The Clementine Mission

– Initial Results from Lunar Mapping

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Abstract Clementine was a mission designed to test the space-worthiness of a variety of advanced sensors for use on military surveillance satellites while, at the same time, gathering useful scientific information on the composition and structure of the Moon and a near-Earth asteroid[1]. Conducted jointly by the Ballistic Missile Defense Organization (BMDO, formerly the Strategic Defense Initiative Organization) of the US Department of Defense and NASA, Clementine was dispatched for an extended stay in the vicinity of Earth's moon on 25 January 1994 and arrived at the Moon on 20 February 1994. The spacecraft started systematic mapping on 26 February, completed mapping on 22 April, and left lunar orbit on 3 May. The entire Clementine project, from conception through end-of-mission, lasted approximately 3 years.

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1. The Clementine mission and lunar exploration

The pressing need for global mapping of the Moon, by a variety of remote-sensing techniques, has been stressed repeatedly in every lunar science report for the last 20 years (e.g. Refs. 2 & 3). The Clementine mission began this task. Global mapping of the Moon is one element of a scientific strategy for lunar exploration. Such a strategy includes additional sensing from orbit, surface networks and automated rovers, reconnaissance sampling of carefully selected targets, and detailed human exploration of complicated geological sites[2]. Clementine obtained the first global digital image data set for the Moon. The imaging sensors were equipped with a variety of filters[1,4] selected to optimise the geological value of the multispectral data. Topographic profiles derived from LIDAR laser altimetry have permitted the construction of the first global topographic map of the Moon, a product that will greatly improve our knowledge of lunar processes and history. Although not carrying X-ray or gamma-ray spectrometers for chemical mapping, significant chemical information can be obtained from multispectral imaging data (e.g. Ti abundance from ratio of 415/750 nanometres (nm); Refs. 5 & 6). It is important to view the Clementine mission in the proper perspective; while not completely satisfying our scientific needs for lunar global mapping, the mission is an impressive beginning towards obtaining such a data set.

Clementine mapped the Moon in 11 spectral bands in the visible and near-IR[1]; although surface resolution of the image data varies because of the spacecraft's elliptical orbit, the average resolution is about 200 m/pixel. The LIDAR instrument made topographic profiles by taking 100 m spot ranging measurements of about 50 m precision at 2 km intervals; the 5-hour orbital period of the spacecraft ensured that adjacent orbital profiles would be spaced by about 2.5° of longitude (about 70 km at the chosen perilune latitudes of ±30°). In addition, the LIDAR imager obtained selected high-resolution images (~20 m/pixel), either as long contiguous strips in a single colour, or shorter, multi-colour images, in up to 4 colours[1,4]. A thermal IR imager obtained selected broadband images in the 8000–10 000 nm region at about 70 m/pixel resolution.

2. The sensors, mission, and data sets

Clementine was a small (140 kg), three-axis-stabilised spacecraft that carried a variety of advanced sensors spanning several wavelengths. The UV-VIS camera covers the spectrum from 250 to 1000 nm. It is a CCD framing imager that contains a six-position filter wheel; selected filters have bands centred at 415, 750, 900, 950 and 1000 nm, and a broadband filter. A near-IR CCD imager covers the spectrum from 1000 to 2800 nm, with six filters at 1100, 1250, 1500, 2000, 2600 and 2780 nm. Collectively, these two instruments make up an 11-channel imaging spectrometer that mapped the surface composition of the Moon. In addition to acquiring such multispectral data, Clementine also carries an imaging LIDAR, which operated as both a high-resolution colour imager (typical resolution about 20 m/pixel) and as a laser altimeter whenever the spacecraft was closer than 640 km to the Moon. A broadband, mid-IR imager (8000–10 000 nm) obtained selected images of the Moon at a resolution of about 20 m/pixel.

