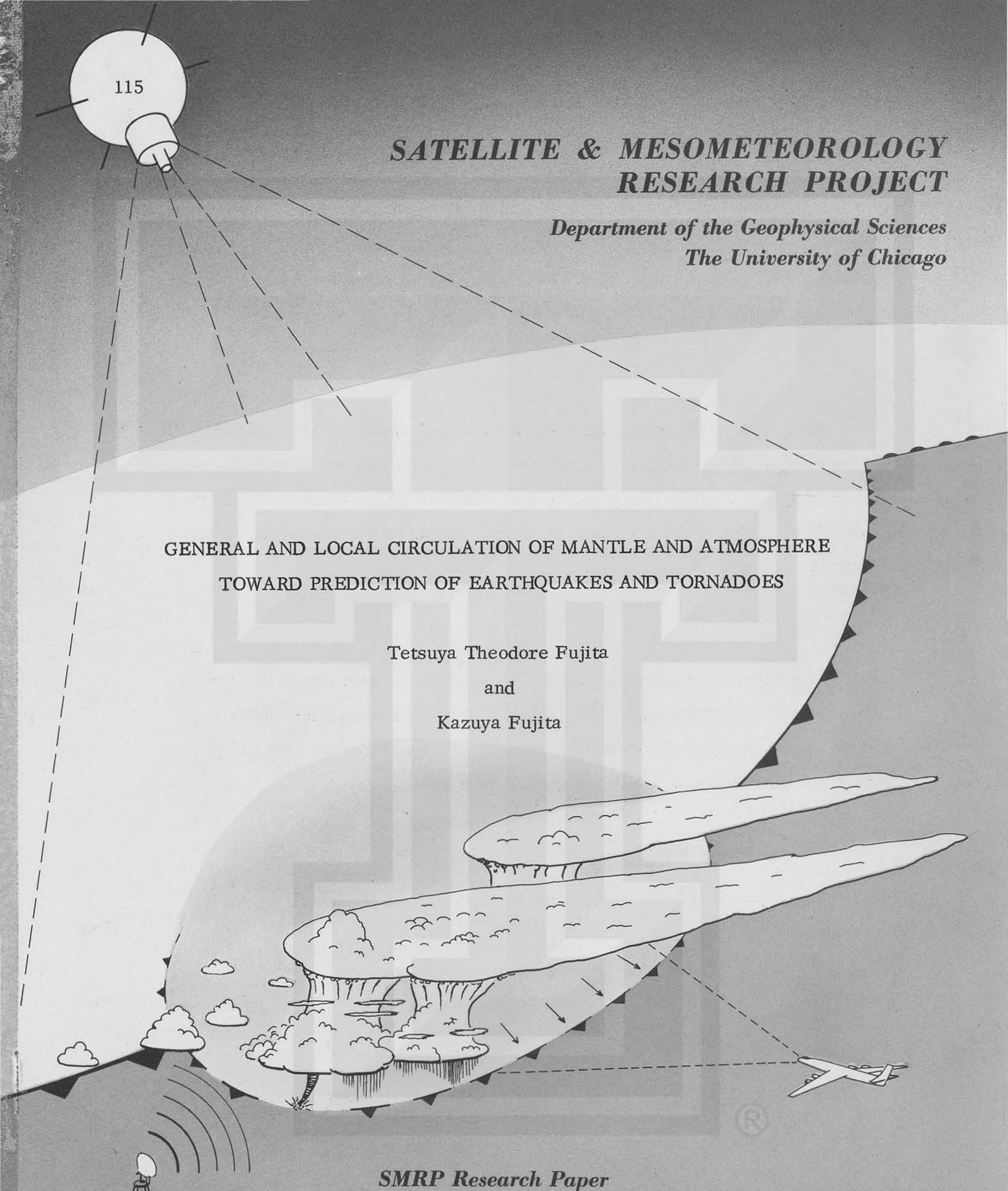

SATELLITE & MESOMETEOROLOGY RESEARCH PROJECT

Department of the Geophysical Sciences
The University of Chicago

GENERAL AND LOCAL CIRCULATION OF MANTLE AND ATMOSPHERE TOWARD PREDICTION OF EARTHQUAKES AND TORNADOES

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and

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TORNADOES and EARTHQUAKES occur when the energy stored either in the atmosphere or inside the earth's crust is released abruptly. The energy release often occurs so suddenly that even an attentive person has no time to respond effectively. The energy for the violence is stored in a rotating thunderstorm or a strained crust, which are harmless and hard to be detected.

Basic flow of the atmosphere and the mantle appears to be responsible for the energy accumulation. The most favorable locations are fronts or zones where the gradient of the flow velocity is significant. For instance, the earth's crust on both sides of the San Andreas fault is sitting on the mantle flow moving in opposite directions.

A generalized concept of "Plates" in tectonics is very similar to that of "air masses" in meteorology. The global circulation of both atmosphere and mantle may be considered essential as the ultimate source of the energy, giving rise to the occurrence of TORNADOES and EARTHQUAKES.

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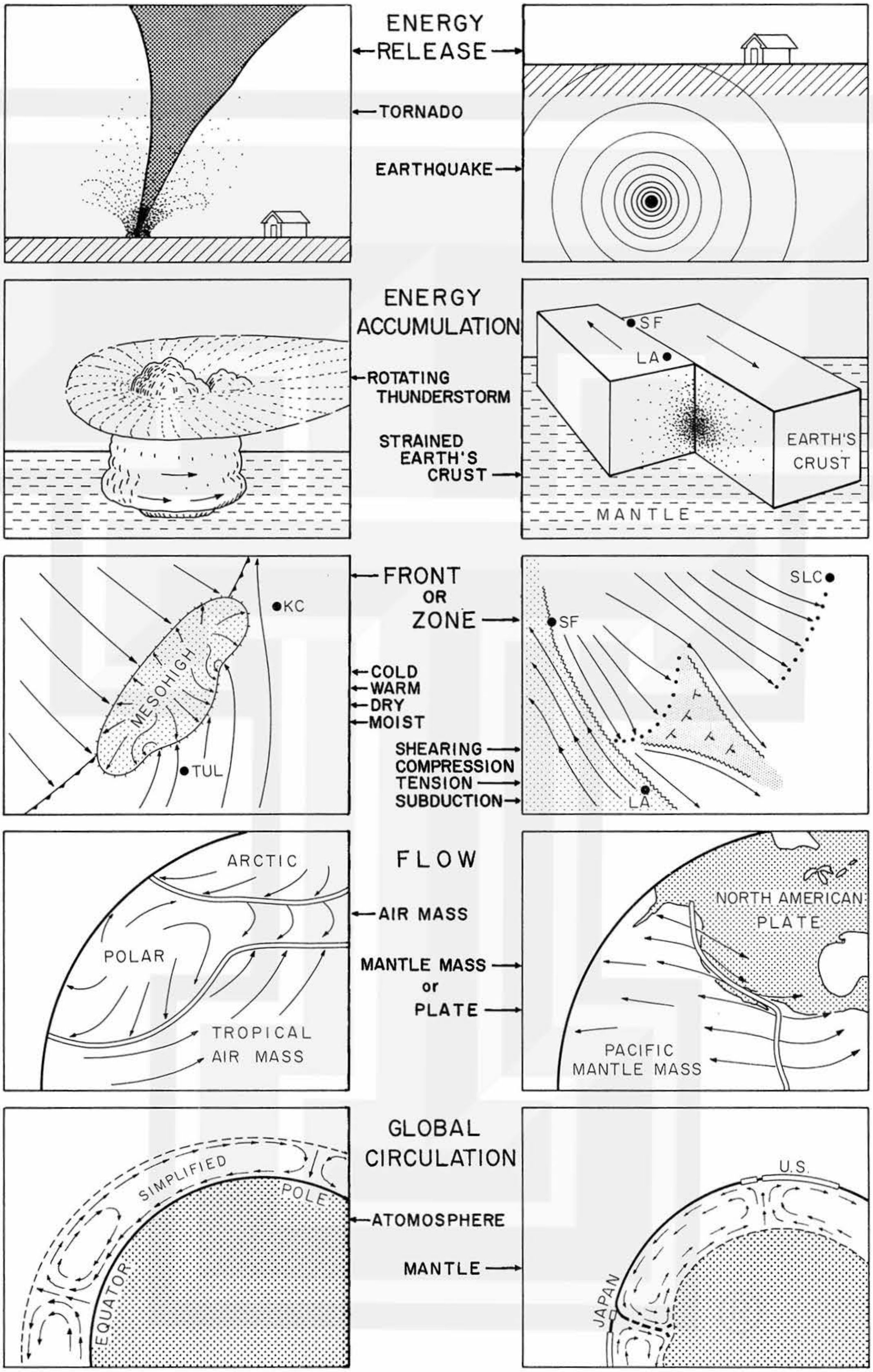

ENERGY
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TORNADO
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COMPRESSION
TENSION
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ARCTIC
AIR MASS
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NORTH AMERICAN
PLATE
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or
PLATE
PACIFIC
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GLOBAL
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SIMPLIFIED
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ATOMOSPHERE
MANTLE
U.S.
JAPAN

GENERAL AND LOCAL CIRCULATION OF MANTLE AND ATMOSPHERE TOWARD PREDICTION OF EARTHQUAKES AND TORNADOES

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and

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Earthquakes and tornadoes are the most violent disturbances created by Mother Nature. Despite the difference in the occurrence locations, above or below the surface of the earth, they are strikingly similar in various respects. The majority of these disturbances are unpredictable, especially when the exact time and location are specified. Recent studies revealed, however, that a gradual concentration of energy takes place prior to the violent release of either strain energy of the crust or kinetic energy of the atmosphere.

