SIMULTANEOUS IMPACT AND LUNAR CRATERS

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Abstract. The existence of large terrestrial impact crater doublets and Martian crater doublets that have been inferred to be impact craters demonstrates that simultaneous impact of two or more bodies occurs at nearly the same point on planetary surfaces. An experimental study of simultaneous impact of two projectiles near one another shows that doublet craters with ridges perpendicular to the bilateral axis of symmetry result when separation between impact points relative to individual crater diameter is large. When separation is progressively less, elliptical craters with central ridges and central peaks, circular craters with flat floors containing ridges and peaks, and circular craters with deep round bottoms are produced. These craters are similar in structure to many of the large lunar craters. Results suggest that the simultaneous impact of meteoroids near one another may be an important mechanism for the production of central peaks in large lunar craters.

1. Introduction

In the past it has usually been assumed that impact of cosmic debris against lunar and planetary surfaces produces spacially and temporally random crater distributions. However, there is a considerable body of evidence that suggests that the impact process produces craters near one another at the same time. The Clearwater Lakes impact crater doublet, shown in Figure 1, is an example of two impact craters produced at the same time. One crater is 32 km in diameter and the other is 22.5 km in diameter. A detailed study of the Clearwater Lakes crater doublet has resulted in the conclusion that two large meteoroids impacted simultaneously near one another to produce the doublet members (Dence, 1965), and there is a possibility that the meteoroids could have been coupled before entry into the atmosphere (Tanner, 1963). The Ries Crater and the Steinheim Basin are two other craters that have been considered to have formed at the same time (Shoemaker, 1962). In addition, Nininger (1963) has discussed evidence that many of the terrestrial crater fields have been produced by swarms of meteoroids entering the Earth's atmosphere. There is now evidence of simultaneous impact on the planet Mars. A recent study of Mariner 6 and 7 photographs of Mars revealed more crater doublets than should have been observed if all craters were products of random single body impact events, yet there was strong evidence that crater doublet members were impact craters (Oberbeck and Aoyagi, 1972). All of these observations suggest that there may be a fundamental cause for the production of paired or clustered meteoroids.

In the study of Martian craters, observed crater distributions were shown to be consistent with a meteoroid tidal fission model recently proposed by Sekiguchi (1970). This model describes the relationship between tidal forces from the impacted planet or satellite and the stresses produced in a meteoroid that can split the meteoroid when

