CHAPTER 1

Preview of the orbital perspective: the million-year day

1.1 Introduction

"The present is the key to the past." This axiom is familiar to all geologists, expressing the belief that the Earth has evolved over billions of years by processes still going on today. In recent years there has been something of a revival in catastrophism, with the realization that rare events such as meteoritic impacts and sudden glacial floods do occasionally happen. These events – and better known sporadic ones, such as volcanic eruptions and great earthquakes – require us to reconsider our concept of the geologic "present." How long must we watch the Earth to get a realistic picture – a day in the life of the Earth, so to speak – of geologic processes?

The geologic events of a month or even a decade clearly do not represent the full spectrum of geologic activity. The map (see Fig. 1.1) that opens this book, derived largely from space-acquired data, was designed to illustrate the tectonic and volcanic activity of the last one million years – a "million-year day." Mathematically-inclined readers may think of it as a first derivative – the instantaneous rate of change – of a conventional tectonic map. The tectonic activity map and related ones are presented at this point as a preview, to demonstrate at once the fundamental impact of orbital data on geology and geophysics.

1.2 A digital tectonic activity map of the Earth

It is only in the last 40 years, since about 1965, that we have finally arrived at something like a true understanding of "the way the Earth works" in the title of Wyllie's (1976) geology text. As late as 1962, for example, it could still be reasonably proposed in a leading journal (Chenoweth, 1962) that the deep ocean floor, if uncovered, would be a primordial cratered surface resembling the face of the Moon. As it happened, the same year saw the publication of Hess's (1962) classic "essay in geopoetry" (his words), which laid the foundation for the new global tectonics, soon to be termed "plate tectonics," showing that the oceanic crust is geologically young and mobile.

Plate tectonic theory holds that roughly two-thirds of the Earth's crust, the ocean basins, is both active and, in a geologic sense, ephemeral. Oceanic crust, chiefly basaltic, or "mafic," is continually generated by volcanic eruptions along features known but little understood for years: the mid-ocean ridges such as that bisecting the Atlantic Ocean. Its Pacific counterpart is the East Pacific Rise. These ridges are seismically active, an expression of processes in the deep interior generating basaltic magma that is erupted along the ridges (generally under water with the notable exception of Iceland, sitting astride the Mid-Atlantic Ridge). This newly generated crust moves away from the ridges at a few centimeters a year in the now-familiar process of "sea-floor spreading," a term coined by Dietz (1961), who credited Hess with the concept although an earlier version had been proposed by Arthur Holmes (1931).

The Earth is tectonically a closed system, and newly generated crust in most areas is eventually destroyed by "subduction," in zones several hundred kilometers deep in which the oceanic crust descends, to be re-absorbed in the mantle by processes still not fully understood. (Most active volcanos, notably those of the Pacific rim, occur over these subduction zones.) These phenomena collectively account for the term "ephemeral" used to describe oceanic crust, in that sea-floor spreading and subduction recycle this crust in a few hundred million years. Far from being primordial as suggested by Chenoweth, very little of the basaltic ocean crust is more than about 200 million years old. The continental crust in contrast is at least four billion years old and as will be argued later – from comparative planetology – may be fundamentally "primordial."

Since the emergence of the theory just outlined, many global tectonic maps have been published. However, regardless of the validity of plate tectonic theory itself, these maps have all been unconstrained by time limits, showing all mappable features of whatever age. The word "features" is critical to understanding the map presented here, which is focussed on phenomena rather than features, the phenomena being tectonic and volcanic activity of the "million-year day."

Two versions of the digital tectonic activity map (DTAM henceforth) are presented. The first (Fig. 1.1) is a composite of shaded relief with superimposed tectonic and volcanic features; the second (Fig. 1.2) is a schematic map showing the same features in purely symbolic form, with the addition of continental/oceanic crust boundaries. The following discussion of the DTAM will be focussed

