Glacial Sedimentological Interpretation from Microresistivity Images, Al Khlata Formation, Oman*

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Abstract

High-resolution borehole microresistivity images from 14 vertical wells were used for glacial sedimentological interpretation in a field in Oman. The interpretation was based mainly on the characteristics of glacial depositional environments, as depicted in the images. The characteristics involve sedimentary lithotypes and deformation sedimentary structures, such as diamictites, crossbedded pebbly sandstones, sandstone breccias, dm-scale faults, sandstone steep beddings, and slump structures. Diamictite deposition is associated with the glaciolacustrine depositional environment, and crossbedded pebbly sandstones correspond to glaciofluvial depositional processes. The breccias, faults, steep beddings, and slump structures indicate ice-contact glacial depositional processes, which were caused by collapse of supporting ice when buried ice melted away. These glacial-specific characteristics are easily recognized on the borehole microresistivity images, which provide continuous records of sedimentary features along well trajectories. These glacial-specific characteristics are difficult to recognize on conventional openhole logs and in poor-resolution seismic data.

The 14 wells cover an area of about 400 km^2, and the minimum extent of space between 2 of the 14 wells is about 2.4 km. The main challenge to the sedimentological interpretation in this field was that the glacial deposition caused extremely rapid vertical and lateral variability of lithofacies and completely unpredictable geology. There was poor seismic resolution of the field and limited available core data; only one 18-m-thick core was acquired in this field. Hence, the 14-well borehole microresistivity image data was the main resource for the sedimentological interpretation.

The paper highlights the glacial sedimentological interpretation of the 14 wells and demonstrates how to set up a conceptual sedimentological model for further development of a 3D facies model. The case study in this paper improved our understanding of the glacial sedimentological properties and reservoir characteristics of the field, and it also provided a new approach to maximize the usage of borehole image data to perform sedimentological interpretation in glacial depositional formations.

Introduction

The sedimentary facies in this case study formed in the Late Carboniferous−Early Permian proglacial depositional environments during deglaciation phases of the Al Khlata Formation in Oman. This formation is present widely in the subsurface of Oman. It has a wide range of thicknesses (100−800 m); the variability is largely due to syndepositional subsidence and erosional palaeorelief of the pre-Al Khlata Unconformity. The Al Khlata Formation consists of a complex package of clastic lithologies that range from conglomerates through diamictites, gravels, pebbly sandstones, and siltstones to silty shales. The sedimentary facies of this formation comprise glaciofluvial, glaciodeltaic, and glaciolacustrine lithofacies associations. Abrupt lateral and vertical changes of lithofacies in sediment type are characteristic of the depositional environments, which represent a selection of deposits from warm interglacial periods.

The main objectives of the geological study in the Al Khlata Formation were (1) to better understand the sedimentological characteristics, depositional evolution, and paleoenvironments to determine suitable water-disposal targets, and (2) to constrain the depositional setting and the likely areal and stratigraphic distribution of different facies types and assess the implications for the aquifer architecture.

To determine areas suitable for water disposal, a stratigraphic section or lithologic correlation between wells was very important. Palynology was the primary method of correlating the subsurface glaciogenic Al Khlata Formation of Oman, owing to the considerable lateral variability of lithofacies and the poor resolution of seismic data. However, it relied on a core sample and provided only discrete point data analysis. With the advent of high-resolution borehole microresistivity image tools and geostatistic techniques, it is possible to provide continuous records of sedimentary lithofacies and a 3D facies model for the stratigraphic section or lithologic correlation, as well as for the depositional environment interpretation.

Depositional Setting–Facies

Generally speaking, a facies is characterized by depositional-specific characteristic grouping and stacking patterns to interpret depositional processes and ultimately the depositional environment. In the 14 wells, five main facies associations with environmental significance have been interpreted within the Al Khlata Formation, which formed in proglacial and ice marginal environments during the Late Carboniferous−Early Permian deglaciation phases. A detailed description of each of these facies associations is given:

Facies Association 1–Rainout-debris flow diamictites (FA1) consist predominantly of massive and irregularly laminated diamictites. FA1 is mainly associated with the deposits of Facies Association 2 (FA2) and occasionally with the clean sandstones of Facies Association 4 (FA4).

Description: FA1 comprises diamictites with poorly sorted, highly argillaceous, fine- to very fine-grained siltstone matrix, with common “floating” granules and pebbles of various clast types. Clasts are predominantly extraformational, but rarely do intraformational diamictite clasts occur. Individual units are blocky in the gamma ray (GR) profile and are dominated by massive internal structure, with local faint, highly disrupted to deformed lamination visible on the borehole images. Locally developed stratification is often deformed.

Interpretation: The deposits of FA1 are believed to have formed by ice-contact deposition mainly from the rapid rainout of suspended sediment and ice-rafted debris onto the basin floor in a predominantly glaciolacustrine environment. Because most localized deformation is observed over rather small intervals of typically 1 to 2 m (only rarely up to 5 m), these features are believed to be unrelated to any (larger scale) tectonic events.

Facies Association 2–Glaciolacustrine deposits (FA2) consist predominantly of laminated (possible varved-like), slumped or disrupted shales; disrupted argillaceous sandstones; massive, disrupted, or slumped mudstones; and laminated or disrupted heterolithics. The deposits of FA2 are closely associated with those of FA1.

Description: FA2 is characterized by massive to very finely laminated mudstones to argillaceous sandstones with abundant, often extreme deformation. The fine lamination typically consists of clean siltstone laminae alternating with argillaceous sandstone to mudstone laminae. The observed deformation features are abundant and include slumping of the original lamination; small-scale, low-angle, syn-sedimentary fractures; and brecciation fabrics.

Interpretation: The presence of very finely laminated mudstones with diamictites is consistent with deposition in a glaciolacustrine environment. Common diamictites are evidence of an ice-contact lake, even though the actual ice cover could have been several kilometers away from the site of deposition. Argillaceous siltstone and mudstone laminae probably represent low-energy deposition from suspension in glacial lakes when glacial melt-out was suppressed. Interlaminated, coarser grained argillaceous sandstones, on the other hand, are believed to represent higher energy deposition by means of high-density meltwater streams.

Facies Association 3–Channelized glaciofluvial conglomerates and pebbly sandstones (FA3) consist of laminated to massive, crossbedded, pebbly sandstones and, to a lesser extent, massive conglomerates. FA3 is closely associated with the deposits of FA4.

Description: FA3 comprises matrix-supported to locally clast-supported conglomerates and pebbly sandstones. Conglomeratic units are mostly massive and the clasts are supported predominantly by a clean sandstone matrix. Pebbly sandstones are medium to coarse grained, crossbedded, with a variety of deformation, such as slumping, tilting, and faulting; particularly the tilting and faulting are very developed.

Interpretation: The coarse grain size and crossbedded appearance of the FA3 deposits are believed to indicate high-energy deposition by glacial meltwater streams. The deformation of slumping, tilting, and faulting is indicative of ice-contact glacial deposits by collapse of supporting ice when ice melted away.

Facies Association 4–Channelized glaciofluvial sandstones (FA4) consist predominantly of massive and crossbedded sandstones. FA4 is closely associated with the deposits of FA3 and is occasionally interbedded with diamictites of FA1.

Description: FA4 comprises fine- to coarse-grained sandstones organized into blocky or weakly upward-fining units with abundant crossbedding and occurrence of slump structures. Pebble horizons, comprising both intraformational shale clasts and extraformational lithic clasts, occur at the base of beds overlying erosional surfaces. This facies association commonly occurs overlying and interbedded with the channelized conglomerate association (FA3).

