HIGH RESOLUTION AIRCRAFT SCANNER MAPPING OF GEOTHERMAL AND VOLCANIC AREAS

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SUMMARY- High spectral resolution GEOSCAN MkII multispectral aircraft scanner imagery has been acquired, at 3-6 m spatial resolutions, over much of the Taupo Volcanic Zone as part of continuing investigations aimed at developing remote sensing techniques for exploring and mapping geothermal and volcanic areas. This study examined the 24-band: visible, near-IR (NIR), mid-IR (MIR) and thermal-IR (TIR) imagery acquired over Waiotapu geothermal area (3 m spatial resolution) and White Island volcano (6 m resolution). Results show that colour composite images composed of visible and NIR wavelengths that correspond to colour infrared (CIR) photographic wavelengths can be useful for distinguishing among bare ground, water and vegetation features and, in certain cases, for mapping various vegetation types. However, combinations which include an MIR band (~ 2.2 μm) with either visible and NIR bands, or two NIR bands, are the most powerful for mapping vegetation types, water bodies, and bare and hydrothermally altered ground. Combinations incorporating a daytime TIR band with NIR and MIR bands are also valuable for locating anomalously hot features and distinguishing among different types of surface hydrothermal alteration.

1. INTRODUCTION

Geothermal systems are important sources of energy for many countries, including several of the developing nations. Unfortunately, the initial and very important reconnaissance and exploration phases of these systems can be very demanding and expensive, because of their relatively large surface extent (≥ 10 km^2) and the often generally small size (typically ≤ 10 m) of easily observable surface features. These drawbacks are exacerbated by the difficult terrain and dense vegetation common in temperate and tropical zones. This usually means relatively costly and lengthy surface based surveys (e.g. resistivity soundings and traversing, geochemical sampling, etc.) are conducted with very little prior information available to guide them in these earliest phases of investigation- at a time when there is little enthusiasm for spending. Detailed surface feature mapping and monitoring of geothermal systems in both natural and exploited states provides even bigger challenges (Mongillo, 1994; Mongillo and Bromley, 1992).

The identification and mapping of active and potentially active volcanos also presents serious challenges to investigators (Mouginis-Mark *et al.*, 1989), though lack of knowledge in this case can have devastating consequences. Volcanos and their eruptions are difficult to study due to the dangers inherent with close-up observation of the violent activity and their global distribution and remote location. The large scale of explosive and lava producing eruptions often precludes comprehensive ground based determination of the spatial and temporal 'developments of lava flows and ash plumes.

Satellite remote sensing methods used for the study of geothermal and volcanic phenomena have progressed significantly in the past 5 years or so, and can now provide valuable information not easily, or even previously, available. Existing earth resources satellites including LANDSAT, SPOT, JERS-1 and IRS are capable of providing frequent, repetitive and relatively high spatial resolution imagery (18-30 m) over most regions of the world. During the past three years, a joint New Zealand/French project has been evaluating the use of SPOT PAN, SPOT XS and LANDSAT TM satellite imagery for identifying and mapping geothermal areas in the Taupo Volcanic Zone (TVZ) of New Zealand. Work by Deroin *et al.* (1995), and preliminary studies by Cochrane *et al.* (1994) and Mongillo *et al.* (1995), have demonstrated the ability of SPOT and LANDSAT TM imagery for detecting and mapping the larger surface thermal features, such as sinter terraces, bare altered ground, fumaroles, hot pools, and especially the associated *geothermally stressed* vegetation caused by the presence of elevated ground temperatures, geothermal fluids and anomalous soil chemistry. These investigations emphasised the ability of the MIR wavelength (~ 1.65 μm) to discriminate the stressed vegetation, which is an important target for satellite remote sensing in geothermal reconnaissance and exploration because it can extend over much larger areas than individual surface manifestations. The importance of high spatial resolution data was emphasised with the problems of insufficient spatial resolution (≥ 80 m) cited in the studies of Camacho *et al.* (1982) and Jinich *et al.* (1981). Ruiz-Armenta and Prol-Ledesma (1995) also demonstrate the present capability for detecting hydrothermal alteration in densely vegetated areas.

