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Remote Sensing Analysis of Selected Terrestrial Impact Craters and a Suspected Impact Structure in South Korea using Space Shuttle Photographs

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Key words: Shuttle photographs, meteoritic craters, Manicouagan, Aorounga, Roter Kamm, Meteor Crater, South Korea.

Ključne riječi: snimci sa Space Shuttle-a, meteoritski krateri, Manicouagan, Aorounga, Roter Kamm, Meteor Crater, Južna Koreja.

Abstract

Typical morphological elements for impact craters were detected on all analyzed Shuttle photographs. Features with diameters smaller than 2 km could not be successfully analyzed. The search for suitable Shuttle scenes was successfully performed using on-line Internet databases.

Image enhancement and lineament analysis were also performed on the acquired Shuttle, Landsat and SPOT images of a suspected impact feature in South Korea. A fault bounded polygonal rim and a central uplift were identified on all images. A distinct system of annular and radial faults was not detected. The results of the study do not exclude the possibility of a meteoritic origin of this structure.

Sažetak

Morfološki elementi terena tipični za udarne strukture identificirani su na svim proučavanim fotografskim snimcima sa Space Shuttle-a. Strukture manje od 2 km nije bilo moguće uspješno analizirati. Identifikacija odgovarajućih fotografija sa Shuttle-a ostvarena je pretraživanjem mrežnih baza podataka s Interneta. Analizirani Shuttle, Landsat i SPOT snimci moguće meteoritske strukture u Južnoj Koreji pokazuju rasjedima okruženi poligonalni rub te centralno uzdignuće, no jasan sustav anularnih i radijalnih rasjeda nije bio registriran. Rezultati analize nisu osporili mogućnost da je meteoritski udar uzrokovao postanak ove strukture.

1. INTRODUCTION

The objective of this research was to explore the potential of hand held Space Shuttle photographs for remote sensing analysis of meteorite impact craters. Functionality of the existing on line databases was also studied and results obtained from other sensors (SIR-C/X-SAR) are discussed and compared.

1.1. METEORITIC IMPACT CRATERS

Meteoritic craters are circular depressions formed by the impact of a meteorite on a planetary body. Explosive impact craters are formed by large meteorites (HODGE, 1994). Smaller meteorites (up to few metres in diameter) do not have a sufficient energy to cause an explosion. They produce dug craters with diameters of less than 10 metres (HODGE, 1994).

Morphologically impact craters can be divided into two main groups: simple craters (Fig. 1) and complex structures (craters) (Fig. 2) (GRIEVE, 1991).

Simple craters consist of a bowl shaped depression with an uplifted rim. Complex structures (Table 1) form at crater diameters above 2 km in sedimentary rocks and greater than 4 km in magmatic rocks. They consist of a central peak, an annular trough and outer uplifted rim (GRIEVE, 1991).

As a result of his study of lunar craters MELOSH (1989), defined multiring basins as a separate class of features characterized by at least two asymmetrical scarped rings (one of which may be the original rim of the crater).

In 1996, 153 terrestrial impact craters were known (GRIEVE et al., 1995). Their diameters vary from 10 m to 300 km (since pits smaller than 10 m are not included in the record) (HAMILTON, 1996). The earth's meteoritic record, when compared to other terrestrial planets shows a deficit of smaller and older features. This phenomenon reflects the processes of erosion and sedimentation that are active on the earth surface and tend to "heal" impact effects (GRIEVE, 1990).

Shock metamorphic effects are exclusively associated with meteoritic impacts. No other natural process generates such extreme pressures and temperatures in such short time (GRIEVE, 1990). They include shatter cones, formation of planar deformation features in quartz and feldspar grains, formation of diaplectic glass and high-pressure polymorphs of some minerals.

1.2. USE OF REMOTE SENSING IN THE ANALYSIS OF METEORITIC IMPACT CRATERS

Remote sensing has been successfully used for the analysis of meteorite craters on the Earth as well as on the other planets and the Moon.

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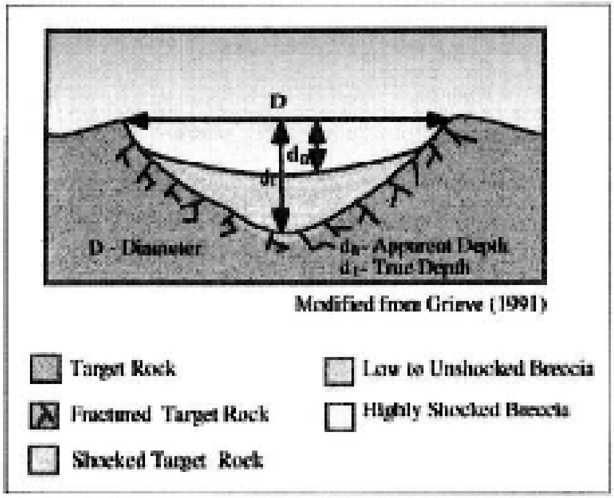

Fig. 1 Schematic presentation of a simple crater (modified from GRIEVE, 1991).

Sl. 1 Shematski prikaz jednostavnog kratera (prema GRIEVE, 1991).