Interpretation: The presence of frequent crossbedding and erosive bed bases suggests that tractional currents under a predominantly fluvial regime deposited these sandstones. It is believed that the deposits of FA4 represent fluvial channel sands deposited on a broad, braided outwash plain fed by large volumes of meltwater from adjacent glacier or ice sheets. In addition, the occurrence of diamictites (FA1) and pebbly sandstones (FA3) suggests these sediments may represent the extensive reworking of earlier glacial deposits. However, some sandstones with slump structures suggest the imprint of glacial deposition on stagnant ice under ice-contact glaciofluvial depositional environments.

Facies Association 5–Pooly confined glaciofluvial deposits (FA5) consist predominantly of massive sandstones with some rare pebble-grade conglomerates. FA5 is closely associated with channelized deposits of FA3 and FA4.

Description: FA3 comprises thick, largely trendless successions of horizontally bedded and low-angle crossbedded sandstones. Interbeds of massive sandstones are common. Very rarely, pebble-grade conglomerates occur in beds a few clasts thick.

Interpretation: The horizontally bedded and low-angle crossbedded and massive sandstones are indicative of upper flow-regime conditions and rapid deposition from hyperconcentrated flows, respectively. The presence of crossbedding indicates fluctuations in flow power. The trendless organization of much of this association implies an unconfined overland flow origin, while the examples that show fining-upward trends reflect minor channelization and streamflood origin. This facies association probably forms part of a glacial outwash plain or braid delta plain.

Sedimentological Interpretation

Identification of the specific characteristics of glacial sediments from the depositional settings is important to glacial sedimentological interpretation. Borehole microresistivity images provide continuous records of sedimentary features to enable the easy identification of glacial-specific characteristics and their grouping to interpret depositional processes, which complement the sedimentological interpretation of core data.

Figure 1 shows examples of the glacial-specific characteristics on the borehole images. The tilting, faulting, slumping, breccia and diamictite correspond to ice-contact glacial depositional processes, such as ice-contact glaciofluvial and ice-contact glaciolacustrine.

The Al Khlata Formation in this case study is subdivided from oldest to youngest into three geologic units of depositional evolution: Unit 1, 2 and 3.

Unit 1 paleocurrent directions in the north area are more scattered than those in the south area as shown in Figure 2.

In the north area of Unit 1, the deposits mainly include diamictites, massive sandstones, and massive pebbly sandstones associated with a variety of deformations. The deformations include tilting, faulting, and folding, such as high-angle beddings and minor faults in Well 13, Well 12, and Well 7. The diamictite deposition suggests a glaciolacustrine environment, while the tilted and faulted massive pebbly sandstones are indicative of ice-contact glacial deposits, which were caused by collapse of supporting ice when ice melted away. The sedimentary environment of the north area corresponds to an ice-contact glaciolacustrine environment, or ice margin lake, which involves the facies associations FA1, FA2, FA3, and FA4 (Figure 2 and Figure 3).

In the south area of Unit 1, the deposits mainly include crossbedded sandstones, massive sandstones, and massive pebbly sandstones associated with a variety of deformations such as tilting and faulting. The crossbedded sandstone depositions suggest a glaciofluvial environment because the deposits involve transportation by meltwater streams; these deposits exhibit better sorting and stratification than diamictites. The tilted and faulted massive sandstone and massive pebbly sandstones are indicative of ice-contact glacial deposits, which were caused by collapse of supporting ice when postdepositional ice melted away. The sedimentary environment of the south area is believed to be an ice-contact glaciofluvial environment which involves the facies associations FA3, FA4, and FA5. The trend of the ice-contact glaciofluvial channel is parallel to the NE-SW direction (Figures 2 and Figure 3).

Unit 2 paleocurrent directions are generally more scattered than those in underlying Unit 1, except that the paleocurrent directions of Wells 4 and 2 are consistent with those of Unit 1 (Figures 2 and Figure 4). The scatter is believed to be the result of increased glaciolacustrine deposition in locally developed lakes, and the consistent direction suggests a remnant ice-contact glaciofluvial channel (Figure 4).

The Unit 2 deposits mainly include diamictites, crossbedded sandstones, massive sandstones, and massive pebbly sandstones associated with slumping, tilting, and faulting. The diamictite deposition suggests a glaciolacustrine environment; the slump structure and tilting and faulting exhibit ice-slump deformation that occurs when supporting ice melts away. Very strong evidence is the breccia from the interval of xx27.7 m to xx29.7 m in Well 4 (see the first slide in Figure 1), which was caused by collapse of supporting ice. Actually, postdepositional melting of ice can produce extensive internal deformation of sediments. The sedimentary environment found in this unit corresponds to an ice-contact glaciolacustrine environment, or ice margin lake, which involves FA1, FA2, FA3, FA4, and FA5. (Figure 4 and Figure 5).

Unit 3 is believed to represent the onset of the final warming stage and subsequent ice retreat. Melting glaciers formed deltaic deposits from the mass of sediments supplied by the rivers. The delta build-out, however, was restricted by the relative rise in lake level and diminishing sediment supply, because the actual sediment source was retreating. At maximum ice retreat, the lakes are believed to have covered the entire studied area, with mudstones blanketing the older deposits.

The scattered easterly sedimentary transport directions observed in this unit are believed to reflect deposition into such a rising lake environment (Figure 6).

The Unit 3 deposits mainly include crossbedded sandstones, massive sandstones, and massive pebbly sandstones. The crossbedded sandstone depositions suggest a glaciofluvial environment because the deposits involve transportation by meltwater streams; such deposits exhibit better sorting and stratification than diamictites. The scattered easterly sedimentary transport directions are indicative of a glacial braided outwash plain. Sediments deposited from glacial meltwater often have the imprint of glacial environments, such as the slumping that occurred in Well 13 during the period of the Unit 3 (Figure 7). Although mechanisms of transportation and deposition show similarities to those of other fluvial environments, large fluctuations in discharge on a daily, seasonal, or long-term basis produce abrupt particle-size changes and sedimentary structures that reflect the fluctuating discharges and proximity to glacials, such as the conglomerates and pebbly sandstones still observed in this unit. The sedimentary environment of this unit is believed to be a glacial braided outwash plain, which involves FA3, FA4, and FA5. (Figure 6 and Figure 7).

Single-Well Sedimentary Analysis

Well 1 intersects a succession of Unit 3 crossbedded, pebbly sandstones; Unit 2 diamictites and massive pebbly sandstones; and Unit 1 massive pebbly sandstones (Figure 8). As discussed, the Unit 3 deposits are interpreted to result from a glacial braided outwash plain environment, which involves FA4 (channelized glaciofluvial sandstones) and FA3 (channelized glaciofluvial pebbly sandstones). The Unit 2 deposits are interpreted to belong to an ice-contact glaciolacustrine environment, which involves FA1 (rainout-debris diamictites) and FA3 (channelized glaciofluvial pebbly sandstones). The Unit 1 deposits are interpreted to be an ice-contact glaciofluvial environment, which involves FA3 (channelized glaciofluvial pebbly sandstones).

Well 7 intersects a succession of Unit 3 crossbedded sandstones and crossbedded pebbly sandstones; Unit 2 shaly sandstones with slump structure and massive pebbly sandstones; and Unit 1 massive pebbly sandstones and trendless massive sandstones with a little diamictite (Figure 8). The Unit 3 deposits are interpreted to result from a glacial braided outwash plain environment, which involves FA4 (channelized glaciofluvial sandstones) and FA3 (channelized glaciofluvial pebbly sandstones). The Unit 2 deposits are interpreted to belong to an ice-contact glaciolacustrine environment, which involves FA1 (rainout-debris diamictites), FA2 (glaciodeltaic foresets), and FA3 (channelized glaciofluvial pebbly sandstones). The Unit 1 deposits are interpreted to be an ice-contact glaciolacustrine environment, which involves FA1 (rainout-debris diamictites), FA5 (poorly confined glaciofluvial), and FA3 (channelized glaciofluvial pebbly sandstones).

