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Flume experiments on the sand dunes under bidirectional flows with angular variation: the formation process and resultant topography depending on the angular variation and intensity ratio

Keisuke Taniguchi
Graduate School of Science, Osaka University, Japan

2009
Doctoral thesis

Flume experiments on the sand dunes under bidirectional flows with angular variation: the formation process and resultant topography depending on the angular variation and intensity ratio

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（二方向流下の砂丘に関する水槽実験：その変形過程と発達した地形とに見られる二方向流の角度変化量と二つの流れの強度比の影響）
Abstract

Sand dunes are formed by the interactions between sand particles and the surrounding fluid. The process is not yet understood in detail due to the large time and space scale of the deformation. A series of flume experiments aiming to understand the formation process of isolated sand dunes under bidirectional flows showed that the angular variation $\theta$ of two flows is the most effective on the resultant types of topography. The directional shift of sand movement due to the flow direction change led three kinds of deformation process depending on $\theta$. The resultant topographies after repetition of bidirectional flows can be categorized into four types. As they are formed by one or two deformation processes and $\theta$ is the ruling parameter on the processes, it can be concluded that the angular variation is the dominant condition. On the other hand, the intensity ratio $\alpha$ influences only the shape of crest lines whether linear or crescentic, not effective on the kind of deformation process. In addition, particular topographies were formed under flows with 75, 90 and 180 degrees angular variation. Based on the results, a new diagram of relationship between dune shapes and conditions in respect to bidirectional flows is presented and applied to three field observations on Earth and Martian surfaces.
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1 Introduction

1.1 Significance of studies on sand dunes

Understanding the shapes and formation processes of aeolian sand dunes will make prediction of the movement of sand dunes and estimation of flow conditions forming dune shapes possible. Therefore, this study has applications in the prevention of damage caused by moving sand dunes in marginal areas of deserts and to estimation of wind conditions from satellite images of the Earth’s surface or other planets such as Mars and Venus.

1.1.1 Dunes in deserts

Deserts are arid areas where plants do not readily grow due to high surface evaporation compared with the rainfall. Ezcurra et al. (2006) introduced the Aridity Index, which is the ratio between the averaged annual rainfall $P$ and the amount of water lost from the surface through evaporation and transpiration of plants $PET$ (defined by Thornthwaite, 1948), and is a prevailing measure of aridity. Arid areas have a $P/PET$ ranging from 0.05 to 0.20, and hyperarid areas have a $P/PET$ value
of no more than 0.05. Deserts include both arid and hyperarid areas, and cover 20% of the Earth's land area (UNEP, 1997). Figure 1 shows the global distribution of deserts (after Mountney, 2006).

Deserts are divided into three classes depending on their surface conditions. An erg refers to a desert covered with large amount of sand as in the popular image of desert, a rock desert (hamada) has many exposed rocks, and a rocky desert (reg) is covered with gravel. Weathered desert rocks are the source of sand and gravel in ergs and regs. The weathered rocks are eroded and transported by rare rainfall events and aeolian processes, and rocky deserts and ergs develop as a result.

Migration of sand dunes by wind often causes damage to artificial objects in areas surrounding deserts. For example, Fig.2 shows barchan dunes migrating across an agricultural field in Peru. In addition, Gay Jr. (1999) reported some barchan dunes interrupted Marcona highway in Peru between 1943 and 1952. Knowledge of the relationship between dune shapes and their formation processes and the surrounding conditions is important in order to mitigate such damage.
1.1 Significance of studies on sand dunes

1.1.2 Dunes as a measure of the surrounding wind conditions

Early in the history of the study of deserts, the main methods were local observation such as topographic survey of dunes, wind measurements around the dunes or photogrammetry using aerial photographs. Local measurement allows continuous observations to be conducted for several years where the measurement area is very small. On the other hand, photogrammetry can cover a larger measurement area, although it is difficult to carry out continuous observation.

Since the 1970s, space technology has enabled the measurement of much larger areas through satellite images. After the discovery of sand dunes on Mars by Mariner 9 mission from 1971 to 1972, many artificial satellites took photographs of the Martian surface. In particular, the Mars Global Surveyor (MGS) by NASA observed the Martian surface from 1997 to 2006 and took many high-resolution photographs. In addition, Greeley et al. (1992) reported sand dunes on the Venusian surface from photographs taken by Magellan in 1990. Recently, the Cassini-Huygens satellite by NASA and ESA arrived at Titan, the largest moon of Saturn, and it is expected that sand dunes should be observed there in the near future. Now, researchers can freely
view satellite images of not only the Earth's surface but also the surface of Mars and Venus on the internet.

It is impossible to conduct wind measurements around sand dunes on other planets at this time. Therefore, the wind condition can be estimated by using types of dunes for which the formative conditions are known. In the 1970s, barchan dunes, transverse dunes, reversing dunes and wind streaks were used to analyze the wind regime. For example, Sagan et al. (1973) stated that wind streaks on Mars indicate the averaged wind direction. Thomas and Veverka (1979) compared photographs taken by Mariner 9 in 1971-1972 with photographs taken by Viking in 1976 and reported that seasonal and secular variation of wind streaks were caused by changes in the wind direction. Breed et al. (1979b) compared the shape and size distribution of barchan dunes on Mars with those on the Earth. Tsoar et al. (1979) used barchan, transverse and reversing dunes in order to estimate the wind directions in the Martian north polar sand sea. In the 2000s, when high-resolution photographs became available, detailed analyses of the wind regime were carried out. For example, Fenton et al. (2003) estimated the wind regime from the shapes of dunes within the Proctor Crater in Noachis Terra on Mars. Several sand topographies for which the formative condition
was unknown, however, were newly discovered. Therefore, studies of the formative conditions are required in order to analyze the prevailing wind conditions.

1.2 A brief review of previous studies on sand dunes

Bagnold (1941) researched the movement of sand particles in the formation of sand dunes by wind or water flows. Studies on the formation processes of sand dunes followed the classification of dune topography. The “Drift Potential (DP)” method was proposed as a quantitative measure of the effect of wind effect on sand dunes based on the traction load (Fryberger, 1979). Wasson and Hyde (1983) presented a phase diagram of dune forms between available sand volume and wind regime complexity using RDP/DP, which is the ratio between the absolute value of the vectoral sum of DPs in all flow directions and the scalar sum of the absolute value of the DPs. Then, experimental studies including numerical simulations and flume experiments allowed observation of the process of the formation of sand dunes. The numerical simulations successfully reproduced an isolated barchan topography under a unidirectional flow (Schwämmle and Herrmann, 2004) and application to dunes under multi-directional flows was attempted (Parteli and Herrmann, 2007a,b) as was the interaction between
several barchan dunes (e.g. Katsuki et al., 2005b). The analog experiments, conducted in a water flume in order to form small barchan topography, succeeded in reproducing sand dunes under unidirectional flow (e.g. Niño and Barahona, 1997). A major issue which remains is the formation process of sand dunes under variable flow conditions.

1.2.1 Grain movement

- **Grain movement mode**  There are three main modes of particle movement on a sand bed under fluid flow such as wind and water flow (Fig.3). In suspension, particles float for long distances, such as the yellow sand phenomenon in China. In saltation, particles travel via a series of short-distance jumps. Rolling and sliding refer to sand movement where the particles do not lose contact with the bed. Sliding was also called drugging and creeping, because it is movement without rotation, while rolling refers to rotational movement. Traction is the general term for saltation, rolling and sliding and sand movement on sand dunes via traction.

- **Threshold flow velocity**  Sand particles are driven by the shear stress $\tau$ from fluid flow on the surface of the sand bed. Shear velocity on the surface $u_*$ is defined
1.2 A brief review of previous studies on sand dunes

as follows:

\[ u_* = \sqrt{\frac{\tau}{\rho_f}} \]  \hspace{1cm} (1)

where \( \rho_f \) is the density of the fluid. The vertical distribution of the flow velocity is logarithmic, because the boundary layer of turbulent flow near the bottom surface includes the scale of sand particles. Therefore, the flow velocity at the height \( z \) from the bottom surface \( u(z) \) is as follows;

\[ u(z) = u_* \frac{1}{\kappa} \ln \frac{z}{z_0} \]  \hspace{1cm} (2)

where \( \kappa \) is von Karman's constant (approximately 0.4) and \( z_0 \) is the roughness length of the surface.

Bagnold (1941) formulated the lower limit of the shear velocity at which traction occurs, threshold shear velocity, \( u_{*t} \), through a series of wind tunnel experiments as:

\[ u_{*t} = A \sqrt{\frac{\rho_s - \rho_f}{\rho_f} gD} \]  \hspace{1cm} (3)
where $D$ is the particle diameter, $\rho_s$ is the density of the particle, $g$ is gravitational acceleration and $A$ is the non-dimensional proportionality constant. The value of $A$ is approximately 0.1 in the case where the grain is lifted by the shear stress of the surrounding fluid only (fluid threshold). In the case where the effect of impacts between grains is strong, $A$ is approximately 0.08 (impact threshold) (Fig. 4). The impact between a saltating grain and grains on the bed causes a chain reaction of saltation (Fig. 5), therefore, the impact threshold is smaller than the fluid threshold. In the case of $D \leq 0.1\text{mm}$, the threshold shear velocity is significantly larger due to inter-particle viscosity.

The fluid shear velocity (equation (3)) can be explained using a simple model (Fig. 5). A sand particle on a homogenous bed with grain diameter $D$ (the circle in Fig. 5) can be moved when the clockwise moment around point A, which is the contact point between the particle and the next particle on the leeward side, is larger than the counterclockwise moment. Therefore, the momentum balance around point A is given by

$$F_d \frac{D}{2} \cos \phi \geq (W - F_l) \frac{D}{2} \sin \phi$$  

(4)
where $F_d$ is the drag force from the flow, $\phi$ is the angle of packing of the grain, $W$ is gravity and $F_l$ is buoyancy. Since the particle is a sphere of diameter $D$,

$$F_d = \tau \pi \left( \frac{D}{2} \right)^2 = \frac{1}{4} \pi D^2 \rho_f u_*^2$$

(5)

$$W - F_l = (\rho_s - \rho_f) g \frac{4}{3} \pi \left( \frac{D}{2} \right)^3 = \frac{1}{6} \pi g D^3 (\rho_s - \rho_f)$$

(6)

Equations (5) and (6) are substituted in equation (4) to yield,

$$u_* \geq \sqrt{\frac{2}{3} \tan \phi \frac{\rho_s - \rho_f}{\rho_f} g D}$$

(7)

Equation (7) is proportional to equation (3).