Clementine was launched on a Titan II booster from the US Air Force's Vandenberg Launch Facility in California on 25 January 1994. After a day or so in Earth orbit, its kick motor sent Clementine to the Moon via two highly eccentric 'phasing orbits', each having its apogee near the lunar orbital distance; this 'slow boat' route to the

Moon gave Clementine a seven-day launch window, while at the same time lowering the total delta-V requirements for lunar orbit insertion. Clementine mapped the Moon from an eccentric polar orbit (about 400 by 8300 km). For the first month, the spacecraft perilune was near 30° south latitude; a phasing burn moved the perilune point to 30° north latitude for the second month's mapping. In two months of mapping, Clementine imaged the entire Moon in 11 spectral bands and obtained laser-ranging altimetric data for the Moon from 70° north to 70° south latitude.

During the course of its lunar mapping, Clementine returned over 2.5 million images of the Moon from all mission sensors, over 300 topographic profiles covering the entire Moon, and over 1000 h of radio tracking data that permit us to resolve the lunar gravity field at surface resolutions of a few hundred kilometres. Sensors met or exceeded expectations, providing us with a global, comprehensive data set for the Moon.

After mapping the Moon, Clementine departed for a flyby of the asteroid 1620 Geographos on 3 May 1994. After a few days, while rehearsing the data-collection sequence for the asteroid flyby, a software fault resulted in the firing (until fuel depletion) of the attitude-control thrusters. The spacecraft was spun up to over 80 rpm and could not be de-spun. Thus, the asteroid portion of the mission was cancelled. After flying near the Moon on 20 July 1994, Clementine went into solar orbit; it is hoped that renewed contact with the spacecraft can be established, in which case we will collect engineering data to Earth so that we can monitor the health and degradation of its sensors in a deep-space, hard-radiation environment.

3. Initial science results

Over the course of 71 days in lunar orbit, Clementine systematically mapped the 38 million square kilometres of the Moon in eleven colours in the visible and near-infrared parts of the spectrum. In addition, the spacecraft took tens of thousands of high-resolution and mid-infrared thermal images, mapped the topography of the Moon with a laser-ranging experiment, improved our knowledge of the surface gravity field of the Moon through radio tracking, and carried a charged-particle telescope to characterise the solar and magnetospheric energetic particle environment. We have had our first view of the global colour of the Moon, identifying major compositional provinces, studied several complex regions, mapping their geology and composition in detail, measured the topography of large, ancient impact features, including the largest (2500 km diameter), deepest (more than 10 km) impact basin known in the Solar System, and deciphered the gravity structure of a young basin on the limb of the Moon, finding that a huge plug of the lunar mantle is uplifted below its surface.

The images from Clementine constitute the first global digital data set we have for the Moon. The Science Team advised the project on the selection of colour filters for the two principal mapping cameras: the UV-VIS camera (sensitive to light in the visible part of the spectrum, from about 300 to 1000 nm) and the near-IR camera (which collects light in the near-infrared spectrum, from about 1000 to 2800 nm). The colour of the Moon in the visible to near-infrared part of the spectrum is sensitive to variations in both the composition of surface material and the amount of time material has been exposed to space. The Clementine filters were selected to characterise the broad lunar continuum and to sample parts of the spectrum that are known to contain absorption bands diagnostic of iron-bearing minerals. By combining information obtained through several filters, multispectral image data are used to map the distribution of rock and soil types on the Moon.