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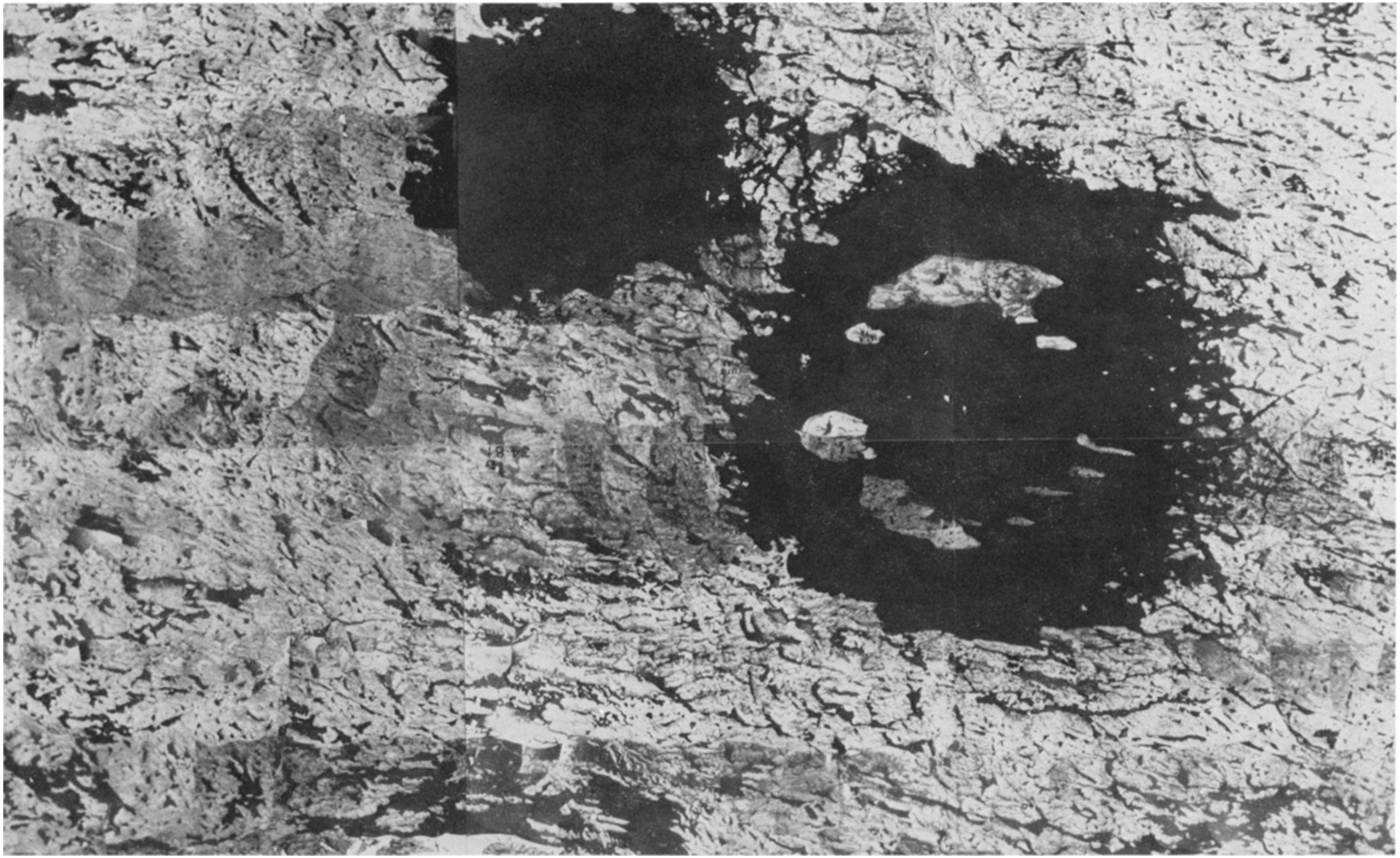

Fig. 1. Dominion Observatory photograph of the Clearwater Lakes impact craters.

stresses exceed the tensile strength. The analysis of splitting of a meteoroid due to the gravitational field of the impacted planet is important because it offers a plausible mechanism for the production of paired meteoroids that is required in order to explain terrestrial and Martian crater doublets. This mechanism leads to consideration of the simultaneous impact process. It has long been known that a planetesimal approaching a planetary body would break up due to the effect of the gravitational field of the larger body on the other; breakup occurring at a critical distance known as the Roche limit. However, until now, no consideration has been given to the types of craters that could be produced by simultaneous impact of the fission products at nearly the same impact point. The purpose of this paper is to present some preliminary results of a series of simultaneous impact cratering experiments and to show that the craters produced are similar in structure to many of the large lunar craters.

2. Modeling Simultaneous Lunar Secondary Craters

In order to determine the types of craters that would form as a result of simultaneous impact of large meteoroids, the simultaneous impact process will be examined in the laboratory. However, in order to increase the reliability of these studies we may begin by attempting to model the overlapping lunar secondary craters that are the only lunar craters known to have been produced at the same time. If these craters can be modeled, modeling of larger primary simultaneous events can be attempted.

Apparently, the most characteristic feature of lunar secondary craters, aside from being elongate and found in strings of craters, is the fact that there is a peculiar 'V' shaped ridge that often projects from the craters (Guest and Murray, 1971). Sets of these ridges were described by O'Keefe *et al.* (1969) and attributed to base surge gases accompanying the formation of large lunar craters. Guest and Murray (1971) have also studied these features and favor their production by deposition of material from formation of the large central impact crater. However, they indicate that they appear to be related to formation of the secondary craters because they are always found in association with the secondary craters.