The values of $u_{*t}$ on other planets such as Mars and Venus are a indicator of the range of wind velocity on a planet. However, it is difficult to estimate the value of $u_{*t}$ on other planets, because the proportional constant $A$ in equation (3) can vary due to several factors. For example, Bagnold (1941) pointed the value of $A$ is proportional to the frictional Reynolds number $Re^*$.

$$Re^* = \frac{u_{*t} D}{\nu}$$

(8)
where \( \nu \) is the kinematic viscosity. Iversen and White (1982) conducted wind tunnel experiments on the variation of \( u_{*t} \) in a fluid with a wide density range and estimated that \( u_{*t} \) on Mars is one order of magnitude larger than that on Earth while \( u_{*t} \) on Venus is one order of magnitude smaller.

- **Sand flux** The flux of traction load \( q \) is proportional to shear velocity raised to the third power (Bagnold, 1941). Lettau and Lettau (1978) suggested an equation for flux of traction load related to the threshold shear velocity;

\[
q = C \frac{\rho_f}{g} u_*^2 (u_* - u_{*t})
\]

where \( C \) is a proportional constant, with a value of approximately 4.1.

- **Saltation layer** The saltation layer, which was introduced by Sauermann et al. (2001), consists of saltating sand and the surrounding fluid just above the ground covered with available sand. The saltation layer is stable when the number of sand particles entering the layer from the ground is balanced with the number of sand particles dropping out of the layer. The saltation layer can not become saturated in a case where the length of the ground is too short compared to the saltation distance.
of the sand due to the lack of incoming sand. For equilibrium of the saltation layer, the stable layer must have at least a length in the same order as the saturation length $l_s$;

$$l_s = \frac{\rho_s D}{\rho_f}$$ (10)

1.2.2 Classification of sand dunes

**Morphologic classification** The general classification of dune topography is showed in Fig.6 (modified from McKee, 1979).

Transverse dunes (Fig.6 (a)) form under unidirectional flow and have linear crest lines perpendicular to the flow direction. The windward side has a gentle slope and the leeward side has a steep slipface where the sand avalanche occurs.

Reversing dunes (Fig.6 (b)) have a unique structure in cross-section. Unlike transverse dunes, reversing dunes have a small slipface caused by the secondary wind (the arrow at the top right of Fig.6 (b)). Therefore, the crest of reversing dunes is sharper than that of transverse dunes.

Barchan dunes (Fig.6 (c)) are isolated dunes with a crescentic crest line, and are
formed by unidirectional flow. Both ends of the crest line indicate the leeward direction of the flow. Therefore, barchan dunes can be used to estimate the wind direction as mentioned in Section 1.2.1.

Seif dunes (Fig.6 (d)) form under bidirectional flows crossing obliquely and have linear crest lines parallel to the average flow direction. These are also known as are longitudinal and linear dunes.

Parabolic dunes (Fig.6 (e)) are U- or V-shaped dunes in the planar view. Although they are formed under unidirectional wind (arrow in Fig.6 (e)), the fixing of sand by vegetation is essential in their formation.

Star dunes (Fig.6 (g)) have branched crest lines and radial shapes, and are formed by variable wind directions.

Classification based on a hierarchy structure A hierarchical structure is used to classify dunes as having simple, compound and complex topography (McKee, 1979). Simple dunes have basic structures. Compound dunes have smaller dunes superimposed on a larger dune of the same type. Complex dunes have smaller dunes superimposed on a larger dunes of a different type. Complex and compound dunes
often form in ergs. Figure 7 shows a field example of a complex barchan dune superimposed on by transverse dunes in the Moroccan Sahara (Elbelrhit et al., 2005).

**Dune classification by wavelength** Wilson (1972) suggested a classification based on the distribution of the wavelength of dunes (Fig. 8). Wind ripples have the wavelength in the range from $10^{-2}$ to $10^{-1}$ m, the typical wind ripple is transverse-type (Bagnold, 1941). The wavelength of dunes and draa are $10$ to $10^2$ m and $10^2$ to $10^3$ m, respectively. The topography of these dunes has large variability depending on the surrounding conditions (as already mentioned in Fig. 6). Large dunes and draas are often complex or compound forms.

### 1.2.3 Formative conditions of each type of dunes

Studies on the formative condition of each type of dune were conducted with the advance of studies on the classification of dune shapes. Hack (1941) considered wind conditions, sand supply and vegetation, and presented a triangle diagram showing formative conditions of transverse, seif (longitudinal) and parabolic dunes. The diagram shows that transverse dunes form in the case of large sand supply whilst seif dunes develop in areas lacking sand supply, and that parabolic dunes require
some vegetation (Fig. 9). McKee (1979) categorized sand dunes into five categories: crescentic (including barchan and transverse in Fig. 6), linear, reversing, star and parabolic. McKee reported that the wind complexity increases in order of crescentic, linear, reversing and star dunes, except for parabolic which depend on vegetation.

The wind condition has many elements such as velocity, duration, direction and the number of wind directions (e.g. unidirectional, bidirectional or more) that affect dune topography. Therefore, a quantitative measure was required to analyze wind conditions. Drift Potential (DP), introduced by Fryberger (1979), is the most popular measure of the wind conditions. The DP of winds from each azimuth can be calculated by wind direction, wind velocity and duration (equation (11));

\[ DP = V^2(V - V_t)t \]  

(11)

where \( V \) is the flow velocity at 10 m above the flat surface (10 m is the standard height of measurement of wind velocity), \( V_t \) is the threshold flow velocity at 10 m height and \( t \) is the time ratio expressed as the percentage of the duration of the wind blowing from a given direction to annual sum of the duration of winds. \( V^2(V - V_t) \) in equation
(11) is proportional to the sand flux (cf. equation (9)), hence DP is the measure of the effect of the wind on the sand bed based on the traction load. Resultant Drift Potential (RDP) is defined as the vectorial sum of DPs for all directional winds. The value of RDP denotes the resultant movement of sand particles and the direction of RDP (so-called Resultant Drift Direction, RDD) gives the average wind direction. The definition of RDP/DP, which is the most popular measure of wind complexity, is as follows.

$$\frac{\text{RDP}}{\text{DP}} = \frac{|\sum \text{DP}|}{\sum |\text{DP}|}$$  \hspace{1cm} (12)

In the case that the winds are almost unidirectional, the value of RDP is close to one, whilst when multi-directional flows offset each other, the value of RDP is zero.

Wasson and Hyde (1983) showed a phase diagram of dune types between RDP/DP and average sand thickness (Fig.10). In areas where there is insufficient sand to cover the substratum, seif dunes form under low RDP/DP values (RDP/DP < 0.4) and barchan dunes form under high RDP/DP values (RDP/DP > 0.75). On the other hand, in areas where the whole surface is covered by available sand, transverse dunes form under high RDP/DP values (RDP/DP > 0.5) and star dunes form under
multi-directional flows associated with low RDP/DP values (RDP/DP < 0.2). Since
the formative conditions of well-known dune topographies are clearly classified, this
phase diagram has been used to estimate flow conditions from dune topographies.

The phase diagram, however, does not provide a unique flow condition, because
the RDP/DP can have the same value under a number of flow conditions. It does
not uniquely identify flow conditions such as flow velocity, duration, flow direction
and the number of the wind directions which contribute to the formation of the dune
topography. Therefore, in order to obtain more detailed information on the flow
conditions from the dune topography, the effect of each element of the flow conditions
on dune formation should be studied through the observation of dune formation under
various flow conditions.

1.2.4 Experimental study on isolated dunes

It is impossible to observe the whole process of dune formation in the field due
to the long time scale. Field observations can capture only the seasonal change of
the dune shape (e.g. Bishop, 2001) or snapshots at certain intervals (e.g. Khalaf and
Al-Ajimi, 1993; Gay Jr., 1999). Numerical simulation and analog experiments are
methods that make observation of the whole process possible.

- **Numerical simulation**  Numerical simulation studies aim to reproduce dune topographies by numerical calculation using computers. There are two general approaches: first principle models based on the basic principles of physics, and phenomenological models that start from the intrinsic processes occurring on dunes.

  Models constructed by purely physical formulae are currently impractical due to the large amount of calculations. Therefore, a new model, which is simplified by inclusion of the saltation layer, was suggested by Kroy et al. (2002). Schwämmle and Herrmann (2004) proposed a three-dimensional model, making the numerical simulation of a barchan dune possible. This type of simulation can be applied to isolated dunes. For example, Parteli and Herrmann (2007a,b) conducted numerical simulation under bidirectional flows and succeeded in reproducing Martian isolated dunes that had unknown formative conditions. In addition, since this model includes the physical processes in the saltation layer, the saturation length $l_s$ (c.f. equation (10)) can be used as a scaling law (e.g. Claudin and Andreotti, 2006; Parteli et al., 2007).
Phenomenological models are constructed by the modeling of dominant processes on dunes. The small computing cost of this type of model makes it possible to investigate several dunes or groups of dunes. Katsuki et al. (2005b) constructed a model of the collision between two barchan dunes using a cell model including saltation, sand avalanche and a recirculation bubble behind the dune. Then, Katsuki et al. (2005a) succeeded in the reproduction of the evolution of a dune field from a flat sand bed into a barchan corridor including many barchan dunes.

