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LANDSAT (ERTS) IMAGES USED AS A BASIS FOR GEOLOGICAL-
VOLCANOLOGICAL MAPPING IN THE CENTRAL ANDES

S. Kussmaul and C.E. Brockmann

Translation of "Satelliten-Aufnahmen als Grundlage für geologisch-
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16. Abstract ERTS images of the central Andes (N-Chile, W-Bolivia) were effectively used for volcanological mapping of an area about 160,000 km ² . The map shown exhibits more and better details than the older small-scale geological maps of that area. Because of the large area they cover, satellite images make it possible to recognize geological and structural features within large areas. Further, the images are well suited to volcanic morphology studies. Even on a scale of 1:1,000,000 details greater than 200 m in size are recognizable. The interpretation of ERTS images makes it possible to establish relative age sequences of strato-volcanoes. Finally, the images will also be helpful in prospecting for mineral deposits and geothermal sources.			
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VOLCANOLOGICAL MAPPING IN THE CENTRAL ANDES

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Introduction

The purpose of this work was to test what possibilities satellite images offer for volcanological mapping and what volcanic forms can be seen in the photographs. The map presented here is based exclusively on the evaluation of black and white photographs taken by the ERTS-1 satellite on a scale of 1:1,000,000. Existing geological maps of the area studied were not consulted. Later accessible enlargements on a scale of 1:500,000 and 1:250,000 and false color photographs together with subsequent terrain observations were not taken into consideration in the map. /134¹

The Earth Resources Technology Satellite (ERTS-1) was started in July, 1972. Since the end of 1972 Bolivia has been taking part in this NASA scientific program in the areas of Hydrogeology, Geomorphology, Regional Geology, Mineralization, Soil Science and Vulcanism.

The ERTS satellite circles the earth at a height of 915 km and has an orbit time of 103 minutes. Due to the rotation of the earth the satellite passes over the same area every 18 days. The surface of the earth is photographed by means of a multispectral scanner which works in the green, orange-red, red-infrared and infrared regions of the spectrum (channels 4, 5, 6 and 7). Thus the satellite produces four congruent black and white images of each area photographed. For geological evaluations the infrared

1. Numbers in the margin indicate the pagination in the foreign text.

photographs (channels 6 and 7) proved to be the best, since the various lithological details and geological structure show up in them in greater contrast and are more strongly differentiated. By combining different filter photographs it is possible to produce a false color image. The most common combination is 4, 5, 7 (green, red, infrared). In the resulting false color photograph solid rocks are shown in colors ranging from green to brownish green; water in blue; clays, salts and snow in white and living plants in red. This 4-5-7 combination is used primarily for the study of vegetation [3]. By changing the filter combination and the film emulsion it is possible to obtain a large variation in color tones, color intensity and color distortion. /135

Each photograph covers an area of 180x180 km or 32,000 km². Distortions due to photographs which deviate from the perpendicular, as a result of the height of the relief in relation to the flight altitude, or distortions due to the curvature of the earth are very small, and on a scale of 1:1,000,000 they lie within the range of the accuracy of the signal. ERTS images can therefore be used directly as topological data. On a scale of 1:1,000,000 seas, lagoons, small rivers and mountain ridges can be very easily recognized in the satellite image. By contrast, streets and railroads can only rarely be detected.

The advantage of satellite photographs in comparison with aerial photographs consists of the fact that large areas of the earth's surface can be shown in a continuous picture with hardly any distortion. The photographs thus provide a good overview of the layout and relationship of large geological forms and structures. Factors such as clouds and vegetation which interfere with geological evaluations are nearly nonexistent in the highland of the Andes. The Altiplano together with the bordering west and east cordillera is completely treeless and largely devoid of plant growth. In addition, during the winter months (May to

October) the sky is for the most part free of clouds.

The available pictures consist of six ERTS photographs on an approximate scale of 1:1,000,000 (Fig. 1).

