a **Mudstone (Def.14)** which is constituted-by a *Collection of Grains,* and major *Grain* are mainly less than 0.004mm in diameter (bear **Grain Size (Def.19)** in positive real number value bless than 0.004mm).

(Def.14) Mudstone is-a **Clastic Rock (Def.8)** which is constituted-by a *Collection of Grains,* and major *Grain* are mainly less than 0.06mm in diameter (bear **Grain Size (Def.19)** in positive real number value less than 0.06mm).

(Def.15) Geometry is-a *Quality (BFO)* which is quality-of the *Geological Object (GeoCore)* and describes the external three-dimensional form of the *Geological Object (GeoCore).*

Note: Geometry is not a numerical expression of the geometric shape, but a simplified geometrical description of it.

(Def.16) Length is-a *Quality (BFO)* which is quality-of the *Independent Continuant (BFO)* which measures the maximal longitudinal distance between the two ends of an *Independent Continuant (BFO).*

(Def.17) Width is-a *Quality (BFO)* which is quality-of the *Independent Continuant (BFO)* which measures the maximal transverse distance between the two ends of an *Independent Continuant (BFO).*

(Def.18) Thickness is-a *Quality (BFO)* which is quality-of the *Independent Continuant (BFO)* which measures the maximal vertical distance between the two ends of an *Independent Continuant (BFO).*

(Def.19) Grain Size is-a *Quality (BFO)* which is quality-of the **Clastic Rock (Def.8)** and is given by the diameter of the major *Grain* of the **Clastic Rock (Def.8)**(Gautam Kumar, 2016). It has three corresponding value domains based on the widest accepted grain-size scale chart of Udden (1914) and Wentworth (1922) (Table 2).

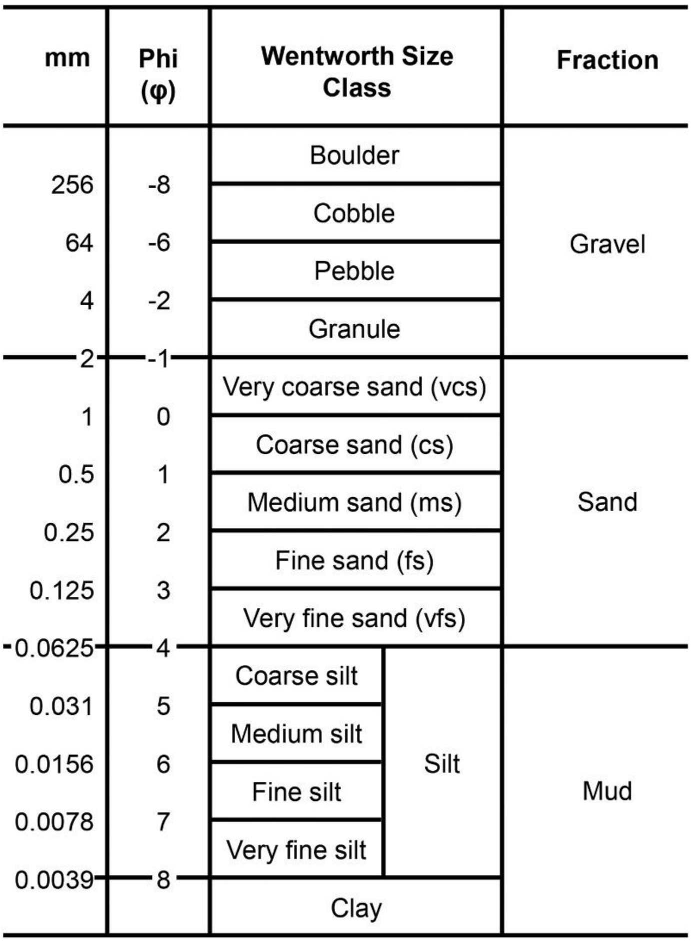
- Domain 1: Positive real number values, measures the diameter of the major particles in millimeter.

  Range: [0.001, 256]
- Domain 2: Real number values, based on the equation used by Wentworth (1922) :

  $\phi = -\log_2 d$ (ϕ relates to grain size and *d is* the measurement in mm for the diameter)

  Range: [-8, 10]
- Domain 3: Nominal values

  Range: {Boulder, Cobble, Pebble, Granule, Very coarse sand, Coarse sand, Medium sand, Fine sand, Very fine sand, Coarse silt, Medium silt, Fine silt, Very fine silt, Clay}



mm	Phi (φ)	Wentworth Size Class		Fraction
		Boulder		Gravel
256	-8	Cobble		
64	-6	Pebble		
4	-2	Granule		
2	-1	Very coarse sand (vcs)		Sand
1	0	Coarse sand (cs)		
0.5	1	Medium sand (ms)		
0.25	2	Fine sand (fs)		
0.125	3	Very fine sand (vfs)		
0.0625	4	Coarse silt	Silt	Mud
0.031	5	Medium silt		
0.0156	6	Fine silt		
0.0078	7	Very fine silt		
0.0039	8	Clay		

Table 2. Terms for different values of grain-size (Mattheus et al., 2020).

(Def.20) Sorting is-a *Quality (BFO)* which is quality-of the **Clastic Rock (Def.8)** and defined as the standard deviation calculated from phi values of the size of the *Collection of Grains* of the **Clastic Rock (Def.8)** (Folk, 1980)**.**

$$Standard\ Deviation = \frac{\Phi_{84} - \Phi_{16}}{4} + \frac{\Phi_{95} - \Phi_5}{6.6}$$ (Folk, 1980)

It has two corresponding value domains (Table 3 and Figure 4.2):

- Domain 1: Positive real number values (ϕ)

  Range: Standard Deviation >=0

- Domain 2: Nominal values

  Range: {Extremely poorly sorted, Very poorly sorted, Poorly sorted, Moderately sorted, Moderately well sorted, Well sorted, Very well sorted}

Standard deviation (nominal value)	ϕ (positive real number value)
Extremely poorly sorted	>4.00
Very poorly sorted	2.00-4.00
Poorly sorted	1.00-2.00
Moderately sorted	0.71-1.00
Moderately well sorted	0.50-0.71
Well sorted	0.35-0.50
Very well sorted	<0.35

Table 3. The nominal values and corresponding positive real number values as defined by Folk (1980).

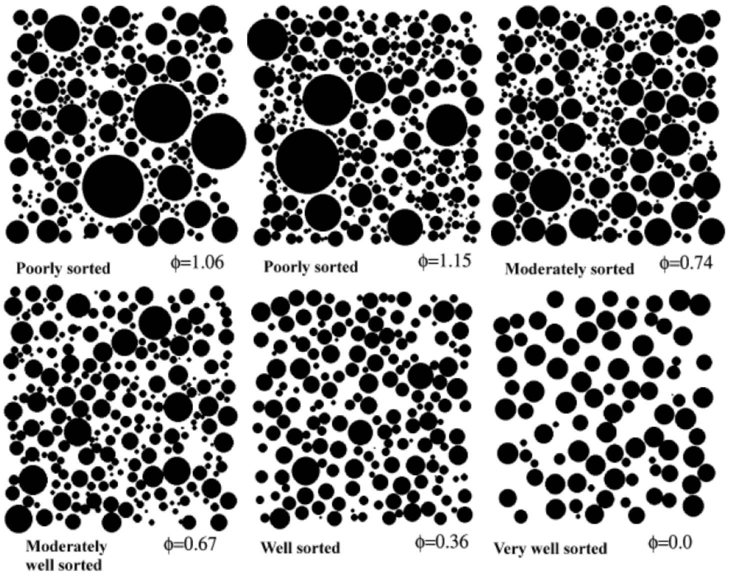


Figure 4.2 Visualization examples of sorting (Jerram, 2001; Meunier, 2019).

(Def. 21) Angularity is-a *Quality (BFO)* which is quality-of the **Clastic Rock (Def.8)** and is given by the shape of the corners of the *Collection of Grains* of the **Clastic Rock (Def.8)** (Tucker, 2011).

Domain: Nominal Values
Range: {Very angular, Angular, Sub-angular, Sub-rounded, Rounded, Well-rounded}
The visual Comparators are presented in Figure 4.3.

(Def.22) Sphericity is-a *Quality (BFO)* which is quality-of the **Clastic Rock (Def.8)** and is given by how closely the shape of the *Collection of Grains* of the **Clastic Rock (Def.8)** resembles that of a perfect sphere (Tucker, 2011).

Domain: Nominal Values
Range: {Low sphericity, High sphericity}
The visual Comparators are presented in Figure 4.3.

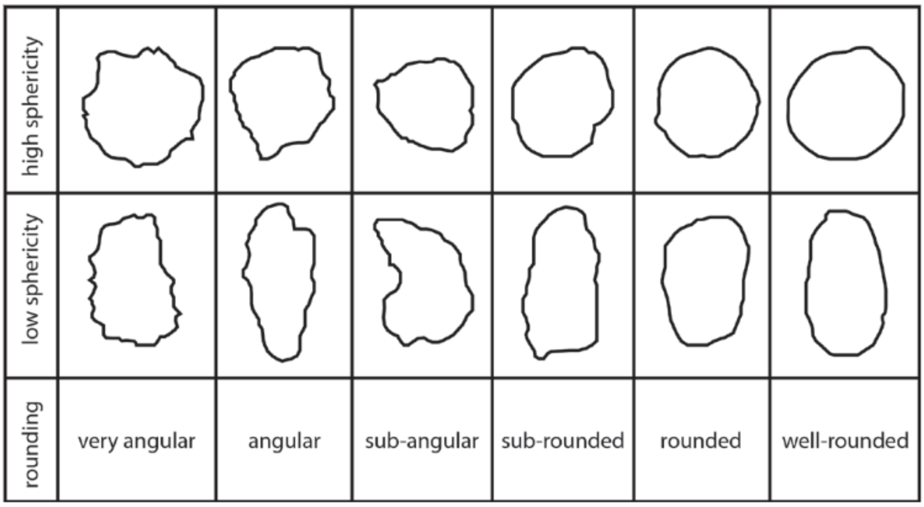


Figure 4.3 The visual comparators of angularity and sphericity (McAvaney et al., 2015)

(Def.23) Induration is-a *Quality (BFO)* which is quality-of the **Sedimentary Rock (Def.7)** and is the hardness of the **Sedimentary Rock (Def.7)**. The domain values of the Induration is given by Tucker (2011), and descriptions are presented in Table 4.

Domain: Nominal Values

Range: {Unconsolidated, Very friable, Friable, Hard, Very hard, Extremely hard}

Values of induration	**Description**
Unconsolidated	Loose, no cement whatsoever
Very friable	Crumbles easily between fingers
Friable	Rubbing with fingers frees numerous grains, gentle blow with hammer disintegrates sample
Hard	Grains can be separated from the sample with a penknife and the sample breaks easily when hit with a hammer
Very hard	Grains are difficult to separate with a penknife, and the sample is difficult to break with a hammer
Extremely hard	The sample requires a sharp and hard hammer to blow, and it breaks across most grains

Table 4. The values of induration and corresponding descriptions (Tucker, 2011).

(Def.24) Degree of weathering is-a *Quality (BFO)* which is quality-of the **Sedimentary Rock (Def.7)** and represents the state of weathering of the **Sedimentary Rock (Def.7)**. The domain values of the Degree of weathering is given by Tucker (2011), and descriptions are listed in Table 5.

Domain: Nominal Values

Range: {Fresh, Slightly Weathered, Moderately weathered, Highly weathered, Completely weathered, Residual soil}

Degree of weathering	**Description**
Fresh	No visible sign of rock weathering; perhaps slight discoloration on major discontinuity surfaces.
Slightly Weathered	Discoloration indicates the weathering of rock material and discontinuity surfaces. All the rock may be discolored by weathering.
Moderately weathered	Less than half of the rock material is decomposed or disintegrated to a soil. Fresh or discolored rock is present either as a continuous framework
Highly weathered	More than half of the rock material is decomposed or disintegrated to a soil. Fresh or discolored rock is present either as a continuous framework
Completely weathered	All rock material is decomposed and/or disintegrated to soil. The original structure is still largely intact.
Residual soil	All rock material is converted to the soil. The rock structure and material fabric are destroyed. There may be a change in volume, but the soil has not been transported

Table 5. Six degrees of the weathering of sedimentary rocks (Tucker, 2011).

(Def.25) Porosity is-a *Quality (BFO)* which is quality-of the *Rock (GeoCore)*. It is the ratio of the void space to the bulk volume and is reported as a decimal. Porosity determines reservoir storage capacity (Cone and Kersey, 1992).

Domain: Decimal values

Range: (0,1)

(Def.26) Permeability is-a *Quality (BFO)* which is quality-of the *Rock (GeoCore)*. It measures the conductivity of the pores to determine the capability of the *Rock(GeoCore)* that how much can fluids flow through the *Rock(GeoCore)*in response to an applied pressure gradient (Ohen and Kersey, 1992).

Domain: Real number values (millidarcy)

Range: >0

(Def.27) Sand Content is-a *Quality (BFO)* which is quality-of the **Clastic Rock (Def.8)** and is the ratio of the *Collection of Grains* that has diameters between 0.0625-2mm to the total volume of the **Clastic Rock (Def.8)**.

Domain: Decimal values

Range: (0,1)

(Def.28) Mud Content is-a *Quality (BFO)* which is quality-of the **Clastic Rock (Def.8)** and is the ratio of the *Collection of Grains* that has diameters smaller than 0.00625mm to the total volume of the **Clastic Rock (Def.8)**.

Domain: Decimal values

Range: (0,1)

(Def.29) Clastic Forming Duration is-a *Quality (BFO)* which is quality-of the **Clastic Unit (Def.2)**. It is the duration of time taken by the **Mechanical Process (Def.38)** to-generate a **Clastic Unit (Def.2)**, and it participates-in a **Clastic Forming Interval (Def.43)**. The measuring unit is million years (Myr).

(Def.30) Sedimentary Structure is-a *Geological Structure (GeoCore)* which dependent-on **Clastic Unit (Def.2)** that is constituted-by **Clastic Rock (Def.8)**. It is the pattern of internal arrangement that is-concretized-as one or more *Specifically Dependent Continuant (BFO)* inhere-in the **Clastic Rock (Def.8),** which constitute- the **Clastic Unit (Def.2)**. It is generated-by one or more **Sedimentary Process (Def.36)**.

Note: It is a fundamental tool for understating the depositional environments.

(Def.30A) Sedimentary Structure Quality is-a *Quality (BFO)* that is the pattern concretizes-a **Sedimentary Structure (Def.30).**

(Def.31) Sediment Fabric is-a *Geological Structure (GeoCore)* which dependent-on **Clastic Unit (Def.2)** that is constituted-by **Clastic Rock (Def.8)**. It describes the mutual arrangements of a *Collection of Grains* in the **Clastic Unit (Def.2)** and is generated-by some **Sedimentary Process (Def.36)**.

(Def.32) Ichnofabric is-a *Geological Structure (GeoCore)* which dependent-on **Clastic Unit (Def.2).** It is generated-by **Bioturbation (Def.37),** which represents the destruction degree of **Sedimentary Structure (Def.30)** or **Sediment Fabric (Def.31)** (Tucker, 2011).

(Def.33) Lithofacies is-a *Generically dependent continuant (BFO)* which dependent-on the **Clastic Unit (Def.2).** A **Lithofacies (Def.33)** is-concretized-as multiple *Quality (BFO)* such as **Grain Size (Def.19)**, **Sorting (Def.20)**, **Angularity (Def.21)**, **Sphericity (Def.22)**, **Sedimentary Structure Quality (Def.30A)** on a **Clastic Unit (Def.2)**.

(Def.33A) Lithofacies Association is-a *Generically dependent continuant (BFO)* which dependent-on the **Clastic Complex (Def.3)**. A **Lithofacies Association (Def.33A)** is composed-of some **Lithofacies (Def.33)**, it is not only concretized-as multiple *Quality(BFO)* on multiple **Clastic Unit (Def.2)** that compose- a **Clastic Complex (Def.3)**, but also concretized-as **Clastic Unit Relation (Def.79)** among these **Clastic Unit (Def.2)**.

Geological Contact (GeoCore) is defined in the GeoCore ontology, in this ontology-based knowledge model, nominal values of the *Geological Contact (GeoCore)* are defined:

Domain: Nominal values

Range: {Erosional Geological Contact, Depositional Geological Contact

- **(Def.34) Erosional Geological Contact**: a nominal value of *Geological Contact (GeoCore)* which represents that within two adjacent *Geological Object* (GeoCore), the later formed *Geological Object* (GeoCore) was generated-by an **Erosional Mechanical Process (Def.39),** or generated-by a **Depositional Mechanical Process (Def.40)** after an **Erosional Mechanical Process (Def.39)** (Campbell, 1967).

- **(Def.35) Depositional Geological Contact**: a nominal value of a *Geological Contact (GeoCore)* which represents that two adjacent *Geological Objects (GeoCore)*, the later formed *Geological Object* (GeoCore) was generated-by a **Depositional Mechanical Process (Def.40).**

(Def.79) Clastic Unit Relation is-a *Relational Quality* (BFO*)* that inheres-between two or more vertical adjacent **Clastic Unit (Def. 2)**. It is a vertical change of the **Sedimentary Structure (Def.30)** and *Quality (BFO)* in this model that inheres in different **Clastic Unit (Def. 2)**.

Note: this quality is useful for geologists to describe the depositional system. In the deep-marine clastic depositional system, for example, the Bouma sequence and Lowe sequence are two frequent used terms. In the ontological view, they are:

- Bouma Sequence is a Clastic Unit Relation inheres between some vertical adjacent Turbidite that generated by the Low-density Turbidity Current. It describes the upward changes of Grain Size from gravel (> 2mm) at the bottom, to the fine grain sand (0.125-0.25mm) to clay (< 0.0039mm) at the top, the Sedimentary Structures change from Normal Graded Bedding and Dish Structure at the bottom to Planar Lamination and Sole Marks, to Ripple Cross-Lamination, and to Planar Lamination in the end at the top (Bouma, 1962).

- Lowe Sequence is a Clastic Unit Relation inheres between some vertical adjacent Turbidite that generated by the High-density Turbidity Current. It describes the upward changes of Grain Size from gravel (> 2mm) at the bottom coarse grain sand (0.5 – 1mm) at the bottom to fine grain sand (0.125 - 00.25mm) at the top. The Sedimentary Structures change from Parallel Stratification and Cross-Stratification at the bottom to Reverse Graded Bedding in the middle, and to Dish Structure at the top (Lowe, 1982).

(Def.80) Sandstone Amalgamation Ratio is-a *Relational Quality* (BFO*)* that inheres-between some adjacent **Clastic Unit (Def. 2)** or **Clastic Complex (Def. 3)**. It represents a phenomenon that some **Sandstone (Def.10)** which constitute- a **Clastic Unit (Def. 2)** are directly in contact with some **Sandstone (Def.10)** which constitute- another **Clastic Unit (Def. 2)** (Zhang et al., 2017b). It has a numerical expression:

Domain: Decimal values, it is given by the fraction of sand-sand contacts relative to all sand-sand, sand-mud and mud-mud contacts in one-dimensional profile (e.g. well logs, outcrop logs), and contact length and area in two and three-dimensional profile respectively (Chapin et al., 1994; Stephen et al., 2001). The ratio calculated from different dimensions can be different.

Range: (0,1)

4.2.2 Occurrents of the general clastic depositional system

The hierarchical taxonomy of occurrents is presented in Figure 4.4. Some occurrents from the BFO are not presented here, such as the Process Boundary and Spatiotemporal Region. These occurrents are not presented in the knowledge model is because they are sufficient and no need to further define. For example, the Process Boundary is the boundary where Process begins and ends, no matter what kind of process occurs, the definition of the Process Boundary wouldn't change.

(Def.36) Sedimentary Process is-a *Geological Process (GeoCore)* that generates- **Sedimentary Rock (Def.7)**. This process involves in the deposition of a *Collection of Grains* from pre-existing *Rock (GeoCore)*, cementation of *mineral* or organic particles, and subsequent lithification (Tucker, 2009).

Note: Based on the different mechanisms of the sedimentary processes, the **Sedimentary Process (Def.36)** can be subdivided into three: **Mechanical Process (Def.38)**, **Biochemical Process (Def.39)**, and **Chemical Process (Def.40)**.

(Def.37) Bioturbation is-a *Geological Process (GeoCore)* which is the disruption of a *Collection of Grains* by the biological activity, and generates- the **Ichnofabric (Def.32)** (Meysman et al., 2006).

(Def.38) Mechanical Process is-a **Sedimentary Process (Def.36)** in which erode, transport, deposit, and compact a *Collection of Grains* from pre-existing *Rock (GeoCore)* mechanically (Schön, 2015). The **Clastic Rock (Def.8)** is generated-by the **Mechanical Process (Def.38).** Note: Each **Mechanical Process (Def.38)** has-temporal-parts: **Erosional Mechanical Process (Def.39)** and **Depositional Mechanical Process (Def.40)**.

(Def.39) Erosional Mechanical Process is temporal-part-of the **Mechanical Process (Def.38),** which is the wearing away a *Collection of Grains* from pre-existing *Rock (GeoCore).*

(Def.40) Depositional Mechanical Process is temporal-part-of the **Mechanical Process (Def.38),** which is dumping a *Collection of Grains* from pre-existing *Rock (GeoCore).*

(Def.41) Biochemical Process is-a **Sedimentary Process (Def.36)** which involves biological precipitation and organic material accumulation during the process (Schön, 2015).

(Def.42) Chemical Process is-a **Sedimentary Process (Def.36)** which involves mineral solution and chemical reprecipitation during this process (Schön, 2015).

(Def.43) Clastic Forming Interval is-a *Geological Time Interval (GeoCore)* of one or more **Mechanical Process (Def.38)** to-generate a **Clastic Unit (Def.2)**.

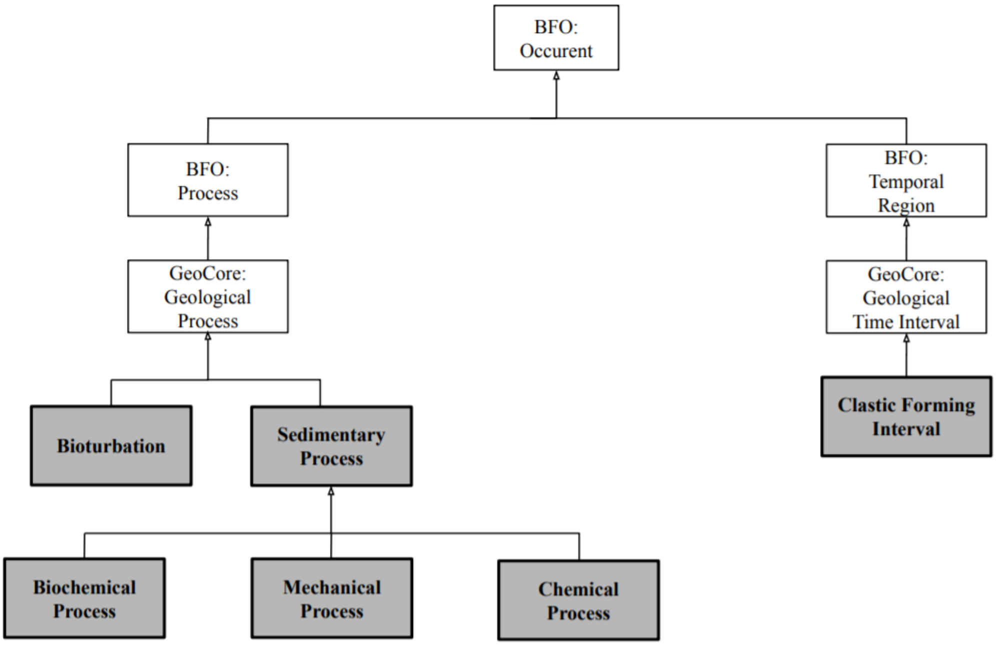


Figure 4.4 Occurrents of the general clastic depositional system and their relationships

4.3 The knowledge model for the deep-marine clastic depositional system

4.3.1 Continuants of the deep-marine clastic depositional system

The hierarchical taxonomy of continuants is illustrated in Figure 4.5. In this subsection, all presented continuants are defined for the deep-marine clastic depositional system.

(Def.44) Deep-marine Depositional Unit is-a **Depositional Unit (Def.4)** that is member-of a **Deep-marine Clastic Depositional System (Def.46)**. It carries identity from **Depositional Unit (Def.4)**, holds unity criteria, and is anti-rigid.

(Def.45) Deep-marine Depositional Complex is-a **Depositional Complex (Def.5)** that is composed-of more than one **Deep-marine Depositional Unit (Def.44)**. It carries identity from **Depositional Unit Complex (Def.5)**, holds unity criteria, and is anti-rigid.

(Def.46) Deep-marine Depositional System is-a **Depositional System (Def.6)** located in the deep-marine environment which is over 200m water depth from the continental shelf-edge down to the basin floor (McHargue et al., 2011; Shanmugam, 2006). It supplies its own identity criteria, holds unity criteria, and is rigid.