LANDSAT TM, and the much coarser spatial resolution (1 km) AVHRR weather sensors, can provide very frequent coverage (up to twice daily), and have proven useful for identifying and analyzing eruptions (Mouginis-Mark *et al.*, 1994), mapping and monitoring the evolution of thermal anomalies on remote volcanoes (Gaonac'h, *et al.*, 1994; Mouginis-Mark, *et al.*, 1989) and for measuring the temperature of the crater lake at Poás volcano, Costa Rica (Oppenheimer, 1993).

Aircraft remote sensors have also proven very valuable for certain volcano and geothermal studies because of the good spatial detail, high spectral resolution and wide spectral wavelength range data they are capable of providing. The airborne thermal infrared multispectral scanner (TIMS) has been successfully used to estimate the sulphur dioxide flux from Mt. Etna, Italy (Realmuto e?*al.*, 1994) and map the temperature and emissivity (which can be related to relative age) of young basaltic lava flows of Kiluea volcano, Hawaii (Realmuto e?*al.*, 1992). Oppenheimer e?*al.* (1993) used the airborne visible/infrared imaging spectrometer (AVIRIS) to map the temperature distribution of hot spots on Mt Etna and Mt Stromboli (Italy).

Various airborne TIR scanners have also been used to map active geothermal areas in several countries. In New Zealand, for example, Mongillo and Bromley (1992) used a video TIR scanner to map the entire Rotorua geothermal field as part of a thermal feature baseline monitoring survey and Mongillo (1994) used the GEOSCAN multispectral TIR data to map the thermal features associated with the Waimangu-Waiotapu geothermal region.

Unfortunately, the practical application of multispectral airborne scanners is often limited by both accessibility and cost, which can be substantially more than that of acquiring satellite imagery of the same area. Consequently, the use of multispectral aircraft scanners is usually limited to special study cases, for example, where the value of a potential mineral discovery or cost of volcanic destruction far outweighs the cost of the survey, or for studies where the scanners are used to develop new satellite sensors by simulating them or to help develop new techniques for interpreting existing or new satellite data. With further data analysis and interpretation development, existing earth resources satellites (LANDSAT, SPOT, JERS-1, IRS) will be capable of providing rapid and very cost-effective tools for conducting both the initial investigations and the intermediate scale ($\geq$ 10-20 m) mapping and monitoring of geothermal and volcanic areas. The new satellite scanners now being planned (e.g. ASTER, HIRIS) will extend these capabilities by including more spectral information at higher spatial resolution. Consequently, it is important to understand and develop the techniques required for such satellite remote sensing applications.

The present studies were undertaken as the first stage of a longer term development of LANDSAT TM and JERS-1 satellite image analysis and interpretation procedures, and to aid development of future satellite scanners such as ASTER and HIRIS. The abundance of accessible geothermal and active volcanic systems in the Taupo Volcanic Zone (TVZ) of New Zealand, for which detailed information presently exists, and the existence of JERS-1, LANDSAT TM, and SPOT PAN and XS satellite images and GEOSCAN aircraft scanner imagery for the area provides the opportunity. This study presents preliminary results obtained from the analysis of the GEOSCAN spectral bands which correspond to those available on the LANDSAT TM scanner. The work here is guided by the results of our previous satellite investigations (Cochrane e?*al.*, 1994; Deroin e?*al.*, 1995; Mongillo e?*al.*, 1995).

2. STUDY AREAS

The Waiotapu geothermal area and White Island volcano were chosen as the first New Zealand test sites for evaluating the application of the GEOSCAN aerial multispectral scanner (Fig. 1).

2.1 Waiotapu Geothermal Field

The Waiotapu geothermal field is located in the central pan of the Taupo Volcanic Zone (TVZ), about 50 km NE of Taupo (Fig. 1) (see Hedenquist, 1986 for details). Though one of over 20 major geothermal fields within the TVZ (Mongillo and Clelland, 1984), Waiotapu is a major tourist area noted for its outstanding surface geothermal features.