**Analog experiments** Analog experiments reduce the time and space scales involved in researching dune formation and change by formation of small topography in the laboratory. Analog experiments on isolated dunes have often targeted barchan dunes, because these can be formed under simple unidirectional flow. Wind tunnel experiments on barchans can temporarily form barchan-like topographies, however, the topography cannot be maintained for long enough to investigate the deformation process (Andreotti et al., 2002; Dauchot et al., 2002). Using water flow instead of wind make it possible to form smaller barchans, because the value of $l_\gamma$ in the water is smaller than in air due to difference in density (c.f. equation (10)).
1.2 A brief review of previous studies on sand dunes

Flume experiments on barchan dunes have been conducted using not only a flume where the flow is generated by a pump but also a water tank that consists of a tray moving horizontally (Hersen et al., 2002; Hersen and Douady, 2005; Hersen, 2005) and the annular flume (Hori et al., 2007). Such sub-aqueous barchans formed in flume experiments have the same features as aeolian barchans in the field. Both migrate in the leeward direction while maintaining their crescentic shape (Niño and Barahona, 1997; Hersen et al., 2002; Kleinhans et al., 2002; Endo et al., 2004).

There have been few earlier flume experiments on isolated dunes under flows with angular variation. Hersen (2005) observed that a barchan transformed into a barchan adapted to the new flow direction after a one-time change of flow direction with an angular variation of $90^\circ$ and $180^\circ$. Rubin and Ikeda (1990) reproduced some linear dunes such as transverse, seif (longitudinal) and oblique dunes from a flat sand bed covered with sufficient sand by the repetition of bidirectional flows with angular variation of $45^\circ, 67.5^\circ, 90^\circ, 112.5^\circ$ and $135^\circ$. In their experiments, transverse dunes were formed when the angular variation was $45^\circ$ and $67.5^\circ$, and longitudinal dunes were formed when the angular variation was $135^\circ$. At intermediate angular variations, dunes with both orientations were produced, but transverse dunes were dominant at
90°, and longitudinal dunes were dominant at 112.5°.

1.2.5 Major issues

A major issue identified through the review of studies on dunes is the formation process of sand dunes. An understanding of dune formation will allow estimation of detailed flow conditions from dune shapes.

Although studies on the movement of one particle by fluid flow have clarified the process of traction occurring on dunes (Bagnold, 1941), the interaction between a group of sand particles and surrounding flow remains unresolved.

Field observations showed that the amount of available sand, the wind complexity and vegetation have an effect on the type of the dune topography. However, the wind complexity, represented by RDP/DP, does not indicate a unique set of flow conditions.

Experimental studies such as numerical simulations and flume experiments have demonstrated the formation and migration of barchan dunes. As a next stage, the process of dune formation under variable flow conditions should be investigated.
1.3 Introduction of flume experiments

In this study, a series of flume experiments on the development of isolated sand dunes under bidirectional flows were conducted in order to obtain more information on flow conditions than through use of RDP/DP. Flume experiments are a method of analog experiment where a small isolated sand form on the scale of 10 cm can be formed and the topography can be maintained for a long time. The flume experiments primarily considered the effect of angular variation of two flows on dune formation.

1.3.1 Isolated dunes under bidirectional flows

In this paper, a series of flume experiments on isolated sand dunes under bidirectional flows were conducted. The bidirectional flows were assumed to provide an analogue of the seasonal change in wind direction. Isolated dunes, such as barchan and seif dunes, are formed where the amount of available sand is not sufficient to cover the whole surface.

Early field observations on isolated sand dunes showed that the angular variation of flows have an important role in the formation of the dune topographies. Hunter et al.
(1983) and Tsoar (1986) reported that barchan dunes are stable where the angular variation of flows is no more than $15^\circ$. On the other hand, seif dunes develop under bidirectional flows with angular variation (Tsoar, 1983; Tsoar and Yaalon, 1983).

Barchan dunes have a crescentic crest line bending in the upstream direction (Fig.11 (a)). The upstream side of the crest line is the body and the two tips on the downstream side are the horns. The profile of the vertical cross-section shows that the upstream side has a gentle slope whilst the leeward side has a steep slipface, the same as transverse dunes. Barchan dunes have a lower limit of the size of approximately 10 m in width and length and 1 m in height (Bagnold, 1941). The minimum size of barchan dunes is the same order as the saturation length $l_s$ of the saltation layer (Hersen et al., 2002). Seif dunes have a linear crest line parallel to the average flow direction. Seif dunes with a meandering crest line are called sinuous seif dunes. The profile of the vertical cross-section perpendicular to the crest line is almost symmetrical. Unlike barchan dunes, there is no lower limit of the size of seif dunes.

The author has previously conducted a flume experiment on the deformation process of a barchan dune under alternating water flows with $180^\circ$ angular variation
1.3 Introduction of flume experiments

(Taniguchi and Endo, 2007). Under each reverse flow, a “rear slipface” (slipface occurring at the opposite side of barchan’s crest line (Bishop, 2001)) appeared in all runs regardless of the flow conditions. Four types of deformed barchans developed depending on the time ratio of the two flows and the absolute value of the flow velocities.

1.3.2 The aim of this study

The present study carried out a set of flume experiments under bidirectional flows with various angular variations. The purpose was to investigate the effect of angular variation on the development of isolated sand dunes under bidirectional flows through analysis of both temporary features caused by changes in the flow direction and cumulative deformation after repetition of bidirectional flows. Then, the results were applied to some unresolved problems in field studies such as the transition from barchan to seif dunes and resolution of the wind conditions forming lines of sand dunes in the Western Sahara and Martian teardrop-shaped dunes.
2 Materials and Methods

2.1 Apparatus

Experiments were carried out using a water flume (Fig.12 (a)). The flume consisted of an open channel (50 cm wide, 5.6 m long and 50 cm deep) and a water tank at the upstream end of the channel. The water tank had a triangle weir through which water currents flow into the channel. The channel was equipped with a gate at the downstream end in order to adjust the outflow discharge. A rotatable disk (48.5 cm in diameter) and a surrounding board made of plastic with uniform surface roughness, were installed on the bottom of the channel. Although water currents always run in one direction, the rotatable disk enabled the sand on it to be subject to flows from any direction.

2.2 The initial topography and flow conditions

The initial topography for all runs was a conical sand pile of 15 g weighted silica sand (80 μm in mean diameter and 2.64 g/cm³ in density) (Fig.13). The width of the
2.2 The initial topography and flow conditions

Pile was in the range of 6 to 7 cm and the height was from 1.2 to 1.5 cm. The flow velocity of all runs was 21 cm/s at 0.6 cm above the bottom of the flume. This value was determined from the result of the preliminary experiments to find the appropriate current velocity for the generation of a barchan that could migrate constantly (here at 0.012 mm/min.) (ref. Appendix A). The migration rate was in the same order of magnitude as that of Set 1 in Taniguchi and Endo (2007).

Alternately bidirectional flows with a given angular variation were realized by rotation of the disk by $\theta$ back and forth repeatedly. At first, the primary flow (the left diagram in Fig.14 (a)) affected the topography. After stopping the current, the disk was carefully rotated through $\theta$ as not to disturb the topography. Then, the secondary flow acted on the topography (the right diagram in Fig.14 (a)). From the viewpoint of the topography, these flows appeared as bidirectional flows with an angular variation of $\theta$ (Fig.14 (b)). The duration of the two flows and the number of repetitions of the cycle were varied from run to run.
2.3 Index of variation of flows

The absolute values of DP under bidirectional flows are denoted as follows;

\[ |\text{DP}_p| = f(v) \frac{t_p}{t_p + t_s} \]  
\[ |\text{DP}_s| = f(v) \frac{t_s}{t_p + t_s} \]

where \( t_p \) and \( t_s \) are duration of the primary and secondary flows respectively. In these experiments, \( f(v) \) is constant because the flow velocity was the same for all runs. Therefore, the DP ratio \( \alpha \) between two flows is equal to the ratio of their durations.

\[ \alpha = \frac{|\text{DP}_s|}{|\text{DP}_p|} = \frac{t_s}{t_p} \]

Since RDP is the vectoral sum of \( \bar{\text{DP}}_p \) and \( \bar{\text{DP}}_s \), the absolute value is denoted as follows from their geometric relation (Fig.15);

\[ |\text{RDP}| = |\text{DP}_p| \sqrt{(1 + \alpha \cos \theta)^2 + (\alpha \sin \theta)^2} \]
Substituting equations (13), (14) and (16) into equation (12) gives following equation;

\[ \frac{RDP}{DP} = \sqrt{1 + \frac{2\alpha}{(1 + \alpha)^2} (\cos \theta - 1)} \]  

(17)

The averaged flow direction \( \phi \) is defined as the angle between the directions of the primary flow and RDP (Fig.15).

**Series A experiments**  The experiments in Series A included 22 runs of the same duration \( t \) between two directions of flow. Table 1 shows the experimental conditions of all runs in Series A. In Runs 1 to 12, the value of \( t \) was two minutes, while the angular variation \( \theta \) was varied from 15° to 180° in 15° intervals in order to examine the effect of the angular variation of bidirectional flows. In Runs 13 to 22, the angular variation was varied from 60° to 120° in 15° intervals and flow duration was varied between one and three minutes, to elucidate the dependence of the topography on the flow duration. In Series A, RDP/DP depended on only the angular variation \( \theta \) because the duration of the two flow directions were the same in each run. Therefore,
equation (17) can be simplified as:

\[
\frac{\text{RDP}}{\text{DP}} = \sqrt{\frac{1 + \cos \theta}{2}}
\]  \hspace{1cm} (18)

Series B experiments The experiments in Series B from Run 23 to 33 had different duration of flow between the two directions in each run. Table 2 shows the experimental conditions of all runs in Series B. In order to investigate the influence of the variation of \( \alpha \), the value of \( \alpha \) was varied from 0.60 to 0.09.

3 Results and discussion

3.1 Series A experiments

3.1.1 Temporal change of the crest line with changes in the flow direction

The change in flow directions gave rise to three processes of deformation of the crest line, depending on the flow angular variation \( \theta \). For convenience, these are respectively referred to as the “shared”, “reversing” and “independent” processes in order of increasing angular variation (Fig.16). In this section, the features of these deformation processes are described by explaining the deformation caused by the
3.1 Series A experiments

second current of the first cycle.

In the "shared" process, a crescentic crest line is shared under the primary and secondary flows (Fig.17 (a)). When the secondary flow was active, the crest line maintained its crescentic shape and migrated in the downstream direction of the secondary flow. This process was observed in runs where the angular variation $\theta$ was below 30°.

