by Everly Driscoll

A look inside the moon

Three years of study indicates the moon is warm-to-hot in the interior, chemically very complex and structurally layered

Amazing, in lunar science, how quickly new views become orthodox and how slowly some orthodox views are relinquished.

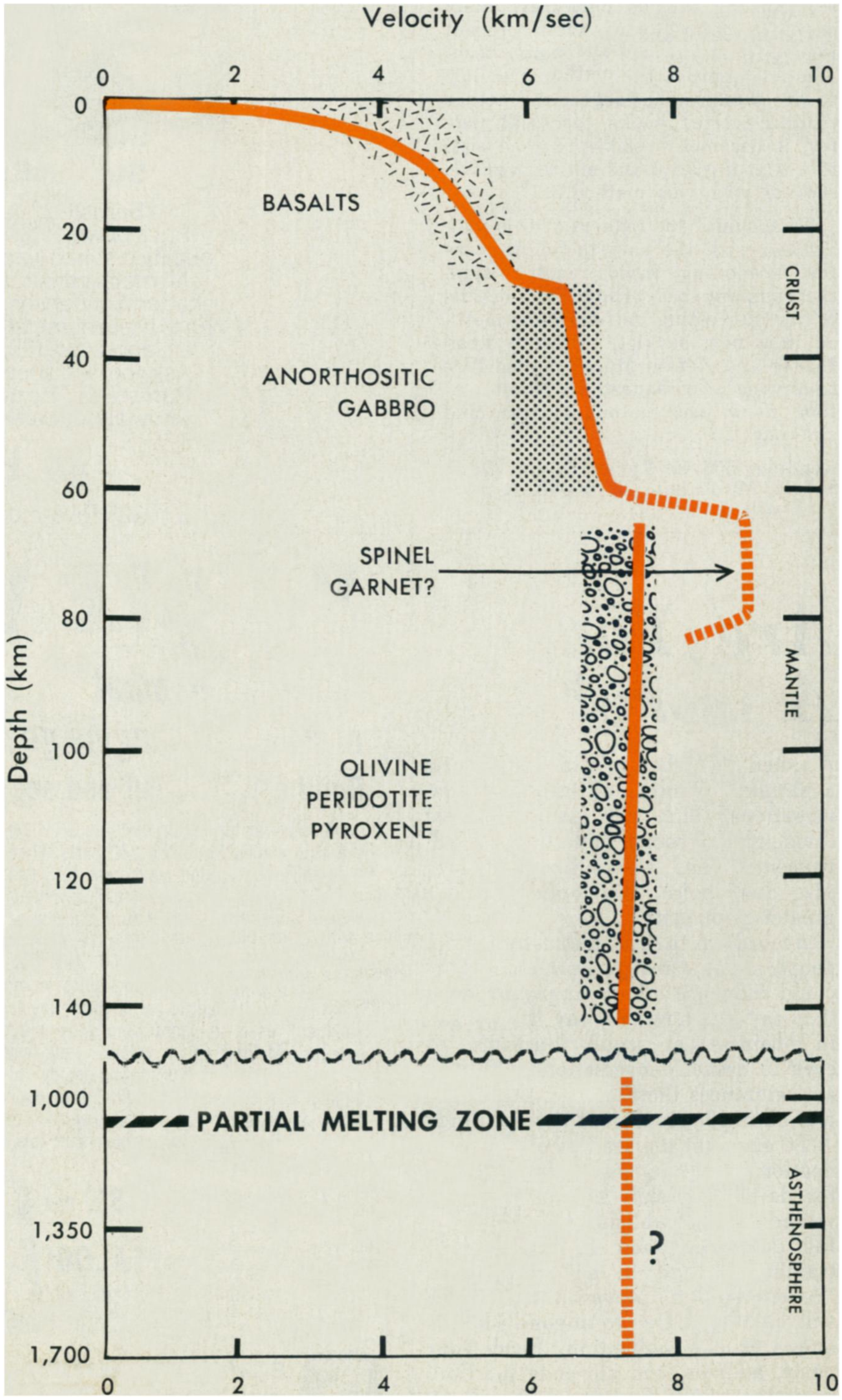
The most significant orthodox view to begin changing is the idea the moon is now, and has forever been, relatively cold. Many scientists are now talking about a warm interior for the moon. Some bravely say "hot."