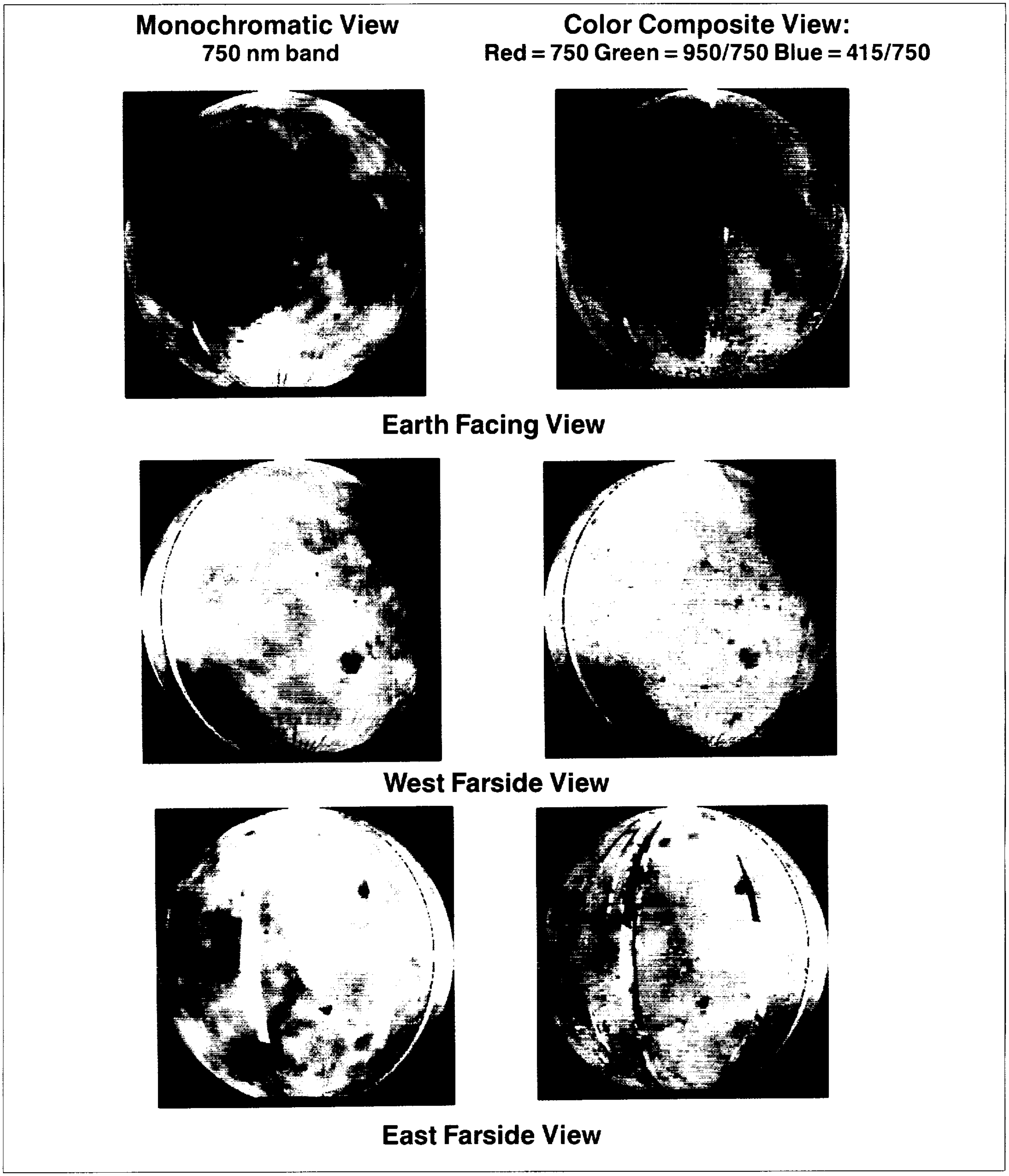


Figure 1. Clementine global colour ratio images of the Moon.

One of the major scientific goals of the Clementine mission was to map the colour of the Moon in 11 different wavelengths in the visible and near-infrared parts of the spectrum. The filter colours of the Clementine cameras were carefully chosen to depict those parts of the lunar colour that have compositional meaning. In our first look at the global colour, each image made by the UV-VIS sensor in three of its five wavelengths (415, 750 and 950 nm) has been reduced to a single pixel, based on its average brightness value; these pixels have been made into a picture of the Moon at very low resolution (about 50 km/pixel). The pictures show the albedo (brightness at 750 nm) and colour of the Moon from three aspects: the Earth-centred view (near side) with a 0° central longitude, and two far-side views with 120°E and 120°W central longitudes. The colour images have been made by assigning primary colours to the relative reflectance values and their ratios obtained through various filters, resulting in a map showing the compositional variation of the Moon

(Image processing by ACT Corp.)