Well 2 intersects a succession of Unit 3 crossbedded sandstones and crossbedded pebbly sandstones; Unit 2 shaly sandstones with slump structure and a little diamictite, crossbedded sandstones, and trendless massive sandstone; and Unit 1 crossbedded sandstones and trendless massive sandstones (Figure 9). The Unit 3 deposits are interpreted to result from a glacial braided outwash plain environment, which involves FA4 (channelized glaciofluvial sandstones) and FA3 (channelized glaciofluvial pebbly sandstones). The Unit 2 deposits are interpreted to belong to an ice-contact glaciolacustrine environment, which involves FA1 (rainout or debris diamictites); FA2 (glaciolacustrine mudrock); FA4 (remnant channelized glaciofluvial sandstones); and FA5 (poorly confined glaciofluvial). The Unit 1 deposits are interpreted to result from an ice-contact glaciofluvial environment, which involves FA4 (channelized glaciofluvial sandstones) and FA5 (poorly confined glaciofluvial).

Well 8 intersects a succession of Unit 3 crossbedded, massive sandstones; Unit 2 massive sandstones and massive pebbly sandstones; and Unit 1 diamictites (Figure 9). The Unit 3 deposits are interpreted to result from a glacial braided outwash plain environment, which involves FA4 (channelized glaciofluvial sandstones). The Unit 2 deposits are interpreted to belong to an ice-contact glaciolacustrine environment, which involves FA3 (channelized glaciofluvial pebbly sandstones) and FA4 (channelized glaciofluvial sandstones). The Unit 1 deposits are interpreted to result from an ice-contact glaciolacustrine environment, which involves FA1 (rainout or debris diamictites).

Well 3 intersects a succession of Unit 3 crossbedded sandstones and crossbedded pebbly sandstones; Unit 2 trendless massive sandstones with a little diamictites; and Unit 1 massive pebbly sandstones and trendless massive sandstones with a little diamictite (Figure 9). The Unit 3 deposits are interpreted to result from a glacial braided outwash plain environment, which involves FA3 (channelized glaciofluvial pebbly sandstones) and FA4 (channelized glaciofluvial sandstones). The Unit 2 deposits are interpreted to belong to an ice-contact glaciolacustrine environment, which involves FA5 (poorly confined glaciofluvial) and FA1 (rainout-debris diamictites). The Unit 1 deposits are interpreted to result from an ice-contact glaciofluvial environment, which involves FA5 (poorly confined glaciofluvial) and FA1 (rainout or debris diamictites).

Well 4 intersects a succession of Unit 3 crossbedded sandstones and crossbedded pebbly sandstones; Unit 2 shaly sandstones with slump structure and a little diamictite, and crossbedded sandstones; and Unit 1 massive pebbly sandstones and crossbedded sandstones (Figure 10). The Unit 3 deposits are interpreted to result from a glacial braided outwash plain environment, which involves FA3 (channelized glaciofluvial pebbly sandstones) and FA4 (channelized glaciofluvial sandstones). The Unit 2 deposits are interpreted to belong to an ice-contact glaciolacustrine environment; very strong evidence is the breccia that was caused by postdepositional melting of ice. Unit 2 involves FA1 (rainout-debris diamictites), FA2 (glaciolacustrine mudrock); and FA4 (remnant channelized glaciofluvial sandstones). The Unit 1 deposits are interpreted to result from an ice-contact glaciofluvial environment, which involves FA3 (channelized glaciofluvial pebbly sandstones) and FA4 (channelized glaciofluvial sandstones).

Well 5 intersects a succession of Unit 3 crossbedded sandstones; Unit 2 diamictites and trendless massive sandstones; and Unit 1 crossbedded sandstones and trendless massive sandstones (Figure 10 or Figure 11). The Unit 3 deposits are interpreted to result from a glacial braided outwash plain environment, which involves FA4 (channelized glaciofluvial sandstones). The Unit 2 deposits are interpreted to belong to an ice-contact glaciolacustrine environment, which involves FA1 (rainout-debris diamictites) and FA5 (poorly confined glaciofluvial). The Unit 1 deposits are interpreted to result from an ice-contact glaciofluvial environment, which involves FA4 (channelized glaciofluvial sandstones) and FA5 (poorly confined glaciofluvial).

Well 6 intersects a succession of Unit 3 crossbedded sandstones; Unit 2 trendless massive sandstones and massive pebbly sandstones; and Unit 1 trendless massive sandstones and massive pebbly sandstones with a little diamictite (Figure 11). The Unit 3 deposits are interpreted to result from a glacial braided outwash plain environment, which involves FA4 (channelized glaciofluvial sandstone). The Unit 2 deposits are interpreted to belong to an ice-contact glaciolacustrine environment, which involves FA5 (poorly confined glaciofluvial). The Unit 1 deposits are interpreted to result from an ice-contact glaciofluvial environment, which involves FA5 (poorly confined glaciofluvial) and FA1 (rainout or debris diamictites).

Reservoir Characteristics

Based on the described sedimentary analyses and stratigraphic correlations of Units 1, 2, and 3, the reservoir and sedimentological characteristics of the field were analyzed as follows:

The Unit 1 depositional sequence forms good targets for water disposal in the field. However, the south and north areas of the field should be separately considered for this purpose; the sedimentary analysis of Well 8 exhibits the 69-m-thick (MD) diamictite that occurred in this period of the Al Khlata deposition (Figure 9).

The Unit 2 sediments are extremely difficult to correlate as a result of widespread successive erosion and deposition (numerous ice advance-retreat cycles). The ice-contact glaciolacustrine and ice-contact glaciofluvial deposits tend to be laterally discontinuous and isolated (ice margin lake and associated braid plain deposits).

Properties for water injection are generally not as good in Unit 2 as in the underlying Unit 1 sediments because of the more heterolithic content of the deposits. The finer-grained glaciolacustrine sediments tend to act as baffles to flow or might even prevent water injection altogether. Where reservoirs are present in the Unit 2 sequence, they are possibly in communication with those of the underlying Unit 1 deposits and occasionally with the overlying Unit 3 deposits.

The Unit 3 depositional sequence suggests another good target for water injection. The Unit 3 deposits exhibit better sorting and stratification than those of the underlying Unit 2 and Unit 1 sediments.

Conclusions

The high-resolution and large coverage of good-quality microresistivity images along the borehole wall make them indispensable for identifying these sedimentary structures and lithotypes, particularly in glacial depositional processes and environments. We observed a variety of strong evidence in the images reflecting glacial depositional features, such as slumping on stagnant ice; tilting and faulting due to supporting ice collapse; as well as diamictites, pebbly sandstones, and sandstones. We further validated all these depositional features and sequences using core data and outcrop observations. Moreover, borehole images have a unique advantage over core data; they can provide continuous records of sedimentary lithofacies associated with the orientation of depositional features, which also indicate directions of sediment transport.

