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MSc Minithesis on Petroleum Geology

Sedimentological re-interpretation of zone 3 (Upper Shallow Marine) of selected wells, Bredasdorp Basin (Offshore South Africa).

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I declare that my research work titled "Sedimentological re-interpretation of zone 3 (Upper Shallow Marine) of selected wells, Bredasdorp Basin,Offshore South Africa" is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledge by means of complete references.

Nqweneka Veronica Magobiyane.

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ABSTRACT

The Bredasdorp Basin is located on the southern continental margin, off the coast of South Africa. It is mostly filled by marine Aptian to Maastrichtian deposits, overlaying pre-existing Late Jurassic to Early Cretaceous fluvial and shallow marine synrift deposits. The basin is a southeastern trending rift basin, located between the Columbine-Agulhas and Infanta arches. Its basement is made up of slates of the Bokkeveld Group (Devonian) and or quartzites of the Table Mountain Group (Ordovician-Silurian).

The study area extends from X-X field to Y-Y field and encompasses only four wells for this investigation; well A, B, C and D respectively. This study was done through the interpretation; integration and juxtaposing of the results from core analysis with wireline log analysis (gamma ray) using Petrel software to display and correlate the well logs. Through core analysis which is the main source of information for this study, seven facies were identified and interpreted for the entire study. These facies alternate throughout each well and between different wells, but they are not evident in all the cores. Throughout the study, well A has been used as a reference well, since it appears (according to the interpretations) to record all seven facies and has the thickest section of zone 3. This zone reflects more accommodation space than the other studied wells at the time of deposition. Facies analysis of cores and well log correlation provide evidence that the studied USM sandstones are compatible with a wave dominated estuary/island-bar lagoon system to shoreface of a wave dominated marine shelf. It has previously been demonstrated that on the northern shelf of the Bredasdorp Basin, the USM typically has an hour-glass gamma ray log signature as a result of long-term transgression and regression and this typical log shape was also identified in this study from well A .

CHAPTER 1

1.1 INTRODUCTION

This report focuses on the sedimentological re-interpretation of Zone 3 (Upper Shallow Marine, USM) of selected wells, between X-X and Y-Y fields, block 9, Bredasdorp Basin (Offshore). Previously a sedimentological study was carried out for USM in the X-X field and according to the results reported by S. Hills in 1994, this zone exhibit sedimentological features that best describe a fluvio-deltaic environment that was somehow affected by a marine influence during the time of deposition. Later in the Y-Y field a re-evaluation was carried out for USM and it incorporated new 3D seismic survey over that field in 1997/8 and results from the satellite field development. The findings show that in Block 9, USM are Tidal/Estuarine to shoreface sediments (PGS, 1999).

Therefore this study will reinterpret and tune the correlation of the reservoir sandstones in USM between two fields (X-X and Y-Y) on the northern flank of the basin, and it is expected to give a mutual understanding of depositional environment responsible for USM sediments. The USM are Berriasian to Valanginian sediments and they comprise the main reservoir interval in the basin. Particularly in the X-X field, this unit (USM) shows a defined log pattern and sedimentary features. Correlating these beds with other areas will allow knowing the reservoir characteristics and range of variation, and this could help in future exploration.

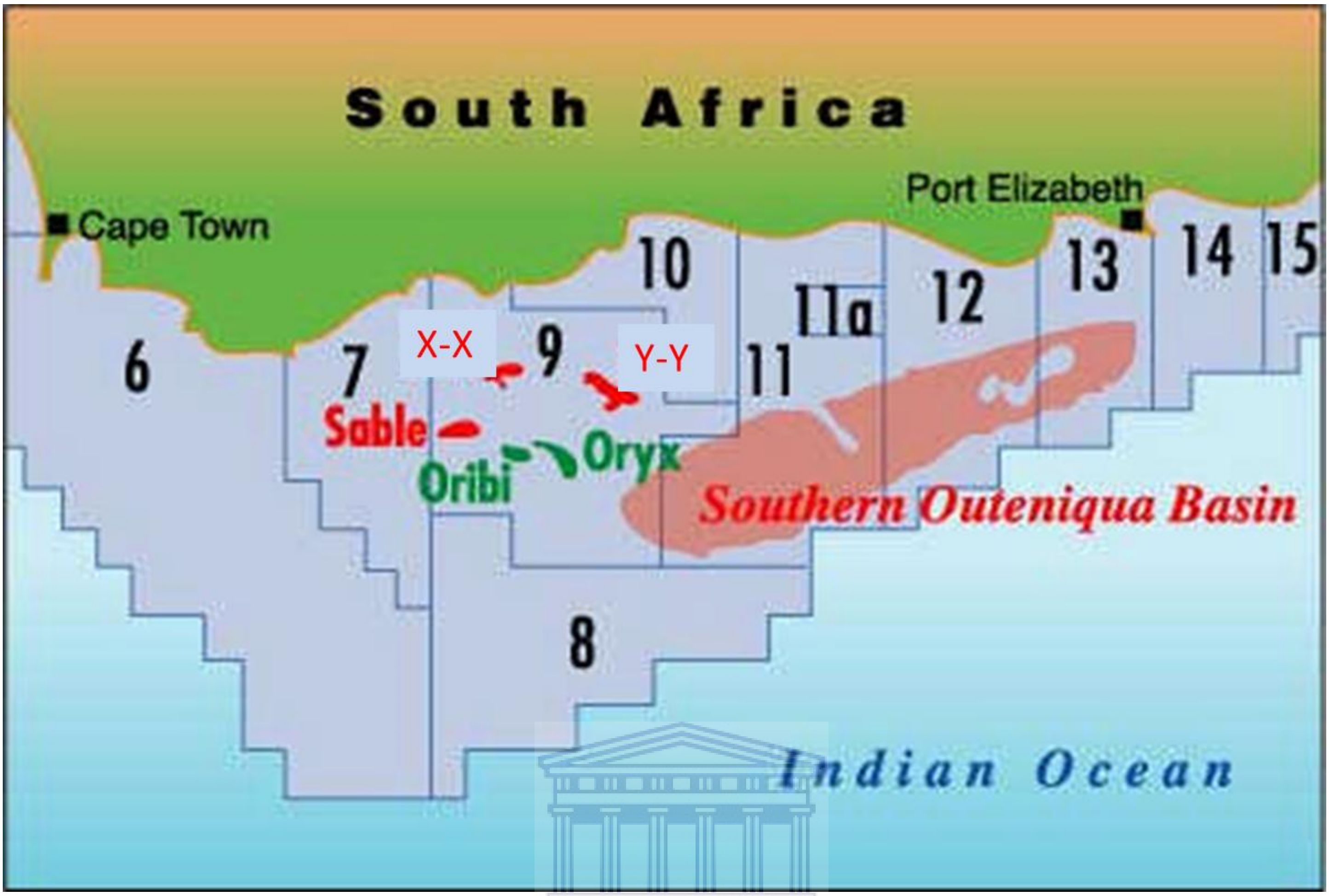


Fig 1: Location map of study area, showing the fields of interest (modified after Lagos, 2000). See ***Appendix 2*** for alignment of wells of study.

The Bredasdorp Basin forms a sub-basin of the Outeniqua Basin at the southernmost continental boundary of South Africa. The South African continental plate margins are believed to be a direct result of the break-up of the west Gondwana supercontinent into the African and South American continental plates (Broad et al., 2006). This break-up was caused by extensional forces that commenced during the Early Mesozoic. The separation is the result of continental drifting that began in the Early Cretaceous and is still continuing today (Broad et al., 2006). The extensional force and drifting have resulted in the formation of the three plate margins off the coast of South Africa; the western plate margin, which is a divergent/passive margin and the southern and eastern plate margins, which are transform margins that consist of rift basins modified by strike-slip movements along transform faults (Broad et al., 2006). The geographic focus of this study is on the southern plate margin and will only discuss and evaluate Zone 3 in the central Bredasdorp Basin.

1.2 AIMS AND OBJECTIVES

The main objective of this study is to develop a regional sedimentological model based on the paleoenvironmental reinterpretation of cores. This is expected to give a better understanding of depositional environments and their lateral extent between the two fields of interest (X-X and Y-Y fields). Also to better understand the depositional controls on the reservoir thickness and areal distribution. It is generally expected that an accurate knowledge of the lateral extent, thickness changes and trends and the actual distribution of the reservoir sandstones is key to guide hydrocarbon exploration (Jahn et al., 1998). Therefore the sedimentological model is the base of realistic geologic models and reservoir simulation models in hydrocarbon exploration and oil field development.

1.3 SCOPE OF WORK:

- Visualisation of core for identification of facies
- Facies classification and facies association
- Determination of depositional environments
- Matching of the facies with GR wireline logs
- Regional correlation of facies between the wells studied
- Regional correlation of environments in each well leading to the interpretation of the depositional environment/setting of the basin

CHAPTER 2

2.1 GEOLOICAL FRAMEWORK

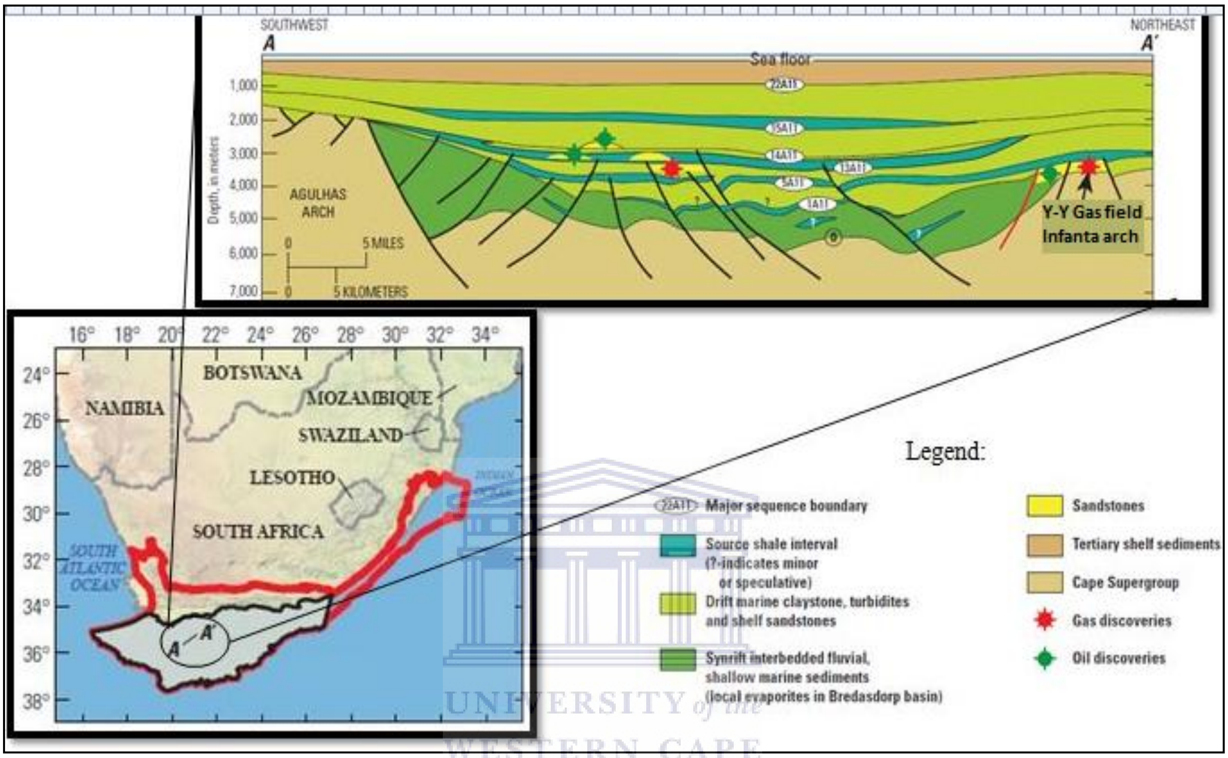


Fig 2: Geological framework of the study area (after Davies, 1997).

Geological setting:

Three offshore basins occur off the margins of South African plate, namely; the south coast basins, east coast basins and the west coast basins respectively. The South Coast basins encompass the Outeniqua Basin, which is subdivided into the Bredasdorp sub-basin, Pletmos sub-basin, Gamtoos sub-basin, Algoa sub-basin and Southern Outeniqua sub-basin (Broad et al., 2006). The focus of this study is the part of Bredasdorp sub-basin of the Outeniqua basin.

Outeniqua Basin

The Outeniqua Basin is located off the southern tip of Africa and is delimited by the Columbine-Agulhas Arch to the west, the Port Alfred Arch to the east and the Diaz Marginal Ridge to the south (Broad et al., 2006). The basin comprises several rift sub-basins namely, from west to east; Bredasdorp, Pletmos, Gamtoos and Algoa sub-basins. This sequence is divided by fault-bounded basement arches composed of metasediments of the Cape Supergroup (Ordovician to Devonian) (Broad et al., 2006). It is believed that areas closest to the Agulhas-Falkland Fracture Zone (AFFZ) (Gamtoos and Algoa sub-basins) have undergone some local deformation (Malan et al., 1990; Ben-Avraham et al., 1993; Thomson, 1999), while there is evidence of tectonic inversion in the Bredasdorp sub-basin, (Van der Merwe and Fouché, 1992 and Fouché et al., 1992).

Bredasdorp sub-basin:

The Bredasdorp Basin is located on the southern continental margin off the coast of South Africa and is mostly filled by marine Aptian to Maastrichtian deposits, which were deposited on pre-existing Late Jurassic to Early Cretaceous fluvial and shallow marine synrift deposits (Grobbler, 2005).

The basin is a southeasterly trending rift basin that lies between the Columbine-Agulhas and Infanta arches. It is approximately 200 m long and 80 km wide, (Broad et al., 2006). The offshore wells; intersected the basement, which is made up of slates of Bokkeveld Group (Devonian) or quartzites of the Table Mountain Group (Ordovician-Silurian). The basin has two synrift sedimentation sequences; synrift I succession and synrift II succession.

2.2 STRATIGRAPHY OF THE BREDASDORP BASIN

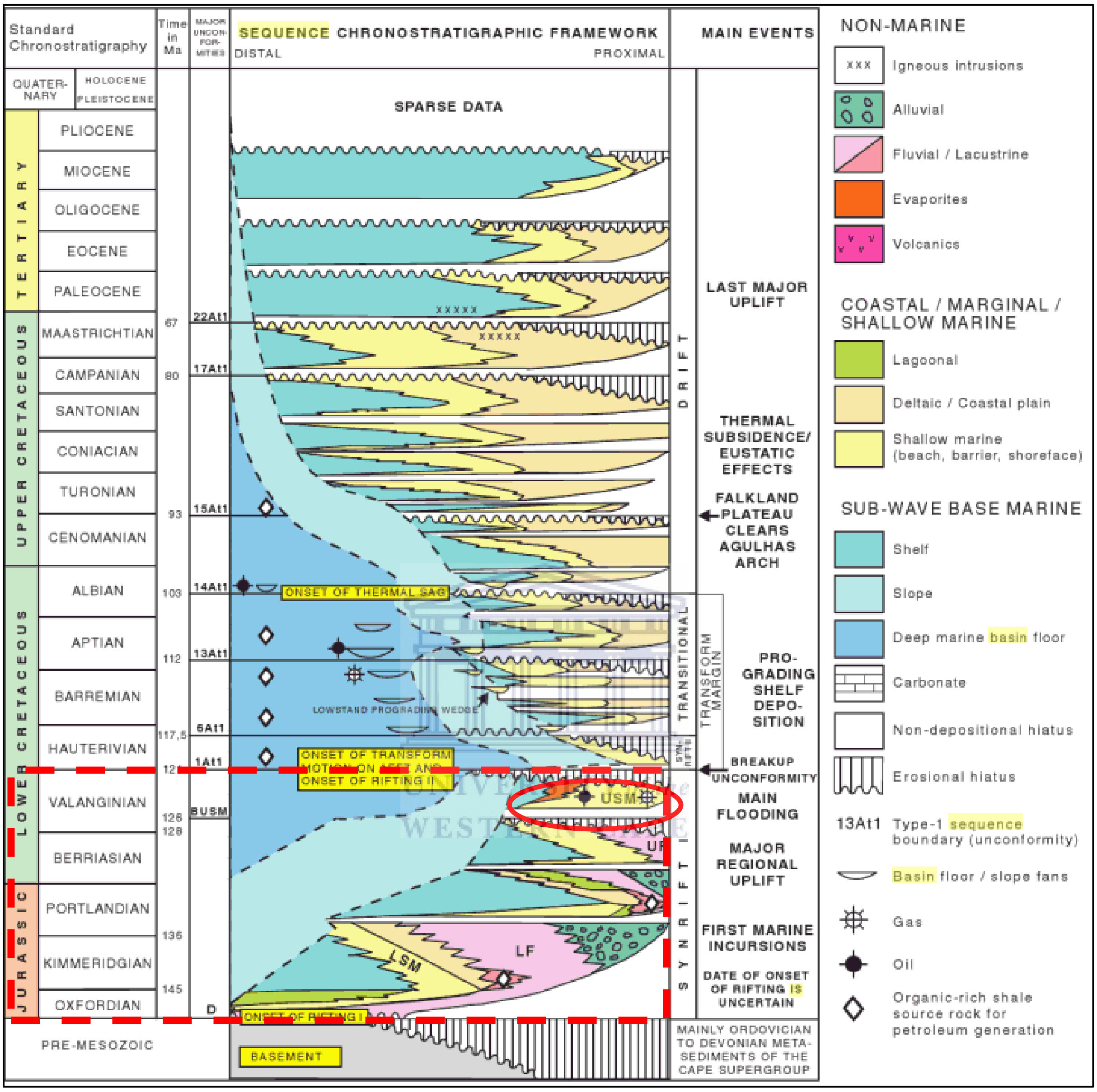


Fig 3: Stratigraphic column (after Roberts and Bally, 2012).

Bredasdorp Basin:

It has been recognized that the Bredasdorp Basin has two phases of synrift sedimentation (Jungslager, 1996): synrift I and synrift II. Synrift I sedimentation occurred during Middle Jurassic-Late Valanginian and is significant on the north flank of the basin, where most drilling has taken place. This sedimentation resulted in four lithogenetic units; lower part of fluvial interval, Lower Shallow Marine interval, upper part of fluvial interval and Upper Shallow Marine interval (Broad et al., 2006).

The lower part of fluvial interval represents early graben fill and comprises claystones, sandstones and conglomerates deposited in alluvial fans and fluvial environments (Broad et al., 2006). Lower Shallow Marine interval denotes the first marine incursion into the basin and consists of glauconitic fossiliferous sandstones, indicating progradational beach deposits of Portlandian age (dated by foraminifera). The upper part of the fluvial interval comprises alluvial floodplain and meandering fluvial deposits. Finally the Upper Shallow Marine interval has massive glauconitic fossiliferous sandstones of Late Valanginian age which was deposited as transgressive beach facies along the north and south flanks of the basin, extending into the adjacent sub-basins (Broad et al., 2006).

The synrift I succession is truncated by a regional unconformity which separates the Upper Shallow Marine sediments below from overlying deep-marine sediments. This unconformity indicates the onset of a renewed phase of rifting (synrift II) that was initiated as a consequence of early movement along the AFFZ at about 121 Ma (Valanginian/Hauterivian boundary) (Jungslager, 1996). This regional tectonism resulted in structures suitable for accumulation of oil and gas of economic importance. (Van der Merwe and Fouché, 1992).

2.3 PETROLEUM SYSTEM REVIEW

Generally it is known that for a field to be under production or if it has once produced,then its petroleum system is complete/working (Jahn et al., 1998). This means that all the components that led to the accumulation and preservation of hydrocarbons are presently in place. This section will only give a brief overview of all petroleum components present in the study area.

The source rock for this basin is the deep marine basin floor, which is made up of organic – rich shales of sequence 1A to 13A that were deposited since Late Valangian to Aptian (PASA, 2012). The reservoir rocks from which the Y-Y and X-X gas fields produce are Early Cretaceous (Late Valangian) sandstones deposited on a shallow marine shelf along the northern flank of the basin (PASA, 2012). The Z-Z and F-F oil fields (see figure 1) produce from Early Cretaceous (Mid-Albian) sandstones deposited in a deep water submarine fan channel complex in the axial part of the basin (PASA, 2012). The S-S field (see figure 1) also produces from a similar Albian age basin floor submarine fan complex (PASA, 2012).

The trapping mechanisms for the synrift reservoir of shallow marine to fluvial origin are structural and truncational traps and are mostly tilted fault blocks, and the seal for these reservoirs are drift marine shales.The drift sandstone reservoir of deep marine turbidites deposits are trapped by a variety of low relief closures such as; compactional drape anticlines, stratigraphic pinch-out traps and inversion-related closures (PASA, 2012).

CHAPTER 3

3.1 MATERIAL AND ANALYTICAL METHODS:

This chapter describes the techniques and workflow pattern used for the study in order to obtain the aims and objectives outlined earlier. The initial step was visualization and description of all cores involved as a set, where facies were identified and analyzed. It was then followed by the determination of facies association and of the depositional environment. This was followed by a well log analysis of trends from the GR log and then related those trends to possible depositional sequence of events. It was then followed by matching GR log and facies (from the core) and this resulted into shifting of some cores that didn't fit well with GR log depths. Lastly was a regional correlation between the selected wells based on GR trends and associated facies and depositional environments. The correlation would allow understanding of thickness, lateral extent of facies distribution and related depositional setting and may give ideas on what might have controlled the depositional system.

3.1.1 Workflow chart

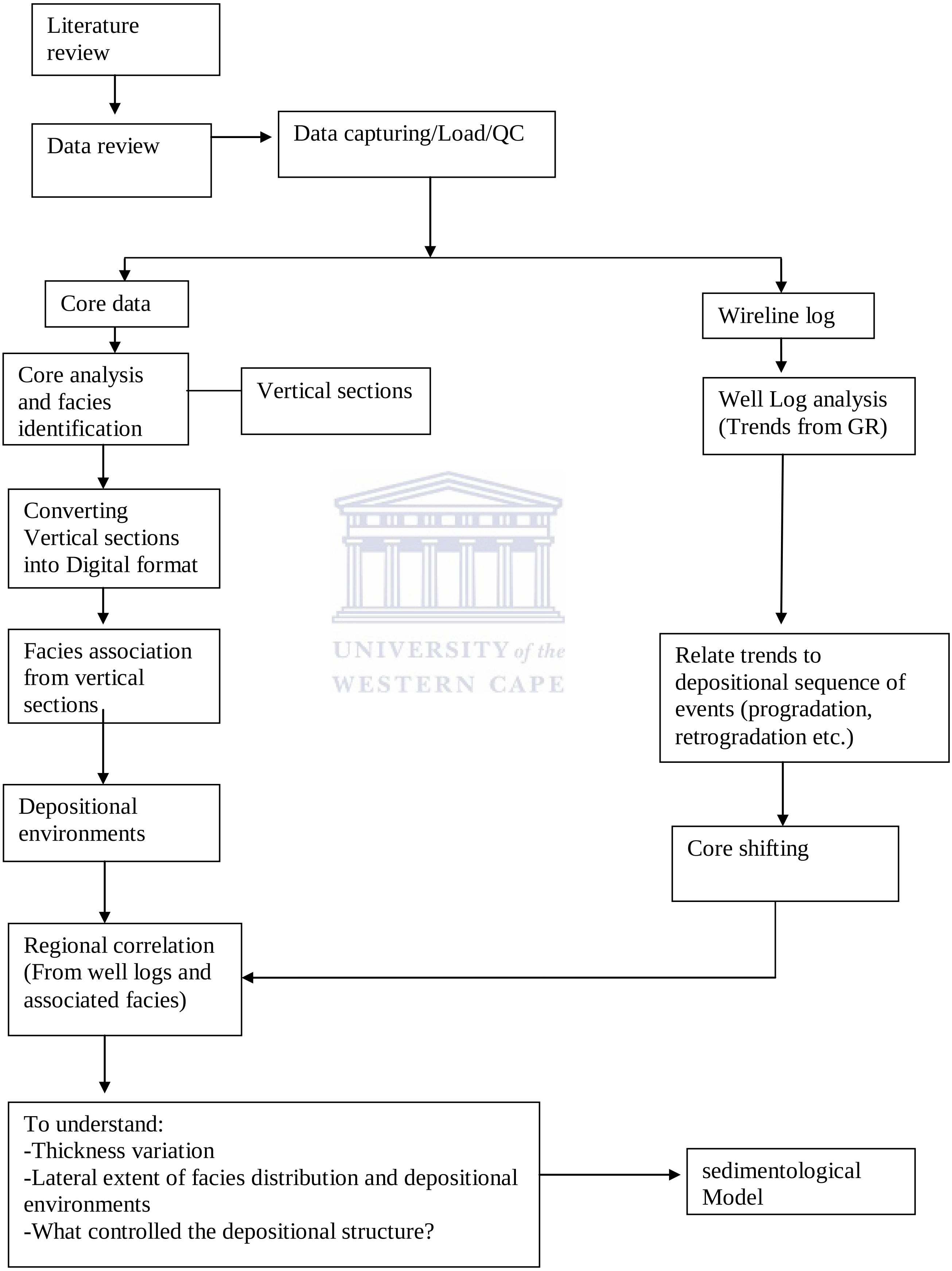


Fig 4: Chart showing the methods followed for this study

3.1.2 The data set for this study includes:

-Base map showing location of the wells (from PetroSA)

-Digital wireline logs (GR) (from PetroSA)

-Conventional core data reports (from PetroSA)

-Cores (from PASA)

-Well completion reports (PetroSA)

-Drill stem test analysis reports (PetroSA)

3.1.3 Flow of events/ Work flow description:

Core description:

Core description is a manual basic study and is the foundation upon which the entire investigation rests. The description mainly describes the physical properties of the rock at penetrated depths. It includes; description of visible sedimentary structures, grain size distribution, mineral and fossil assemblage and colour, sorting etc. Cores give direct details of the penetrated formations (true lithologies, grain size, minerals, fossils, colour etc.) and therefore give the ground truth. Core analysis is used to define not only the porosity and permeability of the reservoir rock, but also to unearth the fluid saturation and grain density. Furthermore, core description is used to understand the depositional environments of the study area, using facies described from the cores. This is a very important initial stage in the oil industry, as it locates potential fields (good reservoir and seals) for exploration and production. All of these measurements help geologists, engineers and drillers better understand the conditions of the well and its potential productivity. A core is a cylindrical sample of rock taken from a reservoir or interval of interest of a drilled oil or gas well.

