otherwise similar pyroxenes from different rocks. This indicates that these minerals have different sources, that is parent magmas.

The origin of the parent magma for the crystalline rocks is uncertain. It may have been derived by partial fusion at depth caused by radiogenic heating or perhaps by melting triggered by impact of very large bodies. In any event, the textures are typical of igneous rocks which cooled mainly under static conditions. It is of course possible that the magma from which they crystallized flowed a long distance before crystallization began, as is the case in many terrestrial basalts. The high TiO_2 contents and other composition characteristics of the lunar crystalline rocks indicate that either the processes which produced them or their parent materials were quite unlike terrestrial processes and parent materials. If the great age (*1*) of these rocks holds, one can either presume that the moon was accreted from already differentiated material, or that early in the moon's (and earth's) history large numbers of impacts were a major geological agent creating superheated melts over considerable areas. Similar origins have been suggested for chondrites, that is, that they were created by impacts on relatively small, low density (compared to the moon) bodies (*8*).

K. FREDRIKSSON, J. NELEN
W. G. MELSON, E. P. HENDERSON
Smithsonian Institution,
Washington, D.C. 20560
C. A. ANDERSEN
Hassler Research Center,
Applied Research Laboratories,
Goleta, California 77058

References and Notes

1. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969).
2. L. S. Walter, *Geochim. Cosmochim. Acta* **31**, 2043 (1967).
3. C. A. Andersen, *J. Mass Spec. Ion Phys.* **2**, 61 (1969); *ibid.*, in press.
4. K. Fredriksson and A. M. Reid, *Science* **149**, 856 (1965).
5. H. Wänke, *Z. Naturforsch.* **21a**, 93 (1966).
6. B. Mason, K. Fredriksson, E. Jarosewich, W. G. Melson, E. P. Henderson, J. S. White, Jr., *Science*, this issue.
7. O. Weill, personal communication.
8. K. Fredriksson, *Trans. N.Y. Acad. Sci.* **25**, 756 (1963).
9. We thank G. Moreland who prepared a number of outstanding polished thin sections without which much of this work would hardly have been possible. Also we are indebted to a number of principal investigators and colleagues who openly and generously discussed their results. J. Hinthorne assisted with the ion probe analyses and B. J. Fredriksson with electron probe data evaluation. Supported in part by NASA, contract NAS 9-8015.

5 January 1970

Deformation of Silicates from the Sea of Tranquillity

Abstract. *Plagioclase and olivine crystals in the crystalline rocks from the Sea of Tranquillity show little or no evidence of either static or dynamic deformation. The large disorientations in many of the pyroxene crystals are commonly consistent with slip on the system* T = {*100*}, t = [*001*], *but these distortions are not due to plastic flow. They are ascribed to rapid growth and quenching phenomena as deduced from studies of chondrules and of quenched natural and experimentally produced melts. Some of the silicates in the breccias and regolith show evidence of shock deformation, from mild to intense, as indicated by pervasive fracturing, shock lamallae, and partial transformation of pyroxene and plagioclase crystals to glass.*

Recent static experiments on silica and silicates have demonstrated that the plastic flow mechanisms vary with temperature, with strain rate, and, for some materials, with pressure. The slip mechanisms observed at the higher temperatures and lower strain rates have been successfully correlated with those operative in natural slow deformations. The primary objective of the present investigation of silicates returned from the Sea of Tranquillity was to determine the presence or absence of such deformation features. Given a representative sample from various provinces of the lunar surface, such studies should discern the importance of tectonic activity during the history of the moon. In addition, we have examined the lunar material for evidence of dynamic deformation due to the impact of foreign bodies. In our studies to date we have used primarily optical microscopy and x-ray Laue and precession methods.

Plagioclase in euhedral and subhedral crystals is a common constituent of both the fine- and coarse-grained igneous rocks but shows little or no evidence either of static or dynamic deformation. Thin plagioclase laths are commonly bent slightly, but such bending is also evident in thin laths from experimentally and naturally quenched terrestrial basalts. Olivine crystals in the fine-grained igneous rocks show no deformation whatever. Most of the pyroxenes (chiefly augite), however, show large distortions within individual grains. The disorientations resemble, in many respects, those produced by both static and dynamic deformation of pyroxenes and will be discussed in more detail below.