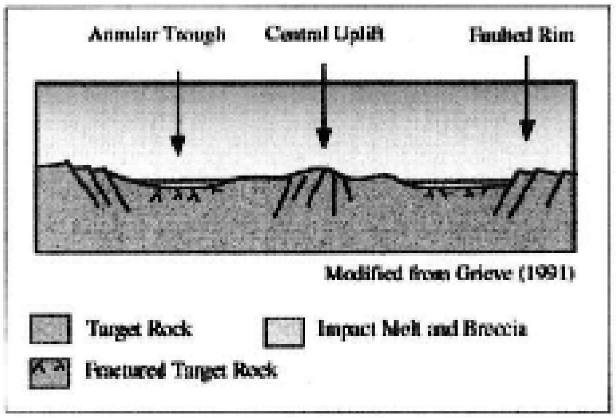

Fig. 2 Schematic presentation of a complex strucuture (modified from GRIEVE, 1991).

Sl. 2 Shematski prikaz kompleksne strukture (prema GRIEVE, 1991).

Typical morphological indicators of impact craters on satellite images include: circular raised rims, polygonal shape (in complex craters), central uplifts (within the craters), radial drainage patterns (GARVIN et al., 1992), and dissected topography (BUTLER, 1994).

Lineament analysis of impact features often reveals radial or annular fault and fracture patterns (Figs. 3 and 4) (INNES, 1964; BUTLER, 1994) in the crater vicinity. SABINS (1996) summarized some remote sensing characteristics of impact craters on Venus and their specific signatures on radar imagery (Table 2).

GARVIN et al. (1992) suggested that the impact induced change of the spectral signatures, characteristic for the mineral quartz in the thermal infrared region, could be used for the recognition of impact features on the multispectral imagery. Impact breccia deposits (GARVIN et al., 1992) showed characteristic signature on the third, fourth and fifth principal component colour imagery of the Zhamanshin crater (Russia).

The proceses of erosion and sedimentation impede recognition of terrestrial crater and they can distort and even totally remove the morphological imprint of a crater. A number of other geological processes (volcanism, doming, folding etc.; ROLAND, 1976) can create ring structures (OLUIĆ, 1983) that may mimic meteoritic craters.

Group	Central peak	One Ring	Few Rings
Central peak craters	yes	no	no
Central peak basins	yes	yes	no
Peak ring basins	yes	yes	no
Multi ring basins	yes	no	yes

Table 1 Groups of complex craters (PIKE, 1985).

2. METHODS

2.1. SPACE SHUTTLE PHOTOGRAPHS

Since 1982 Space Shuttle astronauts have used hand held and mounted cameras to take photographs during their stay in space (EROS, 1996). Each Shuttle mission produces from 4,000 to 5,000 photographs and approximately 125,000 photographs have been taken since the beginning of the project (EROS, 1996). Over eighty percent of the photographs are views of the Earth (EROS, 1996) and display large variations of angle, lighting and season (MUEHLBERGER, 1996). Three main types of cameras used in the project are: Hasselblad 500/M 70 mm, Linhof Aero Technika 45 127 mm and Large Format Camera (LFC) (EROS, 1996) (Table 3).

An LFC camera was used only on the mission 41-G and these photographs provide stereo coverage over certain areas (EROS, 1996). A majority of these images are regular RGB photographs, though some black and white and colour-infrared scenes have been taken (EROS, 1996). Spatial resolution of the photographs is dependent on the camera and the lens used and ranges between 150 and 20 m.

2.2. SPACE SHUTTLE ARCHIVES AND DATABASES

After each Shuttle mission, rolls of film are sent to the Johnson Space Center's Image science division in Houston. Photographs are processed and classified in three groups: earth observation images, experiment images and public release images (JSC, 1994). Datasets are digitized at the capture station and TARGA files of approximately 1.1 M (756 by 486 pixels with 8 bits per colour) are produced (JSC, 1994). A portion of files is displayed to the public over the Internet or in the form of videodisc (JSC, 1994). However, because of relatively poor resolution, scenes from a disc and the Internet are not suitable for the remote sensing analysis.

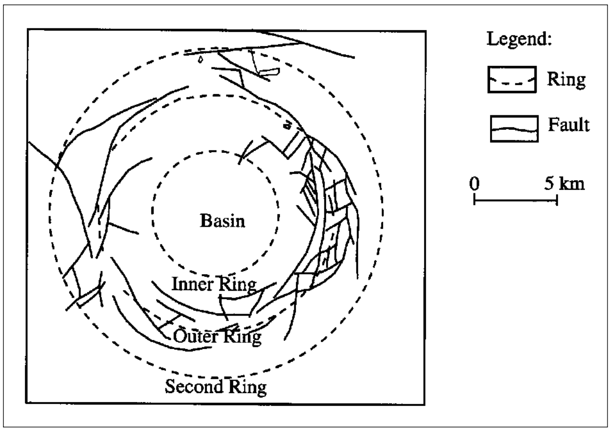

Fig. 3 Rings and faults associated with Haughton impact structure (Canada) (modified from ROBERTSON, 1980).

Sl. 3 Prstenovi i rasjedi vezani za Haughton strukturu (prema ROBERTSON, 1980).

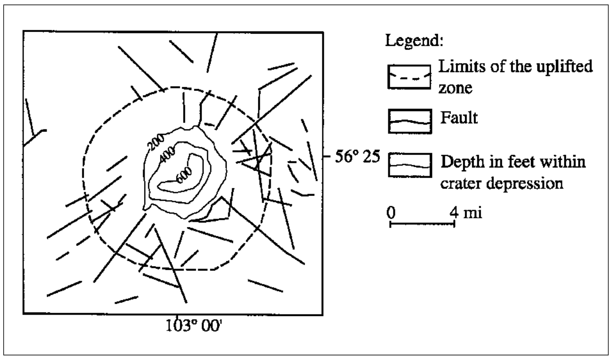

Fig. 4 Schematic map of prominent lineaments around Deep Bay impact structure (Canada) (modified from INNES, 1964).

