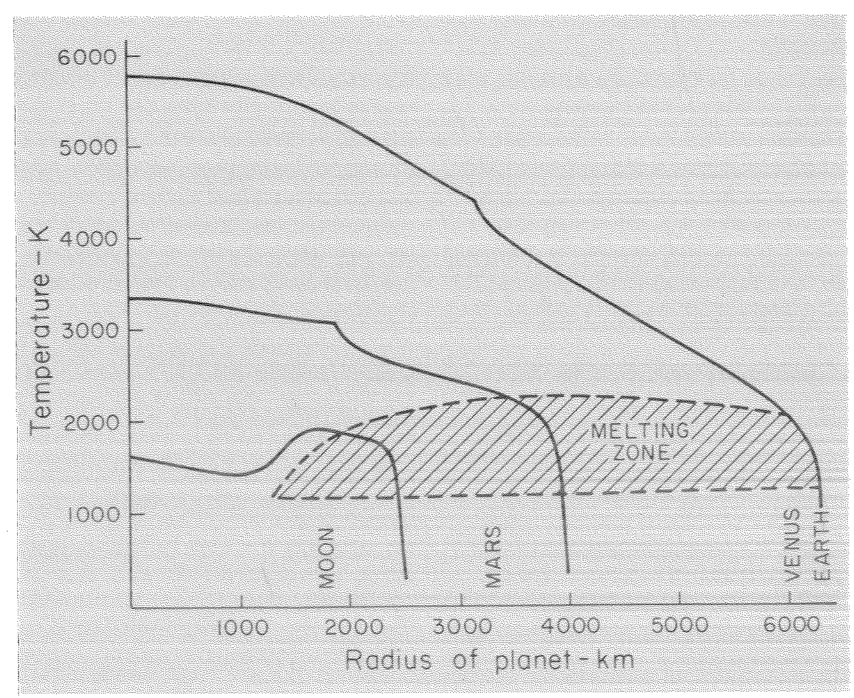
Research in Progress

As the World Churns

Rocks as old as 3.8 billion years have been found on the earth. The earth, however, is estimated to be 4.5 billion years old; where are the 4.5-billion-year-old rocks? Sunk to the bottom of a magma ocean that covered the ancient earth, says Don L. Anderson, professor of geophysics and director of the seismological laboratory.

The idea of a gigantic ocean of molten rock overlying the earth represents a radical departure from recent theories of the earth's early history. These theories generally depict a primordial earth that melted very little and remained basically unchanged from its beginnings until the present. But the chemical differences in the magmas emerging today from oceanic islands and mid-ocean ridges, along with the discontinuities that seismological data have revealed in the mantle, led to Anderson's model.

The earth's mantle, surrounding the superdense nickel-iron core, is a semi-solid region about 3000 kilometers thick on which float the tectonic plates and the thin crust. The mantle hasn't made itself very open to direct observation, but studies of



Temperatures (estimated by Associate Professor of Planetary Science David Stevenson) as a function of radius are shown for planets of various sizes. Temperatures are above the melting point in the region labeled "melting zone." The curves represent the central-to-surface temperatures of successive states of an accreting planet, the bottom one an early state (slightly larger than the moon) and the top curve the later accreted state of an earth-size planet. When a planet grows beyond about moon size, the kinetic energy of accretion is sufficient to melt material in the upper mantle. At great depth the effect of pressure increases the melting point so that the lower mantle is solid. The core is also molten because iron alloys have a low melting point.

seismic waves after large earthquakes have provided a variety of ways of mapping it. Seismic waves behave differently in two regions of the upper mantle. The layer from below the crust down to about 220 kilometers is characterized by low velocity and high attenuation of seismic waves. (This low-velocity zone was discovered in the 1940s by Caltech geophysicist Beno Gutenberg.) The waves have a harder time getting through this region than through the layer between 220 and 670 kilometers, called the transition zone, where seismic waves propagate faster and are less attenuated. At 670 kilometers there is a sharp discontinuity that is an efficient reflector of seismic energy. This is also the depth where earthquakes cease.

