Global Geologic Applications of the Space Shuttle Earth Observations Photography Database

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" ...An astronaut can see all of what's going on in the rift valleys, in the basin and range in the western USA in a way that I never saw in any geology textbooks.. and our photographic cameras do a good job of recording that.." remarked scientist-astronaut Dr. Jay Apt after his maiden voyage into space aboard the Space Shuttle Atlantis in May 1991. The value of remote sensing of Earth during manned space flights has been documented extensively since the Gemini missions in the early 1960s. The imaging of Earth with handheld digital, analog film, and videographic cameras continues to provide the scientific community with an enormous database of imagery of unique views of the planet. This is especially relevant in the era of "Mission to Planet Earth" which focuses on understanding global environmental changes and Earth system science.

During the 32 years length-of-record represented by the growing global database, approximately 180,000 images have been acquired of specific suites of global environmental change and global geologic sites, as well as of various short-lived Earth phenomena that can only be captured in the "discovery mode" that is possible using an intelligent observer in space. Earth imagery acquisitions during these flights are thus not only preplanned, but are also the result of rigorous ground training that allows the astronaut crews to operate in an independent mode while in orbit.

Astronaut photography of the Earth is the result of systematic Earth and environmental science training provided to each astronaut crew prior to flight. Each flight crew is tasked with specific Earth observations objectives, and with acquiring data over specific sites during their mission. Among the many advantages of the astronaut photography during Space Shuttle missions, the following are worth mentioning.

Initial images acquired appear very promising for Earth observation applications.

- Images are obtained at a variety of sun angles—ranging from 1í to about 80í with the majority of pictures having sun angles of about 30í Very low sun angle and some negative sun angle photography has provided unique topographic views of remote mountainous areas otherwise poorly mapped. Additionally, a variety of different sun angles of the same area in the imagery database allows discrimination of geologic characteristics that is not possible with constant sun angle imagery.

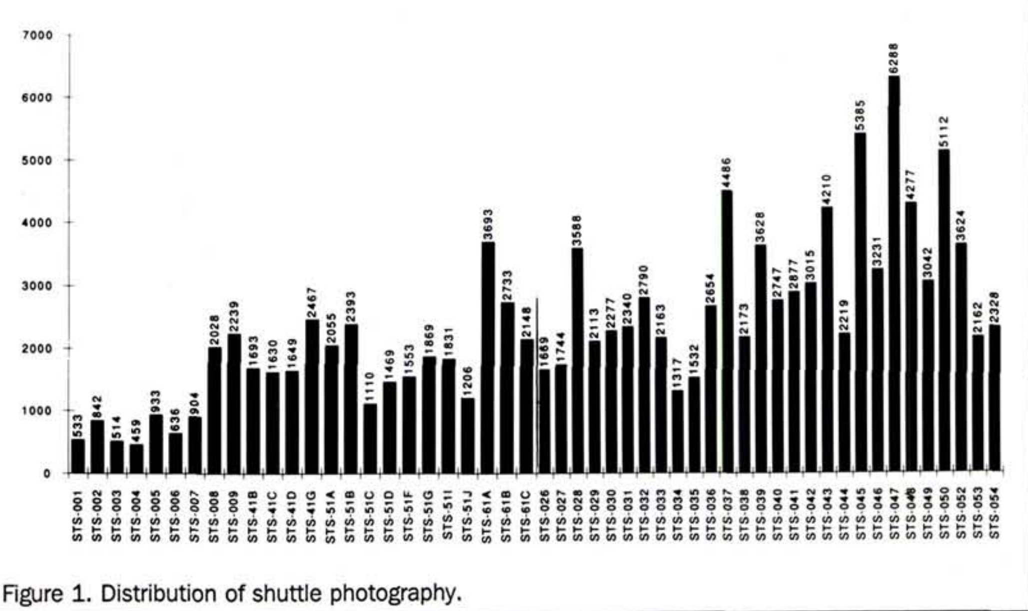

Figure 1. Distribution of shuttle photography.