In an attempt to predict tornadoes, meteorologists have long been investigating storm environments which give rise to their formation and subsequent development. It does not seem to be practical to make an attempt to predict all tornadoes in the United States because their occurrence is overwhelmingly too frequent. The annual occurrence was 888 in 1971, 740 in 1972 and an estimated 1000 in 1973.

As in the case of earthquakes, not all tornadoes are alike in intensities. Some are strong but others are weak. It was only three years ago when a tornado scale devised by Fujita was experimentally applied to all U. S. tornadoes for the assessment of intensity distribution. The Fujita scale is a coarse measure of the damaging windspeed devised by connecting Beaufort force 12 with Mach number 1 in 12 non-linear steps. Statistics for the past 3 years revealed that F 3 or stronger tornadoes were only 10% of the total frequencies (see Table I).

Table I. Fujita-scale tornado windspeed (m/sec) and frequency distribution.

Fujita Scale	0	1	2	3	4	5	Total
Windspeed	17-32	33-49	50-69	70-92	93-116	117-142	
1971	183	379	232	70	22	2	888
1972	201	301	148	79	9	0	740
1973, through July	172	365	207	51	17	1	813

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[2] Graduate student of geology.

Earthquake assessment in terms of magnitude is far more advanced than that of tornadoes. The Richter-scale magnitude has been in use for over 20 years. Moreover, the magnitude scale is estimated from seismograph records based on the amplitude-distance curve. The only way to estimate the tornado intensity is to evaluate the worst damage within each tornado area. It will take years before a tornado signature of some kind, seismological, electromagnetic, or acoustic, is utilized to determine the absolute strength of tornadoes based on signature-distance curves.

Both theoretical and analytical studies of the energy transformation leading to the formation of violent tornadoes are more advanced in meteorology than in geotectonics. Within the last decade, it became evident that a violent tornado does not dip down from an ordinary thunderstorm. Instead, the parent thunderstorm is in a state of rotation prior to the tornado formation. This means that a thunderstorm stores rotational kinetic energy, preparing for its sudden release. A portion of the earth's crust accumulates and stores strain energy prior to its release in the form of an earthquake. These processes are very similar in a sense in that the atmosphere stores kinetic energy while the crust stores potential energy.

Such a form of energy must come from somewhere. The cascade of energy down to the scale of a rotating thunderstorm can be traced all the way back to the general circulation of the atmosphere. The chain of the energy flow can be explained as follows: A thunderstorm acquires rotation when it is embedded inside a field of mesoscale circulation which is one order of magnitude larger than an individual thunderstorm itself. An intense mesoscale circulation is found predominantly near a frontal zone where warm air meets cold air. An extratropical cyclone extending 1000 km or more in horizontal directions provides a most favorable playground where the cold air meets the warm air in order to spin around.

Development of the concepts and theories of general circulation during the past 50 years has clarified the mechanism by which extratropical cyclones develop by drawing energy from the general circulation of the atmosphere involving the entire globe. This means that the energy to produce a tornado cascades down all-the-way from (1) general circulation scale to (5) tornado scale by way of (2) cyclone scale, (3) front and mesoscale, and (4) thunderstorm scale. It should be noted, however, that the water vapor stored in the atmosphere behaves like fuel whenever it is given a chance to condense into numerous water droplets. The release of latent-heat provides the atmosphere with an additional energy supply which, in effect, enhances each one of these scales of motion. The ratio of enhanced and cascaded energy usually increases as the scale becomes smaller. For mesoscale or smaller circulations, the enhanced energy often becomes more significant than the cascaded one, resulting often in a feedback of energy toward larger scale atmospheric motions.

Despite such a complication in energy and circulation processes, it is absolutely necessary to understand the global circulation of the atmosphere for a better and improved prediction of tornadoes. If we apply the sequence of logic in tornado prediction to earthquake problems, it would be necessary to determine the global circulation of the mantle as well as that of the earth crust floating on the mantle under slow flowage.

Exactly as in the case of meteorology let us use the customary "hydrostatic assumption" which will permit us to determine the pressure inside the mantle below the level of isostasy. The isostasy can be achieved only by introducing a mountain root which is somewhat like the root of a floating iceberg. The ratio of the mountain height and the root depth can be computed from

$$\frac{\text{Height of Mountain}}{\text{Depth of Root}} = \frac{\text{Density of Mountain}}{\text{Density of Mantle minus root}} = \frac{2.7}{0.5} .$$

This ratio is about 5, meaning that the root must be at least 5 times the mountain height.

It is of extreme importance to realize that the vertical distribution of the density inside the crust varies from location to location. The young sediment is the lightest, followed by the upper crust and the lower crust which sits on top of the Moho-discontinuity. Within these layers the density increases from 2.3 to about 2.9 g/cm^3 while the mantle density is about 3.4.

As in the case of meteorology, hydrostatic assumption cannot be applied in the vicinity of subduction zones which are characterized by a strong mass convergence. When a small-scale motion is considered, we must also abandon the hydrostatic assumption. Therefore, a mountain root is a product of the joint effort of individual ridges, each of which pushes the underlying crust downward. It is very unlikely that a final equilibrium can ever be reached, because the horizontal flow of the mantle undercutting the mountain root will generate an everlasting cycle of the crust movement.

HOT-TONGUE OF MANTLE FLOW

When a thunderstorm reaches its mature stage, with heavy rain falling beneath the cloud, rain-chilled cold air rushes out at high speed toward the storm's advancing direction. A tongue of the cold-air outflow accompanied by gusty winds travels through a considerable distance even after the dissipation of the parent thunderstorms. Frequently seen along the leading edge of a cold tongue is an arc of small clouds called the arc cloud (see Fig. 1). Since large-scale views of clouds became available from satellite platforms, Mr. Vincent Oliver of the National Environmental Satellite Service has attempted to search for arc clouds which might not be recognized unless one looks for them. The attempt was successful. Now he finds arc clouds in satellite pictures wherever thunderstorms are in progress or were in existence. It is Mr. Oliver's research and development that triggered our research early in 1973.

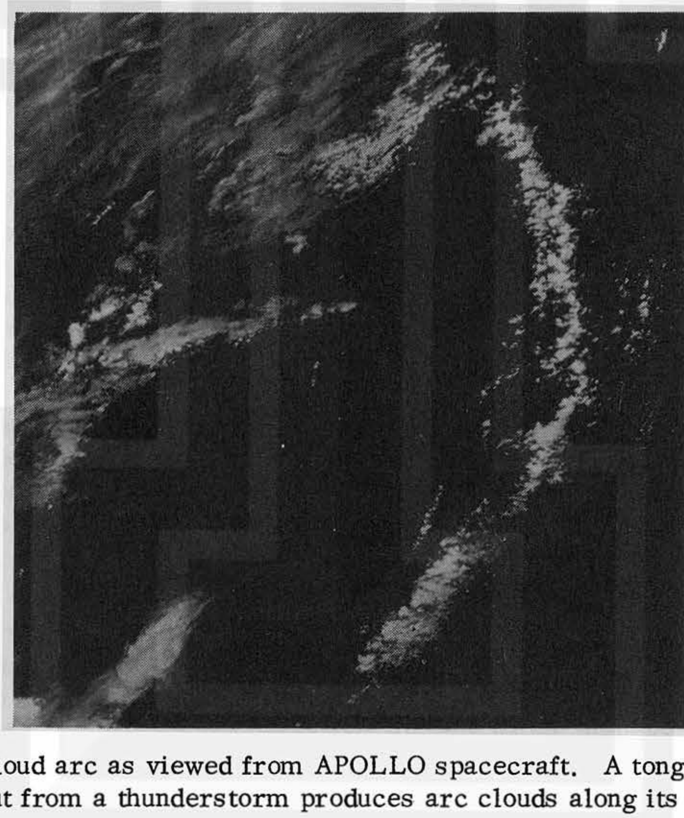

Fig. 1. A cloud arc as viewed from APOLLO spacecraft. A tongue of cold air moving out from a thunderstorm produces arc clouds along its leading edge.