(Def.47) Deep-marine Erosional Feature is-a *Site (BFO)* confined-by *Rock (GeoCore)*, it has-function the **Deep-marine Conduit (Def.48)** and is generated-by one or more **Deep-marine Gravity Driven Process (Def.92)** on the continental slope and basin floor. It has an elongated form with negative relief of topography, and one or more **Deep-marine Depositional Complex (Def.45)** are located-in it. The **Deep-marine Erosional Feature (Def.47)** is ended when it has-no-function of the **Deep-marine Conduit (Def.48).** It is rigid and provides its own identity and holds unity.

(Def.48) Deep-marine Conduit is-a *Function (BFO)*, which is being a conduit for the **Deep-marine Gravity Driven Process (Def.92)** and transporting a *Collection of Grains*, which is function-of the **Deep-marine Erosional Features (Def.47)**.

(Def.49) Canyon is-a **Deep-marine Erosional Feature (Def.47)** on the steep gradient continental slope and characterized by a v-shaped transverse profile (Normark et al., 1993). It carries identity criteria from the **Deep-marine Erosional Feature (Def.47)**, holds unity and it is rigid.

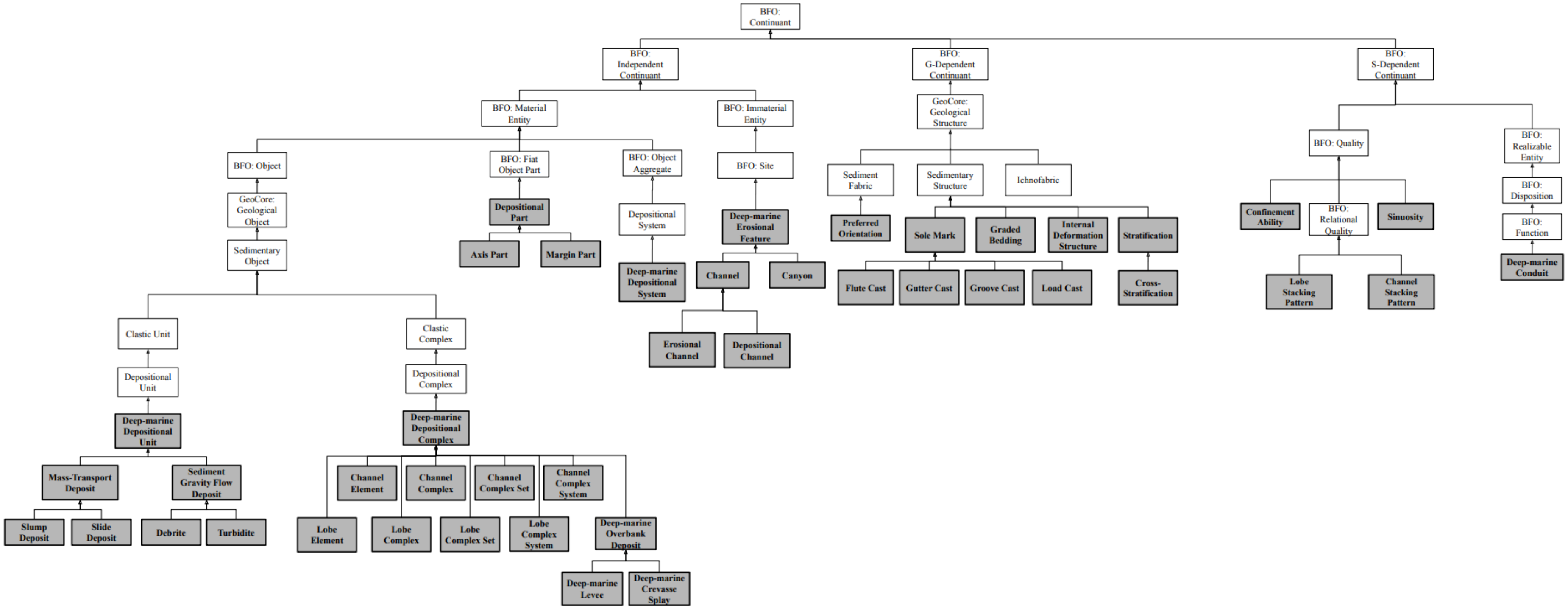


Figure 4.5 Continuants in the knowledge model of the deep-marine depositional system, and their relationships.

(Def.50) Channel is-a **Deep-marine Erosional Feature (Def.47)** on the relatively moderate gradient continental slope or basin floor and characterized by the concave-up shape

In transverse profile. It is generated-by some **Deep-marine Gravity Driven Process (Def.92)**, mostly are **Sediment Gravity Flow(Def.96)** (Arnott, 2010). The Channel carries identity criteria from **Deep-marine Erosional Feature (Def.47)**, holds unity, and is rigid.

Note: **Erosional Channel (Def.51) and Depositional Channel (Def.52)** are part-of the **Channel (Def.50).**

(Def.51) Erosional Channel is part-of the **Channel (Def.50)** and is generated-by some **Sediment Gravity Flow (Def.96)**, which is not bounded-by any **Deep-marine Overbank Deposit (Def.67)**.

Note: the transverse profile is showing in Figure 4.6 A (Arnott, 2010). The plain view of the Channel will display a narrow-straight shape.

(Def.52) Depositional Channel is part-of **Channel (Def.50)** and is generated-by the **Confined Sediment Gravity Flow (Def.96)**, which is bounded-by some **Deep-marine Overbank Deposit (Def.67)**.

Note: the transverse profile is showing in Figure 4.6 B (Arnott, 2010). The plain view of the Channel will display a high-sinuous shape.

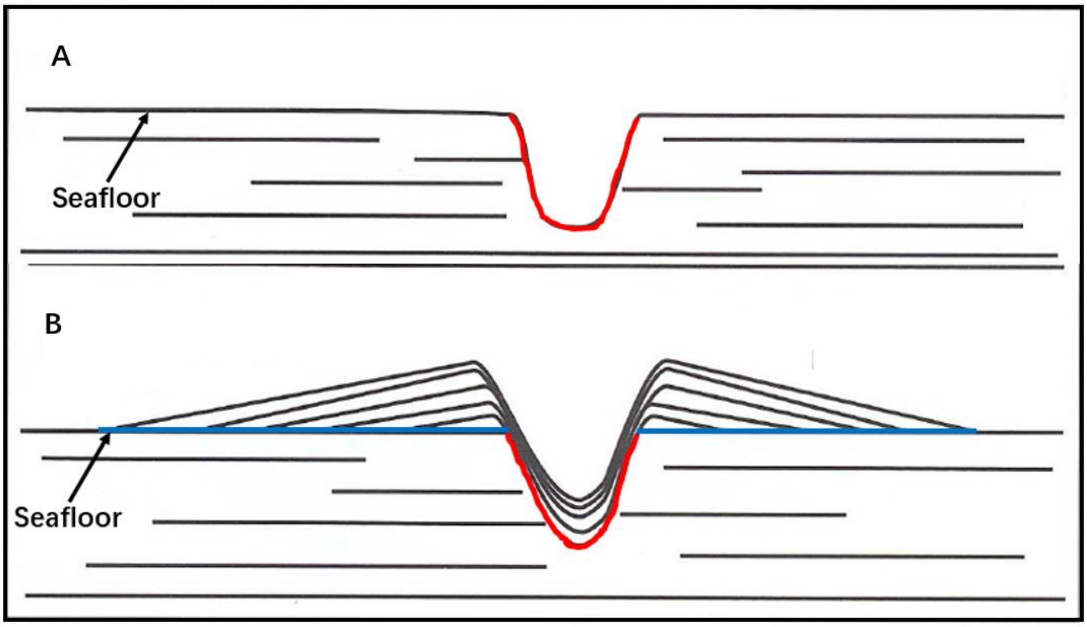


Figure 4.6. The Erosional Channel and Depositional Channel are illustrated in the figure. The red lines in the figure represent the Erosional Geological Contact, and the blue lines in the figure represent the Depositional Geological Contact, modified from Arnott (2010)

(Def.53) Channel Element is-a **Deep-marine Depositional Complex (Def.45)** which is composed-of more than one **Deep-marine Depositional Unit (Def.44)** with steady aggradation that are located-in the **Channel (Def.50)**, and it has-quality **Geometry (Def.15)** in nominal value: **Channel Geometry (Def.70)**. It represents the smallest hierarchical level of a **Deep-marine Depositional Complex (Def.45)** that is generated-by one or more **Deep-Marine Gravity Driven Process (Def.92),** mostly are **Sediment Gravity Flow** in a **Channel (Def.50)** (McHargue et al., 2011). Four hierarchical levels: **Channel Element (Def.53), Channel Complex (Def.54), Channel Complex Set (Def.55), and Channel Complex System (Def.56)** are presented in Figure 4.8.

Figure 4.7 is an example taken from the seismic data in the Polvo field. Figure 4.7 A & B are the Time Slices 1700ms and 1800ms in Sweetness seismic attribute, sweetness seismic attribute is very useful to show the picture pf the depositional system. The Channel in these two figures are illustrated by the black color lines, the separation is based on the shape and difference in seismic amplitude and continuity. Figure 4.7 C is a cross-section of the target Channel in Xline 3043ms and represented by the red color line in Figure 4.7 A&B. While Figure 4.7 D is a cross-section of the target Channel in Inline 1807ms and represented by the yellow color line in Figure 4.7 A&B. The Channel Element that fills in the target Channel is bounded by the blue color line in Figure 4.7 C & D. The identification of the Channel Element is based on the shape, reflection amplitude, continuity, and frequency.

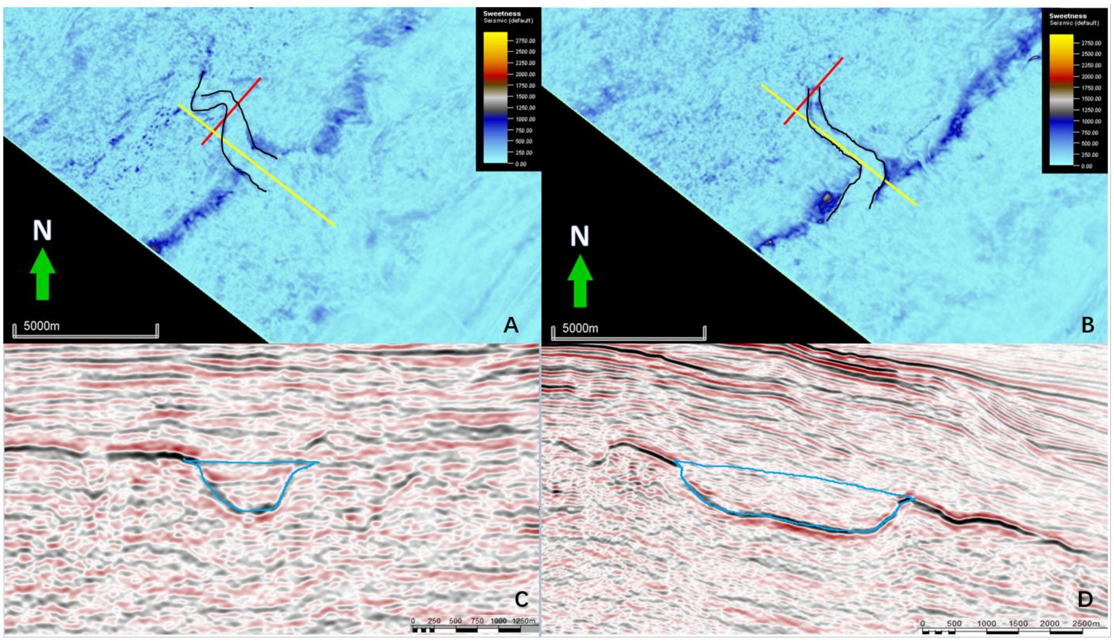


Figure 4.7 A Clastic Unit in deep-marine channel taken from seismic data in the Polvo field. Figure A is the time slice 1700ms and figure B is the time slice 1800ms. The red color line represents the xline slice showing in figure C and the yellow color line represents the inline slice showing in figure D.

(Def.54) Channel Complex is-a **Deep-marine Depositional Complex (Def.45)** which locates- in a **Channel (Def.50)** and is composed-of more than one **Channel Element (Def.53)** that are generated-by some **Deep-Marine Gravity Driven Process (Def.92),** mostly are **Sediment Gravity Flow (Def.96)**.

(Def.55) Channel Complex Set is-a **Deep-marine Depositional Complex (Def.45)** which locates- in a **Channel (Def.50)** and is composed-of more than one **Channel Complex (Def.54)** that are generated-by some **Deep-Marine Gravity Driven Process (Def.92),** mostly are **Sediment Gravity Flow (Def.96)**.

(Def.56) Channel Complex System is-a **Deep-marine Depositional Complex (Def.45)** which locates- in a **Channel (Def.50)** and is composed-of more than one **Channel Complex Set (Def.55)** that are generated-by some **Deep-Marine Gravity Driven Process (Def.92),** mostly are **Sediment Gravity Flow (Def.96)**.

(Def.57) Lobe Element is-a **Deep-marine Depositional Complex (Def.45)** which is composed-of more than one **Deep-marine Depositional Unit (Def.44)** with steady aggradation. It is generated-by one or more **Deep-marine Gravity Driven Process (Def.92),** mostly are **Turbidity Current (Def.98)** when the **Channel (Def.50)** is ended and not has-function **Deep-marine Conduit (Def.48).** It represents the smallest hierarchical level of a **Deep-marine Depositional Complex (Def.45)** that is generated-by one or more **Deep-Marine Gravity Driven Process (Def.92)** when the **Channel (Def.50)** is ended and not has-function **Deep-marine Conduit (Def.48)** (Arnott, 2010; Zhang et al., 2017a)**.** The **Lobe Element (Def.57)** is necessarily has-quality **Geometry (Def.15)** in nominal value: **Lobe Geometry (Def.71).** Four hierarchical levels: **Lobe Element (Def.57), Lobe Complex (Def.58), Lobe Complex Set (Def.59), and Lobe Complex System (Def.60)** are presented in Figure 4.9.

(Def.58) Lobe Complex is-a **Deep-marine Depositional Complex (Def.45)** which is composed-of more than one **Lobe Element (Def.57)** and generated-by some **Deep-Marine Gravity Driven Process (Def.92),** mostly are **Sediment Gravity Flow (Def.96)**.

(Def.59) Lobe Complex Set is-a **Deep-marine Depositional Complex (Def.45)** which is composed-of more than one **Lobe Complex (Def.58)** and generated-by some **Deep-Marine Gravity Driven Process (Def.92),** mostly are **Sediment Gravity Flow (Def.96)**.

(Def.60) Lobe Complex System is-a **Deep-marine Depositional Complex (Def.45)** which is composed-of more than one **Lobe Complex Set (Def.59)** and generated-by some **Deep-Marine Gravity Driven Process (Def.92),** mostly are **Sediment Gravity Flow (Def.96)**.

(Def.61) Sediment Gravity Flow Deposit is-a **Deep-marine Depositional Unit (Def.44)** which does not have any **Deep-marine Clastic Depositional Unit (Def.44)** as its part, and it is generated-by **Sediment Gravity Flow (Def.96)**. The **Channel Element (Def.53)** or **Lobe Element (Def.57)** is mainly composed-of the **Sediment Gravity Flow Deposit (Def.61)**.

(Def.62) Debrite is-a **Sediment Gravity Flow Deposit (Def.61)** which is generated-by **Debris Flow (Def.97)** (Stow, 1984).

(Def.63) Turbidite is-a **Sediment Gravity Flow Deposit (Def.61)** which is generated-by **Turbidity current (Def.98)** (Kuenen, 1957).

(Def.64) Mass-Transport Deposit is-a **Deep-marine Depositional Unit (Def.44)** which is generated-by **Mass-Transport Process (Def.93).**

(Def.65) Slump Deposit is-a **Mass-Transport Deposit (Def.64)** which is generated-by **Slump Process (Def.95)** and bears the **Internal Deformation Structure (Def.88)** (Tucker, 2011).

(Def.66) Slide Deposit is-a **Mass-Transport Deposit (Def.64)** which is generated-by **Slide Process (Def.94)**. The **Clastic Rock (Def.8)** that constitute- **Slide Deposit(Def.66)** has-quality **Grain Size (Def.19), Sorting (Def.20), and Induration (Def.23)** has similar values before and after the **Slide Process (Def.94)** (Posamentier and Martinsen, 2011).

(Def.67) Deep-marine Overbank Deposit is-a **Deep-marine Depositional Complex(Def.45)** which is adjacent-to the **Channel (Def.50)**, and is generated-by **Sediment Gravity Flow (Def.96)** on the basin floor when the **Channel (Def.50)** temporarily or permanently has-quality **Confinement Ability (Def.77)** in the nominal value: low confinement. In other words, **Deep-marine Overbank Deposit (Def.67)** is not located-in the **Channel (Def.50)** (Arnott, 2010).

(Def.68) Deep-marine Levee is-a **Deep-marine Overbank Deposit (Def.67)** which is adjacent-to the **Channel (Def.50)**, and is generated-by **Sediment Gravity Flow (Def.96)** on the basin floor when the **Channel (Def.50)** permanently has-quality **Confinement Ability (Def.77)** in the nominal value: **Low Confinement (Def.77B)**. It has-quality **Geometry (Def.15)** in the nominal value: **Levee Geometry (Def.72).**

(Def.69) Deep-marine Crevasse Splay is-a **Deep-marine Overbank Deposit (Def.67)** which is adjacent-to the **Channel(Def.50)**, and is generated-by **Sediment Gravity Flow (Def.96)** on the basin floor when the **Channel (Def.50)** has-quality **Confinement Ability (Def.77)** temporarily in the nominal value: **Low Confinement (Def.77B)**.

In the ontology-based knowledge model of the deep-marine clastic depositional system, the **Geometry (Def.15)** has values in:

Domain: Nominal value

Range: {Channel Geometry, Lobe Geometry, Levee Geometry, Tabular Geometry}

Four nominal values are described below with the illustration in Figure 4.10 (Haughton, 2013)

- **(Def.70) Channel Geometry**: the Geometry which displays a sinuous and ribbon shape in the bird's-eye view and overall concave-up shape in the transverse view (Zhang et al., 2017a).
- **(Def.71) Lobe Geometry**: the Geometry of which displays a lobate shape in the bird’s eye view and overall convex-up shape in the transverse view.
- **(Def.72) Levee Geometry**: the Geometry which shows a pattern along the channel in the bird’s eye view and displays a wedge-like, wing form shape in the transverse view.
- **(Def.73) Tabular Geometry**: the Geometry which displays a more or less flat layer in the transverse view and no particular shape in the bird’s eye view.

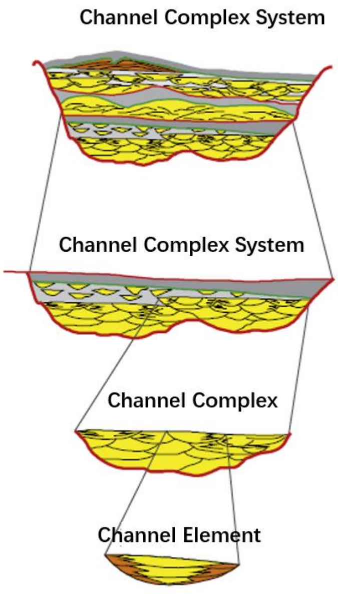


Figure 4.8 The hierarchical levels of Channel Element, Channel Complex, Channel Complex Set, Channel Complex System, modified from Sprague et al. (2005)

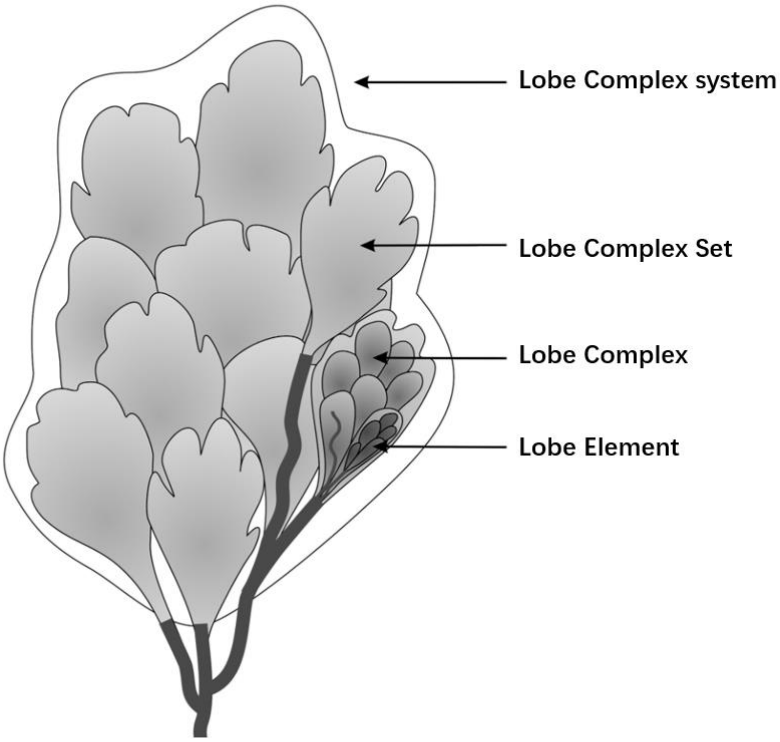


Figure 4.9 The hierarchical levels of Lobe Element, Lobe Complex, Lobe Complex Set, Lobe Complex System, modified from Prelat et al. (2010)

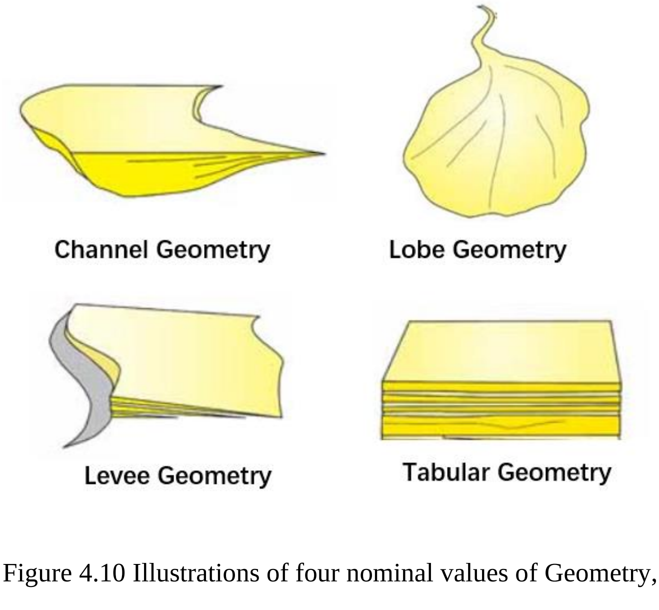


Figure 4.10 Illustrations of four nominal values of Geometry, modified from Haughton (2013).

(Def.74) Depositional Part is-a *Fiat Object Part (BFO)* which is part-of the **Channel Element (Def.53), Channel Complex (Def.54), Channel Complex Set (Def.55), Channel Complex System (Def.56), Lobe Element (Def.57), Lobe Complex (Def.58), Lobe Complex Set(Def.59), or Lobe Complex System (Def.60),** and is not necessary to be distinguished by any physical discontinuities. The **Depositional Part (Def.74)** can be considered homogeneous even. It is rigid because no depositional part can cease being a depositional part. It holds unity criteria and provides its own identity criteria.

(Def.75) Axis Part is-a **Depositional Part (Def.74)** which is the thick part of its whole. For this *Universal,* the **Sand Content (Def.27)** has a higher value than **Mud Content (Def.28)**. It is formed by a high energy stage of the **Deep-marine Gravity Driven Process (Def.92)**, mostly is **Sediment Gravity Flow (Def.96).**

(Def.76) Margin Part is-a **Depositional Part (Def.74)** which is the thin part of its whole. For this *Universal,* the **Sand Content (Def.27)** has a lower value than **Mud Content (Def.28)**. It is formed by a high energy stage of the **Deep-marine Gravity Driven Process (Def.92)**, mostly is **Sediment Gravity Flow (Def.96).**

Note: Based on illustrations in McHargue et al. (2011), Sprague et al. (2005), and Soutter et al. (2019), Figure 4.11 presents the difference between an Axis Part and Margin Part in a Channel Element and a Lobe Element.

(Def.77) Confinement Ability is-a *Quality (BFO)* which is quality-of a **Deep-marine Erosional Feature (Def.47)** which describes the ability of a **Deep-marine Erosional Feature (Def.47)** to limit the **Deep-marine Gravity Driven Process (Def.92)** in it. It has two nominal values:

Domain: Nominal values

Range: { High Confinement, Low Confinement}

- **(Def.77A) High Confinement:** when the **Deep-marine Gravity Driven Process** is completely flowing in the **Deep-marine Erosional Feature (Def.47)**
- **(Def.77B) Low Confinement:** when the **Deep-marine Gravity Driven Process** does not completely flow in the **Deep-marine Erosional Feature (Def.47)**

Illustrations of High Confinement and Low Confinement are displayed in Figure 4.12.

(Def.78) Sinuosity is-a *Quality (BFO)* which is quality-of a **Channel (Def.50)**. It has values in the real number.

Domain: real number values, is represented by the ratio of the channel-axis length divided by straight path length of the channel (Janocko et al., 2013).