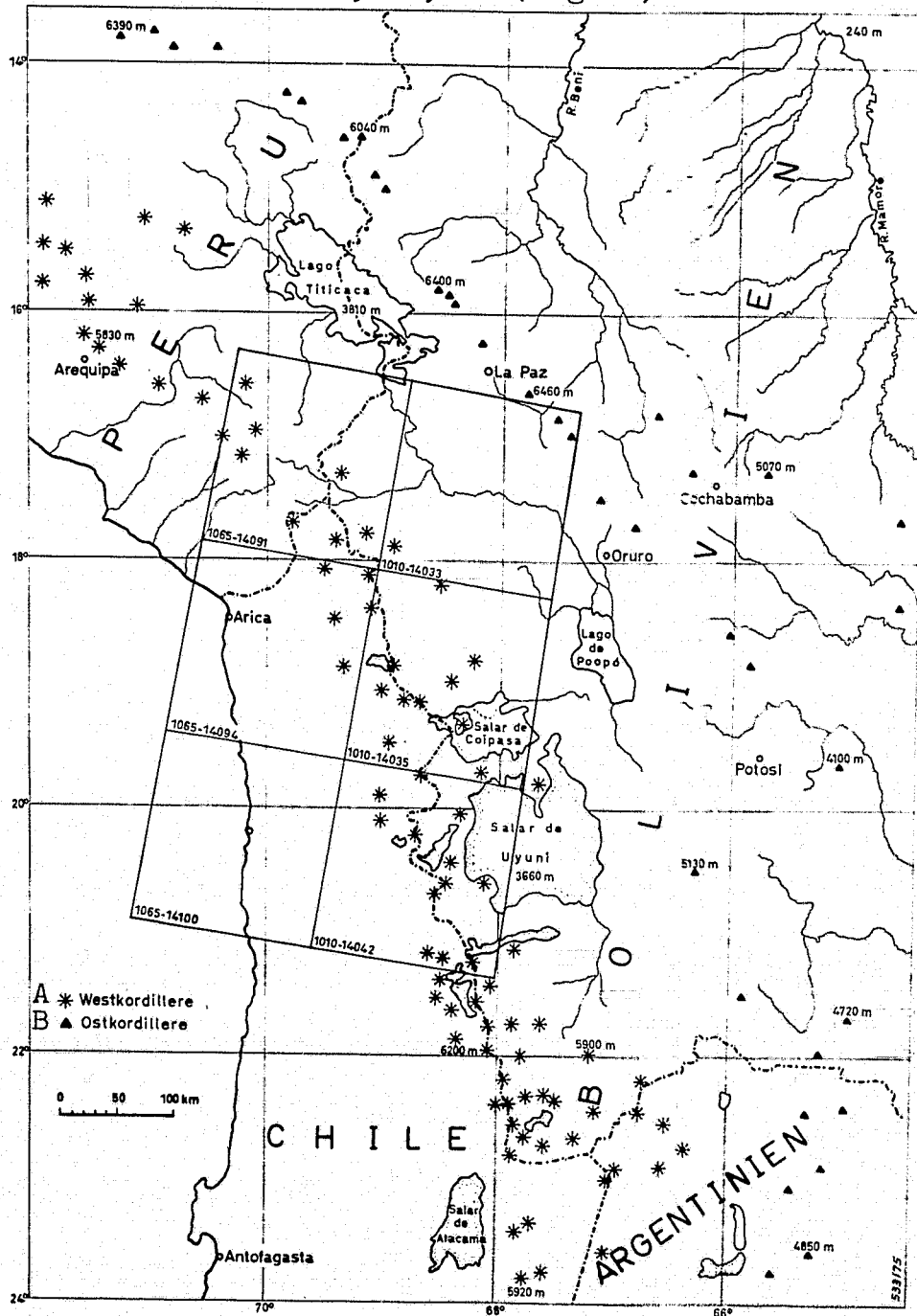


Fig. 1. Geographical position of the 6 ERTS photographs evaluated. Three of these are reproduced in this article. The images cover the outlines area. The numbers correspond to the different ERTS photographs. (Key: A. West Cordillera, B. East Cordillera)

The series of pictures on the east side were taken on August 2, 1972, and those on the west side were taken on September 26, 1972. The interpretation was done on black and white photographs of channels 6 and 7. A comparison of black and white and color picture interpretation shows that in general the false color photographs provide more information and are superior because they show a sharper relief [4] [5]. This greater amount of information is due mainly to the much greater color scale of the color pictures. Thus in false color photographs it is now and then possible to further distinguish large rock details such as quaternary sediments or tertiary ignimbrite.

The photographs overlap each other in the north-south direction (same pass over of the satellite) by about 16 km, and in the east-west direction (2 different pass overs) by about 44 km. The total surface area covered by these six satellite pictures is about 160,000 km². The area covered by the photos extends from the East Cordillera in the north east to the Pacific Ocean in the south west and includes the southern most portion of Peru, the northern part of Chile and west Bolivia.