Knowledge of the temperature conditions in the moon is basic to unraveling the moon's evolution. From thermal models and from the chemical composition of the surface material (which presumably has flowed to the surface), geochemists weave their way back to the primeval moon. Heady stuff, but it's happening.

After Apollos 11 and 12 the moon's interior was considered to be about 800 degrees C. This may seem hot, but for a planetary interior it is regarded as relatively cool. These temperatures were derived from measurements of electrical conductivity, and were generally accepted, although there were some scientists who talked of temperatures as high as 1,100 degrees. Scientists thought the moon was solid. Most minerals at depths greater than 500 kilometers in the moon could remain solid up to temperatures of about 1,400 degrees C. At 1,500 degrees they would begin to melt, and at 1,600 to 1,700 degrees all minerals would be completely molten.

Now magnetometer people, such as Palmer Dyal and Curtis W. Parkin of the NASA Ames Research Center and the University of Santa Clara, are talking about temperatures in the moon increasing to about 1,400 to 1,600 degrees C. down to depths of 1,100 kilometers. This is about half as hot as the earth's interior at that depth. Marcus Langseth has found that the flow of heat from the moon's interior today is about half that of the earth's. The baffling remanent magnetic field frozen in the moon's outer shell requires a much more complex thermal history than anyone envisioned three years ago (SN: 5/27/72, p. 346).

The seismic data and the enormous differentiation of the moon rocks also give hints about the moon's interior. From the velocity and paths of seismic waves through the moon, geophysicists can tell something about the temperatures (whether the material is molten or solid), the layering and the chemical composition of the interior. Gary Latham of the University of Texas' earth and planetary sciences division in Galveston has been analyzing the signals from four passive seismometers at the sites of Apollos 12, 14, 15 and 16. Thousands of moon quakes and mete-



Davida Daemon from M. N. Toksöz

Seismic waves reveal a crust, a mantle and a deep, partially molten zone.

orite impacts, as well as a few jolts from the crashes of manmade objects, have been recorded. The most sensitive station, Apollo 16, recorded an average of 3,200 events last year.

Latham sees strong evidence for a crust, a mantle, and then a very active zone at 1,000 to 1,100 kilometers depth in the moon where temperatures may approach the melting point (SN: 11/18/72, p. 324). The first major discontinuity occurs between 55 and 65 kilometers, which Latham interprets as the crust-mantle boundary. Team member M. Nafi Toksöz of the Massachusetts Institute of Technology reports that the crust is layered in some areas. The upper 20 kilometers beneath the maria are basaltic. Beneath this layer, seismic velocities are consistent with anorthositic gabbro rocks. The thickness of the crust may vary. Some suggest it is much thicker on the far side. One signal at one station only indicates a high velocity zone between 60 and 80 kilometers depth. This is very tentative and the data will have to be verified. But if the increase is real, it could mean a thin layer of spinel, or possibly garnet, between the anorthositic crust and the silicate mantle.

From 65 to 1,000 kilometers the seismic velocities are fairly constant. The composition of the mantle is still in debate, but the velocities suggest a fairly homogeneous mantle with uniform density. This would not rule out a wide range of rock types which the geochemists would like in order to produce the diversity of surface rocks.

A fortuitous event occurred last summer—a large impact on the moon's far side. The compressional waves from the impact traveled through the moon to the nearside stations. But the shear waves did not. This was the first direct evidence for a molten or partially molten zone deep in the moon. (Shear waves cannot travel through a liquid.) Latham located the zone between 1,000 and 1,100 kilometers, but as yet he can't tell whether the partially molten pocket is a shell or extends to the center of the moon.

This partially molten zone may explain the occurrence of moon quakes at great depths. Most originate in 43 active zones between 750 and 1,100 kilometers. This is far deeper than earthquakes, most of which occur at depths less than 100 kilometers. The moon quakes are highly predictable and are of tidal origin. They occur monthly and peak at roughly two-week intervals coinciding with the apogee and perigee of the moon's orbit. Latham sees indications of two longer-term cycles as well: one seven-month cycle resulting from the gravitational pull of the sun and variations in the orbit of the earth-moon system; and one six-year cycle caused by gravitational influences of all the planets. Most of the energy release from the moon today is associated with all these tidal stresses.