Figure 2 shows the lunar crater Copernicus and part of the ejecta field of the crater. Three groups of Copernicus secondary craters are indicated; magnifications of these craters are shown in inserts at the top of the figure. The 'V' shaped ridge from crater string *a* is slightly displaced from a radial line from Copernicus but a ridge projects from each side of the crater doublet. For crater doublet *b*, the 'V' shaped ridge is better developed especially where the craters overlap. The point of the 'V' shaped ridge points back to Copernicus. The secondary crater string *c* is nearly concentric with the rim of Copernicus. The ridges between these craters are very well developed and are almost perpendicular to a line connecting crater centers. Ridges are most well developed at the point of crater intersection.

A theoretical analysis of the formation of the crater Copernicus by Shoemaker (1963) yields ejection angles for secondary forming fragments of 14°–22°. Thus, in order to model formation of overlapping Copernicus secondaries, two projectiles

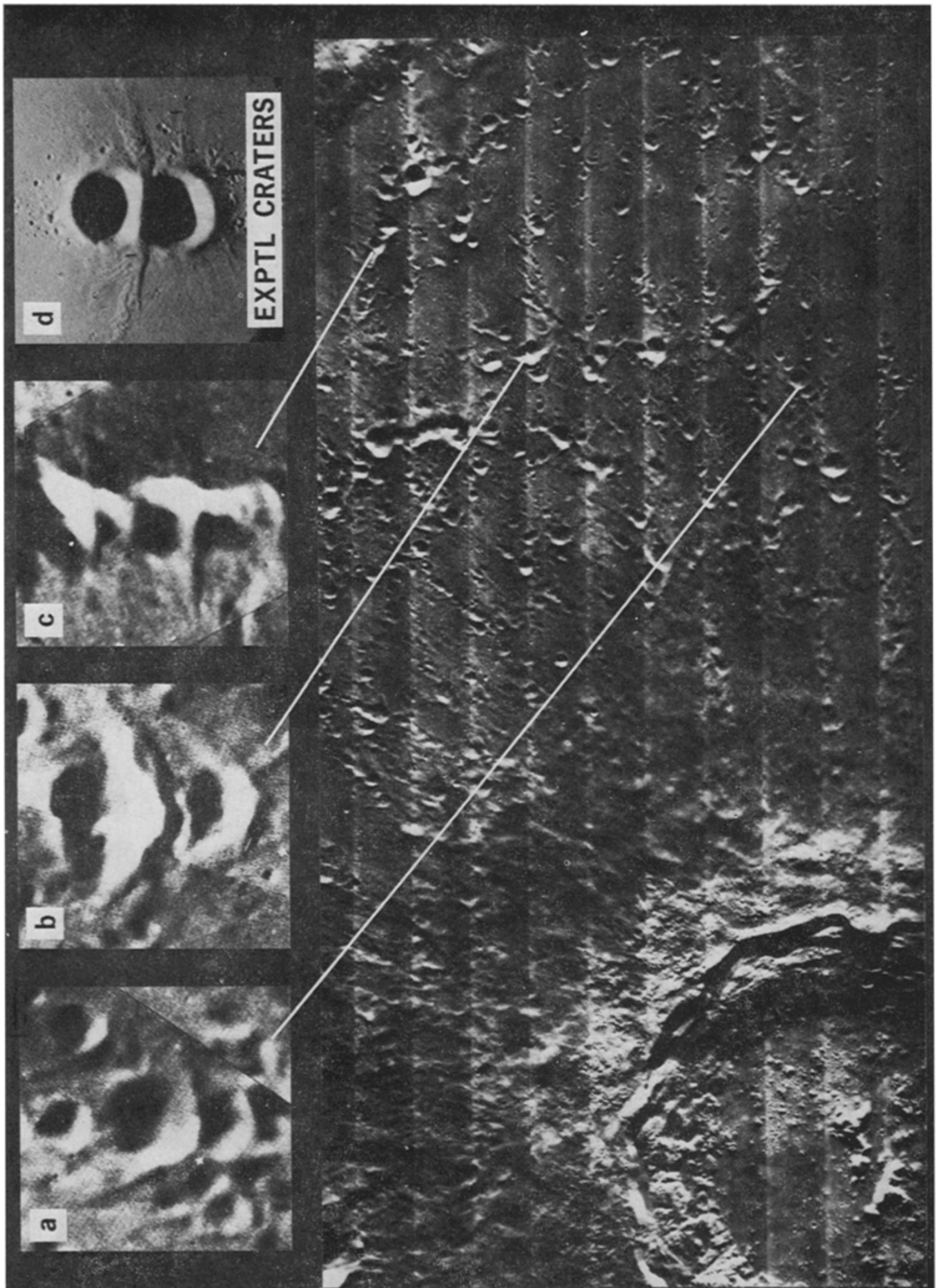

Fig. 2. Northeast quadrant of lunar crater Copernicus and secondary craters *a*, *b*, *c*. Two craters, *d*, produced simultaneously at impact angle measured from horizontal of 20°.

were launched simultaneously in an evacuated ballistic range and allowed to impact against a quartz sand target at an impact velocity of approximately 2 km s^{-1} and at an angle from horizontal of 21°. Impact velocity of 2 km s^{-1} is higher than necessary for correct modeling of these secondaries but no effect of velocity on shape of the 'V' shaped structure has been noted. Figure 2d shows the result of this experiment. A 'V' shaped ridge emanates from the point of overlap of the two craters. The 'V' opens in a direction downrange from the impact direction and is most well developed where the craters overlap. The modeled secondary crater is quite similar to the Copernicus secondaries shown in Figures 2a, b, c.