Waiotapu has the largest area of surface thermal activity (18 km^2) of any field in New Zealand and is considered to be an active epithermal mineral depositing system (Hedenquist, 1986). The surface activity consists of large areas of steaming ground, fumaroles and associated collapse craters, mudpools, silica deposits (especially the large silica terrace), hot pools, hydrothermal eruption craters and alteration due to acid-sulphate fluids. Four large hydrothermal eruption craters are present in the south, two of which contain Lakes Ngakoro and Whangioterangi and one forming Champagne Pool, the largest chloride discharge feature at Waiotapu (Simmons e?*al.*, 1992). Two dacite domes mark the northern extent of the field.

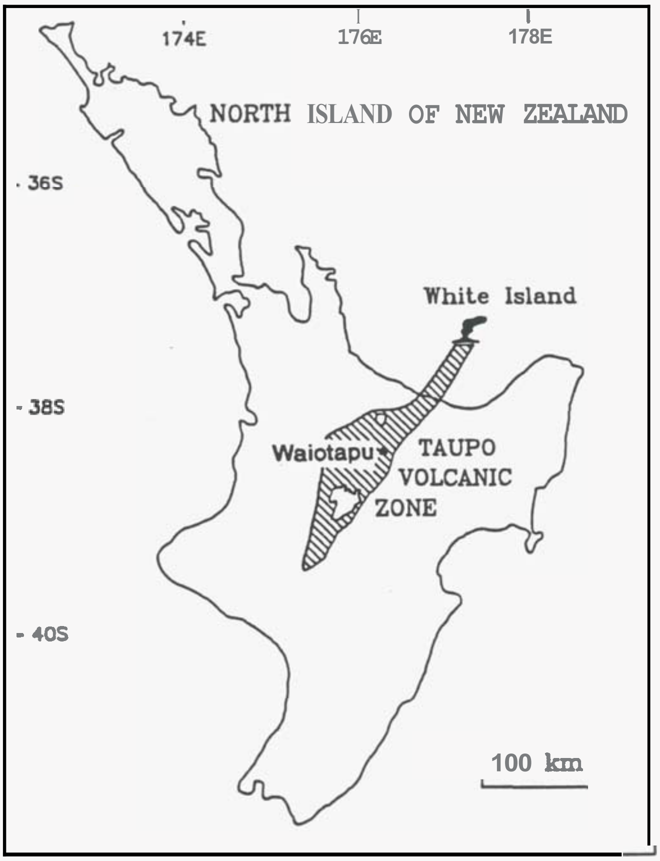

Fig. 1 Sketch map showing the locations of Waiotapu geothermal field and White Island volcano in the TVZ.

2.2 White Island Volcano

White Island is an active volcano situated at the northern end of the TVZ, about 50 km NE of Whakatane, in the Bay of Plenty (Fig. 1). Detailed descriptions of the geology, eruptive history, physical and chemical characteristics and vegetation can be found in Hamilton and Baumgart (1959), Houghton and Nairn (1989) and in Immediate Reports (IGNS files).

The Main Crater floor surface deposits consist of both unaltered and altered andesitic tephra. The altered tephra consists of opal-cristobalite, anhydrite, natroalunite, and pyrite (Nairn, 1992). Locally, post-eruption acid-alteration zones are also present. The alteration zones contain alunite, cristobalite, kaolinite and anhydrite/gypsum (Houghton and Nairn, 1989). Sulphur is also being deposited in areas of intense steaming ground and around fumaroles.

3. METHODS

3.1 The GEOSCAN Instrument

The GEOSCAN MkII is an advanced airborne multispectral scanner produced and used by GEOSCAN Pty. Ltd. (Perth, Western Australia) for commercial geological mapping, mineral and hydrocarbon exploration, agriculture and environmental monitoring. The scanner is operated from a Cessna 404 aircraft and incorporates GPS navigation. Aircraft roll, pitch and yaw variations are compensated for.