Anderson connects this evidence of layering in the upper mantle with geochemical findings that the concentrations of a dozen or so trace elements — including potassium, rubidium, strontium, barium, thorium, and uranium — are enriched in the mantle material emerging from "hot spots" where the magma punches up through continents (volcanoes and geothermal areas such as Yellowstone National Park) and ocean islands (Iceland, Hawaii). On the other hand, the same trace elements are depleted in the material coming out of the mid-ocean ridges forming new crust. These two types of magma are complementary; that is, if they were combined, the resulting mixture would have a pattern similar to estimates of the average composition of the earth. They might be complementary because a melt or fluid that extracted trace elements migrated from one source into the other. Anderson's analysis of how migrating materials would extract trace elements suggests that most of these elements are distributed between the two upper mantle reservoirs, which correspond to the layers between the seismic discontinuities.

The magma ocean postulated by Anderson's model would have melted from the heat of accretion as the initial nucleus of the planet, which had condensed out of the solar nebula, was bombarded by other pieces of matter. The heat generated by this accretion process (when the planet had grown beyond moon size) would have been sufficient to keep most of the outer layer continually melted. As the earth kept growing through accretion, these outer layers became inner ones and solidified because the increased pressure at greater depths also increased the melting point. All the mantle material, however, at some time would have gone through the melting process.

When it reached its present size and began to cool, the earth would have still been covered by a molten ocean 300 to 500 kilometers deep. This ocean would be capped by a thin, transient crustal layer. As it cooled, the first rocks to crystallize out of the magma would have been denser than the remaining molten rock and would have sunk. They would have continued sinking even below the floor of the molten ocean until they met the even denser material of the lower mantle. The 670-kilometer seismic discontinuity marks the bottom of this descent and the 220-kilometer demarcation its eventual top, according to Anderson's theory.

At the same time, a thin crust of less dense material would have risen to the top of the melt — like ice on water. But because this first crust would have been so fragile and the convection beneath it so violent, it would have been dragged back down and mixed back into the upper mantle. In between this thin crust and the top of the rock layer that had crystallized out earlier, would lie the last concentrated dregs of the melt, stripped out during the fractionation process. This layer would contain heavy concentrations of all those large atoms that resist crystallization, including those of heat-producing elements such as potassium, thorium, and uranium.

Anderson's model provides an explanation for the appearance of high concentrations of these elements where mantle melt oozes out from continental and oceanic hot spots. This enriched magma is coming from the shallow mantle layer above 220 kilometers characterized by seismic-wave measurements as the low-velocity zone. New crust being formed from the mantle at spreading mid-ocean ridges comes from the transition zone — the region between 220 and 670 kilometers, which would be depleted of those elements not concentrated in the early-forming crystals such as garnet. In this zone would lie the "lost" 4.5-billion-year-old rocks, fractionated as the earth formed. The oldest rocks found on the surface today would be remnants of the first crust formed after the outer layer had become strong enough and thick enough to resist being dragged back down into the hot mantle. □

Talking Back

Overcoming language barriers is not a problem solely of tourists, exchange students, diplomats, and missionaries; the barrier also exists between man and machine. Computers have heretofore been able to understand only their own languages, and while a computer language like Basic or Pascal may be easier for us to learn than French, the ability to communicate in English (or any other "human" language) would make the vast potential of computer technology much more widely accessible.

The task of teaching English to computers has brought the fields of linguistics and computer science into close alliance. At Caltech, one of a handful of institutions in this country where the field of computational linguistics is being explored, Bozena Henisz Thompson, senior research associate in linguistics, and Frederick B. Thompson, professor of applied philosophy and computer science, have been working in this area for nearly a decade. The Thompsons' research interest is in how humans — for example research teams and management staffs — communicate in problem-solving situations. Their research strategy has been to provide a similar capability between man and computer and then to use this capability as an experimental tool to investigate the nature of the communication process.