The "independent" deformation process generated a new crest line independently in another place from the existing crest line. Figure 17 (b) was taken for the first secondary flow on the topography. The new crest line was formed along the crest line on the existing horn on the upstream side of the secondary flow direction, whilst the existing horn located on the leeward side remained. Under the next primary flow, the crest line formed under the last secondary flow remained, and after that, the horn located on the leeward side of the present flow direction always remained. This process was observed when the angular variation $\theta$ was between 45° and 135°.

The "reversing" deformation process was observed with large angular variation $\theta$, between 90° and 180°. Under the secondary flow, a new slipface formed immediately on the opposite side of the existing crest line (Photograph 2 in Fig.17(c)). The crest
line migrated in the downstream direction of the secondary flow, i.e., the reverse direction compared to under the primary current (Photograph 3 to 6 in Fig.17 (c)). The name of this "reversing" process comes from this inversion of the migrating direction of the crest line.

In addition to the three processes mentioned above, the "independent" and "reversing" processes occurred simultaneously in some cases for $90^\circ \leq \theta \leq 135^\circ$. In these cases, a new opposite slipface was formed on the leeward end of the existing horn as soon as the secondary current started due to the "reversing" process (white arrows in Photograph 2 in Fig.18 (a) and (b)). At the same time, a new crest line was formed at the center of the topography due to the "independent" process (black arrows in Photograph 2 in Fig.18 (a) and (b)). The crest line developed by the two processes marched towards the leeward direction of the secondary flow.

3.1.2 Cumulative deformation of a sand pile after repetition of bidirectional flows: a brief description

After repetition of the cycle of bidirectional flows with angular variation, four types of topography were formed due to differences in the deformation processes of the crest
3.1 Series A experiments

line due to the change of flow directions.

The "barchan-type" has the same features as a barchan dune under unidirectional flow: a crescentic crest line, two horns pointing in the leeward direction and migration towards the average flow direction (Fig.19 (a)). This type was formed by the "shared" deformation process.

The "dome-type" has straight or sigmoidal crest lines formed at the different places under each of the two flows, not at the location of the crescentic crest line between the two horns (Fig.19 (b)). The repetition of the "independent" process caused the development of this type.

The "seif-type" consists of an upstream fan-shaped part and a downstream bar-like part (Fig.19 (c)). The upstream part is formed by the "independent" process while the downstream part is formed by the "reversing" process. The downstream end has two morphological features in common with seif dunes observed in the field: it migrates towards the leeward direction of the average flow and the axis of the crest line is moved laterally and alternately by each of the two flows. The upstream end supplies sand to the downstream end and allows the downstream end to elongate in the leeward direction.
The "reversing-type" has a straight crest line extending across the whole topography and showed lateral movement of the crest line caused by the change in the flow directions. Unlike the "seif type", however, the "reversing-type" has no upstream dome-shaped part (Fig.19 (a)). The resultant topography is named after reversing dunes that are formed when transverse dunes are exposed to alternate flows. In the present study, the direction in which the sand topography elongates intersects obliquely with the average flow direction.

The Series A experiments showed the four types of resultant topography caused by one or a combination of deformation processes due to the directional change of flows, depending on the angular variation θ. These topographies are independent of the flow duration t, since the boundary angular variation between the "dome-type" and "seif-type" is 90° in Runs 1 to 12 of two minute duration as well as in Runs 13 to 22 of one and three minute duration. Figure 20 displays photographs taken after the primary current of the final cycle, showing the deformation of the crest line and the resultant topography.
3.1.3 The transitional topography between “dome-type” and “seif-type”

The transitional topography between “dome-type” and “seif-type” occurred at an angular variation of 75° and 90°. In the case of $\theta = 75^\circ$, although the resultant topography was classified as the “dome-type” because the bar-shaped part did not form at the downstream side, the topography during the run sometimes displayed a faint feature of the “reversing” process during the run. This feature of the “reversing” process did not exist for a long time because it was filled up with sand or removed when the flow direction changed. On the other hand, although when $\theta = 90^\circ$, the topography frequently split into the fan-shaped upstream part and the bar-shaped downstream part, the downstream part did not migrate far away in comparison to the case for $\theta = 75^\circ$. Hence the bar-shaped downstream part formed and elongated in the average flow direction like typical “seif-type” topographies because it was supplied with sand from the upstream part.

In order to investigate the reason why the “reversing” process sometimes occurred at $\theta = 75^\circ$, the distance between the two “horns” was measured for “barchan-type” and “dome-type” topographies. This distance was found to decrease with increasing $\theta$ and
became zero for $\theta = 75^\circ$. Here, the parameter $W_h$ is defined as the distance between two horns in the direction perpendicular to the average flow direction. In the case of the “dome-type” topography, $W_h$ can be interpreted as the “crossing length” between two independent crest lines (Fig. 21 (a)). $W_h/W$, where $W$ is the width of the whole topography, denotes the normalized distance between two horns. The $W_h/W$ value at $\theta = 75^\circ$ reached zero, although that of the other cases converged to a particular value for each case, respectively (Fig. 21 (b)). Figure 21 (c) shows the relationship between $\theta$ and the average value of $W_h/W$ over 15 to 20 cycles. The $W_h/W$ value after 20 repetitions of bidirectional flows monotonically decreased with increasing $\theta$. This result implies that $\theta$ around 75° is the boundary between the “dome-type” and “seif-type” because “seif-type” topographies formed when $90^\circ \leq \theta \leq 135^\circ$ have no crossing of crest lines, meaning that $W_h/W$ is zero.

The observation of topographies for $90^\circ \leq \theta \leq 135^\circ$ showed that the boundary part between the bar-shaped part on the downstream side and the fan-shaped part on the upstream side became constricted and the width of the downstream part became narrow with decreasing $\theta$ (Fig.22). The constriction resulted from the discrepancy between positions of the new crest line due to “reversing” process and “independent”
3.1 Series A experiments

process when the flow direction changed. For example, in the case of $\theta = 90^\circ$ where the constriction occurred, the new crest line due to the "independent" process (a black arrow in photograph 2 in Fig.18 (a)) was formed at a position apart from the crest line owing to "reversing" process (a white arrow in the same photograph). Then, the "independent" part caught up with and linked to the "reversing" part, resulting in one crest line severely bent at the inflection point (photograph 6 in Fig.18 (a)). On the other hand, in the case of $\theta = 135^\circ$ where the constriction did not occur, the new crest line due to "independent" process originally linked to the crest line due to the "reversing" process (photograph 2 in Fig.18 (b)). Therefore, there was no inflection point at a sharp angle on the deformed crest line. Although the constriction in the boundary area was formed when $\theta = 90^\circ$, $105^\circ$ and $120^\circ$, the splitting occurred only in the case of $\theta = 90^\circ$ where the width of the bar-shaped part was narrower than for $105^\circ$ and $120^\circ$.

Both the transitional "dome-type" in the case of $\theta = 75^\circ$ and the transitional "seif-type" in the case of $\theta = 90^\circ$ experience the "independent" process and the "reversing" process. The difference between the two types results from whether or not the downstream part formed due to the "reversing" process could be fed with sufficient
sand from the upstream part due to the "independent" process. The transitional "dome-type" does not have the bar-shaped topography due to a lack of sand supply. In the case of $\theta = 75^\circ$, the "reversing" process does not always occur. Therefore, the split part migrates far away and the upstream "dome-type" topography remains. On the other hand, the transitional "seif-type" forms even if the split in topography temporarily occurs, because the bar-shaped topography can develop owing to sand supply from the upstream part.

3.2 Series B experiments

The aim of the Series B experiments was to investigate the effect of the duration ratio $\alpha$ on the boundary angle of the development patterns mentioned in the previous section.

3.2.1 The effect of asymmetry in duration on the dependence of dune topography on the angular variation $\theta$

In Runs 25 to 28, the angular variation $\theta$ was varied from $60^\circ$ to $150^\circ$ in $30^\circ$ intervals for a value of $\alpha$ of 0.06. Here the effect of varying $\alpha$ is discussed through comparison
with runs from Series A with the same angular variation.

The value of $\alpha$ does not change the type of deformation process that occurred (Fig.24). However, the amount of migration after the crest line deformation occurred depended on the duration (e.g. Photograph 3 in Fig.24 (a), Photograph 2 in Figs.24 (b)). For $\theta$ equals 60°, two crest lines alternately occurred due to the change of flow directions in both Runs 4 and 25 (Fig.24 (a)). For other angular variation values, the same deformation processes occurred in both Series A and B (Figs.24 (b)-(d)).

In Run 26 where $\theta$ equals 90°, the transitional “dome-type” topography formed although runs in Series A with the same value of $\theta$ showed the transitional “seif-type” topography (Fig.25 (b)). This result was caused by insufficient sand supply from the upstream side due to inequality in the duration of the two flows. On the other hand, Runs 25, 27 and 28 showed the same topography as runs in Series A with the same value of $\theta$ (Figs.25 (a), (c) and (d)). The bar-shaped part formed by the “reversing” process of the crest line, however, bent in an arc towards the downstream direction of the major flow in Runs 27 and 28 (Figs.25 (c), (d)).
3.2.2 The boundary between two types of resultant topography

The experiments at the angular variation of 75° and 90°, which is the transitional area between "dome-type" and "seif-type", showed that the shape of resultant topographies were affected by the value of $\alpha$. In Run 26 ($\theta = 90^\circ, \alpha = 0.33$), the bar-shaped part on the downstream side did not develop due to the lack of sand supply due to the splitting of the downstream end of the fan-shaped part (Fig.26 (a)). The transitional "dome-type" topography formed in Run 29 ($\theta = 75^\circ, \alpha = 0.14$), however, in contrast to runs with 75° of angular variation in Series A, a tiny "reversing" part at the downstream end often developed and split from the sand body (Fig.26 (b)). In Run 32 ($\theta = 90^\circ, \alpha = 0.09$), splitting did not occur, and the bar-shaped downstream part had a sinuous crest line rather than a straight crest line (Fig.26 (c)). This sinuous crest line only appeared when $\alpha$ was very small. Therefore, this topography is useful for close estimation of not only $\theta$ but also $\alpha$.