By far the largest portion of the area is occupied by volcanic rocks. The West Cordillera, which is built up of quaternary volcanoes, passes through the photographed region in a NNW-SSE direction (Fig. 1). Adjoining on the west and east are vast ignimbrite layers. The region between the West Cordillera and the East Cordillera -- the Altiplano, which consists of paleozoic rock -- is filled with tertiary sediments. This borders with volcanic material on the west.

The Altiplano consists of a series of basins and plateau landscapes. The closed basins and the arid climate in the southern portions of the Central Andes favor the formation of salt lakes. In the northern most basin of the Bolivian Altiplano

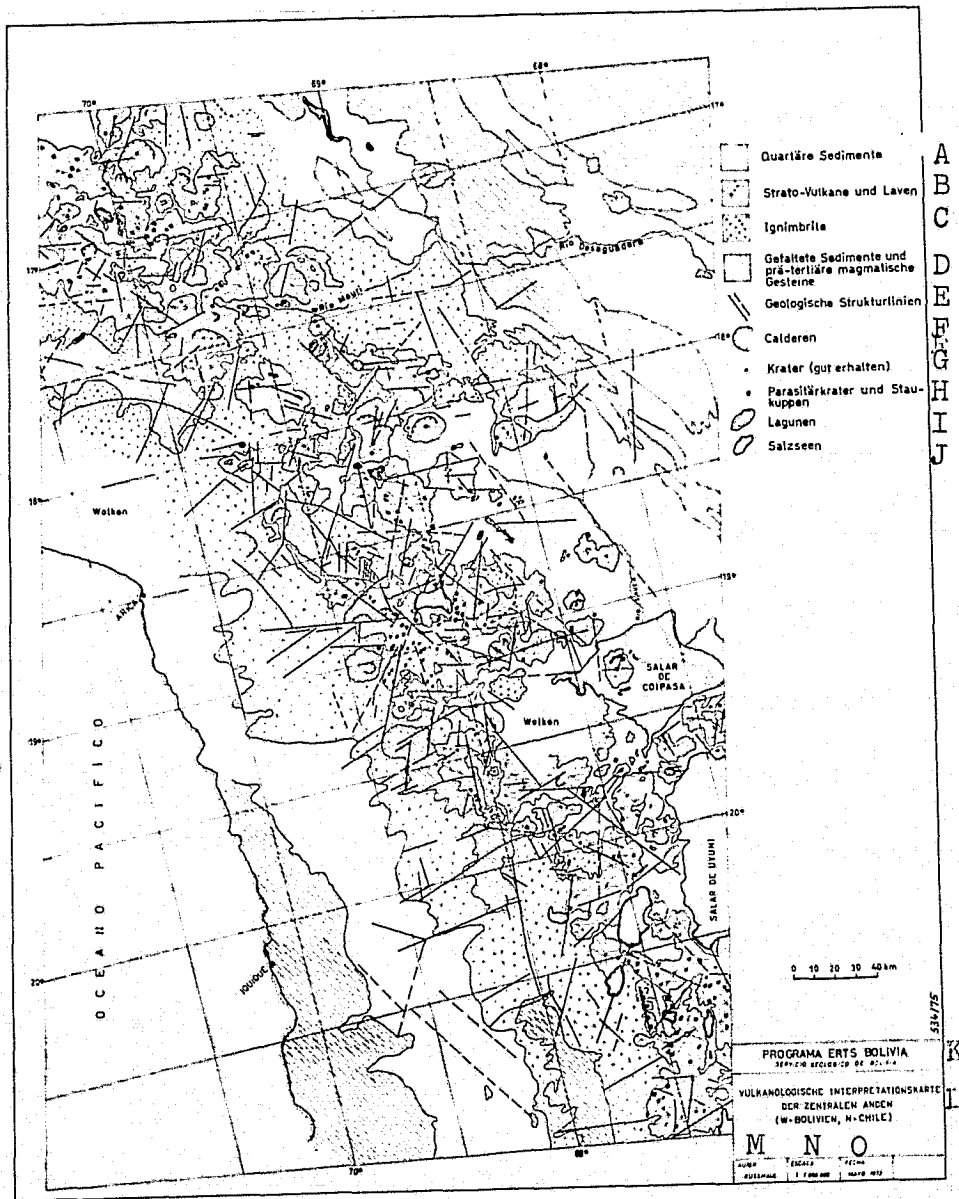


Fig. 2. Volcanological survey map of a portion of the central Andes based on ERTS photographs. (See Fig. 1 for the map location.)