Sl. 4 Shematski prikaz značajnijih lineamenata u okolici Deep Bay strukture (prema INNES, 1964).

Datasets with a higher resolution must be obtained directly from JSC.

In this study, the initial search for suitable scenes of impact craters was performed through the online databases at the Earth Science Branch of the Lyndon B. Johnson Space Center web site (http://www.jsc.nasa.gov). The database, Space Shuttle Earth Observations Project Database of Photographic Information and Images (JSC, 1996) http://eol.jsc.nasa.gov/sseop) was accessed through the Internet (WWW) and a text search was performed.

Space Shuttle Earth Observations VideoDisc (1981-1991), released to the public by Johnson Space Center, with approximately 91,500 still images of the Earth taken during the Space Shuttle missions STS-1 through STS-44 was used to identify optimal scenes.

The film rolls with selected scenes were later located in the Shuttle Archive at the Lockheed Martin Building in Houston and transported to the Lyndon B. Johnson Space Center. A Limhof digital camera, Adobe PhotoShop software and Macintosh hardware were used in the center to digitize the photographs. Nominal resolution was around 500 DPI and the size of created files varied between 5 and 10 M.

The original resolution of Shuttle photographs was inevitably reduced during the process. The main limiting factors were mounting and the optical characteristics of the Limhof camera.

Material	Description	Radar Signature
Lava plain	Lava flows impacted by the bolids. Many plains are flat and featureless. Others are faulted and folded to various degrees.	Dark to intermediate depending on roughness. Bright linear features are fault scarps.
Rim	Ejecta deposited up to three crater radii from the centre. Coarse hummocky material near the centre becoming somewhat finer outward.	Bright near rim, becoming intermediate outward with bright patches.
Wall	Rough terraced deposits on steep inner slopes. Slump blocks and talus are common.	Bright to intermediate. Annular zone surrounding the crater floor.
Floor	Level to smooth interior plains ranging from smooth to hummocky surfaces. Materials include impact melt, shocked rock, fallback or volcanic fill.	Bright to dark, circular to irregular outline. Very bright with characteristic
Peaks and rings	Peaks and ridges within the craters that rise above the floor materials. Uplifted, shocked, crushed and sheared rock.	morphology.
Outflow	Fluidized material formed by impact that resembles a lava flow. At some larger craters outflows extend for hundreds of kilometres.	Bright to intermediate with flowerlike outline.

Table 2 Impact affected materials on radar imagery (SABINS, 1996).

Camera	Lens	Spatial Resolution	Sensor With a Comparable Resolution
Hasselblad 500 EL/M	100 mm	150 m	MSS (80 m)
Hasselblad 500 EL/M	250 mm	30 m	TM (30 m)
Linhof Aero Technika	250 mm	30 m	TM (30 m)
Large Format Camera	N/A	20-30 m	Spot HRV* (20 m) - TM (30 m)

Table 3 Spatial resolution of Space Shuttle photographs (EROS, 1996).
*) Multispectral mode.

Data were stored on an external hard drive and transported to the Texas Christian University Center for Remote Sensing and Energy Research for further processing.

2.3. SIR-C/X-SAR IMAGES AND DATABASES

SIR-C/X-SAR (Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar) was flown on two Shuttle missions in 1994 (EVANS & PLAUT, 1996). It combines two radar devices: SIR-C and X-SAR. The instrument acquires quad polarized (L, C band) as well as single polarized (X-band) impulses (FREEMAN, 1996). The resolution varies between 10 and 50 m (EVANS & PLAUT, 1996).

To create SIR-C/X-SAR false colour images red, green and blue colours are assigned to different band/polarization combinations (JPL, 1996).

Radar scenes used in this study were downloaded from JPL's Space Radar Images of the Earth web site (http://www.jpl.nasa.gov/radar/sircxsar) This web page displays over 150 SIR-C/X-SAR false colour images classified in eight thematic categories and listed by geographic locality. Each image can be downloaded over the World Wide Web as a JPEG file with a low (size around 140 K) and high (file size around 10 M) resolution.

2.4. IMAGE PROCESSING AND LINEAMENT DETECTION

Image processing was performed at the Texas Christian University Center for Remote Sensing and Energy Research on a Power Macintosh 9500/132 with 50 M RAM. The Dimple image-processing program was utilized for relative rectification of the Shuttle Photographs to SIR-C/X-SAR image. A linear GCP model and nearest neighbour resampling method were used. True north was determined on all the images. Image datasets were either geographically corrected (radar) or fairly undistorted (Shuttle). Since only the relative position of the detected features in respect to the impact structures was significant in this study, strict geographical rectification was not performed.

Adobe PhotoShop was used for image enhancement. Contrast stretching was applied on all Shuttle photographs and four custom directional convolution kernels were used for edge enhancement: north, east, northwest and southwest illumination.

The original image and four derived filtered images were placed in separate layers of a single Adobe Illustrator document.

A lineament is defined as a "mappable, simple or composite linear feature of a surface whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differ distinctly from the patterns of adjacent features" (O'LEARY et al., 1976). An additional layer in the Adobe Illustrator was used for tracing of the lineaments. The results obtained from various image layers were compared and an attempt was made to eliminate all lineaments that were not structurally related (e.g., sand features caused by prevailing winds).

Mapict software (developed by Dr. Arthur BUSBEY at TCU) was used to digitize traced lineaments and create text files, which were imported into Rosy (Rockware) software for production of rose diagrams.