The boundary between the "seif-type" and the "reversing-type" did not change with the value of $\alpha$. The "seif-type" topography was formed in the cases of $\theta = 135^\circ$, while the "reversing-type" topography was formed in the cases of $\theta = 150^\circ$. 
3.2 Series B experiments

(Fig.27). The bar-shaped part in the “self-type” and the whole topography in the “reversing-type” became elongated in common with the case of $\alpha = 1$, however the direction of elongation bent towards the direction of the primary flow unlike the case of $\alpha = 1$.

3.2.3 Cases of $180^\circ$ angular variation

The deformation of the topography under $180^\circ$ angular variation was investigated including data from the Set 1 experiments by Taniguchi and Endo (2007), because similar topographies were formed both in their study and the present study. Table 3 showed the flow conditions of Set 1 experiments in Taniguchi and Endo (2007). The resultant topography of Run 24 had a crest line crossing perpendicular to the flows in the same way as that of Set 1 Case 2 (Fig.28 (a)). In Run 24, the topography formed a sigmoidal crest line and then the crest line split at the inflection point of the sigmoidal crest line into several parts. This splitting phenomenon is in common with Set 1 Case 5 (Fig.28 (b)). These comparison show that the same topography formed under flow condition with same $\alpha$ value.

In all runs conducted in Taniguchi and Endo (2007), the formation and
disappearance of a "rear slipface", as observed by Bishop (2001), occurred. This phenomenon is the same as the "reversing" process introduced in this paper.

Taniguchi and Endo (2007) reported three types of resultant topographies from the Set 1 experiments. Type I topography (Fig.29 (a)) has a linear crest line roughly parallel to the flows in common with the "reversing-type" topography. Type II topography (Fig.29 (b)) had the same shape as the "barchan-type" topography except for the "rear slipface". Type III topography (Fig.29 (c)) has an inflection point on its crest line, and then the topography split at the inflection point. In this paper, the type III topographies are referred to "splitting-type".

The shape of the crest line of these three types gradually varied depending on the value of $\alpha$, exemplified by analysis of the position of the inflection point of the sigmoidal crest line of the "splitting-type" topographies. The centerline of the topography was defined as the line passing the most leeward point of the crest line and extending parallel to the flow. The length between the line and the inflection point is $l_i$, and the length between the line and edge of the crest line is $l_h$ (Fig.30 (a)). The plot of $\alpha$ and $l_i/l_h$ (Fig.30 (b)) showed that $l_i/l_h$ decreased with increasing $\alpha$ with one exception (Set 1 Case 4). The inflection point gets gradually closer to the
centerline with increasing $\alpha$. This suggests that the shape of the crest line gradually changes from crescentic ("barchan-type") to linear ("reversing-type") with increasing alpha (Fig.29 (c)).

The gradual evolution of the topographies depending on the value of $\alpha$ only occurs where the angular variation lies in a narrow range around 180°. The resultant topography for $\theta = 150^\circ$ and $165^\circ$ was elongated in one direction unlike for $\theta = 180^\circ$. Runs with $\theta$ of $180^\circ$ had an average flow direction in common with the primary flow direction, therefore, in those runs, the initial sand pile elongated in two directions crossing at nearly right angles against the primary flow and unique resultant topographies were formed.

3.3 Summary of flume experiment results

3.3.1 The effect of angular variation $\theta$ between two flows on dune topography

This experiment showed the strong influence of the angular variation of two flows on the formation conditions for barchan and seif dunes, although Wasson and Hyde (1983) used RDP/DP to distinguish between the formation of these types.
Figure 31 is a phase diagram between RDP/DP and $\theta$ based on these experiments. Although there are field observations of stable barchan dunes where the angular variation of two flows is no more than 15°, "barchan-type" topographies formed for experiments for $\theta \leq 30^\circ$. The "barchan-type" topographies for $\theta = 180^\circ$ included the formation and disappearance of a "rear slipface". Both "barchan-type" topographies formed for RDP/DP < 0.97. On the other hand, the flow conditions required to form the "seif-type" topographies (including the transitional topography) were $90^\circ \leq \theta \leq 135^\circ$ and $0.38 < \text{RDP/DP} < 0.86$.

The ranges of RDP to form "seif-type" and "barchan-type" topographies, respectively, in these experiments were narrower than the phase diagram by Wasson and Hyde (1983) based on field data (Fig.10). In addition, the absolute values of RDP/DP were larger than found by Wasson and Hyde (1983). The reason is that these experiments were conducted under purely bidirectional flow, while field data may include many irregular winds, which may not contribute to the formation of dune topographies. Therefore, the result of these experiments are useful to identify the effective secondary flow amongst many irregular winds.
3.3.2 A new phase diagram of isolated dunes between $\theta$ and $\alpha$

As the conclusion of these experiments, a new phase diagram of dune shapes under bidirectional flows between the angular variation $\theta$ and the DP ratio $\alpha$ is suggested (Fig.32). This phase diagram is applicable to isolated sand dunes affected by bidirectional flows.

The use of this phase diagram makes it possible to investigate the bidirectional flows that have a large influence on the formation of dune topography. The resultant topography can be used as an indicator of the angular variation $\theta$, and the crest line curvature can be used as an index of the DP ratio $\alpha$ excluding a few exceptions such as cases of $\alpha \approx 0$ where “barchan-type” topographies are formed independent of $\theta$ (e.g. Runs Set 1 Case 8 and Set 1 Case 9). For $\theta > 30^\circ$, the crest line of the “barchan type” topography deforms under the minor secondary flow (e.g. "rear slipface" at $\theta = 180^\circ$). Except for the cases of $\alpha \approx 0$, the angular variation $\theta$ can be firstly estimated by the type of topography, and then the DP ratio $\alpha$ can be evaluated from the shape of the crest line.

Some special features such as the splitting phenomena in the case of $\theta = 180^\circ$ and
the transitional for $75^\circ \leq \theta \leq 90^\circ$ depend strongly on the value of $\alpha$, hence these structures can indicate stricter flow conditions than other topographies.

3.4 Applications

3.4.1 The transition from barchan to seif dunes

The transition process from a barchan dune to a seif dune has been studied by several geologists. The first mention of the process was made by Bagnold (1941). He suggested a model where a barchan dune becomes a seif dune through elongation of the horn located on the windward side of the average wind under bidirectional winds where one is the main gentler wind and the other the minor stronger wind (Fig. 33 (a)). Bagnold's model was supported by observations by Lancaster (1980) of the wind regime and sand movement on asymmetric barchan dunes in the northern part of the Namib desert. On the other hand, Tsoar (1983) presented a model where the horn on leeward side of the average wind becomes longer from field observations on the Sinai Peninsula.

The experiments in this study support Tsoar's model. In these experiments, elongation occurred on the leeward part of the topography in the average flow direction
3.4 Applications

under bidirectional flows with the angular variation $\theta$ exceeding $90^\circ$, while there was no case supporting Bagnold’s model where elongation occurs on the windward part (Fig. 20, 23).

Lancaster (1980) introduced a group of dunes located in the north of the Namib sand sea as a field example of Bagnold’s model (Fig. 34 (a)). At the site, there were many asymmetric barchan dunes with a long sinuous horn on the southern side (Fig. 34 (c)). He proposed that the asymmetrical barchans migrated mainly under the major flow blowing from the WSW. The topographies were sometimes affected by the minor wind including suspended sand from the SSW or SW trapping sand on the horn on the windward side. Then, the horn elongated to the ENE direction under the main wind from the WSW.

Lancaster (1980) defined the wind from the WSW as the primary wind and the wind from the SSW as the secondary winds by duration. However, annual sand movement measured at Narabeb (25 km WSW of the site) indicated that the amount of sand movement by the wind from the SSW was approximately three times larger than that by the wind from the WSW (Fig. 34 (c)). Therefore, it is suggested that Lancaster’s observations provide evidence supporting Tsoar’s model rather than Bagnold’s model.
since the wind from the SSW should be considered as the primary flow.

The formative condition of sand topography supporting Bagnold’s model can be predicted from the results of the flume experiments. The angular variation $\theta$ is likely in the range of $45^\circ$ to $75^\circ$ since the horn on the leeward side remains due to the “independent” process whilst the “dome-type” topography is formed. The new tip on the lower side of horn B in Photograph 2 of Fig.33 (a) seems to be formed by the “independent” process (Fig.16 (b)). The elongation of the horn on the upstream side did not occur at all in the flume experiments due to the lack of sand supply. Since sand can not move against the flow direction, sand supply from outside is required to elongate the horn on the upstream side.

Tsoar’s model is taken to be the transitional “seif-type” topography as a result of the “independent” and “reversing” processes. On the other hand, Bagnold’s model is most likely of the “dome-type” topography caused by the “independent” process and sand supply from outside of the topography. Bagnold’s model could be reproduced by flume experiments replicating the “dome-type” topography with sand supply.
3.4 Applications

3.4.2 Lines of sand dunes in the Western Sahara

There are the lines of sand dunes in the southwest of the Western Sahara (Fig.35 (a) and (b)). These lines are located in a coastal area approximately 50 km away from the Atlantic Ocean. The annual wind data from Port-Étienne (Nouadhibou) in Mauritania (cited by Breed et al., 1979a), located 120 km south west of the dune corridor, showed that the annual sand movement is roughly unidirectional (Fig.35 (c)).

According to Breed et al. (1979a), the surface wind in the western Sahara is controlled by the Azores and Sahara high pressure cells and the Intertropical Convergence Zone (ITCZ). Generally speaking, the wind blows from northeast or north from the northern high pressure to the southern ITCZ. In winter, the Azores high is close to the African continent and the Sahara high becomes strong. Therefore, the winds from northeast or east blow in the western Sahara (Fig.36 (a)). In summer, the thermal low in the Sahara desert forms due to the high air temperature (Fig.36 (b)). Hence, summer winds in the western Sahara are from the north or north east flowing around the Azores high. This seasonal change causes the bidirectional
distribution of annual wind directions at many observation point in the Western Sahara except for Port-Étienne on the coast.