Both island arcs and mountain arcs are common features seen in various parts of the world. To explain these arcs, the "hot tongue hypothesis" will now be introduced (see Fig. 2). The formation of a hot tongue takes place if

a. A flow of mantle is warmer than its both-side environments. Such a situation will arise when mantle flows beneath the continental crust of excessive radioactivity, or when mantle spreads from a fast-rising portion of a rift.

b. A flow of mantle is faster than its both-side environments. Such a differential speed takes place when mantle emerges from between mountain roots of significant depth and dimension.

In both cases the hot tongue is characterized by a self-maintaining mechanism. Namely, the tongue of either hot or fast-moving mantle tends to spread out horizontally from the center axis. To compensate for the divergence thus generated, the mantle at the lower levels rises toward the Moho, transporting both heat and momentum from below.

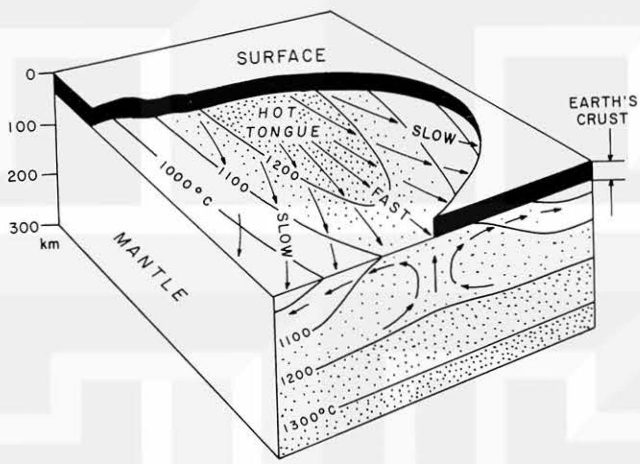

Fig. 2. A 3-dimensional view of a hot tongue hidden beneath the earth's crust. A hot tongue is characterized by a divergent and upwelling flow beneath the M-discontinuity.

Because of the self-maintaining mechanism achieved by tapping both heat and kinetic energy from below, a hot tongue pushes through a considerable distance while creating folding mountains along its leading edge. One of the most complicated examples is seen in southern Europe (see Fig. 3). It is obvious that the flow is relatively smooth beneath the flat plane where mountain roots are insignificant. Nonetheless, there must be variations in the depth of the Moho-discontinuity due to the differential crust density. If one attempts to look up beneath the European continent from the center of the earth, major obstacles to the mantle flow are the mountain roots corresponding, more or less, to high ranges. These roots or upside-down mountains would appear as if they were a number of giant stalactites hanging from a spherical limestone cave with the size of the earth.

A significant hot tongue extending from the deep Bay of Biscay to the Gulf of Lions is pushing the southern tip of Italy and Sicily, thus forming a peninsula-island combined arc. Apparently, preexistent land crust was pushed down beneath the Tyrrhenian Sea so rapidly that it is still sinking deep into the mantle. This is the only place in the world where deep-focus earthquakes are being created outside the general regions of subduction trenches. Both Corsica and Sardinia are being pushed toward the Italian peninsula and will hit the Rome-Naples area in 10 to 20 million years.

Repeated closings of the Strait of Gibraltar are likely to be a result of the periodic intensification of the western branch of the hot tongue. The Gibraltar area appears to be receiving more pressure from the Mediterranean side rather than from the Atlantic side which is closer to the mid-Atlantic rift.

The Wien-Budapest hot tongue extends into the Adriatic Sea, cracking up the Yugoslavian coast into over 100 islands. Another branch of the tongue pushes almost straight east to Transylvania basin, in an attempt to move the folding mountains all the way to the Black Sea.

The Ukraine hot tongue is a powerful one. Its branch moving beneath Bucharest created an "Iron Gate" on the Danube, which is a land counterpart of Gibraltar, as long as the mantle-flow tectonics are concerned. The south-going branch with its center just west of Istanbul undercuts the Aegean Sea, creating at least 5 island arcs connecting the coasts of Greece and Turkey. Thereafter, all island arcs were fractured into numerous pieces of which Crete is the largest remaining piece.

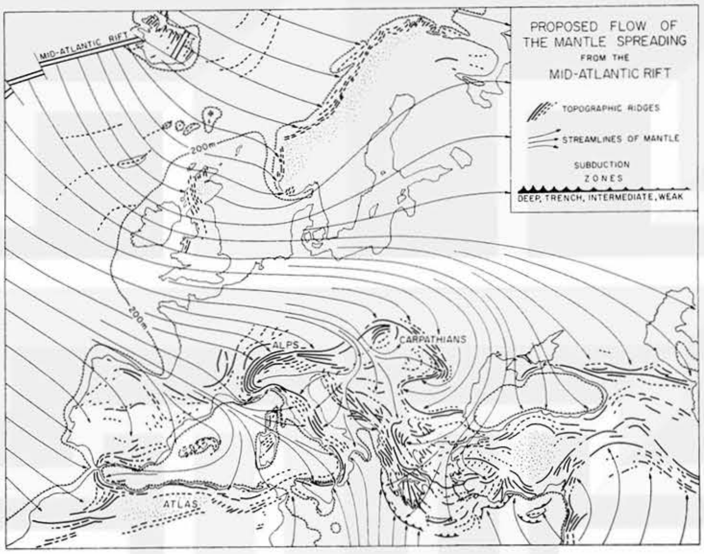

Fig. 3. Extremely complicated flow of the mantle spreading from the mid-Atlantic rift. Hot tongues are pushing out in all directions.

In accordance with the tectonic theory, the weak crust undergoes foldings oriented in the direction perpendicular to the flow direction. When a crust is strong enough to withstand the compression, a large number of shear cracks are generated in the directions 45-degrees from the flow direction. The Atlantic coasts of Scotland and Norway have long been withstanding the enormous force from the mid-Atlantic rift. Numerous cracks there, limited within about 50 km from the coast, are oriented 45 degrees to the direction of the oncoming mantle flow.

The authors' estimates of the hot tongues over the western United States revealed a striking relationship with the earthquake locations. In general, normal-focus earthquakes are found along the leading edge of hot tongues (see Fig. 4).

Yellowstone is located on the leading edge of the Snake River hot tongue which extends from Eugene, Oregon to Yellowstone by way of Harvey Basin and Snake River Plain. As shown in Fig. 4, recent lava flows, such as Craters of the Moon, are found along the center line of the hot tongue. The earthquake locations in the figure clearly show that there are no earthquakes near the center line of this hot tongue. Frequent earthquakes are concentrated along the horse-shoe shaped front where the hot tongue appears to be producing an arc of folding mountains.

The second hot tongue, which may be called the Nevada hot tongue, extends from Crater Lake to the south of Provo, Utah. The Wasatch Range is located along the front where frequent earthquakes are occurring. The combined front of these two hot tongues form a large overall mountain arc which extends over 1000 km. Numerous ripple-like mountains are seen within the tongue area covering most of the state of Nevada. A north-south earthquake zone in west-central Nevada is the front of a secondary hot-tongue advancing inside the primary one.

The third hot tongue which may be called the San Joaquin hot tongue diverged out on both sides of the center line which runs through the valley. The formation mechanism of San Joaquin Valley is very similar to that of Snake River Valley, except that no recent lava flow is seen in San Joaquin Valley. This hot tongue opened up the Valley while applying its maximum impact toward the 4418 m Mt. Whitney.