Three types of disorientations are observed in the pyroxene grains: (i) uniform sweeping undulatory extinction (Fig. 1a) over angles ranging to 100°; (ii) discontinuous changes in extinction with subboundaries separating zones of uniform extinction—somewhat similar to kink bands or polygonization in crystals; and (iii) more irregular disorientations in which the grains are composed of mosaics of irregularly shaped blocks having different orientations. Universal stage measurements of the variation in crystal orientations in grains showing disorientations of types i and ii generally indicate that an axis near [010] (rotation axis) is common to the various subgrains with [001] nearly normal to zones of undulatory extinction or subgrain boundaries. If the bending is interpreted as being due to plastic flow, the slip system T (slip plane) = {100} and t (slip direction) = [001] is inferred from the measurements. The slip system {100} [001] has been observed in clinopyroxenes deformed experimentally at high temperatures (*1*).

Six small grains extracted from both the crystalline rocks and regolith have been examined by x-ray Laue and precession methods. All of these crystals except one show some disorientation or mosaic structure; the disorientations differ in degree, but the rotational patterns are similar. In each crystal, rotations are greatest about the [010] axis, as is shown by a representative precession photograph in Fig. 2. Most of the Laue and precession photographs also show complexities that are not yet fully understood.

The more irregular disorientations (type iii) do not exhibit any simple crystallographic relationship between subgrains. For the simplest of these, the "hour glass" structure, the various zones tend to share the [010] axis, but the boundaries between zones are not, in general, rational. Optic angle-measurements suggest that the disorientations generally are not related to changes in