The GEOSCAN instrument can acquire imagery simultaneously in 24 geometrically registered wavelength bands which span four spectral regions in the 0.49-12.0 µm range. The set-up used in this study included four contiguous channels in the visible (0.50-0.7 µm), six channels in the NIR (0.7-0.91 µm), ten channels in the short wavelength IR (2.04-2.35 µm) and six channels in the thermal IR (8.38-11.55 µm). The imagery is digitized to an 8-bit dynamic range and recorded directly onto 5.25 inch optical disks having a capacity of 325 Mbytes/side (650 Mbytes total).

3.2 The Survey

Waiotapu geothermal field- The first comprehensive, high spatial resolution, survey of the Waiotapu geothermal area was performed on 21 January 1993. Imagery was acquired during the period 01:25:10-01:38:12 (New Zealand Daylight Time, NZDT) in the 24 bands covering the spectral range 0.49-12 µm. The survey altitude was 1430 m above ground level, providing a swath width of 3 km and a nadir ground spatial resolution of 3 m. A 100 km^2 area, 5.5 km wide and 19 km long, extending from southern Lake Tarawera to northern Reporoa, was covered with two parallel flight lines having an overlap of about 0.5 km. Weather conditions for several days prior to, and during, the surveys were stable, warm and dry. To take advantage of the maximum dynamic range of the instrument, detector gains and offsets were set while flying over the survey areas immediately prior to imagery acquisition.

Ground truth investigations were conducted in January 1993, on 30 August 1994 and 21 April 1995 at which time surface features were identified on field prints of GEOSCAN imagery.

White Island volcano- GEOSCAN multispectral daytime imagery was obtained over White Island on 18 January 1993. The imagery was acquired in all 24 bands covering the visible, NIR, MIR and TIR wavelengths during the period 01:55:18-01:56:37 NZDT and the entire island was covered in a single image at a ground spatial resolution of 6 m.

Ground truth surface information in the Main Crater area was obtained on 21 January 1993. On 26 May 1995, detailed ground studies were also conducted over the outer flanks of the island to accurately define the type, health and distribution of vegetation. Healthy, dead and regenerating pohutukawa (*Metrosideros excelsa*), iceplant (Disphyme *australe*) and flax (*Phormium tenax*) were identified as the major vegetation types present.

3.3 Image Processing and Analysis

Image processing was performed using two systems: the ERDAS/IMAGINE 8.1 system (ERDAS Inc., Atlanta, Georgia, USA) operating on a Silicon Graphics (SGI) workstation and the PC-EPIC system operating on a standard 486/33 PC, with a 330 Mbyte hard disk and a MATROX MVP-AT real-time processor. This dual approach provided processing flexibility since each system could perform certain operations more easily than the other.

GEOSCAN Pty., Ltd. provided the GEOSCAN imagery corrected for tangent-theta geometric distortion and atmospheric backscatter. The Waiotapu images were rectified to the New Zealand Metric Grid using 1:50 000 series maps to allow accurate location and mapping of features. A third order mapping polynomial and cubic convolution interpolation were utilized for the warping procedure. The resulting rectified images were used for the analysis and interpretation presented here. Since White Island was located near the centre of its image, it exhibited no major geometric distortion after tangent-theta correction. Consequently, it was not rectified for this initial study.

Various wavelength (band) combinations were used for both the Waiotapu and White Island images to create colour composites that were visually assessed, with emphasis placed on combinations previously found to be of value in satellite investigations of geothermal areas (Cochrane *et al.*, 1994; Deroin et *al.*, 1995; Mongillo et *al.*, 1995). The LANDSAT TM CIR Combination ($TM2_b3_g4_r$) was approximated by the GEOSCAN combinations: $GEO2_b3_g8_r$, $GEO2_b4_g8_r$, $GEO2_b4_g9_r$. The GEOSCAN imagery does not have a TM5 (1.65 µm) equivalent, consequently, the strong positive correlation known to exist between the TM5 and TM7 (2.2 µm) was used. The TM visible-NIR-MIR combination ($TM3_b4_g5_r$), found to be so useful for stressed vegetation mapping, was therefore replaced by the GEOSCAN combinations: $GEO2_b8_g15_r$, $GEO2_b8_g17_r$, $GEO3_b7_g11_r$, $GEO2_b8_g15_r$, $GEO4_b8_g15_r$, where GEO15 and GEO17 are in the 2.2 µm region. Visible-NIR-TIR ($GEO4_b7_g20_r$) and NIR-MIR-TIR ($GEO8_b15_g20_r$) combinations were also examined to investigate what information the TIR might add. Computer classification of the Waiotapu $GEO4_b8_g15_r$ was also assessed.