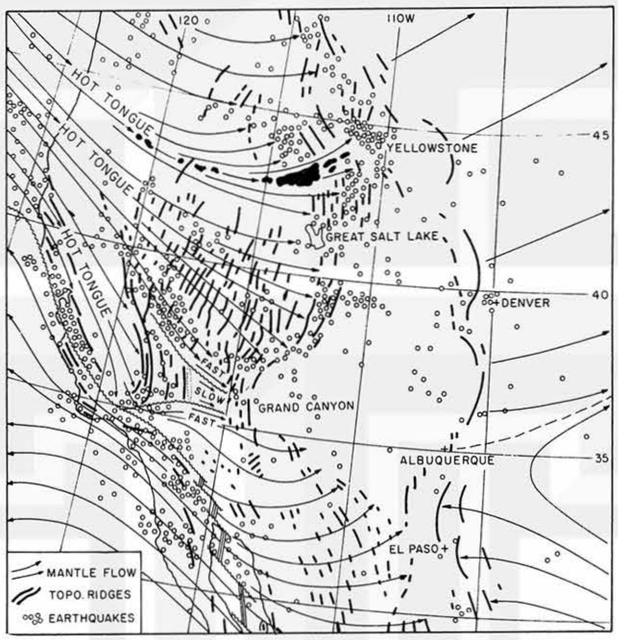

Fig. 4. Three major hot tongues beneath the western United States. Black areas denote recent lava flows from the Snake River hot tongue.

MOUNTAIN SHADOW OF THE SIERRA NEVADA

Death Valley, the lowest spot, 86 m below sea level is located only 130 km from Mt. Whitney, the highest spot within the 48 states. According to our mantle-flow chart, this is not an accidental occurrence. Now, we shall try to explain the cause and effect relationship based on the mountain shadow hypothesis.

A violent push of a hot tongue results in an arc of folding mountains which, in turn, will behave like an obstacle against the push. If the depth of a mountain root is 5 times the mountain height, the San Joaquin hot tongue must be blocked by the Sierra Nevada root, some 20 km deeper than the surrounding roots. The growth of the mountain root acts naturally as a self-destruction mechanism of a hot tongue. A shadow flow is produced behind the range, resulting in a slow flow inside the shadow. On the other hand, the flow on both sides of the shadow will travel much faster, because it travels around the mountain root. The shearing stress, thus created, is responsible for the formation of shear faults on both sides of the mountain shadow. These faults, identified as Garlock Fault and Furnace Creek Fault, are shifting in such a manner that the ground just outside the shadow moves downwind faster than that inside the shadow area.

The shearing stress on both sides of the shadow boundary keeps pulling the shadow area away from Sierra Nevada, thus developing deep fault valleys parallel to the orientation of the parent mountains. The authors were surprised to observe spectacular succession of cliffs when they traveled from Death Valley to Bishop years ago. The San Andreas Fault is located in the shear zone of mantle flows which are moving in the opposite directions. The existence of the San Joaquin hot tongue enhanced the shear flow simply by creating a bottleneck of the mantle flow beneath the Los Angeles area. Since the San Joaquin hot tongue is still very powerful and active, its southern tip is likely to move further south, thus causing more earthquakes along the compression front. The San Andreas Fault northwest of Los Angeles will eventually be bent west-southwest and a tighter bottleneck created.

The magnetic anomaly patterns between Mendocino and Murray fractures reveal that the ocean-floor spread there is much slower than the neighbors. The Los Angeles bottleneck probably caused such a slow spreading. Further tightening of the bottleneck might shut off the spreading flow completely.

A photograph of a U.S. relief map presented in Fig. 5 gives the various topographic features discussed herein. The picture was taken with a simulated low-angle morning sun.

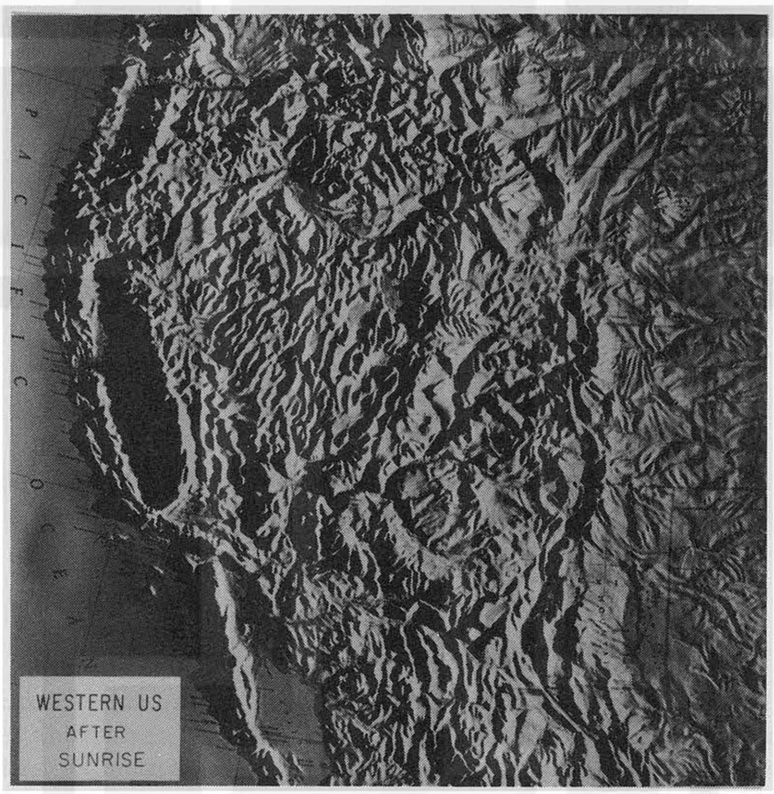

Fig. 5. A view of the western United States obtained by photographing a relief map by Aero Service Corporation.

KANTO EARTHQUAKE

Since the 50th anniversary of the Kanto earthquake of 1923 which killed over 100,000 people, residents of Tokyo and vicinity are now worrying about the occurrence of a second major earthquake. An attempt was made to produce a mantle-flow chart for a possible explanation of the earthquake mechanism.

After investigating clear-day ERTS pictures covering the islands of Japan, the authors reached a conclusion that a hot-tongue flow from the northwest weakened after producing the old island arc along the tectonic line running through Kyushu, Shikoku, Kinki, and central Chubu. There are reasons to believe that a new hot tongue is now working its way from almost due west. The estimated center line extends from the southern tip of Korea to central Chubu where Japan Alps and Akashi Ranges are the dominant orographic features (see Fig. 6).

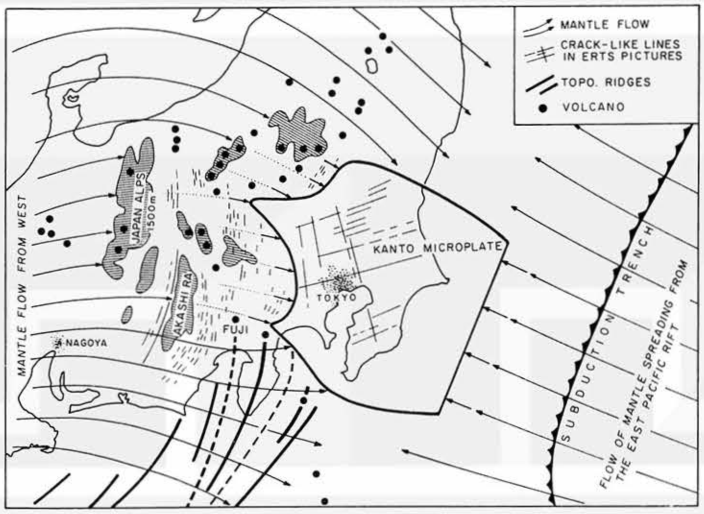

Fig. 6. The Kanto microplate of Japan suffering from compressional stresses.

The Kanto plain may be identified as a stiff microplate located in the shadow of the Alps and Akashi. The microplate is being pushed by the mantle spreading from the east Pacific rift and also by the mantle flowing slowly inside the mountain shadow. Analyses of ERTS pictures by the authors revealed the existence of a number of crack-like lines oriented in a 45-deg direction from that of the obvious compressional stress. The microplate must, therefore, be shrinking in the NW-SE direction while stretching in the SW-NE direction. These forces are likely to be responsible for the normal-focus earthquakes taking place beneath the microplate.

The real troublemaker which caused the 1923 earthquake appears to be the hot-tongue mantle flow from the west. The faster flow, as in the case of Sierra Nevada, is forcing the upper crust to dive under the microplate. Such a process may be identified as being the forced subduction of the island crust which is more rigid than rift slabs. Sagami bay, southwest of Tokyo is very deep along the microplate boundary, implying that the forced subduction is maintaining the depth against isostasy. The fact that the southwest edge of the microplate was elevated as much as 3 m following the 1923 earthquake implies an upward bending of the southwest edge of the microplate.