Over this last decade they have developed two English language systems — REL (Rapidly Extensible Language) and its even more articulate successor, POL (Problem Oriented Language). REL is designed as a data-base management system, intended for use by a group in a relatively narrow field maintaining large banks of data. The system itself is very broad and flexible and is not limited in vocabulary or syntax to any particular discipline; it "knows" more than raw data and can figure out fairly complex definitions and relationships. The goal of a natural language system like REL is to come as close as possible to normal human communication. The Thompsons' REL comes pretty close. Its rapid response time also makes it extremely useful, and it has already leaped beyond its original status as a research tool. For instance, IBM has already im-

Fred and Bozena Thompson converse with a Hewlett-Packard 9845.

plemented sister systems in Germany and Japan.

Bozena Thompson has applied REL in an extensive series of experiments using a real-life task — loading Navy cargo ships. She analyzed how this problem was solved in three different ways: two persons talking face to face; two persons typing out their discussions on separate but connected terminals; and a person "conversing" with a computer in REL. These controlled experiments (involving more than 100 subjects and 80,000 words) confirmed some expected differences in these modes of communication. But some quite surprising similarities also showed up, especially in sentence length and the frequency of sentence fragments. This substantiated the Thompsons' thesis that ordinary conversation exhibits definite, identifiable structural patterns, particularly when that conversation concerns a serious task.

Teaching English to computers has some features in common with translation by computer from one language to another, an undertaking that has largely been abandoned in the United States (although successful applications are being made in Europe and Canada). Bozena Thompson does not agree with the negative assessment of machine translation in this country; even though such translations may not sound natural or be stylistically elegant, they are quite adequate — and helpful — to users familiar with the subject matter. Indeed, in a study of actual users of machine translation (in Euratom and our own atomic energy communities), she found that scientists preferred computer to human translation because the machine translation was "more honest," that is, it had fewer of the distortions that the non-scientist translators tend to make for stylistic purposes.

Natural language systems store vocabularies and rules that enable the computer to analyze a query or command and then generate a program to retrieve the answer or carry out the instruction. Currently, communication between human and computer is via typewriter keyboard, but one long-range goal for natural language systems is to come as close as possible to understanding speech. In general, research in computational linguistics aims at gaining a deeper understanding of how the vast domain of knowledge that underlies human communication can be effectively stored and utilized. What distinguishes the research at Caltech is the emphasis on the experimental method, using real tasks as a primary source of insights into the underlying linguistic aspects of communication.

Linguistic problems abound. Pronouns and conjunctions are only slowly yielding to linguistic analysis. For example, in the sentence, "The lawyer approached the parking-lot attendant and demanded his car," we would assume the lawyer wanted his own car; but in "The thief approached the parking-lot attendant and demanded his car," quite another interpretation is possible. Worse yet is a sentence such as "John came up to Peter and took five dollars out of his pocket." Researchers in computational linguistics are scrutinizing how we ourselves bring to bear our moral judgment about the intentions of thieves and lawyers to determine the more likely antecedent of the pronoun. Similar problems with other forms of ambiguity resolution appear to depend on identifying the participants' common frame of reference and keeping track of it over the development of a dialogue. Surgical reports, for instance, usually end with the statement that "the patient left the operating room in good condition." While doctors would understand that the phrase refers to the person's condition, some of us might imagine the poor patient wielding a broom to clean up the mess.

What the Thompsons learned from their experiments with REL influenced the design of POL. This successor language system, for example, can identify words not in its vocabulary and cope with poor or ambiguous punctuation, spelling, or grammar from its human partner. The commercial version of POL also will not require a room full of machinery. The Thompsons now have it operating on a desk-top Hewlett-Packard computer — an enormous step in reducing the cost of such a system and making it available to the many new users that a natural language system will attract. Fred Thompson predicts that within a decade a typical professional will carry a pocket computer capable of communication in natural language.

One component of human speech that the Thompsons are still working on is phatics — utterances such as "well," "wait," or "you turkey" (all found in the actual person-to-computer protocols) that don't serve the direct purpose of communication but that keep the conversation running. They're natural, all right, but some perhaps are not all that necessary. The optimum degree of human-like behavior on the computer's part is still uncertain, but the POL-speaking computer is not likely to learn to respond in kind to a frustrated user's swearing. □