4. RESULTS and DISCUSSION

The nature of the GEOSCAN imagery, i.e. its 24 multispectral bands and its un-calibrated nature, which results from the separate channel gains and offsets, make it much more difficult to analyze than standard satellite data. However, the spectral detail provided by the 24 bands covering the visible, NIR, MIR and TIR give it great potential. Several different image processing techniques were investigated to assess their utility for identification and delineation of surface features present both in the Waiotapu geothermal area and on White Island. Examples

Fig. 2 This small scale $GEO2_b3_g8_r$ colour composite (CIR equivalent) image covers the central Waiotapu geothermal area. North is to the top.

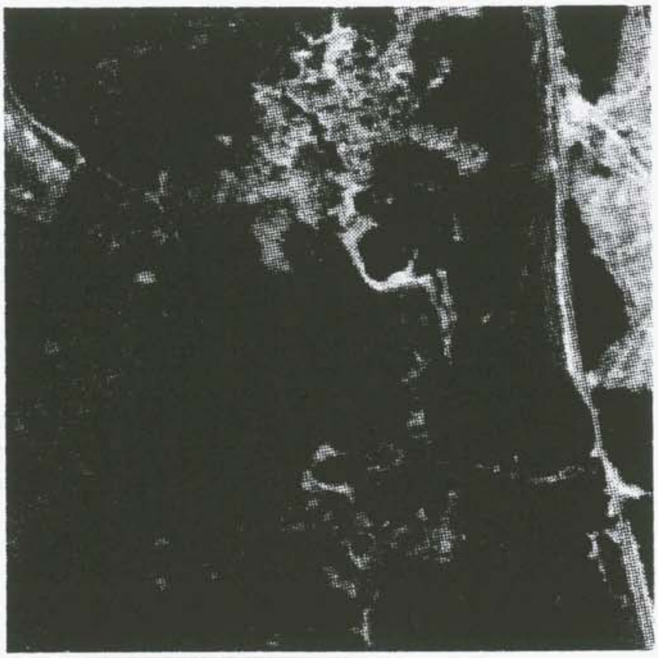

Fig. 4 This central Waiotapu $GEO8_b15_g20_r$ colour composite image incorporates NIR, MIR and TIR information. North is to the top.

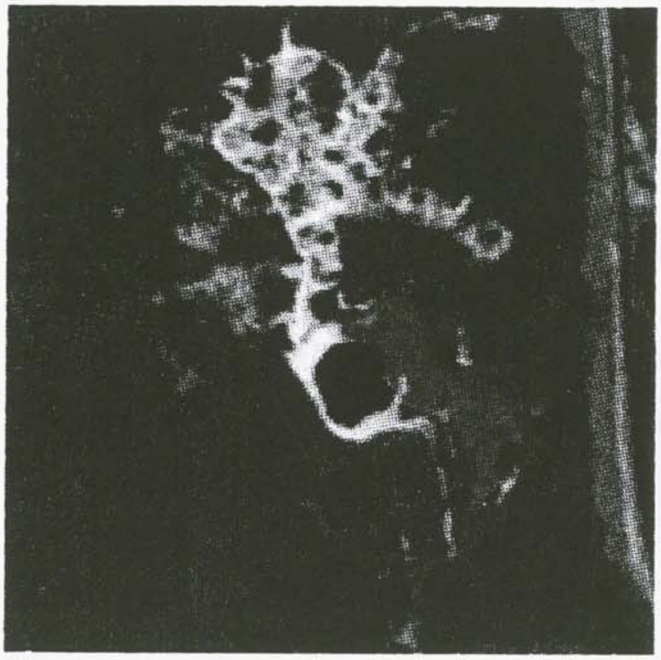

Fig. 3 This enhanced $GEO2_b8_g15_r$ colour composite image of the central Waiotapu thermal area is equivalent to the TM145 visible-NIR-MIR combination. North to top.