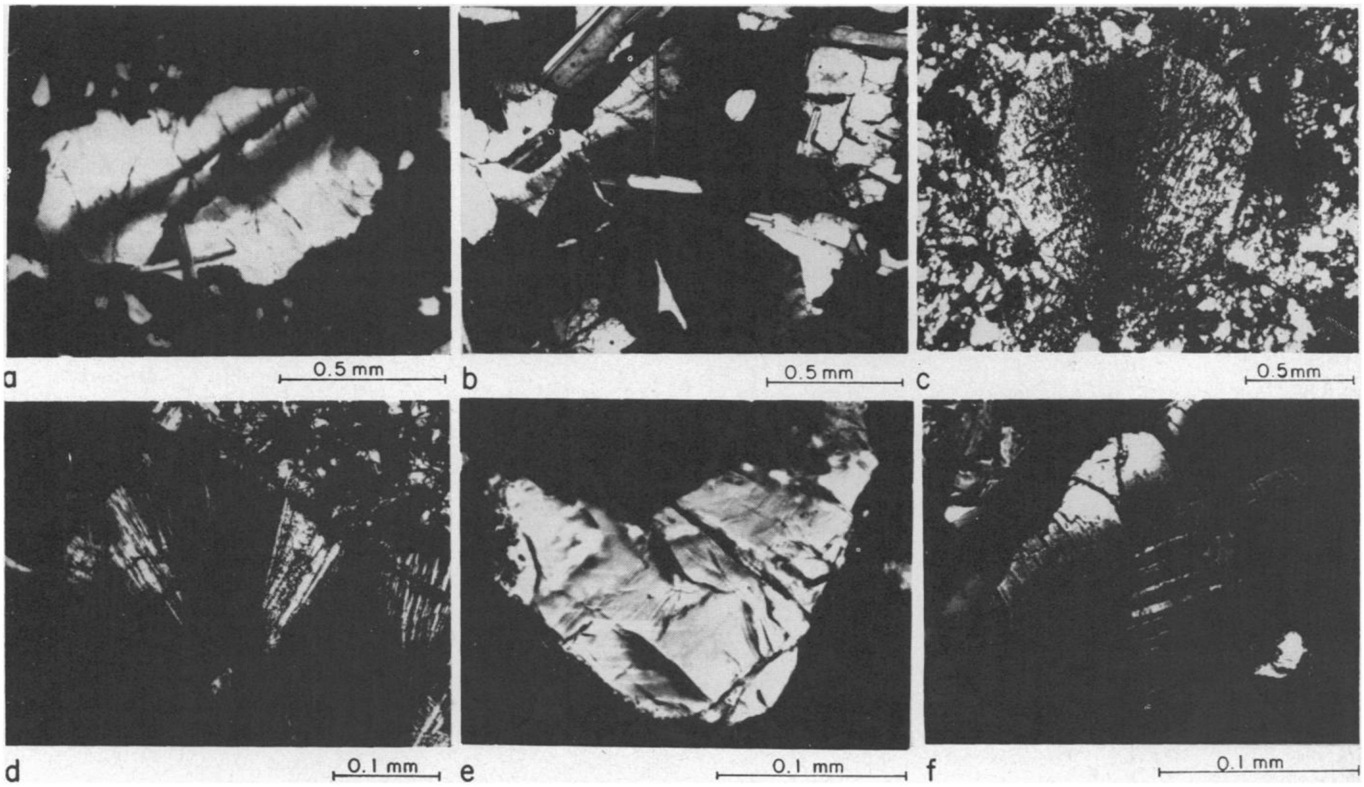

Fig. 1. Photomicrographs taken between crossed polarizers. (a) Pyroxene showing strong undulatory extinction from beccia 10046. (b) Distorted pyroxene grain containing plagioclase laths in rock 10047. Note the thin vertical plagioclase lath in highly distorted area of pyroxene near top of photograph. (c) Pyroxene from Pantar olivine-bronzite chondrite. (d) Radiating fibers of enstatite in rapidly quenched experimentally melted pyroxene rock. (e) Shock lamellae (light, east-west linear features) in pyroxene from lunar regolith sample 10085. (f) Deformation twins (light northeast-trending bands) in pyroxene in fine-grained crystalline rock in lunar regolith sample 10085.

chemical composition. That is, the optic angle varies as much within a single optically homogeneous zone as it does from zone to zone. Confirmation of this conclusion has come from electron-microprobe determinations of Ca, Mg, and Fe distributions in two adjacent highly disoriented zones having the same optical angle (*2*). The variations in these elements are large within each zone but show no significant differences between zones. Such chemical inhomogeneities within small domains may well contribute to the complexities observed in the x-ray photographs. The mosaic structure in this class of pyroxenes (type iii) is distinctly different from the mosaic structure produced in pyroxenes experimentally shocked to high pressures (*3*).

Several lines of evidence indicate that the disorientations in the pyroxenes are not due to plastic deformation. First, there is no evidence of deformation in the other silicates; in particular, olivine, which deforms more readily than pyroxene under both static and dynamic conditions, is totally undeformed. Second, the dominant mode of plastic deformation of monoclinic pyroxenes is twin gliding; only a few broad growth twins were observed in the crystalline rocks. Finally, straight, thin plagioclase laths such as the vertical lath near the top of Fig. 1b are undisturbed in highly bent regions of the pyroxene. Such laths should be uniformly bent or broken if the distortions in the pyroxene are the result of plastic deformation.

Studies of pyroxene chondrules in chondritic meteorites, of similar structures in rapidly quenched experimentally produced melts of pyroxene-bearing rocks, and of rapidly quenched terrestrial basalts suggest that the disorientations in the pyroxenes may be accounted for by rapid growth during quenching and subsequent annealing. Figure 1c shows radiating fibers of pyroxene in a chondrule from the Pantar olivine bronzite chondrite, a structure typical of pyroxene chondrules in many chondrites. A similar radiating structure was observed (Fig. 1d) in a natural eclogite melted experimentally at 1100°C, 15 kb confining pressure at a constant strain rate of 10^{-4}/sec and then quenched rapidly. In that specimen, the enstatite fibers are rotated about [010], as is true also of some of the pyroxene chondrules measured. However, the rotation axes in some of the radiating chondrules are not rational as might be expected from their more complex three-dimensional geometry (*4*). Undulatory extinction very similar to that shown in Fig. 1a has been observed in an augite crystal in molten basalt withdrawn from Kilauea Iki in mullite tubes and quenched rapidly. Again, the axis of rotation is [010], and [001] is normal to zones of undulatory extinction. Thin laths of plagioclase, some of which are bent slightly, as in the lunar samples, were also observed in those specimens.