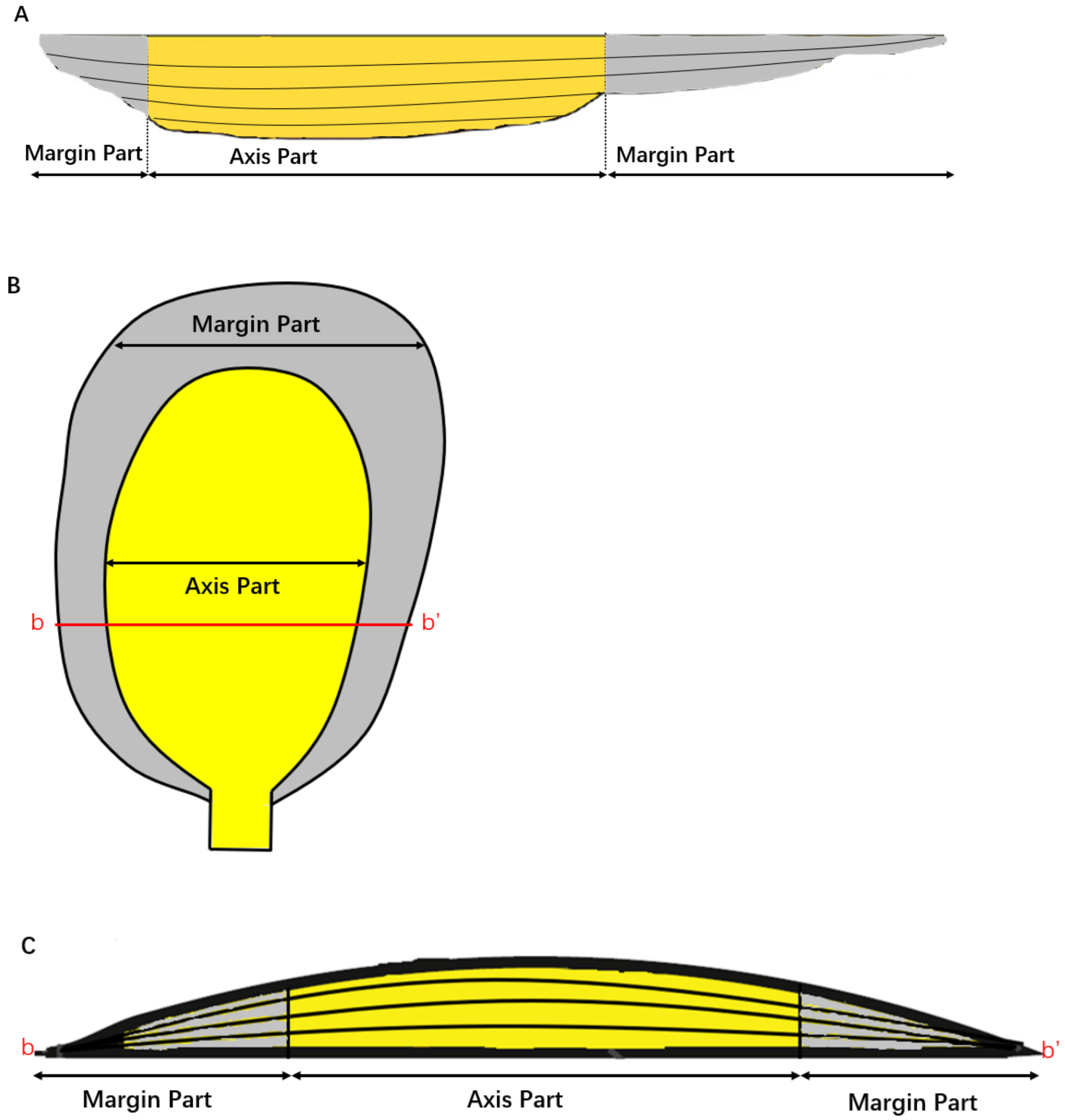


Figure 4.11 Depositional Parts of the Deep-marine Depositional Complex. Figure 4.11 A shows the Axis and Margin Parts of a Channel Element, and Figure 4.11 B shows the Axis and Margin Parts of a Lobe Element, the cross-section bb' of the Lobe Element is shown in Figure 4.11 C. Bird's eye view of the Channel Element is not showing in the figure, this is because deposits in the Channel will not have a lateral spreading pattern. The yellow color represents the Axis Part and the grey color represents the Margin Part.

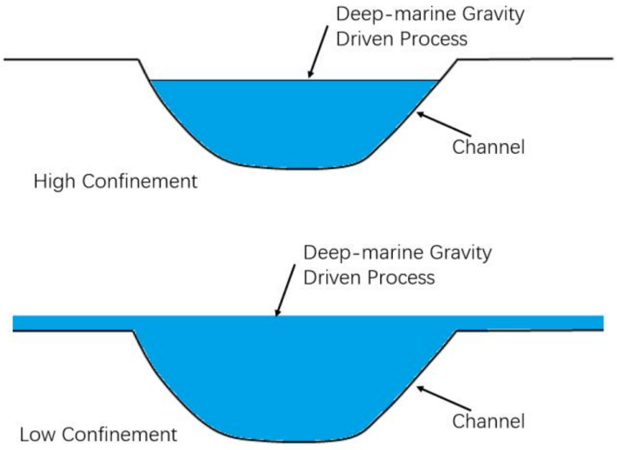


Figure 4.12 Illustrations of High Confinement and Low Confinement

(Def.81) Channel Stacking Pattern is-a *Relational Quality* (BFO*)* that inheres-between some adjacent **Channel Element (Def.53)** within a **Channel Complex (Def.54)**, **Channel Complex (Def.54)** within a **Channel Complex Set (Def.55)**, or **Channel Complex Set (Def.55)** within a **Channel Complex System (Def.56)**. It describes the organization of **Channel Elements (Def.53)** in a **Channel Complex (Def.54)**. It has five nominal values, they are described by Clark and Pickering (1996) and illustrated in Figure 4.13 (Clark and Pickering, 1996).

Domain: Nominal values

Range: {Vertical Stacking, Lateral Stacking, Climbing Stacking, Nested Stacking, Isolated Stacking}

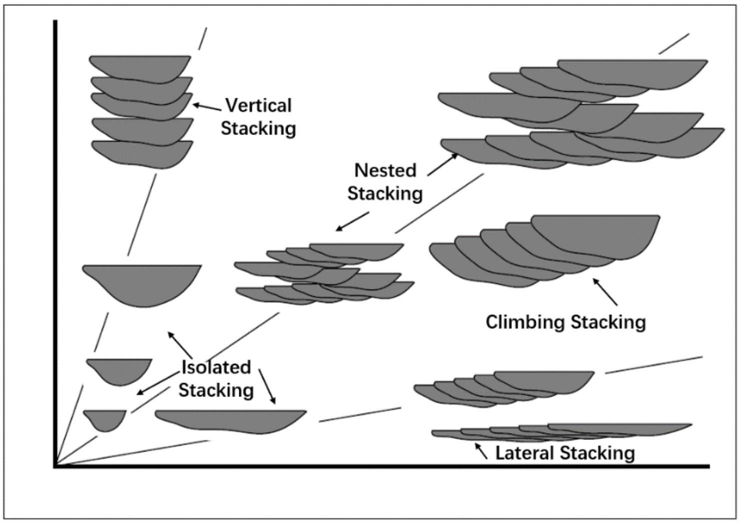


Figure 4.13 Five nominal values of Channel Stacking Patterns are presented here: Vertical Stacking; Lateral Stacking, Climbing Stacking (both lateral stacking and vertical stacking), Nested Stacking (both lateral and vertical directions stacking, the direction of lateral stacking is switching during the stacking), and Isolated Stacking (on obvious stacking direction and pattern are observed) (Clark and Pickering, 1996).

(Def.82) Lobe Stacking Pattern is-a *Relational Quality* (BFO*)* that inheres-between some adjacent **Lobe Elements (Def.57)** within a **Lobe Complex (Def.58)**, **Lobe Complex (Def.58)** within a **Lobe Complex Set (Def.59)**, or **Lobe Complex Set (Def.59)** within a **Lobe Complex System (Def.60)**. It describes the organization of **Lobe Element (Def. 57)** in a **Lobe Complex (Def. 58)**. It has four nominal values, they are described by Zhang et al. (2016) and presented in Figure 4.14 (Zhang et al., 2016):

Domain: Nominal values

Range: {Inordered Stacking, Lateral Stacking, Retrograding Stacking, Prograding Stacking}

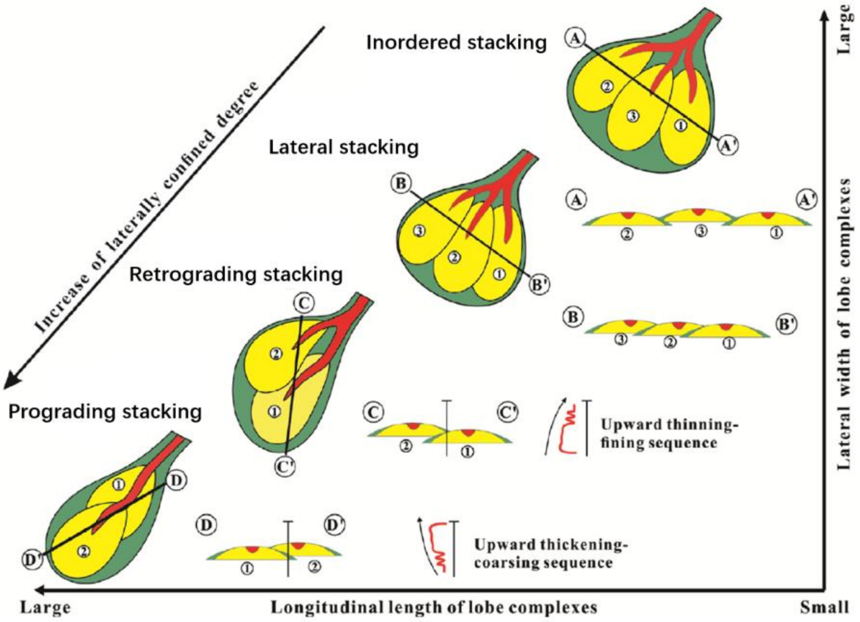


Figure 4.14 Four nominal values of Lobe tacking patterns are presented here: Inordered Stacking, Lateral Stacking, Retrograding Stacking, and Prograding Stacking (Zhang et al., 2016).

(Def.83) Sole Mark is-a **Sedimentary Structure (Def.30)** that only on the sole (undersurface) of a **Clastic Unit (Def.2)**. It is the depression pattern and generated-by a **Mechanical Process (Def.38)** (Tucker, 2011).

(Def.84) Flute Cast is-a **Sole Mark (Def.83)** which is the erosional depression and generated-by a **Turbidity Current (Def.98)** on a *Collection of Grains* with major grain diameter less than 0.06 mm and filled with another *Collection of Grains* later. In plain view, the Flute Cast is elongate to triangular with a rounded or pointed part pointing upstream and flare towards downstream. It is asymmetric in the cross-section view with the shallow part in the downstream direction of the **Turbidity Current (Def.98)** (Tucker, 2011). The size of a Flute Cast varies from few to tens centimeters.

(Def.84A) Gutter Cast is-a **Sole Mark (Def.83)** which is the erosional depression and generated-by a **Turbidity Current (Def.98)** on a *Collection of Grains* with major grain diameter less than 0.06 mm and filled with another *Collection of Grains* later. In plain view, it is a linear to sinuous shape; in the cross-section view, it has U-shape (Allaby, 2013). It is parallel to the flow direction (Allaby, 2013),

(Def.85) Groove Cast is-a **Sole Mark (Def.83)** which has an elongate ridge and tends to show a parallel trend with other **Groove Cast (Def.85)** and is generated-by a **Turbidity Current (Def.98)**. It is the groove formed by cutting and dragging of a small *Geological Object (GeoCore)* on the base and filled with a *Collection of Grains* later during **Turbidity Current (Def.98)**. The size of the **Groove Cast (Def.85)** varies from a few millimeters to tens centimeters (Tucker, 2011).

(Def.86) Load Cast is-a **Sole Mark (Def.83)** which is generated-by the *Geological Process (GeoCore)* through the differential sinking between vertical adjacent **Clastic Unit (Def.2)**. The structure has a bulbous or rounded shape. The *Grain* with a diameter less than 0.06mm can be injected up into the *Collection of Grains* with a diameter between 0.06-2 mm to form a flame-like structure in the cross-section view (Tucker, 2011).

(Def.87) Graded Bedding is-a **Sedimentary Structure (Def.30)** which is-concretized-as **Grain Size (Def.19)** with a systematic change in values from the lower side to the upper side (Tucker, 2011). It subsumes two *Universals*:

- **(Def.87A) Normal Graded Bedding** is-a **Graded Bedding (Def.87)** which has the positive real number value of **Grain Size (Def.19)** decreasing upward.
- **(Def.87B) Reverse Graded Bedding** is-a **Graded Bedding (Def.87)** which has the positive real number value of **Grain Size (Def.19)** is increasing upward.

(Def.88) Internal Deformation Structure is-a **Sedimentary Structure(Def.30)** which is generated-by the **Mass-Transport Process (Def.93)** and shows folding in recumbent folds, asymmetric anticlines, and synclines, or thrust folds(Tucker, 2011).

(Def.89) Stratification is-a **Sedimentary Structure (Def.30)** which is the pattern of a set of distinct physical lines, and is generated-by a **Sediment Gravity Flow (Def.96)**. The set of lines is formed by cyclic changes of a **Sediment Gravity Flow (Def.96)**, the **Stratification (Def.89)** is-concretized-as **Grain Size (Def.19)**, and other *Quality (BFO)* inhere-in the **Clastic Rock (Def.8)**. These cyclic changes are within a single **Clastic Forming Interval (Def.43)**, and the major values of multiple *Quality (BFO)* (for example, the **Grain Size (Def.19)** in nominal value: sand) inhere-in the **Clastic Unit (Def.2)** will not be affected by these changes.

The **Stratification (Def.89)** subsumes *Universal:* **Bedding (Def.89A)** and **Lamination (Def.89B)**, based on different thicknesses.

- **(Def.89A) Bedding** is-a **Stratification (Def.89)** with a thickness between lines is larger than 10mm.

- **(Def.89B) Lamination** is-a **Stratification (Def.89)** with the thickness between lines less than 10mm.

The **Stratification (Def.89)** also subsumes two other sets of *Universal:* **Planar**, **Wavy**, and **Curved** are three **Stratification (Def.89)** based on the shape of lines; **Parallel**, **Non-Parallel**, and **Discontinuous** are three **Stratification (Def.89)** based on the connectivity of lines (Tucker, 2011). In Figure 4.15, Tucker (2011) illustrated 9 combined **Stratification (Def.89)**.

The Discontinuous/Non-parallel Curved Bedding is a worth notable **Stratification (Def.89)**, it is more well-known as "dish structure" by geologists. It is common for geologists to recognize it as a **Sedimentary Structure (Def.30)** that dependent-on **Sediment Gravity Flow Deposit (Def.61)** and is formed during the liquefaction of the lateral and upward current through the soft sediments, in a geological point of view (Crook, 1961; Lowe, 1975; Tucker, 2011; Wentworth, 1967).

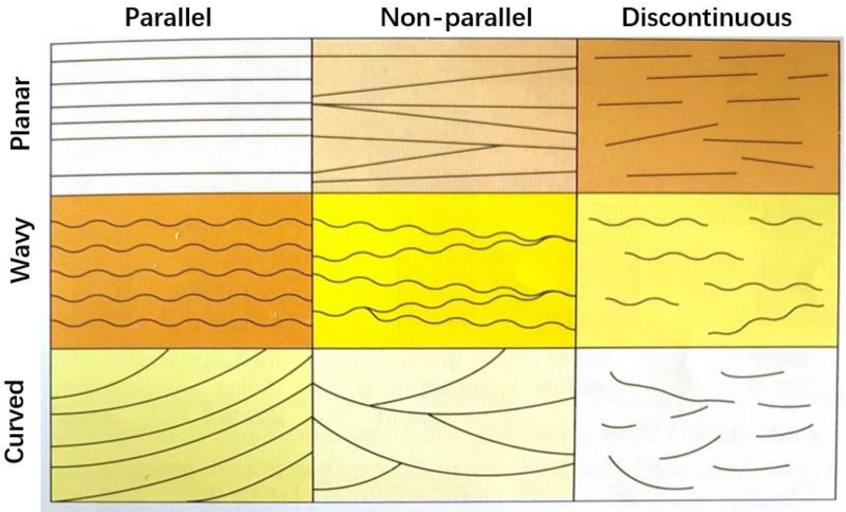


Figure 4.15 Examples of nine combined Stratification (Tucker, 2011).

(Def.90) Cross-Stratification is-a **Stratification** that secondary set of distinct physical lines within the major set of lines with an angle to the *Geological Boundary (BFO)* of the **Clastic Unit (Def.2).**

The **Cross-Stratification (Def.90)** subsumes two *Universals:*

- **(Def.90A) Cross-Bedding** is-a **Cross-Stratification (Def.90)** with a thickness between lines that is larger than 10mm.
- **(Def.90B) Cross-Lamination** is-a **Cross-Stratification (Def.90)** with the thickness between lines less than 10mm.

Based on the shape of lines, another set of **Cross-Stratification (Def.90)** are **Tabular Cross-Stratification, Trough Cross-Stratification,** and **Ripple Cross-Stratification**.

(Def.91) Preferred Orientation is-a **Sediment Fabric** which is normal or parallel to the flow direction of the **Deep-marine Gravity Driven Process** , and is given by the elongate shape of a *Collection of Grains* (Tucker, 2011).

4.3.2 Occurrents of the deep-marine clastic depositional system

The hierarchical taxonomy of continuants is illustrated in Figure 4.16. In this subsection, all presented occurrents are defined for the deep-marine clastic depositional system.

Based on different classification from several researchers, Shanmugam (2006) made use of terminologies in existence to describe a general downslope event in the deep-marine environment as the deep-marine gravity driven process. Besides, he broadly classified the deep-marine gravity driven process into mass-transport process and sediment flow. The main types of mass-transport processes and sediment flow are showing in Figure 4.17. These events are not steady, it is common to have flow transformations as they travel basinward. Flow transformation could the cohesive, plastic-laminar to non-cohesive, turbulent flow, and vice versa. Two flow transformations examples: from Debrite Flow to Turbidite Current; from Turbidite Current to Composite Flow are illustrated in Figure 4.17.

In this subsection, defined occurrents shall stay close to the terminologies and the definitions given by Shanmugam (2006).

(Def.92) Deep-Marine Gravity Driven Process is-a **Mechanical Process (Def.38)** that is under 200m depth of the sea surface, driven by the gravity and has-participant *Water,* **Clastic Rock (Def.8),** and a *Collection of Grains* downslope (Shanmugam, 2006). All *entities* in the deep-marine clastic depositional system are related to this *Process (BFO).*

Note: The most common reason to initiate a **Deep-Marine Gravity Driven Process (Def.92)** is the shelf-edge failures (Shanmugam, 2006). Factors that trigger the shelf-edge sediment failures include but not limited to the following: storm waves, earthquakes, submarine volcanic activity, high sedimentation rate, etc.

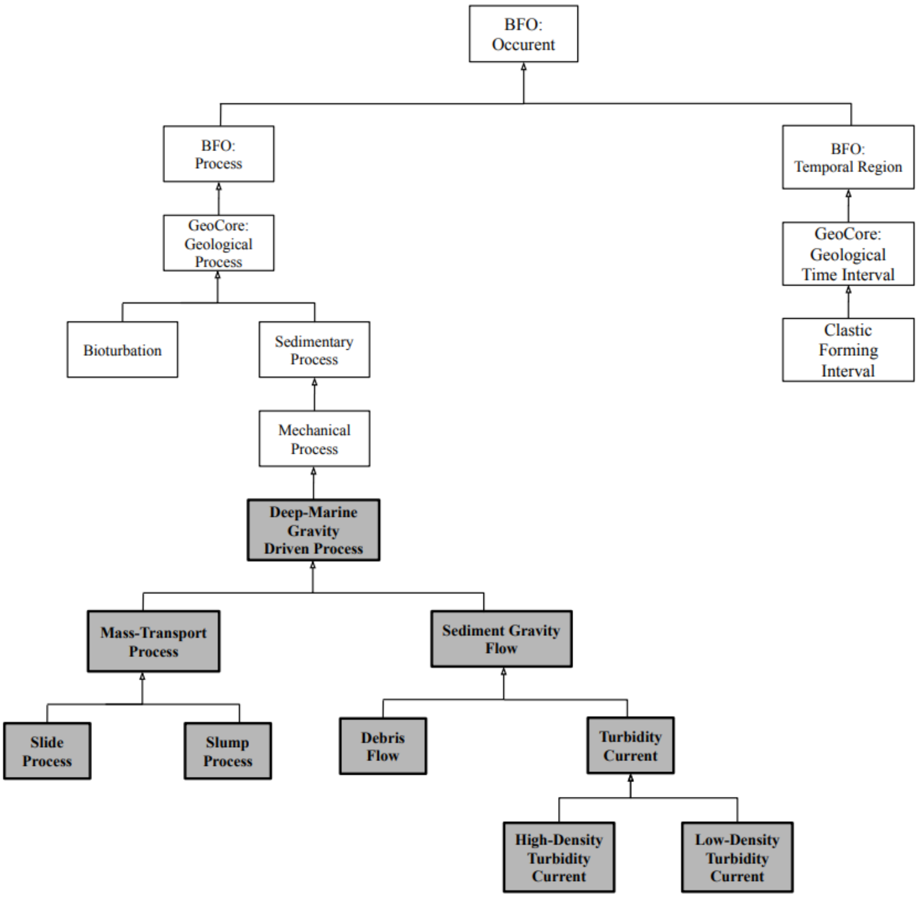


Figure 4.16 Occurrents of the deep-marine depositional system of and their relations.

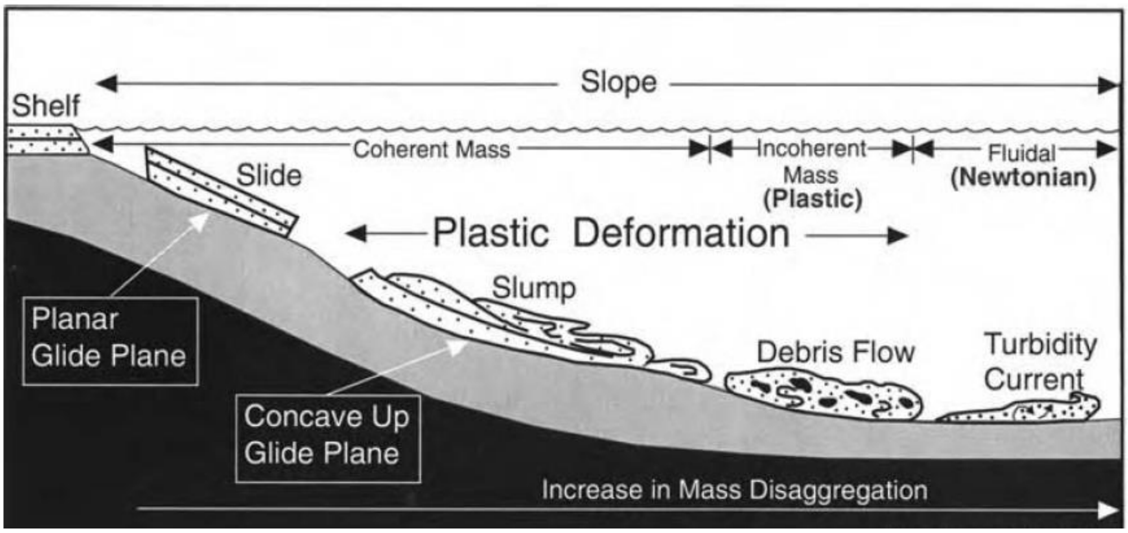


Figure 4.17 Different Deep-Marin Gravity Driven Processes: Slide Process, Slump Process, Debris Flow, and Turbidity Current (Shanmugam et al., 1994).

(Def.93) Mass-Transport Process is-a **Deep-Marine Gravity Driven Process (Def.92)** that generates- **Mass-Transport Deposit (Def.64),** and has-participant the *Water,* and the coherent **Clastic Rock (Def.8)**. It is the *Process (BFO)* of failure, dislodgement, and downslope movement of previously *Rock* (GeoCore) or a *Collection of Grains*.

Note: The term Mass-Transport Process has also been called a mass movement, mass wasting, or landslide by different researchers (Shanmugam, 2006). It is an important process for transporting gravel and sand in the deep-marine environment. The mass-transport process can be subdivided into Slide Process and Slump Process. Terms used by sedimentologists such as flow slide, debris slide, and creep are ambiguous, the main differences between them are relative velocity and mass size. Therefore, these terms are classified into two main types and not considered in this knowledge model. The main classification criteria is according to the existence of internal deformation during the process.

(Def.94) Slide Process is-a **Mass-Transport Process (Def.93)** which generates- the **Slide Deposit (Def.66),** and has-participant the *Water,* and the well-consolidated **Clastic Rock (Def.8)**.