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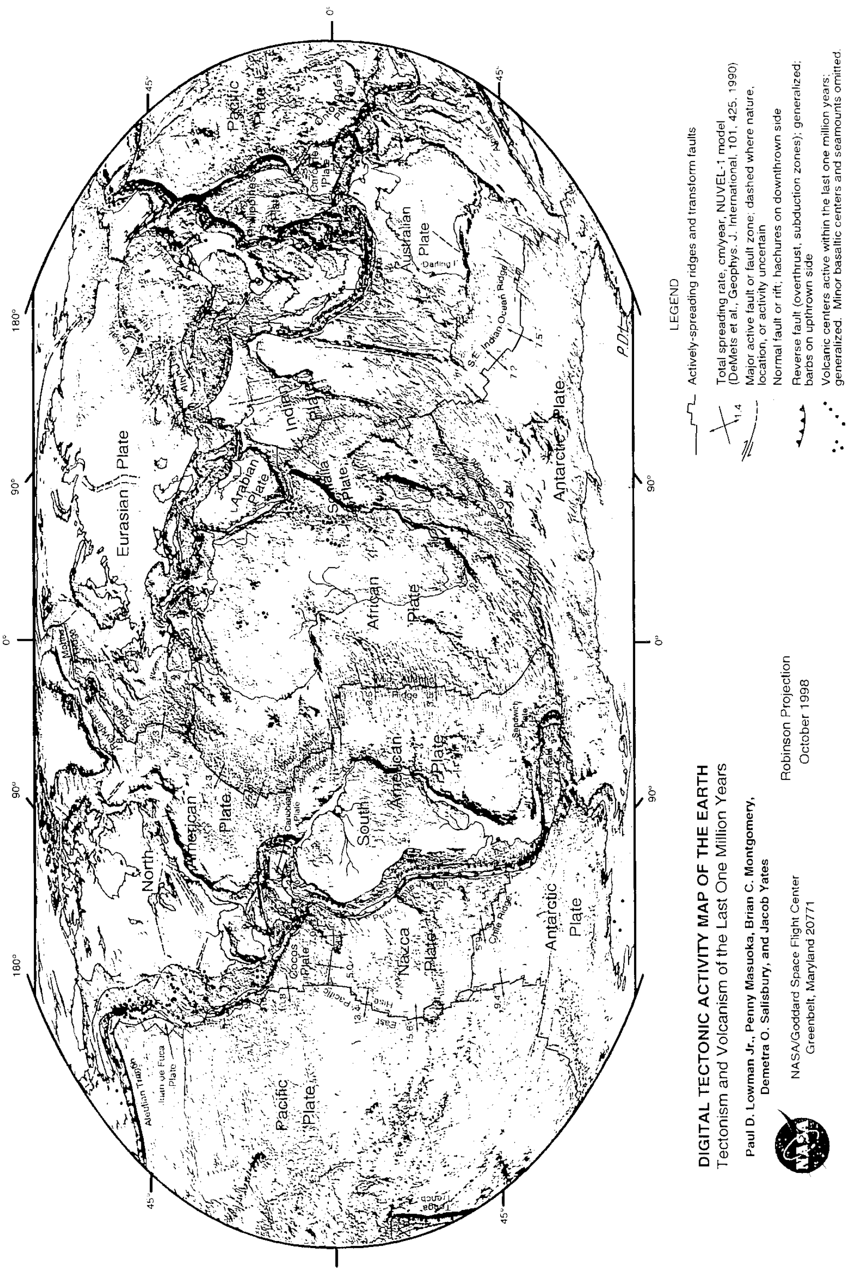

Fig. 1.1 (See also Plate I) Digital tectonic activity map (DTAM) of the Earth, based on shaded relief map largely generated from satellite altimetry.