- Sequential photo graphs with different look-angles provide stereo-views. Stereo strip photography has been acquired of a number of different locales around the globe.
- Seventy five percent of the photographs in the archive cover the regions between 28í N and 28í S latitudes providing coverage for many, otherwise little-known tropical areas which are undergoing the most drastic environmental transformations.
- Twenty-five percent of the views cover regions between 30í-60í N and S latitudes.

Figure 1 shows the distribution of Shuttle photography acquired during the past fifty-two Space Shuttle flights (1981-1993). Figure 2 is a map depicting the regions of North America over which the Shuttle photography has been acquired. Each dot on this map represents the location of images over that area. One dot may represent multiple images.

These images are all in the public domain, and products are available at the cost of reproduction through public archives. An electronic catalog of metadata of the entire archive is also accessible via global electronic networks (see footnotes 1 and 2). In addition, the entire suite of Shuttle photography from 1981 through 1992, totalling some 91,500 images has been transferred onto a laser-disk for easy access as a part of the Image Acess and Management System Project of the NASA-Johnson Space Center. We are begining to exploit CD-

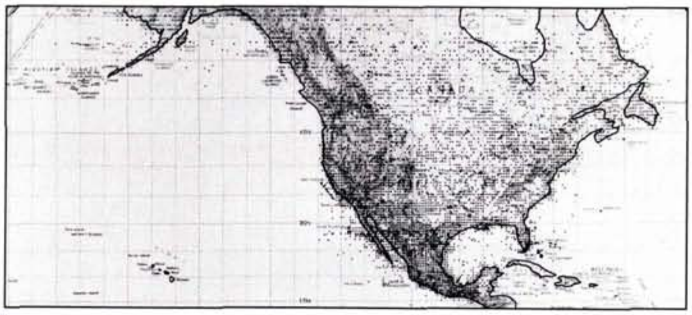

Figure 2. Regions where Shuttle photography has been acquired.

ROM disk technology. A few experimental disks containing selected suites of digitized images have been produced. These products will enhance the utility of the imagery for both research and teaching.

Selected photographs have been digitized and added to the existing electronic database for remote downloading by world-wide users. Digitization, rectification, multi-layering (GIS), classification, and mensuration of these digitized analog images is now fairly routine and such imagery has been used in image analysis and interpretation projects. Of particular interest to the geologists, is the availabilty of stereo and long strips of images over hundreds of sites. See, for example, Figure 3, which is a mosaic of 15 images extending from the Dead Sea to the Gulf of Aqaba. These strips and stereo images provide an opportunity to interpret geologic features at both regional and local scale level.

Each new Space Shuttle mission now returns 3000-7000 new large-format photographs of the Earth. Much of each mission's new data consists of revisits to areas imaged as early as 1962 in order to detect and quantify changes over time, and to understand the identity and rates of processes operative within specific regions. The number of images acquired over time has been increasing since 1989. As an example, about 10,000 new large-format Earth photographs are planned for acquisition during the flight of Space Radar Laboratory (SRL) on STS-59 alone, now planned for the late spring of 1994.

The normal analog film cameras used onboard the Space Shuttle for dedicated Earth observations include the Hasselblad 70-mm film format and AeroTechnika 5-inch film format systems. Color visible and color infrared films are used for both these systems. Nikon 35-mm film format and videocamcorders are also routinely used. However, technological evolutions and interest in digital imaging from the Space Shuttle has matured to such an extent that electronic imaging cameras have now been developed for Earth observations use during missions.