Note: in geology, the slide is a translational moved coherent mass of previously well-consolidated sediments that moves along a planar glide pane and shows no internal deformation, and generate the Slide Deposits (Shanmugam, 2006). The term slide can refer to both a type of mass-transport process and the deposit generated by this process. In order to avoid the ambiguity of the term, in this knowledge model, the process will be named as Slide Process.

(Def.95) Slump Process is-a **Mass-Transport Process (Def.93)** which generates- the **Slump Deposit (Def.65),** and has-participant the *Water,* and the poorly-consolidated **Clastic Rock (Def.8)**.

Note: in geology, the slump is a rotational moved coherent mass of previously poorly-consolidated sediments that moves on a concave up glide plane with internal deformation and generates the Slump Deposit (Shanmugam, 2006). Same as the slide, the term slump can refer to both a type of mass-transport process and the deposit generated by this process. In order to avoid the ambiguity of the term, in this knowledge model, the process will be named as Slump Process.

(Def.96) Sediment Gravity Flow is-a **Deep-Marine Gravity Driven Process (Def.92)** that generates- **Sediment Gravity Flow Deposit (Def.61),** and has-participant the *Water,* and the incoherent **Clastic Rock (Def.8)** or *Collection of Grains.*

Each **Sediment Gravity Flow (Def.96)** has-temporal-parts:

- **(Def.96A) Confined Sediment Gravity Flow**: the temporal-part-of the **Sediment Gravity Flow (Def.96),** when it flows in a **Channel (Def.50)**.

- **(Def.96B) Unconfined Sediment Gravity Flow**: the temporal-part-of the **Sediment Gravity Flow (Def.96),** when the **Channel (Def.50)** is ended and not has-function the **Deep-marine Conduit (Def.48)**, the **Sediment Gravity Flow (Def.96)** flow on the basin floor.

Note: in a geology point of view, the sediment gravity flow is an interstitial fluid is driven by the grains moving downslope under the influence of gravity, carries the sediment load basinward (Shanmugam, 2006). Based on the rheology, state of turbulence, Haughton et al. (2009) defined that the sediment gravity flow can subdivide into the debris flow and turbidity current. This model will follow this classification. An illustration of sediment gravity flow is presented in Figure 4.18.

(Def.97) Debris Flow is-a cohesive, plastic, and laminar **Sediment Gravity Flow (Def.96)** which generates- **Debrite (Def.62),** and has-participant the *Water,* and the incoherent **Clastic Rock (Def.8)** or *Collection of Grains.*

Note: from a geology point of view, the debris flow is a high sediment concentration (25-95%), laminar cohesive flow with plastic rheology, and carries gravel and sand into the deep-marine environment(Haughton et al., 2009). The term mudflow is also classified into the Debris Flow in this knowledge model because comparing with debris flow, the mudflow just carries relative more sand and water than debris flow without a distinct definition, which is ambiguous. This process travels long distances (even 100km is possible) on the basal water layer with only slight erosion, and it freezes when gravity force equal to the shear resistance (Haughton et al., 2009).

(Def.98) Turbidity Current is-a non-cohesive, turbulent, and Newtonian **Sediment Gravity Flow (Def.96)** which generates- **Turbidite (Def.63)**, and has-participant the *Water,* and the incoherent **Clastic Rock (Def.8)** or *Collection of Grains.*

Note: from a geology point of view, the turbidity current is a low sediment concentration(1-23%), non-cohesive flow with the turbulent state to support its sediments, and Newtonian rheology (Haughton et al., 2009; Shanmugam, 2000). The deposition of the process is the frictional freezing.

In the turbidity current, the term high-density turbidity current is used to describe the scenario when the turbulence becomes fully developed and is no longer liquefied, in other words, it is steady, and no sediment is continuously settling out (Lowe, 1979; Middleton, 1967). While the low-density turbidity current is on the contrast.

- **(Def.98A) High-density Turbidity Current** is-a **Turbidity Current (Def.98)**, which is no longer liquefied.
- **(Def.98B) Low-density Turbidity Current** is-a **Turbidity Current (Def.98),** which is still liquefied.

Besides, the Lateral migration is a temporal part of the Turbidity Current:

- **(Def.98C) Lateral migration** is-a *Geological Process (GeoCore),* which is temporal-part-of a **Turbidity Current (Def.98)** when the **Turbidity Current (Def.98)** is gradually cutting the outer bank and abandoning the inner bank of a **Channel (Def.50)**.

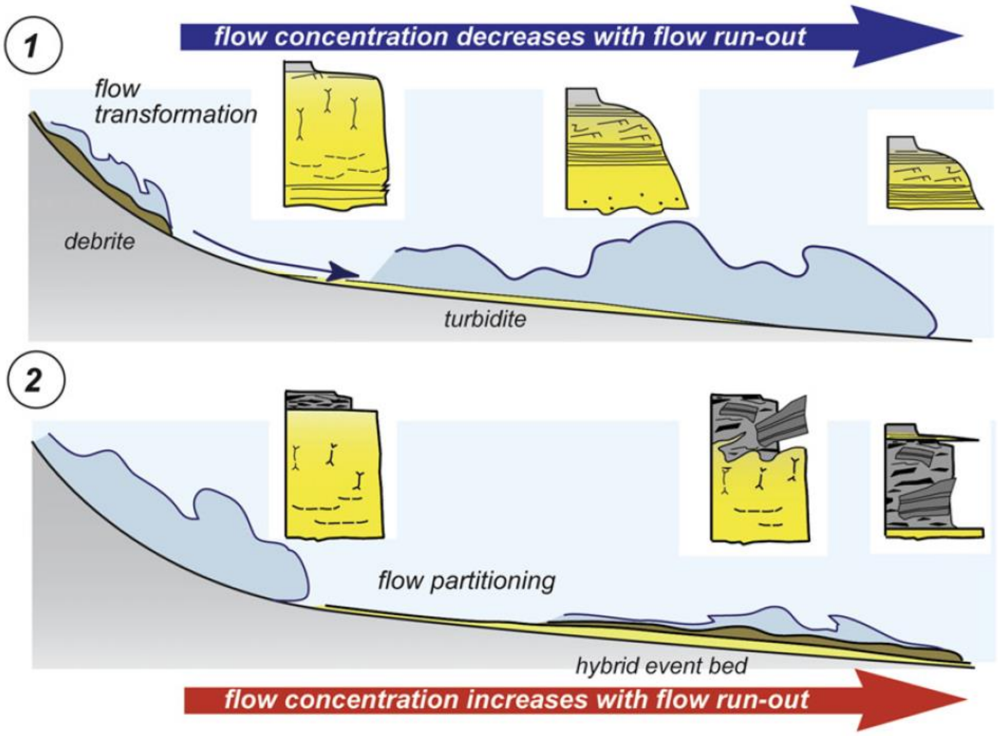


Figure 4.18 1. Flow transformation from cohesive, plastic laminar to non-cohesive, turbulent flow; 2. Flow transformation from poorly cohesive, turbulent flow to increasingly cohesive, laminar flow (Haughton et al., 2009).

4.4 The seismic domain

This section demonstrates "what is the seismic data" under the scope of Information Artifact Ontology, the subsumption relations are displayed in Figure 4.19.

(Def.99) Seismic Data Bearer is-an *Information Artifac*t *(IAO)* that is created to bear the **Seismic Data Content (Def.100)** in the real world. This entity carries identity criteria from *Information Artifact (IAO)*, it holds unity criteria and is rigid.
For example, a hard disk drive, a solid-state drive, or a USB flash drive can be the Seismic Data Bearer to bear the Seismic Data Content.

(Def.100) Seismic Data Content is-an *Information Content Entity (IAO)* which is-about the feature of the Earth's subsurface in reality. It is data of reflected seismic waves of the Earth's subsurface and captured by some receivers that can register the variance of them. It is designed by geophysicists and bore by Seismic Data Bearer in a data format.

(Def.101) Seismic Data Quality is-an *Information Quality Entity (IAO)* which concretizes- the **Seismic Data Content (Def.100)**, allows the **Seismic Data Content (Def.100)** to be stored in reality, and be readable and interpretable by experts.

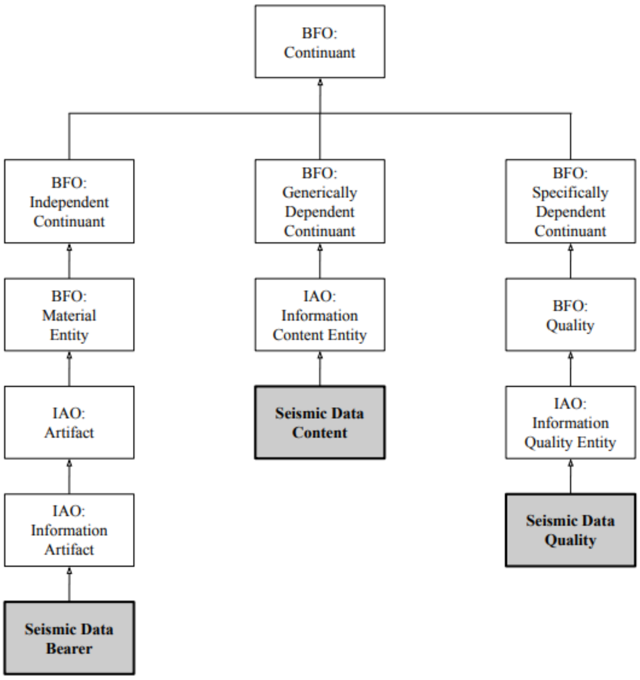


Figure 4.19. The subsumption relationships of the seismic continuant.

5 Model testing

In this chapter, in order to exemplify the proposed knowledge model, the data from the subsurface analysis of the Niger delta basin in offshore West Africa (Zhang et al., 2016; Zhang et al., 2018; Zhang et al., 2015) and outcrop study of the Ainsa-Jaca basin in Spain (Bell et al., 2018) have been applied to test the model. All definitions from the knowledge model in the following chapters begin with a capital letter (e.g. Clastic Rock, Channel Element).

5.1 The Niger delta basin, Gulf of Guinea, offshore of West Africa

In this subsection, the target deep-marine depositional system – the Niger delta basin – is divided into two parts: the channel study and the lobe study. The channel study was conducted by Zhang et al. (2015) with abundant cores, well-logging, and seismic data, the goal was to explore the factors that control the reservoir quality in a sinuous deep-water channel system. While the study of the lobe was published by Zhang et al. (2016) with rich seismic data, well-logging, and cores, authors presented an architecture model for the lob system and built a foundation for the future exploration and research. The study of (Zhang et al., 2018) is mainly focused on the duration and interval of channels within the Niger delta basin.

The target study area of Zhang et al. (2015) is around 20km away from the Port Harcourt, covering region approximately 1500 km^2, and is located in the southern part of the Niger Delta Basin, where the water depth is around 1300-1700m (Figure 5.1 B). The study interval is mainly the interval of Agbada formation during the middle of Miocene, which contains both channel and lobe deposition (Navarre et al., 2002) (Figure 5.1 A). The paleo topography of the study interval was changing from a basin floor setting to a more slope setting, as a result of the regression (Figure 5.1 A).

5.1.1 Geological setting

The Niger delta basin is located in the southern Nigeria margin of the Gulf of Guinea on the West African margin which is situated at the costal and oceanward region of the Benue Trough. The formation of the Benue Trough started during the late Jurassic to early Cretaceous when the supercontinent Gondwana started the separation between South America and Africa with the opening of the Atlantic Ocean (Burke, 1972; Reijers et al., 1997; Samuel et al., 2009; Zhang et al., 2018). With the opening of the Atlantic Ocean, from the Late Cretaceous, the marine environment was started to dominate in the Benue Trough. As a result of the ocean incursion, the clastic sediments were constantly brought from the onshore into the offshore by the Niger River and formed the Niger delta basin (Corredor et al., 2005; Doust and Omatsola, 1990).

From a structural perspective, the Niger delta basin developed large-scale fault-related folds and a piggyback basin with an overpressured mudstone detachment surface (Corredor et al., 2005). Because of the gravitational detachment of the continental margin, the basin mainly contains three main zones: extensional zone (tensional-fault belts, beneath the outer continental shelf and upper slope), translational zone (thrust-fault belts, beneath the continental slope) and crushed zone (outer thrust-fault belts, beneath the lower continental slope) (Corredor et al., 2005; Damuth, 1994). Starting from the Eocene, the sedimentary environment of the Niger delta basin had gradually switched from a deep-marine basin floor fan environment to a deep-marine slope fan environment, due to the large scale regression (Avbovbo, 1978; Short and Stäuble, 1967). The target deep-marine depositional system is on the lower continental slope of the basin floor, which is situated in the southern part of the transitional zone. This deep-marine depositional system has three main formations, from oldest to youngest, they are Akata, Agbada, and Benin formations (Figure 5.1 A). The Akata formation is a thick (more than 6km thick) source rock formation, which is constituted by marine mudstone and contains abundant organic matter (Corredor et al., 2005). The Agbada Formation is around 3 to 4.5 km thick and rich in fluvial and marine sands and with minor shales in the top part, which is the ideal deep-water hydrocarbon reservoir (Short and Stäuble, 1967). As the youngest formation in the basin, the Benin Formation is dominated by fluvial deposits such as sands and gravels, and marked as its base by an unconformity (Corredor et al., 2005; Reijers et al., 1997).

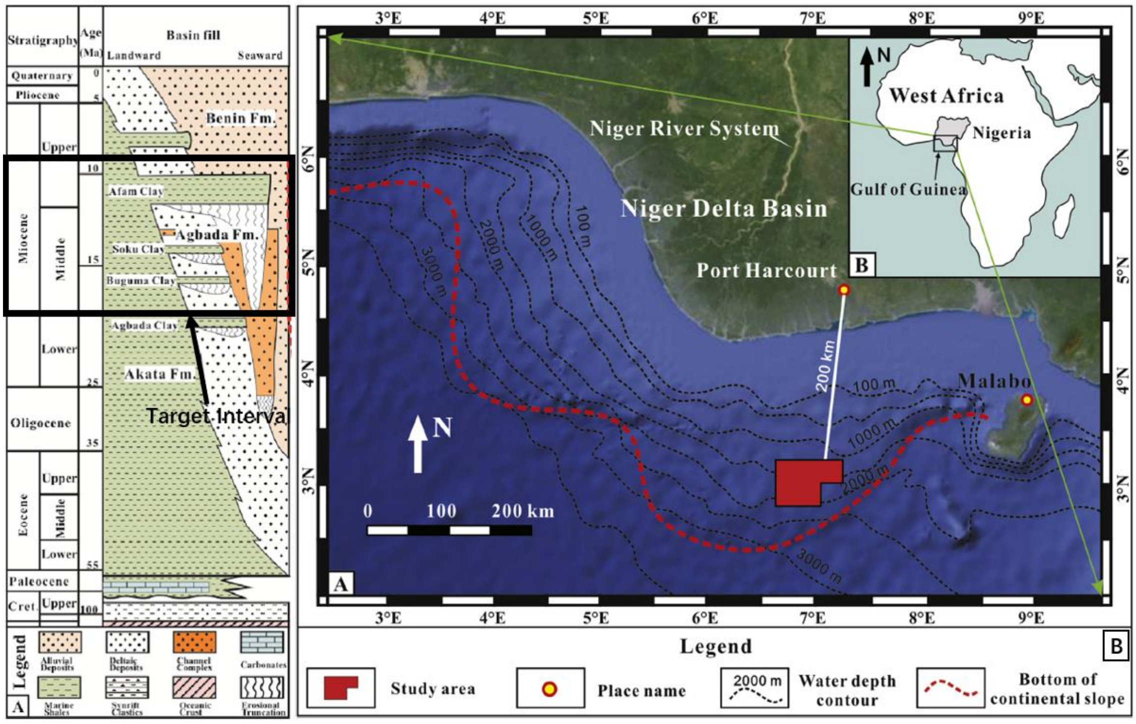


Figure 5.1 A: the lithostratigraphy of the target interval in the Niger delta basin. B: The geographic map of the study area, which is in the south deep-water zone of Niger Delta Basin, Gulf of Guinea, West Africa. It is around 200km south from the Port Harcourt, and the total area is about 1200km2. The red dash line represents the bottom of the continental slope (Zhang et al., 2016).

5.1.2 The channel study

In the study of Zhang et al. (2015), two high sinuous channel systems are in the target region, namely the western channel system and the eastern channel system, two channel branches are found in the western channel system called the west branch and the east branch. The map view of the western- and eastern channel systems is illustrated in Figure 5.2 A. The cross-line A-A' in Figure 5.2A is the seismic cross-section profile of both two channel systems and illustrated in Figure 5.2B. In this cross-section, through the difference of two-way travel time between two channel systems, the western channel system is deeper than the east channel system. the west channel system formed earlier than the east channel system. Figure 5.2C is the seismic cross-section of the cross-line B-B' in Figure 5.2 A, which is crossing the east branch of the western channel system and the eastern channel system. In this profile, the east branch of the western channel system is partly eroded by the eastern channel system, and the eastern channel system is identified into five channel complexes (A1-A5) by Zhang et al. (2015). Figure 5.2 D is the cartoon illustration of the seismic interpretation of the eastern channel system in Figure 5.2 C.

In this study, the authors use the term channel system to refer to two different hierarchy orders of channels. The term channel system is first used in the title of this paper: *Reservoir quality variations within a sinuous deep water channel system in the Niger Delta Basin, offshore West Africa.* It is obvious that the channel system here refers to a collection of all deep-marine channels within the study area. However, the term channel system has also been used by authors to describe two main channels in the area: the western channel system and the eastern channel system. As a geologist, it is clear that these two channel systems are two members of the deep-water channel system mentioned in the title. Thus, a mixing use of the term channel system caused a vague of the hierarchy in the deep-marine depositional system. By applying the knowledge model of the deep-marine clastic depositional system here, such an ambiguous issue can be avoided. In the knowledge model, the whole depositional system in the study area is a Deep-Marine Depositional System, and all channels in the study area are Deep-Marine Depositional Complexes. The deep-water channel system in the title is an instance of the Channel Complex System (Figure 5.3 A), which is composed of the eastern- and the western channel system these two instances of the Channel Complex Set (Figure 5.3 B&C). Thus, a hierarchical relationship is well established with no ambiguity of the hierarchy.

According to the seismic interpretation in Figure 5.2 C&D, the eastern channel system is classified into A1-A5 five different channel complexes, and each channel complex has several individual channels as its parts, which are the smallest scale of the channel in the study. From the perspective of the knowledge model, A1-A5 are instances of the Channel Complex (Figure 5.3 D) and each individual channel is an instance of the Channel Element (Figure 5.3 D). As the lowest hierarchical order, a Channel Element is representing the smallest channel-like unit in the data that is generated by a Sediment Gravity Flow. The outer levees illustrated in Figure 5.2 D acts as the most top part of the eastern channel system. In the sense of the domain ontology, the outer levees are Levee, which is a Deep-marine Depositional Complex.

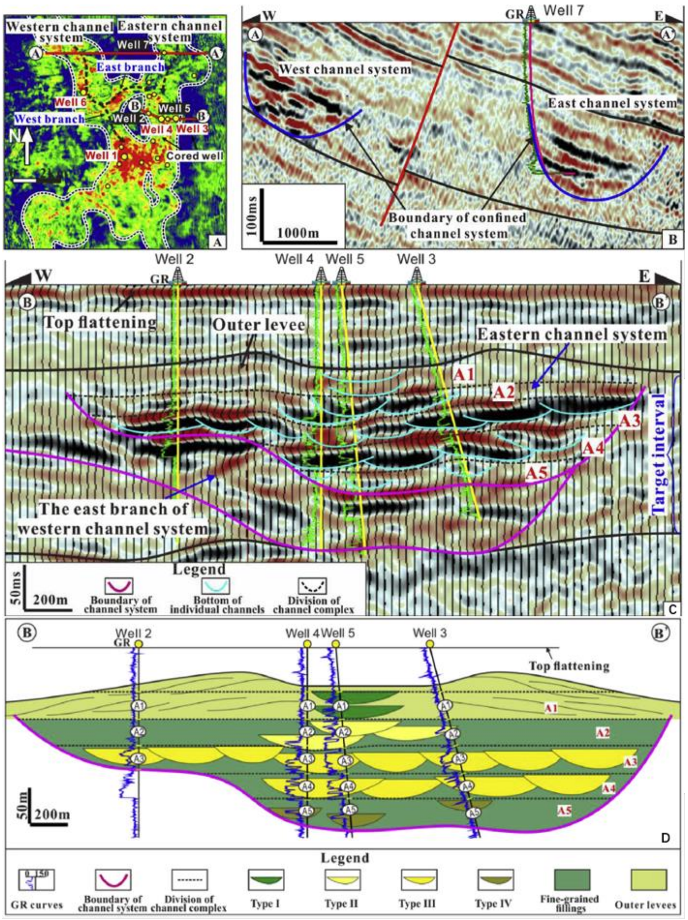


Figure 5.2 A: the seismic time slice view of the study area with the root mean square attribute. Two channel systems: western and eastern channel systems are showing in the map, and the western channel system is subdivided into the west and east branch. Directions of channels are represented by black arrows with dash lines. B: the seismic cross-section of A-A’. C: the seismic cross-section of B-B’. D: the cartoon illustration of the seismic interpretation of the cross-section B-B’. Modified from Zhang et al. (2015).

According to Zhang et al. (2015), the eastern channel system is about 200m thick and 1500-200m wide, while an individual channel is around 10-30m and 150-300m in thickness and width respectively. Furthermore, Zhang et al. (2018) demonstrated that in the study area of Niger delta basin a Channel Complex System was formed in 12.5-10.5 Ma; a Channel Complex Set is last for around 0.3-0.6 Myr; a Channel Complex is last for about 0.1-0.2 Myr. The duration of the Channel Element is not presented in detail, but it will at least less than 0.1 Myr. In the viewpoint of the knowledge model, the thickness, width and time duration are three Qualities (Figure 5.4). While the time interval 12.5-10.5 Ma of the Channel Complex System is a Clastic Forming Interval instead of a Clastic Forming Duration, the 2 Myr (12.5Myr-10.5Myr) of time within this Clastic Forming Interval of the Channel Complex is the Clastic Forming Duration (Figure 5.4). Another time entity: the middle of the Miocene in the study is a Geological Interval, not a Clastic Forming Duration nor a Clastic Forming Interval (Figure 5.4). And values: 0.3-0.6 Myr, 2Myr, and < 0.1 Myr that are noted by authors in the paper are three values of the Clastic Forming Duration.

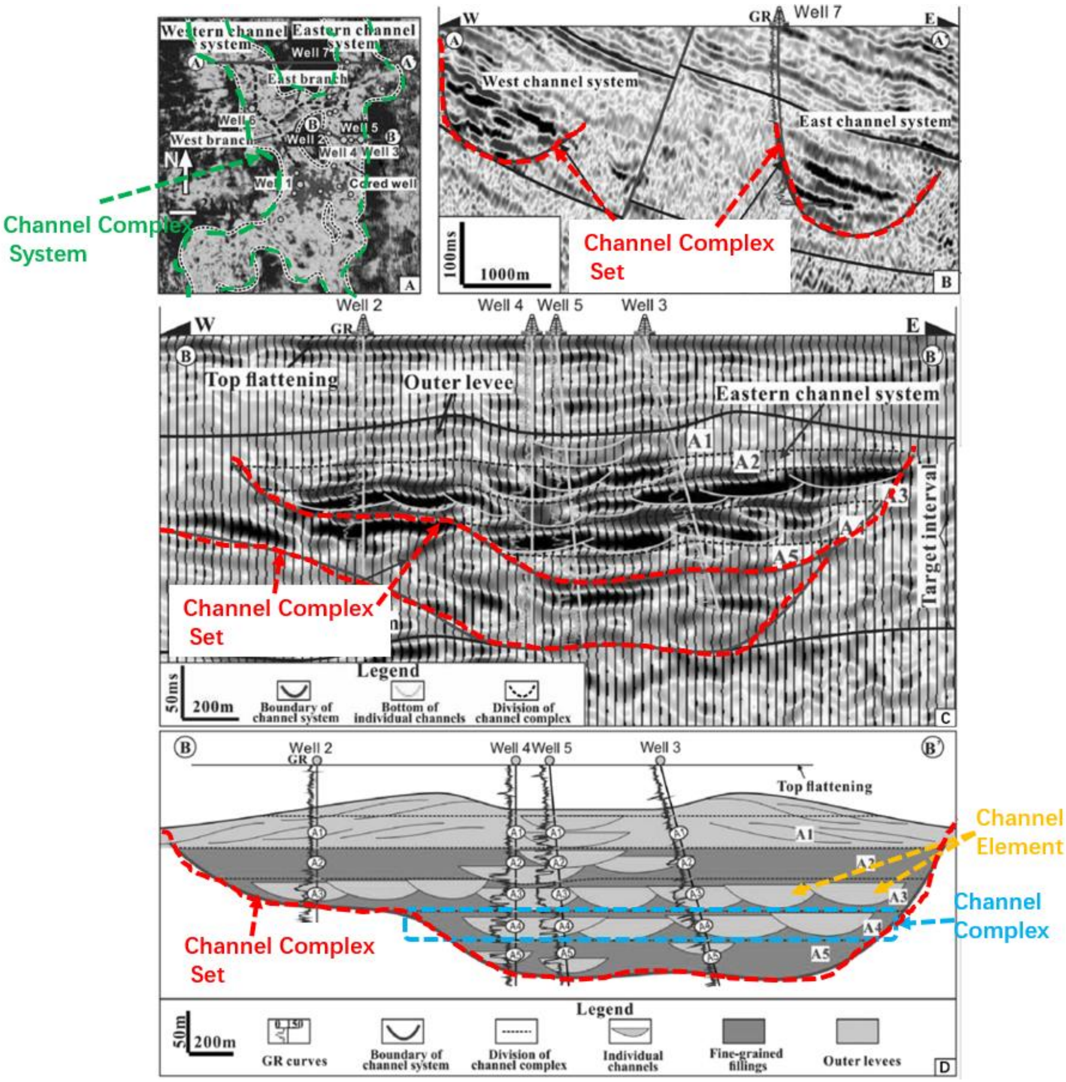


Figure 5.3 The hierarchy of target channels from the viewpoint of the knowledge model, modified from the seismic profiles in Zhang et al. (2015). The green dash line represents the Channel Complex System, red dash lines represent the Channel Complex Set, blue dash line represents the Channel Complex, and orange arrows are pointing two instances of the Channel Element.