Clementine was successful in systematically mapping the Moon in these 11 colours at an average surface resolution of about 200 m/picture element. Our initial examination of the data attests to its excellent quality. We have completed a preliminary look at the Clementine data on a global basis[7] by reducing the resolution by a factor of several hundred, allowing the immense data volume to be easily manipulated (Fig. 1). Several major compositional provinces are evident, including the volcanic lavas of the maria (the dark regions of the Moon), young and fresh craters, and the immense South Pole-Aitken basin, a compositional anomaly on the far side of the Moon. Major compositional provinces in the highlands are evident. The large dark red-grey region on the far side is the South Pole-Aitken basin, an ancient impact feature that apparently contains rocks of distinct composition[7,8]. A newly discovered compositional anomaly on the east limb of the Moon (pink area near centre of 120°E image) may be related to ancient flows of lavas. The colour picture shows that very high titanium lavas (deep blue and cyan colours) appear to be largely confined to the Oceanus Procellarum, Mare Imbrium, and Mare Tranquillitatis areas (near side). These views of the Moon in three colours only hint at the scientific richness contained within the Clementine global data in eleven colours in the visible and infrared parts of the spectrum.

Preliminary studies of areas of already-known geological complexity allow us to identify and map the diversity within and between geological units, which have both impact and volcanic origins. An example of the quality of the multispectral mapping data is shown by the mosaic of the Aristarchus Plateau[9] (Fig. 2). The Aristarchus Plateau is a rectangular, elevated crustal block about 200 km across, surrounded by the vast mare lava plains of Oceanus Procellarum. Clementine altimetry shows that the plateau is a tilted slab, sloping down to the northwest, that rises more than 2 km above Oceanus Procellarum on its southeastern margin. The plateau was probably uplifted, tilted, and fractured by the Imbrium basin impact, which also deposited hummocky ejecta on the plateau surface.

The plateau has experienced intense volcanic activity, both effusive and explosive. It includes the densest concentration of lunar sinuous rilles, including the largest known, Vallis Schröteri, which is about 160 km long, up to 11 km wide, and 1 km deep. The rilles in this area begin at 'cobra-head' craters, which are the apparent vents for low-viscosity lavas that formed the rilles. These and other volcanic craters may have been the vents for a 'dark mantling' deposit covering the plateau and nearby areas to the north and east. This dark mantling deposit probably consists primarily of iron-rich glass spheres (pyroclastics or cinders), and has a deep-red colour on this image (Fig. 2). Rather than forming cinder cones as on Earth, the lower gravity and vacuum of the Moon allows the pyroclastics to travel to much greater heights and distances, thus depositing an extensive regional blanket.

The Aristarchus impact occurred relatively recently in geologic time, after the Copernicus impact but before the Tycho impact. The 42 km diameter crater and its ejecta are especially interesting because of its location on the uplifted southeastern corner of the Aristarchus plateau. As a result, the crater ejecta reveal two different stratigraphic sequences: that of the plateau to the northwest, and that of a portion of Oceanus Procellarum to the southeast[9,10]. This asymmetry is apparent in the colours of the ejecta as seen in this image, which is reddish to the southeast, dominated by excavated mare lava, and bluish to the northwest, caused by the excavation of highlands materials in the plateau (Fig. 2). The extent of the continuous ejecta blanket also appears asymmetric: it extends about twice as far to the north and east as in other

Figure 2. Multispectral mosaic of the Aristarchus Crater and Plateau.
About 500 Clementine images acquired through three spectral filters (415, 750 and 1000 nm) have been processed and combined into a multispectral mosaic of this region (latitude 18°–32°N, longitude 42°–57°W). Shown here is a colour-ratio composite, in which the 750/415 nm ratio controls the red-channel brightness, its inverse (415/750 nm) controls the blue, and the 750/1000 nm ratio controls the green. Colour ratios serve to cancel out the dominant brightness variations in the scene, which are caused by albedo variations and topographic shading, thus isolating the colour differences related to composition or mineralogy. This mosaic covers only 0.4% of the lunar surface in three spectral bands, whereas the complete Clementine data set covers nearly 100% of the Moon in 11 spectral bands. This dataset will be invaluable for mapping the geology of the Moon and planning future exploration and utilisation of lunar resources
(Image processing by US Geological Survey, Flagstaff, Arizona)

directions, approximately following the plateau margins. These ejecta lobes could be caused by an oblique impact from the southeast, or it may reflect the presence of the plateau during ejecta emplacement.