3. RESULTS AND DISCUSSION

Pictures of several impact structures were retrieved from the Shuttle database. Those with the best characteristics for remote sensing were selected (Table 4, Fig. 5). They represent various size categories of mappable impact craters on Earth. Diameters of the studied features ranged between 1.2 and 100 km.

3.1. THE MANICOUAGAN

The Manicouagan (Canada) impact structure (Figs. 5 and 6) is located at 51°23'N 68°42'W (FLORAN & DENCE, 1976). The age is estimated to be around 214 Ma (FLORAN & DENCE, 1976). The impact area is in the Grenville province of the Canadian Shield (OR-

Feature	Size	Size Rank
Manicouagan (Canada)	100 km	5
Aorounga (Chad)	17 km	40
Roter Kamm (Namibia)	2.5 km	119
Meteor Crater (Arizona)	1.2 km	130
Suspected structure in South Korea	13 km	-

Table 4 Impact structures with the best characteristics for remote sensing.

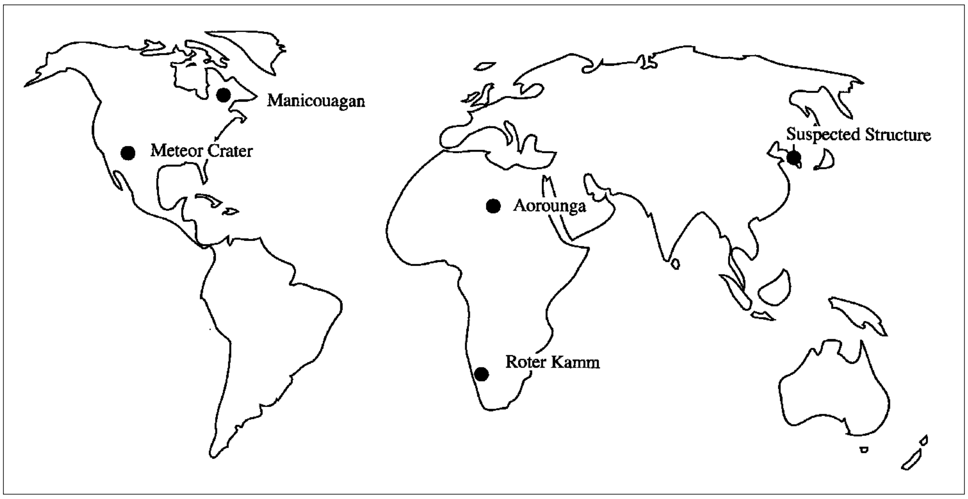

Fig. 5 Locations of selected craters.

Sl. 5 Položaj odabranih kratera.

PHAL, 1978). Petrological Grenville units recognized in the Manicouagan area (Fig. 7) include meta-gabbros, meta-anorthosites and granitic gneisses (ORPHAL, 1978). Long periods of erosion and glaciation have substantially affected the appearance of this structure (FLORAN & DENCE, 1976).

Remote sensing analysis of the Manicouagan crater shows the typical pattern of annular lineaments that define the polygonal rim of other complex impact structures. Orientation of these faults coincides with the typical fault and fracture patterns in the area (NE, N) and supports the assumption (FLORAN & DENCE, 1976) that these faults follow preimpact structures and zones of weakness. Radial drainage and other characteristics typical for such features (central uplift annular trough) were also identified on the photograph.

3.2. AOROUNGA

The Aorunga impact structure (Figs. 8 and 9) is located at 19°06'N and 19°15'E near the Tibesti massif in the Borkou region of eastern Chad (BECK-GIRADUON et al., 1992). The diameter of the crater is around 17 km (JPL, 1996) The age of the structure was estimated as late Devonian on the basis of the overlying sediments (OCAMPO, 1996).

A Shuttle photograph of the feature was analyzed and compared with the SIR-C/X-SAR (Fig. 9) dataset that was downloaded from the JPL Internet site.

All the elements of the structure are well developed and easily recognized. Crater rim, peak ring and central uplift were identified on both images. On the Shuttle image, sand covered areas are lighter coloured while exposed bedrock is displayed as a dark gray. Central uplift can be identified as a dark patch of the exposed

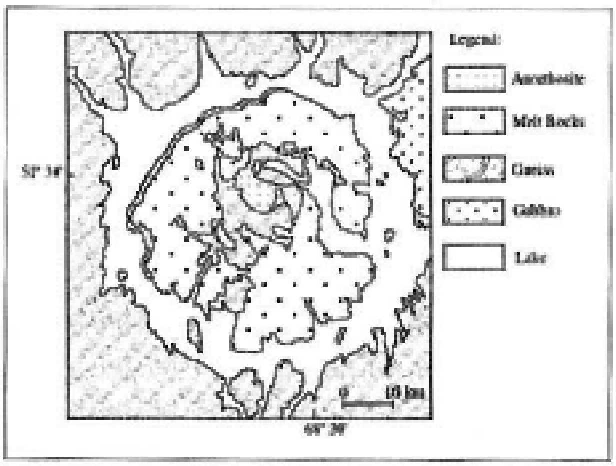

Fig. 6 Schematic geologic map of the Manicouagan structure (modified from ORPHAL, 1978).

Sl. 6 Shematska geološka mapa strukture Manicouagan (prema ORPHAL, 1978).