NASA has built and flown two generations of digital electronic imaging camera with downlink capabilities. The present electronic imaging camera is the Electronic Still Camera (ESC). Initial images acquired appear very promising for Earth observation applications. The ESC is based upon a 1024x1024 Charged Coupled Device (CCD) black-and-white pixel array. The camera is also designed to accept a 2048x2048

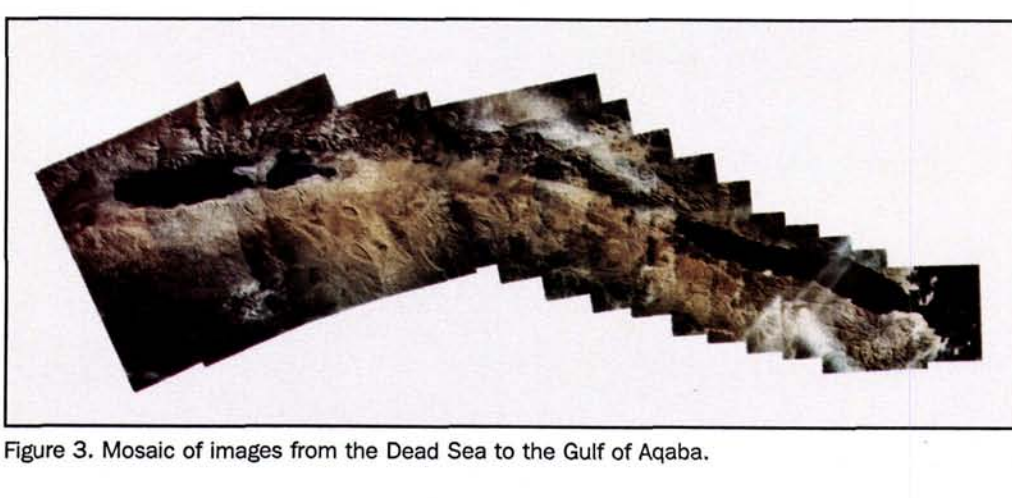

Figure 3. Mosaic of images from the Dead Sea to the Gulf of Aqaba.

CCD black-and-white pixel array, and to be upgradable to a 1024x1024 pixel array three-band color system.

The ESC camera was designed using astronomical-grade CCDs instead of video-grade CCDs. This approach has resulted in near-film-quality imaging, and has far exceeded the quality of analog video imaging downlinked during earlier Shuttle flights. The new system is a bridge between analog film and digital video, bringing the advantages of both into one system. The ESC CCD also has a spectral response (400-1100) nan-nometers, which significantly exceeds that of films currently flown on the Space Shuttle. Available sensors which could be later used in the ESC system are sensitive into the near infrared to X-ray wavelengths. This system is expected to enhance the results of scientific experiments and studies, and allows for the very rapid dissemination of data throughout the scientific and educational communities. Figure 4 is an example of an ESC image useful for geologic applications.

The imagery from the database has been digitized and used in GIS applications in several projects. Both the ESC images and digitized photographs have been classified and integrated into GIS layers for spatial analysis. Most of the early efforts at the NASA-Johnson Space Center have included projects involving the measurement of areal changes in water cover of Pleistocene continental internal drainage areas (e.g., Great Salt Lake, the Aral' Sea, the Zaliv Kara-