Acknowledgements

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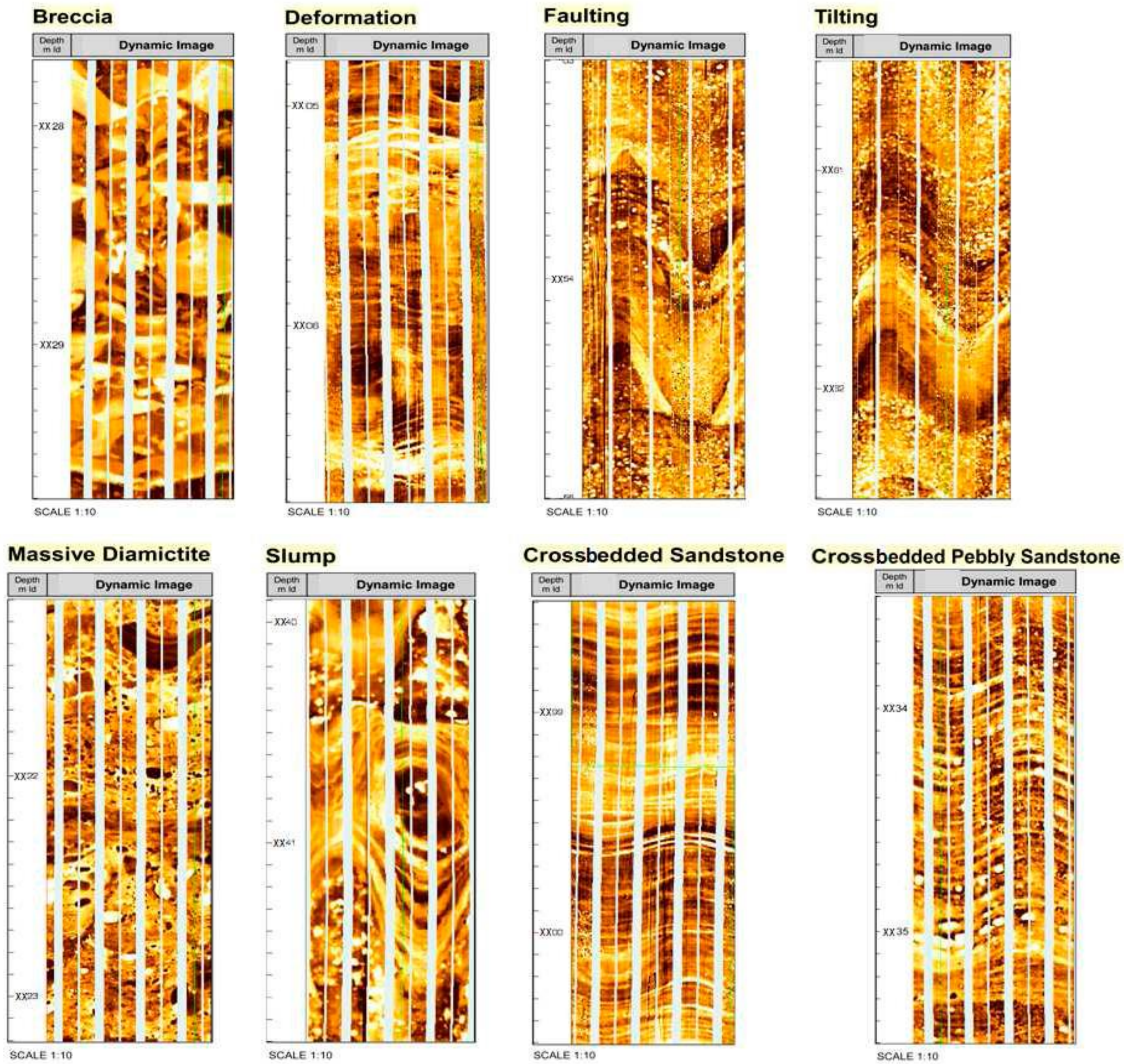

Figure 1. Examples of the specific characteristics of glacial depositional environments on borehole images.

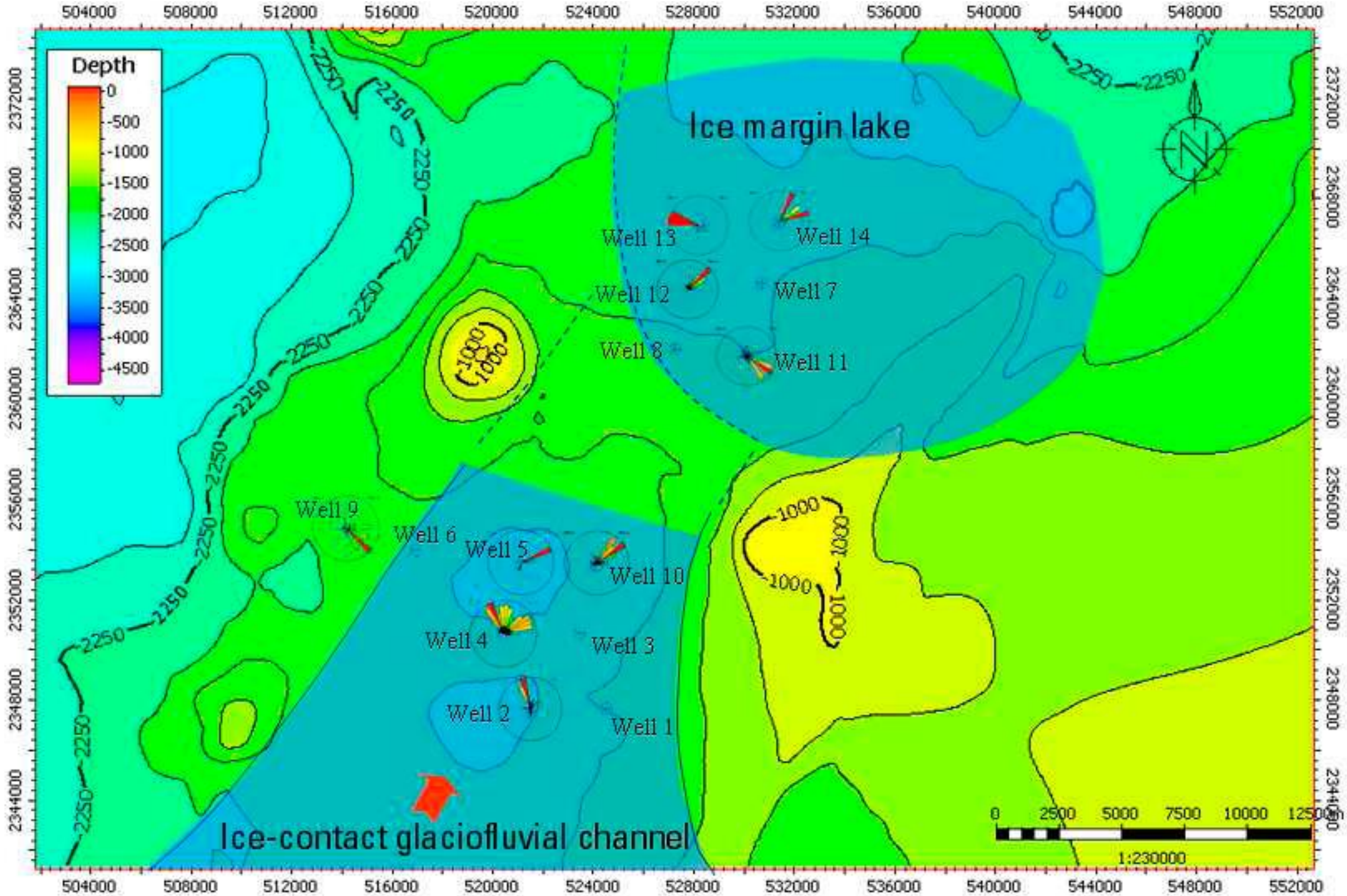

Figure 2. Geographical extent and Paleocurrent directions of Unit 1.