Detailed examination of the ocean-bottom topography confirms the existence of ridges and troughs perpendicular to the hot-tongue flow pushing from the west. It is of interest to find that each of the volcanoes, Fuji, Hakone, and Oshima, is located either on a ridge or a trough. These tectonic ridges and troughs will eventually work their way toward the subduction zone to dive deep into the mantle sinking beneath the island arc of Japan.

URANIUM DEPOSITS

It has been known that the rate of heat release by radioactive material inside the continental earth crust is one order of magnitude larger than that of the slabs covering ocean floors. Since the distribution of the in-crust radioactivity is not uniform throughout a continental plate, it is likely that radioactively hot spots can be found if we carefully look for them. Such a hot spot, acting as an in-crust heat source, will appear as a divergence center of the mantle just below the Moho-discontinuity. The local convection, thus triggered, will transport upward the mantle material from the lower levels. The base of the lower crust will be heated by both radioactive and convective heat sources, resulting in a significant upwelling circulation.

Expected is a ring-shaped mountain which circles around an extensive deposit of radioactive materials. A spectacular mountain ring, some 600km in diameter is seen around the 4-state corners where the largest uranium deposit in the U.S. has been found and mined. The mountain ring can be followed by identifying several key locations. They are Grand Canyon, Flagstaff, Mogollon Mesa, Baldy Peak, Santa Fe, Sangre de Cristo Range, North of Grand Junction, Bryce Canyon, and back to the north rim of Grand Canyon. This ring may be called the 4-state mountain ring.

As shown in Fig. 7, the boundary of the upwelling convection seems to extend further out from this mountain ring. The westernmost upwelling boundary extends toward the mountain shadow of Sierra Nevada where the mantle flow of San Joaquin hot tongue from the Pacific is weak. The horizontal stratification of Grand Canyon has been protected against the invasion of the hot tongue, because the front between the San Joaquin hot tongue and the upwelling from the 4-state corners is located along the east bank of the Colorado River south of Lake Mead.

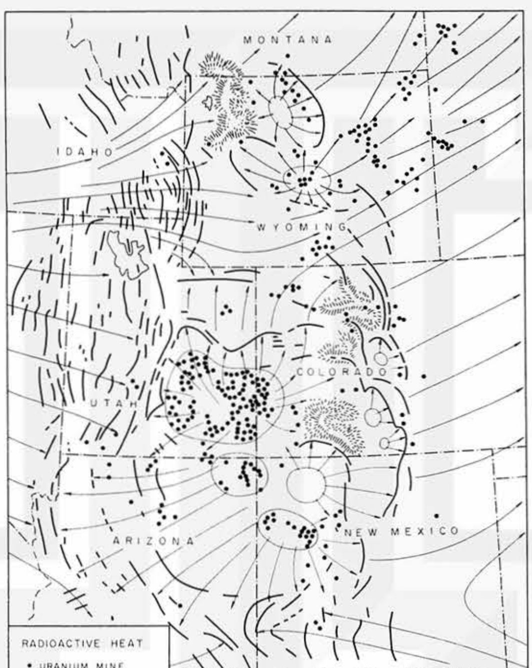

Fig. 7. 4-State mountain ring likely to be produced by the upwelling of the uppermost mantle caused by the uranium deposits.

The battle between the Nevada hot tongue and the upwelling flow is vicious along the front between Bryce Canyon and Provo, Utah. The front runs through the center of the well-known earthquake risk zone. Note the existence of high-density uranium mines on both sides of the Colorado River in Utah.

The arc of Sangre de Cristo Range embracing San Luis Valley of Alamosa is arranged so nicely that its formation cannot be just accidental. We may suspect a radioactive deposit deep beneath the valley. An extensive arid land southeast of Durango is acting as an upwelling center. A bowl-shaped geosyncline is filled with the Eocene and Paleocene continental deposits which sit on top of older sediments of Cretaceous and Jurassic age. To the northeast of the basin, on the southeast slope of the San Juan mountain arc, the age of the rocks gets progressively older to pre-Cambrian partially covered with Tertiary volcanic rocks forming peaks up to 4360 m high. A tremendous thrust in radial directions from the geosyncline center must have been applied in order to maintain these high peaks against the gravitational pull to subside mountains. Should the upwelling die out, the flow-generated stress would disappear, thus eliminating the strain in the San Juan mountain arc. The relaxed mountain arc, without stress, will gradually sink to the environmental level as the mountain root is slowly eroded by the undercutting mantle flow.

Above discussion leads to a speculation that the stress generated by the mantle flow is the major force to maintain or even enhance the body of a mountain arc. What we see in topographic maps with additional evidence from geologic and tectonic maps are the time-integrated effects during the past several million years.

Distribution of the recent lava flows inside and around the 4-state mountain ring implies the existence of the active upwelling. Examples of lava beds are found to the north of White Sands, near Grant, N.M., and numerous other locations. Lines of lava flows are seen on both sides of the 100-km long Echo Cliff, northeast of the Grand Canyon. The cliff is parallel to the 4-state mountain ring.

The speculative discussion presented herewith may provide a key toward the initial selection of the deposit areas of uranium and other radioactive materials. ERTS pictures are of extreme importance to determine the recent cracks related to the direction of the stress. Mapping of these micro-cracks will permit us to narrow down the locations of the upwelling in various scales. This technique will be applicable in mountain regions where upwelling convection will persist for a long time. Beneath the continental shield, where mantle flow is predominant, the heat generated by radioactivity will be transported out so rapidly that the formation of a sustained mountain building is not feasible. The uranium-rich zone extending from the Black Hills northeastward and Canadian deposits, mostly concentrated in the Blind River and Great Bear Lake areas, are very hard to detect by this method, because the generated heat is continuously washed away toward the northeast (refer to the general circulation).

It would be proper to speculate that the northeasterly flow enhanced by these two heat sources is pushing Greenland northeastward. Meanwhile the mantle spreading from the North Atlantic rift pushes Greenland westward, resulting in the overall motion of Greenland toward the Arctic Sea.

Another speculation is the source regions of the hot tongues giving rise to the development and the maintenance of island arcs. We know that major island arcs are located along the leading edge of suspected hot tongues from Eurasian continent. May we suspect a large deposit of uranium in the source region of the hot tongue, originating beneath a flat region of the continent?

GENERAL CIRCULATION OF MANTLE

Discovery of warm and cold fronts by Scandinavian meteorologists back in the 1920s, changed the entire concept of the extratropical cyclones. Until then, people had long been identifying storms as being the areas of low atmospheric pressure, toward which air spirals in, to produce high winds, clouds, and precipitation. This is why some barometers still show the weather types, such as fine, rainy, and stormy, corresponding to the pressure values on the dial.

The frontal theory quickly concluded that it is the battle between warm and cold air that produces heavy rain. A field of low pressure simply provides a favorable location for cold air to plow into the warm air to initiate a vicious squall front. Thereafter, the frontal theory was expanded into global scale by introducing three basic air masses, identified as tropical, polar, and arctic. A further breakdown will result in the five air masses on the earth which are arctic, north-polar, tropical, south-polar, and antarctic. If we correspond these five air masses to the six plates in plate tectonics, meteorologists would imagine that plate and air-mass theory is conceptually identical. In both cases, there are fronts between air masses or plates.

The second major breakthrough in meteorology was achieved by the invention of rawinsonde capable of measuring both wind and temperature all-the-way up into the lower stratosphere. Discovery of the jet stream during the second World War signaled the beginning of dynamical analyses of upper-air charts. As a by-product of the war, the concept of the atmospheric circulation quickly expanded into the global scale, including the entire troposphere along with the lower stratosphere.

Invention of electronic computers coupled with the global synoptic data touched off an extensive research and development program of the numerical weather prediction. National Weather Service offices are being modernized, taking advantage of the automated objective weather map analyses. Long-range trend is to replace forecasters by machines which will collect data from automatic weather stations to perform objective analyses. Analyzed maps are fed into computers to make an objective weather forecast. There are some objections, naturally, as to the complete automation of the weather forecasting business, because a forecaster on duty is the one who gets the blame ... not the machine. Moreover, the forecast accuracy decreases in proportion to the scales of the motion. The most violent storms, which must be predicted with a high degree of accuracy in both time and space, are tornadoes. Likewise, earthquakes must be predicted with a similar accuracy.

In light of the foregoing discussion, the authors attempted to produce a general circulation model applicable to the earth's mantle. A two-dimensional circulation model, conceptual in nature, can be made based on the meteorological analogy of the mantle circulation (see Fig. 8).