- | | |
|---|---|
| Key: A. Quaternary sediments | I. Lagoons |
| B. Strato-volcanoes and lavas | J. Salt lakes |
| C. Ignimbrite | K. Bolicia ERTS Program, Geological Service of Bolivia |
| D. Folded sediment and pre-tertiary magmatic rock | L. Volcanological interpretation map of the central Andes (West Bolivia, North Chile) |
| E. Geological structure lines | M. Author |
| F. Caldera | N. Scale |
| G. Craters (well preserved) | O. Date, May 1972 |
| H. Parasitic craters and crater lakes | |

is located the slightly salty Lake Titicaca at an elevation of /138
3,810 m. Poopo Lake, whose water is already quite salty, is
located in another large basin. The Salar de Coipasa is
largely covered with a salt layer. The largest salt lake in
South America is the Salar de Uyuni with a surface area of
9,000 km² at an altitude of 3,660 m. It is completely covered
with a thick layer of salt 2-8 m thick [1] [2]. Between the
large strato-volcanoes of the West Cordillera there are small
lagoons which become increasingly salty the farther south they
lie.

Evaluation Results

The photographs supply excellent data for young volcanic
rocks. On the basis of color differences, surface structure,
the weathering pattern and the drainage system different litho-
logical-petrographical details can be differentiated one from
another. Gray tone differences are very important for sub-
dividing rocks. A more precise evaluation of the photographs
must therefore be done with densitometers with which the dif-
ferent gray tones can be much better detected than with the
eye. But in so doing it must be taken into consideration that
the gray color apart from the initial rock also depends on the
age of the rocks. Due to the weathering and plant growth
(lower plant species) the vulcanites show up in lighter colors
with increasing age.

In the ERTS photographs three different kinds of volcanic
details can be distinguished:

1. Ignimbrites

Ignimbrites form vast, horizontal layers. In the black and
white photographs they show up medium gray and in the 4-5-7 color

pictures they show up light green. They have a smooth surface or a fine dendritic drainage pattern. Canyon-like dry valleys are often cut into the surface. Steep steps often appear at the edge of the Ignimbrite layers. The above characteristics are normally observed only in the case of young or strongly fused Ignimbrites. The lack of vegetation and the large daily fluctuations in temperature cause intense and rapid weathering. This leads first to thin, platy separation and then fine flaky breakdown of the rock. Finally, the end product consists of a fine sand. The sand collects in basins while the fine, flaky material remains on the surface. Therefore in the photographs the Ignimbrites present a smooth and homogeneous surface and only a very weakly developed drainage pattern. Due to the covering with weathered material the colors are considerably lighter and the basins filled with sand appear almost white.

Ignimbrites are usually produced by linear eruptions. It is extremely difficult to locate volcanic rents in the ground. By combining ground observations with ERTS photograph interpretations it is however possible to locate a few rents or at least limit them to a rather confined region. For example, in south west Bolivia it was possible to show that Miocene Ignimbrites flowed out of the north-south running rent in the eastern portion of the Altiplano. The volcanic rents of Pliocene Ignimbrites, on the other hand, were concentrated in the region of the present West Cordillera. However they can also be found in the central and southern parts of the Bolivian Altiplano.

2. Strato-Volcanoes

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Strato-volcanoes are characterized by dark gray or dark green to brownish green colors. They have rounded tips and usually show a radial drainage pattern. The West Cordillera and the

higher, separately standing volcanoes of the Altiplano were glaciated. Due to large differences in degrees of erosion a relative age sequence of the volcanoes and a classification inot three different age groups can be drawn up:

- a) Miocene to Pliocene volcanoes: in a few palces these volcanoes were covered with Ignimbrite layers. These structures are flat dome-shaped and deeply carved by erosion. The drainage pattern is very thick, radial to irregular.
- b) Pleistocene volcanoes: these volcanoes sit on top of the Ignimbrite layers and have been glaciated at least once. The majority of strato-volcanoes belong to this group. In the ERTS photographs these pre-glacial volcanoes are for the most part somewhat darker than the Miocene-Pliocene volcanoes and in contrast to the latter they taper to a point. Wide radial galcial valleys can be obserced on the slopes.
- c) Holocene volcanoes: these volcanoes were no longer glaciated. In the black and white photographs they appear dark gray to black and reveal still well maintained apical craters and slopes without deep erosion.

The photograpahs also show that the large volcano structures consist mostly of several main craters. It is often possible to detect a multiple crater shift in a westerly direction. Frequently parasitic craters or crater lakes can be seen sitting on the slopes. On a few strato-volcanoes separate large lava streams can be distinguished. Because of their black color they stand out clearly from the surroundings.