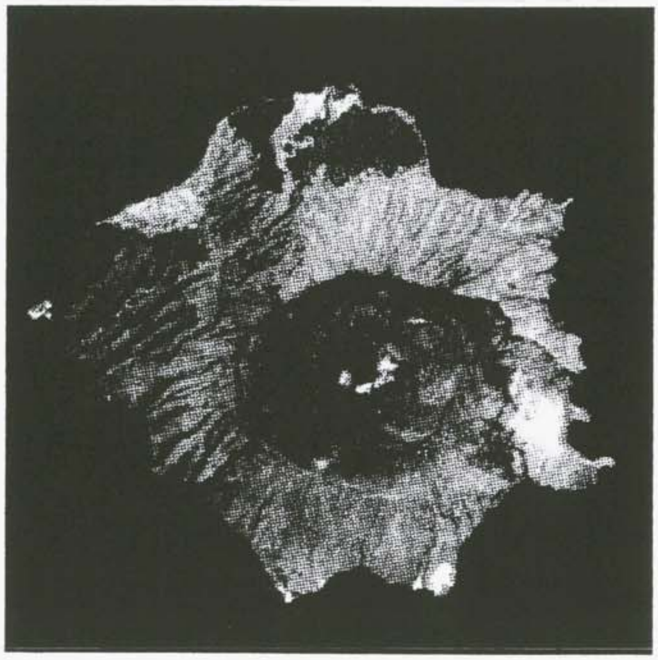

Fig. 5 This $GEO2_b8_g17_r$ colour composite image of White Island covers similar visible-NIR-MIR to the Waiotapu image at the left (Fig. 3). North to top.

illustrating a few of our preliminary results are presented in Figs 2-5. Note that the colour printer reproductions presented here are of reduced quality.

4.1 Waiotapu Geothermal Area

Three colour composites were found to be very useful. The first, GEO $2_b3_g8_r$ (Fig. 2), corresponds to colour-IR photographic wavelengths, and the LANDSAT TM $2_b3_g4_r$ and SPOT XS $1_b2_g3_r$ combinations which were shown to be valuable for mapping surface cover in geothermal areas (Cochrane, *et al.*, 1994; Mongillo, *et al.*, 1993; 1995). Fig. 2 is a small scale view of the main thermal area. Vegetation appears as a range of dark red to orange hues, with dense *Pinus spp.* being the brightest red (central and west areas). The pods in the Alum Cliffs and Frying Pan Flat areas and Lakes Ngakoro (south) and Whangioterangi (east) appear dark blue, while the smaller pools in the west are black. The dark circular patch near the north central shore of Lake Whangioterangi identifies an area where sulphur is upwelling from the bottom (Simmons, pers. comm., 1995). The white to grey coloured areas are zones of bare and hydrothermally altered ground. Champagne pool appears as the central dark circular feature. The shades of pink to grey present in the silica terraces region suggest differences in surface mineralisation and algal cover. The white-grey coloured area in the southeast of the image and east of the central north-south running road (orangish linear feature) is the site of a little known thermal area.

Figs. 3 and 4 show magnified views of the central portion of Waiotapu presented in Fig. 2. The visible-NIR-MIR combination, consisting of GEO $2_b8_g15_r$ is shown in Fig. 3. It is superior to the CIR combination of Fig. 2 in several respects. It very clearly separates the vegetation in shades of green. The vertically orientated light green linear feature at the left is the grassy verge along the road. The darker green, coarser textured parts of the image arise from healthy *Pinus spp.*. However, it is the ability of this band combination to clearly distinguish stressed vegetation, which appears as the brown-brownish green areas, which is one of its most important contributions. The bare and altered ground zones appear white. The pinkish hues from the bare ground at the north are thought to be related to a region having iron-oxide alteration. The blue portions of the silica terrace may be due to the presence of silica, or to a combination of silica and the thin layer of water which almost always covers it.