Facies analysis:

Facies is a characterization of a deposit by a particular combination of lithology, sedimentary structures and fossils that are evidence in sedimentary processes (Walker 1992) which are comparable to the ones occurring in current sedimentary environments. In this project the facies were defined based on grain size, sedimentary structures, type of contacts, bed pattern, thickness, presence and type of bioturbation, minerals, body fossils and colour distribution.

This was done also following the Miall’s (1988) facies classification scheme (***appendix 1***). The core logging and description started from the bottom to the top of the core for each well. It was then followed by grouping the recognized facies, based on their similarities, bed patterns and relationship between them, in facies associations. Facies associations are groups of genetically linked facies that record the processes that occur in a certain part of an environment (Walker 1992). Therefore, based on this well-known relationship for recent environments, these facies associations were then linked to a certain part of the environment that is likely to have such features due to the processes active. This was done for all the cores in all the wells involved in this study.

Well logs:

Well logging, also known as borehole logging is the process of making a detailed record of the geologic formations penetrated by a borehole. The log may be based either on visual inspection of samples brought to the surface (geological logs) or on physical measurements made by instruments lowered into the hole (geophysical logs) (Rider, 1996). Well logging can be done during any phase of a well's history; drilling, completing, producing and abandoning. Well logging is done in boreholes drilled for oil and gas, groundwater, minerals, geothermal, and for environmental and geotechnical studies. Geophysical logs are very important because the cuttings sampling (geological logs) during drilling are imprecise, thereby giving just scattered records of the formation penetrated (Rider, 1996). Though geological logs results are clear and reliable, bringing the cores out to the surface by mechanical coring is very expensive and the process is slow. On the other hand geophysical logging is not as clear, but is precise and continuous but needs interpretation in order to make geological or petrophysical sense (Rider 1996).

Matching well logs (GR) with core logs (Facies):

Petrel software was used for loading and displaying the log curves (GR), Well tops and creation of facies logs for correlation. As this enables matching of the gamma ray log (GR) and vertical section created from the core descriptions for regional correlation. The main objective in matching these two sources of data was to create a regional correlation between the wells of study, to understand facies distribution and depositional environments. Walther's Law is the law of correlation of facies and is an important statement relating to the manner in which a vertical sedimentary sequence of facies develops. The law states that a vertical sequence of facies will be the product of a series of depositional environments which lay laterally adjacent to each other (Stanley, 1999). This law is applicable only to situations where there is no break in the sedimentary sequence which is the situation for Zone 3 of this study.

Most importantly before correlation, it was checked if the core depths match with the GR depths as this is known to be a common problem between cores and wireline logs. For this reason, shifting was applied (where needed) to account for this problem. Shifting the depths applies when the core depths do not match the well log depths, which is the gamma ray log for this study. In order to shift, a well reference point is needed to calculate the depth of the shift. For this study muds and/or siltstones were used as a point of reference. Argillaceous minerals contain substantial amounts of clay-like components and generally clays most likely contain radioactive elements (such as potassium, uranium and thorium) (Badawy, 2009). Since gamma ray measures the radioactivity in rocks, it will give high API values for sections where fine sediments and muds occur. Using the fine sediments as a reference point for shifting is precise and since the well logs (GR) are also better in recording depths than cores (which are good for lithology), it has been a success to shift the cores around to fit the gamma ray log. Once all the cores that needed shifting were shifted, the correlation was made based on the similarities in the trend in the GR log. This was followed by building a conceptual sedimentological model, which is a map that aims to understand ancient environmental conditions by studying the constituents, textures, structures, and fossil content of deposits.

CHAPTER 4

4.1 RESULTS AND INTERPRETATION

Shift table: Table 1

Well A	**Original depth (m)**	**Shifted depth (m)**	**Shift depth (m)**
Core 3	2546-2565	2542.96-2562.41	-3.04
Core 4	2565-2584	2562.41-2576.55	-2.59
Core 5	2584-2600.30	2576.55-2592.42	-7.45
Core 6	2600.30-2615.25	2592.42-2607.11	-7.88
Core 7	2615.25-2625.82	2607.11-2617.68	-8.14
Well B			
Core 1	2188-2207	2183.76-2202.76	-4.24
Core 2	2207-2217	2200.55-2210.55	-6.45
Core 3	2237-2255	2236.54-2254.54	-0.46
Core 4	2255-2269.5	-	No shift
Well C			
Core 2	2378.5-2396.87	-	No shift
Core 3	2397.5-2415.37	-	No shift
Core 4	2415.4-2422.39	-	No shift
Well D			
Core 2	2719-2733.03	-	No shift
Core 3	2737.03-2755	-	No shift
Core 4	2755-2773.22	-	No shift

4.1.1 Core description

Well-A

Five cores were described from well A; core 3 to core 7. Core 3 was taken from the depth of 2546 m to 2565 m; core 4 from 2565 m to 2584 m; core 5 from 2584 m to 2600.30 m; core 6 from 2600.30 m to 2615.25 m and core 7 from 2615.25 m to 2625.82 m.

Core 7:

Core 7 is predominantly composed of fining upwards units ranging, from very coarse sandstone beds to silty and very fine sandstone beds; showing a pebbly lag, planar cross-bedding or a massive interval at the base. It grades into plane lamination and/or ripple lamination towards the top. The basal lag is composed of green and dark grey claystone clasts, white to light grey quartz pebbles, dark brown siltstone clasts, plant and coal fragments. The basal lag as well as some of the mentioned intervals can be absent.

These lag deposits grades into coarse-medium sandstones that ranges from medium grey to light grey and clear in parts and are composed of dark grey quartz grains in parts that defines the parallel lamination. In other parts, the parallel lamination is defined by siderite and carbonaceous silt layers. Near the top, sandstone grades into dark grey to light (green) grey siltstone or dark grey claystone in parts. These fine sediments are argillaceous and pyrite is common in the form of nodules, fragments and/or lenses in places. The plant fragments are identified on bed planes.

These fining upward bed sequences alternate with coarsening upwards, which are mostly medium-coarse and rarely very coarse grained sandstones. Generally the sequence ranging from heterolithic (with flaser and mud drapes) are fine sandstone near the base, up to very coarse sandstones which are; either massive, planar-cross bedded or trough-cross bedded and up to gravelly sandstones with lags in places near the top. Soft deformation structures such as; water-escape, load-cast and ball-and-pillow structures, are common in parts. Erosive bases were spotted in some beds. The sands are carbonaceous and argillaceous where fine grains and pyrite are present in some parts of the core. Sandstone is very coarse (gravelly lag) near the top, these pebbles include: quartz, siderite, green-grey claystone, pyrite nodules and coal filaments. (See figure 5 below).

Core 7 of Well A

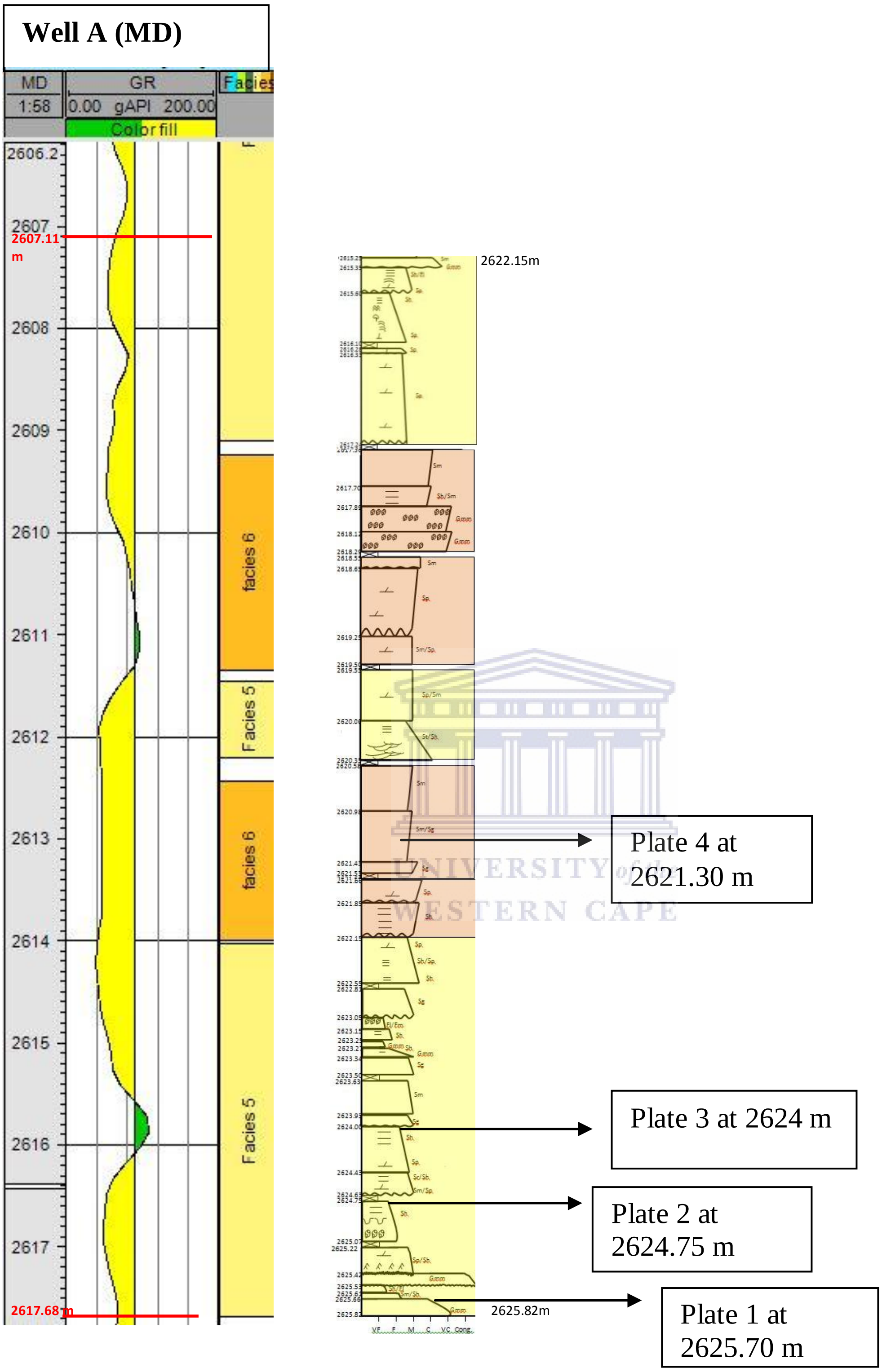


Fig 5: Core 7 vertical section against a GR log.

Refer to appendix 3 for detailed vertical section and note that all the depths that are marked for location of the plates refer to core depths rather than shifted depths. Refer to plates below to see features of the core and the graphical scale on plates; pencil length is 15 cm, coin diameter is 1.7 cm and the ruler length is 10 cm.

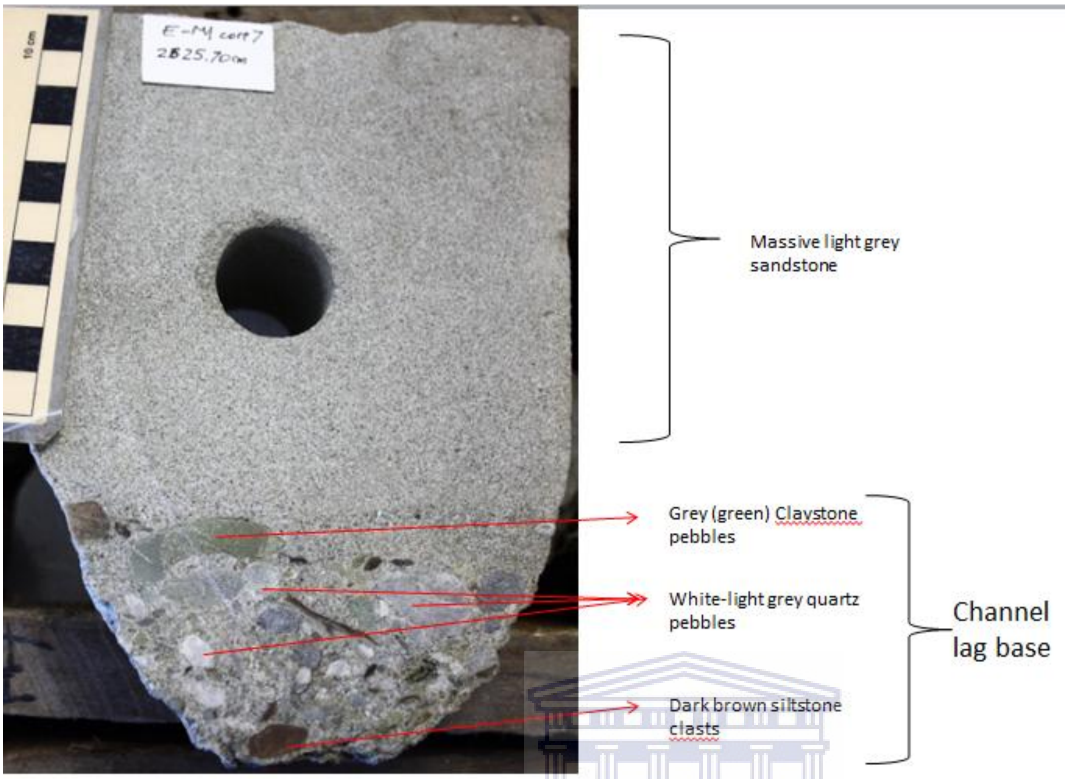


Plate 1: Facies 5, showing a lag base followed by massive sandstone taken at 2625.70 m

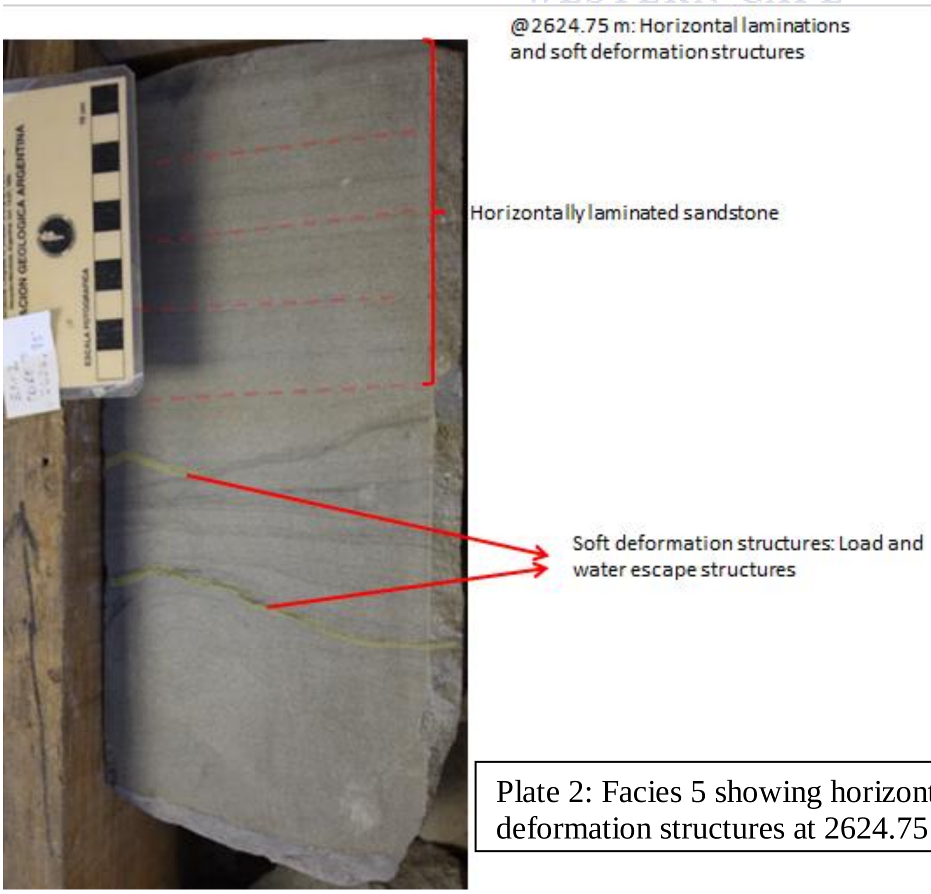


Plate 2: Facies 5 showing horizontally laminated sandstone with soft deformation structures at 2624.75 m.

Plate 3: Showing sandstone with planar-cross beds and streaming lineation and/or horizontal laminations at 2624 m.

Plate 4: Facies 5, massive sandstone of a tidal bar, taken from 2621.30 m. Coin diameter: 1.7cm

Core 6:

Core 6's basal beds are closely identical to basal beds described in core 7.From the vertical section it can be noted that this base is the continuation of what was described as the base in core 7. The base is a fining upward sequence, composed of very coarse gravelly sandstone beds mostly grade into coarse planar-cross bedded and fine laminated sandstones in some parts. It is overlain by a relatively thin unit of coarsening upward, medium grain sandstone bed, with visible trough-cross bedding near the top. These two beds are similar to the beds described in core seven. This thin sandy unit is overlain by thick silty mudstone (with beds thickness ranging from 10 cm to 2m). The sequence is generally continuous and ranges from fining upward silty mudstones to thick continuous mudstones. This unit is argillaceous and highly bioturbated and its colour ranges between light (green) grey to dark (green) grey and dark brown in some parts. Some load structures were identified in some parts.

On top of this muddy unit are fining upward gravelly, trough-bedded sandstones, grading into medium grain, ripple sandstones. It is overlain by mostly medium grain sandstone (with beds ranging from 10 cm to 1m thick), showing slight fining upward to a more blocky sequence. These beds appear to have hummocky cross stratification (HCS) and/or ripple-cross bedding near the base, grading into wavy ripple-laminated near the top. Soft deformation structures have been identified, such as; load and ball-and-pillow structures. The HCS structures are highly abundant throughout the beds. These sandstones are light green grey to medium grey and light brown in parts. Burrowing and bioturbation is common throughout. The sandstone has carbonaceous laminae and is calcareous throughout.

The HCS sand beds are overlain by alternating fining upward, medium and/or fine sandstones/siltstones beds with mudstone near the top. The beds range from 12 cm to 40 cm in thickness. These beds show HCS, fine laminated and/or small ripple structures and are highly bioturbated and mottled. The fine sandstone and siltstone are mostly light green grey and light brown grey, followed by dark brown claystone near the top. This silty laminated unit is bounded on top by beds similar to those which underlie it, and therefore it is both underlain and overlain by medium HCS beds.

Core 6 of Well A

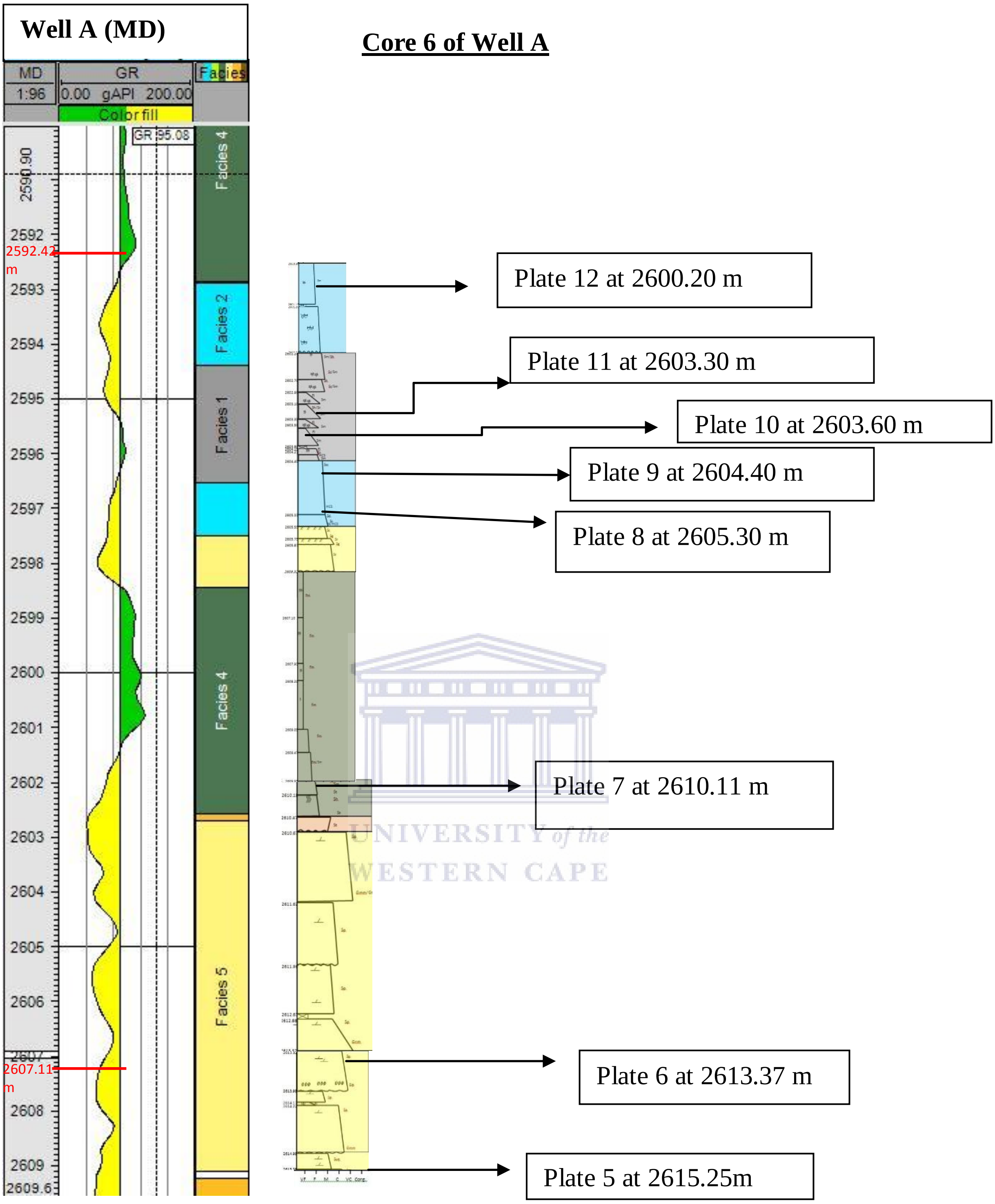


Fig 6: Core 6 vertical section against gamma ray log

Refer to appendix 3 for detailed vertical section and note that all the depths that are marked for location of the plates refer to core depths rather than shifted depths. Refer to plates below to see features of the core and the graphical scale on plates; pencil length is 15 cm, coin diameter is 1.7 cm and the ruler length is 10 cm.

Plate 5: Contact between core 6 and 7 at 2615.25 m, showing facies 5. Pencil length: 15cm

Plate 6: Gravelly sandstone at 2613.37 m (facies 5) showing planar-cross bedding. Coin diameter: 1.7cm

@2610.11 m: faint cross-lamination on a fine silty sandstone

Plate 7: Showing faint lamination on fine silty sandstone at 2610.11 m. Coin diameter: 1.7cm

Plate 8: showing some hummocky cross stratification and water escape structures at 2605.30 m. Coin diameter: 1.7cm

Plate 9: Showing wavy laminations at 2604.40 m. Tag length: 3 cm.

@2603.60m :Transition zone, showing bioturbated siltstone

Plate 10: Showing bioturbated siltstone from the transitional zone at 2603.60 m. Pencil length: 15cm

Plate 11: Showing silty to muddy sandstone with moderate bioturbation at 2603.30 m. Pencil length: 15cm

Plate 12: Showing highly bioturbated, muddy-siltsone at 2600.20 m. Coin diameter: 1.7cm

Core 5:

The base of the core is composed of thick silty mudstones that are generally blocky and slightly fining upward, with few beds showing coarsening upward (from muds to silt). These beds mostly consist of fining upward, silty mudstones that grade into thick mudstone that is argillaceous and highly bioturbated. The colour ranges between light (green) grey to dark (green) grey and dark brown in parts. Some load structures were spotted in parts.

These mudstones are overlain by fining upwards sandstones, ranging from very coarse to silty very fine sandstone; showing a pebbly lag, planar cross-bedding or a massive interval at the base, and plane lamination and/or ripple lamination towards the top. The basal lag is composed of green and dark grey claystone clasts (up to boulder size), white to light grey quartz pebbles, dark brown siltstone clasts, plant and coal fragments. The basal lag, as well as some of the mentioned intervals can be absent. These lag deposits grade into coarse-medium sandstones with planar-cross , horizontal laminations and ripple-cross beds to some extent and they range from medium grey to light grey and are clear in colour. Water escape structures and wood fragments were identified in one of the beds. At depth 2589.69 m, these sandstones are intercalated by relatively thin medium grain, coarsening upward sandstone similar to the ones described in the above mentioned cores.