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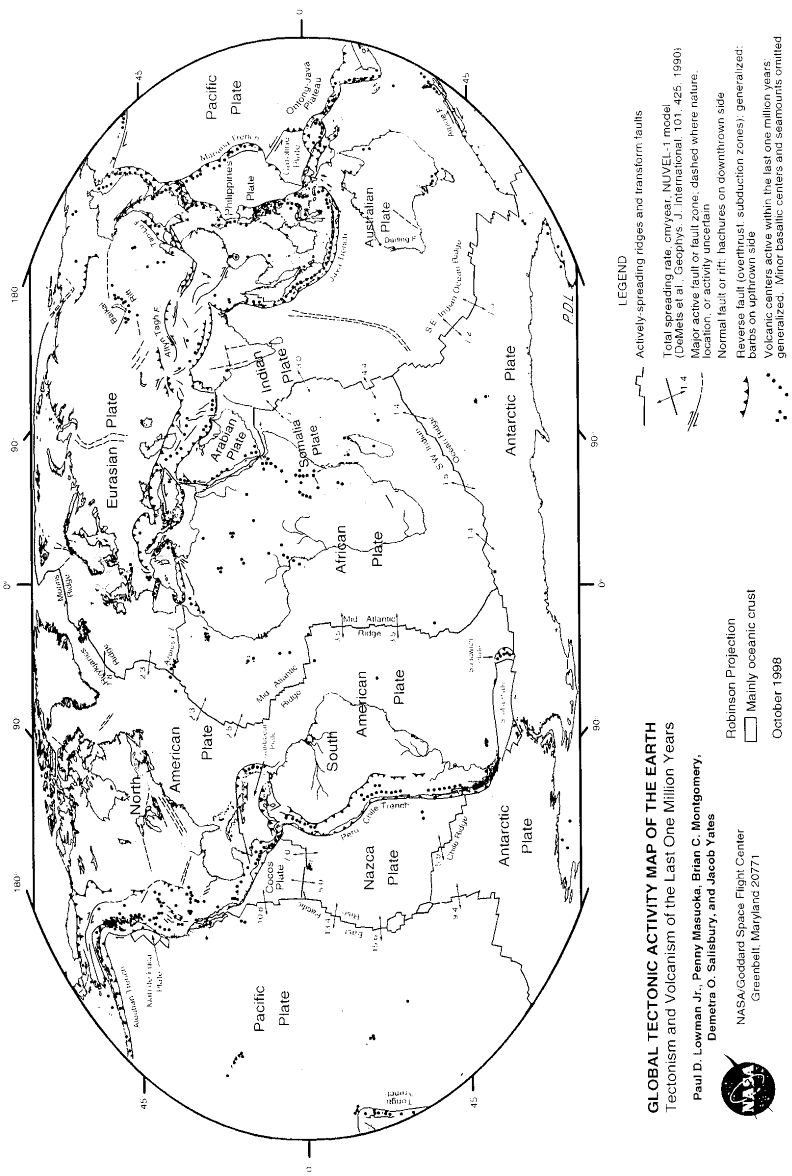

Fig. 1.2 (See also Plate II) Schematic global tectonic activity map (GTAM), from Fig. 1.

primarily on the relief version, with the objective of summarizing the contributions of space data to its compilation. A series of seismicity maps, computer-drawn with the same scale and projection, was essential for the DTAM and one is accordingly included (Fig. 1.3). Software and major data sources are given by Lowman *et al.* (1999) and Yates *et al.* (1999).

1.3 Sea-surface satellite altimetry

The DTAM is derived from an enormous data base of surface and space-related surveys and studies. The contribution of space data begins with the delineation of the topography of the ocean basins (that is, bathymetry) by satellite altimetry. Comparable maps became available in the 1960s with publication of the now-classic hand-drawn maps of Bruce Heezen and Marie Tharp, for several decades familiar features of most introductory geology books. The Heezen–Tharp maps were based on conventional marine surveys, chiefly echo-sounding. But, since such surveys produced depth data along single survey lines they could not begin to show the topography of large uninterrupted areas of the ocean basins. Consequently, many features had to be drawn by extrapolation in unsurveyed areas.

This situation has now been remedied by sea-surface satellite altimetry (Sandwell, 1991; Smith and Sandwell, 1997). This method (discussed in detail in Chapter 2) depends on the fact, first demonstrated in 1973 by a radar altimeter carried on *Skylab*, that the mean sea surface (after correction for tides, currents, and the like) forms a very subdued replica of the underlying ocean-floor topography. The effect is suggestive of snow-covered ground. It is caused by the lateral gravitational attraction of ocean-floor relief features. A submerged volcano, for example, will pull the surrounding ocean toward itself, forming a very slight hump (generally a few meters at most) on the overlying ocean. The ocean floor adjacent to a trench will similarly pull the water very slightly away from the trench, which will thus be mirrored in the overlying sea surface.