Fig. 4 presents a NIR-MIR-TIR (GEO$8_b15_g20_r$) combination which provides much detailed information on the surface alteration and surface feature temperatures. The brightest red features are the sites of the highest temperature thermal manifestations. For example, Champagne Pool (75 °C) stands out as do the smaller hot pools located in the hydrothermal eruption craters in the north. The yellow-blue hues represent differences in surface alteration. Great care must be taken when interpreting this image combination because of solar heating effects, however, night-time TIR imagery provides valuable aid for the unravelling of this interference (Mongillo, 1994).

4.2 White Island

The visible-NIR-MIR colour composite image of White Island presented in Fig. 5 is very similar to that shown for Waiotapu in Fig. 3, except that it uses the GEO17 MIR band GEO $2_b8_g17_r$. It is superior to the colour-IR combination (not shown here) in several respects. This combination clearly locates the regions of healthy pohutukawa present in the north and west parts of the island as shades of green. These are easily distinguished from the areas of unhealthy (darker green) and dead pohutukawa (reddish-brown to tan), with the dead pohutukawa also separated from the bare ground of the upper southern flanks. The alteration zones located within Main Crater, near to and west of Acid Stream, are easily discerned by their blue colour from the surrounding bare, unaltered ground. As with the colour-IR combination, the bare areas in the eastern subcrater and at the island extremities also appear white, indicating high reflectance at all wavelengths. The steam plumes originating from the active craters (image centre) and that from Noisy Nellie fumarole are clearly represented as white patches.

5. CONCLUSIONS

Recent work has demonstrated the great potential for using existing satellite imagery for the investigation of geothermal and volcanic phenomena. However, real advances will come from the development of new satellite scanners, which will provide more timely, very cost-effective and detailed information. The preliminary results introduced here clearly illustrate the power of the remote sensing method. Further investigation into the application of aircraft scanner data will not only help develop better analysis and interpretation techniques for the use of present satellite data, but is necessary for the development of future satellite scanners (Windeler, 1993).

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Cochrane, G.R., Mongillo, M.A., Browne, P.R.L. and Deroin, J-P. (1994). Satellite studies of the Waimangu and Waiotapu geothermal areas, TVZ. *Proc. 76th New Zealand Geothermal Workshop 1994*, 181-187.

Camacho, S., del Rio, L., Sanchez, L. and Gonzalez, J. (1982). Impact of hydrothermally altered soil on vegetation as a tool in geothermal exploration. *Proceedings 16th International Symposium on Remote Sensing of Environment, Buenos Aires*, Argentina, 145-153.

Deroin, J-P., Cochrane, G.R., Mongillo, M.A., Browne, P.R.L. (1995). Methods of remote sensing in geothermal regions: the geodynamic setting of the Taupo Volcanic Zone (North Island, New Zealand). *Int. J. Remote Sens.*, *11*, 1664-1678.

Gaonac'h, H., Vandemeulebrouck, J., Stix, J. and Halbwachs, M. (1994). Thermal infrared satellite measurements of volcanic activity at Stromboli and Vulcano. *Journal Geophysical Research*, *99*, 9477-9485.

Hamilton, W.M. and Baumgart, I.L. (1959). White Island. *DSIR Bulletin* 127, 84 p.

Hedenquist, J.W. (1986). Waiotapu geothermal field In: Henley, R.W., Hedenquist, J.W. and Roberts, P.J. (Eds.) ***Guide to the Active Epithermal (Geothermal) Systems and Precious Metal Deposits of New Zealand.*** Gebruder Bomtraeger, Berlin, 65-80.

Houghton, B..F. and Naim, I.A. (Editors) (1989). The 1976-82 eruption sequence at White Island Volcano (Whakaari), Bay of Plenty, New Zealand. ***N.Z. Geological Survey Bulletin 103,*** 138 p.