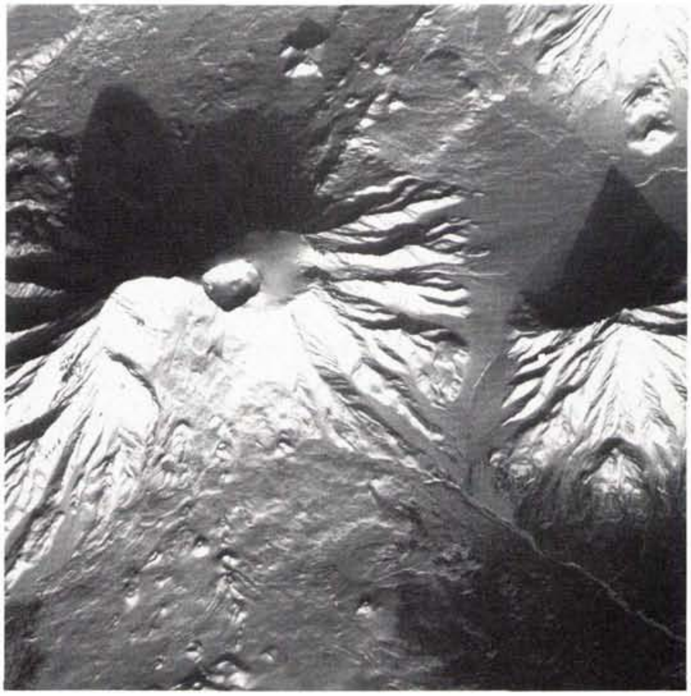

Figure 4. An ESC image for geologic applications.

Bogaz-Gol' of the Caspian Sea, Lake Eyre in Australia, and Lake Chad in the Sahelian Zone of Africa), and rapid deltaic growth or estuarine filling (e.g., The Omo River Delta of Lake Turkana, the Betsiboka River Delta extension in the Bahia de Bombeteka in northwestern Madagascar, and Bahia del Carmen in Mexico). These data also have been used to model land use changes in

Figure 5. Recent pyroclastic deposits.

Botswana. Future experiments using the 1962-1993 time series are envisioned for identifying and quantifying rapid deforestation and resultant changes in hydrology and sedimentation such as characterizes Central Sumatra and portions of Kalimantan (Borneo), the forests and stream drainage patterns of Nepal and Assam (NW India), the Okavango Swamp (Botswana), the Western Ghats of India and selected areas of the Brazilian Amazon. Digital Elevation Model (DEM) and Shuttle images have been used to create three-dimensional views of several sites.

To illustrate the global and multidisciplinary nature of this database a few selected examples of geologic applications are provided below:

Philippine Islands: The Eruption of Mount Pinatubo—Perhaps the most spectacular example of rapidly changing surface geology is the documentation of changes around Mt. Pinatubo after its June 1991 eruption. Pinatubo is one of about 20 active volcanoes in the Philippines. Its eruption in 1991 was one of the largest global volcanic events of this century. During the major eruptive episode in 1991, the ashas column reached 40 kilometers altitude, and has recently been cited for lowering global temperatures.

A baseline photograph of the area was acquired in 1982 (STS3-10-567). This early photograph clearly shows the region north of Manila and the line of volcanoes which includes Pinatubo. We have no imagery of the actual eruption, which coincided with a typhoon over the same part of the Philippines. The Space Shuttle Earth Observations Photography database does include a substantial time series of post-eruption photographs of the volcano. This time series starts in December 1991 (STS044-82-33) and continues to the present (STS055-151A-184, a 5-inch format color photograph, and STS055-86-118, a 70mm color infrared photograph).

The Pinatubo imagery suite includes photographs from a variety of look angles, and highlights the large areal extent of the region directly effected by the volcanic blasts and still deeply covered with ash (STS050-52-26). Near-nadir views of the volcano summit in Figure 5 (STS046-75-79A) clearly show the distribution of very recent pyroclastic deposits, newly-clogged drainages, and lahar (volcanic mudflow) deposits. Wider-angle views show the distal ends of the lahar deposits, far downstream from the mountain peak.

The series of images acquired during April, May, July, and August of 1992 allows changes in the distribution of downslope lahars over the summer monsoon season to be mapped. Most river valleys are now filled to capacity with mud. The lahars intermittently bring large volumes of unstable volcanic debris from the upper slopes of the mountain down the river drainages to lower regions. Triggered by heavy rainfall, these erosive and high-velocity mudflows cause massive floods. The Pinatubo lahars cut into riverbanks at rates as great as 1m/sec, wash out transportation routes (roads and bridges), cover towns and villages with many meters of debris, and cannot be controlled by the post-eruption dikes of unreinforced lahar deposits which were constructed to contain the later mudflows. The deposits are extremely soft and can not be crossed on foot for several months into the dry season. Many small lakes have formed where drainages became dammed by lahar deposits. The dams can be eroded through by subsequent lahar flows, or fail by overflowing waters, resulting in the breakout of the temporary lakes, and subsequent massive floods downstreams These conditions make comprehensive mapping of lahar deposits from the ground impossible, especially in the short time frame between rains and new depositional episodes, and point to the value of the regional views provided by repetitive Space Shuttle photographs.