Successful modeling of lunar secondary craters indicates that we can apparently model simultaneous production of large lunar craters with small laboratory experiments. The ridge between the experimentally produced craters is most well developed where the craters intersect and is a product of strong vertical deformation in this area. We should expect, therefore, that one property of simultaneous impact of large meteoroids aside from the 'V' shaped ridge is strong vertical deformation between the points of impact. Simulation of simultaneous impact of large meteoroids at progressively smaller separation distances can now proceed.

3. Modeling Simultaneous Impact of Paired Meteoroids

For this study all experimental craters were produced by cylindrical projectiles of Lexan plastic that were bisected longitudinally to a point within 0.2 mm from the end of the projectile. Projectiles were launched normal to the fine grained quartz sand target at 2.3 km s^{-1} and projectile spin imparted during launch by gun barrel rifling was sufficient to sever the small amount of material holding together the two halves of the projectile. Typically, projectile separation at impact was about 6 cm for those projectiles launched with a gun barrel having one turn of rifling per 254 cm of gun barrel and about 4 cm separation for gun barrels having one turn of rifling per 330 cm of gun barrel. Except for one experiment, one impact occurred within five microseconds of the other impact. In this series of experiments the primary subject of investigation was the effect of variation of the ratio S/D where S is separation between impact points and D is the diameter of the craters produced by the projectile halves. This ratio is important because it varies for different conditions of impact on planetary surfaces (Oberbeck and Aoyagi, 1972) and this produces craters with different morphologies. Individual crater size was varied by increasing or decreasing projectile length (mass).