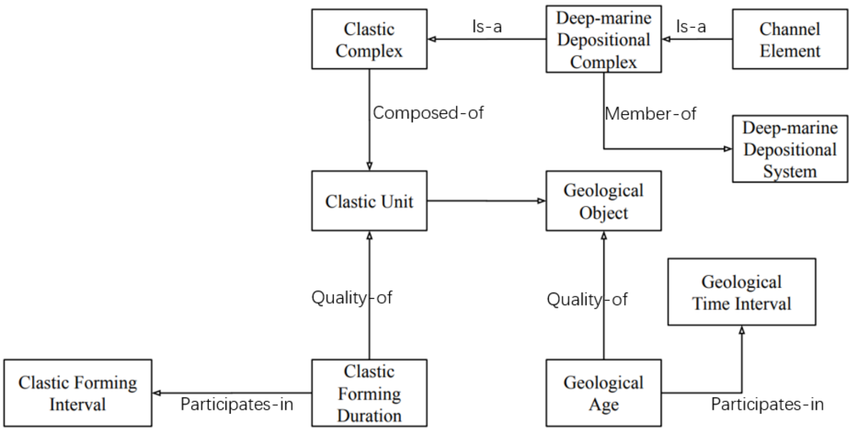


Figure 5.4 Relationships between Clastic Forming Duration, Clastic Forming Interval, Geological Age, and Channel Element, from a viewpoint of the proposed knowledge model.

Through the analysis of abundant cores from the study area, based on different values of grain size value, the authors conclude four main lithofacies types (Table 6): sand-conglomerate, sandstone, siltstone, and mudstone. And according to the different clay content, sorting, and sedimentary structures, four main lithofacies are further classified into eleven lithofacies: massive sand-conglomerate, massive mudclast sand-conglomerate, massive muddy mélange sandstone, massive gravelly coarse sandstone, massive medium to coarse sandstone, massive fine to medium sandstone, parallel-laminated fine to medium sandstone, cross-laminated fine sandstone, muddy siltstone, silty mudstone, and mudstone (Table 6). The values of grain size, clay content, porosity, and permeability of lithofacies are presented in Table 7.

Under the scope of the knowledge model, eleven types of lithofacies are eleven instances of the Lithofacies, which is not referring to any physical core unit or rock in reality. According to Lithofacies (Def.33) in chapter 4, these eleven instances of Lithofacies are entities that are concretized by eleven sets of Qualities (e.g. Grain Size, Clay Content, Sorting, Sedimentary Structure Quality) in specific values on Clastic Units. The Lithofacies can migrate from one Clastic Unit to another Clastic Unit, but not representing any Clastic Unit in reality. For example, the massive sand-conglomerate is an instance of the Lithofacies from the study. This Lithofacies is concretized as the Grain Size in average real positive number value: 1.2 mm or nominal value: very coarse sand, Mud Content in decimal value: 2.5% in average, Sorting in nominal value: very poorly sorted or positive real number value: 2.5 in average, Porosity in decimal value: 18.8% in average, and Permeability in real positive number value: 725.3mD in average (Figure 5.5). And these Qualities inhere in the Clastic Rock that generated by a High-density Turbidity Current, and these Clastic Rocks constitute the Clastic Unit, and the Lithofacies is generically dependent on this Clastic Unit (Figure 5.5). In this Deep-marine Depositional System, this Clastic Unit is an instance of the Deep-marine Depositional Unit. Furthermore, since the Clastic Rocks are generated by High-density Turbidity Current, this Deep-marine Depositional Unit is an instance of the Turbidite. These entities and their relationships are all illustrated in Figure 5.5, which demonstrates again that the Lithofacies in the knowledge model is not any physical unit or rock. The other ten lithofacies can also be fully described in the proposed knowledge model.

After the detailed study of different lithofacies in the target area, based on data from seismic, well-logs, and core samples, individual channels are classified into four types: Type I, Type II, Type III and Type IV (Figure 5.6). And the relationships among Channel Element, Deep-marine Depositional Unit, and Classic Rock are illustrated in Figure 5.6 B. In Zhang et al. (2015), for example, Type I contains six lithofacies: silty mudstone, muddy siltstone, cross-laminated fine sandstone, massive sand-conglomerate, fine to medium sandstone, and mudstone, and these lithofacies are interacting with each other. From bottom to the top, the channel shows a general fining upward trend with few cross-lamination sedimentary structures. In both geology and the proposed knowledge model viewpoints, these four types are four Lithofacies Associations. In the proposed knowledge model, the Type I is an instance of the Lithofacies Association, it is composed of 6 different Lithofacies, concretized as the Clastic Unit Relation among Deep-marine Depositional Units demonstrates changes of lithology within a Channel Complex, and dependent on a Channel Complex. Same as the Lithofacies, the Lithofacies Association can migrate from one bearer to another one, it is not referring to any physical entity in reality.

Based on the results from Table 7, all lithofacies in the Type I channel has turbidity current as their genesis. Thus, in this knowledge model, all these Deep-marine Depositional Units are Turbidites, these Turbidites compose a Channel Element, which the Type I Lithofacies Association is dependent on. The other three types of individual channels can also be described in this way.

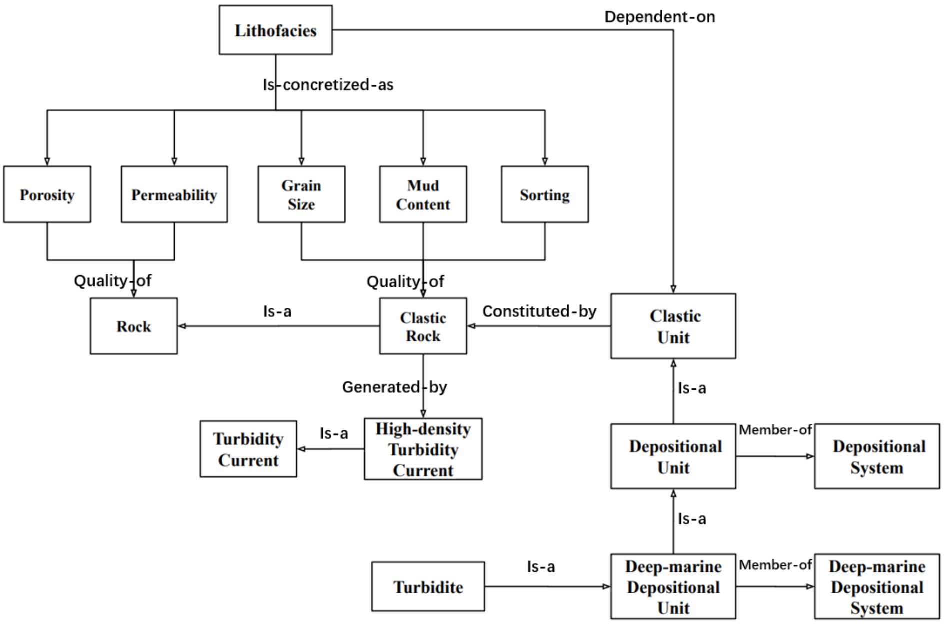
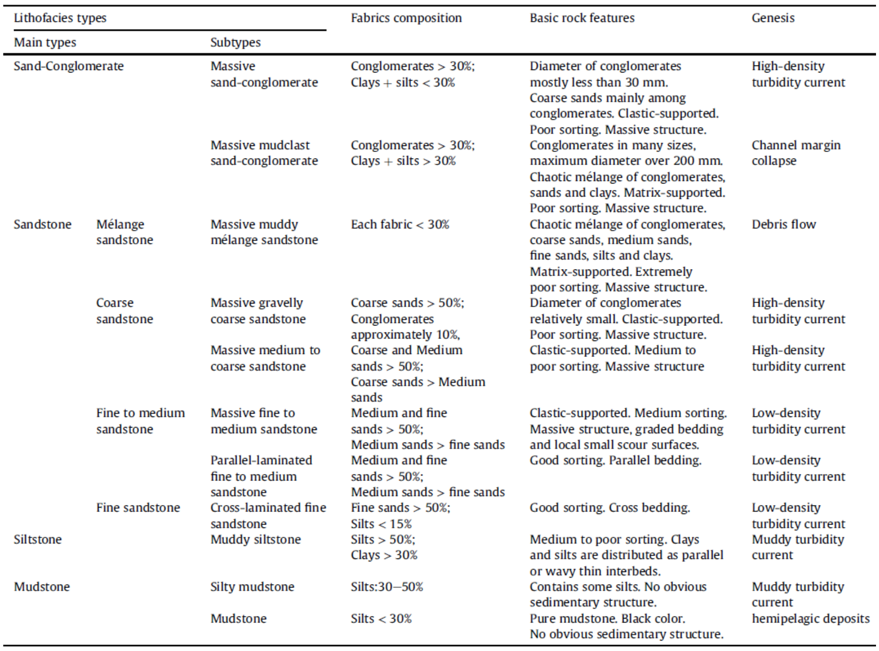
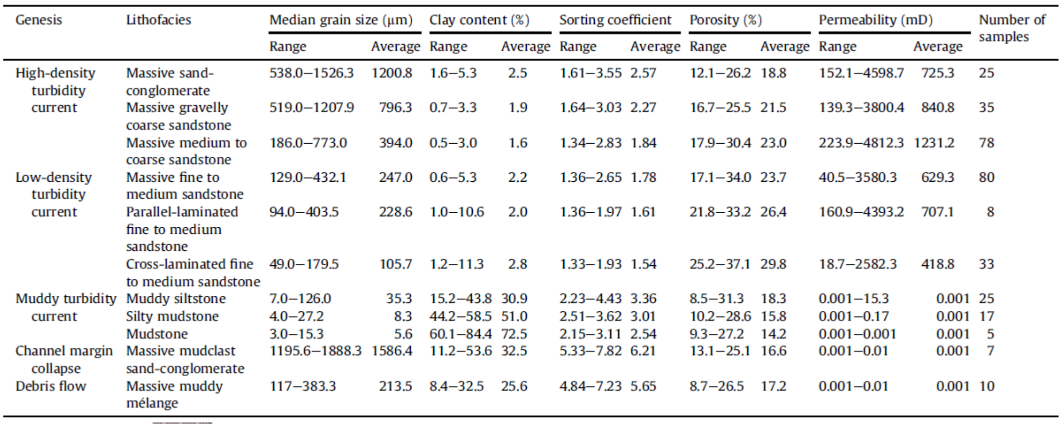


Figure 5.5 Entities and their relationships in the example of the massive sand-conglomerate Lithofacies.



Lithofacies types			Fabrics composition	Basic rock features	Genesis
Main types		Subtypes			
Sand-Conglomerate		Massive sand-conglomerate	Conglomerates > 30%; Clays + silts < 30%	Diameter of conglomerates mostly less than 30 mm. Coarse sands mainly among conglomerates. Clastic-supported. Poor sorting. Massive structure.	High-density turbidity current
		Massive mudclast sand-conglomerate	Conglomerates > 30%; Clays + silts > 30%	Conglomerates in many sizes, maximum diameter over 200 mm. Chaotic mélange of conglomerates, sands and clays. Matrix-supported. Poor sorting. Massive structure.	Channel margin collapse
Sandstone	Mélange sandstone	Massive muddy mélange sandstone	Each fabric < 30%	Chaotic mélange of conglomerates, coarse sands, medium sands, fine sands, silts and clays. Matrix-supported. Extremely poor sorting. Massive structure.	Debris flow
	Coarse sandstone	Massive gravelly coarse sandstone	Coarse sands > 50%; Conglomerates approximately 10%,	Diameter of conglomerates relatively small. Clastic-supported. Poor sorting. Massive structure.	High-density turbidity current
		Massive medium to coarse sandstone	Coarse and Medium sands > 50%; Coarse sands > Medium sands	Clastic-supported. Medium to poor sorting. Massive structure	High-density turbidity current
	Fine to medium sandstone	Massive fine to medium sandstone	Medium and fine sands > 50%; Medium sands > fine sands	Clastic-supported. Medium sorting. Massive structure, graded bedding and local small scour surfaces.	Low-density turbidity current
		Parallel-laminated fine to medium sandstone	Medium and fine sands > 50%; Medium sands > fine sands	Good sorting. Parallel bedding.	Low-density turbidity current
	Fine sandstone	Cross-laminated fine sandstone	Fine sands > 50%; Silts < 15%	Good sorting. Cross bedding.	Low-density turbidity current
Siltstone		Muddy siltstone	Silts > 50%; Clays > 30%	Medium to poor sorting. Clays and silts are distributed as parallel or wavy thin interbeds.	Muddy turbidity current
Mudstone		Silty mudstone	Silts:30–50%	Contains some silts. No obvious sedimentary structure.	Muddy turbidity current
		Mudstone	Silts < 30%	Pure mudstone. Black color. No obvious sedimentary structure.	hemipelagic deposits

Table 6. The main types and subtypes of lithofacies within the study area, with fabrics composition, basic rock features, and genesis of lithofacies as further descriptions (Zhang et al., 2015).



Genesis	Lithofacies	Median grain size (μm)		Clay content (%)		Sorting coefficient		Porosity (%)		Permeability (mD)		Number of samples
		Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	
High-density turbidity current	Massive sand-conglomerate	538.0–1526.3	1200.8	1.6–5.3	2.5	1.61–3.55	2.57	12.1–26.2	18.8	152.1–4598.7	725.3	25
	Massive gravelly coarse sandstone	519.0–1207.9	796.3	0.7–3.3	1.9	1.64–3.03	2.27	16.7–25.5	21.5	139.3–3800.4	840.8	35
	Massive medium to coarse sandstone	186.0–773.0	394.0	0.5–3.0	1.6	1.34–2.83	1.84	17.9–30.4	23.0	223.9–4812.3	1231.2	78
Low-density turbidity current	Massive fine to medium sandstone	129.0–432.1	247.0	0.6–5.3	2.2	1.36–2.65	1.78	17.1–34.0	23.7	40.5–3580.3	629.3	80
	Parallel-laminated fine to medium sandstone	94.0–403.5	228.6	1.0–10.6	2.0	1.36–1.97	1.61	21.8–33.2	26.4	160.9–4393.2	707.1	8
	Cross-laminated fine to medium sandstone	49.0–179.5	105.7	1.2–11.3	2.8	1.33–1.93	1.54	25.2–37.1	29.8	18.7–2582.3	418.8	33
Muddy turbidity current	Muddy siltstone	7.0–126.0	35.3	15.2–43.8	30.9	2.23–4.43	3.36	8.5–31.3	18.3	0.001–15.3	0.001	25
	Silty mudstone	4.0–27.2	8.3	44.2–58.5	51.0	2.51–3.62	3.01	10.2–28.6	15.8	0.001–0.17	0.001	17
	Mudstone	3.0–15.3	5.6	60.1–84.4	72.5	2.15–3.11	2.54	9.3–27.2	14.2	0.001–0.001	0.001	5
Channel margin collapse	Massive mudclast sand-conglomerate	1195.6–1888.3	1586.4	11.2–53.6	32.5	5.33–7.82	6.21	13.1–25.1	16.6	0.001–0.01	0.001	7
Debris flow	Massive muddy mélange	117–383.3	213.5	8.4–32.5	25.6	4.84–7.23	5.65	8.7–26.5	17.2	0.001–0.01	0.001	10

Table 7. The main subtypes of lithofacies within the study area with range and average values of physical properties: the median grain size, clay content, sorting coefficient, porosity, and permeability (Zhang et al., 2015).

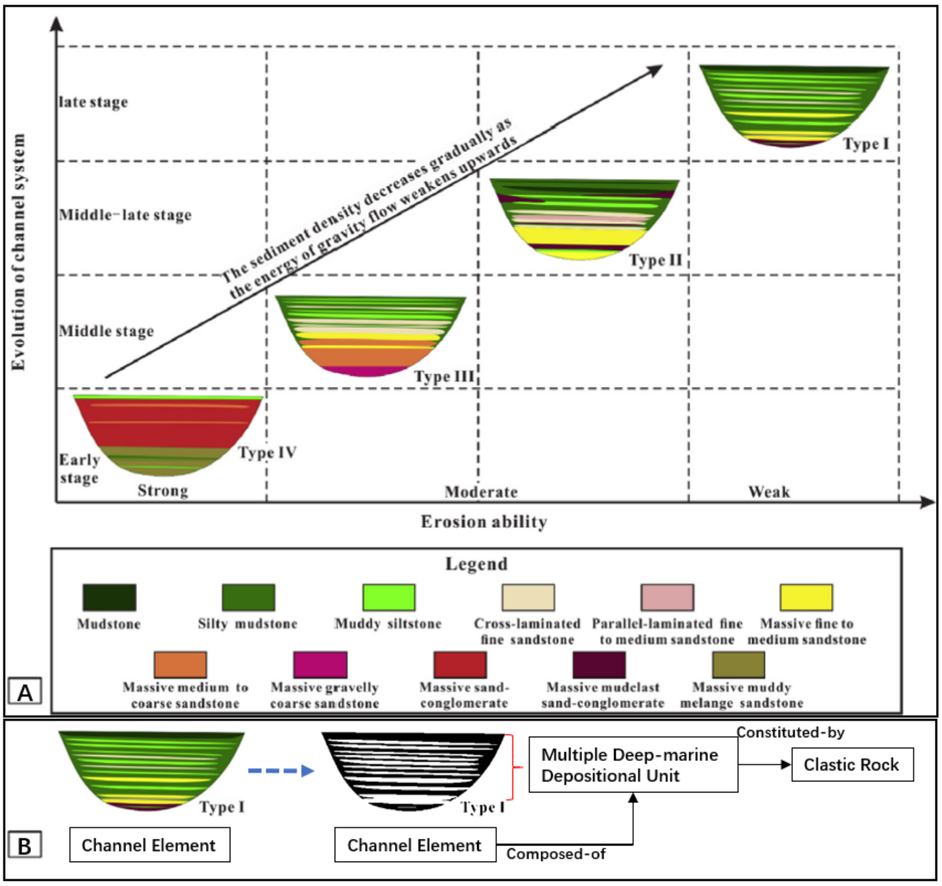


Figure 5.6 A: Four types of individual channels and lithofacies of their channel fills. From type IV to I, erosion ability is weakening, and the channel system is evolving (Zhang et al., 2015). B: An instance of the Channel Element and its relationship with Deep-marine Depositiona Unit and Clastic Rock, in the sense of the knowledge model, modified from Zhang et al. (2015).

In the study of Zhang et al. (2015), the authors concluded that due to the different grain size and clay content, the channel axis of an individual channel has better permeability and porosity than channel margin, this distribution is illustrated in Figure 5.7 A. In the sense of the knowledge model, here are authors talking about the Axis Part and the Margin Part of the Channel Element, which are constituted by Deep-marine Depositional Units. These two Depositional Parts inherit Qualities of Rocks and Clastic Rocks. In Figure 5.7, compared with the instance of the Margin Part, the instance of the Axis Part has Qualities in a larger value of Grain Size, lower value of Caly Content, and higher values of both Permeability and Porosity than the same set of Qualities that are bored by Margin Part of the same Channel Element. The spatial distribution of instances of the Axis Part and the Margin Part are presented in Figure 5.7 B.

In the analysis of Zhang et al. (2015), with a viewpoint from the proposed knowledge model, an instance of the Channel Complex Set - the eastern channel system is composed of A1-A5 five instances of the Channel Complexes. Each Channel Complex is composed of several instances of the Channel Elements (Figure 5.2&5.3). Channel Complex A1 is composed of Type 1 Channel Elements, Channel Complex A2 is composed of Type II Channel Elements, Channel Complex A3, and A4 are composed of Type III Channel Elements and Channel Complex A5 is composed Type IV Channel Elements (Figure 5.2 D & 5.3 D). And the Permeability and Porosity inhere in Type II and III Chanel Element have higher values than the other two types. Authors also noted that Type IV Channel Element is formed in the early stage of a channel, Type II and III are formed during the middle stage of a channel, and Type IV is formed in the late stage of a channel. Stage differences of a channel under the scope of the knowledge model are described as the Erosional Channel and the Depositional Channel. And these instances of the Channel Element are generated by various Deep-marine Gravity Driven Process and located in Erosional Channel or Depositional Channel.

All Qualities that inhere in Channel Elements will also inhere in the Channel Complex. And in Zhang et al. (2015), the values of these Qualities will be represented by the average value. However, there are still some Qualities that do not inhere in a single Channel Element, for example, the *Relational Quality(BFO)*: Channel Stacking Pattern. As parts of the Channel Complex A1, Type I Channel Elements bear Channel Stacking Pattern in nominal value: Vertical Stacking. While the Type IV Channel Elements, as parts of the Channel Complex A5, they bear the Stacking Pattern in nominal value: Isolated Stacking. The Channel Complex Set – Western channel system, and the Channel Complex System are not described in the study of Zhang et al. (2015). Thus, the research results of channels in the Niger delta basin are generally described by the proposed knowledge model.

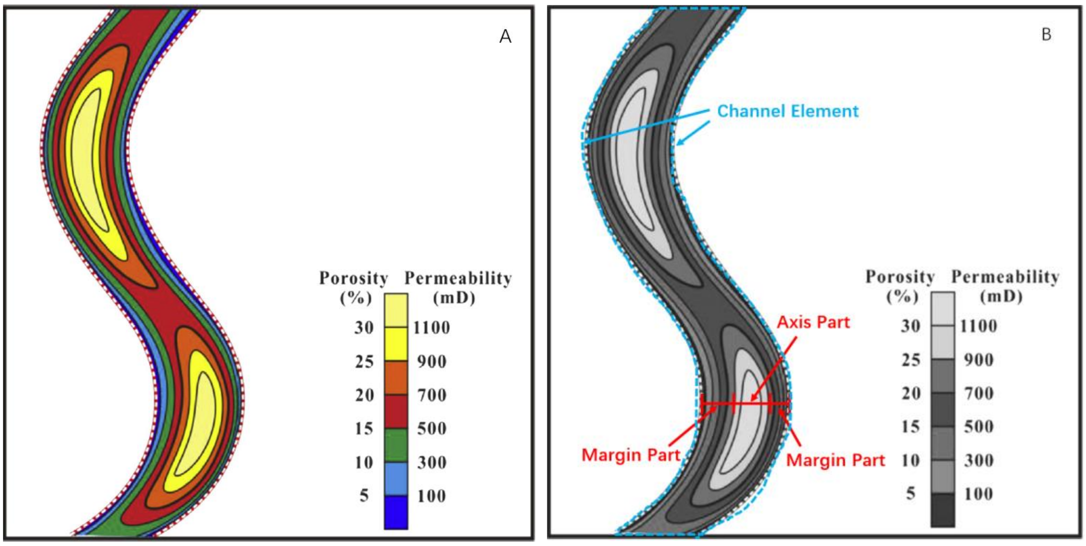


Figure 5.7 A: Distribution of porosity and permeability in an individual channel (Zhang et al., 2015). B: The knowledge model viewpoint of figure A, modified from Zhang et al. (2015). The blue dash line represents the Channel Element and the red lines represent the Axis Part and the Margin Part.

5.1.3 The lobe study

This subsection is focusing on applying the proposed deep-marine clastic depositional system knowledge model to describe the results from the study of Zhang et al. (2016). By focusing on two lobe complexes in the target area, the authors came up with the stacking relationships among individual lobes and sand bodies within the individual lobes, and factors controlling the variations of thickness, length, and width of individual lobes.

In the study of Zhang et al. (2016), two submarine lobes are recognized, namely: the basin floor fan lobe complex and the slope fan lobe complex. The RMS maps of these two lobes are shown in Figure 5.8 A and Figure 5.10 A respectively. The names of these two lobe complexes represent the different topography settings during their formation. Figures 5.8 B and 5.10 B are dissections of the basin floor fan lobe complex and the slope fan lobe complexes. In Figure 5.8 B, three individual lobes I, J and K are identified within the basin floor fan lobe complex, while in Figure 5.10 B, eight individual lobes (A-H) are recognized within two slope fan lobe complexes where the western side lobe complex is composed of individual lobes A-E and the eastern side lobe complex is composed of individual lobes F-H. In the sense of the proposed knowledge model, all individual lobes in the study are instances of the Lobe Element, while three lobe complexes in the study are instances of the Lobe Complex (Figures 5.9 &5.11). The knowledge model views of hierarchies of these fan lobe complexes are illustrated in Figure 5.9 and Figure 5.11 respectively.