3. Lava Plateaus

North of the Sajama volcano (Fig. 3, lower left) small lava plateaus appear. They consist of horizontal lava flows which

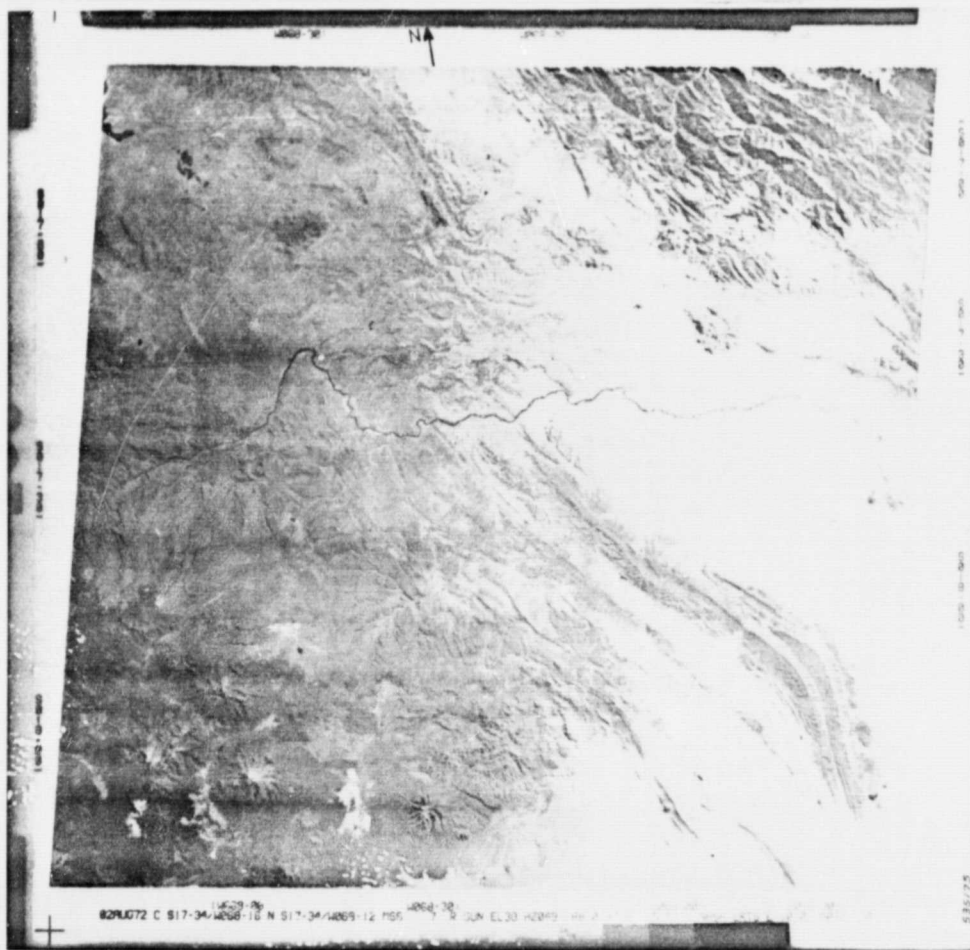


Fig. 3. ERTS-1 1010 14033, infrared; photographed on Aug. 2, 1972

Upper right the East Cordillera with the snow covered intrusion bodies of the Tres Cruces Cordillera; in the upper left corner a vermicular outlet of Lake Titicaca. This drains via the Rio Desaguadero into Lake Poopo. The upper course of the Rio Desaguadero can hardly be distinguished; this is probably due to the fact that the river carries so much mud. The Rio Desaguadero first comes clearly into view below the point where the Rio Mauri runs into it (sharp bend in the course of the river) flowing towards the center of the right hand edge of the picture. Lower left: volcanoes of the West Cordillera. These are the snow covered peaks of the Parincota (holocene), of the Pomerape and the Sajama, which at 6556 m is the highest mountain in Bolivia. Dark, flat lava plateaus lie in the north east of the volcano group. Further towards the NE is a young Ignimbrite plateau which terminates in the south on the Turaquiri volcanic edifice (lower center). The Turaquiri Massif involves a Miocene to

Pliocene (?) volcano group which is very deeply carved by erosion. Tertiary sediments pass through the picture in a NW-NE direction. In the lower portion the folding of the sediments and the bending of the trend from NW to N-S (Andes bend) can be easily recognized.

have flowed out of small slag craters. The craters stand out clearly in the photograph. The surface of the lava plateau appears dark gray, homogenous and without a drainage pattern.