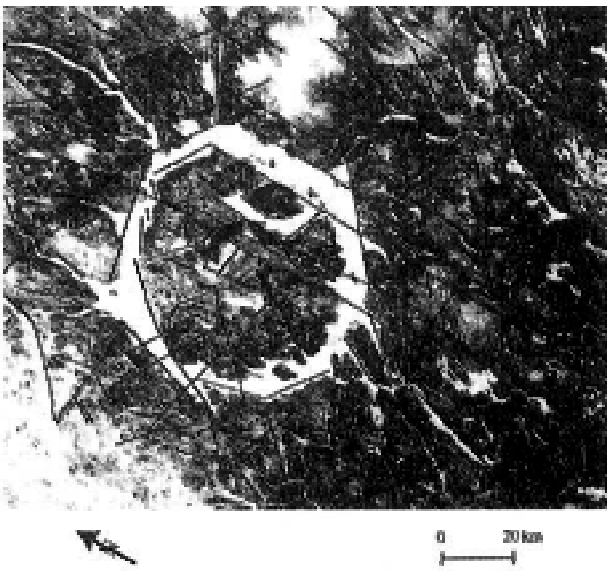

Fig. 7 Lineament map of the Manicouagan impact crater based on Shuttle photograph (photograph credit: JSC, 1996).

Sl. 7 Karta lineamenata oko kratera Manicouagan temeljena na Shuttle fotografiji (izvor snimka JSC, 1996).

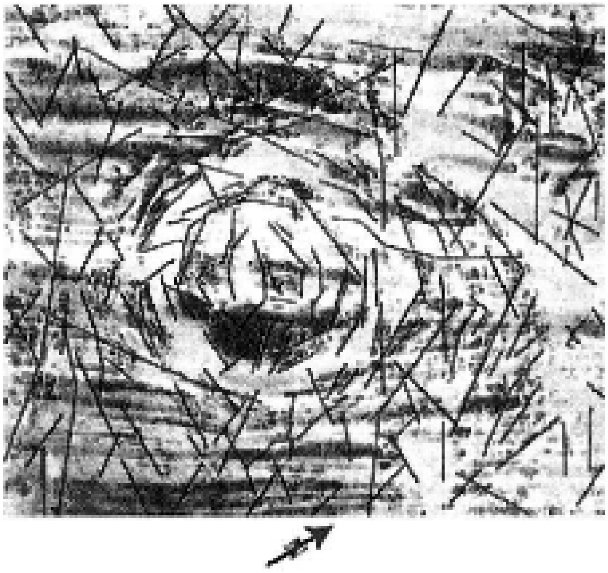

Fig. 8 Lineament map of the Aorounga impact structure based on Shuttle photograph (image credit: JPL, 1996).

Sl. 8 Karta lineamenata oko kratera Aorounga temeljena na Shuttle fotografiji (izvor snimka JPL, 1996).

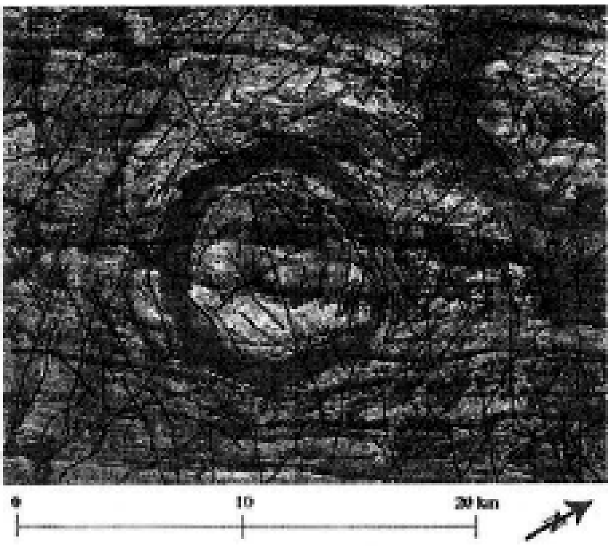

Fig. 9 Lineament map of the Aorounga structure based on SIR-C/X-SAR image.

Sl. 9 Karta lineamenata oko kratera Aorounga temeljena na SIR-C/X-SAR snimci.

bedrock in the centre of the structure. Radar penetrates up to several feet of dry sand (McHONE et al., 1996) showing more accurate morphology of the structure than the Shuttle image.

The polygonal shape of the fault-bounded crater and annular system of lineaments, typical for an impact structure, were observed on both images. A comparison of the obtained results has shown that a larger number of lineaments was detected on the radar image. The frequency of N-S lineaments was also higher on this image. One of the main problems in the analysis was distinction between the structurally related lineaments and typical eolian features (orientation NE-SW) These masking effects, that were more pronounced on the Shuttle photograph, are probably the main cause for the mentioned differences of the results obtained from the analysis of two images.

3.3. SMALLER FEATURES: ROTER KAMM AND METEOR CRATER

The Roter Kamm impact crater is located at 27°46'S and 16°18'E in the southern part of the Namib desert (Namibia) (FUDALI, 1973). The crater has a diameter of 2.5 km and its age has been estimated around 3.7 Ma (GRIEVE et al., 1995).

Meteor Crater is located at the 35°02'N and 111°01'W in the Canyon Diablo region of the north central Arizona (USA) (SHOEMAKER, 1977). The age of the impact is around 49 Ka (GRIEVE et al., 1995). The structure has a diameter of 1,220 m (GRIEVE et al., 1995).

On the Shuttle photographs of these two smaller features, both located in the arid region, only the polygonal fault bounded rim and very few lineaments could be identified. The main problems were the small size of the features, low resolution of the photographs and sand cover.

3.4. SUSPECTED IMPACT STRUCTURE IN SOUTH KOREA

A suspected impact structure in south Korea is centred at 37°49'N and 127°03'E (JONES et al., 1995). It is located 20 km north of Seoul near the town of Uijongbu in the vicinity of the demilitarized zone (JONES et al., 1995). In 1994, the crew of the Space Shuttle Endeavor (STS-59) took the first photograph of the structure. JONES et al. (1995) have described the structure and discussed its formation.

