Justification of windward and leeward carbonate geometry using experimental approach

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Abstract. Windward and leeward positioning on carbonate system gives significant effect on structure formation. Since the location of oil and gas reserve is affected by the position, it is important to establish the relation between surface and subsurface carbonate geometry. An experimental approach using flume tank modelling was performed to replicate the natural process which formed the windward and leeward geometry. The model was based on actual recent atoll with ideal characteristics, scaled down spatially and temporally to lab-sized experiment. The effect of windward and leeward positioning was replicated successfully and the density difference between the sediments used in the experiment was proven not to give any observable effects on geometry formation. Given the same ocean condition between the present and the past, the model gives insight to the shape of subsurface carbonate geometry found by seismic imagery.

Keywords: Windward and leeward, carbonate geometry

1. Introduction
The windward and leeward in geology denotes the direction of marine waves from an island’s point of view. The leeward is the side pointing to the direction of the travelling waves, while windward points to the origin of the wave direction [1].

Windward and leeward positioning on carbonate gives significant effect over a long time. The structures formed along the leeward side might be distinguishable from its windward counterpart. One such case on observable effect of windward and leeward positioning comparable to modern time can be observed on the Triassic carbonate margin facies in Northern Italy [2]. The consistency of the directions does not correspond well to the effect of annually changing sea wave direction. Instead, the windward and leeward direction is more related to the sides exposed to open water.

In carbonate reservoir system, the reserve of oil and gas mostly lies on the windward part of the carbonate since it is more oxygenated, encouraging growth of metazoan-dominated reef in the past [3]. For that reason, the determination of windward direction proves to be important in deciding the exploration area. However, the difficulty arises on identifying the relation between surface geometry and its subsurface counterpart. Therefore, a better understanding of the subject is needed to assess the course of exploration, especially in carbonate reservoir.

The objective of the experiment is to replicate the natural process scaled down spatially and temporally in order to accurately represent the distribution of windward and leeward geometry in the subsurface carbonate.
2. Data and method
The procedure was started by gathering satellite images of atolls around the world through Landsat Copernicus data provided by Google Earth [4] at 30 m spatial resolution. [5] From the images, the geometry parameters that were measured are average inner diameter and outer diameter, and the width of leeward-facing and windward-facing area. Additional measurement including the horizontal scale, which is measured from the outer part of the atoll beach towards the center of the land, stopping at the line still affected by the sea wave. The next data gathered was sea wave monitoring including daily wave height and velocity. However, some atolls do not have any sea wave monitoring data available.

To create the model of the atoll, plain circle-shaped atoll with visible windward and leeward direction is preferred for its simplicity both in flume tank model reconstruction and visibility of windward and leeward effects. An atoll located in Maldives as shown in figure 1a (3.2498° N 73.4261° E) [4] was found to be eligible with the shape shown in figure 2 [4]. Nearest station recording wave heights around the atoll is found at Minicoy Island, Lakshadweep, India (8.30° N 73.0° E), located 563 km from the selected atoll as shown in figure 1b [6].

The ratio between the real atoll and its model (table 1) was based on Reynolds’ model ratio with an adjustment in the ratio between the horizontal scale and total diameter of the atoll [7]. The adjustment

![Figure 1](image1.png)

(a) Map of Maldives, marked by red ellipse. The location of the selected atoll is marked by a yellow dot and (b) Wave height contour map of the region, the recording station marked in red.

![Figure 2](image2.png)

Figure 2. The selected atoll to be modeled with marked windward and leeward effect. The white circle represents approximate initial model before windward-leeward differentiation which became the basis for the atoll model.
Table 1. The ratio between the actual atoll and the model

| Parameters                  | Actual | Experiment | Ratio | Rule |
|-----------------------------|--------|------------|-------|------|
| Celerity (m/s)              | 0.5    | 0.055      | 0.110 | 1    |
| Wave Height (m)             | 2      | 0.01       | 0.071 | 1    |
| Time (s)                    | 43200  | 600        | 0.014 | 2    |
| Horizontal Scale (m)        | 108.51 | 0.2        | 0.002 |      |
| Ratio of Horizontal Scale v. Celerity |       |            | 0.017 | 2    |

was needed due to spatial constraint of the available flume tank. Keeping the original ratio required either an exceedingly large atoll diameter or an impossibly small horizontal scale. Since the emphasis of the experiment lies in the effects on windward and leeward side of the atoll and not the circumference, it was decided that the diameter would be shortened.