The most exciting and puzzling aspect of the active zones is their distribution. They seem to lie in two belts—one trending north-south, the other, northeast to southwest. The belts are at least 1,000 kilometers long and 1,000 kilometers deep and do not appear to intersect (SN: 3/17/73, p. 164).

Why do the zones lie in belts? "I'm mystified," admits Latham. "We can't explain it yet." He does rule out great fracture systems, since the quakes in a given belt do not show a systematic correlation with lunar tides. The zones could be associated with residual stress from the early formation of the moon (the moon may not be completely adjusted to its gravitational field). Another possibility is that they are composed of material such as embedded blocks of iron that would cause them to have different elastic properties from the rest of the moon.

So the seismic picture shows a differentiated, layered moon with lunar basalts for upper layers in some regions, anorthositic gabbros for the crust, and a questionable layer between the crust and mantle. The velocities for the mantle are consistent with a mixture of olivine and pyroxene, and perhaps minerals such as spinel and plagioclase. Beneath the partially molten zone at 1,100 kilometers is a question mark.

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What kind of moon does one start with to get the observed moon of today? "You have to play a very fine game with condensation [from the solar nebula] and accretion models," says Toksöz. What does accretion produce? What does subsequent melting produce? A lot depends on how much of a given material melted at a given temperature and pressure within the moon. The presence or absence of water would alter the processes considerably.

"After Apollo 11," says Gerald J. Wasserburg of the California Institute of Technology, "there were still people talking about the moon as a good solar system average." But, he says, "The planets are very fractionated relative to the solar nebula. The details of these accretion processes are one of the most profound problems we must face."

To almost everyone's surprise, the moon is not a solar system average. It did not accrete from the same materials—or at least from materials in the same proportion—as the earth. Now the geochemists are busily trying to figure out how the moon accreted with less iron, more aluminum and other refractory elements and more uranium than the earth. "It ain't easy," quips one geochemist.

The surface rocks themselves show that the moon has gone through extensive differentiation. The highlands are enriched in calcium and aluminum and depleted in iron, magnesium and titanium compared with the maria. Some rocks have almost no strontium and europium; others have large amounts of these elements. Even rocks from the maria vary; basalts from the eastern maria are richer in titanium than rocks from the western maria. In general there are four broad rock types: rocks high in uranium, thorium, potassium, rare-earth elements and phosphorus; maria basalts; basalts high in aluminum; and anorthositic rocks with greater than 24 percent aluminum oxides.

Paul Gast, N. J. Hubbard and Lawrence E. Nyquist of the Johnson Space Center in Houston have come up with some *constraints*, at least, for making the layered moon. "The problem," says Gast, "is how to make all the basalts." Some basalts are high in iron and titanium compared with others; others are high in radioactive elements; still others are high in aluminum. This requires partial melting in the interior of the moon at different times (probably) and at different depths (certainly). The "orthodox" view now is that the moon's outer few hundred kilometers melted first and that melting has proceeded downward since. One of their constraints, for example, is that the very highly radioactive basalts cannot be left over from the formation of anorthosites or from the crystallization of very high aluminum basalts. The younger basalts that have higher iron-to-magnesium ratios came from liquids derived from deeper sources in the moon than the aluminum and high radioactive basalts. The source regions were richer in iron and poorer in calcium and aluminum.

Another condition necessary to produce the moon as seen now is that the outer 200 to 300 kilometers of the early moon must have consisted of a zone rich in calcium and aluminum. This is a puzzle since aluminum, for example, would be the first to condense out of the nebula, and therefore ought to be in the interior of the moon rather than the crust.

Tying all this together—the geochemistry with the seismic, magnetometer and thermal models—is the first priority of the post-Apollo era. Lunar science is not like physics, says Gast, where you can do one experiment and prove or disprove a theory. He thinks it will probably take five years—at least—to synthesize all the bits and pieces of lunar science.

Right now, says Wasserburg, "We are too close to crawling." □