In the decades since the phenomenon was first demonstrated, satellite altimetry has become an essential tool for mapping the ocean floor. Hundreds of thousands of satellite altimetry passes have been combined to produce a digital elevation model, available from the National Geophysical Data Center, of almost the entire ocean floor. It is that model on which the computer-drawn shaded relief map of Fig. 1.1 is based. The software used for its construction exaggerates the relief, emphasizing it with pseudo-illumination from the northwest. However, this map is fundamentally different

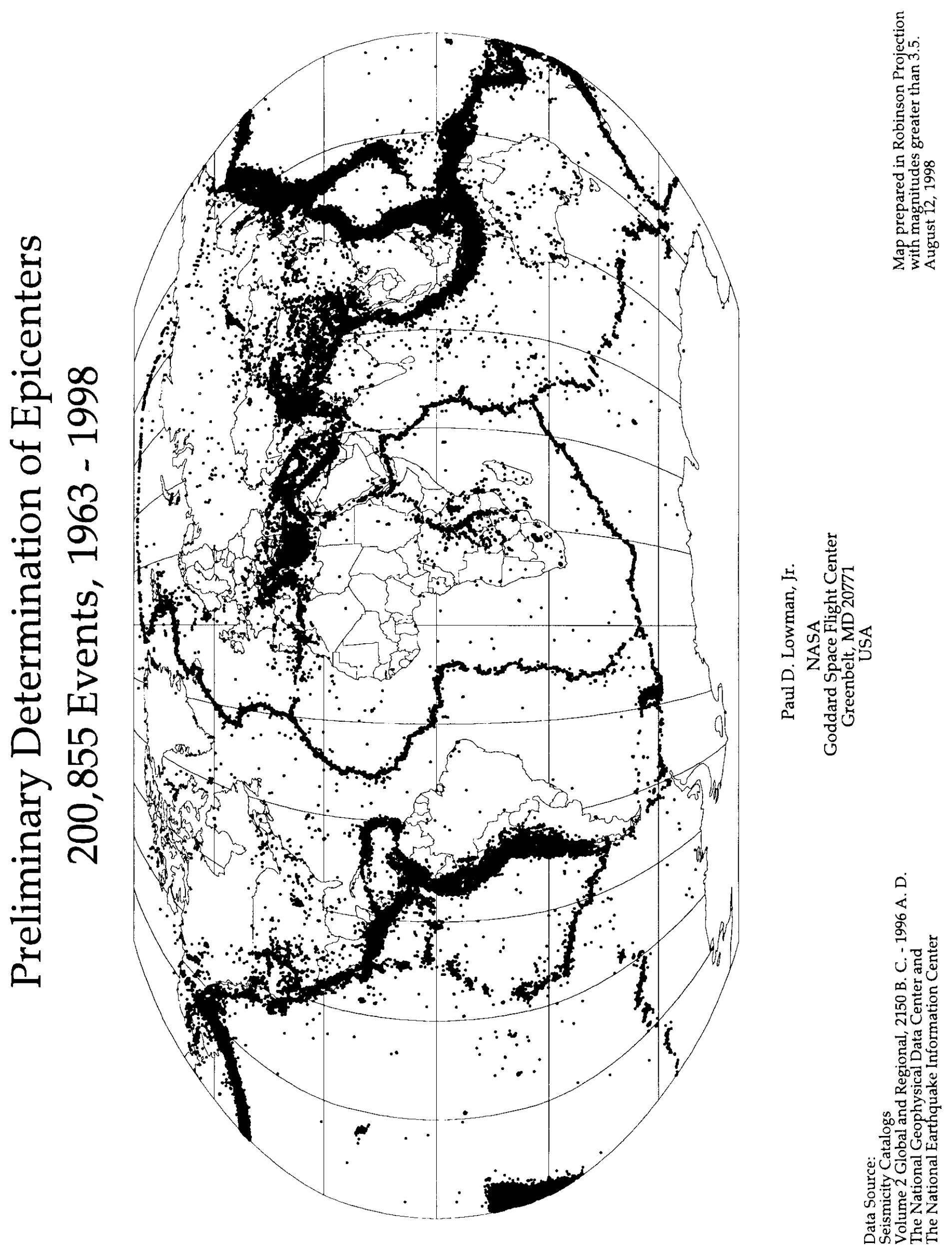

Fig. 1.3 Earthquake epicenter map, used to delineate zones of tectonic activity.

from previous maps in being an objective one, not an artist's rendition. Subject to scale and resolution limits, satellite altimetry has given us a view of some ⅔ of the Earth's surface that was until recently much more poorly mapped than the near side of the Moon. The active tectonic features shown in the schematic DTAM (Fig. 1.2) are thus offered as reasonably objective representations.