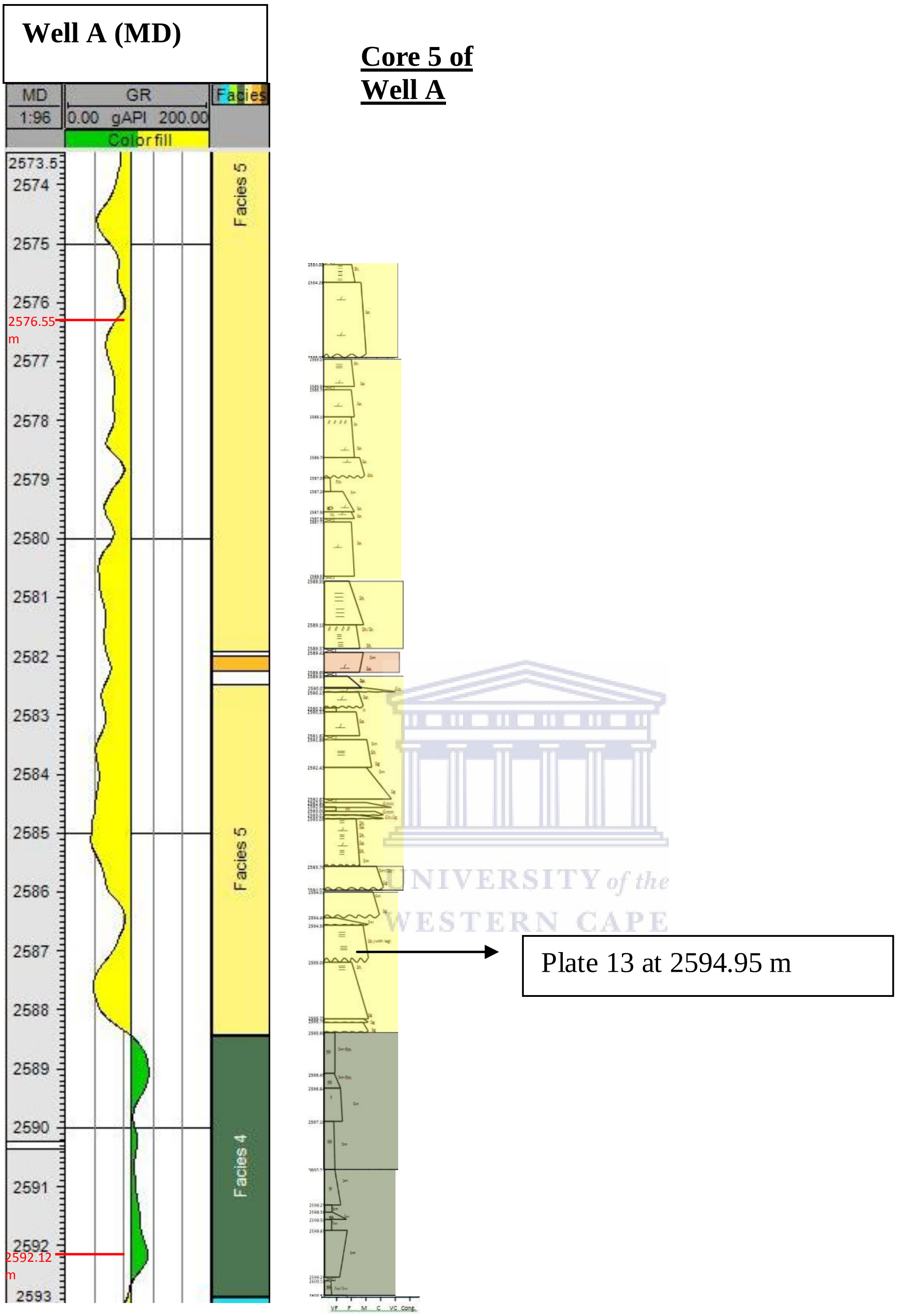


Fig 7: Core 5 vertical section against gamma ray log.

Refer to appendix 3 for detailed vertical section and note that all the depths that are marked for location of the plates refer to core depths rather than shifted depths. Refer to plates below to see features of the core and the graphical scale on plates; pencil length is 15 cm, coin diameter is 1.7 cm and the ruler length is 10 cm.

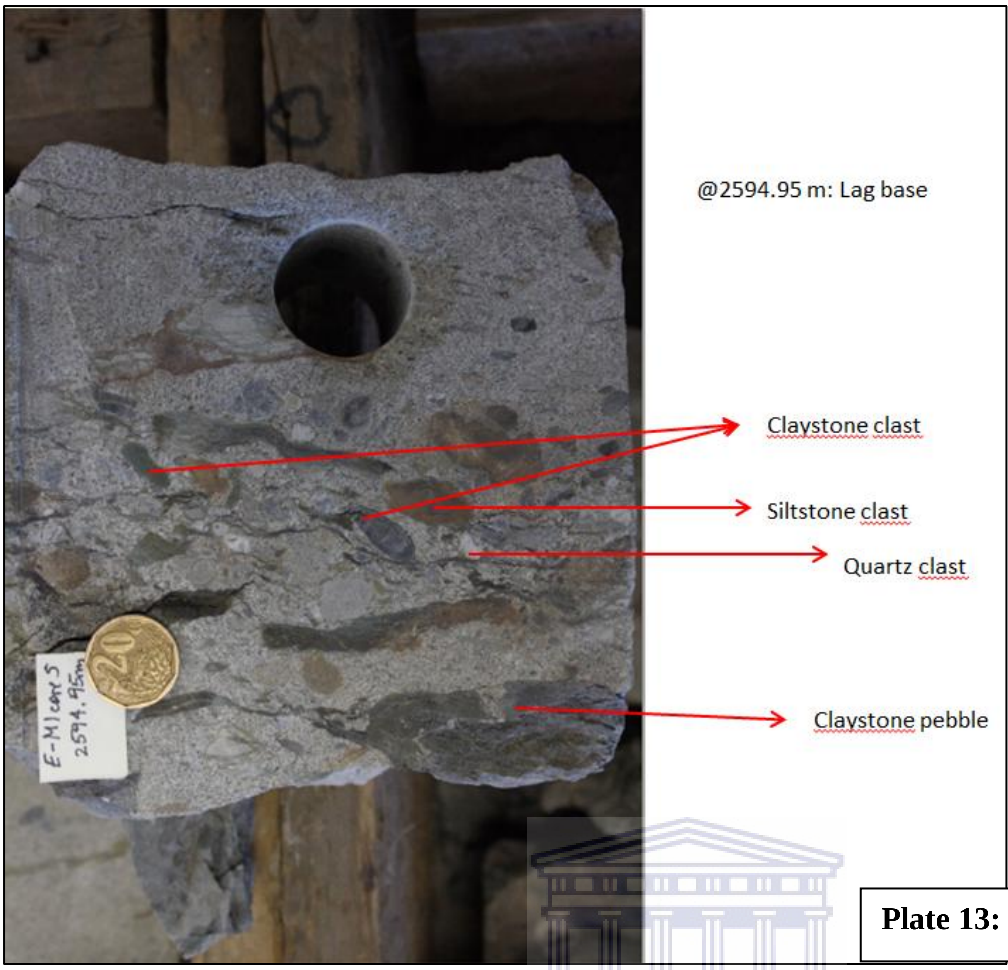


Plate 13: Showing a lag base at 2594.95 m

Core 4:

Core 4 is also predominantly composed of the thick fining-upward sandstones very similar to that of core five in relation to sedimentary structures, trends and other features described. Near the top, these sands are intercalated by a thin layer of dark greyish mudstone (about 60 cm thick), which is overlain by about 53 cm of mostly coarse grained to conglomeratic deposits. This conglomerate has a more varied composition of clasts compared to the other lag deposits described. It is poorly sorted, angular and it appears to be thick rather than just a lag at the base. Its pebbles range from 0.5-2cm in diameter. The interval is argillaceous and composed of pyritised and coalified wood fragments (with 4cm length) and is carbonaceous in parts. It is non-calcareous to calcareous in parts and chlorite was identified occasionally. It appears to have vugs (oversized pores) and the colour changes from clear to light grey and dark grey with brown in places.

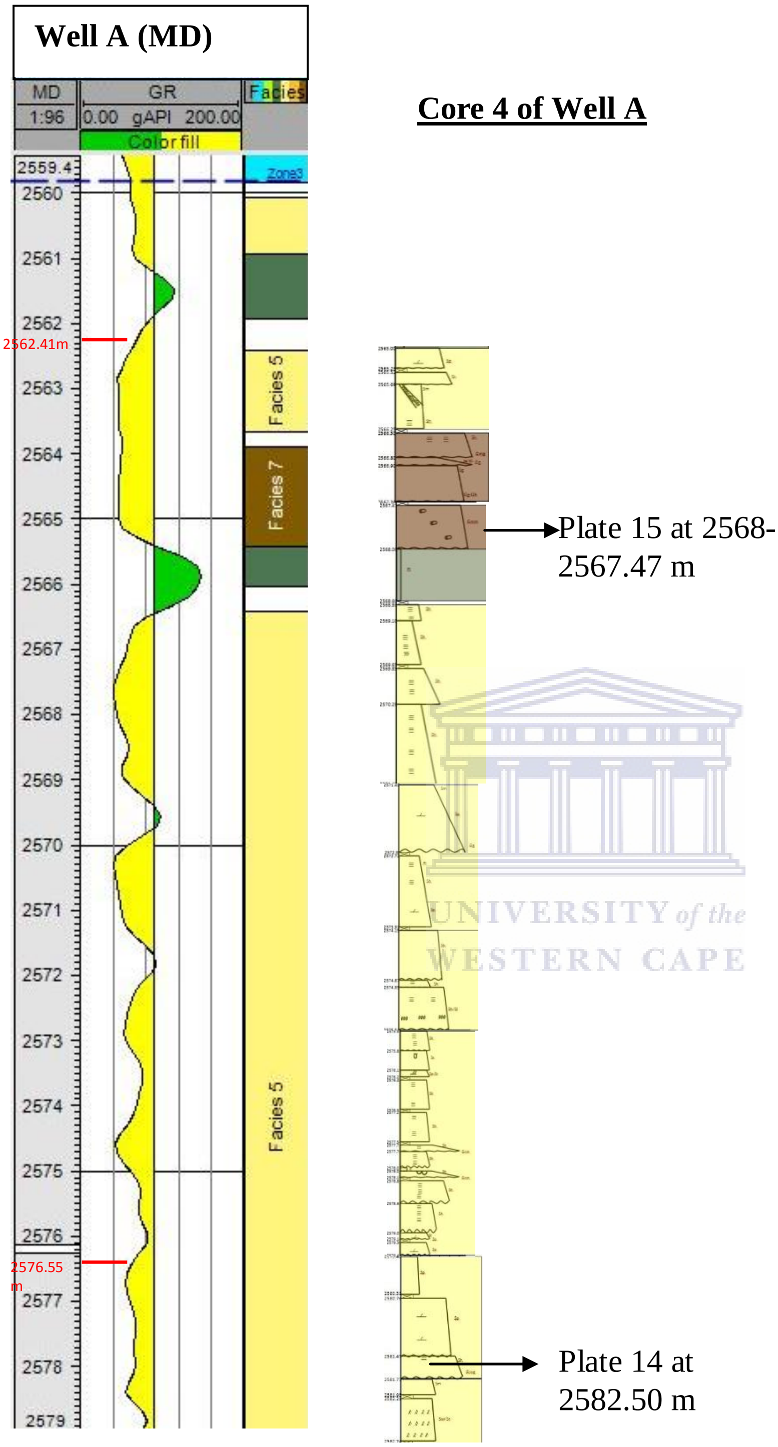
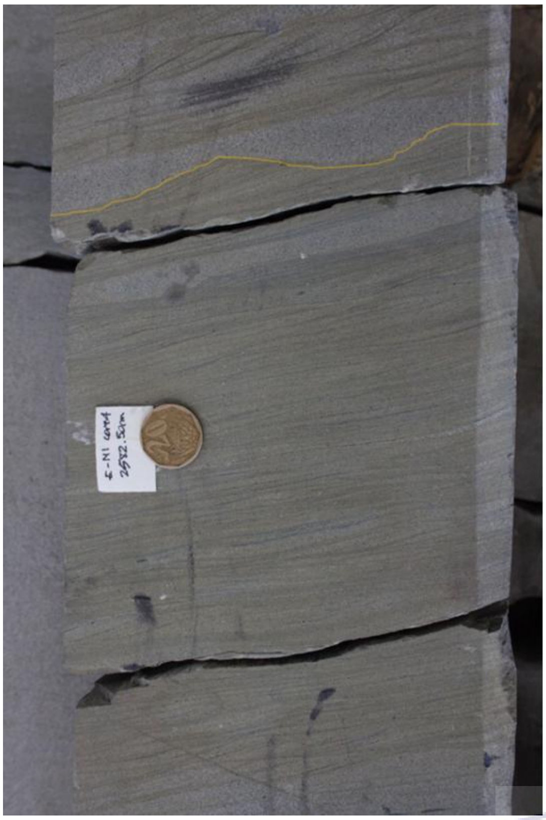


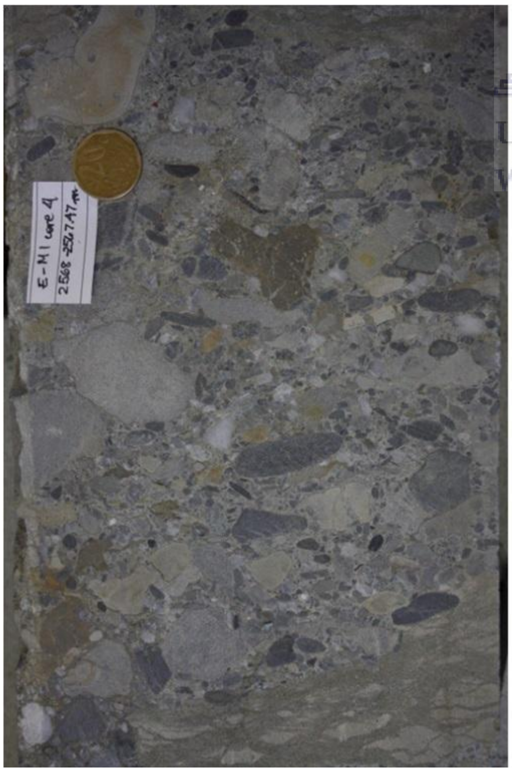
Fig 8: Core 4 vertical section against gamma ray log.

Refer to appendix 3 for detailed vertical section and note that all the depths that are marked for location of the plates refer to core depths rather than shifted depths. Refer to plates below to see features of the core and the graphical scale on plates; pencil length is 15 cm, coin diameter is 1.7 cm and the ruler length is 10 cm.



@ 2582.50 m: Medium grain sandstone with wave ripples

Plate 14: Showing medium grain sandstone with wave ripples. Coin diameter: 1.7cm



@ 2568-2567.47 m: Fluvial channel showing thick conglomerate with abundant clay, quartz and silt pebbles and cobbles

Plate 15: Showing thick conglomerate (facies 7) with abundant quartz, clay and silt pebbles and cobbles at 2568-2567.47 m. Coin diameter: 1.7cm

Core 3:

Core 3 is composed of dark green, argillaceous, blocky mudstone at the base, overlain by coarse grained horizontally laminated and planar-cross bedded, fining upward sandstone beds with an erosive base. These sand beds are overlain by a thick sandy unit of beds, showing blocky to fining upward medium grained sequences and are mostly composed of horizontal laminations. In some of the beds these sands appear to have wavy lamination, HCS, planar-cross bedding and are deformed (fractured). On top of this unit is the coarser, thin unit of sandstone, also comprising of horizontal lamination and showing a slight fining upward sequence with some HCS.

Towards the top of the succession is a thick coarse to medium grained fining upward sandstone, with lag base in some beds. They appear to have horizontal laminations, planar cross laminations, wavy laminations, flaser and trough bedding and erosive bases with plant remains in some beds. The sand beds alternate with coarsening upward sequences ranging from fine (heterolithic base) to medium coarse, planar-cross and wavy bedded sandstones with some water-escape structures. Near the top is a thick coarse to conglomeratic unit similar to the one near the top of core four.

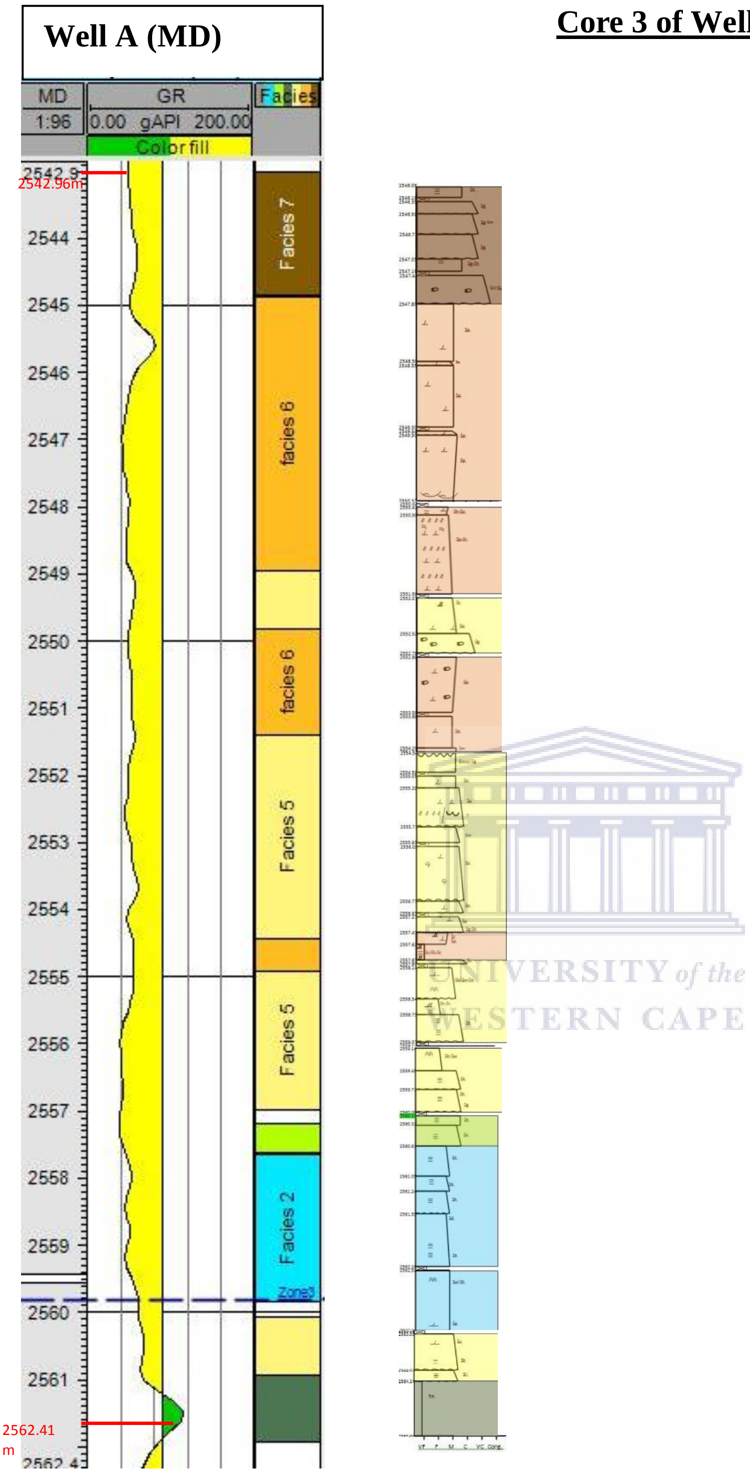


Fig 9: Core 3 vertical section against gamma ray log, refer to appendix 3 for detailed vertical section.

Well B

In well B only four cores were described; core 1, 2, 3 and 4. Core 1 was taken from 2188 m to 2207 m; core 2 from 2207 m to 2217 m; core 3 from 2237 m to 2255 m and core 4 from 2255 m to 2269.5 m. Core 1 and 2 two fall within the reservoir zone, but just above Zone 3; therefore they will not be discussed in detail. Shifting was performed for cores 1, 2 and 3 in this well; therefore all the depths will be shifted except for those in core 4. Since the features of well B and C are no different from those described in cores of well A; well B and C will be described on average and not core by core.

Core 4 and core 3:

These cores are predominantly composed of fining upwards ranging, from coarse sandstone beds to medium and very fine sandstone beds. These beds show a pebbly lag and/or trough beds with lags at the base of the trough beds near the base grading into planar cross-bedded and/or trough bedded sandstone. Grading into ripple and horizontal laminated, flaser bedding, ripple cross laminations, and mud drapes near some top of beds. The basal lag is composed of green and dark grey claystone clasts, white to light grey quartz pebbles, dark brown siltstone clasts, plant and coal fragments. Load cast structures are common and some bioturbation, as well as wood fragments are common too. These beds mostly appear to have an erosive base.

On the other hand the coarsening upwards sandstone beds also appear to be blockier in some intervals and they are composed of coarsening upwards mostly medium-coarse and rarely very coarse grained sandstones. Generally the sequence ranging from heterolithic (with flaser and mud drapes) fine sandstone near the base up to very coarse sandstones which are either massive or planar-cross bedded or trough-cross bedded and up to gravelly sandstones with lags in some parts near the top. Soft deformation structures such as load-casts and ball-and-pillow structures are common in parts and erosive bases were observed in some beds. The sands are carbonaceous and argillaceous where fine and pyrite is present in some parts of the core. Bioturbation and mottling are very common and there is an abundance of greenish mineral grains which could be attributed to glauconite throughout the well.

Core 2:

Core 2 composed of thick silty mudstone (with beds thickness ranging from 10 cm to 2m). The sequence is generally continuous and ranges from very fine-fine silty-mudstones to thick massive mudstones. This unit is argillaceous and highly bioturbated and its colour ranges between light (green) grey to dark (green) grey and dark brown in parts. Some load structures were spotted in parts.

Core 1:

The base of the core is composed of thick silty mudstones that are generally continuous. These beds mostly consist of fining upward, silty mudstones that grade into thick mudstone that is argillaceous and highly bioturbated. The colour ranges between light (green) grey to dark (green) grey and dark brown in parts. Some load structures such as water escape structures were spotted in most parts of the core. It is slightly burrowed and/or mottled in some other parts of the core.

Well C

Three cores were described for well C, namely cores 2, 3 and 4. Core 2 was taken from 2378.5 m to 2396.87 m; core 3 from 2397.5 m to 2415.37 m and core 4 from 2415.41 to 2422.39 m. There is no shifting performed for any of the cores, since all the cores appear to align well with the GR log. Cores of this well (core 4, 3 and 2) are identical to core 3 and 4 of well B in relation to the sand units sequence trends, sedimentary structures and features, minerals and fossil content. The only difference is that the coarsening upward units are thicker than those in well B and the fining sequences are notably thinner than those in B. The greenish mineral is also abundant.

Core 4, 3 and 2:

These cores are predominantly composed of coarsening upwards sandstone beds that also appear to be continuously massive in some intervals alternating with fining upward sequence. The coarsening upward sandstones are mostly medium-coarse grained. Generally the sequence ranging from heterolithic (with flaser) fine-medium sandstone near the base up to very coarse sandstones which are either massive or planar-cross bedded or trough-cross bedded and up to gravelly sandstones with lags in some parts near the top. Soft deformation structures such as slump deposits are common in some parts and erosive bases were observed in some beds. The sands are carbonaceous and argillaceous where fine and pyrite is present in some parts of the core. Bioturbation and mottling are very common and there is an abundance of greenish mineral grains which could be attributed to glauconite throughout the well.

The fining upward sequence ranges, from very coarse sandstone beds to medium and very fine sandstone beds. These beds show a pebbly lag and/or trough beds with lags at the base of the trough beds near the base grading into planar cross-bedded and/or trough bedded sandstone. Grading into ripple and horizontal laminated, flaser bedding, ripple cross laminations, and horizontal and/or wavy laminated near some top of beds. The basal lag is composed of green and dark grey claystone clasts, white to light grey quartz pebbles, dark brown siltstone clasts. The slump deposits are common and some bioturbation. At 2406.14 m there is a coarser, thin unit of sandstone, also comprises of horizontal laminations and showing a slight fining upward sequence with some HCS.

Well D

In this well only three cores were described for this study, core 2, 3 and 4. Core 2 from 2719 m to 2737.03 m; core 3 from 2737.03 m to 2755 m and core 4 from 2755 m to 2773.22 m. Shifting was not performed for the cores in this well; therefore all the depths to be mentioned in this study's interpretation and discussion of this well are original depths from the cores. There is only one common unit that dominated all the studied cores for this well.

Well D is mainly composed of light grey, coarsening upwards sequence of medium grained sandstone that contains echinoderm fragments and bivalve shells in places. These sequences start with ripple-cross beds at the base and then grade into horizontal lamination up to massive sandstone near the top. At some depths, especially in core 3; the coarsening upward sandstone shows only hummocky cross stratification (between 2737.25-2743.94 m). The bioturbation degree is high within core 4 and core 3. Bioturbation slightly decreases and range between medium and low within core 2. At 2754.74 m is a medium to coarse grained fining upward sequence of about 1 m and it shows planar-cross bedding with scattered small quartz pebbles. Calcite cement and pyrite grains have been identified in places and glauconite is also present and appears to be abundant (giving greenish colour to the rock).

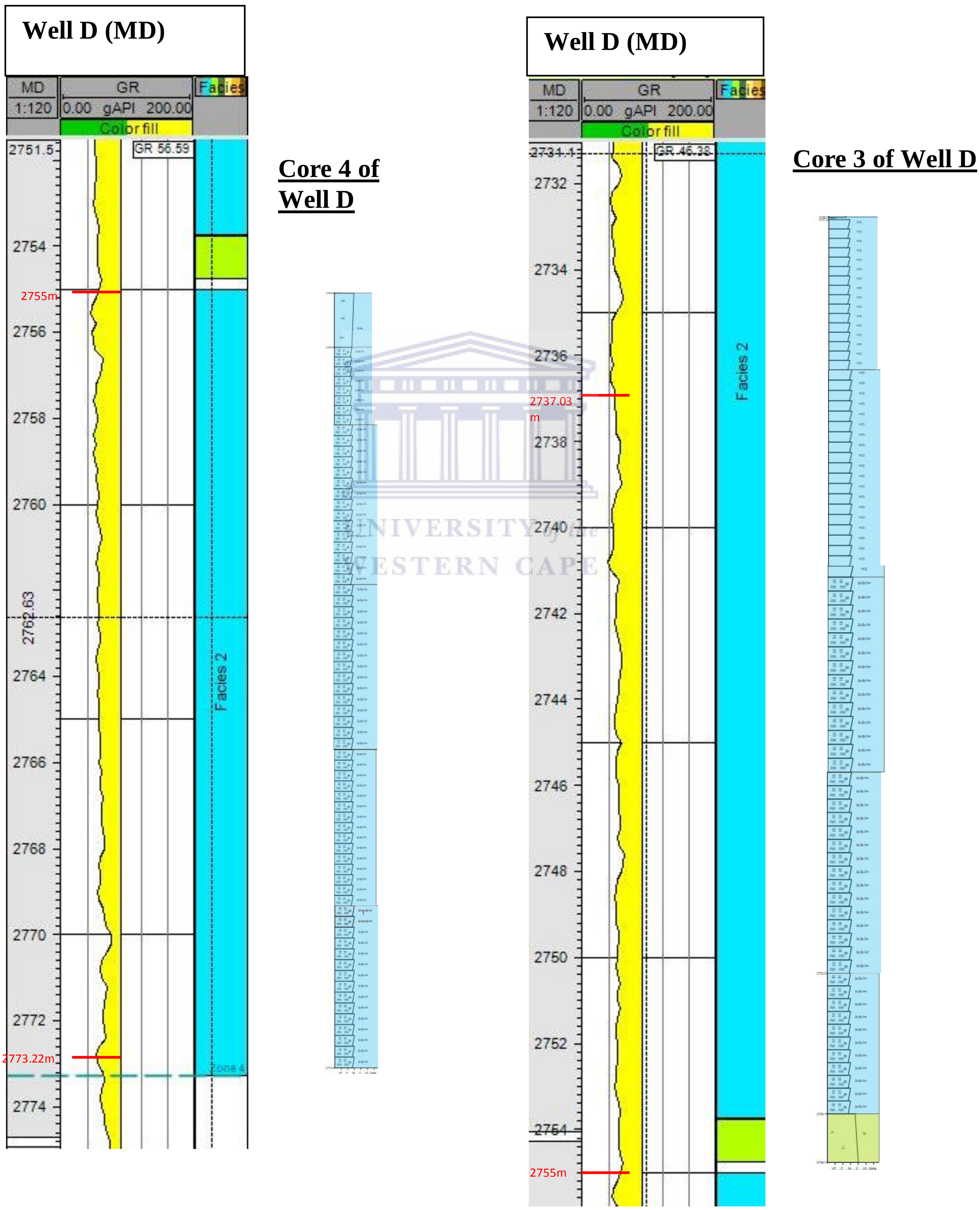


Fig 10: Core 4 (left) and core 3 (right) vertical sections against gamma ray log. Refer to appendix 3 for detailed vertical section.