Shuttle photographs can help refine estimages of pall size, structure, and optical properties.

The photograph in Figure 5 (STS46-75-79A), when viewed in conjunction with others mentioned above, shows several important changes on and around the mountain. The time series is being used to document the distribution of ash, mud, and debris flows around the mountain after two tropical storms and a second eruption in July 1992. Features of note on this photograph include:

- The crater lake inside the two-kilometer wide caldera is clearly visible, as is the newly formed lava dome (the small islet in the middle of the lake). Philippine volcanologists estimated the dome (at this stage) to be about 300 meters wide and 100 meters high.
- A newly-formed muddy lake appears near the headwaters of the Pasig River (upslope from Clark AFB). Normal stream drainage has been completely disrupted, and pyroclastic flows have buried the divide between the Pasig and Sacobia River and diverted water from the Sacobia River into the Abacan River (which flows just south of Clark AFB). The resulting floods and mudflows eroded through the city of Angeles, a large city on the outskirts of Clark, and buried part of the major highway which runs north from Manila.
- A new lake at the junction of the Mapanuepe and Marella Rivers is easily visible (southwest of the mountain, half-way between the summit and Subic Bay). This is the largest of the new lakes formed from clogged drainages. Should the dam (formed from loosely consolidated ash and debris) fail, a large amount of flooding will occur downstream.
- Fresh lahar deposits can be identified in the Bucao, Balin Baquero, O'Donnell, Sacobia and Pasig drainages (late July, 1992 deposits).
- A large area appears flooded/buried near Poonbato (Bucao River). Because the area does not appear flooded on an STS-50 photograph, it must have occurred in late July 1992.
- One can identify and map the distal end of lahars along the mountains eastern slope where the rivers enter into the central valley.

Russia: Heat flow and Ice cover on Lake Baikal in Siberia—Lake Baikal, the world's most voluminous freshwater lake, occupies an active continental rift zone in southern Siberia which includes large faults and hydrothermal and volcanic fields. Recently, active hydrothermal plumes similar to those found on deep ocean spreading centers, were discovered along a fault boundary in the lake. In addition to the specific occurrence of hydrothermal vents, very high heat flow measurements have been made throughout the lake.

Earth photography from the Space Shuttle is used to examine the ice cover on Lake Baikal, and correlate the patterns of weakened and melting ice with known hydrothermal areas in the Siberian lake. Photographs of the Lake Baikal ice cover taken from the Space Shuttle were taken on several missions. Darkened ice representing probable melt zones are observed on an April 1985 (STS51B) photograph, and on detailed coverage of the lake's late winter ice cover during a late April 1991 flight (STS-39). Exceptionally warm, clear weather over eastern Siberia during the STS-39 flight allowed remarkable imagery of the lake's ice cover to be collected (see Figure 6). This very thin ice cover in the central basin of Lake Baikal was also documented during Space Shuttle mission, STS-56, in the early spring of 1993.

Particular zones of melted and broken ice may be surface expressions of elevated heat flow in Lake Baikal. We have digitized and rectified the photographs of late spring ice cover on the lake, and mapped out melt zones, which are observed in the lake's ice cover in Space Shuttle photography, for two regions: 1) Frolikha Bay in the northeast corner of the lake (where hydrothermal plumes were observed), and 2) the Academic Ridge, a steep, fault-bounded submarine ridge with high heat flow values which extends north from Olkhon Island.