A circular rim with a 13 km diameter and a central uplifted region characterize the crater like feature (JONES et al., 1995). Relief from the bottom to the crest is greater than 400 m (JONES et al., 1995). Hilly uplifted terrain encircles the structure, which is situated in the Jurassic granites and surrounded by the 2 GA old metamorphic complex of gneiss and schist. The north-south oriented Tongducheon fault cuts the structure in half (JONES et al., 1995).

KANG et al. (1985) suggested that fracturing along the circular joint during cooling of the granite pluton induced formation of the structure. JONES et al. (1995) questioned the possibility of a magmatic origin for the structure and suggested that it was caused by a meteoritic impact. Future study of rock samples from the site is expected to give definite information about its formation.

The analysis has shown that the identification of lineaments was equally successful on Shuttle and Landsat TM images. A somewhat bigger number of lineaments were detected on the SPOT image due to its better spatial resolution

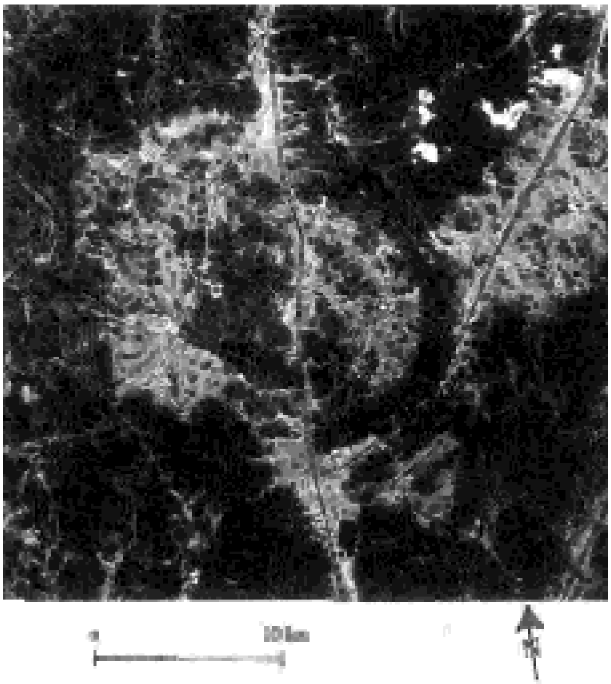

Fig. 10 Lineament nap of the Korean structure based on Shuttle photograph (photograph credit: JSC, 1996).

Sl. 10 Karta lineamenata oko Korejske strukture temeljena na Shuttle fotografiji (izvor snimka JSC, 1996).

The possible crater rim and uplifted peak were recognized on the Shuttle photograph (Fig. 10) as well as on studied Spot and Landsat TM scenes. However, the eastern part of the rim is much better defined on the images than the western half. Two large lineaments that cut the structure (one of them corresponding to the Tongduchen fault) are clearly visible.

Lineaments identified on the images mark a characteristic fault-bounded polygonal rim. Besides these well-pronounced lineaments of the "crater rim" numerous shorter lineaments with various orientations were detected on the scenes. They represent linear ridges and valleys. Though some of them have annular and radial orientations with respect to the structure, this information is not significant in the view of the large overall dispersion of lineament azimuths. In lower elevation areas covered by agricultural fields detection of lineaments was not possible.

The structure does show some typical elements that were identified on the Shuttle photographs of other proven impact features but they are not completely developed and the results of the analysis do not provide definite arguments for either hypothesis about the formation of the structure.

4. CONCLUSION

Space Shuttle photographs have a good remote sensing potential but their use for the remote sensing analysis of impact craters was limited. Limiting factors include relatively low photographic resolution, nondigital format and restricted areal coverage. Identification of the scenes with craters can be successfully performed from online and videodisc databases and a text search by the key word or geographic location is the fastest way to obtain the required data.

Image enhancement and edge enhancement techniques were successfully applied on the scanned Shuttle photographs. However, limited mapping could be performed. Some elements of characteristic fault and fracture patterns for the impact features were identified on all studied images but results obtained from the photographs of features smaller than 2 km were significantly inferior.

Improved resolution, digital format and a mission dedicated to the photography of impact craters are needed to improve the potential of Space Shuttle photographs for analysis of impact craters.

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Analiza odabranih meteoritskih kratera i moguće meteoritske strukture u Južnoj Koreji na temelju Space Shuttle-ovih fotografija

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1. UVOD

Cilj ovog rada bio je istražiti potencijalnu vrijednost fotografija snimljenih iz letjelice Space Shuttle za analizu struktura meteoritskog podrijetla primjenom metoda daljinskih istraživanja. Testirana je i funkcionalnost postojećih baza podataka na Internetu te mogućnost brze identifikacije odgovarajućih Shuttle-ovih fotografija ovim putem.

Rezultati dobiveni na temelju fotografija sa Shuttle-a uspoređeni su s onima dobivenima pomoću drugih senzora pa su tako pri analizi strukture Aorounga korišteni i radarski snimci sa letjelice Shuttle (radi se o uređaju SIR-C/X-SAR, Spaceborne Imaging Radar-C/X-band Synthetic Aperture Radar (FREEMAN, 1996) - Slikovni radar za snimanje iz svemira-C/X-radar sa sintetičkom antenom (BAJIĆ, 1985; OLUIĆ, 1985)).