1.4 Satellite measurement of plate motion and deformation

The digital tectonic activity map shows recent estimates of total sea-floor spreading rates from the mid-ocean ridges. These estimates owe nothing to space techniques, being based on the distances of dated magnetic anomalies from spreading centers, as will be explained in Chapter 3. However, space geodetic techniques (Robbins *et al*., 1993), specifically satellite laser ranging (SLR) and very long baseline interferometry (VLBI) have made it possible to measure intercontinental distances with precisions on the order of one centimeter. The *Global Positioning System* (*GPS*) is now filling in areas with denser measurement nets. It is hardly necessary to point out that such an achievement was unimaginable before satellite methods and radio astronomy were available.

The contribution of satellite distance measurements to the DTAM lies in the direct demonstration (Fig. 1.4) independently by SLR and VLBI, that several islands in the Pacific Ocean, such as Kauai, are moving northwest toward Japan at rates of roughly 6–7 centimeters per year. These rates are very close to those implied by the NUVEL-1 sea-floor spreading estimates, which are averages for about the last 3 million years. To extrapolate these spreading rates to the motion of entire plates of course requires the assumption that the plates are internally rigid. But here SLR and VLBI are again useful, by showing that the inter-island distances are essentially constant, that the Pacific Plate is indeed rigid to a close approximation.

In summary, the dynamic behavior of the oceanic crust as outlined by plate tectonic theory has been directly observed by space geodetic methods, confirming estimates made by totally independent measurements along the mid-ocean ridges.

1.5 Satellite remote sensing

The tectonic activity of large areas, especially in southern Asia, as shown on the DTAM is derived to a major degree from satellite remote sensing data, especially *Landsat* imagery. As will be