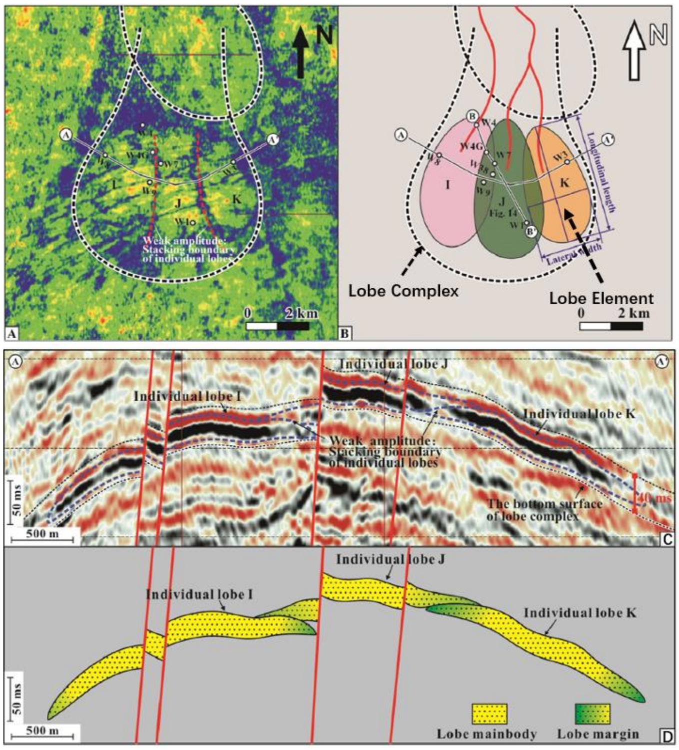


Figure 5.8 The basin floor fan lob complex. A: the RMS map of the lobe complex. B: the cartoon illustration of the RMS map of the lobe complex. C: the seismic cross-section of the basin floor lobe complex along the line A-A’ in figure A with interpretation. D: the cartoon illustration of figure C (Zhang et al., 2016).

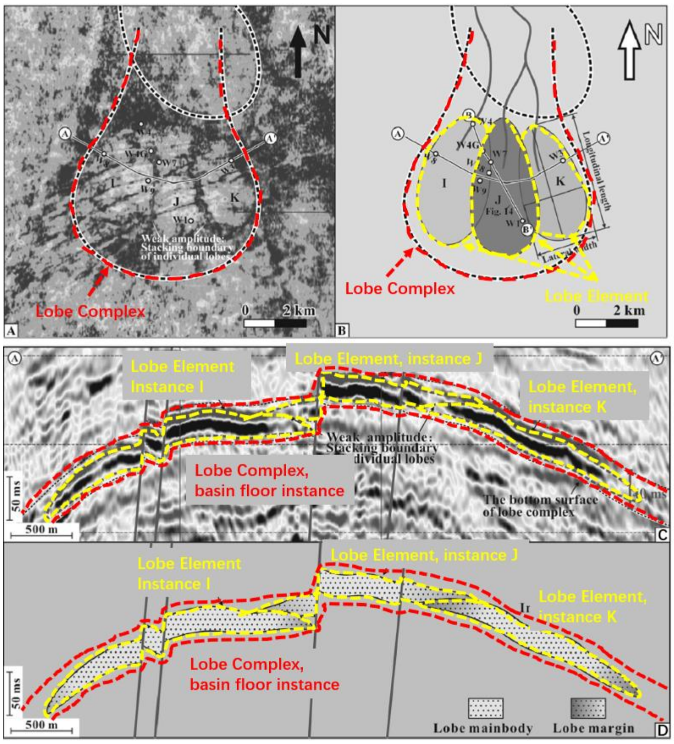


Figure 5.9 The hierarchy in the knowledge model view of the basin floor fan lobe complex from Figure 5.8, modified from Zhang et al. (2016). The red dash line represents the Lobe Complex, and the yellow dash lines represent Lobe Element.

It is worth to note that in the paper, authors use “basin floor lobe complex” and “slope fan lobe complex” refer to the whole geological features of Figures 5.8 & 5.10. This description is sufficient for Figure 5.8 since there is only one Lobe Complex presented in the figure. However, using the “slope fan lobe complex” to describe the geological features in Figures 5.10&5.11 is ambiguous, because figures have two instances of the Lobe Complex and they are composing a larger lobe feature, which is described as “slope fan lobe complex”. The ambiguity is that the term lobe complex is used to describe two different hierarchical orders. In Figure 5.11 B, based on the illustration, it is clear that these two instances of the Lobe Complex are adjacent to a common Channel. Therefore, the slope fan lobe complex in Figure 5.11 A&B is an instance of the Lobe Complex Set which is composed of two instances of the Lobe Complex. And the ambiguity has been avoided.

Figure 5.8 C is the seismic cross-section A-A’ of the basin floor fan lobe complex, and Figure 5.8 D is the cartoon illustration of the seismic interpretation. While Figure 5.10 C&D is the seismic cross-section A-A’ and B-B’ of the slope fan lobe complex. Based on the seismic observation and other researches, Zhang et al. (2016) conclude that the basin floor fan lobe complex is composed of multiple individual lobes in an “inordered stacking pattern”. The slope lobe complex, however, authors come up with a composite pattern with three patterns: lateral, retrograding, and prograding within the slope fan lobe complex and confirmed by two seismic cross-sections A-A’ and B-B’ in Figure 5.10 C&D. In the sense of the proposed knowledge model, as the definition of the Relational Quality: Lobe Stacking Pattern (Def. 82) is given in chapter 4, in the scenario of Figure 5.10, the stacking pattern in the paper is a Lobe Stacking Pattern that inheres among adjacent Lobe Elements within a Lobe Complex. Hence, the Lobe Stacking Pattern inheres among Lobe Elements I, J, K has the nominal value: Inordered Stacking; the Lobe Stacking Pattern inheres among Lobe Elements A, B, C has the nominal value: Lateral Stacking (Figure 5.12); the Lobe Stacking Pattern inheres between Lobe Elements D and E has the nominal value: Lateral Stacking (Figure 5.12); the Lobe Stacking Pattern inheres among the set of Lobe Elements D, E and the set of Lobe Elements A, B, C has the nominal value: Prograding Stacking (Figure 5.12); the Lobe Stacking Pattern inheres among Lobe Elements F, G, and H has the nominal value: Prograding Stacking (Figure 5.12). Two Lobe Complexes are composed of two sets of Lobe Elements A, B, C, D, E, and F, G, H respectively. And the Lobe Stacking Pattern inheres between two Lobe Complexes has the nominal value: Retrograding Stacking (Figure 5.12). Thus, the composite stacking pattern within the slope instance of the Lobe Complex Set is clarified by the ontology-based knowledge model.

Comparing to the lithology study of the deep-marine channel in Zhang et al. (2015), the deep-marine lobes in Zhang et al. (2016) has similar but also simplified types of lithofacies: sand-conglomerate, gravelly coarse sandstone, medium-coarse sandstone, fine-medium sandstone, fine sandstone, siltstone, silty mudstone, mudstone, and mud clast sand-conglomerate. The sedimentary structures such as cross-bedding and parallel bedding are found in the corresponding cores. In the study of Zhang et al. (2016), authors only present a general illustration of lithofacies without further descriptions. From the viewpoint of the proposed knowledge model, these nine different types of lithology are nine different sets of Qualities with particular values that concretize nine instances of the Lithofacies, which is dependent on the Clastic Unit. For example, two core samples are found in Zhang et al. (2016): core 1 has a medium-coarse sand lithology and core 2 has a fine-medium sand lithology. In the knowledge model, these two core samples are two portions of Clastic Rocks which are taken from two different Deep-marine Depositional Units. Qualities in different values inhere in these two portions of Clastic Rocks concretize two Lithofacies. Two portions of Clastic Rocks are physically existence, but not the Lithofacies, which can migrate from one to another bearer. The relationships between Lithofacies, Quality, Deep-marine Depositional Unit, and Clastic Rock are shown in Figure 5.5.

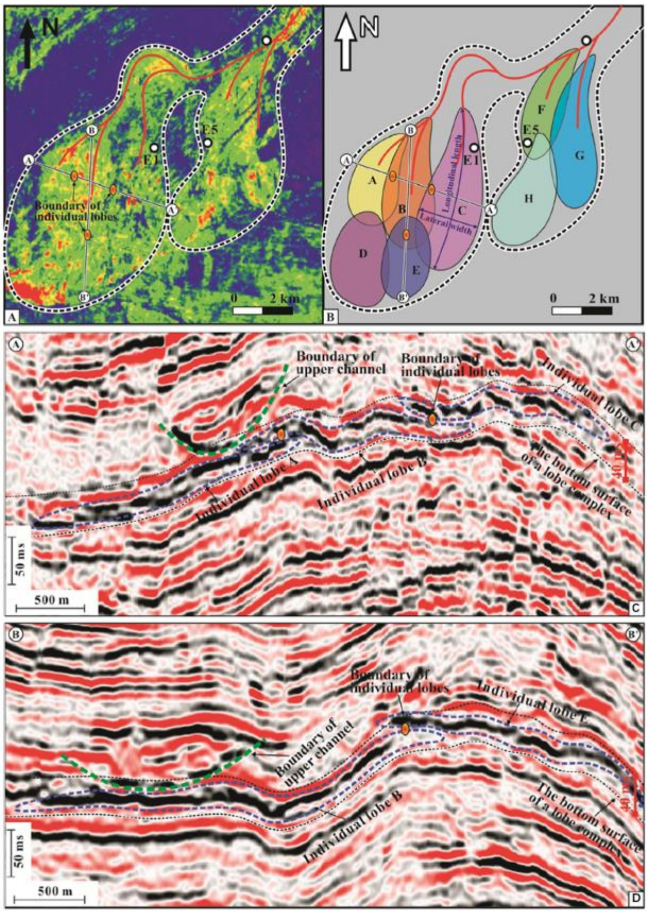


Figure 5.10 The slope fan lob complex. A: the RMS map of the lobe complex. B: the cartoon illustration of the RMS map of the lobe complex. C: the seismic cross-section of the slope lobe complex along the line A-A’ in figure A with interpretation. D: the seismic cross-section of the slope lobe complex along the line B-B’ in figure A with interpretation (Zhang et al., 2016).

Based on abundant seismic data, well-logs, and cores, the length, width, and thickness of eleven individual lobes A-K, which are presented in Figures 5.8&5.10 are measured by the Zhang et al. (2016). According to the study, the length of an individual lobe in the study area varies from 2-4 km, the width is between 1-3km while the thickness is about 15-30m. The lobe complex in the basin floor setting has a length around 6km, width around 8km, and thickness around 30m, while two lobe complexes in the slope setting have similar width about 5km, similar thickness 35 m and different length 8 km and 10 km respectively. The thickness here measures the thickest part of a lobe. All these measures can be fully described by the proposed knowledge model. For example, the Lobe Element A in the study region of Zhang et al. (2016) bears three Qualities: Length, Width and Thickness in 2.2km, 1.3km and 25m respectively, the Lobe Complex in the basin floor setting bears Length, Width and Thickness in 6km, 8km and 30m respectively. However, the relationship between these numerical measurements and different hierarchical levels of Deep-marine Depositional Complexes are not described in the knowledge model. Since these relationships are unclear in the present stage of geology knowledge, and what geologists conclude from observations are empirical, exceptions always exist.

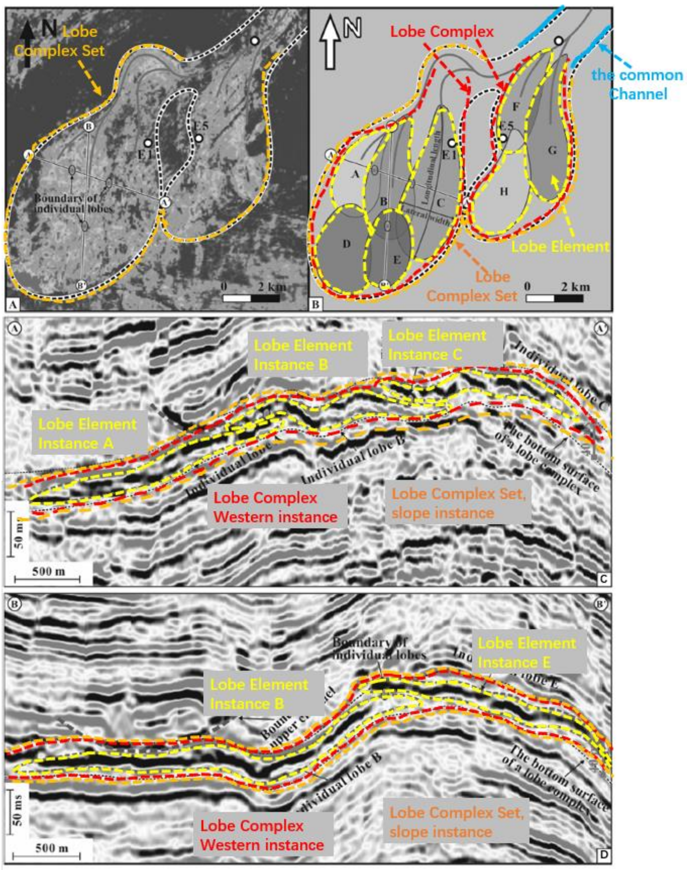


Figure 5.11 The hierarchy in knowledge model views of the slope fan lobe complex from Figure 5.10, modified from Zhang et al. (2016). Orange dash lines represent the Lobe Complex Set, red dash lines represent the Lobe Complex, the yellow dash lines represent Lobe Element, and the blue line represents the Channel.

In Figure 5.8 D, the cartoon illustration of the seismic cross-section demonstrates that each individual lobe has a lobe main body and lobe margins as its parts. The study of Zhang et al. (2016) shows that in the target area, the main body of the individual lobe contains lithology such as sand-conglomerate, gravelly coarse sandstone, medium-coarse sandstone, fine-medium sandstone, and fine sandstone. While the margin lobe contains fine sandstone, siltstone, and mudstone that are interbedded with each other. Besides, the lobe main body has a higher degree of amalgamation than the lobe margin. Under the scope of the proposed knowledge model, authors are describing the Depositional Parts of the Lobe Element, relevant entities and their relationships are illustrated in Figure 5.13. The Axis Part of the Lobe Element is composed of several Deep-marine Depositional Units, which are constituted by five sub-classes of the Clastic Rock. These five sub-classes of the Clastic Rock have Grain Size in five different values respectively. And the Margin Part of the Lobe Element is composed of several Deep-marine Depositional Units, which are constituted by three sub-classes of the Clastic Rock. These three sub-classes of the Clastic Rock bear Grain Size in three different values respectively. The Sand Amalgamation inheres among Deep-marine Depositional Units has a higher value in the Axis Part than Deep-marine Depositional Units in the Margin Part.

The last research point demonstrated by Zhang et al. (2016) is that each individual lobe in the study area of Niger delta basin is generated by mainly two processes: the slump-debris flow and the turbidity current. In the knowledge model perspective, each instance of the Lobe Element in the study area is generated by Slump Process/Debris Flow and Turbidity Current. Therefore, the Lobe Element has Slump Deposits/Debrites or Turbidites as its parts. Qualities such as Sorting, Grain Size, Clay Content, etc inhere in the Clastic Rock, and the Deep-marine Depositional Unit is constituted by these Clastic Rocks.

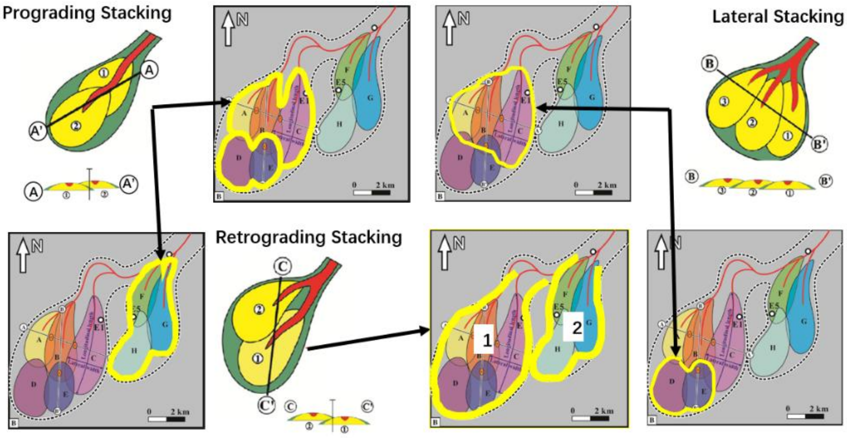


Figure 5.12: Three nominal values of the Lobe Stacking Pattern, which inheres among several Lobe Element or Lobe Complex within the slope fan Lobe Complex Set, modified from Zhang et al. (2016).

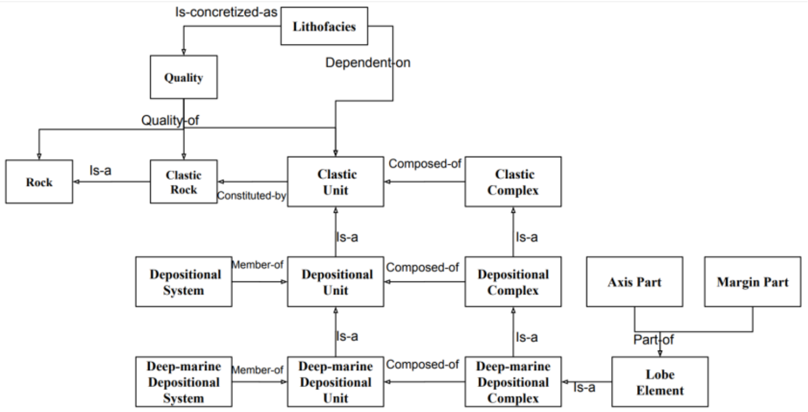


Figure 5.13: Entities and their relationships of the lobe axis and margin in the study of Zhang et al. (2016) under the scope of the proposed knowledge model.

5.2 The Ainsa-Jaca Basin, Spain

In this section, the target deep-marine depositional system: Ainsa-Jaca basin is divided into two parts: the Anisa basin – Gerbe System (channel) and the Jaca basin –Broto System (lobe) (Bell et al., 2018). Different from the subsurface geological data analysis in the Niger delta basin, the study in Ainsa-Jaca Basin is done by field analysis of outcrops. The outcrop provides a great opportunity for geologists to collect abundant samples and have a close observation to study. However, due to the accessibility limitation of the outcrop, the outcrop study is easier to focus on the small-scale analysis rather than a large scale quantitative study. In the study of Bell et al. (2018), to have a better understanding of the reservoir potential, authors have selected one individual channel in the Gerbe System and one individual lobe in the Upper Broto System to study.

5.2.1 Geological Setting

The Ainsa-Jaca basin is one of the most important ideal basins for geologists to understand deep-marine sediments (Gupta and Pickering, 2008). The Ainsa-Jaca basin is located in the southern Spanish Pyrenees, is part of the Gavarnie thrust sheet and bounded by Mediano anticline on the eastern side (Muñoz, 1992; Verges and Munoz, 1990).

The Ainsa-Jaca basin is the combination of two basins: the Ainsa basin and the Jaca basin (Figure 5.14), and these two basins are separated by the Boltana anticline in the middle (Labourdette, 2011). The separation of basins was the result of the collision between the Iberian plate and the Eurasian plate. The collision started during the late Cretaceous, which started to build the symmetric high mountain chain with metamorphic rocks – the Pyrenees Mountains (Dreyer et al., 1999). When the time moved to the Paleogene, from the Paleogene to the middle Eocene, the colliding was continuing, where the Iberian plate subducted towards the Eurasian plate. This process not only built the mountain chain but also built a foreland basin with a fold and thrust belt (Muñoz et al., 2013). The deep-marine sediments in the Ainsa-Jaca basin were deposited during the Early to Middle Eocene and named as the Hecho Group. During this period, the Mediano and Boltana anticlines were generated, and the Ainsa basin and Jaca basin were separated (Gupta and Pickering, 2008).

In total, seven depositional systems (Fosado, Arro/Los Molinos, Gerbe, Banaston, Ainsa, Morillo, and Guaso system) in the Ainsa basin and five depositional systems (Torla, Broto, Cotefablo, Banaston, and Jaca system) were recognized in the Jaca basin (Pickering and Cantalejo, 2015). The Gerbe system in the Ainsa basin is interpreted as the canyon to lower-slope channel system, and the Broto system in the Jaca basin is interpreted as the submarine lobe system (Bell et al., 2018; Clark and Pickering, 1996).

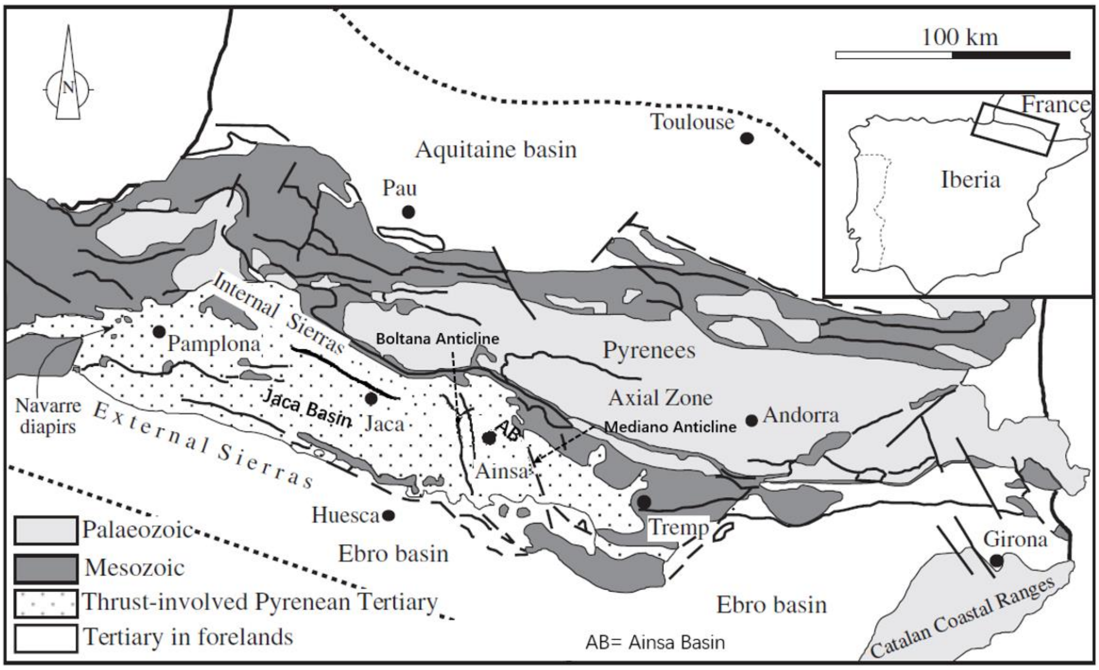


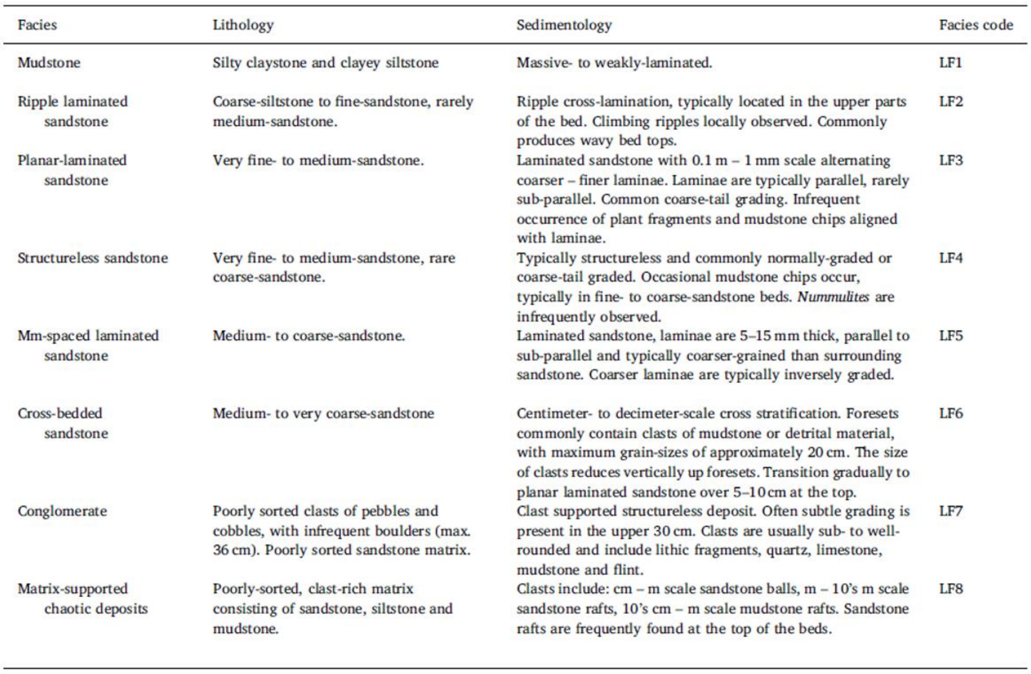
Figure 5.14 The simplified geological map of the Ainsa-Jaca basin and the Pyrenees, modified from Remacha et al. (1998), Gupta and Pickering (2008).