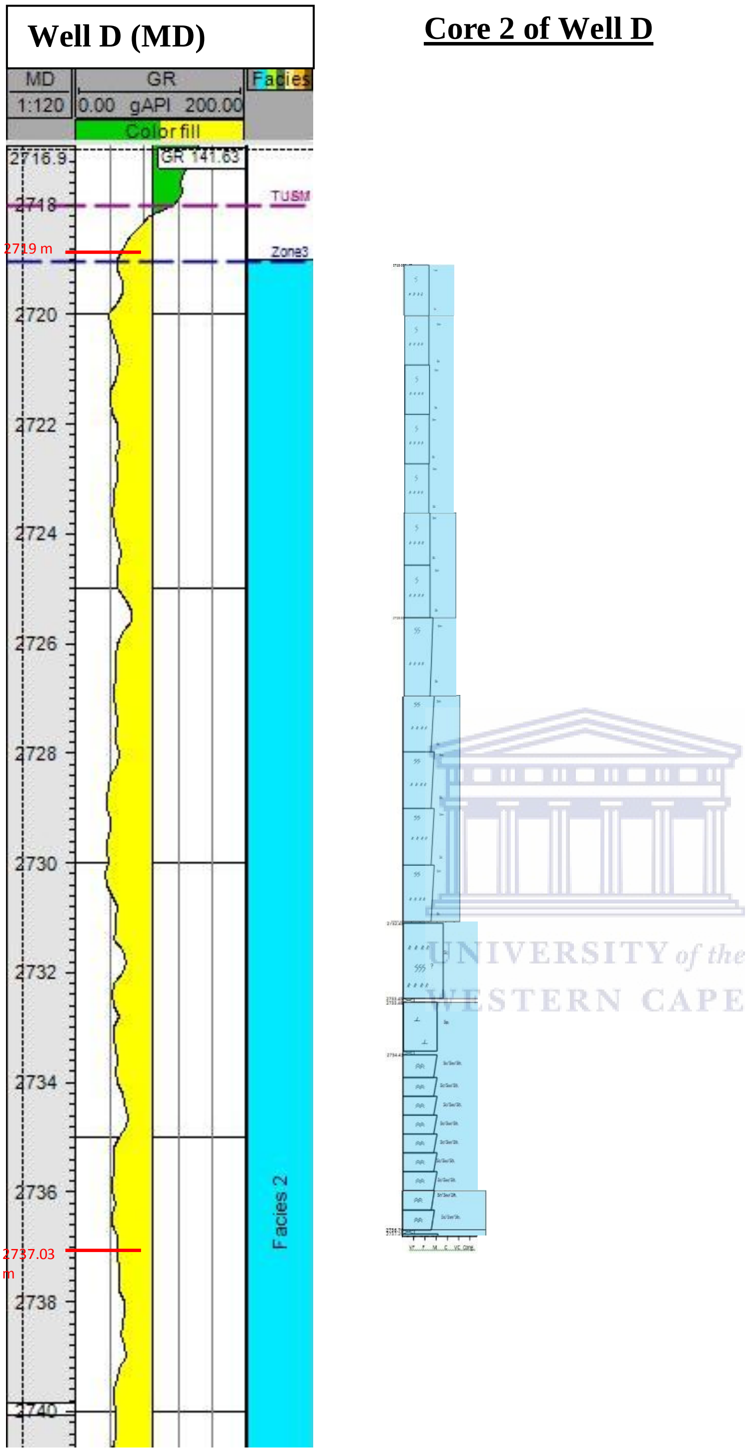


Fig 11: Core 2 vertical section against gamma ray log. Refer to appendix 3 for detailed vertical section.

4.1.2 Facies analysis

Throughout the description of all four wells of investigation only seven facies were identified, (see table 2 below).

Facies groups	Grain size	Sedimentary structures/Features	Colour	Minerals/Fossils
1	Alternating medium and/or fine sandstone/siltstone with mudstone (beds ranging from 12 cm to 40 cm thick)	**Fining upward** Generally Sm grading into Fl and/or Sh,Sr,HCS (hummocky cross stratification). Sorted	Light grey sandstone with Light green to dark green siltstone	Argillaceous (where fine) Calcareous Carboneous Mottled Moderate to highly bioturbated
2	Mostly medium grain sandstone (beds ranging from 10 cm to 1m thick)	**Generally Coarsening upwards and blocky and in parts slightly fining upward.** The beds have HCS and/or Sr grading into Sh/Sw to Sm. There are soft deformation structures (load and ball and pillow structures) HCS (abundant)	Light (green) grey	Moderate to highly bioturbated and Burrowed ip. Highly glauconitic and Carboneceous. Slightly calcareous and pyritic and has Calcite cement ip. Echinoderm and bivalve shells ip (FAD1)
3	Mostly medium to coarse grain sandstone(with small quartz pebbles scattered) (beds ranging from 10 cm to 1m thick)	**Blocky to slightly fining upwards (and coarsening upwards ip)**, but rare) The beds are either Sr/Sm/Sp or Sg granding into HCS (rare) to Sr	Medium to light grey	Moderately glauconitic,calcareous and carboneous.
4	Very fine to fine siltstone and/or thick mudstones (beds ranging from 10 cm to 2m)	**Generally blocky and fining upward ip.** The beds are thick mudstones composed either Fl/Fr/Fm Load structures ip flaser and mud drapes	Light (green) grey to dark (green) grey and dark brown ip	Argillaceous Non calcareous Carboneous (rare) Highly bioturbated Mottled Wood fragments (rare) Shells (rare)
5	gravel lag base to very coarse-coarse-medium sandstones and fine (silty/mudy) near top	**Fining upward** Generally beds have a lag deposit at the base and/or lags on trough bed planes grading into Sp and/or Sm up to Sh/Sr. Slumps deposits ip and load structures Erosive beds Water escape structures Flaser bedding	Colourless-light grey - dark grey and its (green) grey and Green ip. Dark brown ip.	Argillaceous (where fine). Have siderite layers and pebbles and pyrite fragments, nodules and lenses ip. Have Carbonaceous layers, particles and filaments and its siliceous ip. Non-glauconitic to glauconitic ip and non-calcareous. Common coal fragments and filaments and wood fragments. Plant remains are present.
6	Mostly medium-coarse and rarely very coarse grained	**Generally coarsening upwards from heterolithic fine sandstone up to very coarse sandstones (or even gravelly sandstones with lags)** These beds grades from Sh/Sl/Fl (with flaser and mud drapes) into Sm/Sp/St up to gravel lags. Soft deformation structures (Water escape,Load cast, Ball and pillow ip) Erosive base ip	Clear-whitish-light greyish and greenish grey to Green ip.	Argillaceous (where fine) Moderately carboneous ip. Non-calcareous to moderately calcareous, non- glauconitic to moderately glauconitic,its Bioturbated and mottled.
7	Mostly coarse to conglomerate	**Fining upward** Erosive base Generally thick conglomerate deposit (Gmm/Gmg/Gg/Gh/Gt/Gp/Sg) with Sh near top ip. The pebbles range from 0.5-2cm.	Clear-light grey and dark grey with brown ip.	Argillaceous (where fine) Pyritised and coalified wood fragments (4cm length). Carboneous ip, non-calcareous to calcareous ip and Chlorite ip. Vug pores

Table 2: Showing the descriptions and features considered for grouping of facies.

4.1.3 Facies and interpreted sub-environments

As the description of cores was done in a set, seven facies were identified and they occur as grouped in the table above (table 2). This section will discuss the depositional environments associated with those facies.

Figure below shows facies one, two and three with respect to their depositional environments.

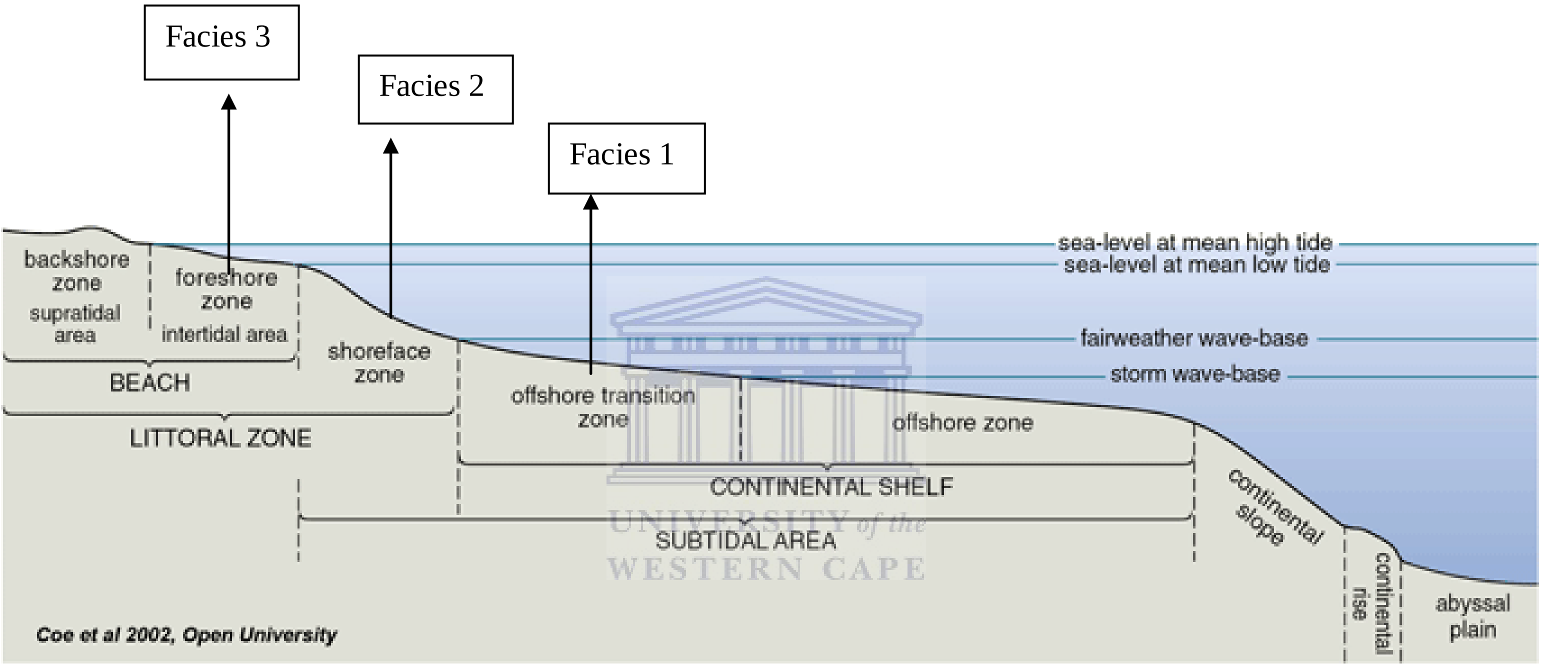


Fig 12: Cross section showing shallow marine environments and offshore environments. (Taken from http://sepmstrata.org/terminology/wavebase.html)

Facies one:

Facies one is interpreted as being associated with a transition zone, which is a zone that marks the end of shallow marine environments and the beginning of offshore marine environments. This zone lies between fair-weather wave base and storm wave base; therefore it may comprise of storm dominated deposits and/or fairweather dominated deposits. The storm deposits are formed during a storm period and normally produce beds of laminated HCS and bioturbated facies. During fairweather periods mud silt interbeds are deposited and therefore depending on the dominating process (storm and/or fair-weather), the zone is generally characterised by thin alternations of very fine sandstones and/or siltstones with muds, resulting into thin beds of fining-upwards sequences. Bioturbation is very high and this could evidence a well oxygenated marine bottom.

HCS was identified in one of the beds of core 6 in well A at 2604.27 m but not abundant and this could mean that the storm deposits with HCS were mostly eroded away if they were once abundant. Also it could mean that the storm activity periods were outperformed by fairweather periods and therefore resulting into fine sands, mud silt interbeds.

Facies Two:

Facies two is associated with a shoreface environment, which is a zone that lies below low tide level and is characterised dominantly by sands that are transported from day-to-day above fair weather wave base (Walker and Plint, 1992). These sands generally show symmetrical ripples passing into asymmetrical ripples landward and possibly dunes. These dunes are frequently wiped out during storm periods and replaced by storm-deposited facies such as; laminated, hummocky cross stratified (HCS) and bioturbated facies (Johnson and Baldwin, 1996). Facies two has shown to have abundant HCS, ripple cross lamination, horizontal laminations and wavy laminations. HCS is a storm deposit (Harms et al., 1975) and is believed to be formed during major storms. Generally this structure is preserved in areas where there is significantly weak fair-weather wave activity, such as below the fair weather wave base (Walker and Plint, 1992). There is no direct observational evidence from modern shallow seas; therefore cores with possible HCS have been taken from the shoreface (Greenwood and Sherman, 1986).

In this study the hummocky cross stratified sandstones ranges from 10 cm to 1 m in thickness and this finding strongly agrees with the description rendered by Walker and Plint (1992). According to their interpretations and observations these sandstone beds mostly range between 10-50 cm and are less likely thicker than 1 m.

Facies two has a significant abundance of glauconite, which is an olive green or blackish green with a dull lustre mineral occurring in marine sediments (Allaby and Argyll, 2008). It forms on continental shelves where there are slow rates of accumulation and decaying organic matter is present in a generally oxidizing environment. This mineral imparts a greenish colour to these sandstones and its significant presence in this facies association shows a deposition in the shoreface of a marine shelf.

Facies Three:

Facies three is not that different from facies two, it only differs in grain size. Facies three is associated with foreshore environment, a zone synonymous with a beach and consists of a portion above low tide line and is dominated by swash and backwash of breaking waves (Walker and Plint, 1992). Foreshore is part of the shallow marine environments, therefore the HCS and occurrence of glauconite is common (as discussed in facies two above). The only difference with this facies from the above mentioned facies (Facies two) is the grain size and low degree of bioturbation. The sandstone here is mostly coarse grained and it's moderately glauconitic, such that it does not impart any noticeable greenish colour to the rock. Bioturbation is very low to insignificant and this could result from the fact that organisms that form bioturbation structures needs an environment with less wave energy and yet enough oxygen to survive. This is not the case in the beach-like settings, as there is a lot of activity where the waves break.

Facies four:

Facies four comprise of thick mudstones and siltstones and the facies is highly bioturbated and mottled to some degree. This facies is associated with tidal flats in areas with large tidal range, rimming the margins of back barrier lagoons, estuaries and the open coast (Dalrymple, 1992).

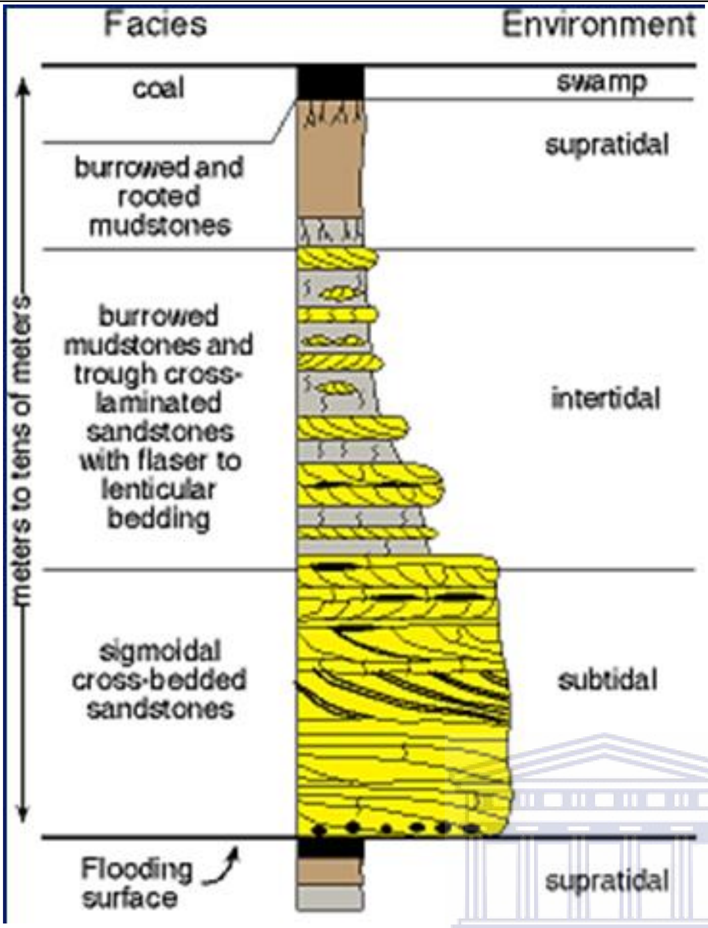


Fig 13: Tidal flat succession in humid climate (taken from http://www.springerimages.com/Images/Geosciences/1-10.1007_978-1-4020-3609-5_86-1)

The figure above shows a succession starting with a subtidal zone comprising of sigmoidal cross-bedded sandstone. It is then followed by an intertidal zone which generally comprises alternating beds of burrowed mudstones and trough cross-laminated sandstones with flaser to lenticular bedding. Burrowed and rooted mudstones of the supratidal zone overlie the intertidal and then lastly the swamp deposits comprising coals.

When compared with the above shown general succession of a typical tidal flat, it can be deduced that the features and structures attributed to facies four strongly resemble the upper part of the intertidal and supratidal flat.

Facies 5:

Facies five is associated with tidal channels and these deposits in general are made up of relatively coarse sands with a fining upward sequence. Shell debris and mud clasts at the bottom of each bed define a basal lag deposit (Johnson and Baldwin, 1996).

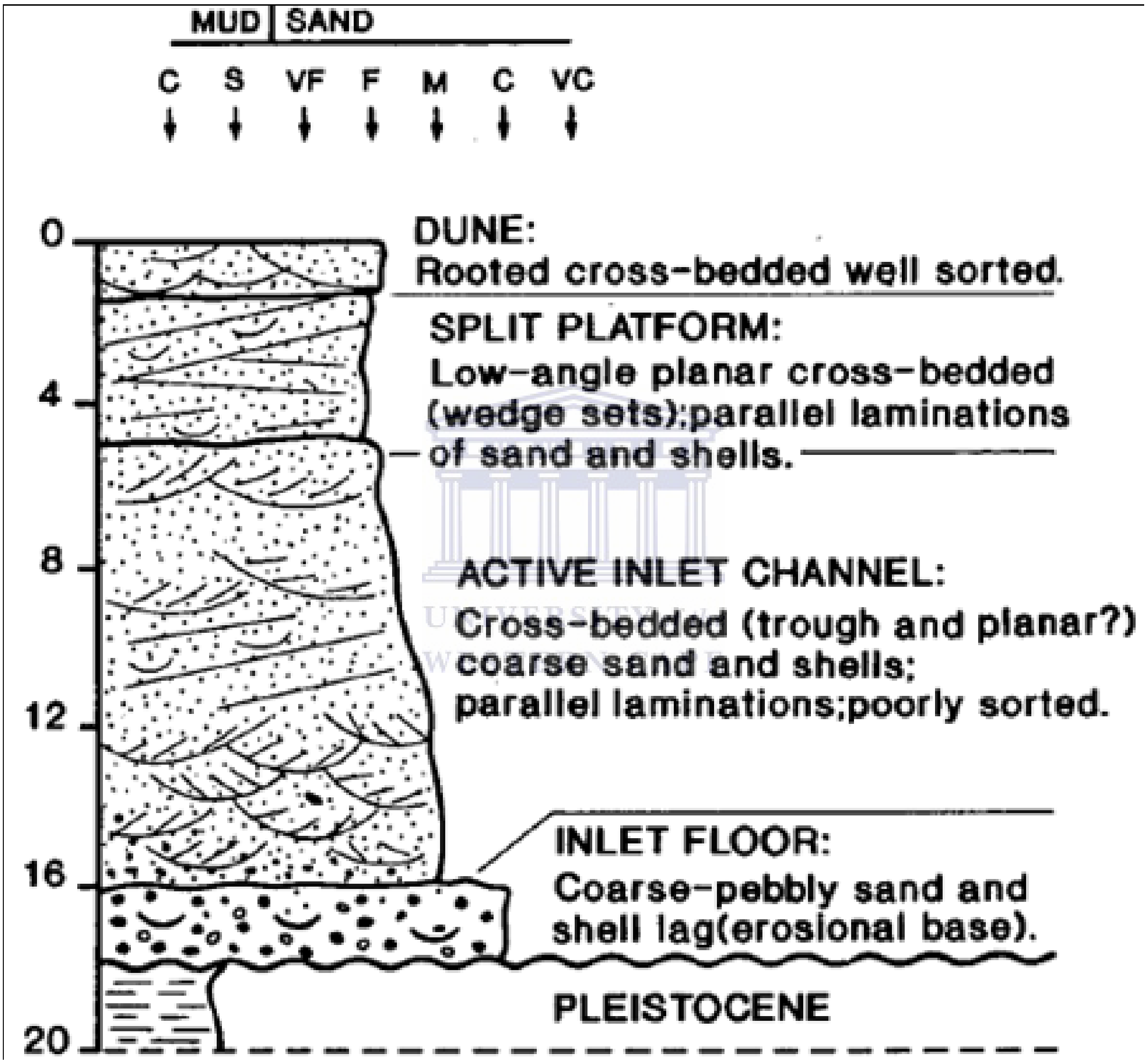


Fig 14: Tidal inlet succession showing tidal channel features (modified after Reinson, 1992).

All the features described from beds that are associated with tidal channels confirm to the above shown succession from Reinson (1992).

Facies 6

Facies six is composed of a heterolithic thin base grading into cross- planar, massive sandstones. It is associated with tidal bars because according to Thomas et al. (1987) tidal point bars are composed of thin, interlaminated clay-silt and sand beds sometimes occurring as tidal rhythmites which form lateral accretion bedding or inclined-heterolithic stratification.

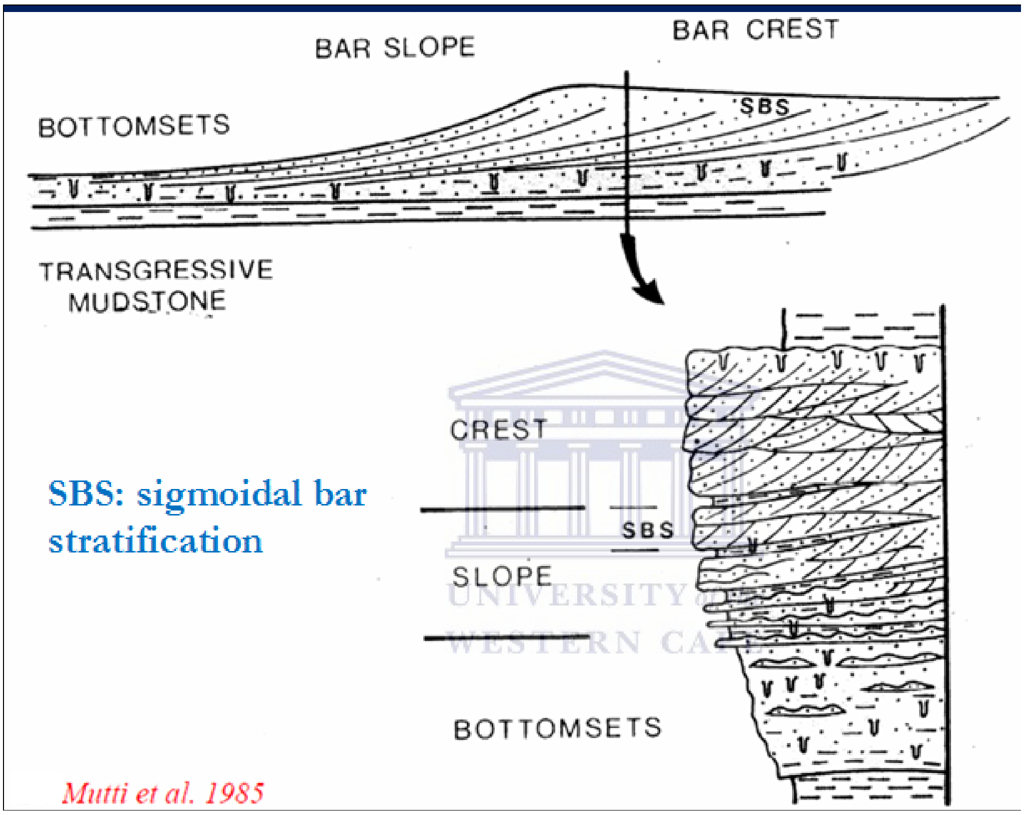


Fig 15: Tidal bars succession (after Mutti et al., 1985).

The coarsening upwards sequence with near-blocky, thick succession at top and sedimentary features including heterolithic bases interpreted from the wells correlate very well with a tidal bar’s general classification above (figure 15).

Facies 7

This facies is poorly sorted and comprised of polymictic, less rounded, coarse grains and is a thick conglomerate deposit rather than a thin lag deposit at the base. The pebbles range from 0.5-2cm. It appears to have vug pores and abundant wood fragments. These features are rather related to a river channel base than tidal channels (Reinson, 1992).