Pri obradi potencijalnog meteoritskog kratera u Južnoj Koreji, uporabljeni su i satelitski snimci dobiveni pomoću tematskog kartografa (TM-Thematic Mapper) sa satelita Landsat te senzora HRV (High Resolution Visible) postavljenog na satelitu SPOT.

1.1. METEORITSKI KRATERI

Meteoritski krateri su kružne depresije nastale djelovanjem meteorita na planetarno tijelo. Eksplozivni krateri nastaju djelovanjem većih meteorita, dok manji meteoriti (do nekoliko metara u promjeru) nemaju dovoljnu energiju da izazovu eksploziju. Oni stvaraju iskopne kratere s promjerima manjim od 10 m (HODGE, 1994).

Morfološki, meteoritski krateri mogu se podijeliti u dvije glavne skupine: jednostavni krateri (sl. 1) i kompleksne strukture (krateri) (sl. 2) (GRIEVE, 1991).

Jednostavni krateri su depresije u obliku zdjele na Zemljinoj površini s uzdignutim rubom. Kompleksne strukture (tablica 1) nastaju kod radijusa većih od 2 km u sedimentnim stijenama i 4 km u magmatskim stijenama. One se sastoje od centralnog uzdignuća kružnog jarka i vanjskog uzdignutog ruba (GRIEVE, 1991).

Na temelju studija mjesečevih kratera MELOSH (1989) je definirao bazene s više prstenova kao posebnu skupinu struktura karakteriziranih sa barem dva asimetrična prstena (od kojih jedan može biti i originalni rub kratera).

Godine 1995. bilo je poznato 153 meteoritskih kratera (GRIEVE et al., 1995). Njihov promjer varira od 10 m do 300 km (udubine manje od 10 m nisu kategorizirane) (HAMILTON, 1996). Kad se broj i veličina meteoritskih kratera na površini Zemlje usporedi s drugim planetima sličnih karakteristika, uočljivo je da se na Zemlji manje i starije strukture javljaju razmjerno rjeđe. Ovaj fenomen odraz je procesa erozije i sedimentacije koji djeluju na njezinoj površini i "brišu" tragove djelovanja meteorita (GRIEVE, 1990).

Metoritski udari uzrokuju ekstremno visoke pritiske i temperature tijekom izuzetno kratkog vremenskog intervala te su oni jedini prirodni proces koji može izazvati pojavu specifičnih "udarnih" metamorfnih efektata (*shock metamorphic effects* - GRIEVE, 1990), koji se smatraju ključnim dokazom meteoritskog podrijetla neke strukture. Neki od tipičnih efekata su nastanak konusnih pukotina (*shatter cones*) u udarom zahvaćenim stijenama, nastanak planarnih deformacijskih pojava u zrnima kvarca i feldspata te nastanak dijaplektičkih stakala i visokotemperaturnih polimorfa nekih minerala (GRIEVE, 1990).

1.2. PRIMJENA DALJINSKIH ISTRAŽIVANJA U ANALIZI METEORITSKIH KRATERA

Daljinska se istraživanja uspješno primjenjuju u analizi meteoritskih kratera na Zemlji, drugim planetima i Mjesecu. Tipični morfološki indikator meteoritskih kratera na satelitskim snimcima su kružni uzdignuti prstenovi, poligonalni oblik (kod kompleksnih kratera) centralna uzdignuća (unutar kratera), radijalni površinski tokovi (GARVIN et al., 1992), te isprekidana topografija (BUTLER, 1994).

Analize lineamenata uz meteoritske kratere obično pokazuju anularne i radijalne sustave rasjeda (sl. 3 i 4) (INNES, 1964; BUTLER, 1994).

SABINS (1996) je prikazao karakteristike kratera na Veneri i njihove tipične odraze na radarskim snimcima (tablica 2).

GARVIN et al. (1992) navode da se udarom izazvane promjene u spektralnim vrijednostima tipičnim za mineral kvarc, u termalnom infracrvenom području, mogu koristiti za prepoznavanje meteoritskih struktura na multispektralnim snimcima. Naslage udarnih breča kod kratera Zhamanshin (Rusija) mogle su se uspješno izdvojiti digitalnim procesiranjem satelitskih snimaka (transformacijom 3., 4. i 5. osnovne komponente) (GARVIN et al., 1992).

Procesi erozije i sedimentacije otežavaju prepoznavanje struktura nastalih meteoritskim udarom i mogu promijeniti ili

Vrsta	Centralno uzdignuće	Jedan prsten	Više prstenova
Krateri sa centralnim uzdignućem	da	ne	ne
Bazeni sa centralnim uzdignućem	da	da	ne
Bazeni sa uzdignućem i prstenom	da	da	ne
Bazeni sa više prstenova	da	ne	da

Tablica 1 Tablični prikaz vrsta kompleksnih kratera prema PIKEU (1985).

Materijal	Opis	Orbitalni radarski snimak
Lavna ravnica	Tokovi lave s djelovanjem bolida. Ravne i monotone ili zahvaćene rasjedanjem i boranjem.	Tamne do srednje tamne ovisno o stupnju hrapavosti površina. Svijetle linearne strukture su rasjedne površine.
Rub	Izbačeni materijal sedimentiran do tri kraterska radijusa daleko od centra. Grubi humčasti materijal postaje finiji prema rubu.	Svijetao u blizini ruba, postaje srednje svijetao s vanjske strane sa svijetlim mrljama.
Zid	Grube terasaste naslage na strmim unutarnjim zidovima. Prevaljeni blokovi i lepeze su česti.	Anularna zona okružuje dno kratera.
Dno	Ravne do glatke unutarnje ravnice koje variraju od glatkih do humčastih površina. Materijal uključuje rastaljene "udarene" stijene, pali materijal te vulkansko ispunjenje.	Svijetao do taman, kružan do nepravilan obris.
Uzdignuća i prsteni	Uzdignuća i prsteni unutar kratera koji se dižu iznad materijala dna. Uzdignute udarene i napregnute stijene.	Vrlo svijetli s tipičnom morfologijom.
Izljevi	Fluidizirani materijal koji podsjeća na tok lave . Kod nekih većih kratera proteže se na stotine kilometara.	Svijetao do srednje svijetao s obrisom u obliku cvijeta.