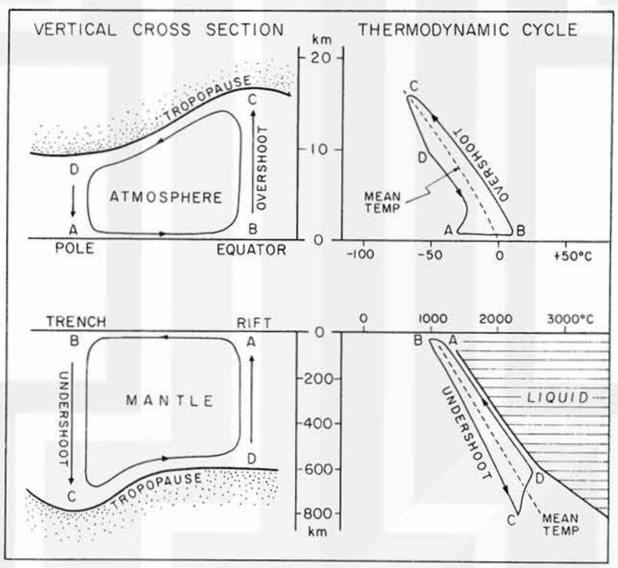

Fig. 8. Thermodynamic cycles of the atmosphere and the mantle. Diagrams are schematic, simply to show the similarity between atmosphere and mantle.

First of all, either atmosphere or mantle must complete its own thermodynamic cycle in order to operate a low-efficiency heat engine involving the global circulation. For the atmosphere, an extremely cold air originating over the polar region, A, receives heat from the underlying ground or the water surface on its long journey to the equator, B. On the corresponding temperature-height diagram, a line A-B is now completed. At point B, the air ascends slowly to C where the rising air pushes the tropopause upward way beyond the mean tropopause height, thus accomplishing a large-scale overshooting into the stratosphere. At this point the air moves poleward to descend toward the ground by way of D.

As for the mantle circulation we start from A, at the rift which is a large-scale divergence zone where slabs are produced to accomplish the ocean floor spreading. Due to the heat flow from the slab surface to the deep ocean water, the slab will lose approximately 1.5×10^{-6} cal/cm^2 sec or 50 cal/cm^2 per year. Since the rate of heat production by radioactive materials within the thin slab is less than 10 cal/cm^2 year, the underlying mantle will be losing some 40 cal/cm^2 year. If we assume that this heat loss is supplied by a 100 m thick mantle beneath the slab, the mantle temperature will drop just about 5°C per million years. This rate appears to be too high. However, the depth of the heat-exchange layer, as well as the radioactive heat production within the uppermost mantle can be assumed to be much larger. This would drop the cooling rate considerably.

This quick estimate implies a significant cooling of the mantle as it travels from the rift to the subduction zone. By the time the mantle reaches B, the trench, both slabs and the uppermost mantle are probably ready to sink. A small triggering force of the arc-island crust, acting as an ice-breaker, will generate a cascade of the slabs descending down to point C. As in the case of the atmosphere, an undershooting is likely to take place. A stratosphere-equivalent depth is selected to be 600 km based on a discussion with Professor Robert C. Newton of the University of Chicago. At this depth, the melting point of the mantle is expected to increase so that the undershooting mantle will meet stiffer resistance.

Existence of deep-focus earthquakes suggeststhe undershooting depth of 700 to 800 km where the mantle starts returning to the normal, 600 km level. An upside-down view of the mantle-motion diagram will permit us to produce a mantle tropopause, as well as stratosphere. During the journey from C to D, the mantle will gradually warm up. It is very unlikely, however, that the mantle at D is able to acquire buoyancy to reach the surface. The mass convergence due to a large-scale confluence appears to be the only mechanism for the mantle to gain buoyancy, because the confluence-forced vertical motion results in a warmer zone of rising mantle. The rising mantle will further increase the temperature contrast, which in turn will stimulate more convection, resulting in a beautiful feedback cycle. The hydrostatic high-pressure ridge created by the upward bulge of the ocean floor along the rift zone produces the horizontal pressure gradient to diverge the uppermost mantle away from the spreading rift axis. A 1000-m difference in the depth of the ocean floor within 100 km on both sides of a rift will result in about 3 bar/km pressure gradient perpendicular to the rift orientation. It should be noted that this value is 1000 times larger than the pressure gradient of the most intense hurricane ever experienced in the world of atmosphere.

A general circulation map of the mantle returning from the undershooting areas to the mid-oceanic rifts has been constructed (see Fig. 9). Since no radiosonde for a vertical sounding of the mantle is available, the undershooting areas were assigned as being the locations of deep-focus earthquakes.

It is amazing to find on the map that the undershooting areas are located near the geometric centers of the rifts. Most of the south Pacific rift is concentric around the Tonga Trench. The Java Trench is located near the center of the south Indian Ocean rift. An eastward bulge of the Pacific rift off Mexico is opposite from the Japan-Mariana Trenches. Two centers of deep-focus earthquakes in South America sit side-by-side near the center of the Pacific and Atlantic rifts combined.

It is of extreme interest to find that there exists a pair of small outflows on both sides of South America, where the mirror-image island arcs are found. They are Lesser Antilles and Scotia arcs. Both arcs, characterized by intermediate-depth earthquakes, are connected with the Pacific rift by way of two separate mesorifts near Galapagos and Easter islands.

Two peculiar centers of outflow must be mentioned. They are located beneath Greenland and Antarctica. No trenches of standard definition are seen around the coasts of these sub-continents. To

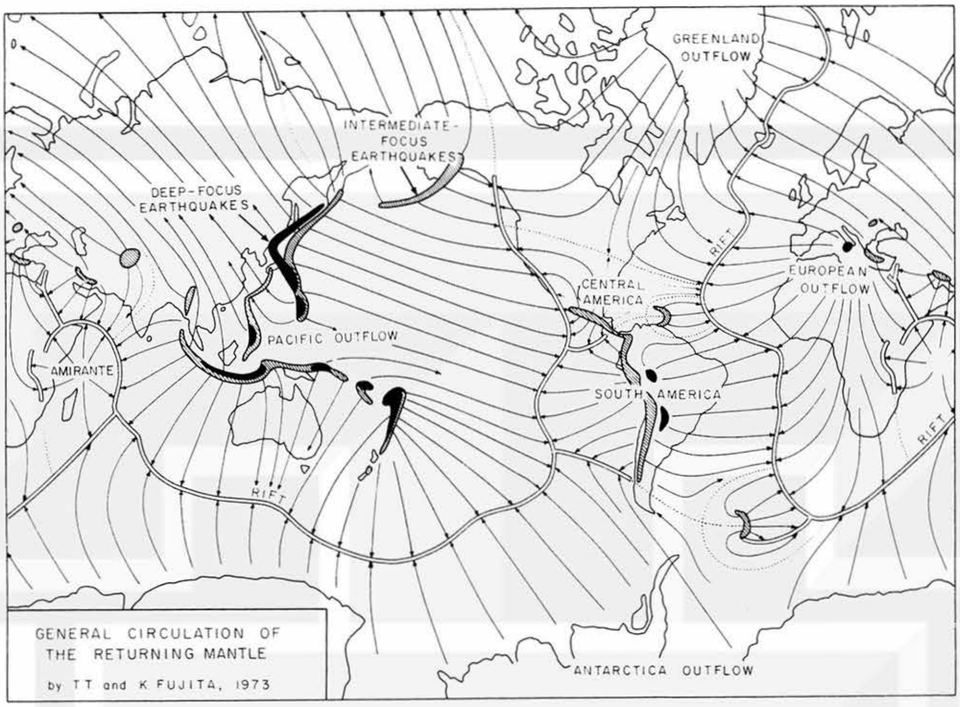

Fig. 9. General circulation of the mantle returning from undershooting areas to the rifts. 250-800 km below sea level.

our knowledge, earthquakes of any depth are very rare or non-existent there, suggesting that the subsidence of mantle must be taking place slowly within a large area beneath the ice-packed crust.

We may assume that the uppermost mantle converging beneath these sub-continent crusts is losing heat much quicker than in any other areas, because the ice in some areas extends below sea level. We shall identify such a sink as "quiet cold sink" because no earthquakes are originated. A large-area sink will be able to accomplish a slow but sufficient mass transport downward to maintain a considerable outflow without undershooting. A quiet outflow should be in existence beneath a quiet cold sink. We would suspect that the sink extends over a large area around the geometric center of an ice-covered continent.