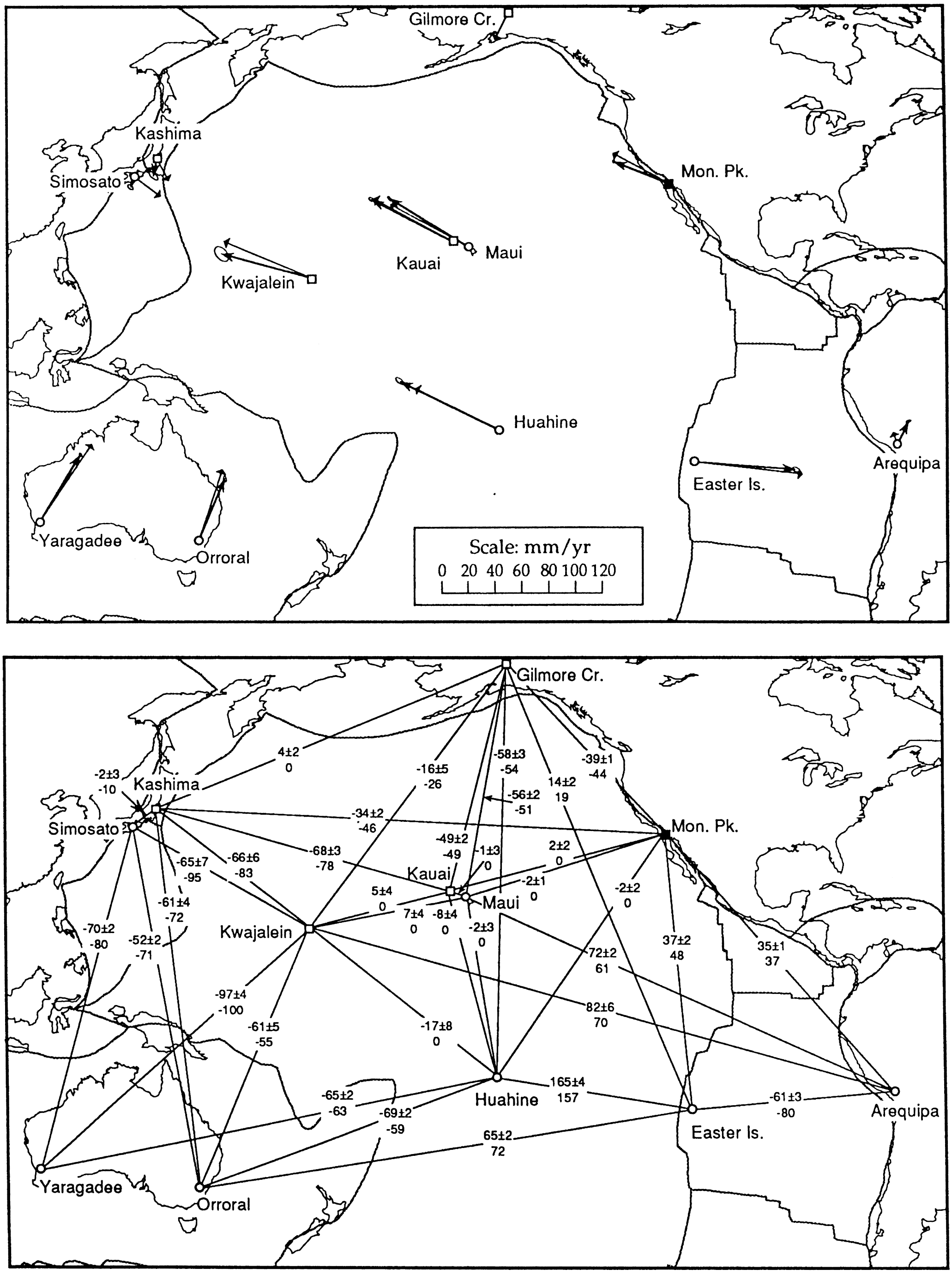

Fig. 1.4 Vectors showing motion of space geodesy sites (*top*) and baseline lengths (*bottom*). Values in lower diagram are observed length changes (combined SLR and VLBI solutions) above and length changes predicted by NUVEL-1 model. From Robbins *et al*. (1993).

Fig. 1.5 (See also Plate III) Gemini 12 photograph S66-63082; view to east over the Zagros Mountains (left), Strait of Hormuz, and Makran Range. Width of view 600 km. From Lowman (1999).

described in Chapter 4, the tectonic structure of Asia, especially north of the Himalayas, was almost completely unknown until the availability of satellite imagery, starting with hand-held 70 mm photographs (Fig. 1.5) taken by *Mercury* and *Gemini* astronauts (Lowman, 1999). The Tibetan Plateau, for example, was essentially inaccessible for many years because of its remoteness and, after World War II, political barriers. Satellites surmounted these barriers, providing superb synoptic views of hundreds of thousands of square kilometers. *Landsat* images were first used to produce tectonic maps of Tibet. Chinese geologists were among the first to use *Landsat* for similar maps, and in the years since, satellite imagery has become widely used to map the tectonic structure of not only southern Asia but other parts of the Alpine fold belt and even supposedly well-mapped areas such as northern Norway.

Satellite imagery not only reveals the existence of large faults in remote areas, but often gives a good idea of their current activity by showing features such as fault scarps and offset streams. This is only the beginning of a rapidly expanding field, since satellite radar interferometry and space geodesy by means of the *Global Positioning System*, to be described in Chapter 2, are rapidly complementing satellite imagery.

The DTAM is explicitly a very generalized map, especially in its representation of continental volcanism. The contribution of space data here also comes from satellite imagery. As will be described, many previously-unmapped volcanos have been found with *Landsat* imagery and astronaut 70 mm photography starting with the *Gemini* missions of the mid-1960s. However, the real value of satellite imagery for showing volcanism is simply in making the map's compiler aware of geomorphically fresh, and hence young, volcanos and lava flows in previously-mapped but remote areas. The best available compilations of active volcanos are restricted to historical records, covering the last 10,000 years. By revealing many other young but historically inactive volcanos and lava flows, satellite imagery has made it possible to produce the first global representation of volcanic activity extending back about one million years.

1.6 Satellite magnetic surveys

The existence of the Earth's magnetic field has been known for centuries, and scientific study goes back to the time of Queen Elizabeth I, as we will see in Chapter 3. However, it has been an extremely difficult feature to study. To begin with, it is highly variable, from minute to minute during solar storms, or over hundreds of thousands of years during reversals of the Earth's main magnetic field. Additionally, the magnetic poles are constantly moving. A recent Canadian geophysical expedition on Ellesmere Island found that the north magnetic pole actually passed under them while they were at one camp site. (Canada has been a traditional leader in geomagnetic studies; it may help to own one of the magnetic poles.) Moreover, magnetism in general was not understood until the 19th century, in particular until the work of James Clerk Maxwell.

Study of the Earth's crustal magnetism was given a jump start, so to speak, during World War II, when greatly improved magnetometers for submarine detection were developed. Aeromagnetic studies in the early post-war years discovered many valuable ore deposits, in Canada and elsewhere. However, such studies are time-consuming and expensive. Mapping of crustal magnetism in the oceans is even more time-consuming when done by ships. The next big step forward in the study of geomagnetism came with the launching of artificial satellites.