We envision the growth process giving rise to disorientations in the pyroxenes in the coarse-grained rocks as shown schematically in Fig. 3. The dominantly pyroxene melt interstitial to the plagioclase-ilmenite network is quenched rapidly, the fibers or platelets nucleating on the framework and growing rapidly preferentially nearly parallel to the {001} plane (Fig. 3, left). This process gives rise to the preferred optical and crystallographic relations shown in Fig. 3 (center),

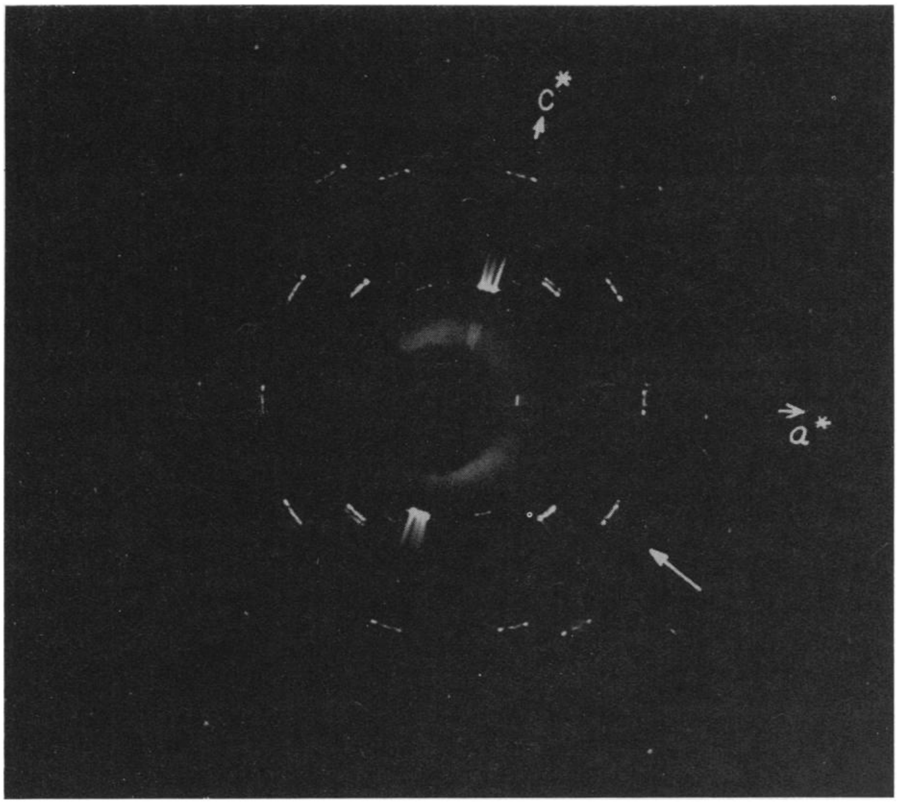

Fig. 2. Precession photograph of *hol* net of a pyroxene grain selected from sample 10084 (fines). Slight displacements of weaker sets of spots in directions nearly normal to the arrow indicate complex structural domains. Zr-filtered Mo radiation (45 kv/20 ma), 66-hour exposure.

although the relations are generally not so simple, as is revealed by the x-ray precession studies. Subsequent annealing permits the fibers or platelets to coalesce into subgrains separated by walls of dislocations as shown in Fig. 3 (right). Study of grains showing the uniform undulatory extinction using phase contrast illumination reveals the presence of many such low-angle subboundaries.

The irregular disorientations in the pyroxenes arise as a natural consequence of the growth scheme proposed. Thus, the "hourglass" structure is explained as having nucleated at the central point of the "hourglass" with radiating growth along oppositely directed conical surfaces. The more irregular mosaics may be the result of sections cut through the pyroxenes at large inclinations to the cone axes. Such irregular disorientations are quite common in thin sections of chondrules and are due chiefly to the orientation of the thin section relative to that of the chondrule (*4*).

The silicates in the lunar breccias and regolith are derived mainly from the crystalline rocks and hence show all of the structures described above. In addition, some of them show evidence of mild to intense deformation due to shock by impact of foreign bodies. The evidence for such deformation is discussed in detail by others and will be treated only briefly here.

Pervasive fracturing in chips of crystalline rock within the breccias and regolith and angular fragments of silicates gives evidence of mild shock (*3, 5*). Shock lamellae (glass) parallel to {001} in some pyroxene (Fig. 1*e*) and plagioclase grains indicate moderate shock deformation, as may mechanically induced pericline twins in plagioclase. Deformation twins parallel to {001} were observed in some of the pyroxenes (Fig. 1*f*); twins of this orientation have been produced in static experiments at low temperature or high strain rates or both (*1*) and by shock deformation experiments (*6*). Slight undulatory extinction in two olivine grains produced by slip parallel to [100] and the {001} twins in the pyroxenes may be ascribed either to static or to dynamic plastic deformation. However, the absence of such deformation in the crystalline rocks suggests that these features were produced by shock, although slip parallel to [001] is most common in shocked olivine (*3*). A few of the plagioclase and pyroxene crystals appear to be partially transformed to glass, suggesting intense shock (*5*).