Jinich, A., Farah, J.L., Garza, M., Velarde, C., Mendez, R., Rosenblueth, J., Alvarez, R., Garcia, G., Hernandez, R. and Lopez, A. (1981). Application of visible and thermal data to the study of the geothermal area of Cerro Prieto, Mexico. ***Proceedings*** 15th ***International Symposium on Remote Sensing of Environment,*** Ann ***Arbor,*** Michigan, 1387-1396.

Mongillo, M.A. (1994). Aerial thermal infrared mapping of the Waimagu-Waiotapu geothermal region, New Zealand. ***Geothermics. 23***, 511-526.

Mongillo, M.A. and Bromley, C.J. (1992). A helicopter-borne video thermal infrared survey of the rotorua geothermal field. ***Geothermics,*** 21, 197-214.

Mongillo, M.A. and Clelland, L. (1984). Concise listing of information on the thermal areas and thermal springs of New Zealand. ***DSIR Geothermal Report No.*** 9. DSIR, Wellington, 228p.

Mongillo, M.A., Browne, P.R.L., Cochrane, G.R. and Deroin, J-P. (1993). Satellite studies of Craters of the Moon geothermal area ***Proc. 15th New Zealand Geothermal Workshop 1993***, 87-92.

Mongillo, M.A., Cochrane, G.R., Browne, P.R.L. and Deroin, J.-P. (1995). Application of satellite imagery to explore and monitor geothermal systems. ***Proceedings of the World Geothermal Congress*** 1995, ***Florence, Italy.***

Mouginis-Mark, P.J., Pieri, D.C., Francis, P.W., Wilson, L., Self, S., Rose, W.I. and Wood, C.A. (1989). Remote sensing of volcanos and volcanic terrains. *EOS,* 26 *Dec. 1989*, 1567-1575.

Mouginis-Mark, P.J. et *al.* (1991). Analysis of active volcanoes from the Earth Observing Platform. ***Remote Sensing Environ. 36,*** 1-12.

Mouginis-Mark, P.J., Garbeil, H. and Flament, P. (1994). Effects of viewing geometry on AVHRR Observations of volcanic thermal anomalies. ***Remote Sensing Environ., 48***, 51-***60.***

Nairn, I.A. (1992). White Island observations: 5,12,13,16 and 17 May 1992. ***Immediate Report:*** WIZ 92/04.

Oppenhiemer, C. (1993). Infrared surveillance of crater lakes using satellite data. ***Journal*** Volcanology and ***Geothermal Research, 55,*** 117-128.

Oppenheimer, C., Rothery, D.A., Pieri, D.C., Abrams, M.J. and Carrere, V. (1993). analysis of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data of volcanic hot spots. ***Int. J. Remote Sensing, 14,*** 2919-2934.

Realmuto, V.J., Abrams, M.J., Buongiorno, M.F. and Pieri, D.C. (1994). The use of multispectral thermal infrared image data to estimate the sulfur dioxide flux from volcanoes: A case study from Mount Etna, Sicily, July 29, 1986. ***Journal Geophysical Research,*** 99,481-488.

Realmuto, V.J., Hon, K., Kahle, A.B., Abbot, E.A. and Pieri, D.C. (1992). Multispectral thermal infrared mapping of the 1 October 1988 Kupaianaha flow field, Kiluea volcano, Hawaii. ***Bull. Volcanol.,*** 55, ***33-44.***

Ruiz-Armenta, J.R. and Prol-Ledesma, R.M. (1995). Identification of hydrothermal alteration using satellite images in areas with dense vegetation cover. ***Proceedings*** of ***the World Geothermal Congress*** 1995, ***Florence, Italy.***

Simmons, S.F., Browne, P.R.L. and Brathwaite, R.L. (1992). Active and extinct hydrothermal systems of the North Island, New Zealand. ***Guidebook Series,*** 15, Society of Economic Geologists.

Windeler, D.S. (1993). Garnet-pyroxene alteration mapping in the Ludwig Skam (Yerington, Nevada) with Geoscan airborne multispectral data. ***Photogrammetric Engineering and Remote Sensing*** 59, 1277-1286.