5.2.2 The Outcrop Study

In the study of Bell et al. (2018), authors have selected one individual lobe of the Broto System and one individual channel of the Gerbe System as study targets. The individual lobe has a total length is around 16km, the width is around 0.9km, and the maximum thickness is around 6.1m (Figure 5.15 A). While the individual channel has the width is about 150m and the maximum thickness is about 8.5m (Figure 5.16 A). In the sense of the proposed model, the analysis targets are one Channel Element has Width and Thickness in positive real number value: 150m and 8.5m respectively, and one Lobe Element has Length, Width, and Thickness in positive real number value: 16km, 0.9km, and 6.1m respectively.

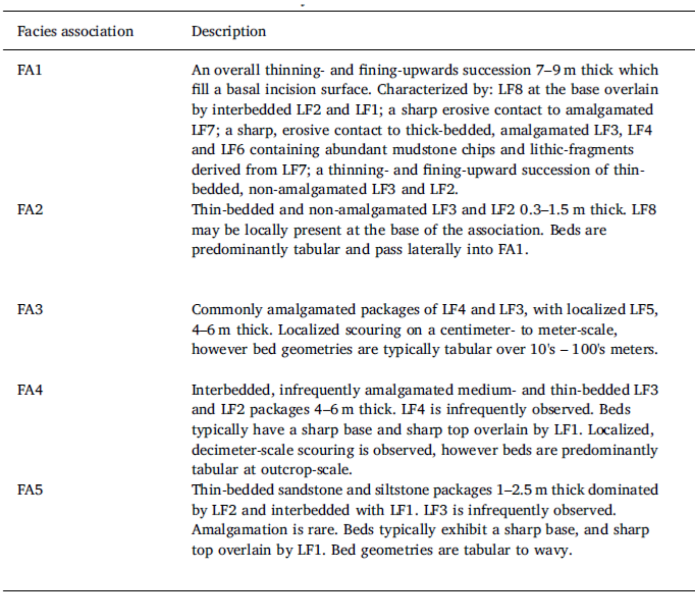
During the outcrop study, in total eleven logs were analyzed by the authors, four logs from the target channel, and seven logs from the target lobe. Through the analyses of these logs, eight facies LF1-LF8 are presented by authors, namely: mudstone, ripple laminated sandstone, planar-laminated sandstone, structureless sandstone, mm-spaced laminated sandstone, cross-bedded sandstone, conglomerate, and matrix-supported chaotic deposits (Table 8). Based on these eight facies, the authors have concluded five facies association: FA1-5 (Table 9). For example, the lithofacies planar-laminated sandstone (LF3) representing the very fine – to medium sandstones with parallel lamination as a sedimentary structure that is found in the target individual channel. While under the scope of the knowledge model, eight types of facies are eight instances of Lithofacies. As an instance of the Lithofacies, the planar-laminated sandstone facies (LF3) is concretized as Grain Size in range of positive real number value from 0.0625mm to 0.5mm and Parallel Lamination on a Deep-marine Depositional Unit. These

Qualities inhere in the Clastic Rocks that constitute the Deep-marine Depositional Unit. The Lithofacies in the knowledge model is not referring to any Deep-marine Depositional Unit in reality, instead, it can migrate from one Deep-marine Depositional Unit to another one. This relationship has been presented in Figure 5.5. The facies association FA1-FA5 are five instances of Lithofacies Association. For example, the FA3 is an instance of the Facies Association, it is a complex of LF3, LF4, and LF5 that are dependent on multiple adjacent Deep-marine Depositional Units, and FA3 is also concretized as Sand Amalgamation and Clastic Unit Relation among these Deep-marine Depositional Units.



Facies	Lithology	Sedimentology	Facies code
Mudstone	Silty claystone and clayey siltstone	Massive- to weakly-laminated.	LF1
Ripple laminated sandstone	Coarse-siltstone to fine-sandstone, rarely medium-sandstone.	Ripple cross-lamination, typically located in the upper parts of the bed. Climbing ripples locally observed. Commonly produces wavy bed tops.	LF2
Planar-laminated sandstone	Very fine- to medium-sandstone.	Laminated sandstone with 0.1 m – 1 mm scale alternating coarser – finer laminae. Laminae are typically parallel, rarely sub-parallel. Common coarse-tail grading. Infrequent occurrence of plant fragments and mudstone chips aligned with laminae.	LF3
Structureless sandstone	Very fine- to medium-sandstone, rare coarse-sandstone.	Typically structureless and commonly normally-graded or coarse-tail graded. Occasional mudstone chips occur, typically in fine- to coarse-sandstone beds. *Nummulites* are infrequently observed.	LF4
Mm-spaced laminated sandstone	Medium- to coarse-sandstone.	Laminated sandstone, laminae are 5–15 mm thick, parallel to sub-parallel and typically coarser-grained than surrounding sandstone. Coarser laminae are typically inversely graded.	LF5
Cross-bedded sandstone	Medium- to very coarse-sandstone	Centimeter- to decimeter-scale cross stratification. Foresets commonly contain clasts of mudstone or detrital material, with maximum grain-sizes of approximately 20 cm. The size of clasts reduces vertically up foresets. Transition gradually to planar laminated sandstone over 5–10 cm at the top.	LF6
Conglomerate	Poorly sorted clasts of pebbles and cobbles, with infrequent boulders (max. 36 cm). Poorly sorted sandstone matrix.	Clast supported structureless deposit. Often subtle grading is present in the upper 30 cm. Clasts are usually sub- to well-rounded and include lithic fragments, quartz, limestone, mudstone and flint.	LF7
Matrix-supported chaotic deposits	Poorly-sorted, clast-rich matrix consisting of sandstone, siltstone and mudstone.	Clasts include: cm – m scale sandstone balls, m – 10's m scale sandstone rafts, 10's cm – m scale mudstone rafts. Sandstone rafts are frequently found at the top of the beds.	LF8

Table 8 Lithofacies of the target channel and lobe in the Ainsa-Jaca basin (Bell et al., 2018).



Facies association	Description
FA1	An overall thinning- and fining-upwards succession 7–9 m thick which fill a basal incision surface. Characterized by: LF8 at the base overlain by interbedded LF2 and LF1; a sharp erosive contact to amalgamated LF7; a sharp, erosive contact to thick-bedded, amalgamated LF3, LF4 and LF6 containing abundant mudstone chips and lithic-fragments derived from LF7; a thinning- and fining-upward succession of thin-bedded, non-amalgamated LF3 and LF2.
FA2	Thin-bedded and non-amalgamated LF3 and LF2 0.3–1.5 m thick. LF8 may be locally present at the base of the association. Beds are predominantly tabular and pass laterally into FA1.
FA3	Commonly amalgamated packages of LF4 and LF3, with localized LF5, 4–6 m thick. Localized scouring on a centimeter- to meter-scale, however bed geometries are typically tabular over 10's – 100's meters.
FA4	Interbedded, infrequently amalgamated medium- and thin-bedded LF3 and LF2 packages 4–6 m thick. LF4 is infrequently observed. Beds typically have a sharp base and sharp top overlain by LF1. Localized, decimeter-scale scouring is observed, however beds are predominantly tabular at outcrop-scale.
FA5	Thin-bedded sandstone and siltstone packages 1–2.5 m thick dominated by LF2 and interbedded with LF1. LF3 is infrequently observed. Amalgamation is rare. Beds typically exhibit a sharp base, and sharp top overlain by LF1. Bed geometries are tabular to wavy.

Table 9 Lithofacies associations of the target channel and lobe in the Ainsa-Jaca basin (Bell et al., 2018).

In order to have a better understanding of the reservoir potential of the target individual channel and lobe, Bell et al. (2018) separate them into channel axis, channel margin, lobe axis, lobe off-axis, and lobe fringe to have detailed analyses ((Figures 5.15 A & 5.16 A). By applying the knowledge model, the target individual channel and lobe are Channel Element and Lobe Element respectively. For the Channel Element, the channel axis is an instance of the Axis Part of the Channel Element, the channel margin is an instance of the Margin Part of the Channel Element (Figure 5.16 B). For the Lobe Element, the lobe axis is an instance of the Axis Part of the Lobe Element, the lobe fringe is an instance of the Margin Part of the Lobe Element. And according to Figure 5.15 A, the Clastic Rock in lobe off-axis has Grain Size in nominal value fine to very-fine sand, with the moderate value of the Mud Content. Thus, the sandstone is the dominated clastic rock in the lobe off-axis, and the lobe off-axis is part of the Axis Part of the Lobe Element (Figure 5.15 B). Each Depositional Part is a part of the Deep-marine Depositional Complex, and it is composed of several Deep-marine Depositional Units or parts of several Deep-marine Depositional Units.

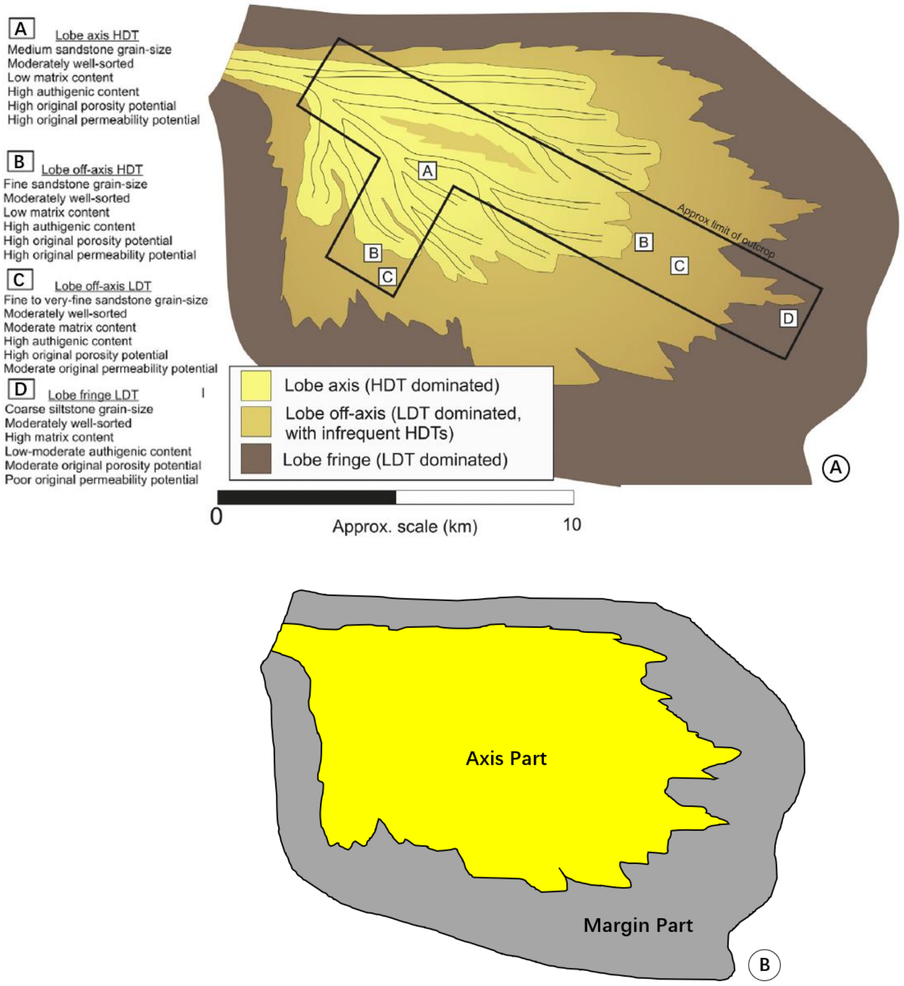


Figure 5.15: A: The cartoon illustration of the target individual lobe in a plain view. Four kinds of deposits A-D are classified in the lobe, based on these four kinds of deposits, authors have separated the target lobe into the lobe axis, lobe off-axis and lobe fringe (Bell et al., 2018). B: The illustration of the Axis Part and the Margin Part of the target lobe, under the scope of the knowledge model, modified from Bell et al. (2018).

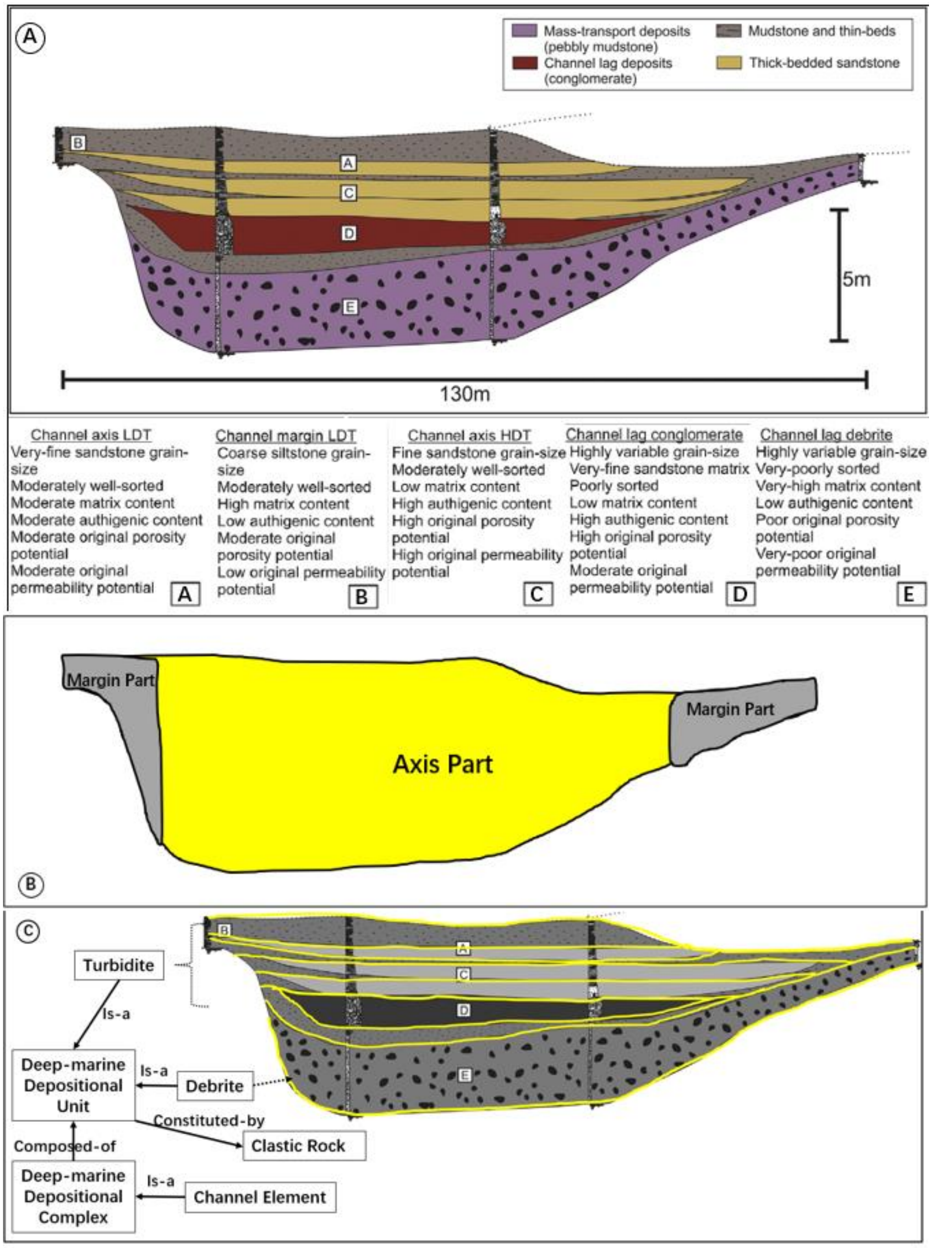


Figure 5.16 A: The cartoon illustration of the target individual channel in a cross-section view. Five kinds of deposits A-E are classified in the channel (Bell et al., 2018). B: The illustration of the Axis Part and the Margin Part of the target channel, under the scope of the knowledge model, modified from Bell et al. (2018). C: The composition of the target channel in the viewpoint of the knowledge model, this channel is an instance of the Channel Element that is composed of Turbidites and Debrites, which are constituted by Clastic Rocks. The relationships among Turbidite, Debrite, Channel Element, and Clastic Rock are also presented, modified from Bell et al. (2018).

Through the study, Bell et al. (2018) identify that the target lobe and channel are composed of layers of turbidites and debrite. From the viewpoint of the knowledge model, Channel Element and Lobe Element are generated by Debris Flow and Turbidity Current, and they are composed of multiple Debrites and Turbidites (Figure 5.16 C). These Deep-marine Depositional Units are constituted by Clastic Rocks, which has various values of the Grain Size. According to the study, from the Axis Part to the Margin Part of the Channel Element, average values of Grain Size, Sand Content, Porosity, Permeability, and Sand Amalgamation are decreasing, while values of Mud Content, Sorting are increasing. Similar to the Depositional Parts of the target Channel Element, from the Axis Part to the Margin Part of the Lobe Element in the study area, average values of Grain Size, Sand Content, Porosity, Permeability are decreasing, values of Mud Content is increasing, while the value of Sorting is moderately constant. All values of these Qualities can be expressed by real number values. Thus, the sedimentological results from Bell et al. (2018) are generally described by this knowledge model.

6 Discussion

6.1 A new scope from the model

Geology is an approximation to reality, and the language used by geologists is sometimes imprecise. The proposed geological knowledge model of the deep-marine clastic system brings a new scope for geologists to reduce the ambiguations, and support geologists to collect data explicitly, regardless of geology experience. This scope shall allow geologists to have a view of ontological analysis, that is to say, to think what differences among geological entities are, what is the relation between a geological body and its part or material, and what are qualities that characterize a geological body, etc. For example, in the eyes of ontologists, when geologists talk about a sandstone, they are talking about an instance of the Clastic Rock (Def.8) that bears Grain Size (Def.19) and has a positive real number value in the range 0.0625 mm – 2mm. So, in what perspectives can geological data be filtered and implemented by this model?

6.1.1 Duration and interval

Time-relevant geological data is considered through the knowledge model perspective, which may provide a new aspect for geologists when dealing with time. Time plays an essential role in the geological study, but a single sentence of the geological time can have multiple meanings and ambiguities may not be noticed by authors. For example, in the field study, a sedimentologist says: “this sandstone layer was deposited during the Paleocene”. This sentence sounds quite normal for other sedimentologists, some might argue “it could have been deposited during the Eocene instead of the Paleocene”, but none of them will ask “ what is the meaning of what you just said ?”. From an ontological point of view, the sentence concluded by the sedimentologist can be understood through different perspectives. The information from that sentence can vary from “the age of that sandstone layer is about 66Ma,” “the sandstone layer was deposited during the Epoch: Paleocene from 66 to 56Ma” to “it took 10 Myr (from 66 to 56Ma) for the sandstone layer to form”. These terms are relevant to each other, but not the same. Based on the top-level ontology BFO, and the core ontology GeoCore, the proposed knowledge model can help geologists and specialists from other subjects to have a useful view to separate such information. The first vital separation is between the Clastic Forming Interval and Clastic Forming Duration. In daily language, these two terms are sometimes mixed in usage, and some may conclude that all intervals are durations. The proposed knowledge model makes the distinction, the Clastic Forming Interval is a *Geological Time Interval (GeoCore)*, while the Clastic Forming Duration is a *Quality (BFO).* In the “sandstone layer case”, the Clastic Forming Duration describes how long time was the sandstone layer formed and has the value 10Myr, the Clastic Forming Interval describes that the sandstone layer formed during the interval of the Paleocene (66-56Ma). If several instances of the Clastic Forming Duration have the same value 10Myr, then they are the same Clastic Forming Duration, though their bearers are different. However, even two instances of Clastic Forming Interval are 10Myr long, they could be different instances since they could occur at a different time (Guarino and Welty, 2009).

The difference between a time interval and an age was characterized by Garcia et al. (2020) in the GeoCore Ontology. The entities and their relationships in the "sandstone layer case" with the ontological point of view are illustrated in Figure 6.1. This characterization shall first help geologists to realize the differences among geological time data, assist informatics professionals to classify and store the geological time data in different types. The age of the sandstone layer is 66 Ma, the time interval of it is from 66Ma to now. It took 10 Myr for the sandstone layer to be generated by some processes, and the interval is 66-56 Ma.

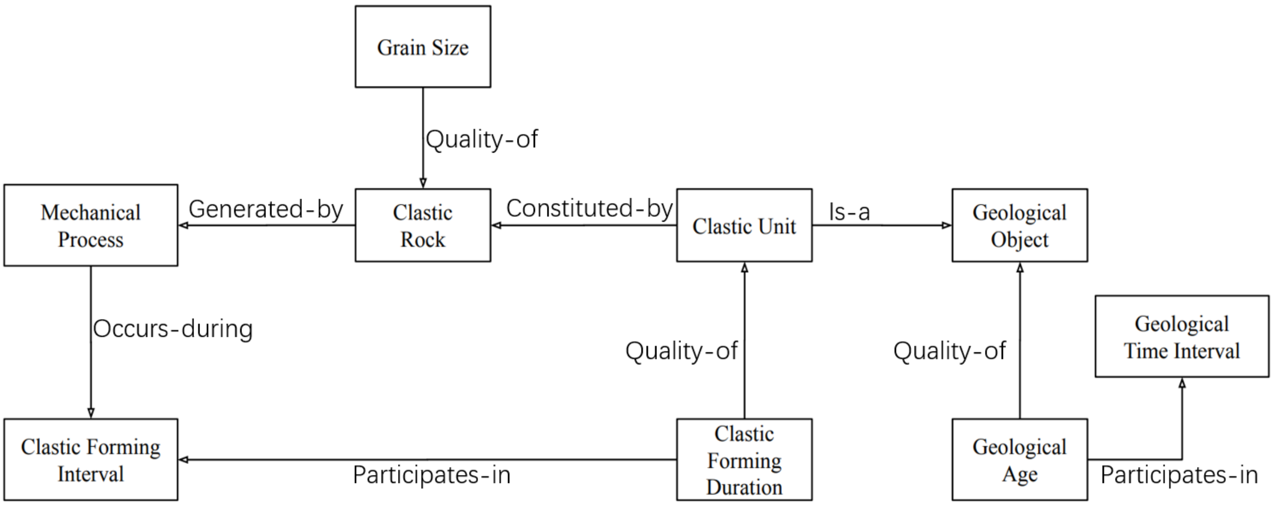


Figure 6.1 Relationships between the entities in the "sandstone layer case", in the sense of the proposed knowledge model.

In section 5.1, the geological time data in the study of Zhang et al. (2018) are analyzed by the proposed knowledge model. Authors are intended to present the Geological Age of the channel system and the Clastic Forming Duration of lower hierarchy channels. However, the sentence such as "a 3rd-order sequence that formed during 12.5–10.5 Ma" leads the geological time data to a vagueness, it could be a data of the Geological Age, the Clastic Forming Duration, the corresponding Geological Time Interval, or the Clastic Forming Interval. Through the ontological analysis that is provided by the proposed knowledge model, this problem can be easily solved, and geologists can have a new perspective to collect the geological data about time, regardless of their experience.

6.1.2 The deep-marine deposits

Based on the proposed knowledge model in chapter 4, through the ontological analysis of the Niger delta basin and the Ainsa-Jaca basin in chapter 5, this subsection will answer why different geologists have diverse ways to describe the same type of geological data? What are these deep-marine deposits and their relationships with clastic rocks? How can the knowledge model provide a new aspect for geologists to collect and record geological data of deep-marine deposits?

In the domain of the deep-marine clastic depositional system, turbidite, slump, slide, and debrite are four main types of deposits that are generated by deep-marine gravity-driven processes. The understanding of these terms is not only essential for geologists, but also for professionals in other relevant subjects. However, some geological terms are highly context-dependent, as a result, these terms are not intelligible for people with limited geoscience experience. The term turbidite refers to the deposits of turbidity current was first used by Kuenen (1957), and the term debrite for deposits of debris flow was introduced by Pluenneke (1976), since then, geologists have been using these terms. However, slump and slides are different, both terms are used by geologists to refer to both the mass transport events and their deposits. As for whether these two terms refer to events or deposits, it depends on the specific context. The problem of the single term refers to multiple entities that have been discussed by Shanmugam (2006), and came up with a broad summary as the result. The proposed ontology-based knowledge model in chapter 4 defines Slump Deposit, Slide Deposit, Slump Process, and Slide Process to make a distinction, and this provides new eyes for geologists to deliberate the entity they are talking about, whether it is a material entity or a process (Figure 6.2). This distinction is small but vital, it shall provide a solid and intelligible foundation for use in interdisciplinary studies. Such a new aspect will not be limited in the deep-marine sedimentology domain, instead, it can apply to all different subjects of geology.