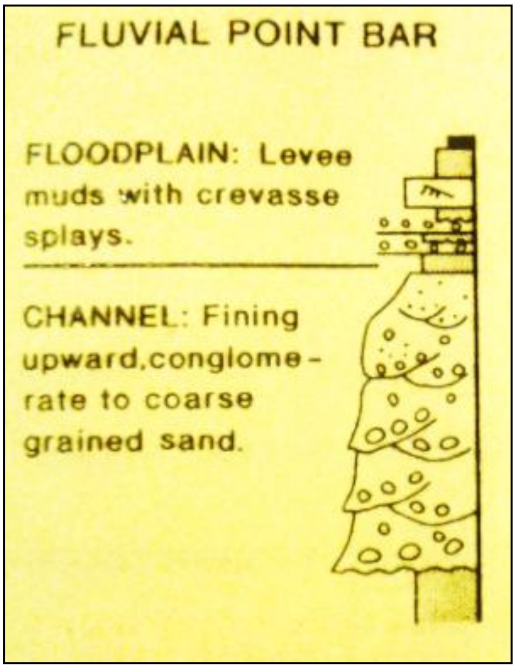


Fig 16: Fluvial point bar succession showing a typical fluvial (river) channel (after Reinson, 1992).

4.1.4 Depositional environments

It has been discussed (PGS, 1999) in the literature that Zone 3 forms in the marginal-shallow marine environment and hence this study's goal is to come up with a conceptual sedimentological model explaining and proving and/or disproving the previous findings. The conceptual sedimentological model, is constructing a map that aims to understand ancient environmental conditions by studying the constituents, textures, structures, and fossil content of ancient deposits. All these sedimentary features are somewhat related to some present-day settings that are currently in processes of forming such structures. This theory is referred to as geological uniformitarianism and was proposed by Charles Lyell (Jurmain et al., 2013). The theory states that the geological processes we see today are the same as those in the past (Jurmain et al., 2013).

This section will discuss the geological setting and environments based on the four wells that were used for the study (well A, B, C and D). Seven different facies have been identified and discussed throughout the study zone and since all these facies appear to be present in well A; this well will be used as a reference well.

It is noted that the thickness, arrangement and predominance of the facies is different for all the studied wells, while the type and features of the facies are identical. The most meaningful reason for this is that these wells all fall in the same depositional setting, being the marginal lagoonal estuary setting. According to Walker and James, (1992) a lagoonal estuary is generally almost enclosed by a barrier bar and it has a small tidal prism and low fresh water input relative to other wave dominated estuarine types (both partially closed and open-ended estuaries). It is generally small and shallow and is characteristic of microtidal coastal areas (Walker and James, 1992). Lagoonal estuaries are similar to other wave dominated estuaries in many aspects (including overlapping facies), but they run parallel to the shore and are more wave dominated (Shepard and Moore, 1960). Estuaries are generally nearly perpendicular to the shore and are tidal dominated (Reinson, 1992). Therefore, since the findings of this study in relation to facies classification does not show abundance/significant presence of facies seven (fluvial channels) relative to other facies, it is strongly believed that this coastal setting is lagoonal rather than partially or open-ended estuarine. The less abundant presence of facies seven reflects the fact that there was very low fluvial input, which in turn reflects low fresh water input into the system. Otherwise the low abundance of fluvial deposits can also evidence a location towards the mouth/barrier of the estuary.

A typical geologic setting example showing the present-day active processes that are believed to have influenced all the sedimentary structures and features as well as the vertical successions in Zone 3 (Bredasdorp Basin) is Plettenberg Bay. This example will be used to explain the possible scenarios responsible for the vertical succession in the study wells, specifically well A as the reference well.

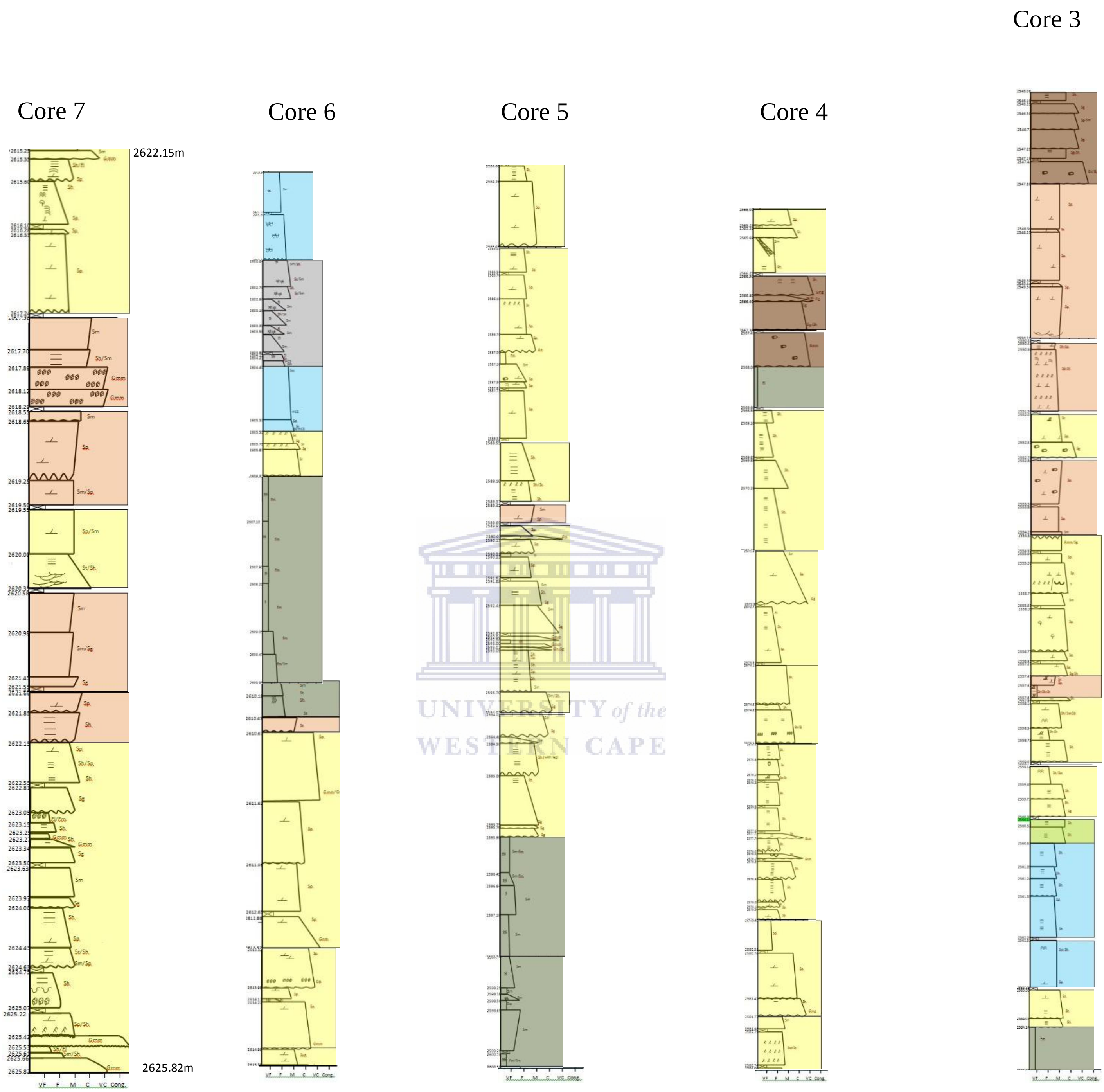


Fig 17: Well A showing core 7-3 vertical sections. Please refer to ***appendix 3*** for a detailed view of these vertical sections.

When applying Walther's Law while looking at the vertical sections for this well one can note that there is a relationship between the facies. Tidal channels (yellow shades) are predominantly overlain by tidal bars (orange shades) and to less extent by shoreface bars and lagoonal muds. On the other hand tidal bars are also predominantly overlain by tidal channels and to a lesser extent by lagoonal muds and fluvial channels. Lagoonal muds are predominantly overlain by tidal channels to a lesser extent by fluvial channels. Shoreface bars are either; overlain by foreshore bars, transitional zone or lagonal muds and underlain predominantly by tidal channels and less commonly by transitional zones respectively. The transitional zone is bounded by shoreface and the foreshore bars are overlain by tidal channels and underlain by shoreface bars. Fluvial channels are overlain by tidal channels and underlain by either tidal bars or lagoonal muds respectively.

These vertical successions' relationships between these facies makes geological sense as these sediments laterally occur next to one another in an active geological setting. It has been mentioned earlier that a very good example explaining this is Plettenberg Bay, on the south coast of South Africa. This lagoonal estuary proves to be a very active setting as it shows changes over time, in that the tidal inlet's position have been and still is changing laterally. The tidal inlet is a narrow channel that connects the open sea with a lagoon. This lateral shifting is produced by the longshore drift and it is understood to result in burial of older sediments by newer sediments. As the inlet shifts, it floods and covers all the adjacent sediments (such as tidal bars, lagoonal muds, and foreshore bar) and deposits newer tidal channels on top of these. The same applies to other sediments. Therefore the sediments' location changes from time to time and covers older sediments and hence produce vertical sections such as that of well A. Figure 18 is a record of a shifting tidal inlet from Plettenberg Bay.

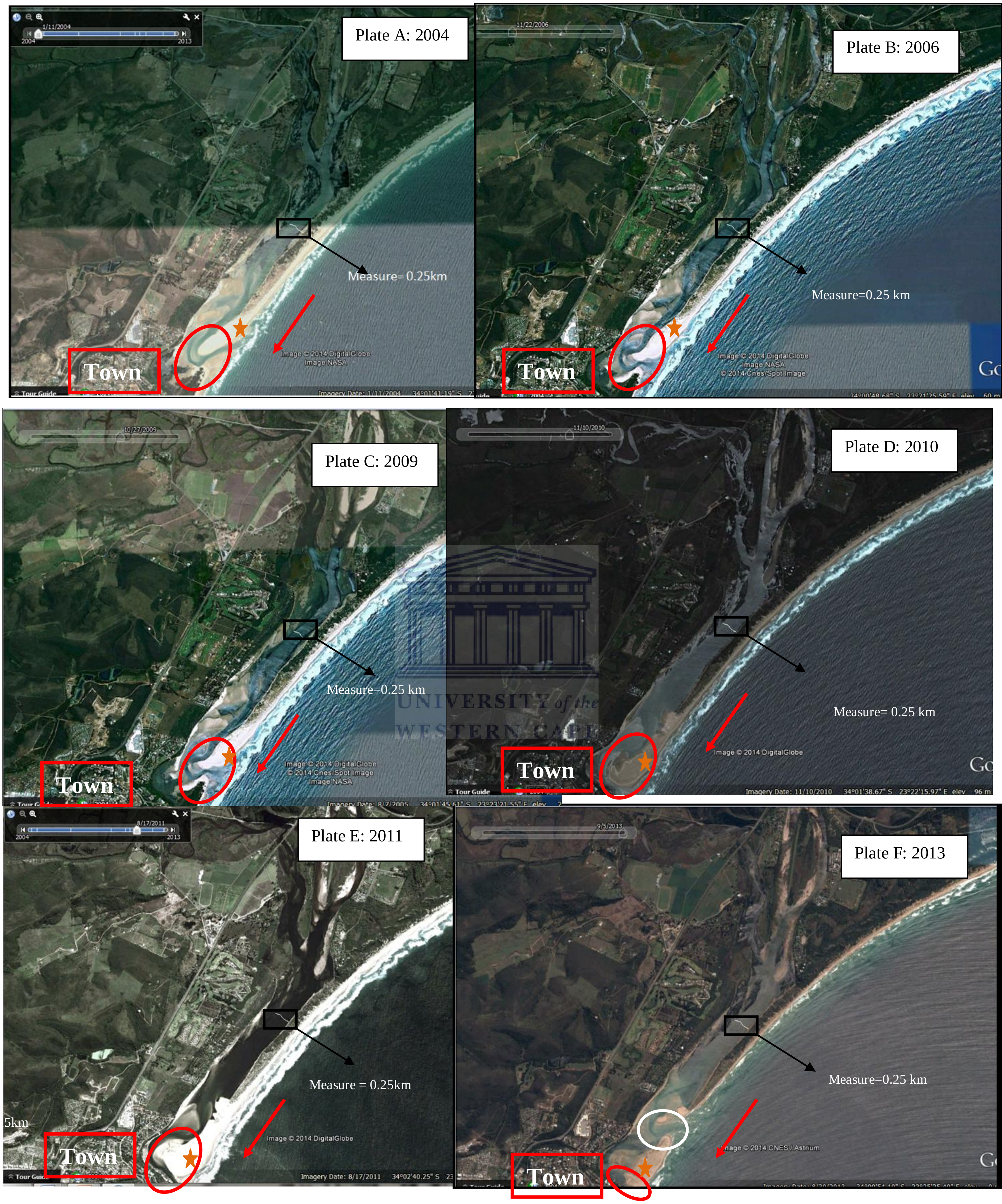


Fig18: Showing images of lagoonal estuary in Plettenberg Bay, South Africa. Plates A-F shows relative changes of the Tidal inlet position over time (from year 2004 to 2013). Red circles refer to the initial inlet position and white circle refers to the new inlet, Orange star refers to a barrier bar, Red arrow refers to shifting direction of the inlet and Red rectangle refers to the coastal town. (Images taken from Google Earth).

In plate A-C the tidal inlet (red arrow) and the barrier bar (orange star), are relatively in a similar position and therefore the shifting is significantly slow and hence showing similar results. This accounts for years 2004 till 2009, but in 2010 it is noted that the inlet is very close to the coast and so is the barrier bar and this is relatively similar for year 2011. In 2013 the barrier bar still appears to be closer to the coast and is wider and similar to 2011, but then the difference is the new conduit (white circle) also connecting the lagoon to the ocean. This means that the earlier barrier bar, back barrier bars and lagoonal mud sediments are covered by the new sediments carried out by this new inlet.

4.1.5 Regional correlation

The sequence boundaries were automatically picked when the wells were loaded in petrel, and these boundaries relatively matched very well with biostratigraphic data for well A, B and C. This was not the case for well D, as biostratigraphic data was not available; therefore this study could not conclude if they match with biostratigraphy or not. This study assumed that the boundaries in well D are correct to proceed with the regional correlation for the wells. The regional correlation within zone 3 (USM) is based on gamma ray signatures, where similar gamma signitures are grouped together.

Refer to figure 19 (below):

Well A to C could be correlated and they show to have similar facies association and this could result from the alignment of the wells, which is nearly parallel to the coast (see appendix 3). Whilst well D is down slope in the marine and aligned nearly perpendicular to the the other three we, its facies changes are different being shoreface and foreshore, rather than tidal facies. When looking at the regional correlation below (figure 19), the facies abundance changes laterally; from well A the tidal channels are pronounced (thicker) and abundant relative to others. Whilst in well B, all the tidal units are relatively thin. In well C, the tidal bars are thick and abundant relative to other facies.

Refer to figure 20 (below):

This lateral change in facies thickness from well to well is best explained by the figure below (figure 20), which shows the possible hypothetic scenario in relation to the well's location in the lagoonal estuarine system (using Plettenberg Bay as the modern environment analogue). Well A is directly located on a tidal channel near the tidal inlet and this point is most likely covered by water entering the ocean. Well B is most likely to be on a tidal flat, right on the rim of exposed tidal bar where water coverage always changes in relation to the tide (high tide and low tide). Well C on the other hand is located on a tidal bar that is likely always covered by a thin film of water and well D is located in the shallow marine setting (shoreface and foreshore).

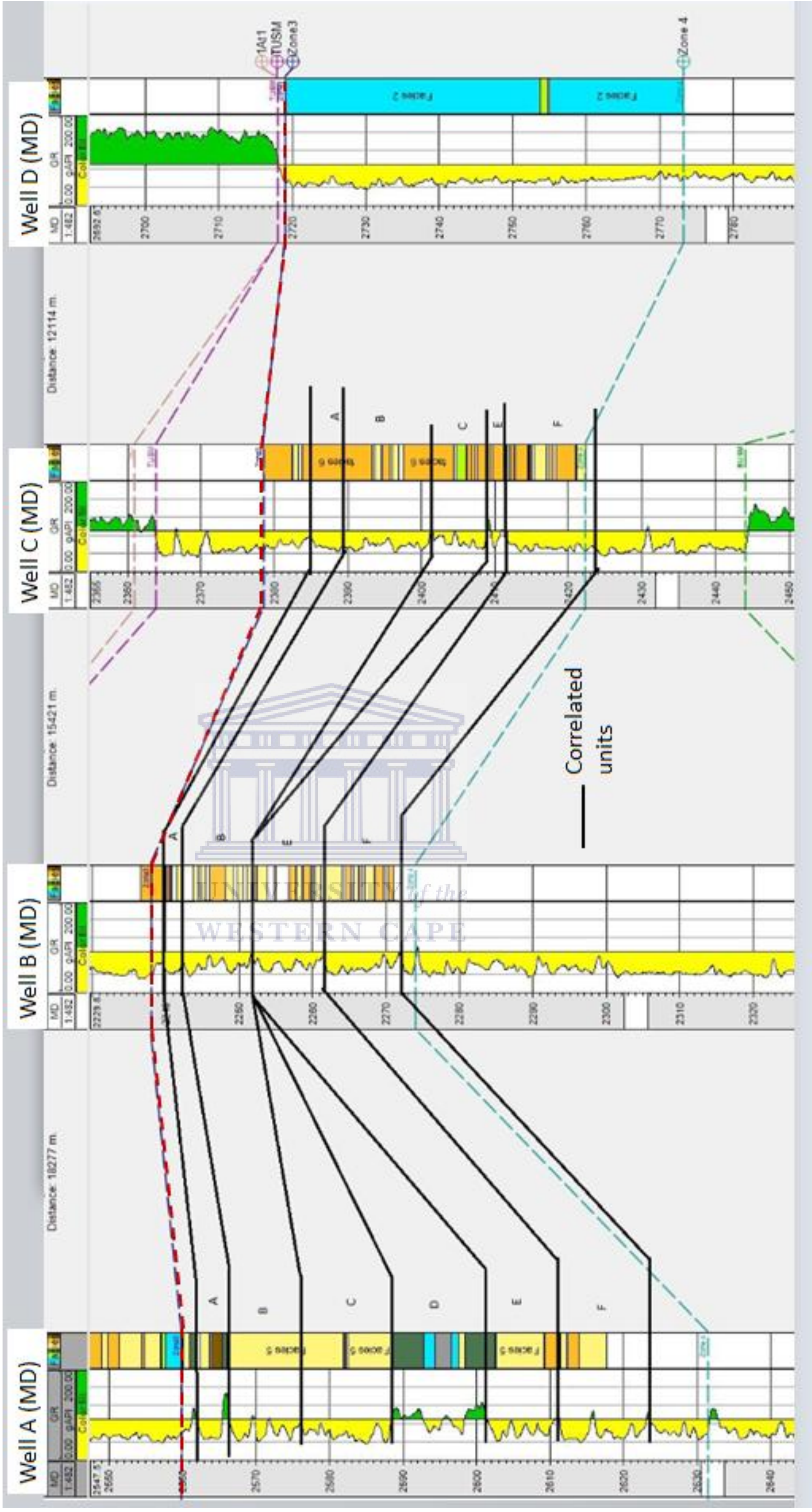


Fig 19: Showing regional correlation of the wells; well A from the left to well D to the right, and the top (maroon dotted line) and bottom (light blue dotted line) of zone 3. Black lines refer to correlated units.

Fig 20: Possible scenario of the study wells location within a hypothetical lagoonal-estuarine system, like the one in Plettenberg Bay. (Images taken from Google Earth).

Figure 21 below shows the possible interpreted trends from the GR log. The interpreted trends for zone 3 appear to give an hourglass shape which shows slight fining-coarsening upward trend. The subtle fining-coarsening upward trend in zone 3 (Upper Shallow Marine) was reported before by PGS (1999.) It is noted that this seems not to be the case for well D as it appear to show only coarsening upwards for zone 3 (Upper Shallow Marine) rather than fining-coarsening upward. It has also been noted that below the base of zone 3 (zone 4) there is a slight fining upward sequence and therefore this trend together with the upper trend (coarsening upward in zone 3) respects the same sedimentary trends and pattern of the other three logs (A, B and C) in zone 3. Based on these patterns, it is suggested for well D to change and lower the base of zone 3 from 2773.22 m to 2800 m as this will complement the well-known hourglass trend shape for zone 3.

These trends reflect two sequence of events in relation to the sea level changes; beginning with transgression followed by regression. Transgression occur when sea level rises, the marine sediments move landward flooding and covering the coastal settings with fine sediments and therefore forming a fining upward sequence (Walker, 1992). On the other hand regression is the opposite, it occurs when sea level falls resulting in coastal deposits moving basin ward, overlying the fine sediments and forming coarsening upward vertical sequences (Walker, 1992). The burial of older sediments during the sea level rise and fall depends on the sediment supply; therefore if there is enough sediment, then there will be significant burial of older sediments by new moved deposited sediments. In the case where there is not enough sediment supply, less burial occurs and this is suggested to be the case for the Upper Shallow Marine.

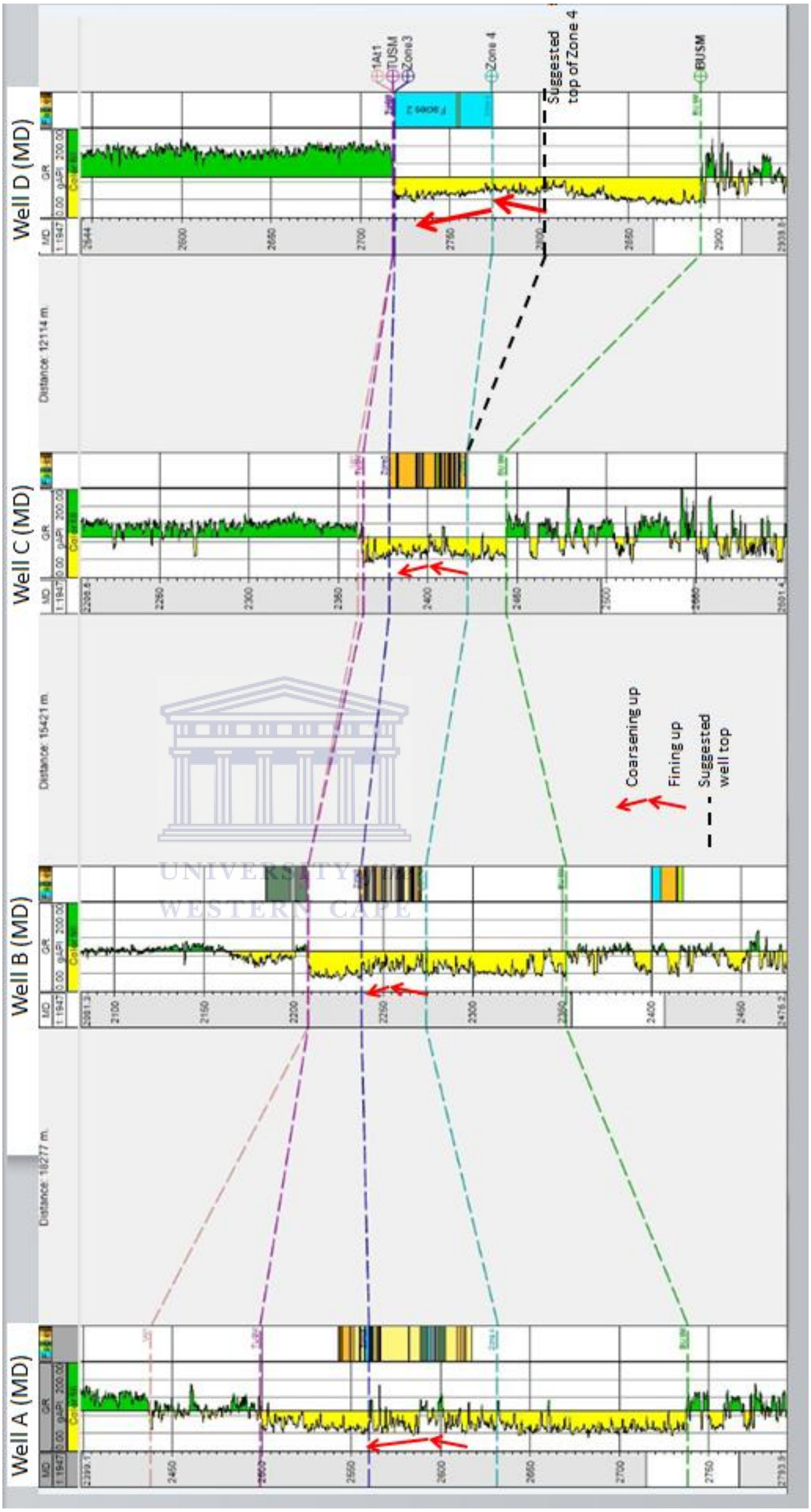


Fig 21: Showing sedimentary trends on a regional scale (**<u>not parasequences</u>**)

Based on all sedimentological evidence and interpretations given by this study; the USM (Berriasian to Late Valanginian) forms in a tidal/estuarine to shoreface environment. These results coincide with all other external discussions and papers related to the aspects (depositional environment review) of the study; that the USM forms in a tidal/estuarine to shoreface setting (PGS, 1999). Below is a sedimentological model driven by this study's interpretation and it shows feasible scenarios of the location of the wells relative to the model.

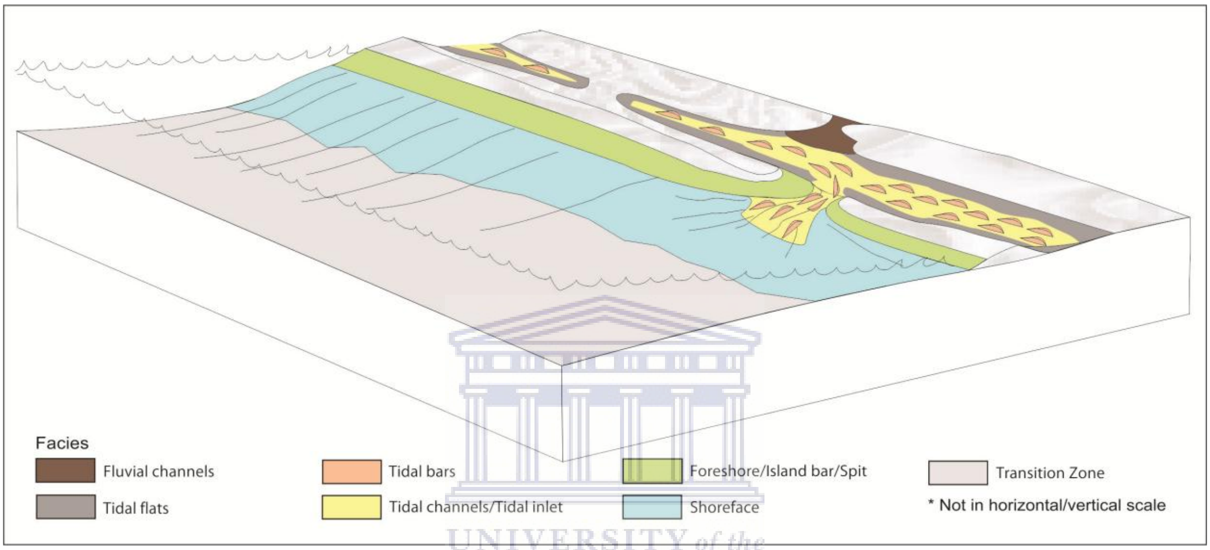


Fig 22: This conceptual model best suits the results and shows the most likely depositional setting for this study. (Not in vertical or horizontal scale).