Figure 3 shows examples of craters produced under different conditions of projectile separation relative to crater diameter. When separation is large relative to crater diameter ($S/D = 1.3$, crater *a*) there is a subdued ridge perpendicular to a line connecting the center of one undisturbed crater with the other. When separation between impact is decreased relative to crater diameter ($S/D = 1.05$, crater *b*) individual crater rims are flattened and the ridge between craters is higher. For still smaller ratios of separation to crater diameter ($S/D = 0.81$, crater *c*) the individual craters begin to lose their separate identity. The ridge between the craters is wider but lower. Crater dou-

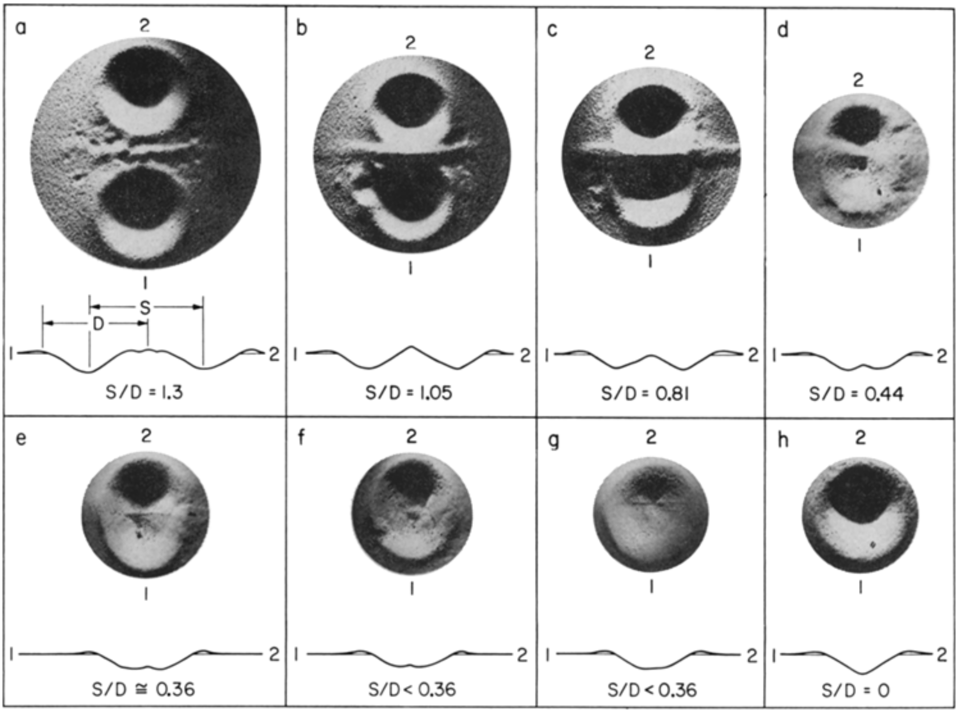

Fig. 3. Impact craters produced by simultaneous impact of two halves of a cylindrical projectile. S = separation distance between impact points; D = diameter of crater produced by 1/2 projectile.

blets characterized by S/D values less than 0.81 begin to resemble one crater rather than two. For example, crater *d* characterized by an S/D value of 0.44 is elliptical. Ridge development outside the crater is poor, but the ridge inside the crater is still quite well developed. When separation between impacting projectiles relative to crater diameter ranges from 0.36–0.0, crater geometry ranges from a single elliptical crater to a single circular crater. For example, crater *e*, characterized by an S/D value of 0.36, is elliptical and has a well developed central ridge. Crater *f*, characterized by an S/D value less than 0.36, is less elliptical and it has a flat crater floor that contains a well developed central peak. For still smaller ratios of S/D (crater *g*) the crater is circular and a series of straight ridges develop on the flat crater floor. There is no ridge development outside the crater. When projectiles are impacted at the same point, within 5 ms of one another, there is no central peak or flat floor. An example, crater *h*, is characterized by an S/D value of 0.0 and it has a deep round bottom. It resembles a crater produced by one projectile.