We conclude that all of the features in the silicates in the crystalline rocks studied by us can be ascribed to growth, quenching, and annealing processes; there is no substantive evidence of static plastic deformation. Shock deformation due to impact, varying from mild to intense, has been operative and may well be the primary disintegrating process giving rise to the lunar regolith.

N. L. Carter
I. S. Leung
H. G. Ave'Lallemant
Department of Geology and Geophysics, Yale University, New Haven, Connecticut

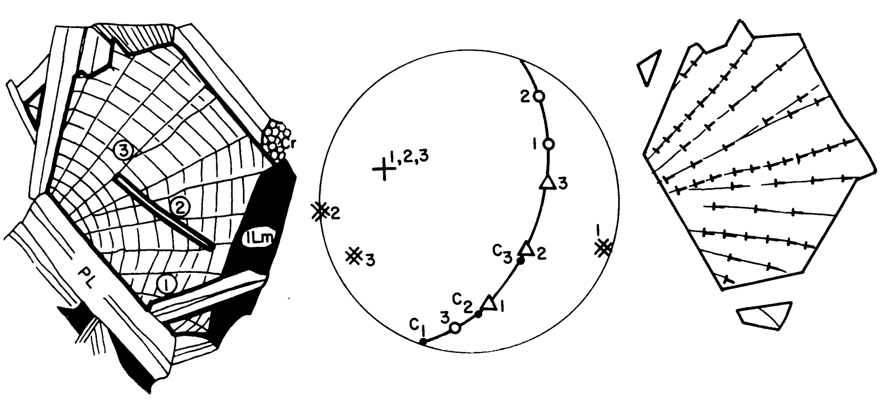

Fig. 3. Schematic diagram showing proposed origin of uniform disorientations in the pyroxene crystals. Pyroxene-rich melt confined in plagioclase-ilmenite framework crystallized rapidly during quenching (left), giving idealized rotations shown in center stereogram. Subsequent annealing causes coalescence of crystallites separated by dislocation walls.

References and Notes

1. D. T. Griggs, F. J. Turner, H. C. Heard, *Geol. Soc. Am. Mem.* **79**, 39 (1960); C. B. Raleigh, J. L. Talbot, *Am. J. Sci.* **265**, 151 (1967).
2. L. Fernandez, personal communication.

3. N. L. Carter, C. B. Raleigh, P. S. DeCarli, *J. Geophys. Res.* **73**, 5439 (1968).
4. K. Fredriksson, *Trans. N.Y. Acad. Sci.* **25**, 756 (1963).
5. E. C. T. Chao, *Shock Metamorphism of Natural Materials* (Mono, Baltimore, 1968), p. 135.
6. C. B. Sclar, personal communication.
7. We are indebted to L. Fernandez for determining the distributions of several elements in a disoriented pyroxene, E. Roedder for use of his photograph published in our Fig. 1a and to B. Skinner for the loan of specimens from Kilauea Iki. Supported by NASA contract NAS 9-9937.

4 January 1970

Shock Metamorphism in Lunar Samples

Abstract. *Indications of shock metamorphism produced by pressures up to the megabar region have been observed in the fine material and the breccias, but very rarely in the coarser fragments of crystalline rocks. These indications are deformation structures in plagioclase and pyroxene, diaplectic plagioclase glasses, and glasses formed by shock-induced melting of lunar rocks. Two sources of shock waves have been distinguished: primary impact of meteorites and secondary impact of crater ejecta. There are two major chemical types of shock-induced melts. The differences in chemistry may be related to impact sites in mare and highland areas.*

The following shock-induced transformations produced by solid-state reactions and melting have been observed in breccias (59, 60, 65, and 27) and fine material (85, 84), besides weaker effects of plastic deformation and fracturing probably due to shock: (i) deformation structures in plagioclase and pyroxene; (ii) diaplectic feldspar glasses; and (iii) glasses produced by shock-induced melting.