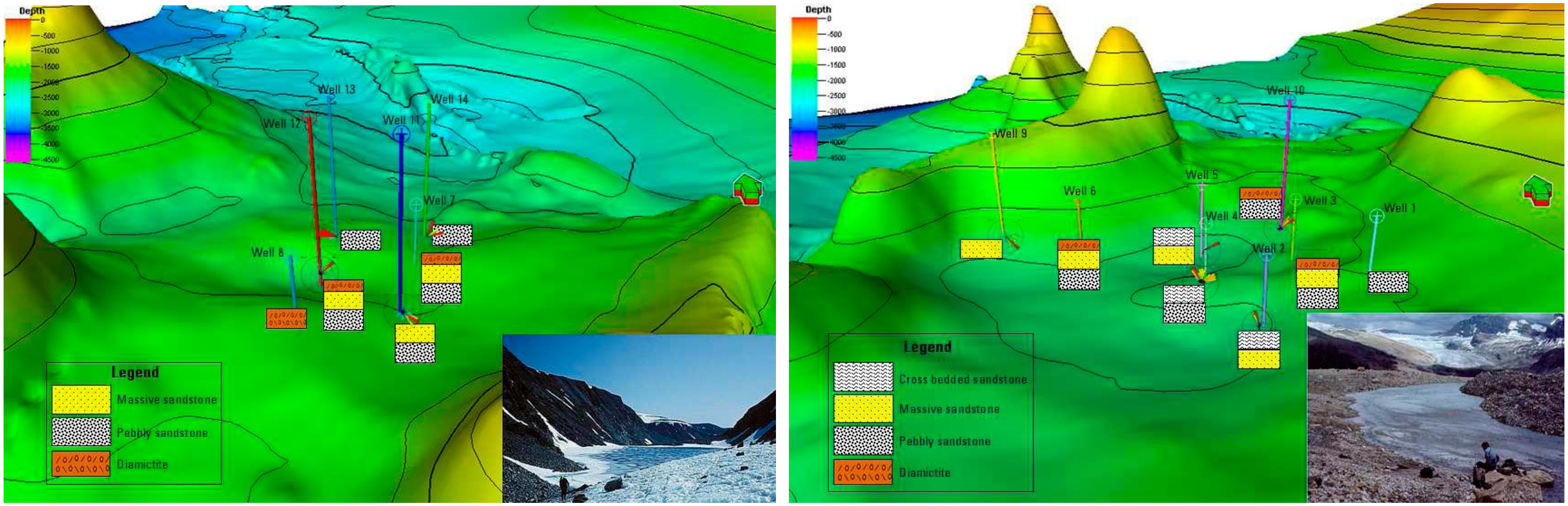

Figure 3. Paleocurrent and sedimentary environment interpretation of Unit 1 in the north area (left) and south area (right).

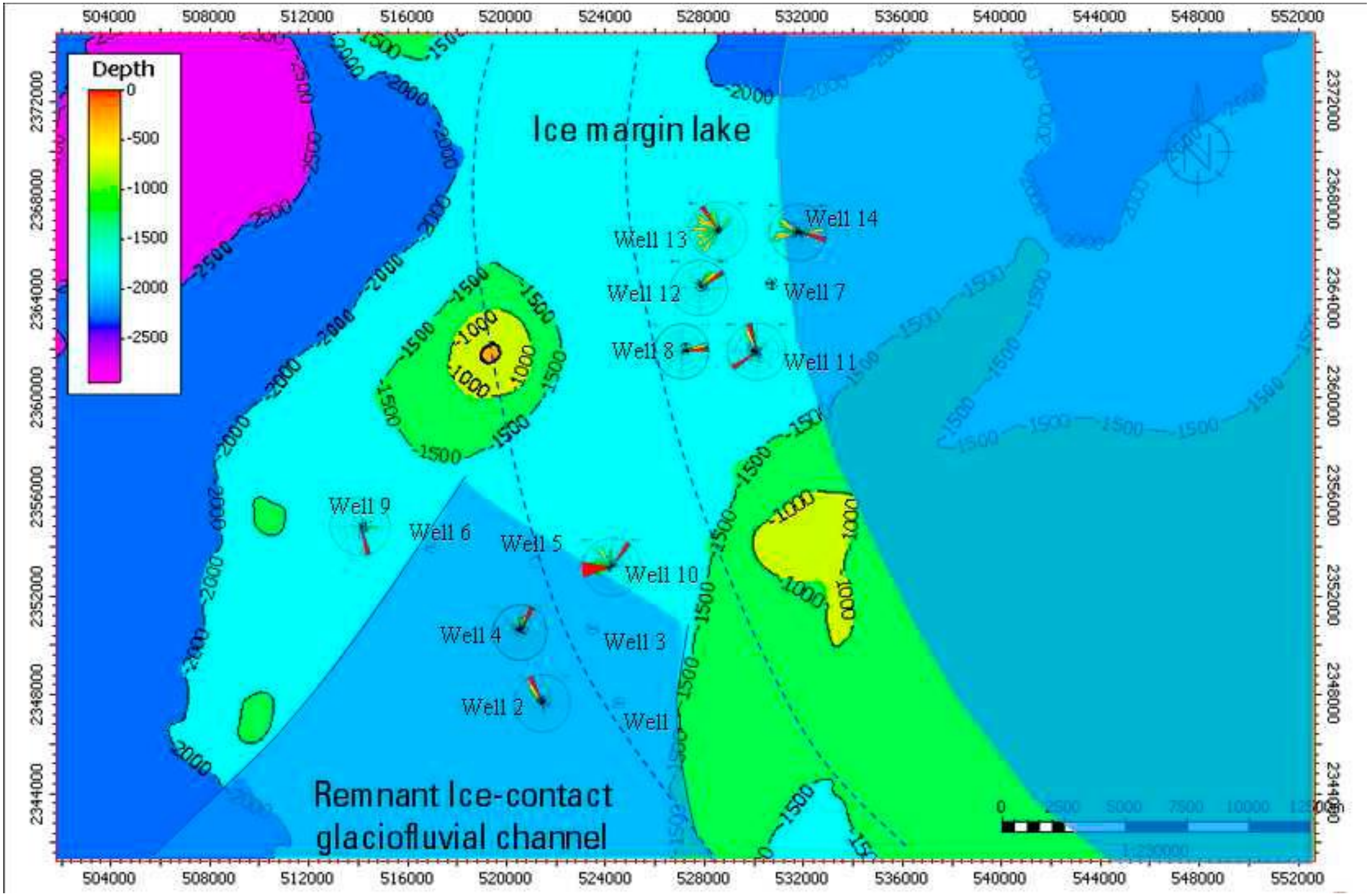

Figure 4. Geographical extent and Paleocurrent directions of Unit 2.