In summary, simultaneous impact of two projectiles in homogeneous targets produces doublet craters with central ridges that extend across the target surface, elliptical craters with central ridges, circular craters with central ridges and central peaks, circular flat floored craters with central peaks and ridges, and craters with spherical seg-

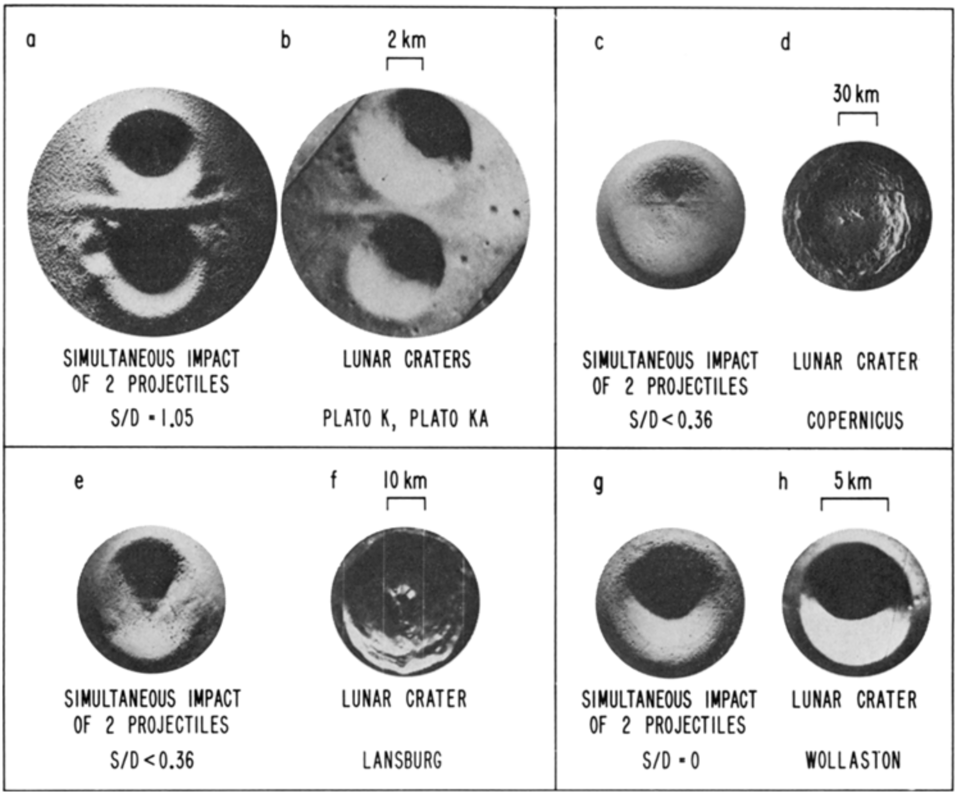

Fig. 4. Comparison of experimental impact craters and large lunar craters.

ment shape. The type of crater produced is dependent on separation between the projectiles relative to crater diameter. Some preliminary experiments have been performed where one projectile impacts behind the other. These results indicate that craters with central peaks and slump features on crater walls may be produced by near simultaneous impact events. For example, impact of a 0.25 gm projectile followed by a 0.43 gm projectile 25 ms later produces a crater with a central peak and terrace-like features on the crater wall. These result from collapse of the growing walls of the first crater as a result of the second impact. Some experiments have also been performed at small angles of incidence to the target surface. These experiments have been limited in number because it is difficult to impact projectiles simultaneously at the desired separation distances when impact angles are small and both projectiles are launched from the same barrel. However, one such experiment has been illustrated in the section of the paper that describes modeling of secondary craters. The value of S/D is approximately 0.8 for this doublet. It resembles some of the experimentally produced doublets of Figure 3 except that the ridge between the craters is not perpendicular to the bilaterial axis of symmetry of the craters. However the ridge is as well developed for the crater produced by projectiles impacting at low angles to the target as it is for those produced by projectiles impacting normal to the target. A limited number of simultaneous impact events have been produced at low angles of incidence and for small values of S/D. The craters produced here are similar to those produced at 90°. For example, circular craters with central peaks have been produced but the peaks are formed at various distances from the crater center.