The mechanism of the quiet cold sink under discussion can be generalized into a possible explanation of the initial breakup of the universal land mass, Pangea. Most geologists, who are in agreement with the continental drift hypothesis, place all continents around the rim of Antarctica. A circular rift which formed around Antarctica some 200 million years ago is considered to be the cause of the break up and subsequent departure of the continents away from Antarctica. As shown in figure 10, a circular rift will have to develop around the ice-capped portion of a continent which extends into extra-polar regions.

Another quiet sink operated by a different mechanism is seen beneath Amirante islands in the Indian Ocean. We had been wondering about the ocean-floor topography around the islands without finding anything peculiar there. Recent maps, however, show the existence of a semi-circular trench, 800 km long and 5349 m deep. The trench is located near the center of the elliptic rift extending from the Indian Ocean rift to the African rift valley.

Other major sinks in the world are noisy ones, characterized by earthquakes and cascade subduction. After completing the returning-flow chart, we believe that the position of the mid-ocean rift will change, affected by the strength of the outflow above the mantle tropopause. A balance between nearby outflows will hold the key in determining the future position of the rift. Because of highly viscous and low Reynold's Number flow, the stream lines, in effect, disregard the rotation of the earth. The returning flow initially chooses the great-circle route between the sink and the nearest rift, only to find that the equation of continuity must be satisfied for the selection of the best possible alternate route.

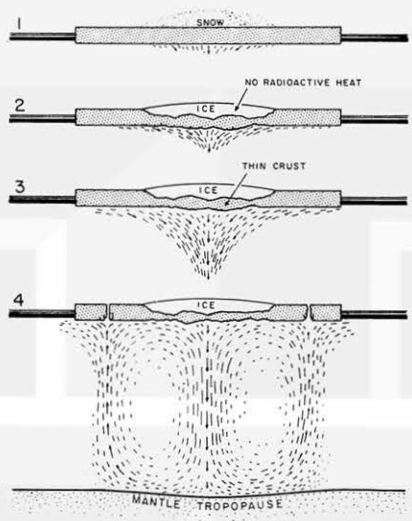

Fig. 10. An extensive ice cap which originates a sinking motion of the uppermost mantle. A quiet sink without earthquakes will develop.

GENERAL CIRCULATION AND HEAT BALANCE

Over 50% of the earth's surface is covered with the deep ocean floor which generates only a fraction of the radioactive heat produced within the continental crust. Nonetheless, the heat flow from the ocean floor is just about one-half that of the continental crust. The vast surface of the ocean floor must be receiving heat from the underlying mantle in order to keep losing more heat than it produces. Likewise, the continental crust must transport the radioactive heat out into the ocean area to avoid a possible overheating. Such an equalization of the heat distribution beneath continental and ocean crusts can be achieved by the general circulation of the mantle.

The general circulation of the atmosphere is important for the transportation of excess heat in the tropics to the higher latitudes. Since the planet earth, with its estimated albedo ranging from 35 to 43 per cent, receives solar radiation at the rate of 1.95 cal/cm^2 min, the global average of the heat received by the earth is calculated to be 0.17-0.21 cal/cm^2 min, which amounts to about 100,000 cal/cm^2 year. This is just about 2000 times larger than the upward heat flow from the solid surface of the earth. This simply means that the atmosphere must work hard to redistribute the heat being received from the sun. Although the mantle will be dealing with a very small amount of heat, compared with the atmosphere, it must also work extremely hard against enormous viscosity.

We have already discussed the evidence for both hot tongue and upwelling convection. An attempt is made now to produce a transport mechanism of heat from beneath the continent to the ocean. Let us consider a continental plate floating on a mantle, traveling at the rate, say, of 5 cm/year, namely 50 km/my. With such a medium flowage rate, it will take just about 25 million years for the mantle to move from Chicago to New York. Such a geological time-scale is long enough to warm up the uppermost mantle to initiate a relatively shallow convection. At this stage, the continent is floating on a warm mantle rising beneath the plate (see Fig. 11).

As the mantle warms up, the outward stress from the plate center begins to produce a mountain arc near the edge of the continent. The mountain root, extending deep into the flowing mantle, cannot hold the mountain arc along the plate edge forever. Thus, the island arcs of various curvatures sail away from the parent continent.

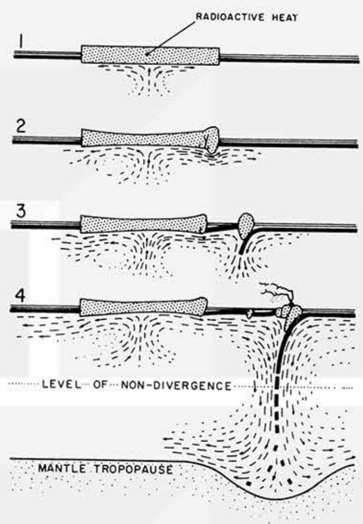

Fig. 11. A continent, riding on hot, uppermost mantle, generates periodically hot tongues which emerge out from the rim, thus producing island arcs and trenches.

The new sea floor, thus created between the continent and an arc, will be carpeted by the slow-spreading slabs produced at the deep-sea floor along the continental rim. This is a proposed new mechanism of sea-floor production at a rate much slower than at the mid-oceanic ridges. The production can be achieved when the uppermost mantle rises slowly into the gap left by the departing slabs with sediment on top. Since no earthquakes occur along the continental rim of a spreading in-arc sea floor, the production rate must be slow, resulting in a tighter spacing of the magnetic anomalies. The heat flow must be high over the general areas of the slab production, where the thickness of the crust is relatively thin.

Examination of island arcs in various parts of the world reveals that a flat portion of a continental edge can be carried away by a hot tongue of a considerable strength. Sooner or later, the chain of islands will be arranged into an arc shape, because the flow speed is the highest near the center axis.

When a traveling island arc overruns the ocean floor, preexistent slabs are forced to sink into the uppermost mantle. A rapid sinking motion of the slabs will take place along the progressing side of the island arc, as long as the slabs are successively pressed down. Slabs may be standing still or may move slowly in the direction of the island-arc motion. The relative motion of the arc and the slabs is what is required. The process is very similar to that of a cold front which plows into warm air. A noisy sink with all-depth-focus earthquakes will occur beneath the arc islands and the in-arc sea spreading behind the islands.

If a number of island arcs are produced, and sail away from a continental plate, the island patterns would appear somewhat like exploded fragments. A spectacular example was made visible by the authors, based on Australia, which drifted away from the cold Antarctic Sea into the warm

Pacific Ocean. The arcs of various sizes, literally, exploded out to as far as 3000 km from the continental rim. It is because the continent drifted toward the equator, thus increasing the solar heating of the surface; meanwhile, the expected high concentration of radioactive material in Australia resulted in a hot mantle beneath the continent. The remnant of the island pieces and the explosive flow patterns are visible in the general circulation map by the authors (Fig. 12).

An initial examination of the general circulation map of the uppermost mantle gives a definite impression that the map appears as if it were a surface weather map in mid winter. This is true because continents are exporting heat by means of the horizontal outflow of the uppermost mantle.

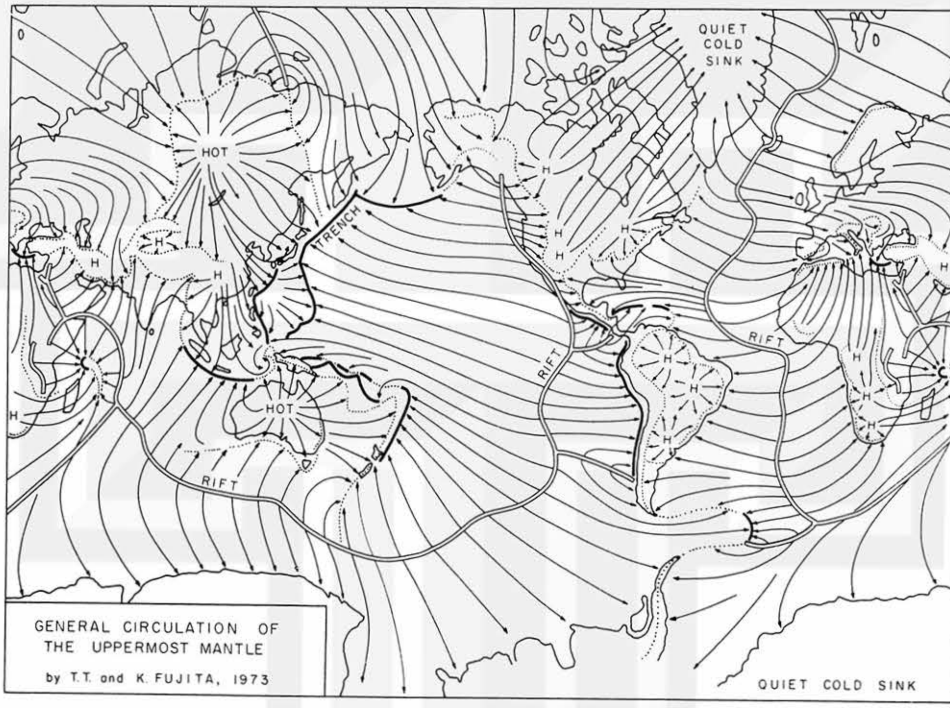

Fig. 12. General circulation of the uppermost mantle. Moho-discontinuity to 250 km below sea level.