The mapped regions were classified into three different ice textures by considering the ice textures analagous to grain textures seen in metamorphosed crystalline rocks. Regions with large, thick, unbroken ice chunks are mapped as relatively stress-free (Class 1). Areas comprising many small, zoned and rotated pieces have clearly experienced stress and subsequent breakup with some recrystallization (Class 2). Dark circular regions are inter- preted to be thinned and melting, and wet ice cover (Class 3). Class 3 areas occur along coastal regions where rivers empty into the lake, and are surrounded by areas of broken and recrystallized ice cover. Some coastal regions in the southern basin of the lake are completely melted and are not included in this classification scheme.

The digitized photographs were rectified to both bathymetric and heat flow maps. The spatial distribution of the thin, dark-colored ice and the regions of broken and recrystallized ice were correlated to the areas of known "hot spots" on a digitized heat flow map to compare specifically thinned or broken ice with the "hot" spots (Figure 6). The regions of known hydrothermal activity and high heat flow correlate extremely well with circular regions of thinned ice, which are sometimes surrounded by zones of broken and recrystallized ice. Bathymetric profiles, and local and regional climate data, other sources of warm water (e.g., river inlets) and the lake's total ice cover were also considered.

It is suggested that hydrothermal vents can introduce local convective flow which disrupts the overlying stable water column, which, in turn, stresses the ice cover. Ice stress is manifested as regions of weakened ice broken into many smaller pieces. If this physical process is indeed present, then Lake Baikal's hydrothermal activity may have broader effects on the lake's water circulation. The proposal that Lake Baikal's high heat flow may influence patterns in its seasonal ice cover is speculative, but it serves as an example of the versatility of the Space Shuttle Earth imagery to generate many ideas about a spectrum of geophysical processes.

Hand-held photography from the U.S. Space Shuttle provides unique remotely-sensed data for geologic applications.

Windblown dust in South America—The geological activity of wind, in the form of dust plumes and larger palls, is seen on all continents through the windows of the orbiting Space Shuttle. Sources and sinks of dust in South America are reviewed here because of our familiarity with the region and the Shuttle photography, and because the data hold unusual geologic and geomorphic interest.

Repeated calls have been made for effective monitoring of global material fluxes. Tropospheric aerosols hold particular interest not only because of their possible effects on regional and global climates, but also, in South America, because of their implications for nutrient cycling in the Amazonian rainforest biome. The examples below suggest that Space Shuttle hand-held photography indeed has a contribution to make. Four zones are examined with respect to the usefulness of Shuttle photography in detecting dust events, especially sources, sinks and sizes, as well as distances and trajectories of transport: The Amazon basin as a sink for interhemispheric dusts from the Sahara Desert of northern Africa; the Altiplano and Andean mountain chain of Argentina, Bolivia and Peru as a source area of windblown material; local rivers in the Gran Chaco as a source of dust to the local dry forest community of southern Bolivia and northern Argentina; and Patagonia in southern Argentina as a source of dust to the neighboring Atlantic Ocean.

The Sahara has been known for some time as a source of vast windblown dust palls which are transported southwest into the tropical Atlantic during winter and somewhat more westerly during summer. More recently, suspicions have been raised that Saharan dust may be depositing large quantities of material in South Amer- ica since some dust out-breaks appear to reach South America every winter. Geostationary

Figure 6. Ice cover in the central basin of Lake Baikal.