The geological data of deep-marine deposits are presented by Zhang et al. (2015) and Bell et al. (2018) differently. Zhang et al. (2015) demonstrate types of clastic rocks of the deposits, together with a detailed study of fabric composition, and then denote the genesis of the clastic rock, instead of using terms such as turbidite, or debrite (Figure 5.6 A). In contrast, Bell et al. (2018) first list types of lithofacies that exist in the study area, then define deposits as turbidite and debrite, and describe the lithology of each type of deposit, without mentioning different types of clastic rocks (Figures 5.15 A & 5.16 A). This difference may be due to the different focuses of observations and analyses of geologists, which is relevant to diverse understandings of the identity of the deep-marine deposits. In the studies of Zhang et al. (2015) and Bell et al. (2018), it is clear that they are describing relevant but different types of deep-marine geological data in the sense of the knowledge model, though in a geology point of view that both of them are describing the same type of data. Zhang et al. (2015) are focusing on presenting different Clastic Rocks that constitute various Clastic Units in the Niger delta basin Deep-marine Depositional System, and relevant processes that were happened during the formation. As a result, they are using Clastic Rocks to describe deep-marine deposits. While Bell et al. (2018) are first focusing on demonstrating what Deep-marine Depositional Units are found in the

Ainsa-Jaca basin Deep-marine Depositional System, and what processes that were involved in the formation of these Clastic Units, so they are using terms turbidite and debrite. Geologists have no problem understanding the geological data of deep-marine deposits that are described in different ways, but computers and people from other subjects do, due to the lack of an inherent understanding of context. Such a difference between descriptions of deep-marine geological data also reflects that the understanding of the relationship between clastic rocks and deep-marine deposits is not unified among geologists.

The proposed knowledge model can support geologists to have a unified ontological point of view to analyze and describe geological data, by proposing clear relationships among different Deep-marine Depositional Units, Clastic Rocks, and corresponding Geological Processes (Figure 6.2). With the assistance provided by the knowledge model and this relationship figure, both geologists and people who are less experienced in geology can understand what geological data geologists are describing.

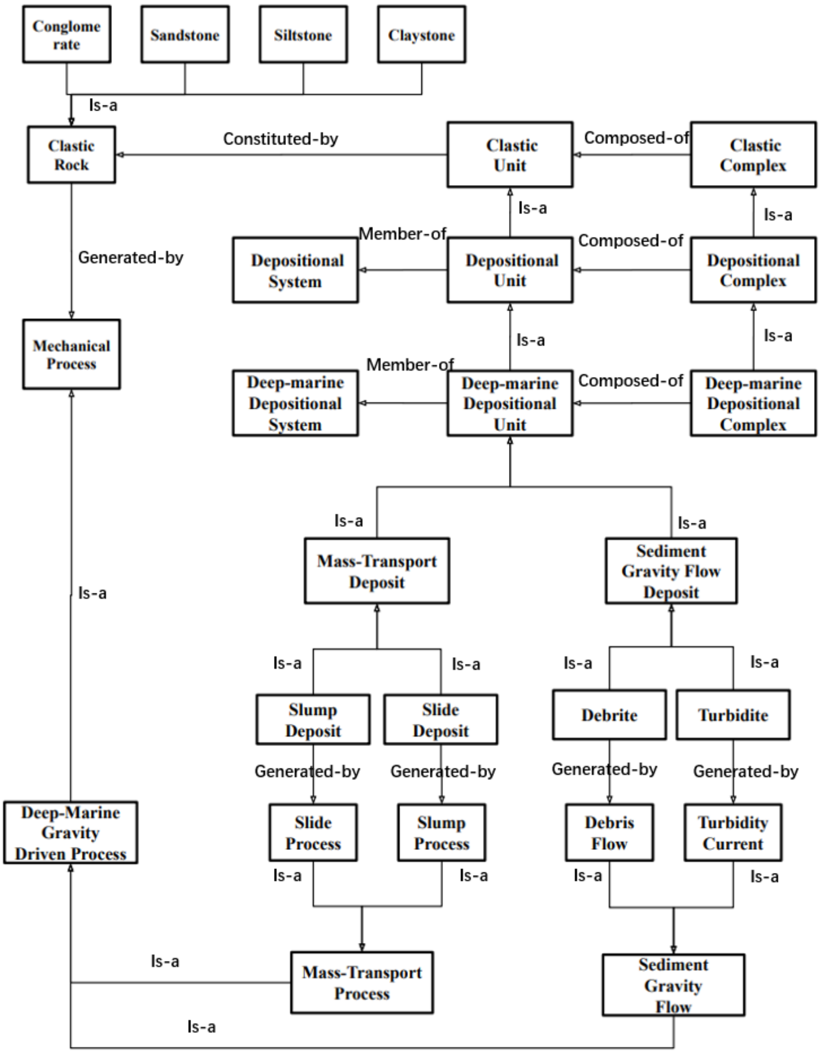


Figure 6.2 Entities of the deep-marine deposits, clastic rocks, the corresponding geological processes, and their relationships in the sense of the proposed model.

Deep-marine deposits and their processes have been studied over decades, however, the classification of debrites has no unified conclusion. The controversial point is whether the debrite is a mass-transport deposit or not. Some geologists conclude debrite as the mass-transport deposit, while some classify it as the deposit generated by sediment gravity flow (Arnott, 2010; Meckel, 2010; Nelson et al., 2011; Posamentier and Martinsen, 2011; Shanmugam, 2006). Again, the knowledge model is not aiming to give a new definition and convince other geologists, but provide a different perspective to discuss. Mass-transport and sediment gravity flow are two types of deep-marine gravity-driven processes. From an ontology point of view, intelligibility is a principle that guides ontology development, which is to make sure the knowledge is understandable for those who are interested in it (Smith, 2006). Following this principle, geological terms in the knowledge model should be understandable not only for geological professionals but also for experts in other related disciplines. Thus, it is more sensible to classify a debris flow as a sediment gravity flow rather than a mass-transport process, since semantically speaking, debris flow is a type of flow instead of a mass movement. Thus, if a debris flow is a sediment gravity flow, then the deposit of this flow is no longer a kind of mass-transport deposit. The classification of the Debris Flow (Def.97), Debrite (Def.62), and their relationship is defined in chapter 4 and also presented in Figure 6.2. The principle of intelligibility could also assist geologists to separate the differences among “turbidite system”, “submarine fan system” and “deep-marine depositional system” by the semantic meaning, although to some degree these terms are mixed up in use by geologists.

6.1.3 Lithofacies

What is the difference between the term lithofacies in geology and the ontology-based knowledge model? In what perspective can this knowledge model assist the digitalization and storage of the geological data?

Lithofacies is one of the most frequent terms used by sedimentologists. Mutti and Ricci Lucchi (1978) defined the lithofacies as a single stratigraphic unit or a group of stratigraphic units (facies association) that are indicated from adjacent units by the lithology features, stratification, sedimentary structures, and texture. Description of lithofacies is essential for sedimentology study since it could allow geologists to infer the genesis of deposits. The lithofacies in the knowledge model is similar but different from the geological definition. Based on the study of Carbonera et al. (2015), in this proposed knowledge model, as the definition in chapter 4, the Lithofacies is a *Generically dependent continuant (BFO).* The ontological analyses of the Niger delta basin and Ainsa-Jaca basin in chapter 5 has demonstrated the difference of lithofacies between geological view and ontological view. In the traditional geology point of view, as the definition above, lithofacies is a characterization as a stratigraphic unit. This means that it is a unit that physically exists in reality. However, in the knowledge model, an instance of

Lithofacies is an instance of a complex of *Qualities (BFO)* that inhere in the bearer. Hence, an instance of lithofacies can migrate from one bearer (Clastic Unit) to other bearers (Clastic Units), instead of referring to a geological unit or layer in reality that has a specific value of grain size, sorting, etc. In the study of Zhang et al. (2015) and Bell et al. (2018), both authors are using mudstone as a lithofacies in their study. It is clear that authors are using this lithofacies to refer to all mudstone units/layers that are found in their core logs or outcrop logs. In the knowledge model, the mudstone Lithofacies is concretized as the Grain Size, Sorting, and other *Qualities (BFO)* with particular values and these *Qualities (BFO)* inhere in a bearer (Deep-marine Depositional Unit). And the mudstone Lithofacies can migrate from one bearer to other bearers in any possible data. Therefore, in the knowledge model, the Lithofacies itself doesn't represent any material in reality. This aspect will bring benefits for geologists to consider what is the intended meaning of lithofacies, and what are they recording, analyzing, and presenting about the lithofacies: the *Rock* (Geocore), the Clastic Unit, or *Quality (BFO)*. Lithofacies such as fine-sandstone, mudstone are no longer a unit, but a set of *Qualities (BFO)* with particular values that can migrate from one bearer to other bearers. This will reduce the complexity of data storage and digitalization. Informatic specialists don't need to keep the separation between rock and lithofacies, and enumerate all possible types of clastic rock with various types of grain size and sorting to match the lithofacies that are defined by geologists. This can increase the succinctness and efficiency for a computer application.

6.1.4 Relative geological terms for a single entity

The scenario that geologists use relative geological terms to describe a single entity is problematic, so how can the knowledge model bring benefit to reduce it? This scenario is not referring to those misused terms for established nomenclatures. For example, Mutti (1999) used the term turbidite to refer to deposits of the sediment gravity flow instead of the turbidity current). Instead, this scenario is referring to terms that are describing relative entities and misused by geologists for a single entity (Shanmugam, 2006).

In the domain of the deep-marine clastic depositional system, a good example of this scenario is the channel lateral migration/stacking/amalgamation/accretion. It is common for geologists to use "lateral migration channel", "amalgamated channel complex", "lateral stacking channel", "lateral accretion package", etc. to describe an instance of the Channel Complex that they find on the outcrop or through seismic data (Figure 6.3). Geology professionals can notice the differences, and conclude them as different entities, while it is not easy for those who are less experienced in this domain. In the paper of Abreu et al. (2003), authors use the term "lateral migration" as a geometry pattern and the term "lateral accretion package" as the body of this geometry pattern. By using the proposed knowledge model as a filter, the lateral migration should be considered a *Process (BFO)*, which has a starting time and ending time as its *Process boundary (BFO)*. The channel accretion refers to the deposits generated by the lateral migration, which is a *Material Entity (BFO)*. For the example Channel Complex in Figure 6.3, accretions are Channel Elements except for the first Channel Element. Thus, accretion is not presented in the model since it is sufficient to use Channel Elements to describe accretion, which is the result of the lateral migration. The Lateral stacking is a value of the Stacking Pattern in the knowledge model, and both Stacking Pattern and Sand Amalgamation are *Relational Quality (BFO)* that inhere between Channel Elements. Terms such as bioturbation, ichnofabric, and trace fossil could also be distinguished by applying this knowledge model. With the ontological analysis of the proposed model, it is much more clear and easier for a geological data user to understand different geological terms than before. It assists geologists in considering what entities are they describing, and what terms they should use, which makes geological data more explicit.

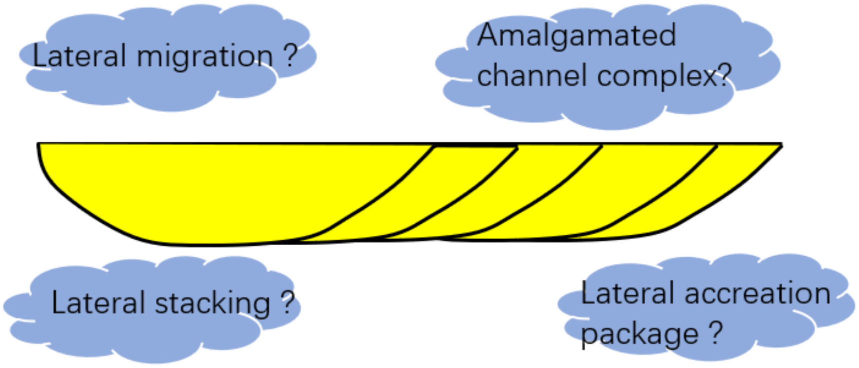


Figure 6.3 An instance of the Channel Complex, several geological terms are here to describe this entity.

6.1.5 Hierarchical classification

Comparing with classic geological hierarchical classifications, what difference is brought by the hierarchical classification in the ontology-based knowledge model? How can geologists benefit from it? The hierarchical classification of the deep-marine elements is essential for understanding the deep-marine clastic depositional system, many geologists based on their research area were trying to conclude universal hierarchical levels for deep-marine channels and lobes (Abreu et al., 2003; Mayall et al., 2006; McHargue et al., 2011; Pickering et al., 1995; Pickering and Cantalejo, 2015; Prelat et al., 2010; Sprague et al., 2005). However, as the related work made by Cullis et al. (2018) concluded that establishing a unified hierarchy is still challenging.

In the general geology study of the deep-marine clastic depositional system, the main hindrance of establishing a standard hierarchy is the scale problem. Through observations to find correlations or connections are vital for scientific researches, especially in geology. By observing and analyzing different geological data, researchers can suggest diverse levels of hierarchy, some of the researchers may conclude that each hierarchical level has its own range values of measurements (e.g. width, length, and thickness) and clastic forming durations. These different range values of measurements are sometimes controversial to results from other studies, which makes the unification difficult. Besides, some geologists suggest that even the smallest scale of channel or lobe, it still composed of channel or lobe stories (Prelat et al., 2010; Sprague et al., 2005), which makes the hierarchical classification more complicated.

In this thesis, four hierarchical orders of channel and lobe are presented in the model (Figure 6.4). For many geologists, the purpose of building a standard hierarchy is to recognize the hierarchical level of a channel or lobe through the thickness and width, and to have a comparative analysis. However, the nature of a channel or lobe in different hierarchical levels is characterized by its composition, instead of just through observations of width, length or thickness, or analysis of clastic forming duration. These measurements are empirical concerns rather than ontological ones, and the correlation is “possible” instead of “necessary”. And this is also the reason that geologists always find exceptions in the hierarchy. Hence, it is not necessary to define a range of values of Width, Length, Thickness, and Clastic Forming Duration for different hierarchical levels of Deep-marine Depositional Complexes. Figure 6.4 illustrates the relationships between lobes/channels in four hierarchical orders. Combing with Figure 6.2, Figure 6.4 also presents the relationships among channels/lobes, deep-marine deposits such as turbidite and debrite, and clastic rocks.

The proposed knowledge model not only provides an overview of lobes/channels, their different parts, and relationships in the deep-marine clastic depositional system, but also assists geologists to reconsider what entities are they observing and analyzing, is it a Channel Complex, a Channel Element, a Turbidite, or Clastic Rock. Though it is usual for geologists to evaluate the porosity or permeability of a Channel Element or a Clastic Unit, all these attributes are actually describing the rocks that constitute a Clastic Unit, and Clastic Units constitute a Channel Element. Besides, the knowledge model avoids the complexity caused by the viewpoint that “the smallest scale channel/lobe is still composed of several channel/lobe shape units”. Because the proposed knowledge model established the relationships of hierarchy, if the smallest scale channel is still composed of several channel shape units, then it is not the smallest scale.

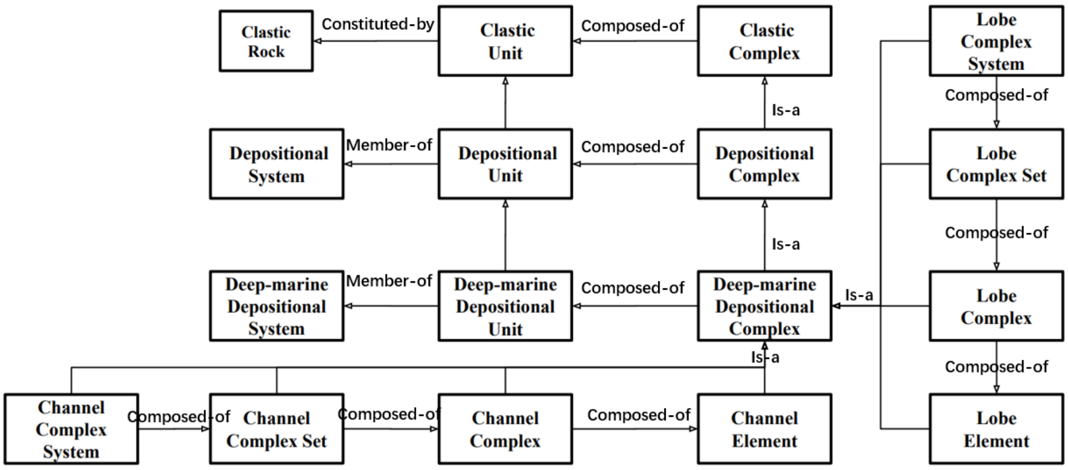


Figure 6.4 Four hierarchical orders of the channel/lobe in the knowledge model of the deep-marine

6.2 Guidance for sedimentology subfields

Besides describing the entities in the deep-marine clastic depositional system, another benefit brought by the ontology-based knowledge model of the deep-marine clastic depositional system is providing a general direction and backbone for developing other sedimentology subfields domain ontologies.

The Sedimentary Process in the model is the root for modeling any events in the sedimentology domain, the Biochemical Process, Mechanical Process, and Chemical Process allow geologists and ontologists to have the basic but fundamental division of the geological events. Depending on the focusing scale of the sedimentology domain, researchers can add more entities to this structure, such as erosion, transportation, and depositional processes. As subsection 6.2.1 discussed, based on the *Temporal Region (BFO)* and *Geological Time Interval (GeoCore)*, the Clastic Forming Interval could help geologists to describe the time interval of the target formation. And geologists can have a more detailed division depending on their needs.

The ontology-based knowledge model could support the development of the knowledge base of a computer application knowledge-based system to perform sedimentological data storage and analysis. For example, Rocks and Sedimentary Rocks are many, in this thesis, the knowledge model presents the classification of the Clastic Rock based on the Grain Size in different values. This succinct classification shows what essentially are sandstone, siltstone, claystone these geological terms, how they are related to each other, and to the Clastic Rock. A conventional database shall enumerate all sandstone data it has to be able to reason about any given sandstone is clastic rock. But with the support of the ontology-based knowledge model, a knowledge base has no need to do this, because it knows the fact about what is sandstone and clastic rock (Jarke et al., 1989). Based on this knowledge model and the taxonomy, geologists have a root to expand the knowledge model to describe other sedimentary rocks.

Besides, section 4.4 has presented "what is seismic data and its relationship with reality" in a point of view from the knowledge model. As an essential tool for geologists to understand the feature of subsurface, it is natural for geologists to link geology bodies in seismic profile to reality. However, for some geophysicists or data engineers, the seismic data are just some reflection signals that can be expressed by equations. Therefore, it is important to illustrate what seismic data is with reality, based on the Information Artifact Ontology. The model in section 4.4 provides a backbone for future expansion with the various aims of seismic data.

In general, the ontology-based knowledge model of the deep-marine clastic depositional system establishes a taxonomy that could also be used as a guidance for building ontology-based knowledge models in other depositional systems, especially for other clastic depositional systems. Different sedimentological bodies can be concluded as different instances of the Sedimentary Object, the Clastic Unit provides the minimum focus of an *Object (BFO)* in any clastic depositional system, and the relation between Clastic Unit and Clastic Complex clarify the relation between a sedimentological research body and its multiple parts. While the relation between Clastic Rock, Clastic Unit, and presented *Qualities (BFO)* would help researchers understand what the essential difference among different types of rock is, such as sedimentary rock, clastic rock, sandstone, turbidite, slump, etc. that geologists concerning about. The presented *Qualities (BFO)* are applicable in the various clastic depositional systems, and researchers could add and delete Qualities (BFO) for developing ontologies in different sedimentology domains.

6.3 Comparison with related works

The Deep-Marine Architecture Knowledge Store is a relational database developed by Cullis et al. (2019), which is aiming to assists researchers in both pure and applied science to have quantitative comparative analyses and characterization of deep-marine depositional system. Comparing with this relational database, though the motivation and the goal aiming to solve are similar, the knowledge model of the deep-marine clastic depositional system takes a few steps forward.

First and foremost, the knowledge model is based on well-found ontologies, that is to say, this model is not only building a standard for geological data integration but also providing a knowledge base for the future development of the computer-assisted sedimentological analysis.

This would help the computer application to understand and answer including but not limited to “what is it” in deep-marine sedimentology. For example, the relational database store facies as the smallest entities that can be described in the database and contained in a single element, which includes texture, grain size, and sedimentary structure, etc. However, it didn’t define the relations between these components in the facies and the single element.

Secondly, due to the different observation scales and various ranges of measurements, the DMAKS doesn’t come up with common hierarchical orders for its elements, instead, it uses child-parent order to do comparative analyses. In the scope of the proposed model, as subsection 6.2.5 discusses, the different correlations between the range of measurements and the hierarchical orders are not a necessary correlation. Thus, a clear hierarchical classification is presented in the proposed model, and it could make the hierarchical identification easier.

Furthermore, Cullis et al. (2019) integrate and store data from diverse sources by creating standard sedimentological data. However, it doesn’t answer what are those sedimentological data, and their relationships in reality. On the contrary, sections 6.2 and 6.3 have discussed how this proposed ontology-based knowledge model assists geologists and other experts in geological data collecting and organizing, and reduce the ambiguities from the beginning when geologists collect data.

Having a similar goal to reduce the heterogeneity of geological data, comparing with the GeoSciML model, the biggest difference and advantage that the ontology-based knowledge model in this thesis brought is the ontological analysis. The model of the GeoSciML is not resting on any top-level ontology, and does not have an explicit ontology behind it. To some degree, both the GeoSciML model and the GeoCore ontology are describing the existence of natural beings in the geoscience domain, however, the GeoCore Ontology as a core ontology is resting on the Basic Formal Ontology, which provides a solid framework to analyze the essential differences and similarities among geological entities. The ontology-based knowledge model of the deep-marine clastic depositional system is rooted in the Basic Formal Ontology and the GeoCore Ontology, therefore, it provides an explicit ontological view in the domain of sedimentology, especially in deep-marine depositional system domain. It not only answers “what is this geologic entity” in the geological point of view but also answers “what are essential differences of different geological entities” or “what kinds of relations among different geological entities”, etc. These answers shall help geologists and other experts to limit complexity and improve data collecting.

6.4 Future potential

This thesis is focusing on building the deep-marine clastic depositional system content in an ontology-based knowledge model rather than on the computational tools and details of ontology implementations. The first perspective that this work needs to be done is to transfer the confined natural language to a formal logic language. This would make the model more explicit and computer-readable, and prepare for the future expansion of the computer-assisted sedimentological data analysis and storage.

In the domain of the deep-marine sedimentology, some perspectives have remained to be further studied and considered in the present model. This thesis has been working on the main geological entities in the deep-marine depositional system and leaving apart some entities in the deep-marine sedimentology. First of all, rocks such as carbonate rocks and salt, which are also important in the depositional system and petroleum exploration need to be modeled in the future. More importantly, extrabasinal factors (allogenic factors) such as climate, global sea-level variations, sedimentary sequence, and provenance type are not considered in this model, which have an obvious influence on the deep-marine depositional system.

A well-described knowledge model is essential, but a large volume of data that covers various deep-marine sedimentology data is also important. This thesis has used data from the Niger delta basin (Zhang et al., 2016; Zhang et al., 2018; Zhang et al., 2015) and the Ainsa-Jaca basin (Bell et al., 2018), more data from different outcrops or subsurface would allow the knowledge model to be more complete and allow the computer programs not only do fully architectural descriptions, but also comparative analyses with quantitative characterization.

7 Conclusion

The proposed ontology-based knowledge model seeks to capture the essentials and formal representations of concepts in the deep-marine clastic depositional system. This model shall provide geologists a unified view of deep-marine sedimentological knowledge over reality. To achieve this, the knowledge model describes important entities and their relationships in the deep-marine clastic depositional system. It not only describes these entities in a way that the geology community would agree with, but also explore the essential differences and similarities among them, and properties that characterize these entities. Thus, the heterogeneity in the deep-marine clastic depositional system will be reduced, and the intelligibility of geological data among specialists with different backgrounds will be increased.

The following benefits have been derived from the knowledge model:

- A new scope for geologists to review the geological terms that describe different geological entities, the intended meanings of these entities and their relationships, especially in the deep-marine clastic depositional system.
- A defined framework that separates essential processes in the deep-marine clastic depositional system, clarifies the deposits that are generated by these processes and their relationships with clastic rocks.
- The differences of lithofacies in geology and knowledge model view, and the relation between lithofacies, clastic rock, and deep-marine deposits.
- A distinction between interval and duration in geology concepts. The knowledge model demonstrates the distinction between geological age, geological interval, clastic forming duration, and clastic forming interval, which assists in differentiating geology concepts that involve time.
- A robust hierarchy for deep-marine channels and lobes. This hierarchy proposed by the knowledge model focuses on the necessary correlation between each hierarchical level rather than possible correlations (e.g. a fixed range of measurements).
- Reducing ambiguities that geologists use relative geological terms to describe a single geological entity.
- An outline for the future development of knowledge models in other sedimentology domains.

The knowledge model in this thesis is one first step forward from the natural geological language to a defined ontological description. Though the model is not perfect and still needs external informatics support to make it formal, it demonstrates a baseline of how to digitize sedimentology knowledge for future knowledge-based systems or artificial intelligence. Such computer programs shall assist geologists to perform various subsurface or outcrop analyses. As more geoscientists begin to use ontologies to analyze the geological knowledge, with the development of the techniques to reduce the uncertainty of geological data, there is no doubt that the computer-based analysis of sedimentological data will enter a new stage, which will bring advantages to the academia and industry.

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