CHAPTER 5

5.1 Conclusions and recommendations

A total of seven facies associations were identified after studying all the wells of interest; Facies 1-3 include deposits of storm dominated shoreface, foreshore and transitional zone, with significant hummocky cross stratification features. Facies 4-7 include deposits of wave dominated estuary with common heterolithic features (flaser bedding, lenticular and mud drapes). Therefore, based on the findings (facies association), it was deduce that the study area lies in a lagoonal estuary to shoreface environment. According to the facies log trends; well A, B and C lies in a tidal environment since they show deposits of wave dominated estuarine with common heterolithic features. On the other hand well D lies in a shallow marine environment as it shows storm dominated deposits with hummocky cross stratification. Finally, Plettenberg Bay is proposed in the study as a good analogous of the interpreted paleoenvironment.

The interpreted gamma ray trends for zone 3 (USM) shows a slight fining-coarsening upward sequence for well A, B and C. The defined trends reflect two sequence of events in relation to the sea level changes; beginning with transgression (fining upward) followed by regression (coarsening upward). This is not the case for well D, as it shows only coarsening upward for zone 3 and therefore reflecting a regression event. Therefore since the time of deposition for zone 3 is the same throughout Bredasdorp basin, it's geologically reasonable that the sequence of events (sea level changes) should be the same and hence reflecting similar trends. Therefore it is recommended to consider changing the base of zone 3 from 2773.22 m to 2800 m deep in well D, as this will complement the fining-coarsening upward trend which is a well-known sedimentary trend of zone 3 (as reported by PGS, 1999). This will significantly change the thickness of the zone 3 in well D and make it the thickest zone relative to other wells (A, B and C). This best complements the location of the well as it's located in the marine environment and therefore reflecting more accommodation space.

It is suggested by this study before shifting the base of zone 3 to 2800 m deep, to re-interpret the biostratigraphy for well D, if it's not yet done and/or get more biostratigraphic information for well D to confirm if the present correlation (present limits of USM) is correct. This was done successfully for other wells as their biostratigraphic information was available for the study. A sedimentological study on core 5 and core 6 which lies below the base of zone 3 is recommended as this will give insight on the facies changes in those depths.

It is generally expected that an accurate knowledge of the lateral extent, thickness changes and trends and actual distribution of the reservoir sandstones is a key to guide hydrocarbon exploration (Jahn et al., 1998). For further insights on how prospective is the field, it is suggested to extend the study area to far west and south of the Y-Y field and perform the same sedimentological study for more wells. This will allow better understanding of the sedimentological review of zone 3 in these parts. Following a sedimentological study, a thorough structural and petrophysical evaluation is needed for both the studied wells and the proposed ones, as this will further allow a full geological model for the area that can be simulated to create flow model for the area.

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A special thanks to the whole Geology department who made it happened by making sure that all the material needed was available and to the Petroleum Agency of South Africa (PASA) thank you for offering the visualization sessions and giving out the data information.

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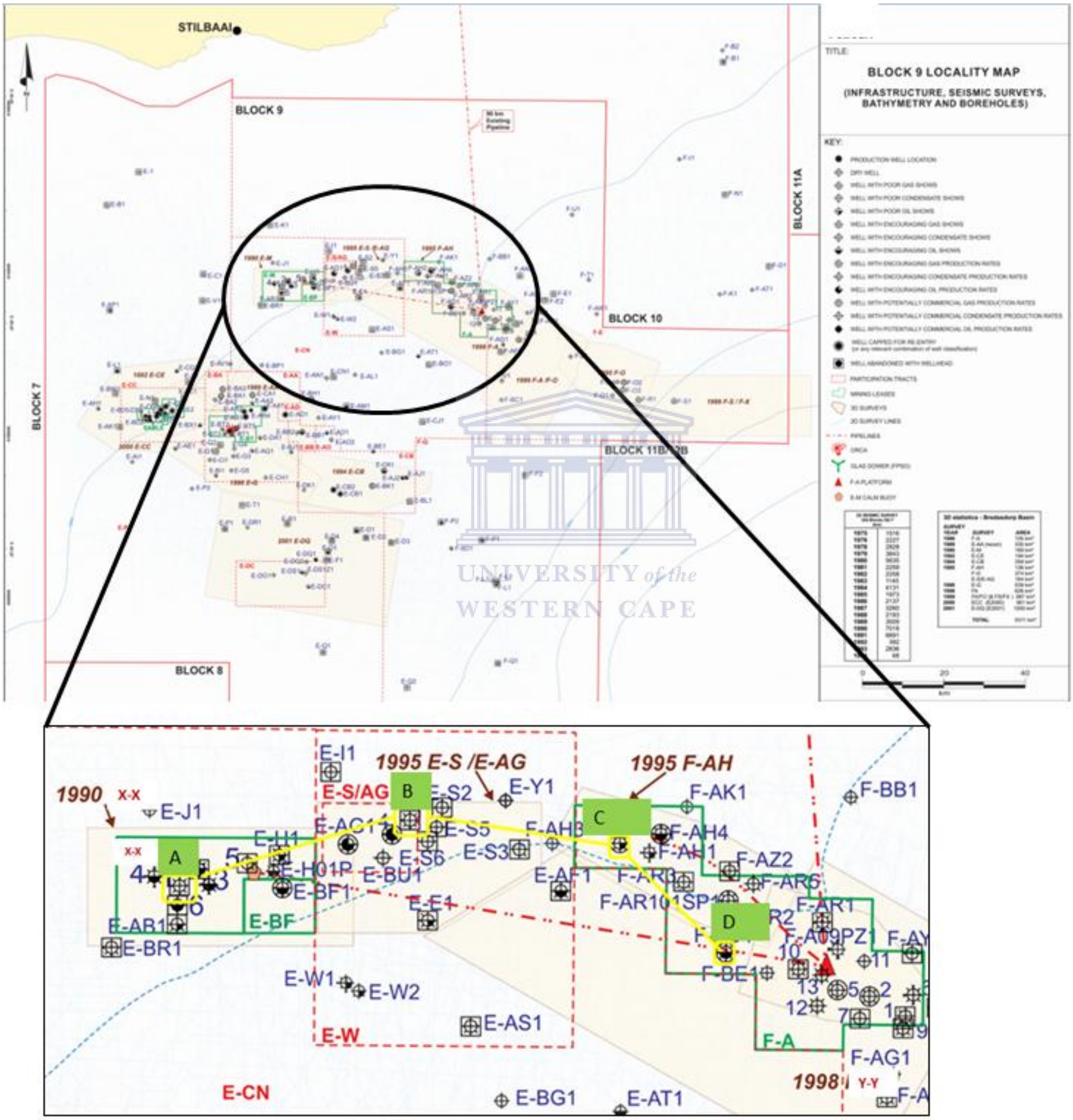
Appendix 1:

Facies classification, modified after Miall, 1978c.

Facies code	**Lithology**	**Sedimentary structures**
Fr	Mud, silt	Massive,roots,bioturbation
Fm	Mud, silt	Massive,desiccation cracks
Fsm	Silt, mud	Massive
Fl	Sand, silt, mud	Fine lamination, very small ripples
Sm	Sand, fine to coarse	Massive or faint lamination
Ss	Sand, fine to very coarse, may be pebbly	Broad, shallow scours
Sl	Sand, very fine to coarse, may be pebbly	Low angle(<15^{O}) cross-beds
Sh	Sand, very fine to coarse, may be pebbly	Horizontal lamination parting or streaming lamination
Sr	Sand, very fine to coarse	Ripple cross-lamination
Sp	Sand, fine to very coarse, may be pebbly	Solitary or grouped planar cross-beds
St	Sand, fine to very coarse, may be pebbly	Solitary or grouped planar trough cross-beds
Sd	Sand, fine to very coarse, may be pebbly	Deformed
Sg	Sand, fine to very coarse, may be pebbly or gravelly	
Sgp	Sand, fine to very coarse, may be pebbly or gravelly	Planar cross-beds
Gp	Gravel, stratified	Planar cross-beds
Gt	Gravel, stratified	Trough cross-beds
Gh	Clast-supported, crudely bedded gravel	Horizontal bedding, imbrications
Gcm	Clast-supported massive gravel	
Gci	Clast-supported gravel	Inverse grading
Gmg	Matrix-supported gravel	Inverse to normal grading
Gmm	Matrix-supported, massive gravel	Weak grading
Gg	Gravel	
HCS	Sand, very fine to coarse	Hummocky cross-stratification
Sw	Sand, very fine to coarse	Wavy lamination

Appendix 2:

Map showing block 9 and the alignment of the wells relative to the coast (modified after PASA 2014).

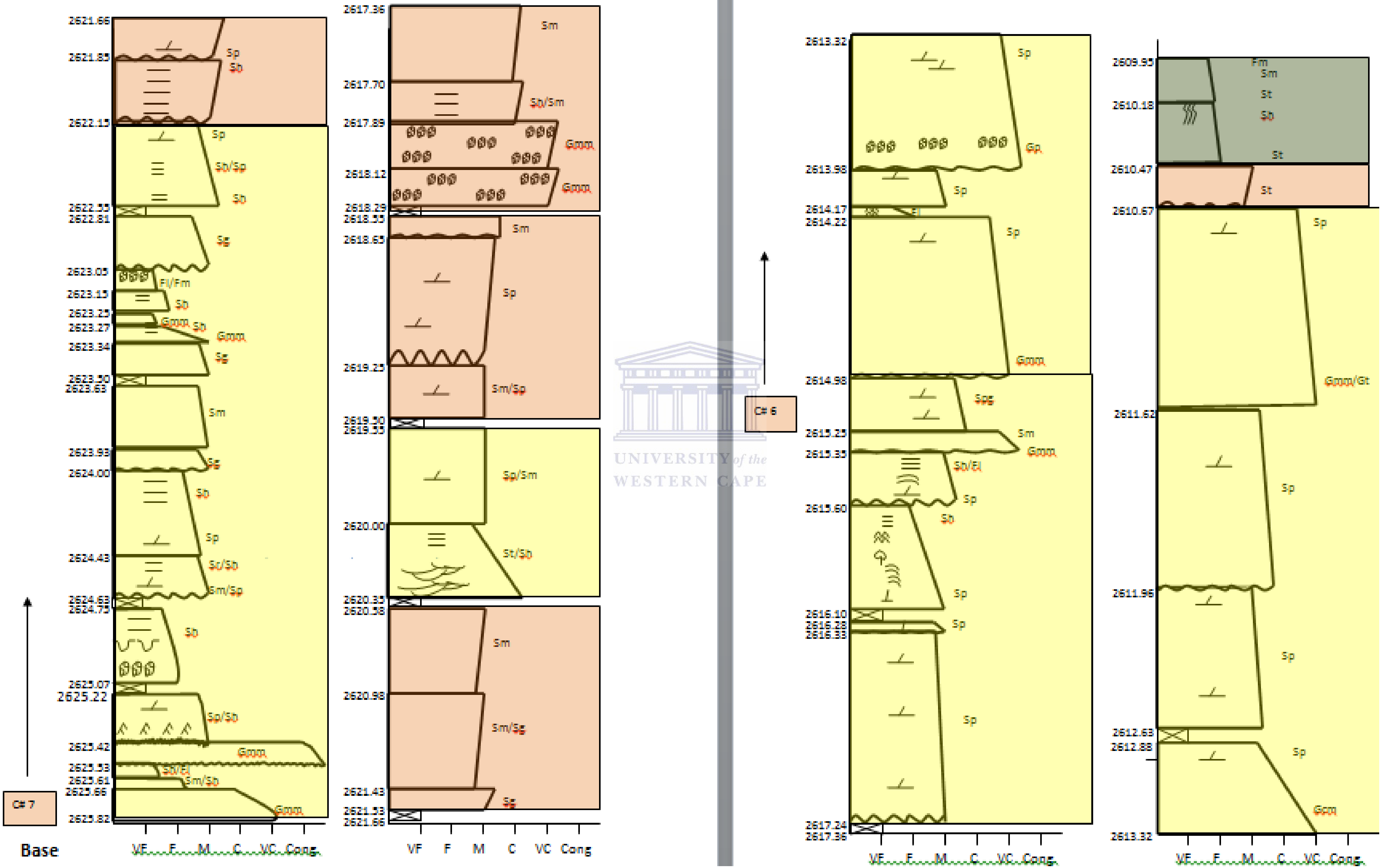


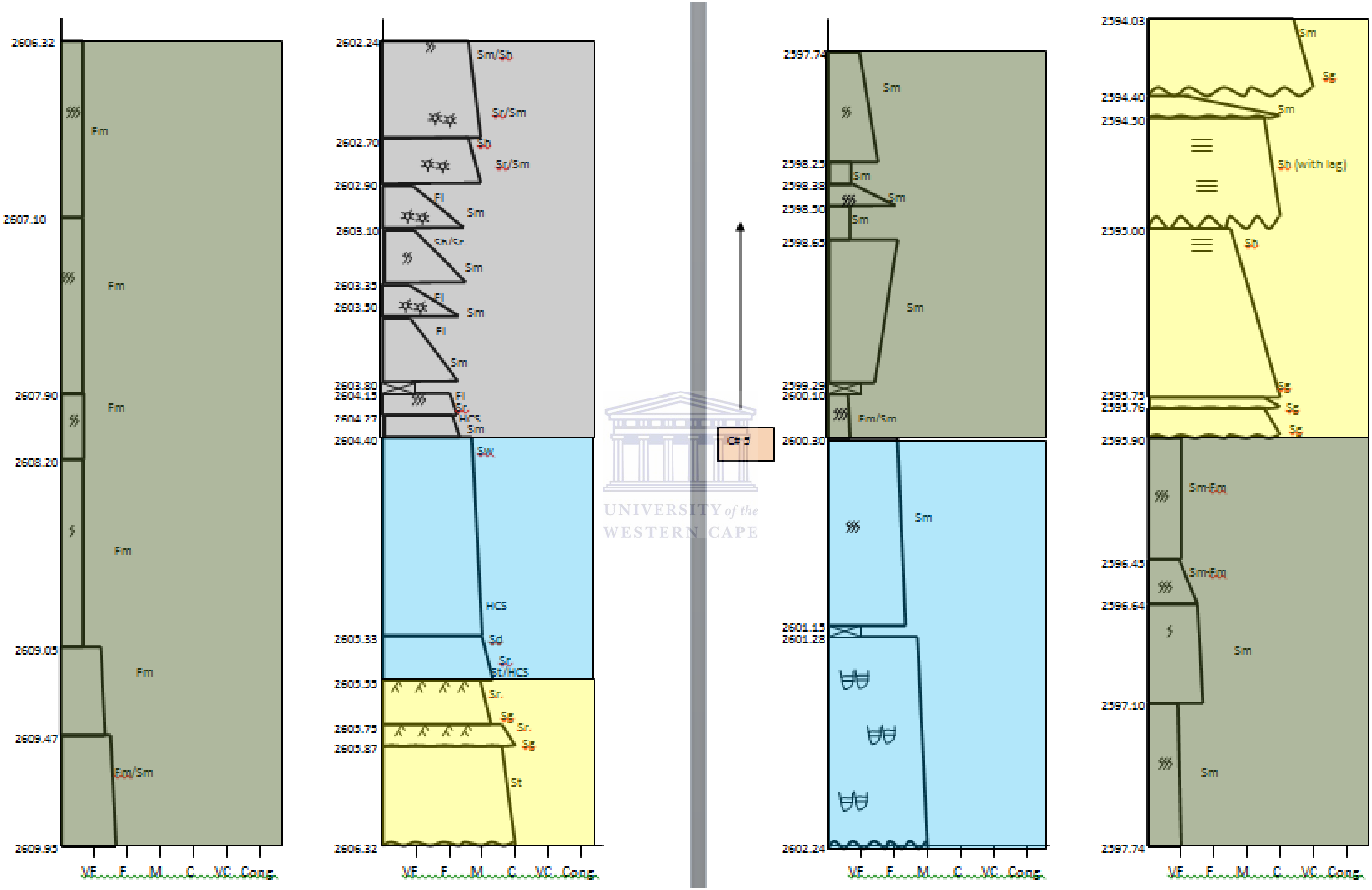
<u>Appendix 3:</u>

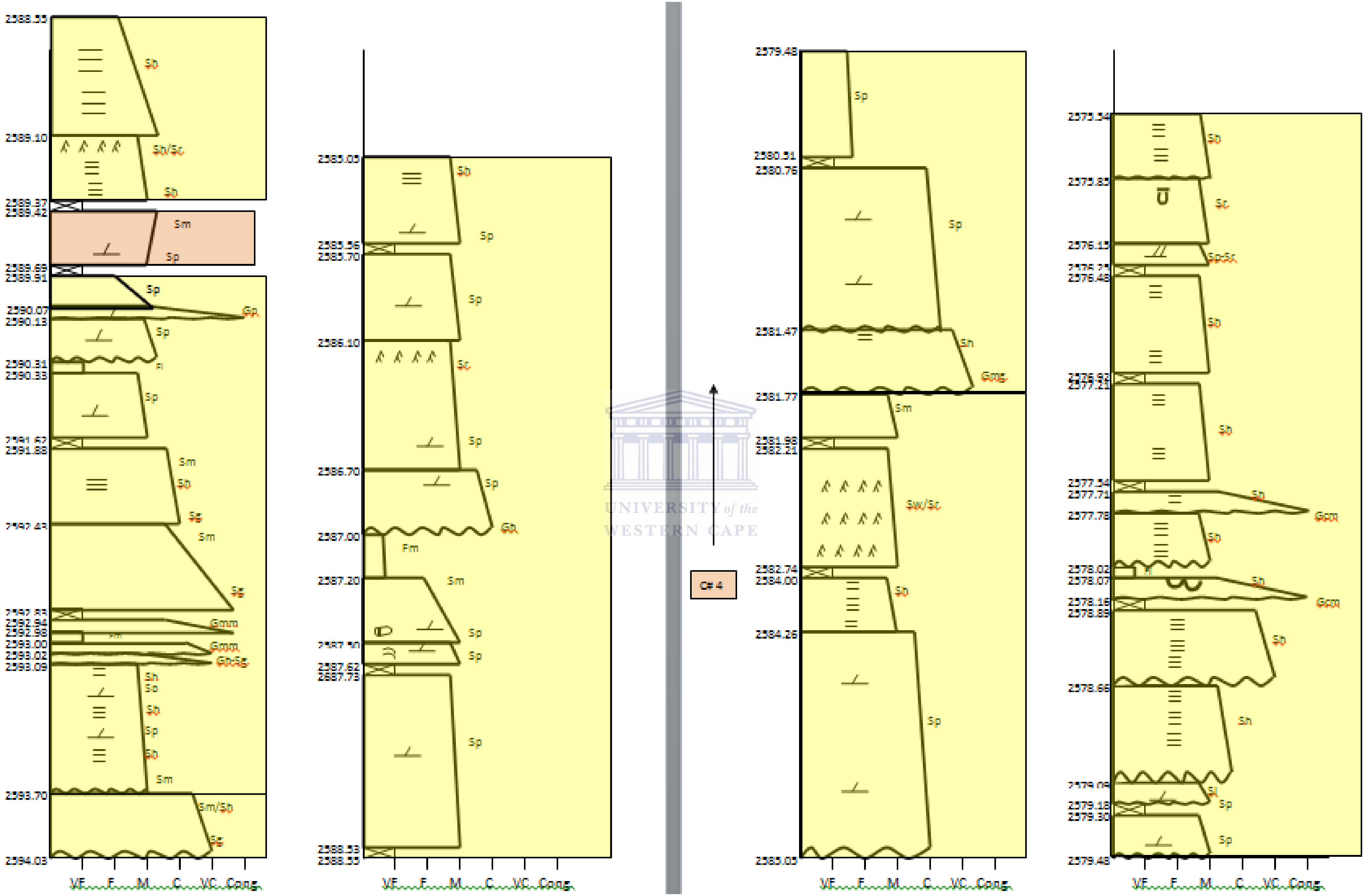
Detailed vertical sections:

Scale: 1m=25cm

Well-A




2606.32
Fm
2607.10
Fm
2607.90
Fm
2608.20
Fm
2609.05
Fm
2609.47
Fm/Sm
2609.95
VF F M C VC Cong.
2602.24
Sm/Sh
Sr/Sm
2602.70
Sh
Sr/Sm
2602.90
Fl
Sm
2603.10
Sh/Sr
Sm
2603.35
2603.50
Fl
Sm
Fl
Sm
2603.80
2604.15
Fl
Sr
HCS
Sm
2604.40
Sw
HCS
2605.33
Sd
Sr
St/HCS
2605.55
Sr.
Sg
2605.75
Sr.
2605.87
Sg
St
2606.32
VF F M C VC Cong.
C# 5
2597.74
Sm
2598.25
Sm
2598.38
Sm
2598.50
Sm
2598.65
Sm
2599.29
2600.10
Fm/Sm
2600.30
Sm
2601.15
2601.28
2602.24
VF F M C VC Cong.
2594.03
Sm
Sg
2594.40
Sm
2594.50
Sh (with leg)
2595.00
Sh
2595.75
Sg
2595.76
Sg
Sg
2595.90
Sm-Fm
2596.45
Sm-Fm
2596.64
Sm
2597.10
Sm
2597.74
VF F M C VC Cong.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2589.10
2589.37
2589.42
2589.69
2589.91
2590.07
2590.13
2590.31
2590.33
2591.88
2593.00
2593.02
2593.09
2593.70
2594.03
Sh
Sh/Sr
Sm
Sp
Gp
Sg
Gmm
Gh-Sg
Sm/Sh
VF F M C VC Cong.
2585.05
2585.56
2585.70
2586.10
2586.70
2587.00
2587.20
2587.62
2588.53
2588.55
Sr
Gh
Fm
C# 4
2579.48
2580.51
2580.76
2581.47
2581.77
2581.98
2582.21
2582.74
2584.00
2584.26
2585.05
Gms
Sw/Sr
2575.34
2575.85
2576.15
2576.48
2577.54
2577.71
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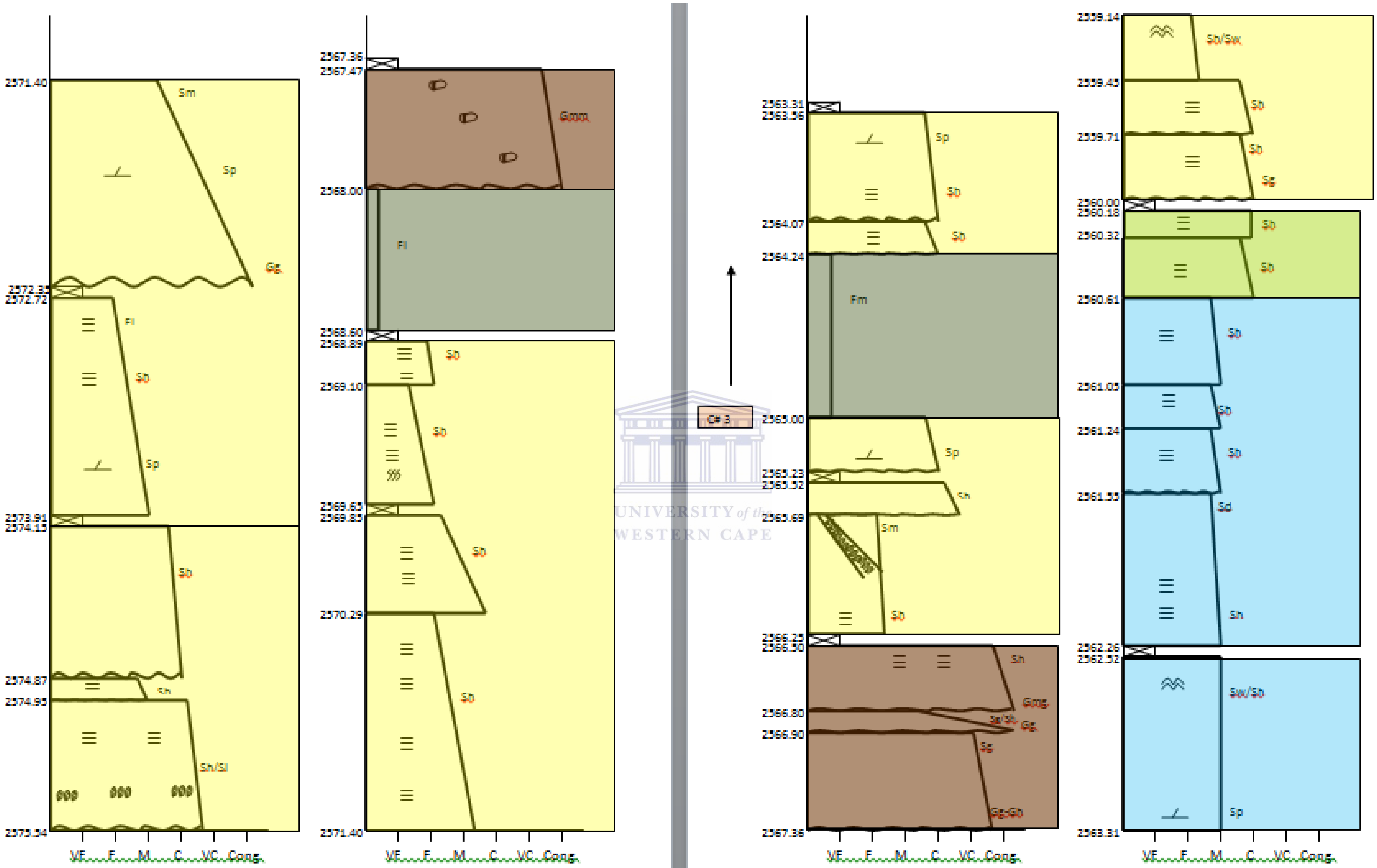
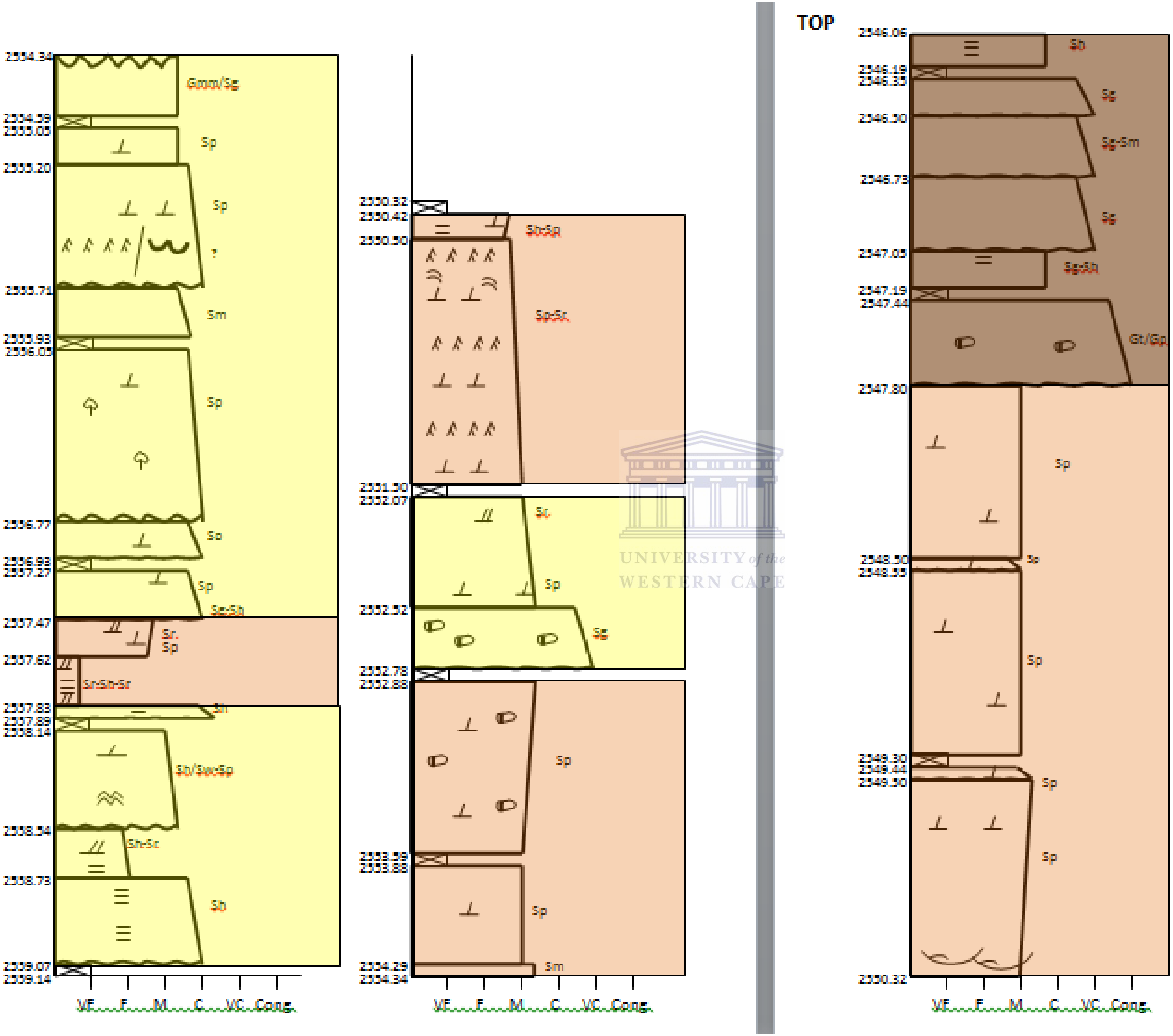
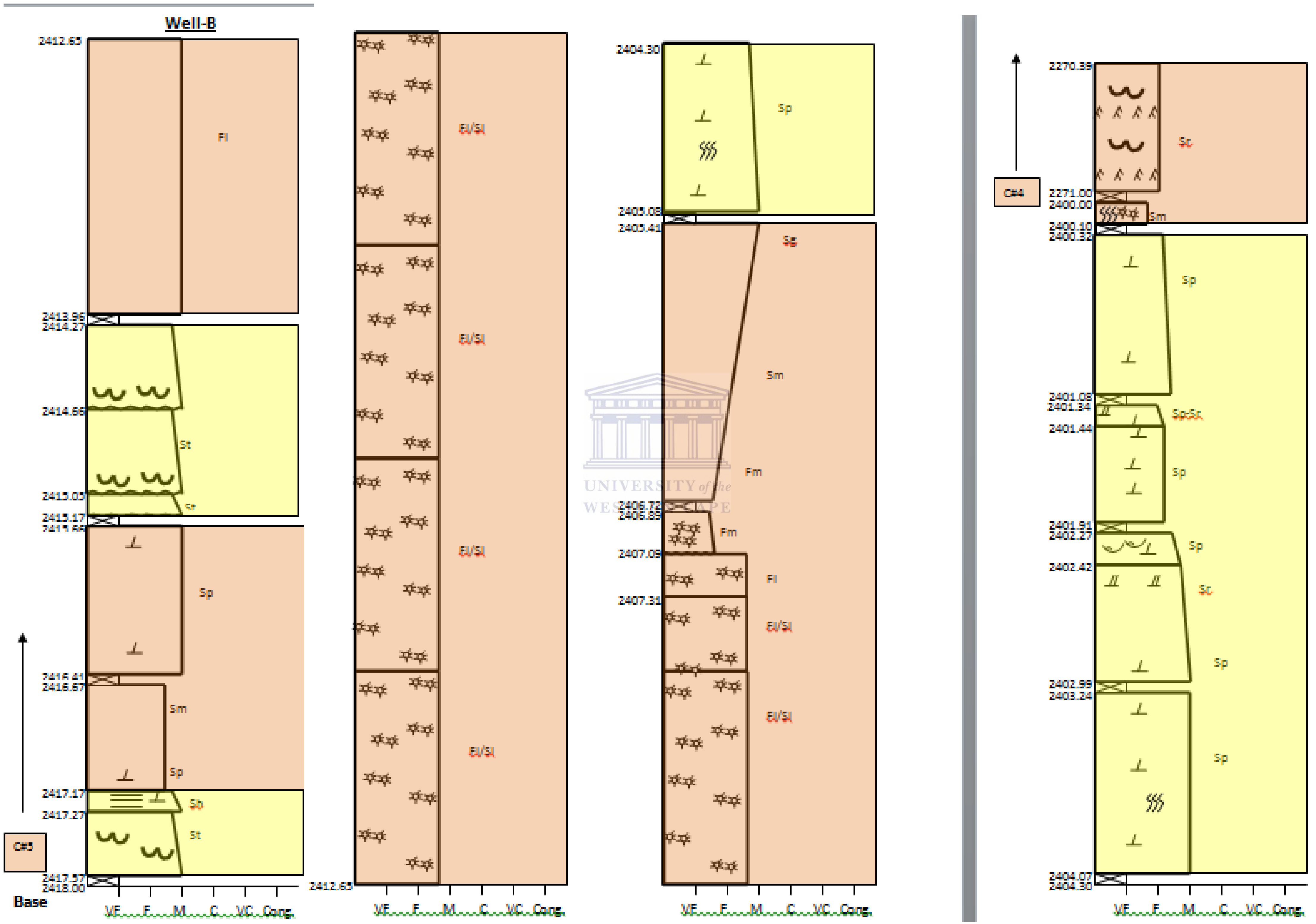
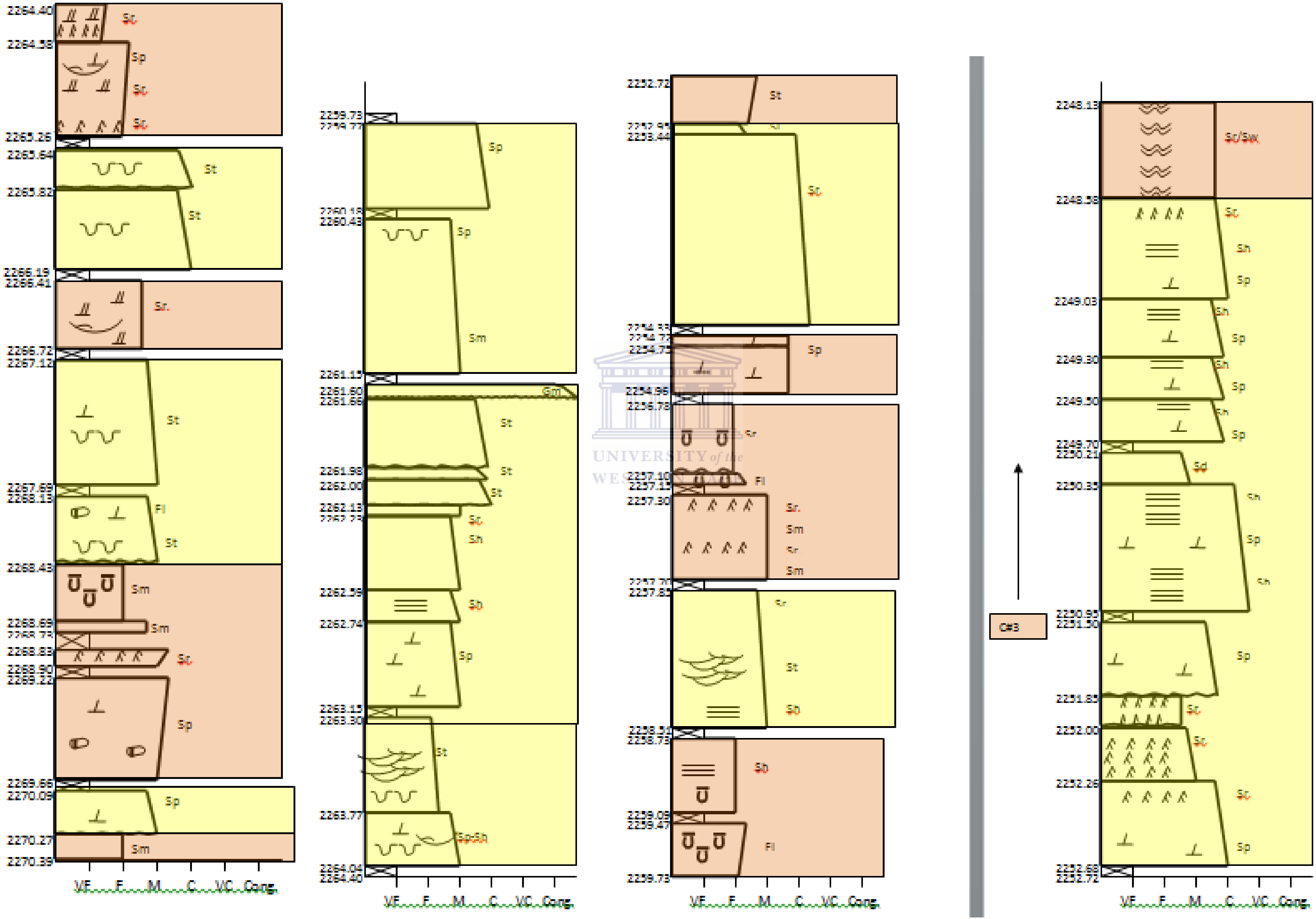
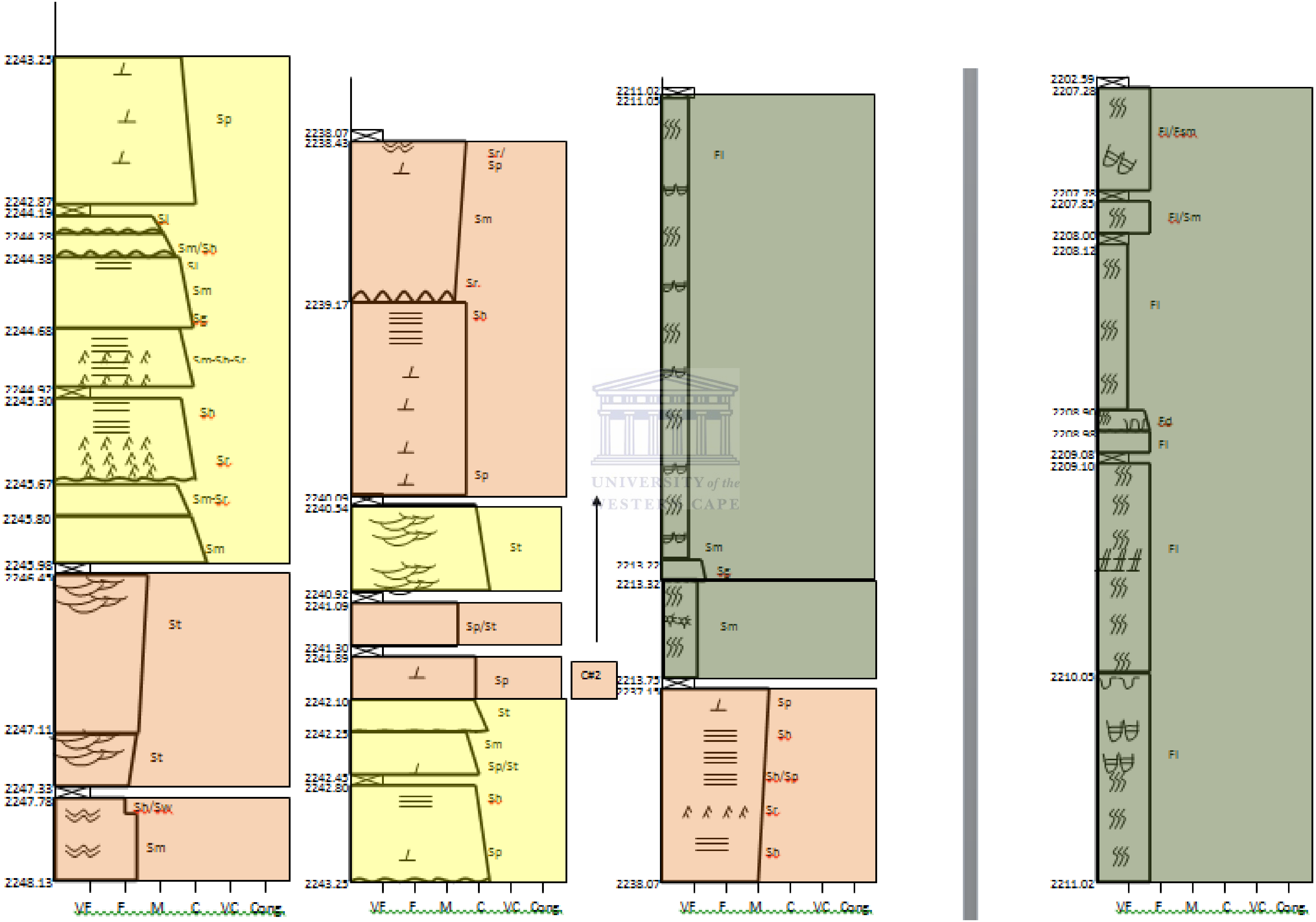
Sp-Sr
Gcm
Sl


2571.40
Sm
Sp
Gg
2572.35
2572.72
Fl
Sh
Sp
2573.91
2574.15
Sh
2574.87
Sh
2574.95
Sh/Sl
2575.54
VF F M C VC Cong.
2567.36
2567.47
Gmm
2568.00
Fl
2568.60
2568.89
Sh
2569.10
Sh
2569.65
2569.85
Sh
2570.29
Sh
2571.40
VF F M C VC Cong.
C# 3
2563.31
2563.56
Sp
Sh
2564.07
Sh
2564.24
Fm
2565.00
Sp
2565.23
2565.52
Sh
2565.69
Sm
Sh
2566.25
2566.30
Sh
Gmg
2566.80
Sr/Sh
Gg
2566.90
Sg
Gg-Gh
2567.36
VF F M C VC Cong.
2559.14
Sh/Sw
2559.45
Sh
2559.71
Sh
Sg
2560.00
2560.18
Sh
2560.32
Sh
2560.61
Sh
2561.05
Sh
2561.24
Sh
2561.55
Sd
Sh
2562.26
2562.52
Sw/Sh
Sp
2563.31
VF F M C VC Cong.

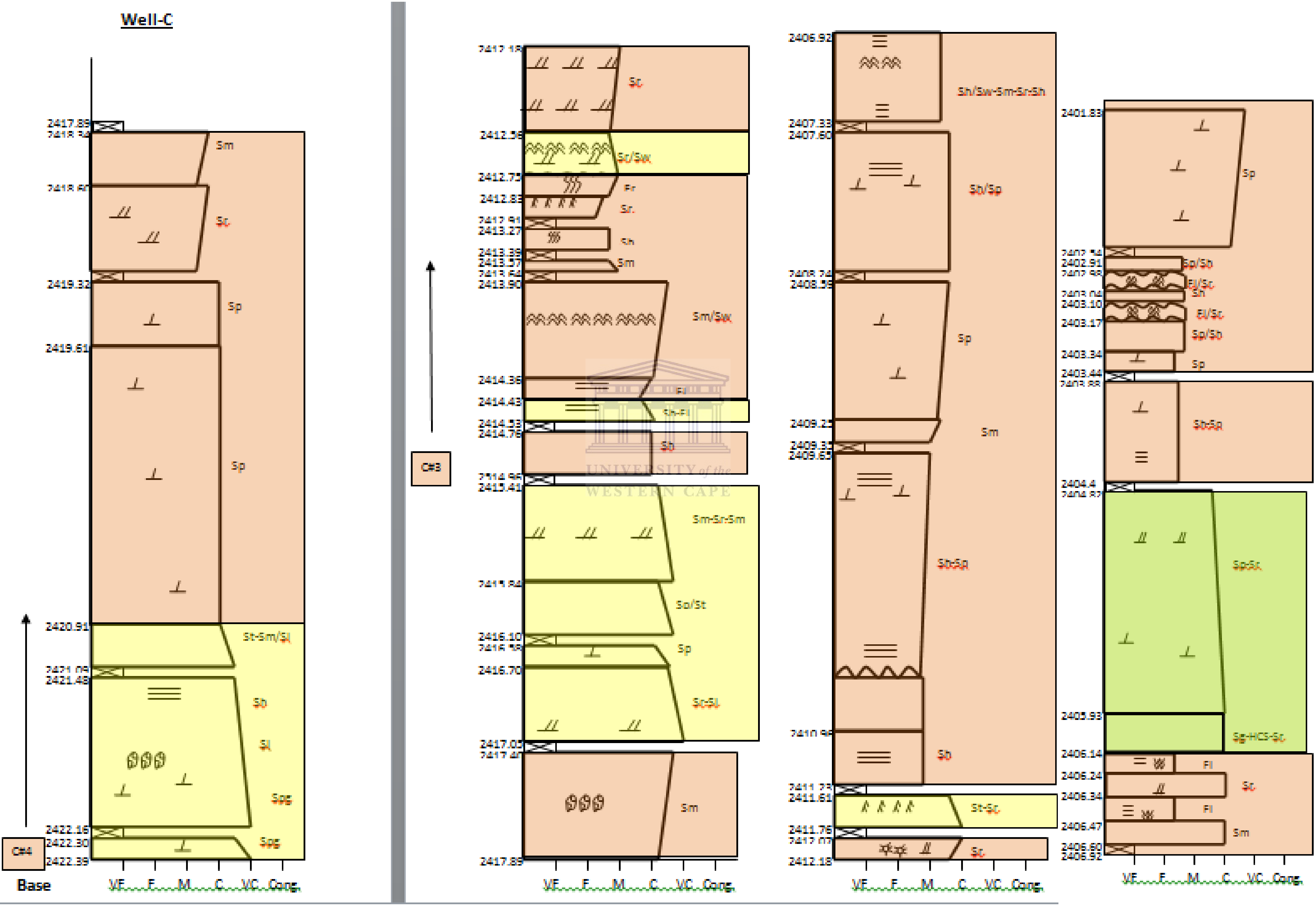

TOP
2554.34
Gmm/Sg
2554.59
2555.05
Sp
2555.20
Sp
?
2555.71
Sm
2555.93
2556.05
Sp
2556.77
Sp
2556.93
2557.27
Sp
Sg-Sh
2557.47
Sr.
Sp
2557.62
Sr-Sh-Sr
2557.83
Sh
2557.89
2558.14
Sh/Sw-Sp
2558.54
Sh-Sr
2558.73
Sh
2559.07
2559.14
VF F M C VC Cong.
2550.32
2550.42
2550.50
Sh-Sp
Sp-Sr
2551.50
2552.07
Sr
Sp
2552.52
Sg
2552.78
2552.88
Sp
2553.59
2553.88
Sp
2554.29
2554.34
Sm
VF F M C VC Cong.
2546.06
Sh
2546.19
2546.35
Sg
2546.50
Sg-Sm
2546.73
Sg
2547.05
Sg-Sh
2547.19
2547.44
Gt/Gp
2547.80
Sp
2548.50
2548.55
Sp
Sp
2549.30
2549.44
2549.50
Sp
Sp
2550.32
VF F M C VC Cong.


Well-B
2412.65
Fl
2413.96
2414.27
2414.66
St
2415.05
St
2415.17
Sp
2416.41
2416.67
Sm
Sp
2417.17
Sh
2417.27
St
2417.57
2418.00
C#5
Base
VF F M C VC Cong.
Fl/Sl
Fl/Sl
Fl/Sl
Fl/Sl
2412.65
VF F M C VC Cong.
2404.30
Sp
2405.08
2405.41
Sg
Sm
Fm
2406.72
2406.89
Fm
2407.09
Fl
2407.31
Fl/Sl
Fl/Sl
VF F M C VC Cong.
C#4
2270.39
Sr
2271.00
2400.00
Sm
2400.10
2400.32
Sp
2401.08
2401.34
Sp-Sr
2401.44
Sp
2401.91
2402.27
Sp
2402.42
Sr
Sp
2402.99
2403.24
Sp
2404.07
2404.30
VF F M C VC Cong.

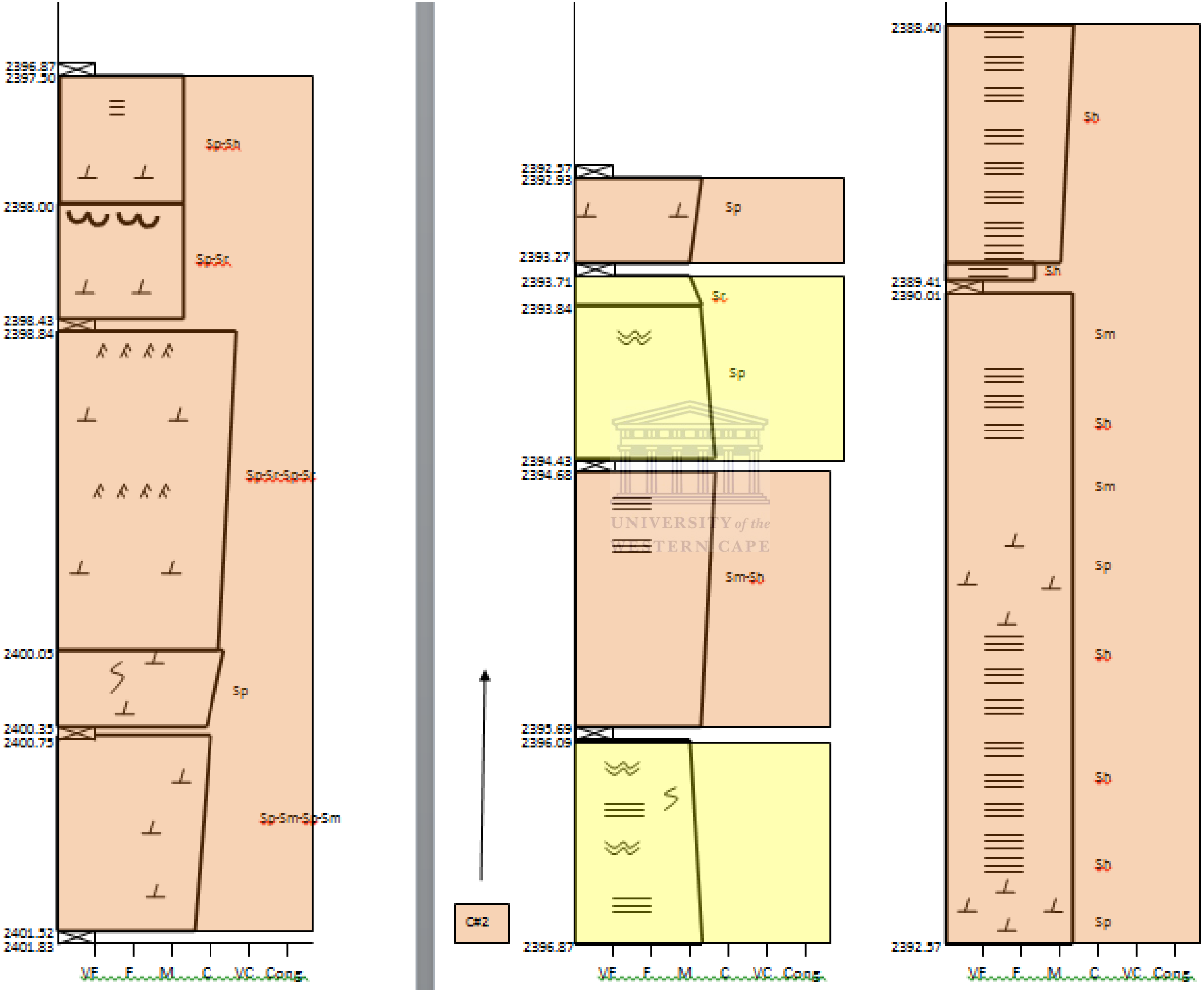

2264.40
2264.58
2265.26
2265.64
2265.82
2266.19
2266.41
2266.72
2267.12
2267.69
2268.13
2268.43
2268.69
2268.83
2268.90
2269.22
2269.66
2270.09
2270.27
2270.39
Sr
Sp
St
Fl
Sm
VF F M C VC Cong.
2259.73
2260.43
2261.15
2261.60
2261.66
2261.98
2262.00
2262.13
2262.59
2262.74
2263.15
2263.30
2263.77
2264.04
2264.40
Sp
Sm
Gm
St
Sr
Sh
Sp-Sh
VF F M C VC Cong.
2252.72
2253.44
2254.75
2254.96
2256.78
2257.10
2257.15
2257.30
2257.82
2258.57
2258.73
2259.09
2259.47
2259.73
St
Sr
Sp
Fl
Sm
Sh
VF F M C VC Cong.
C#3
2248.13
2248.58
2249.03
2249.30
2249.50
2249.70
2250.21
2250.35
2250.95
2251.30
2251.85
2252.00
2252.26
2252.68
2252.72
Sr/Sw
Sr
Sh
Sp
Sd
VF F M C VC Cong.