Through application of the results of this study, the dune topographies in the field suggest that these dunes were formed by bidirectional flows with angular variation of $60^\circ$ to $90^\circ$ and a DP ratio of two flows, $\alpha$, below 0.33. Barchan dunes with a long and sharp horn and one short and rounded horn form as in the case of transitional "dome-type" topographies (Fig.37 (a)). Isolated dunes with a single tip is the same topography as the "dome-type" or transitional "dome-type" topographies for $\theta = 60^\circ$ (Fig.37 (b)). The sinuous seif dunes are similar to the transitional "seif-type" topography in the case of $\theta = 90^\circ$ and $\alpha = 0.09$ (Fig.37 (c)).

From the dune topographies and the results of this study, the bidirectional wind regime was estimated for the coastal area in the south of Western Sahara (near Port-Étienne). It was estimated that the wind from the east is effective in shaping dune topography in the coastal area in common with other observation points in Fig.36.
3.4.3 Martian teardrop-shaped dune

The variation in dune morphology on the surface of Mars is richer than on Earth, because the formation of aeolian dunes is not prevented by aqueous processes and vegetation. "Teardrop-shaped" dunes are a type of isolated sand dune with a rounded body and only one small tip (Fig.39 (a)). The topography was identified from the satellite images taken by the Mars Global Surveyor.

In the present experiments, this teardrop-shaped topography formed for \( \theta = 75^\circ \) and \( \alpha = 1 \) (Fig.39 (a)). The small tip results from the "reversing" process, and it is formed and then buried in the deformation process of the crest line (Fig.39 (b)). Parteli and Herrmann (2007b) identified a similar topography by computer simulation using a first principle model that included the saltation layer (Fig.39 (c)). The numerical study found that the flow conditions for the formation of teardrop-shaped topographies consists of two flows that have the same duration and flow velocities, although the angular variation of 100° was larger than that found in the present experiment.

The topographies in Fig.39 (a) suggest that the teardrop-shaped dunes are formed by bidirectional flows with \( \theta = 75^\circ \) and \( \alpha = 1 \). Such dunes were located in the
Wirtz Crater with a diameter of 129 km at latitude $-48.6^\circ$, longitude $26^\circ$ W. Fenton et al. (2005) conducted a numerical study of climatological conditions in Proctor Crater located at approximately the same latitude as Wirtz Crater. They found that there are two winds affecting Proctor Crater; one from the WSW caused by global geostrophic force, and one from the ENE due to the local geographic conditions. The teardrop-shaped dunes indicate that in the Wirtz Crater, there are two effective winds from the WSW and SSE, and that the intensity ratio between the two flows is the same. The wind from the WSW predicted for the Wirtz Crater may also result from the geostrophic force. The other wind is from approximately the SSE, which is probably the local wind, and it must have the same DP value as the wind from WSW for the formation of this dune type.

4 Conclusion

- Flume experiments  The angular variation of two flows $\theta$ plays a very important role in the development of isolated sand dunes under bidirectional flows. The directional shift of sand movement due to changes in flow direction was shown
to induce three deformation processes depending on $\theta$ through a series of flume experiments.

"Shared" process ($0^\circ \leq \theta \leq 30^\circ$)

There is no change in the position and direction of movement of the crest line.

"Independent" process ($45^\circ \leq \theta \leq 135^\circ$)

After the change of flow direction, the new crest line forms regardless of the position of the existing one.

"Reversing" process ($90^\circ \leq \theta \leq 180^\circ$)

After the change of flow direction, a new slipface opposite the existing one forms and the migrating direction of the crest line is reversed.

The resultant topographies after repetition of bidirectional flows can be categorized into four types. The formative conditions of these topographies depend on $\theta$, as they are formed by one or two deformation processes.

"Barchan-type" ($0^\circ \leq \theta \leq 30^\circ$)

This topography has a crescentic crest line and migrates in the leeward
direction. These dunes are produced by the “shared” process.

“Dome-type” (45° ≤ θ ≤ 75°)

This topography has a rounded body without significant tips and develop due to the “independent” process.

“Seif-type” (90° ≤ θ ≤ 135°)

The upstream side of the average flow direction becomes the fan-shaped topography caused by the “independent” process, while the downstream side forms the bar-shaped topography due to the “reversing” process. The crest line on the bar-shaped topography migrates in the leeward direction and is moved laterally and alternately by each of the two flows.

“Reversing-type” (150° ≤ θ ≤ 180°)

The topography forms a straight crest line perpendicular to the flows due to the “reversing” process.

The intensity ratio of each flow on the topography was defined as the ratio of the absolute value of DP (α). The effect of decreasing α on the topography gradually acts on the curvature of the crest line, from the linear shape for α > 0.60 and the
crescentic shape for $\alpha = 0$. The value of $\alpha$ does not affect the type of resultant topographies, however, the cases of $\alpha \leq 0$ are exceptions where the “barchan-type” topography develops independent of $\theta$.

For $75^\circ \leq \theta \leq 90^\circ$ and $\theta = 180^\circ$, unique topographies were formed as outlined below. Such topographies give more detailed information on the bidirectional flows than other topographies.

**Transitional “seif-type” (with splitting) ($\theta = 90^\circ$ and $0.60 \leq \alpha \leq 1$)**

This topography often split into an upstream fan-shaped part and a downstream bar-shaped part. The splitting results from the constriction of the topography in the boundary area between the two parts and narrowness of the bar-shaped part. Sand supply from the upstream part to the downstream part continuously occurs, thereby allowing the downstream part to elongate.

**Transitional “seif-type” (with sinuous crest) ($\theta = 90^\circ$ and $\alpha = 0.09$)**

This topography forms when the $\alpha$ value is extremely low. The bar-shaped part has sinuous shape, while the splitting does not occur.

**Transitional “dome-type” ($\theta = 75^\circ$, or $\theta = 90^\circ$ and $\alpha = 0.14$)**
This topography has only one small tip due to the "reversing" process. The tip does not morph into the bar-shaped part due to a lack of sand supply from the upstream side.

"Splitting-type" (Type III) ($\theta = 180^\circ$ and $0.049 \leq \alpha \leq 0.60$)

This topography occurs only in the case of $\theta = 180^\circ$. A barchan topography with horns with a sigmoidal crest line is formed, and then the topography splits at the inflection point of the sigmoidal crest line. The position of the inflection point gradually varies with the value of $\alpha$.

A phase diagram of isolated sand topography between the angular variation $\theta$ and the DP ratio $\alpha$ is presented based on the results of the flume experiments under bidirectional flows. This diagram is more detailed than the existing diagram using RDP/DP because the new diagram does not allow for non-unique combination of the estimated flow conditions.

Field applications The results of the flume experiments were applied to the three dune fields on Earth and Mars in order to ascertain the flow conditions.

Bagnold and Tsoar respectively suggested different models for the transitional
process from barchan to seif dunes. Tsoar’s model describes the transitional
“seif-type” (with splitting) topography identified flume experiments. On the other
hand, Bagnold’s model most likely describes a kind of “dome-type” topography with
sand supply from outside of the topography.

There are the transitional “seif-type” and “dome-type” topographies in the lines
of sand dunes located in the coastal area of Western Sahara. Analysis of these
topographies with respect to the results of this study show that the wind regime
is bidirectional with a low $\alpha$ value, although the sand movement data was considered
as unidirectional (Breed et al., 1979a).

On the surface of Mars, teardrop-shaped dunes have been observed in the Wirtz
Crater. Using the results of the flume experiments, the wind conditions in the crater
were estimated as having an angular variation $\theta = 75^\circ$ and relative strength $\alpha = 1$.

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Appendix

A. Preliminary experiment: Migration of a barchan under unidirectional flow

Before running experiments under bidirectional water flows, the author conducted a preliminary experiment under unidirectional flow in order to ensure that the flow velocity is sufficient to form a barchan from a conical sand pile and to cause the barchan to migrate whilst maintaining its crescentic shape.

The initial topography was the same conical sand pile as used in the regular experiments (Fig.13). Unidirectional flow over a total duration of 90 minutes affected the topography. The flow velocity at 0.6 cm above the flume bottom was approximately 21 cm/s as measured by the Acoustic Doppler Velocimetry (ADV). The shear velocity was calculated as approximately 0.89 cm/s.

The position of the topography was measured by the photographs taken every five minutes from the top of the flume (Fig.40 (a)). The topography morphed into the crescentic shape and migrated in the leeward direction. The migration rates
of "bay-head" and "toe" (defined in Fig.40 (b)) were 0.012 mm/s and 0.0086 mm/s, respectively. These rates had the same order of magnitude as the Series A experiments in Taniguchi and Endo (2007).

B. List of published papers


5. 谷口圭輔, 遠藤徳孝, 関口秀雄, 2008. 成因不明の "涙型砂丘" の形成環境 ～斜交する二方向流下での地形発達を調べる水槽実験～. 九州大学応用力学研究所研究集会報告 19ME-83 「地形のダイナミクスとパターン」, 45–50. (査読無)


Fig. 1 The global distribution of deserts on the Earth. (After Mountney, 2006).