The Clementine multispectral data will enable us to reconstruct the three-dimensional composition and geologic history of this region. In this colour-ratio composite, fresh highlands materials are blue, fresh mare materials are yellowish, and mature mare soils are purplish or reddish. The subsurface compositions, buried beneath a few metres or tens of metres of pyroclastics or Aristarchus ejecta, are revealed by craters which penetrated the surface layers, and by steep slopes such as those along the walls of the rilles (Fig. 2). From this mosaic, we can see that the plateau is composed of a complex mixture of materials, but that the rilles formed primarily in lavas, except for the cobra-head crater of Vallis Schröteri, which formed in highland materials[9].

In addition to compositional data from the images, Clementine has allowed us to see either previously unknown regions of the Moon or known areas from a different and unique perspective, in both cases yielding new insights into lunar evolution. The Science Team has completed a mosaic of the South Polar region of the Moon (Fig. 3), using over 1500 images obtained during the systematic mapping of the poles during the first month orbiting the Moon[11]. This mosaic has shown us a previously unmapped portion of the Moon near the pole, south of the Orientale basin, in detail. The impact basin Schrödinger (75°S, 134°E, at mosaic edge near 4 o'clock position) is a two-ring basin, about 320 km in diameter. Clementine images have clarified the geological relations of Schrödinger; it is now recognised to be the second youngest impact basin on the Moon, younger than the great Imbrium basin on the near side, but older than the Orientale basin, as shown by the occurrence on Schrödinger of secondary craters formed by flying debris from the Orientale impact. The centre of Schrödinger is flooded by lavas; these lavas are older than the crater Antoniadi (69°S, 172°W; 135 km diameter, at mosaic outer edge near 6:30 position), as shown by the scoring of the lava surface by Antoniadi secondary craters. Finally, a volcanic vent seen in the floor of Schrödinger is one of the largest single explosive volcanoes on the Moon; its dark ash deposit overlies the secondary craters of Antoniadi, thus indicating that it is significantly younger than lavas filling the basin[11].

A striking result from this new perspective (Fig. 3), evidenced by an extensive region of shadow, is the discovery of a large depression centred very near the South Pole, almost certainly an ancient impact basin about 300 km in diameter[11]. Its significance lies in its geographic position: because the rotation axis of the Moon is nearly perpendicular to its plane of orbit around the Sun (spin axis inclination 1.5°), this dark region near the pole may never receive any sunlight. If so, it is very cold in these regions, possibly only about 40°C above absolute zero (−273°C). It has been suggested that water molecules, added to the Moon from impacting comets, may find their way into these 'cold traps' and, over billions of years, accumulate in significant amounts[12]. Thus, an experiment was improvised during the mission to beam radio waves into the polar areas and receive the scattered radio signals on the large antennas of NASA's Deep-Space Network. This 'bistatic radar' experiment was designed to look for echoes that are diagnostic of water-ice deposits. These data continue to be analysed; no specific results can be reported at this time[1].

The laser-ranging data from Clementine have allowed us to see the large-scale topography (or relief) of the lunar surface on a nearly global basis[13] (Fig. 4). A striking result from this experiment is the confirmation of the existence of a population