Plagioclase grains with lamellae of low index of refraction and low or no birefringence, which might be classed with those from terrestrial meteorite craters and shock experiments, are very rare in the samples studied. For the most part they display only one set of lamellae that are isotropic or of low birefringence. Apparently, the conditions (duration of shock waves, composition of plagioclase, and texture of lunar rocks) do not favor the formation of these structures. This is confirmed by the absence of deformation lamellae in the shocked rock fragment described below.

Very few of the pyroxene grains found in the fine material exhibit multiple sets of closely spaced lamellae similar to those that are well known from shocked quartz.

In the fine material and in the breccias, colorless and isotropic grains of plagioclase composition occur which exhibit no indications of fusion, such as vesicles or flow structures. Some of them show straight grain boundaries and cleavage. Microprobe analyses and refractive index measurements were made on 14 grains, isolated from samples 84,106; 85,25; and 85,26 (Table 1). The densities of six grains were also determined. Figure 1 demonstrates that the refractive indices of these glasses are distinctively higher than those of normal glasses produced by fusion. Likewise, the density is higher than that of fused plagioclase. These observations show that the glasses are not fusion products but are diaplectic glasses (*1*) formed in the solid state by shock waves with amplitudes between about 300 kb and about 500 kb. They have been produced by meteoritic impact on plagioclase-bearing crystalline rocks of the lunar surface which were broken during excavation into fragmental mineral grains. Fragments of such rocks with diaplectic plagioclase glass (very seldom with small isotropic alkali feldspar inclusions) in its original paragenesis with pyroxene and ilmenite are rarely found in the fines and breccias. Diaplectic plagioclase glasses are also known from terrestrial impact craters (*2*), from the Shergotty meteorite (*3*), and from shock wave experiments (*3*). To check further on the diaplectic nature of the lunar glasses, annealing experiments were carried out on various fragments of a large grain (Fig. 2). Annealing at 700° and 800°C increased the index of refraction. The beginning of recrystallization was observed at 900°C, and complete recrystallization at 1000°C. The same increase of refraction on annealing was observed on diaplectic plagioclase glass of the Manicouagan crater (*4*), whereas fused plagioclase shows no change on annealing at temperatures below the transformation point.

Glasses in the fine material and in the breccias occur as (i) bodies of regular spheroidal, ellipsoidal, dumbbell, or teardrop shape, (ii) irregular fragments, and (iii) vesicular coatings on fragments of breccias and crystalline rocks.

1) The spheroidal, ellipsoidal, dumbbell, and teardrop glass bodies form about 10 percent of all glass in the fine material. Their sizes are in the range between 2 mm and 0.3 μm. Red, brownish, and yellow glass bodies are most frequent. About half as many are colorless or greenish. Violet-brownish-colored spherules are rarer. The glasses are generally homogeneous. Some contain vesicles. Schlieren and inclusions of mineral grains (plagioclase, pyroxene), often partially fused, are rarer. Very small spherules of metallic Fe occur in some glasses. Apparently the very regular shape of these bodies and their rotational symmetry resulted from an equilibrium between surface tension and inertial forces acting on liquid drops rotating and falling in the lunar vacuum. Divitrification is rare, but a few devitrified spherules have been found which resemble orthopyroxene chondrules of chondrites. The homogeneity of most of these glasses indicates their initially high temperatures. The rarity of devitrification indicates the predominantly rapid rates of cooling.

2) There are colorless and greenish irregular fragments and about as many red, yellow, and brown pieces. Violet-brownish colors are rarer. Some of these glasses are homogeneous. Glasses containing vesicles, mineral fragments, and flow structures are more frequent than in group 1. Minute Fe spherules are rather frequent in this kind of glass. Devitrified glass fragments with dendritic and skeletal crystals have been frequently found in the breccias.

Microprobe analyses of 13 rounded glass bodies (group 1) and 26 glass fragments (group 2) showed a broad

Table 1. Refractive index n_D, density d, and anorthite (An) content of lunar diaplectic plagioclase glasses.

No.	An (mole percent)	n_D	d
1	74	1.5620	2.650
2	75	1.5651	
3	75	1.5675	2.653
4	83	1.5702	
5	86	1.5709	
6	86	1.5720	
7	86	1.5760	2.673
8	88	1.5747	2.684
9	88	1.5762	
10	89	1.5716	
11	89	1.5772	
12	89	1.5797	2.684
13	91	1.5802	2.684
14	93	1.5807	