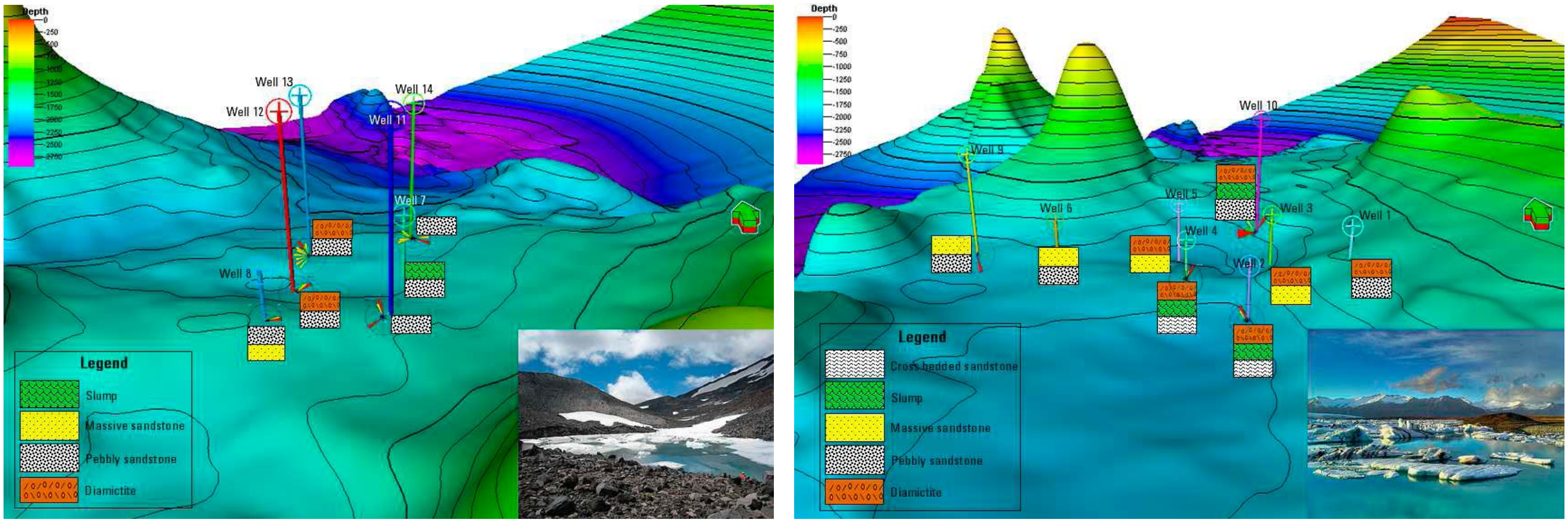

Figure 5. Paleocurrent and sedimentary environment interpretation of Unit 2 in the north area (left) and south area (right).

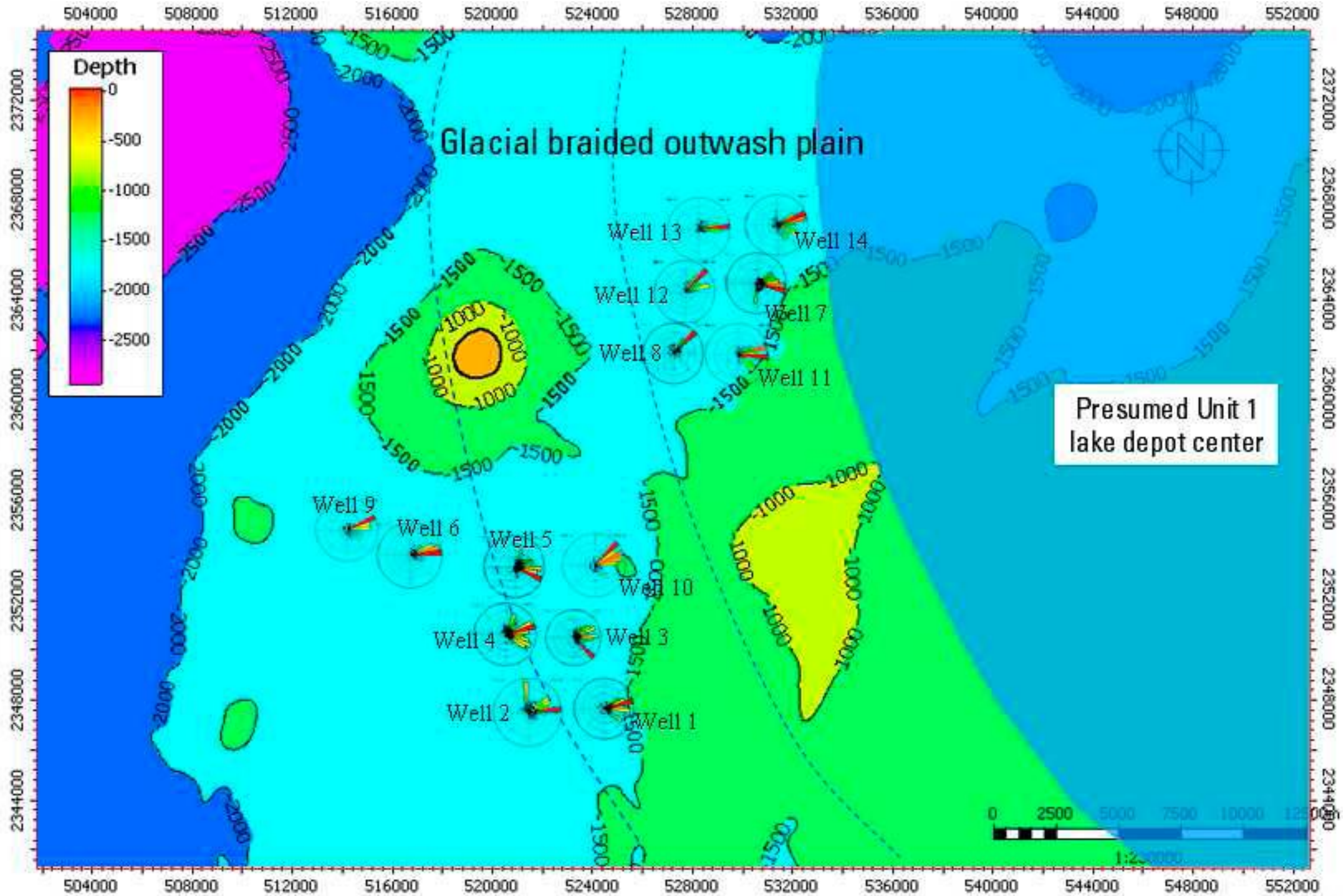

Figure 6. Geographical extent and Paleocurrent directions of Unit 3.

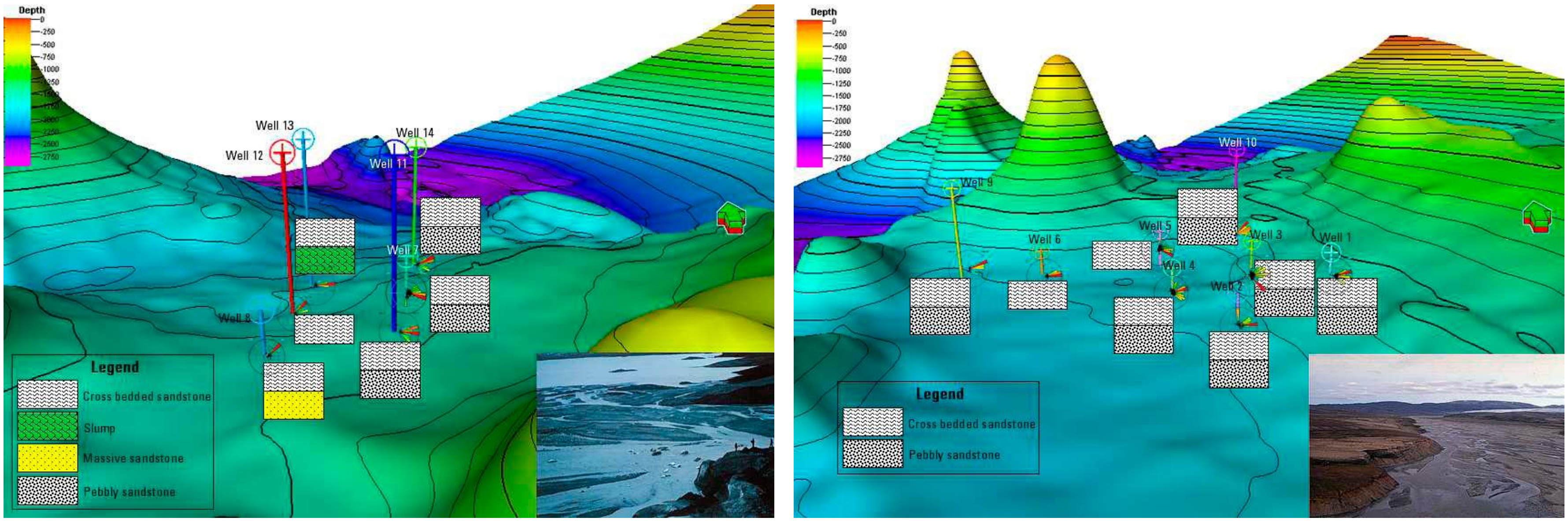

Figure 7. Paleocurrent and sedimentary environment interpretation of Unit 3 in the north area (left) and south area (right).