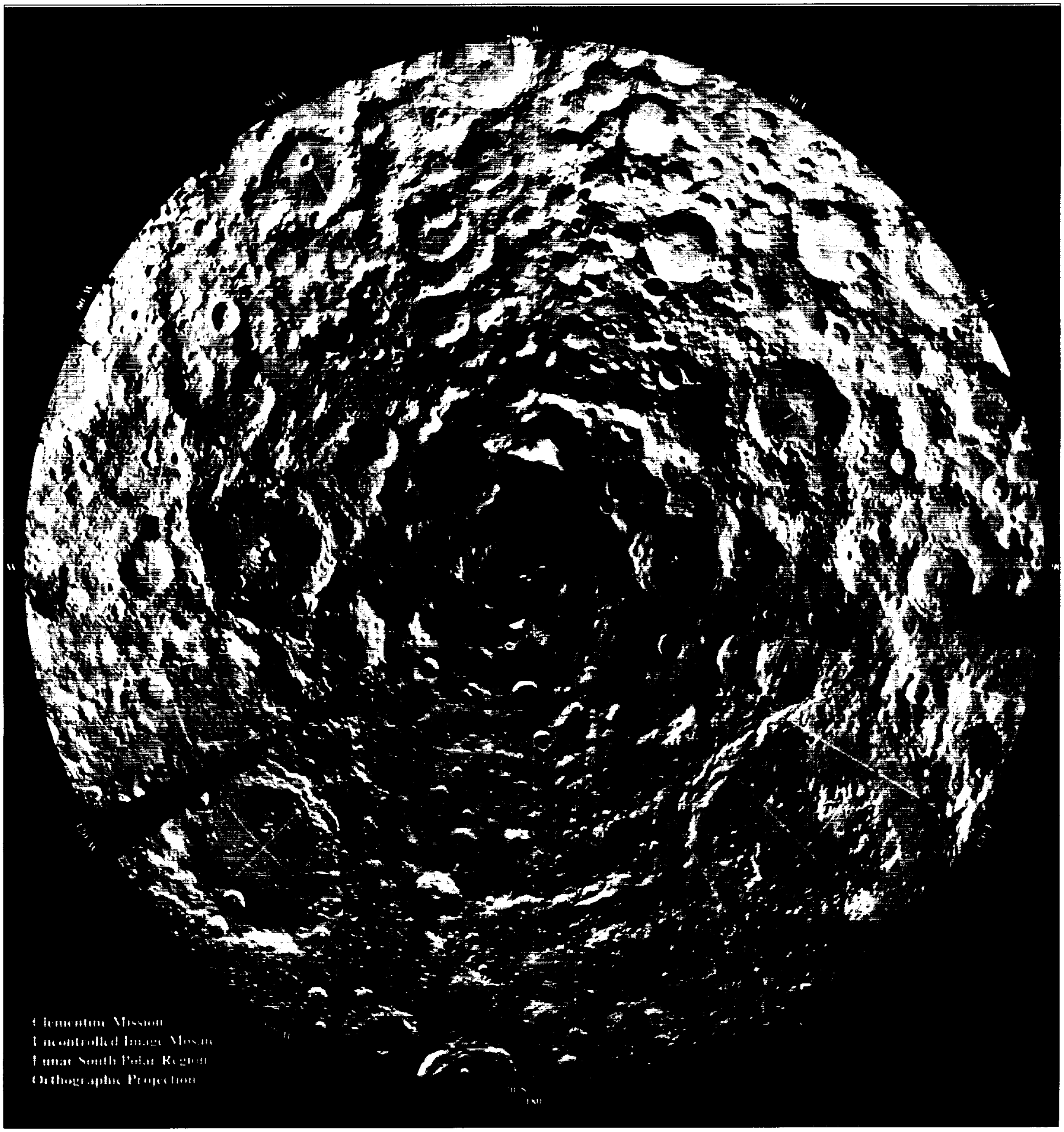


Figure 3. Clementine mosaic of the south pole region of the Moon.
This mosaic is composed of 1500 Clementine images taken from a red filter of the south polar region of the Moon; these images were taken during the first month of systematic mapping. The top half of the mosaic faces Earth. Clementine has revealed what appears to be a major depression near the south pole (centre), evidenced by the presence of extensive shadows around the pole. This depression is probably an ancient basin formed by the impact of an asteroid or comet. A significant fraction of the dark area near the pole may be permanent shadow and sufficiently cold to trap water of cometary origin in the form of ice. The mosaic displays a rich variety of geological relations, the deciphering of which will take lunar scientists many years
(Image processing by US Geological Survey, Flagstaff, Arizona)

of very ancient, nearly obliterated impact basins, randomly distributed across the Moon. These basins had been postulated on the basis of obscure circular patterns on poor-quality photographs; Clementine laser ranging has provided dramatic confirmation of their existence, including their surprising depth, ranging from 5 to 7 km, even for the most degraded features[14]. Gravity data obtained from radio tracking of Clementine indicate that these great holes in the Moon's crust are compensated by plugs of dense rocks far below the surface; such dense rocks are probably caused by structural uplifting of the mantle (the iron- and magnesium-rich layer below the low-density, aluminum-rich crust) beneath these impact basins[13]. Finally, Clementine laser-ranging data have shown us the dimensions of the largest confirmed basin on the Moon, the 2500 km-diameter South Pole-Aitken basin (Fig. 4): this feature has an average depth of over 10 km, making it the largest, deepest impact crater known in the Solar System[14].