Fig. 2 Barchan dunes migrating across an agricultural field in Peru (photo by Google Earth)
Fig. 3 Methods of sand movement by wind. Traction is the general name encompassing saltation, rolling and sliding.
Fig. 4 Relationship between grain diameter and threshold shear velocity. The interval between scale markings on the x-axis is the square root of $D$. 
Fig. 5 The main forces on a sand particle affected by the wind. A sand particle on a sand bed (the circle with a solid boundary) is mainly affected by the dragging force from the wind ($F_d$), gravity force ($W$) and buoyancy force ($F_l$). The curve at the left represents the vertical profile of the wind velocity ($u(z)$). At the scale of sand particles, the profile is logarithmic.
Fig. 6 Typical patterns of sand dunes (modified from McKee, 1979). (a) Transverse dunes (b) Reversing dunes (c) Barchan dunes (d) Seif (Longitudinal) dunes (e) Parabolic dunes (f) Star dunes.
Fig. 7 A field example of complex barchan dunes superimposed on by transverse dunes in the Moroccan Sahara. These photographs were taken in 2004. (after Elbelrhiti et al., 2005)

Fig. 8 Relationship between wavelength of aeolian features and grain diameter \( P \), divided into three groups: ripples, dunes and draa.
Fig. 9 A diagram showing the formation conditions for different dune types (after Hack, 1941).
Fig. 10 A phase diagram for dune forms between available sand volume and RDP/DP. Modified after Wasson and Hyde (1983).
Fig. 11  Schematic diagrams showing typical isolated dunes. (a) Barchan dunes (b) Seif dunes.
Fig. 12 The water flume used in the experiments in the present study: (a) Sketch of the water flume (b) The profile of flow velocity in the flume. (c) The definition of y and z in (b).
Fig. 13 Photographs showing the initial topography of the sand pile used in the experiments in this study.
Fig. 14 Schematic diagrams showing how bidirectional flows with angular variation were generated in the experiments: (a) A schematic diagram from the top of the channel. The left image shows the object under the primary flow and right image shows the object under the secondary flow. After stopping the primary flow, the rotatable disk (a black circle in these pictures) is rotated by $\theta$ degrees, and then the secondary flow is started. (b) A schematic diagram from the viewpoint moving with the sand object. The flow directions appear to change by $\theta$ degrees between the primary and secondary flows.
Fig.15  A schematic diagram showing the calculation of $RDP$ under bidirectional flows.
Fig.16 Schematic diagram of three types of processes causing deformation of the crest line (a) “Shared” process (b) “Independent” process (c) “Reversing” process.
Fig. 17 Photographs showing three types of processes causing deformation of the crest line with change of flow direction. All photographs were taken during the secondary flow of the first cycle. (a) Run 1 ($\theta = 15^\circ$, $t = 2\text{min}$). “Shared” process was observed. (b) Run 3 ($\theta = 45^\circ$, $t = 2\text{min}$). “Independent” process was observed. (c) Run 12 ($\theta = 180^\circ$, $t = 2\text{min}$). “Reversing” process was observed.
Fig. 18 The process of deformation of the crest line: "Independent" and "Reversing" processes were simultaneously observed for angular variation $\theta$ in the range $90^\circ < \theta < 135^\circ$. (a) Run 6 ($\theta = 90^\circ$, $t = 2\text{ min}$). (b) Run 9 ($\theta = 135^\circ$, $t = 2\text{ min}$).
Fig. 19 Four types of resultant topography after repetition of bidirectional flows. All photographs were taken during the last bidirectional flow cycle. (a) “Barchan-type” topography (Run 1, $\theta = 15^\circ$). (b) “Dome-type” topography (Run 4, $\theta = 60^\circ$). (c) “Seif-type” topography (Run 7, $\theta = 105^\circ$). (d) “Reversing-type” topography (Run 12, $\theta = 180^\circ$).
Fig. 20 Photographs showing that the development of isolated sand topographies depends on angular variation $\theta$ rather than duration $t$. All images were taken after the primary flow of the last bidirectional flow cycle. The photograph taken in the preliminary experiment is used for $\theta = 0^\circ$.
Fig. 21. The width between two horns normalized by the width of the whole topography $W/W_h$ in Series A experiments. (a) The definition of $W_h$ and $W$ for “barchan-type” and “dome-type” topographies. (b) Temporal development of $W_h/W$. The value of $W_h/W$ became constant except for $\theta = 75^\circ$. (c) Relationship between $\theta$ and $W_h/W$. The averaged $W_h/W$ values from cycles 15 to 20 were plotted. In the case of $\theta = 75^\circ$, the value of $W_h/W$ became close to zero.
Fig. 22 Photographs of the "seif-type" topographies at the last bidirectional flow cycle. The average flow direction for all images is from the left. (a) Run 6 ($\theta = 90^\circ$). (b) Run 7 ($\theta = 105^\circ$). (c) Run 8 ($\theta = 120^\circ$). (d) Run 9 ($\theta = 135^\circ$).
Fig. 23 Photographs showing the dune topographies depending on $\theta$ and $\alpha$. The value of $\alpha$ does not change the resultant type of topography, however, the transitional topographies depending on $\alpha$ are formed in the cases of $\theta = 75^\circ$, $90^\circ$ and $180^\circ$. 
Fig. 24 Comparison of the process of deformation of the crest line between Series A and B experiments. All photographs were taken in the first cycle and the second cycle. (a) Photographs showing $\theta = 60^\circ$. The value of $\alpha$ is 0.06 in Run 25 and 1 in Run 4. (b) Photographs showing $\theta = 90^\circ$. The value of $\alpha$ is 0.06 in Run 26 and 1 in Run 6.
Fig. 24  Continuation. (c) Photographs showing $\theta = 120^\circ$. The value of $\alpha$ is 0.06 in Run 27 and one in Run 8. (d) Photographs showing $\theta = 150^\circ$. The value of $\alpha$ is 0.06 in Run 28 is 0.06 and one in Run 10.)
Fig. 25 The resultant topographies in Series A ($\alpha = 1.00$) and Series B experiments ($\alpha = 0.33$). The direction of the major flow in series B is right to left. All images were taken in the final cycle. (a) $\theta = 60^\circ$. Run 4 is on the right and Run 25 is on the left. (b) $\theta = 90^\circ$. Run 6 is on the right and Run 26 is on the left. (c) $\theta = 120^\circ$. Run 8 is on the right and Run 27 is on the left. (d) $\theta = 150^\circ$. Run 10 is on the right and Run 28 is on the left.
Fig. 26 Photographs showing the transitional topographies between the “dome-type” and “seif-type”. (a) The transitional “dome-type” topography, (Run 26, $\theta = 90^\circ, \alpha = 0.33$). (b) Transitional “dome-type” topography, (Run 29, $\theta = 75^\circ, \alpha = 0.14$). (c) Transitional “seif-type” topography with the sinuous crest line (Run 32, $\theta = 90^\circ, \alpha = 0.09$).

20 cm
Fig. 27 Photographs showing the boundary between the "seif-type" and "reversing-type" topographies. (a) "Seif-type" topography (Run 23, $\theta = 135^\circ$, $\alpha = 0.60$). (b) "Reversing-type" topography (Run 28, $\theta = 150^\circ$, $\alpha = 0.33$). (c) "Seif-type" topography (Run 30, $\theta = 135^\circ$, $\alpha = 0.14$). (d) "Reversing-type" topography (Run 33, $\theta = 150^\circ$, $\alpha = 0.09$).
Fig. 28  Comparison between the present study and the results of Taniguchi and Endo (2007). (a) The left photograph was taken in Run 24, the right one was taken in Set 1 Case 2 of Taniguchi and Endo (2007). Both had the same value of RDP/DP at 0.75 and formed the same “reversing-type” topography (type I in Taniguchi and Endo, 2007). (b) The left photograph was taken in Run 31 and the right one was taken in Set 1 Case 5 of Taniguchi and Endo (2007). Both had about similar values of RDP/DP at 0.25 and 0.26, respectively, and formed the same “Splitting-type” topography (Type III in Taniguchi and Endo, 2007).
Fig. 29 Photographs showing three topographies under alternating flows after Taniguchi and Endo (2007). (a) “Reversing-type” (Type I) topography. (b) “Barchan-type” (Type II) topography. (c) “Splitting-type” (Type III) topography.
Fig. 30  Deformation of the crest line in the case of $\theta = 180^\circ$.  
(a) The definition of $l_h$ and $l_i$. The measurements of $l_h$ and $l_i$ were conducted just before splitting occurred.  
(b) A diagram between DP ratio $\alpha$ and $l_i/l_h$. The value of $l_i/l_h$ was simply decreasing with increasing $\alpha$ with one exception.  
(c) A schematic diagram showing the relationship between the shape of the crest line and $\alpha$.  
(d) Photographs showing the inflection point of the crest line.
Fig. 31 A phase diagram of isolated sand dunes under bidirectional flows between the angular variation of two flows, $\theta$, and RDP/DP.
Fig. 32 A phase diagram of isolated sand dunes under bidirectional flows between the angular variation of two flows, $\theta$, and the DP ratio of two flows $\alpha$. 

Typical topographies
- "Barchan-type"
- "Dome-type"
- "Seif-type"
- "Reversing-type"

Unique topographies
- Transitional "Seif-type" (with splitting)
- Transitional "Seif-type" (with a sinuous crest)
- Transitional "Dome-type" (with a small tip)
- "Splitting-type" (Type III)
Fig. 33 Two models of the transition from a barchan to a seif dune. Initial barchan has two horns named “A” and “B”. (a) The schematic images showing Bagnold’s model (after Bagnold, 1941). Horn “A” on the windward side elongates. (b) The schematic images showing Tsoar’s Model (Tsoar, 1984). Horn “B” on the leeward side elongates.
Fig. 34. The transitional topographies between barchan and seif dunes in the Namib desert. (a) The sketch of the topographies cited by Lancaster (1980). (b) The annual sand movement at Narabeb, cited by Lancaster (1980). (c) Photograph showing the topographies (photo by Google Earth).
Fig. 35  Dune corridor including the transitional "seif-type" and "dome-type" topographies in Western Sahara. (a) Location of the dune corridor. (b) Satellite image showing the dune corridor (photo by Google Earth). (c) Sand rose at Port Étienne in Mauritania (Breed et al., 1979a).
Fig. 36 Seasonal variation of the Resultant Drift Potential (RDP) at observation points in Mauritania (modified from Breed et al., 1979a). Black arrows indicate the average flow directions at each observation point. Except for the case of Port-Étienne, the wind condition is bidirectional. (a) February (Winter). (b) July (Summer).
Fig. 37 Photographs showing the transitional topographies in Western Sahara and the water flume. The left images were taken in Western Sahara and the right images show the topography in the flume experiments. All photographs of flume experiments were taken after the primary flow with direction from top to the bottom of this figure.