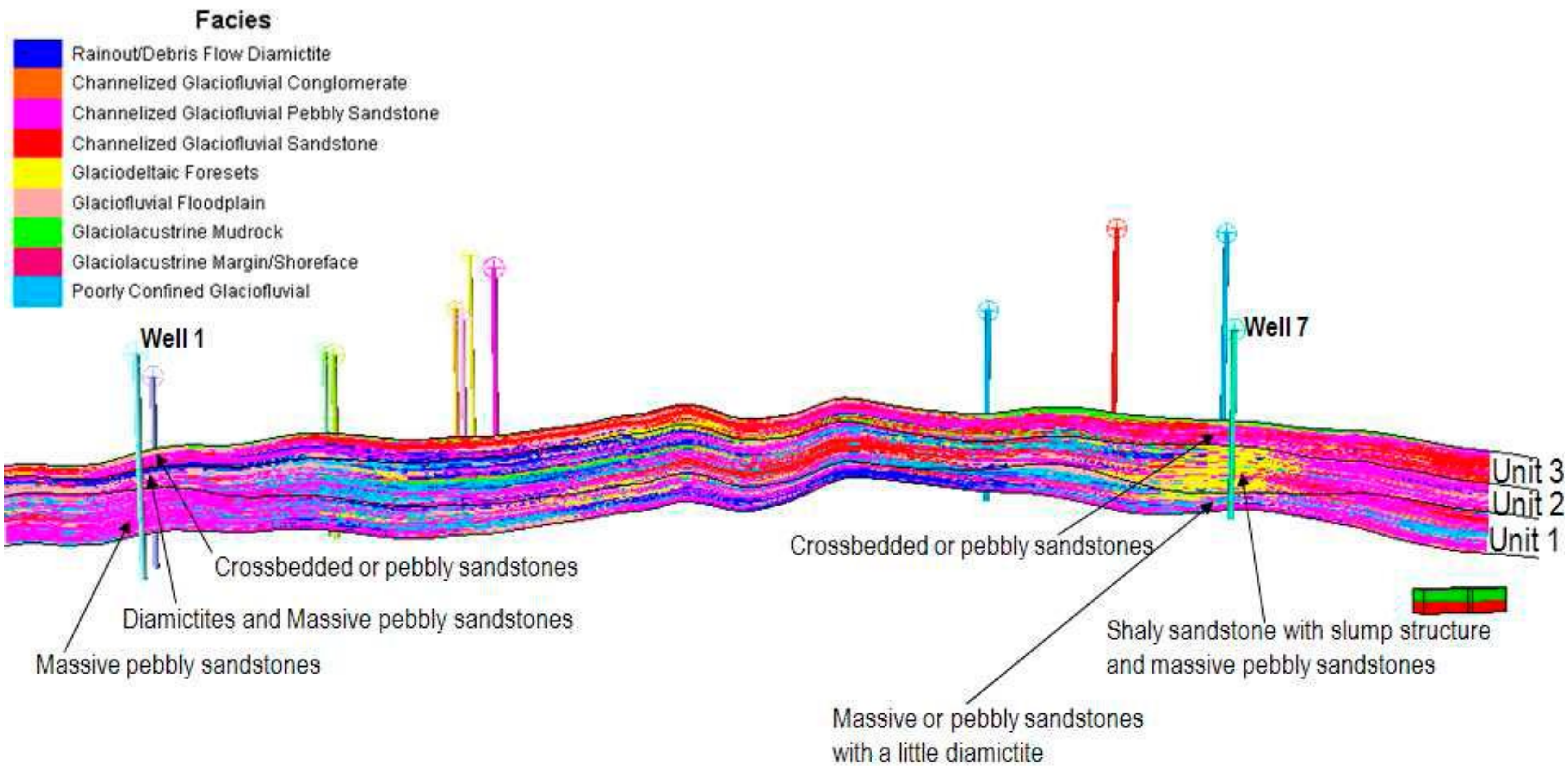

Figure 8. Facies cross section for stratigraphic correlation analysis between Well 1 and Well 7.

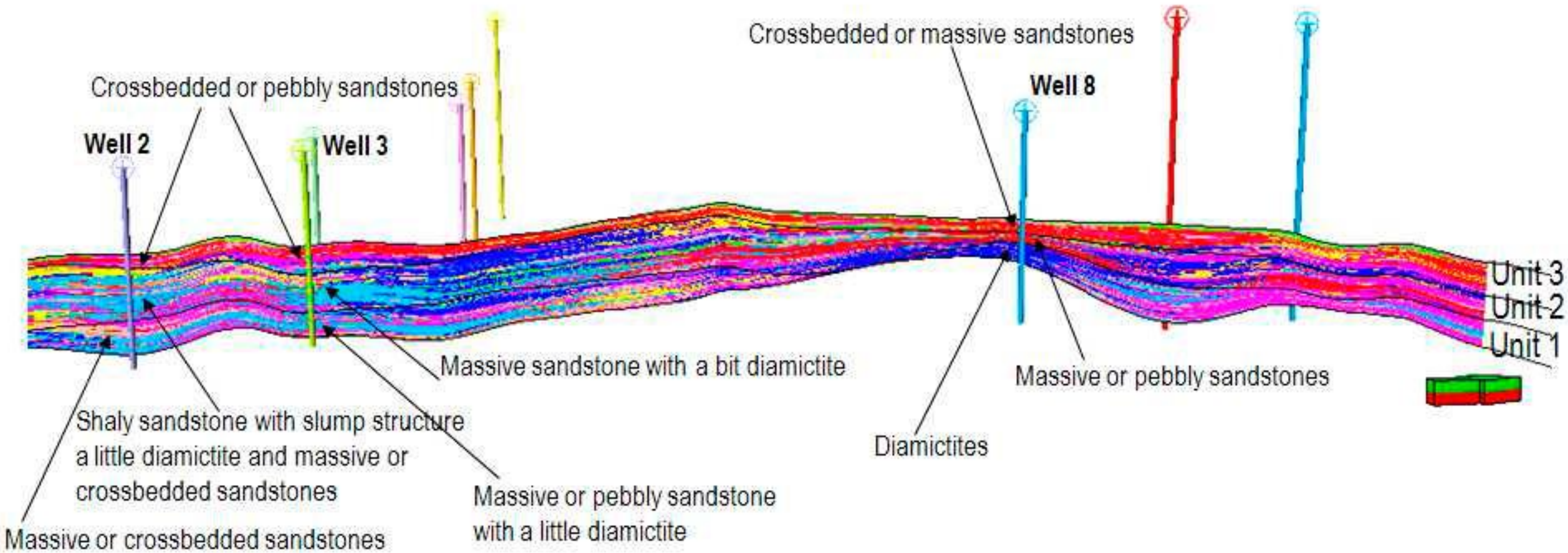

Figure 9. Facies cross section for stratigraphic correlation analysis of Well 2, Well 3, and Well 8.