2243.25
Sp
2242.87
2244.19
Sl
Sm/Sh
2244.38
Sm
2244.68
2245.30
Sh
Sr
2245.67
Sm-Sr
2245.80
Sm
2245.98
St
2247.11
St
2247.33
2247.78
Sh/Sw
Sm
2248.13
VF
F
M
C
VC
Cong.
2238.07
2238.43
Sr/
Sp
Sm
Sr
2239.17
Sh
Sp
2240.54
St
2240.92
2241.09
Sp/St
2241.30
2241.89
Sp
2242.10
St
2242.25
Sm
Sp/St
2242.45
2242.80
Sh
Sp
2243.25
C#2
2211.02
2211.05
Fl
Sm
Sg
2213.32
Sm
2213.75
Sp
Sh
Sh/Sp
Sr
Sh
2238.07
2202.59
2207.28
Fl/Esm
2207.85
Fl/Sm
2208.00
2208.12
Fl
Ed
Fl
2209.08
2209.10
Fl
2210.05
Fl
2211.02


2198.47
Fr/Fl
2199.20
2199.43
Fr
2200.25
2200.45
Fr/Fl
2201.02
Fr
C#1
2202.59
VF F M C VC Cong.
2193.93
Sm
Fl
2194.22
Fr
2195.09
2195.37
Fr
2196.18
2196.54
Fr/Fl
2197.19
2197.49
Fr
2198.47
VF F M C VC Cong.
2188.99
2189.24
Fr
2189.83
2190.17
Fl
2190.78
2191.06
Fl
2191.52
Fl
2191.84
2192.35
Fl/Esm
2193.22
2193.51
Fl
2193.93
VF F M C VC Cong.
Top
2188.37
2188.48
Sg/Sh
Fl
Sg
2188.99
VF F M C VC Cong.



Well-C
2417.89
2419.32
2419.61
2420.91
2421.48
2422.16
2422.30
2422.39
Sm
Sr
Sp
Sp
St-Sm/Sl
Sh
Sl
Spg
Spg
C#4
Base
VF
F
M
C
VC
Cong.
2412.56
2412.75
2412.83
2413.27
2413.39
2413.57
2413.90
2414.36
2414.43
2414.53
2414.76
2415.41
2416.10
2416.70
2417.05
2417.89
Sr
Sr/Sw
Fr
Sr
Sh
Sm
Sm/Sw
Fl
Sh-Fl
Sh
Sm-Sr-Sm
Sp/St
Sp
Sr-Sl
Sm
C#3
2406.92
2407.33
2407.60
2408.59
2409.25
2409.35
2409.65
2411.61
2411.76
2412.18
Sh/Sw-Sm-Sr-Sh
Sh/Sp
Sp
Sm
Sh-Sp
Sh
St-Sr
Sr
2401.83
2402.91
2403.10
2403.17
2403.34
2403.44
2404.4
2405.93
2406.14
2406.24
2406.34
2406.47
2406.60
2406.92
Sp
Sp/Sh
Fl/Sr
Sh
Fl/Sr
Sp/Sh
Sp
Sh-Sp
Sp-Sr
Sg-HCS-Sr
Fl
Sr
Fl
Sm



2396.87
2397.50
Sp-Sh
2398.00
Sp-Sr
2398.43
2398.84
Sp-Sr-Sp-Sr
2400.05
Sp
2400.35
2400.75
Sp-Sm-Sp-Sm
2401.52
2401.83
VF F M C VC Cong.
C#2
2392.57
2392.93
Sp
2393.27
2393.71
Sr
2393.84
Sp
2394.43
2394.68
Sm-Sh
2395.69
2396.09
2396.87
VF F M C VC Cong.
2388.40
Sh
2389.41
2390.01
Sh
Sm
Sh
Sm
Sp
Sh
Sh
Sh
Sp
2392.57
VF F M C VC Cong.
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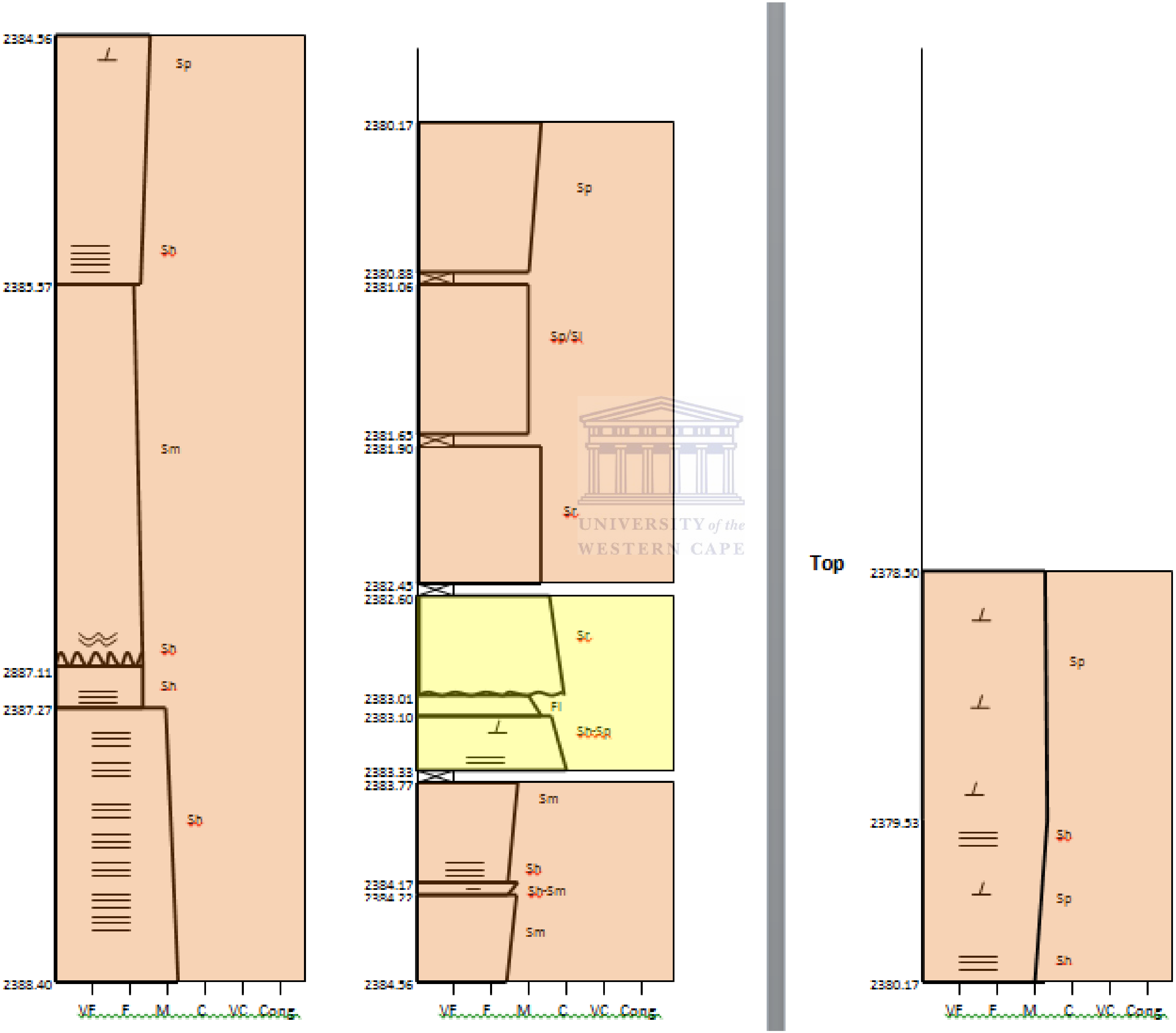
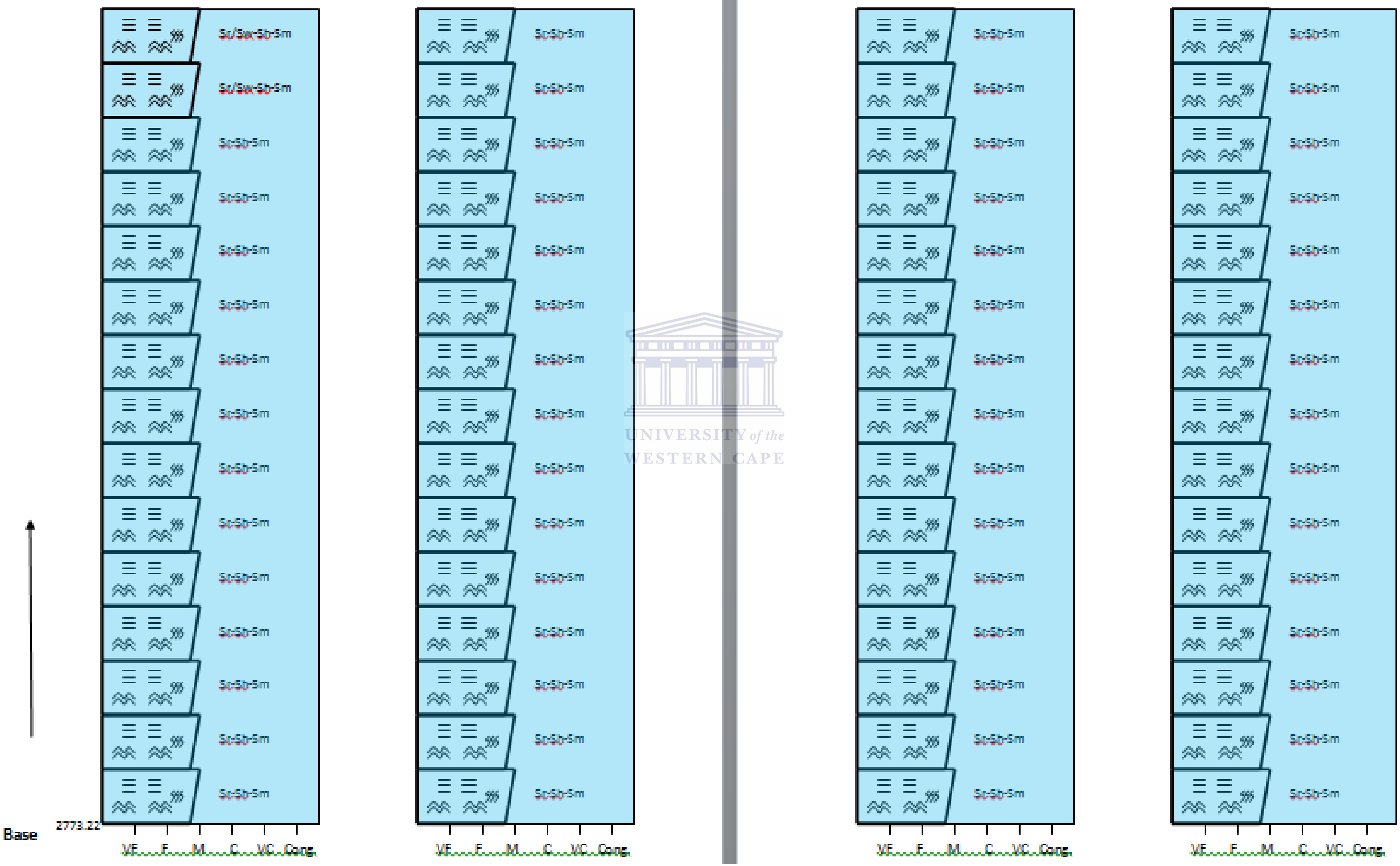
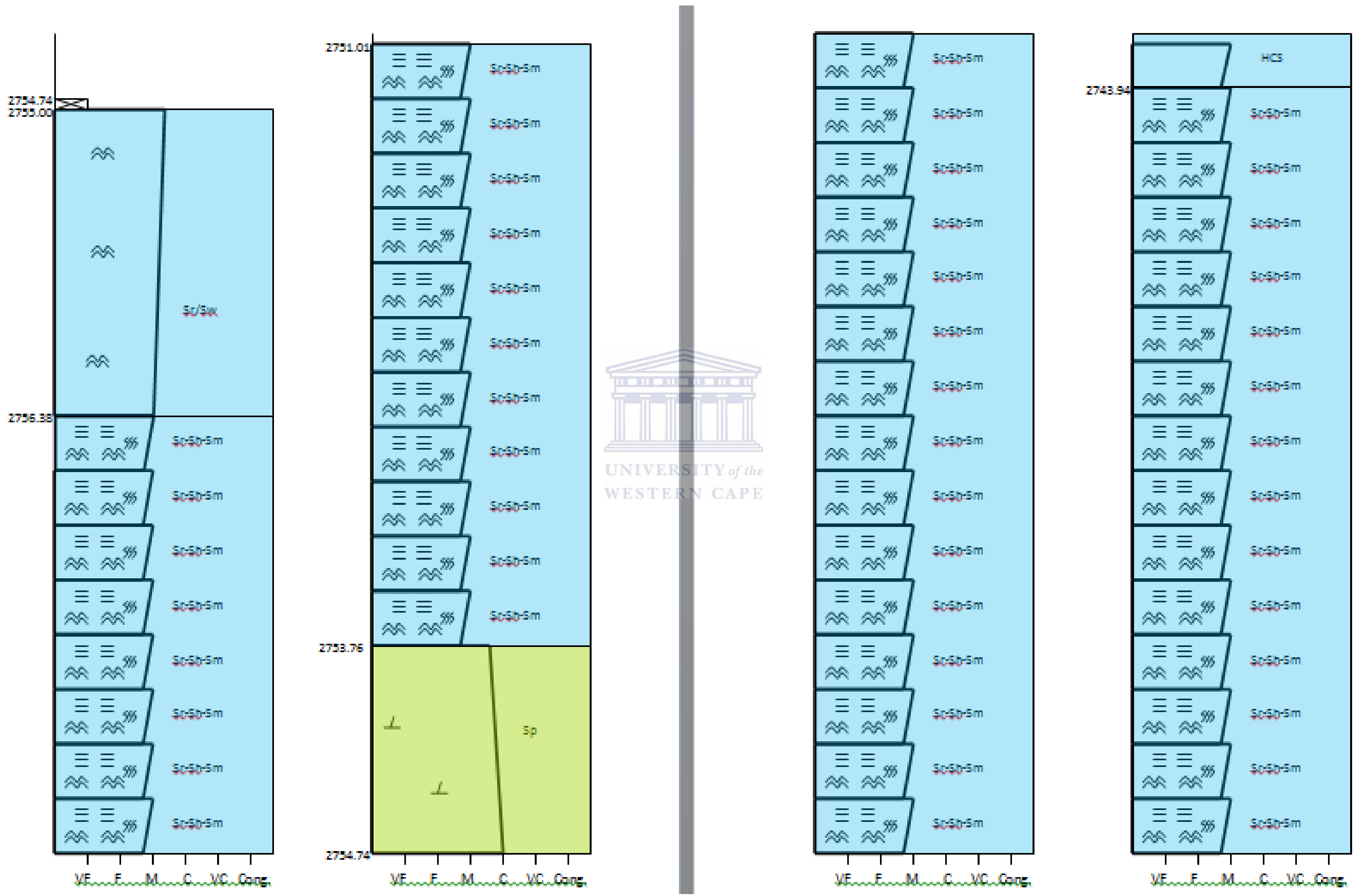
WESTERN CAPE

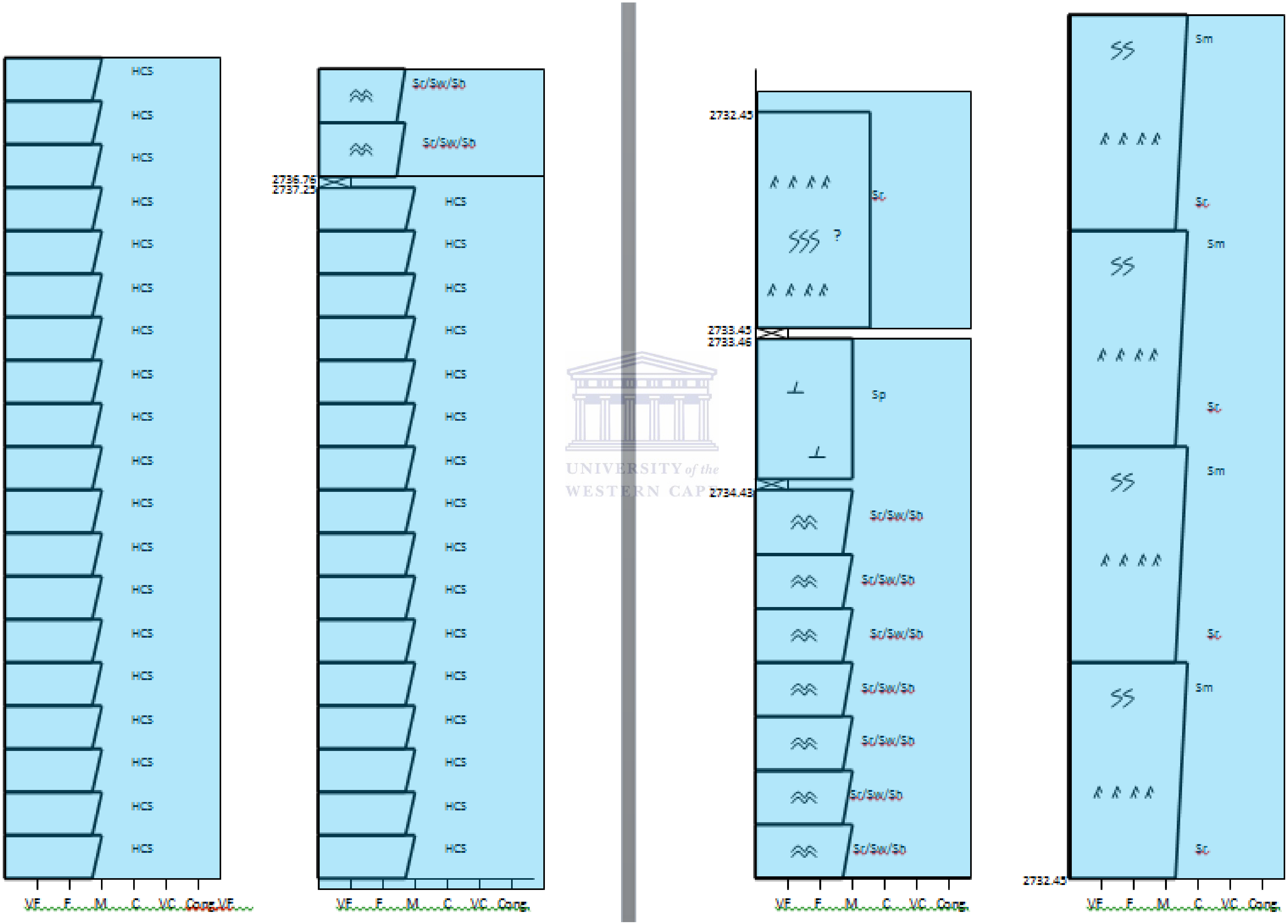


2384.56
Sp
Sh
2385.57
Sm
Sh
2387.11
Sh
2387.27
Sh
2388.40
VF F M C VC Cong.
2380.17
Sp
2380.88
2381.06
Sp/Sl
2381.65
2381.90
Sr
2382.45
2382.60
Sr
2383.01
Fl
2383.10
Sh-Sp
2383.35
2383.77
Sm
Sh
2384.17
Sh-Sm
Sm
2384.56
VF F M C VC Cong.
Top
2378.50
Sp
2379.53
Sh
Sp
Sh
2380.17
VF F M C VC Cong.

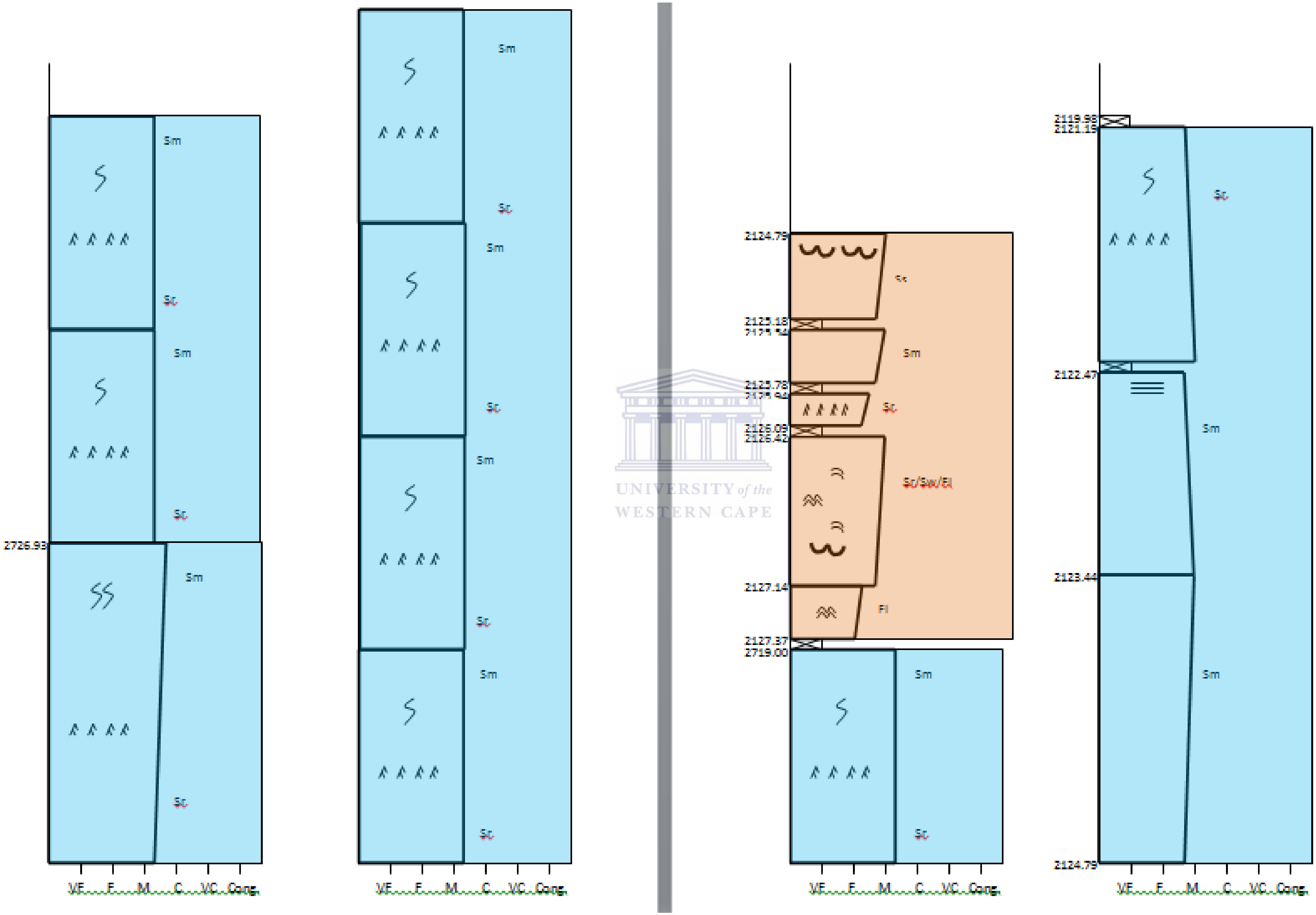
Well-D


Sc/Sw-Sh-Sm
Sc/Sw-Sh-Sm
Sc-Sh-Sm
Base
2773.22
VF F M C VC Cong.
VF F M C VC Cong.
VF F M C VC Cong.
VF F M C VC Cong.

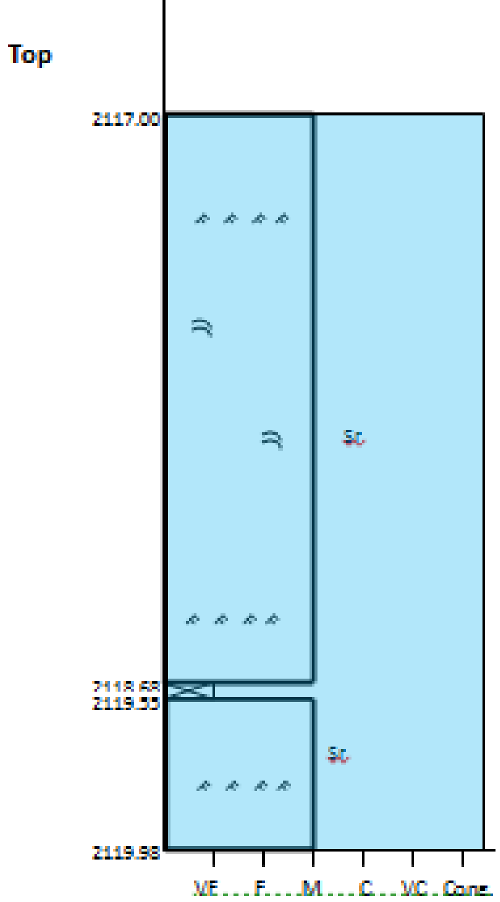

2754.74
2755.00
Sc/Sw
2756.38
Sc-Sh-Sm
VF F M C VC Cong.
2751.01
Sc-Sh-Sm
2753.76
Sp
2754.74
VF F M C VC Cong.
Sc-Sh-Sm
VF F M C VC Cong.
HCS
2743.94
Sc-Sh-Sm
VF F M C VC Cong.



HCS
Sc/Sw/Sh
2736.76
2737.25
2732.45
Sc
?
2733.45
2733.46
Sp
2734.43
Sm
VF F M C VC Cong. VF
VF F M C VC Cong.



Sm
Sr
2726.93
VF F M C VC Cong
2124.79
2125.18
2125.78
2126.09
2126.42
2127.14
2127.37
2719.00
Sr/Sw/Fl
Fl
2119.98
2121.15
2122.47
2123.44
2124.79



Legend:

Dark-brown shades = Fluvial (River) channels

Yellow shades =Tidal Channels

Orange shades =Tidal Bars

Dark-green = Lagoonal muds/Tidal muds

Light-green shades =Foreshore bars

Blue shades =Shoreface bars

Grey shades =Transision zone

Thickness of beds

Scale: 1m=25cm