The outflow patterns are characterized by a number of hot tongues extending from hot areas identified with letter "H". When a hot tongue moves out into an ocean area, an island arc paralleled by a subduction trench forms along the leading edge. Similar to the cold-air outflow from Siberia to the eastern Pacific, surges of hot tongues, young and old and varying in size, are expected to occur.

The mantle flow to the Mariana arc can be traced all the way back to the Central Sibisk Plateau in Siberia, where the center of the mid-winter anticyclone is located. Their coexistence is not accidental, of course. The location is the thermal center of Eurasia, the largest continent on the earth. Note that the latest surge of a hot tongue from Siberia is already in existence, with its leading edge along the Ryukyu Island arc.

Based on the assumption that more heat must be trapped within a large basin or shield surrounded by mountain arcs which are convex outward, a number of hot spots were placed. One of the most significant examples of such hot spots is the 4-state mountain ring. The outflow of mantle from active hot spots may push offshore islands so hard that the islands could drift away from the hot-spot region. Greenland is receiving the full impact of such a mantle outflow.

The flow of mantle spreading out from oceanic ridges is not as complicated as hot-spot outflows, because the radioactive heat production beneath the ocean floor is expected to be minor and negligible. Most of the outflow from rifts moves toward trenches where the mantle materials are subducted down to the undershooting level.

As has been discussed already, the depth of the hot-spot convection is relatively shallow involving probably the uppermost mantle only. The hot-spot flow is by no means a deep convection. Therefore, it is not expected that we will find a compensation current reaching the level of the return flow located below the 300 km depth.

A similar flow in meteorology is the so-called sea-breeze circulation, which is observed around a cold water area surrounded by a sun-heated land area. A sea breeze acts effectively in equalizing the temperature difference between water and land areas. Nevertheless, the depth of the sea breeze is only a fraction of that of the general circulation.

It is important to realize, however, that a continent drift takes place while riding on the flow of the uppermost mantle, as shown in Fig. 11. Likewise, the drifting motion of an island arc or an off-shore island is affected by the flow of the uppermost mantle, on which they float.

ORIGIN OF HAWAII

As has been introduced in the January 1973 issue of National Geographic, the origin of the Hawaiian archipelago is of extreme interest. According to the magazine, the entire seamount chain, extending 6000 km including the Emperor Seamounts, took about 70 million years to form. The newest one is the big island of Hawaii.

The rate of the growth toward the east-southeast is, thus, estimated to be about 85 km/my. The mean distance between islands in the chain is 120 km, suggesting that a new island has been forming at about 1.4-million year intervals. What is causing such a periodic birth of volcanoes for the past 70 million years? A speculative explanation will be offered based on the general circulation model introduced in this paper.

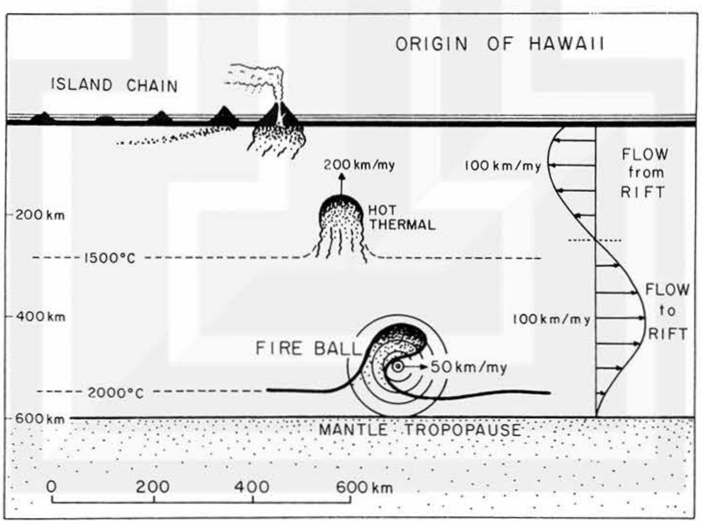

Fig. 13. Hawaii, like thousands of other islands and seamounts in the Pacific, can be produced by "Fire Balls". A fire ball generates a hot thermal once every 1 to 2 million years.

Let us assume that a number of fire balls, somewhat like balls of snow rolling downwind in a blizzard, move just above the mantle tropopause. These fire balls, large and small, will move from undershooting areas to the mid-oceanic rift, while transporting mass and heat efficiently from the tropopause upward. The hot mass, thus brought up toward the upper portion of the fire ball, will soon rise toward the surface being driven by the buoyancy and resisted by the viscosity. Figure 13 was drawn by assuming that the hot thermal, thus generated, rises at the rate of 200 km/my. A new hot thermal must be on its way to the surface to produce Hawaii Junior just about one million years from now.

A hot thermal will remain beneath the bottom of the ocean crust for several hundred thousand years until it drifts away toward the Japanese trench. A long trail of an old thermal could be found beneath the island of Maui toward Honolulu, if one attempts to confirm its existence by some means.

The phase velocity of successive volcano formations is the vector difference between the motions of the fire ball and the ocean floor, on which volcanoes sit. If we assume that the ocean floor moves toward Japan at 35 km/my, the fire ball will be moving toward the U. S. at about 50 km/my in order to produce the 85 km/my rate estimated earlier. These speeds should be revised based on newer estimates whenever available.

If we apply this mechanism to the origin of most seamount chains in the Pacific, the orientations of these chains can be used to estimate the differential motion between the spreading and the returning layers of the mantle. Over 300 seamount and island chains in the Pacific were used to compute the vector differences discussed herein. In fact, the general circulation maps in Figs. 9 and 12 were double checked against each other in order to promote internal consistency within the mantle troposphere.

Island and seamount chains in the Indian and the Atlantic oceans have been assumed to be produced by the hot spots on the mid-oceanic rift. Close examination of the latest ocean-bottom topography reveals, however, that the link of seamount chains at the mid-ocean rift is rather poor. For example, Iceland, known to be a present hot spot, is not accompanied by two chains expected to be seen on both sides of the rift which runs through the island. It would be proper to expand the fire-ball mechanism into these oceans where returning flow appears to be less intense than the Pacific.

CONCLUSIONS

The research reported in this paper was carried out in an attempt to explain various problems in plate tectonics, based on the current knowledge in both meteorology and geotectonics. It is seen throughout the paper that the basic knowledge in one field helped to better the understanding and interpretation of the other.

First of all, the analogy of the thermodynamic cycles of both atmosphere and mantle provided us with a good start to track down the sources of the energy that drives the mantle convection. The hot-tongue hypothesis was then used extensively to accomplish the horizontal transport of heat from beneath continental to oceanic earth crust. A number of problems related to the formation of island arcs and subduction trenches were explained based on a generalized 3-dimensional point of view which is different from current plate tectonics.

Of interest is a speculation of determining local hot spots based on topographic features including hair cracks seen in ERTS pictures. If this is proved to be true and useful, deposits of radioactive materials can be estimated based on ERTS photographs. Very high resolution pictures from the geosynchronous altitude will have numerous applications toward the solution of the problems pointed out in this paper. The appearance of hair cracks will change as the sun angle varies, making it necessary to observe a specific rock formation several times a day -- not once in 16 days. This is very similar to that of the appearance of radial lava flows on the moon's surface, which are visible with specific directions of the sun. Meanwhile, such ultra-high resolution photographs will have potential applications to the detection of tornado producing thunderstorms.

Another important application is the better assessment of the earthquake risk. This paper reveals that the locations of earthquakes are related extremely well with the specific flow patterns of the uppermost mantle.

The most important aspect of this paper is the realization of the similarity between tornado and earthquake prediction. Neither of them can be seen in progress from satellites no matter how their sensor resolution is increased. In both meteorological and geological cases, however, special characteristics leading to the outbreak of these violent disturbances can be detected by means of satellite-based photography.

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