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The greatest advantage of satellite photographs, however, lies in the discovery of volcano-tectonic elements. Ground studies in south west Bolivia and in the Central Altiplano showed that the lineaments discovered in the evaluation can also actually be detected in the ground. The structural elements stand out distinctly because of sharp color differences in adjacent stones, quick changes in the relief, deep valley formations by a shift of characteristic layers and by the lining up of long stretches of morphological elements such as volcanoes and lagoons.

Ground observations have shown that most of the linear structures involve upward thrusts. Horizontal shifts, down-thrusts and fault lines are less common. The lineaments often extend over a length of more than 100 km and can be traced in spite of quaternary sediment covering. Along the lines of disturbance strato-volcanoes are often built up or explosion craters have formed. On a few E-W running lineaments a migration of volcanic activity in a westerly direction can be perceived. In the northern and central Altiplano and in the corresponding section of the West Cordillera the tectonic lineaments follow the main NNW-SSE, E-W and NE-SW trends; in the south there is in addition the main N-S trend.

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Additional noteworthy elements are craters and claderas, i.e. circular or semi-circular volcanic structures. Two types

can be distinguished genetically:

- a) Craters and Explosion Claderas: these include the circular structures which can be observed in the center of the strato-volcanoes. Of the actual summit craters there are transitions to explosion calderas which have a rather large diameter. Explosion caldera also appear outside the area covered by volcanic rocks. East of the Salar de Coipasa craters have been observed in the ground from which only a little slag material has been expelled. The double-ringed crater of Culloma (NE corner of Fig. 4), which is about 5 km across and whose origin has not yet been explained, was probably created by phreatic explosions (Maar).
- b) Collapse Cladera: collapse caldera are most frequently observed on the large strato-volcanoes. Usually their diameter is larger than that of the explosion caldera and they are often eccentrically positioned. In many cases a new volcano has been built up in the interior of the caldera (for example Pumiri in Fig. 4).

In the 4-5-7 false color photographs several small areas or rivers are colored an intense orange-red. This red coloring is due to vegetation, for the chlorophyl contained in the green leaves has a high degree of reflection for infrared rays [3]. Ground observations in the central Altiplano and in south west Bolivia suggest that the vegetation is always connected with the presence of thermal waters.

Miocene subvolcanic intrusions are widely spread out in the south east protion of the Altiplano (outside the area covered by the map in Fig. 2). Most of these intrusions are rich ore carriers (mainly tin, tungsten, antimony, zinc and silver [2]). In ERTS photographs many of these Massif centers show up in light colors. This color change is probably due to rock migrations