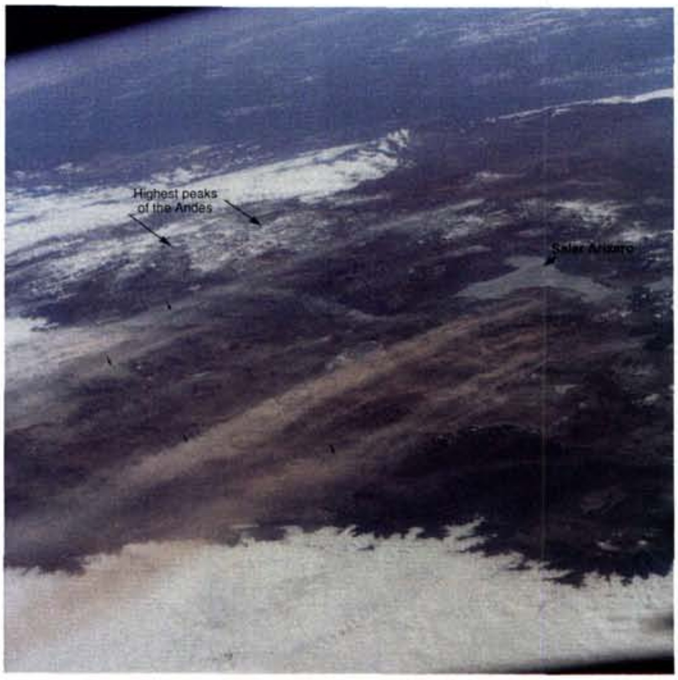

Figure 7. Plumes being whipped up by strong westerly surazo winds.

weather satellites detect these events easily.

Episodic but frequent Shuttle photography documents the boundaries of dust outbreaks at levels of detail unobtainable on the weather satellite data. When palls are thin and boundaries diffuseand especially when boundaries are a great distance from the denser, more detectable central core of a dust pall—Shuttle photographs can help refine estimates of pall size, structure and optical properties. In particular, Shuttle photography gives information on the patterns and behavior of the more subtle vanguard pulses of these large events.

After six weeks the present Saharan dust out-blow event is still active (April-May 1993). It is the longest lasting of any since 1984. The first pulse of this event transported dust all the way to South America in a band 3000 km broad, centered on the Amazon River mouth in Brazil. Several later pulses have done the same. There is no doubt that Saharan dust has been delivered to the rainforest biome of Amazonia. Two Shuttle missions overflew this long duration dust outbreak and captured numerous details over the contrasting background of the ocean surface.

Saharan dust is often advected along the northern coast of South America all the way into the Caribbean Sea. Shuttle photography on a recent mission (STS-56) detected Saharan dust penetrating into the Pacific Ocean beyond Panama.

Shuttle photography has revealed several episodes of dust blowing off the Altiplano, the high arid plateau of Argentina and Bolivia. Four missions between 1983 and 1993 (STS-08, -37, -52, -56) have documented plumes being whipped up by strong westerly surazo winds (Figure 7), suggesting that these events are common features in geological terms. All dust plumes rise on hillslopes (rather than in the great dry lake beds of the Altiplano) and are probably the products of rock weathering. However, a recent mission (STS-55) documented airborne, dust-sized particles blowing off surfaces downwind of Lascar Volcano in Chile (23.4íS 67.7íW). Since Lascar had erupted with a dramatic pyroclastic column one week before the flight, it seems probable that the dust plumes documented by the Shuttle crew are comprised of Lascar's volcanic ash. The sink of this eolian material is apparently the lowlands immediately east of the Andes mountains. Indeed, the plains of the Gran Chaco of northern Argentina are blanketed with windblown loess. The loess is thickest nearest the source, namely against the footslopes of the Andes mountains. Thicknesses of more than 20 meters of uninterrupted loess have been documented.

Altiplano dust plumes have aroused interest as a possible source for some soil nutrient in the rain-forest biome of Amazonia. Although the dust in most plumes seen in the short record of Shuttle photography, is laid down in the Chaco, one instance exists where small plumes can be seen directed in a more northerly direction towards the heart of Amazonia.

For practical purposes, Altiplano dust plumes are too small to be detected on weather satellite imagery. Once Shuttle photography shows their existence, satellite imagery can be enhanced and algorithms developed to reveal them.