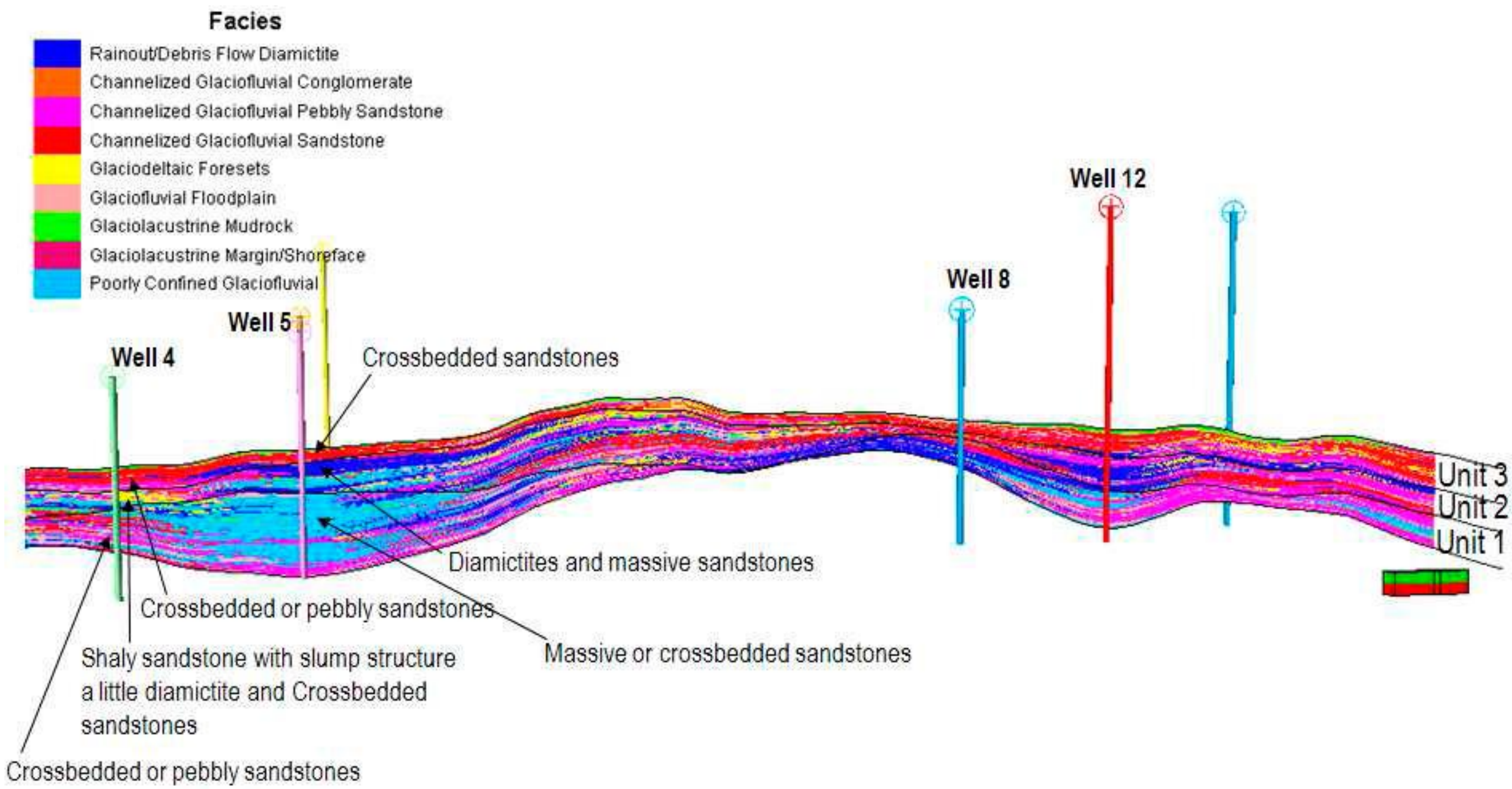

Figure 10. Facies cross section for stratigraphic correlation analysis between Well 4 and Well 5.

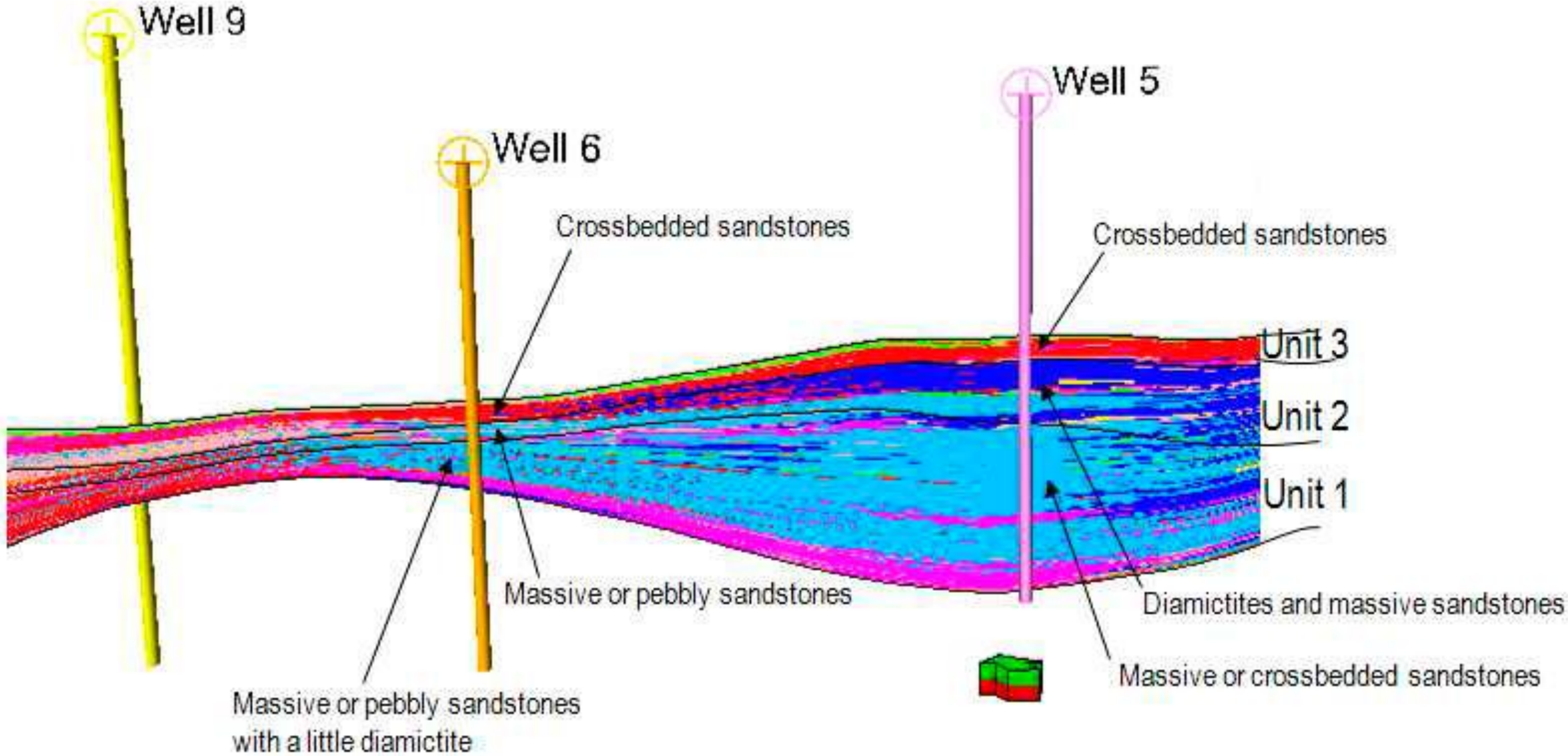

Figure 11. Facies cross section for stratigraphic correlation analysis between Well 6 and Well 5.