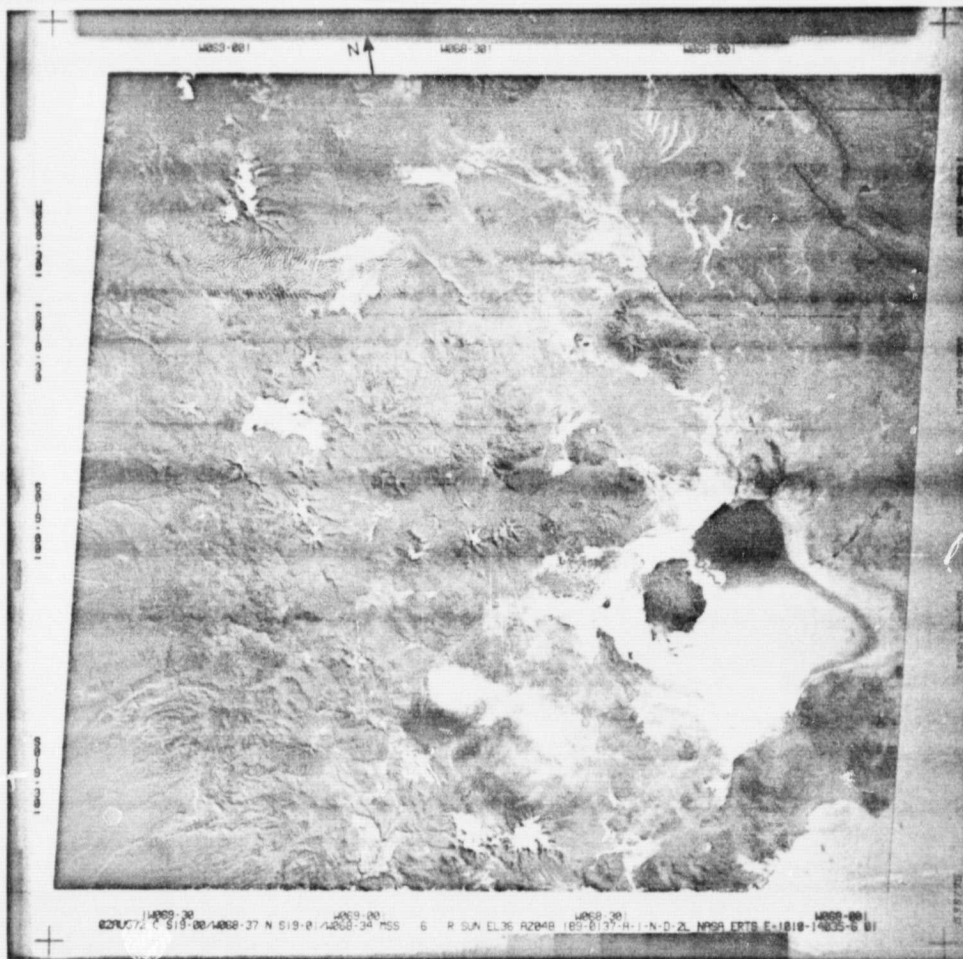


Fig. 4. ERTS-1 1010-14035, red/infrared; photographed on Aug. 2, 1972.

In the left portion the NW-SE running west Cordillera. Adjoining on the east are Ignimbrite plateaus and mesozoic rocks. At the lower right a portion of the Salar de Uyuni which in the north is separated by a chain of volcanoes from the Salar de Coipasa. Coming from the north the Rio Lauca empties into the basin of Coipasa and forms Lake Coipasa (black). The by far largest portion of the basin is covered with salt (white). In the Salar de Coipasa is the Coipasa volcano on the north slope of which sit 5 young and well preserved parasitic cones. North west of the Salar de Coipasa runs an E-W lineament. Lined up along this are 5 largish volcanic structures. In the middle of the volcano complex can be seen a triple crater shift. The volcanic activity in the holocene advanced far to the east: on the NE slope of the Sacasani a parasitic crater was formed, west of this the Tata Sabaya volcano on which 3 young and very well preserved lava flows can be distinguished. North of the Sacasani the

Pumiri volcano stands out. This consists of 2 different old eruption cones. A younger, probably holocene volcano was built up inside a caldera; this can be distinguished by its semi-circular shape. West of the Pumiri lies the Carangas Massif, consisting of a succession of folded Miocene (?) Ignimbrites and lavas. The upper right hand portion of the photograph is covered with quaternary debris. In the upper right are folded tertiary sediments which stand out from the quaternary deposits. West of these tertiary ridges, in the middle of the debris deposits, lies the crater of Culloma.

in the course of mineralization and can therefore serve as an important indication for prospecting studies.

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Conclusions

It was not possible using satellite photographs to detect deformations within the volcanic rock series. This may be due to the similar lithological composition of volcanic rocks, to the small degree of folding of the series or to the small scale of the photographs. By contrast, synclines and anticlines only a few kilometers long can be identified in the tertiary sediments which consist of alternate layers of clay and sandstone.

It was just as impossible to detect a few caldera found on the ground in the ERTS photographs. The reason for this may be that the collapse had only a small throw, that it involved a very old caldera which in the meantime had largely been filled up, or that a young volcano had built up inside the caldera and largely covered the relief differences.

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Moreover, by means of satellite photographs it is not possible to distinguish between the actual volcanoes and the rubble material surrounding them. This is due to their identical petrological composition. For this reason the areas on the map (Fig. 2) which are occupied by volcanoes are for the most part shown too large. As ground observations have shown, strato-