Rivers in the Chaco as a source of dust for the local forest vegetation associations—Local sources and sinks of windblown dust have also been revealed by Space Shuttle photography. Blowing dust is generally thought of as confined to zones of aridity. However, a surprising result of the photography has been the documentation of long dust plumes blowing off the large RÆo Grande and smaller RÆo Parapeti in lowland Bolivia (STS-51I, -43, -48). Northerly winds generate these plumes which extend for tens of kilometers into the surrounding dry forest (Figure 8).

STS-56 was the first mission to photograph a medium sized dust storm blowing ENE into the Atlantic off the great Patagonian promontory of the RÆo Deseado. Looking from a point hundreds of kilometers to the east over the Atlantic, an earlier mission acquired photographs showing thin, diffuse dust plumes blowing out into the ocean.

Since it is located at 47!S, the Patagonian outbreak documented by STS-56 may be related to the strong ash fall deposited in this area by Mt. Hudson in Chile (46!S 73!W) which erupted in August 1991. The thickest palls blowing off Patagonia immediately after the eruption in 1991 were clearly visible on the 5-km data of the GOES weather satellite, even over land. Smaller events over land, however, are almost impossible to observe. Oblique views of the smaller event photographed by the STS-56 crew leave no doubt about the phenomenon or the detail of specific point sources which were either not immediately detectable on the GOES imagery or not detectable at all.

Figure 8. Dust plumes blowing in lowland Bolivia.

Hand-held photography from the U.S. Space Shuttle provides unique remotely-sensed data for geologic applications because of the combination of varying perspectives, look angles, and illumination, and changing resolution resulting from different lenses and altitudes. The comprehensive, regional views provided by these variables allow for new, and sometimes controversial insights into global geologic processes like ephemeral events (such as the post-eruptive changes around Mt. Pinatubo or dust transport), and local and regional problems. Three ways that the Shuttle photography have the potential to broaden geological investigations are: *A new sense of scale*—Regional features and structures from a few kilometers to a few hundred kilometers can be viewed in context with the surrounding structures. This becomes especially true when the Shuttle photographs of different scales of an area are available, and are used in conjunction with ground observations, or even microscopic and geochemical data. Oblique photographs which encompass large regions with varying scale within a photograph often provide key perspective cues for interpreting geological features. A *new sense of local and regional patterns, or change of pattern*—Different geological domains can be identified and mapped. This is also aided by photographs of different look angles and scales. *Changes over time*—Although the photography of short-lived or ephemeral geological phenomena is opportunistic, we have many examples of Astronaut observations of features like volcanic erup- tions and areal changes after eruptions, blowing dust and dust deposition, surface hydrology and associated changes, and coastal/nearshore sedimentation and erosion.

How can you get involved?

Our scientists work and operate in an multi-disciplinary mode while their expertise includes many areas of Earth sciences such as ecology and physical geography, surficial geology and geomorphology, tectonics, volcanism, biological and physical oceanography, meteorology, and climatology. Much of our effort is concentrated upon astronaut training, mission operations, and postflight database updating. Scientific analysis of our data in-house is limited due to our resource levels. While we have some cooperative projects underway, we encourage undertaking joint research projects with universities, other agencies and individual scientists.

You can easily access our electronic database to search for appropriate data. If you wish to have future missions acquire data over specific regions, you may contact us for the details about upcoming missions.

Footnotes:

1. To access the Database though INTERNET: Enter TELNET SSEOP.JSC.NASA.GOV. When queried for "Username" and "Password," enter PHOTOS at each prompt. A menu will enable the user to search the data base for photographic coverage of geographic regions defined by latitude and longitude, to down-load the entire database (45 megabytes), or to download selected digitized photographs.
2. NASA Space Shuttle Photography suppliers include: EROS Data Center, Sioux Falls, SD 57198, tel. 605-594-6151/fax 605-594-6589. Technology Application Center, Uni- versity of New Mexico, Albuquerque, NM 87131-6031 tel. 509-277-3622/fax 509-277-3614. NASA/Johnson Space Center, Houston, Texas 77058