(a) The transitional “seif-type” (with sinuous crest) topography.
(b) The “dome-type” topography.
(c) The transitional “dome-type” topography.
Fig. 38 Photographs showing Martian teardrop-shaped dunes. Modified from the photograph taken by Mars Global Surveyor (E21-00192 Malin Space Science Systems Mars Orbital Camera Image Gallery, 30 September, 2003.)
Fig. 39 Comparison of the teardrop-shaped dune topography on Mars and from the flume experiments. (a) Photographs showing the teardrop-shaped topographies on Mars (left) and in the flume (right). The sand rose in the right image shows the flow conditions. (b) The formation process of the small tip (Cycle 19 of Run 5 in Series A; $\theta = 75^\circ$, $t = 2$ min.). (c) Teardrop-shaped topography generated in a numerical study by Parteli and Herrmann (2007b).
Fig. 40 The formation and migration of a barchan dune under unidirectional water flow. Flow velocity at 0.6 cm above the bottom was constant at 21 cm/s. (a) Photographs showing the migration of the topography. The flow direction is from bottom to top. (b) Photographs showing the definition of “bay-head” and “toe”. (c) Temporal development of the position of the topography.
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<td>0.26</td>
<td>75°</td>
<td>20</td>
<td>Reversing</td>
<td>Reversing-type</td>
</tr>
<tr>
<td>11</td>
<td>165°</td>
<td>2</td>
<td>0.13</td>
<td>82.5°</td>
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<td>Reversing</td>
<td>Reversing-type</td>
</tr>
<tr>
<td>12</td>
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<td>0.00</td>
<td>—</td>
<td>20</td>
<td>Reversing</td>
<td>Reversing-type</td>
</tr>
</tbody>
</table>

(+Reversing) ... sometimes occurred.

Dome-type* ... The transitional "dome-type"  
Seif-type* ... The transitional "seif-type"
Table 1
Continuation.

<table>
<thead>
<tr>
<th>Run No.</th>
<th>( \theta )</th>
<th>( t ) [min.]</th>
<th>RDP/DP</th>
<th>( \phi )</th>
<th>( n )</th>
<th>The deformation process of the crest line</th>
<th>The type of the resultant topography</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>60°</td>
<td>1</td>
<td>0.87</td>
<td>30°</td>
<td>30</td>
<td>Independent</td>
<td>Dome-type</td>
</tr>
<tr>
<td>14</td>
<td>75°</td>
<td>1</td>
<td>0.79</td>
<td>37.5°</td>
<td>30</td>
<td>Independent (+Reversing)</td>
<td>Dome-type*</td>
</tr>
<tr>
<td>15</td>
<td>90°</td>
<td>1</td>
<td>0.71</td>
<td>45°</td>
<td>30</td>
<td>Independent + Reversing</td>
<td>Seif-type*</td>
</tr>
<tr>
<td>16</td>
<td>105°</td>
<td>1</td>
<td>0.61</td>
<td>52.5°</td>
<td>30</td>
<td>Independent + Reversing</td>
<td>Seif-type</td>
</tr>
<tr>
<td>17</td>
<td>120°</td>
<td>1</td>
<td>0.50</td>
<td>60°</td>
<td>30</td>
<td>Independent + Reversing</td>
<td>Seif-type</td>
</tr>
<tr>
<td>18</td>
<td>60°</td>
<td>3</td>
<td>0.87</td>
<td>30°</td>
<td>20</td>
<td>Independent</td>
<td>Dome-type</td>
</tr>
<tr>
<td>19</td>
<td>75°</td>
<td>3</td>
<td>0.79</td>
<td>37.5°</td>
<td>20</td>
<td>Independent (+Reversing)</td>
<td>Dome-type*</td>
</tr>
<tr>
<td>20</td>
<td>90°</td>
<td>3</td>
<td>0.71</td>
<td>45°</td>
<td>20</td>
<td>Independent + Reversing</td>
<td>Seif-type*</td>
</tr>
<tr>
<td>21</td>
<td>105°</td>
<td>3</td>
<td>0.61</td>
<td>52.5°</td>
<td>20</td>
<td>Independent + Reversing</td>
<td>Seif-type</td>
</tr>
<tr>
<td>22</td>
<td>120°</td>
<td>3</td>
<td>0.50</td>
<td>60°</td>
<td>20</td>
<td>Independent + Reversing</td>
<td>Seif-type</td>
</tr>
</tbody>
</table>

(+Reversing) ... sometimes occurred.

Dome-type* ... The transitional “dome-type”  Seif-type* ... The transitional “seif-type”
Table 2  Experimental conditions and results of the Series B experiments

<table>
<thead>
<tr>
<th>Run No.</th>
<th>$\theta$</th>
<th>$t_f$ [min.]</th>
<th>$t_s$ [min.]</th>
<th>$\alpha$</th>
<th>RDP/DP</th>
<th>$\phi$</th>
<th>$n$</th>
<th>The deformation process of the crest line</th>
<th>The type of the resultant topography</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>135°</td>
<td>2.5</td>
<td>1.5</td>
<td>0.60</td>
<td>0.45</td>
<td>18.9°</td>
<td>20</td>
<td>Independent + Reversing</td>
<td>Reversing-type</td>
</tr>
<tr>
<td>24</td>
<td>180°</td>
<td>2.5</td>
<td>1.5</td>
<td>0.60</td>
<td>0.25</td>
<td>0°</td>
<td>20</td>
<td>Reversing</td>
<td>Reversing-type</td>
</tr>
<tr>
<td>25</td>
<td>60°</td>
<td>3</td>
<td>1</td>
<td>0.33</td>
<td>0.90</td>
<td>5.2°</td>
<td>20</td>
<td>Independent</td>
<td>Dome-type</td>
</tr>
<tr>
<td>26</td>
<td>90°</td>
<td>3</td>
<td>1</td>
<td>0.33</td>
<td>0.79</td>
<td>6.3°</td>
<td>20</td>
<td>Independent + Reversing</td>
<td>Dome-type*</td>
</tr>
<tr>
<td>27</td>
<td>120°</td>
<td>3</td>
<td>1</td>
<td>0.33</td>
<td>0.66</td>
<td>5.8°</td>
<td>20</td>
<td>Independent + Reversing</td>
<td>Seif-type</td>
</tr>
<tr>
<td>28</td>
<td>150°</td>
<td>3</td>
<td>1</td>
<td>0.33</td>
<td>0.55</td>
<td>3.5°</td>
<td>20</td>
<td>Reversing</td>
<td>Reversing-type</td>
</tr>
<tr>
<td>29</td>
<td>75°</td>
<td>3.5</td>
<td>0.5</td>
<td>0.14</td>
<td>0.92</td>
<td>1.1°</td>
<td>20</td>
<td>Independent + (Reversing)</td>
<td>Dome-type*</td>
</tr>
<tr>
<td>30</td>
<td>135°</td>
<td>3.5</td>
<td>0.5</td>
<td>0.14</td>
<td>0.79</td>
<td>0.8°</td>
<td>20</td>
<td>Independent + Reversing</td>
<td>Seif-type</td>
</tr>
<tr>
<td>31</td>
<td>180°</td>
<td>3.5</td>
<td>0.5</td>
<td>0.14</td>
<td>0.75</td>
<td>0°</td>
<td>23</td>
<td>Reversing</td>
<td>Splitting-type (1)</td>
</tr>
<tr>
<td>32</td>
<td>90°</td>
<td>5.5</td>
<td>0.5</td>
<td>0.09</td>
<td>0.93</td>
<td>0.5°</td>
<td>20</td>
<td>independent + Reversing</td>
<td>Seif-type*</td>
</tr>
<tr>
<td>33</td>
<td>150°</td>
<td>5.5</td>
<td>0.5</td>
<td>0.09</td>
<td>0.86</td>
<td>0.2°</td>
<td>20</td>
<td>Reversing</td>
<td>Reversing-type</td>
</tr>
</tbody>
</table>

(+Reversing) ...sometimes occurred.

Dome-type* ...The transitional "dome-type"  Seif-type* ...The transitional "seif-type"

(1) ... Type III in Taniguchi and Endo (2007)
Table 3 Experimental conditions in Set 1 experiments (modified from Taniguchi and Endo, 2007).

<table>
<thead>
<tr>
<th>Run No.</th>
<th>( \theta ) [°]</th>
<th>( t_f ) [min.]</th>
<th>( t_s ) [min.]</th>
<th>( \alpha )</th>
<th>RDP/DP</th>
<th>( \phi )</th>
<th>( n )</th>
<th>The deformation process of the crest line</th>
<th>The type of the resultant topography</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-1</td>
<td>180</td>
<td>5</td>
<td>5</td>
<td>0.59</td>
<td>0.26</td>
<td>0°</td>
<td>20</td>
<td>Reversing</td>
<td>Reversing-type (1)</td>
</tr>
<tr>
<td>S1-2</td>
<td>180</td>
<td>1</td>
<td>1</td>
<td>0.59</td>
<td>0.26</td>
<td>0°</td>
<td>20</td>
<td>Reversing</td>
<td>Reversing-type (1)</td>
</tr>
<tr>
<td>S1-3</td>
<td>180</td>
<td>5</td>
<td>5</td>
<td>0.31</td>
<td>0.53</td>
<td>0°</td>
<td>20</td>
<td>Reversing</td>
<td>Splitting-type (2)</td>
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<tr>
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<td>1</td>
<td>1</td>
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<td>0.57</td>
<td>0°</td>
<td>20</td>
<td>Reversing</td>
<td>Splitting-type (2)</td>
</tr>
<tr>
<td>S1-5</td>
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<td>5</td>
<td>1</td>
<td>0.14</td>
<td>0.76</td>
<td>0°</td>
<td>20</td>
<td>Reversing</td>
<td>Splitting-type (2)</td>
</tr>
<tr>
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<td>5</td>
<td>1</td>
<td>0.054</td>
<td>0.90</td>
<td>0°</td>
<td>20</td>
<td>Reversing</td>
<td>Splitting-type (2)</td>
</tr>
<tr>
<td>S1-7</td>
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<td>1</td>
<td>0.049</td>
<td>0.91</td>
<td>0°</td>
<td>20</td>
<td>Reversing</td>
<td>Splitting-type (2)</td>
</tr>
<tr>
<td>S1-8</td>
<td>180</td>
<td>5</td>
<td>5</td>
<td>0.016</td>
<td>0.97</td>
<td>0°</td>
<td>20</td>
<td>Reversing</td>
<td>Barchan-type (3)</td>
</tr>
<tr>
<td>S1-9</td>
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<td>1</td>
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<td>0°</td>
<td>23</td>
<td>Reversing</td>
<td>Barchan-type (3)</td>
</tr>
</tbody>
</table>

(1) ... Type I in Taniguchi and Endo (2007)
(2) ... Type III in Taniguchi and Endo (2007)
(3) ... Type II in Taniguchi and Endo (2007)