Craters produced in the laboratory by simultaneous or near simultaneous impact of two projectiles are similar in structure to craters observed on the Earth, Mars and the Moon. The Clearwater Lakes crater doublet and doublets on Mars have already been compared to experimental craters (Oberbeck and Aoyagi, 1972). Craters produced in the laboratory by simultaneous impact can now be compared to lunar craters. Figure 4 shows photographs of four of the craters produced by simultaneous impact and four lunar craters. The experimental craters represent a wide range in projectile separation. The existence of the lunar crater doublet (Plato K and Plato KA) near the Alpine Valley (crater b) is considered strong evidence for the existence of simultaneous impact on the Moon as well as Earth. It corresponds in every way with the experimentally produced crater doublet *a*. The presence of a ridge perpendicular to the bilaterial axis of symmetry of the doublet is characteristic of simultaneous impact. Both doublets appear to have been formed under similar conditions of separation between projectiles relative to crater diameter. The ridge associated with each doublet is equally developed. Crater *d*, the lunar crater Copernicus, has a flat floor and one long ridge and two parallel short ridges that are connected by a transverse ridge. Crater *c* is an experimental crater produced by simultaneous impact of two projectiles where the separation distance relative to crater diameter is small ($S/D<0.36$). The experimental crater has a flat floor and three subdued parallel straight ridges on the crater floor. In this regard, it is important to note that many of the lunar central peak craters actually contain straight ridges or ridge systems that are similar to those that are produced by simultaneous impact. Circular central peaks also occur such as that in the lunar crater Lansburg (crater *f*). Crater *e*, an experimentally produced crater with a central peak, is an analog for Lansburg. Both craters are characterized by a well developed central peak. Crater *h*, the lunar crater Wollaston, is bowl shaped and is similar to crater *g*, the experimental impact crater produced by simultaneous impact of two projectiles at the same place or by one projectile of twice the mass.

4. Discussion

Simultaneous impact experiments using homogeneous targets have produced craters that resemble craters observed on the lunar surface. This, coupled with evidence for simultaneous impact on Earth, is considered evidence that simultaneous impact of large meteoroids may have produced many of the lunar craters. There is additional qualitative evidence that supports this conclusion. It has long been known that there is a change in structure of lunar craters with diameters greater than 1 km (Quaide *et al.*, 1965; Short and Forman, 1971). Preliminary measurement and classification of a large sample of craters on the Moon's front side performed in this laboratory have documented this change of crater structure with size. The smallest of these lunar craters are round bottomed. The frequency of these decreases as the number of flat bottomed craters increases. Central peak craters are more common for craters larger than the flat bottomed or round bottomed craters, and terraced craters, with and without central peaks, are most frequent in the largest crater classes. This change in crater structure with size resembles in some details the change in crater structure with size for lunar craters less than 400 m in diameter. The structure of small lunar craters has been related to strength differences in the layered near surface structure of the maria (Quaide and Oberbeck, 1968). However, these layering effects do not control crater structure for craters larger than approximately 400 m (Quaide and Oberbeck, 1968). Thus strength differences in rock formations probably cannot account for the structural differences observed in large lunar craters that are discussed in this paper. However, all of these crater types can be produced by simultaneous or near simultaneous impact of two projectiles at various separation distances relative to individual crater diameter in homogeneous targets. Moreover, the mechanism of tidal splitting of meteoroids provides a plausible mechanism for the variation of separation of impact points relative to crater diameter. Since crater structure depends on this ratio, the mechanism could produce craters with geometries similar to those produced in the laboratory.

In summary, the existence of the Clearwater Lakes craters shows clearly that simultaneous impact of meteoroids occurs. Experiments in the laboratory have shown that simultaneous impact of projectiles produces craters with structures similar to those of lunar craters. The most typical characteristic of craters produced by simultaneous impact of projectiles very close to one another is the formation of a central peak or ridge in circular craters. Therefore, some central peaks in lunar craters must have formed by this mechanism. Further study is required in order to evaluate the importance of this mechanism relative to other mechanisms that have been proposed for the formation of central peaks in lunar and terrestrial impact craters.

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