The Charged Particle Telescope on Clementine observed a large burst of particles from the Sun during the period of 20–24 February of this year. It also monitored several additional low-energy particle bursts of magnetospheric origin over the course of the mission[1]. These data will be combined with observations from many additional spacecraft now operating in Earth–Moon space to observe and characterise the plasma environment from many different vantage points.

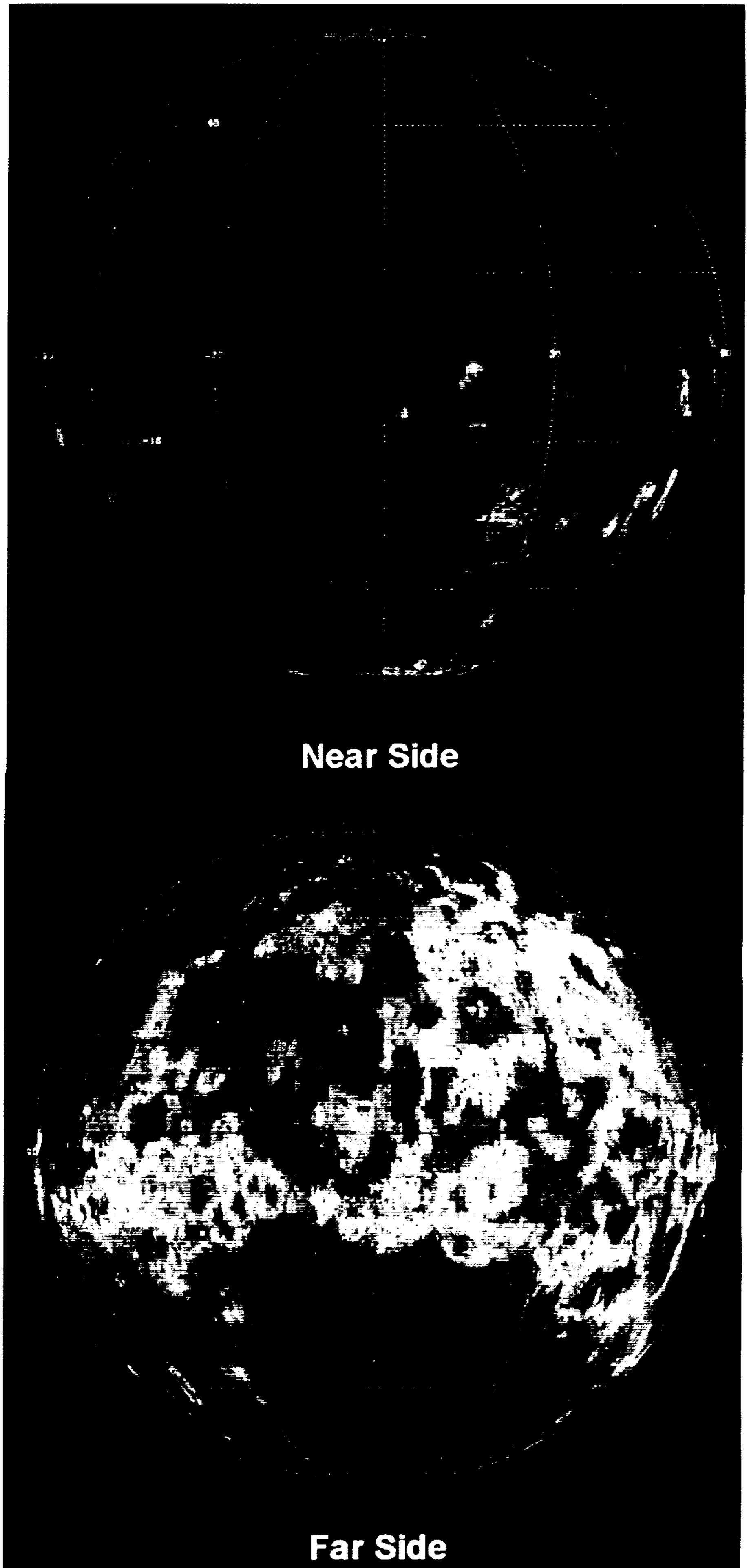
4. What will Clementine data tell us about the Moon?