2.1. Experiment facility
A 3.000 meter by 1.500 meter by 1.000 meter rectangular flume tank was used as the container of the atoll model, with a wave generator at one side to simulate ocean waves travelling towards the model. The atoll side facing towards the wave generator was determined as the windward while the side away from the wave generator was denoted as the leeward.

An initial model of an atoll, with the inner diameter 0.670 m, outer diameter 0.870 m, and height of the barrier 0.050 m from the surface of 0.030 m water was placed at distance 0.350 m from the wave generator. The atoll was made of siliciclastic sand with mean diameter 175.59 μm, well-sorted, and through an analysis by XRD, consisted of more than 90 % quartz. The siliciclastic sand was chosen as the substitute with closest characteristics due to availability at the time of the experiment.

The wave was generated by a wave generator with adjustable wave celerity. However, as the celerity increases, it also affected the wave height, which might cause the horizontal scale to be widened. Therefore, the wave celerity was set at 0.055 m/s to keep the horizontal scale intact while still providing the result.

The atoll was exposed to the wave for 600 seconds. During the run, a camera was placed to record the change of the atoll morphodynamics over time. At the end of the experiment, the elevation was digitized through measuring the elevation as a 18 × 24 grid with 40 mm spacing in between, producing a digital elevation model to be plotted as a 3D surface.

3. Results and discussion
The windward geometry on figure 3b was visible along the side facing the wave source, characterized by a decrease in slope and height as seen on figure 4b with a significant increase in atoll rim width indicated on figure 4a compared to the initial condition on figure 3a. The slope decrease applied to both the outer and inner slope, with the outer slope underwent a more drastic change.

The leeward part was much less affected, with the width mostly unchanged, due to the most of the waves blocked by the windward side of the atoll. However, there is a slight increase of the inner diameter parallel to the wave direction, which is caused by waves crossing over the windward barrier as its height decreased. As a result, the leeward side has higher peak and steeper slope than its windward counterpart.

The success parameter of the experiment is whether the windward and leeward effects observable in nature of the actual atoll can be visibly replicated in the flume tank atoll model. Despite siliciclastic sand is used instead of bioclasts, the effect observed in the model consistently mimics the effect observed on the actual atoll. The density of the siliciclastic sand used is 2,650 kg/m³, while the average density of reef bioclastic sediment is around 2,580 kg/m³ [8]. Therefore, the replication process was a success and the density difference of the sediment types was not a major contributing factor in the geometry formation.
Figure 3. (a) The atoll initial model. (b) The atoll after wave exposure.

Figure 4. (a) Contour map of the result atoll. (b) Digital elevation model of the result atoll.

Given the modern-era ocean characteristics remained mostly similar to the past conditions, the principle of uniformitarianism will apply here. The carbonate geometry observed currently would be comparable to the shapes found in seismic images, helping in determining the windward and leeward directions in subsurface reservoir geometry. However, the atoll model observed is limited to represent ideally-shaped atolls. Furthermore, effect of compaction may alter the volume of subsurface atolls, which in turn affects drilling depth and oil reserve calculation. Therefore, further adjustments are needed to create a more fitting model for atolls with high complexity.

4. Conclusion
Principle of uniformitarianism can be replicated consistently at flume tank scale, which will become helpful at determining the windward and leeward subsurface geometry in oil and gas exploration.
The consistency is not affected by sediment density, since the usage of siliciclastic sediment succeeds at mimicking the process done on reef bioclasts. Further adjustments are possible to be made in order to represent the more complex atoll shapes, and additional steps can be taken to account for effect of compaction.

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