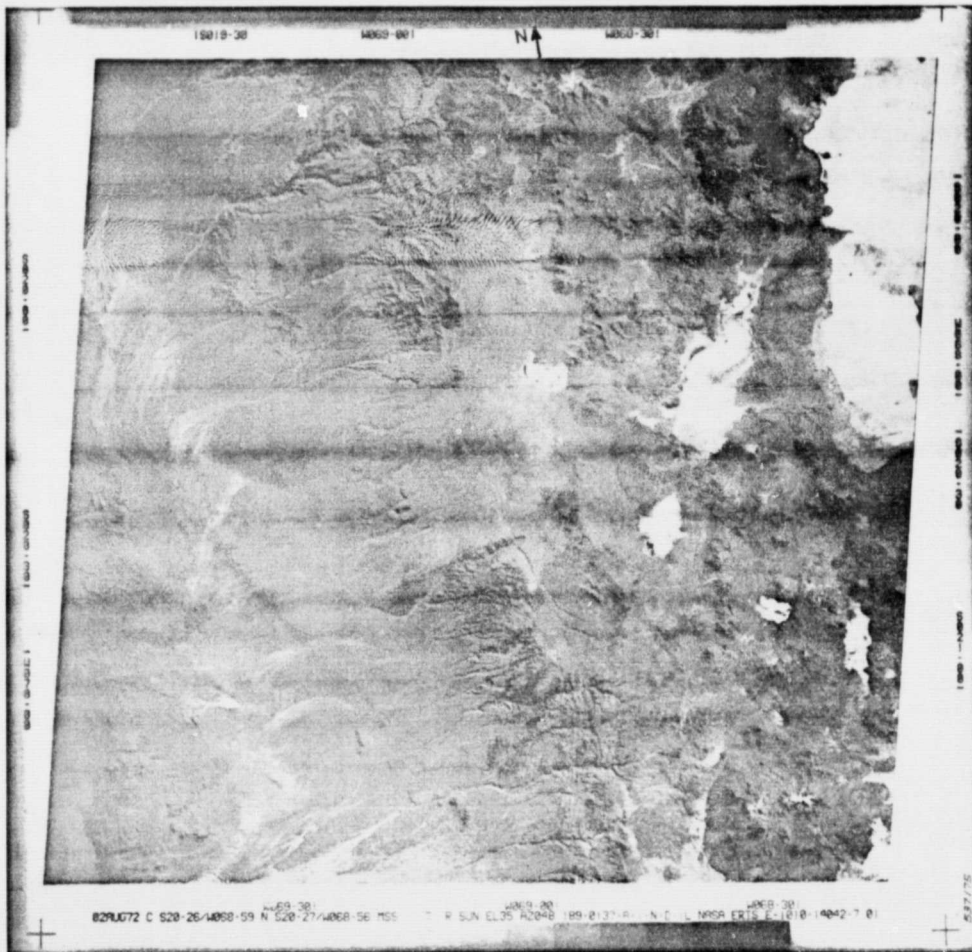


Fig. 5. ERTS-1 1010-14042, infrared; photographed on Aug. 2, 1972.

Area between the West Cordillera (right side of picture) and the coast Cordillera of Chile (left side of picture). Upper right, a portion of the Salar de Uyuni and the Salar de Empexa. Many quaternary strato-volcanoes stand out on the right side of the picture; some of these are post-glacial, such as the Sinalaco volcano (between the the Salar de Uyuni and the Salar de Empexa). It has three well preserved summit craters. In the east (on the bank of the Salar de Uyuni) and especially to the west of the volcano belt there are extensive Ignimbrite plateaus. About in the middle of the picture a ridge of Mesozoic rocks running N-S stands out like a window. The Mesozoic rocks are characterized by a very thick drainage pattern. In the lower left are young debris and gravel deposits which occupy the entire region between the Ignimbrites in the east and the coast Cordillera.

volcanoes generally begin with the rise in the relief.

The above map (Fig. 2), which is based only on the evaluation of satellite photographs, shows how inexact previous geological survey maps of the Andes region are. If we compare it for example with the geological map of Bolivia on a scale of 1:2,500,000 (1968) then we find that this map can fundamentally be improved solely by evaluating satellite pictures.

Summing up, it turns out that because of the large area covered by a satellite photograph it is possible to clarify the geological and structural relationships of a large area. At the same time the pictures enable us to recognize individual strato-volcanoes down to the level of their secondary forms, such as parasitic craters, crater lakes and lava flows. Due to different degrees of erosion it is possible to classify individual strato-volcanoes according to age. But satellite pictures are especially informative for identifying structural elements. Disturbances, strings of volcanoes and calderas are much easier to discover in the interpretation of ERTS photographs than on the ground or in traditional aerial photographs. For this reason the majority of disturbances and calderas are not contained in existing geological maps.

The evaluation of satellite pictures makes it possible to produce small-scale geological maps within a short period of time. This is also possible in areas for which no topographical data is yet available. However for large-scale mapping (1:250,000) and for detailed studies land observations and aerial photograph interpretations will also be indispensable in the future. The combination of ERTS photographs, aerial pictures and ground mappings promise the best results for future geological map making.

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