The scientific significance of the lunar data set from Clementine is immense. For the first time, we have global, multispectral image data (with consistent viewing geometry, resolution, and lighting conditions) for an entire body of planetary dimensions. From the Apollo and Luna programmes, we also have lunar rock and soil samples of known geological context. Such a data set does not exist for any other object in the Solar System, including the Earth. With Clementine data for the Moon, we begin a new era in the exploration of the geology of the planets using global multivariable data sets. On the basis of our initial look at the Clementine data, such a powerful analytical technique will give us new insights into how the Moon has evolved over its protracted and complex history.

After the Clementine mission, we will possess the data needed to construct a global Digital Image Model (DIM) of the Moon. These data are augmented by both the global laser altimetry and the global geodetic control provided by analysis of the imaging data which, when tied to the Apollo data, should permit knowledge of the true positions of lunar-surface features in inertial space to within a few hundred metres. Moreover, during the post-mapping phase, large regions of the western near side and limb of the Moon were imaged in stereo. Thus, maps of the Moon made from Clementine data will enable studies of regional history and permit us to decipher the processes of volcanism, tectonism, and impact that have shaped lunar history. In a supporting mode, the global DIM will serve as a base to overlay other data; the geological context of the multispectral data must be understood to interpret such data properly.

From the combined visible and near-IR cameras, we will have a global colour map from which we can interpret the distribution of rock types on the Moon. At a minimum, we will be able to recognise and discriminate between the absence of mafic minerals (pure feldspar), and the presence of orthopyroxene, clinopyroxene, and olivine, as has been done for the near side of the Moon from Earth-based data (e.g. Ref. 15). Thus we can distinguish, on a global basis, the distribution of anorthosite,

Figure 4. Clementine global laser altimetry. Image showing the global topographic map of the Moon; colours represent 1 km contour intervals. The Moon shows a much greater range of topographic relief than had been previously believed, ranging from about +7 km to −9 km elevation in reference to a uniform sphere of 1738 km radius. Note that the two hemispheres of the Moon are distinctly different, with the near side being smoother and at nearly the lunar mean elevation (green). The far side, however, displays a much wider variation in relief, largely because of the South Pole-Aitken basin, centred on the far side at 60°, 180°
(Image processing by Lunar and Planetary Institute, Houston)



'noritic' rocks, olivine-bearing rocks (dunites and troctolites), and gabbros. For mare deposits, visible colour mapping can classify the mare in terms of Ti abundance[5], an element that can be used to estimate the distribution of solar-wind hydrogen, an important lunar resource[16].

Combined with our knowledge of cratering and the use of basins as probes of the crust, these data will permit us to reconstruct the composition and petrologic structure of the crust in three dimensions. We can address the question of the existence of a magma ocean[2,17], the nature of Mg-suite magmatism, the history and extent of ancient KREEP and mare volcanism[17], the compositional diversity of mare units, and the effects of cratering on the composition of the lunar surface. Topographic data from the LIDAR ranger combined with spectral information will allow us to model and understand the dynamics of large impacts, e.g. the problem of depth of excavation for basin-sized impacts[18].

With high-resolution data from the LIDAR imager, we can study surface processes and compositions in greater detail. Many mare units display significant heterogeneity and colour imaging from Clementine can map different colour units, some of which are perhaps related to individual mare flows. Images of crater walls and central peaks can not only provide high-resolution compositional data, but permit us to understand better the geological setting and processes that have affected given regions, information that may prove critical to the proper interpretation of the regional compositional information. Finally, the high-resolution imaging can be used to make detailed geological studies of areas of high scientific interest (e.g. Ref. 11).

5. Conclusion

The Clementine mission has been a boon to the study of the geological processes and history of the Moon. This mission is an important first step in a renewed effort to explore the fascinating and complex story of our nearest planetary neighbour. Whilst giving us many new insights into lunar evolution, additional missions are necessary in order to completely understand the Moon's complex and protracted history.

6. Acknowledgments

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