Tablica 2 Prikaz udarom zahvaćenih materijala na orbitalnim radarskim snimcima (SABINS, 1996).

čak potpuno uništiti morfološki otisak kratera.

Po svojim karakteristikama mnogi se dokazani meteoritski krateri mogu svrstati u skupinu prstenastih struktura (OLUIĆ, 1983). Ova kategorija obuhvaća sve morfostrukturne elemente reljefa polukružnog ili eliptičnog oblika, i takve forme se vrlo dobro uočavaju na različitim snimcima koji se koriste u daljinskim istraživanjima (OLUIĆ, 1983). Prema istom autoru uzrok nastanka ovih struktura (uz meteoritske udare) mogu biti vulkanska ili magmatska djelatnost, tektonski poremećaji ili dijapirizam.

Meteoritske strukture je često vrlo teško razlučiti od prstenastih struktura drugačijeg podrijetla (ROLAND, 1976) no ako su opisani specifični indikatori dobro očuvani, te ako je prisutno nekoliko karakterističnih elemenata (npr. rub kratera i centralno uzdignuće), rezultati analize metodama daljinskih istraživanja mogu s dosta velikom vjerojatnošću ukazati na postanak putem meteoritskog udara.

2. METODE

2.1. FOTOGRAFSKI SNIMCI NAČINJENI SA SPACE SHUTTLE-A

Od 1982. godine astronauti na Space Shuttle-u se služe ručnim foto kamerama i kamerama na stativu prilikom snimanja iz svemira (EROS, 1996). Svaka Shuttle-ova misija načini nekoliko tisuća fotografija, pa je do sada snimljeno oko 125.000 snimaka (EROS, 1996). Više od 80% fotografija su pogledi na planet Zemlju i načinjene su iz različitih kutova, pod raznovrsnim osvijetljenjima i tijekom svih godišnjih doba (MUEHLBERGER, 1996).

Tri glavna tipa kamera korištenih tijekom Space Shuttleovih misija su: Hasselblad 500/M 70 mm, Linhof Aero Technika 45-127 mm i Large Format Camera (LFC) (tablica 3; EROS, 1996).

Kamera velikog formata je korištena samo u misiji 41 G i tom su prilikom načinjene stereo-fotografije nekih područja (EROS, 1996).

Većinom su to normalne kolor fotografije (RGB), premda su napravljene i neke crno-bijele i kolor-infracrvene snimke. Prostorna rezolucija fotografija ovisi o kameri, visini snimanja i upotrebljenoj leći, te varira između 150 i 20 m.

2.2. SPACE SHUTTLE ARHIVSKI SNIMCI I BAZE PODATAKA

Nakon svake Shuttle-ove misije eksponirani filmovi se šalju u Image Science Division Johnson Space Centra u Houstonu. Fotografije se nakon obrade svrstavaju u tri grupe: slike promatranja Zemlje, slike pokusa, i slike za javnu uporabu (JSC, 1994). Fotografije se zatim digitaliziraju te nastaju TARGA datoteke od oko 1.1 megabajta (Mb) (756 x 486 piksela s 8 bita). Dio datoteka se predstavlja javnosti putem Interneta te u formi videodiska (JSC, 1994). Kako snimci s video diska i Interneta nisu namijenjeni za znanstveno-stručna istraživanja, oni imaju razmjerno slabu rezoluciju te je odgovarajuće datoteke sa višom rezolucijom potrebno dobaviti direktno iz Johnson Space Center-a.

Za ovaj rad inicijalna potraga za odgovarajućim snimkama meteoritskih kratera je izvršena preko Web stranice Earth Science Branch of the Lyndon B. Johnson Space Center (http://www.jsc.nasa.gov/). Mrežna baza podataka "Space Shuttle Earth Observations Project Database of Photographic Information and Images" (JSC, 1996) http://eol.jsc.nasa.gov/sseop/ kontaktirana je preko WWW (World Wide Web) te je izvršeno pretraživanje putem ključnih riječi.

Za identifikaciju optimalnih scena korišten je također i video disk, Space Shuttle Earth Observations Video Disc (1981-1991), u izdanju Johnson Space Center-a s oko 91.500 snimaka Zemlje načinjenih tijekom misija STS-1 do STS-44.

Kolutovi filmova s odabranim snimkama su zatim identificirani u Shuttle arhivu u Lockheed Martin Building (Houston) i prenešeni u Lyndon B. Johnson Space Center. Limhof digitalna kamera, Adobe PhotoShop program i Macintosh računalo su korišteni za digitalizaciju snimaka sa filmova.

Kamera	Leća	Prostorna rezolucija	Senzor s usporedivom rezolucijom
Hasselblad 500 EL/M	100 mm	150 m	MSS (80 m)
Hasselblad 500 EL/M	250 mm	30 m	TM (30 m)
Linhof Aero Technika	250 mm	30 m	TM (30 m)
Large Format Camera	N/A	20-30 m	Spot HRV (20 m) - TM (30 m)

Tablica 3 Usporedni prikaz značajki različitih kamera i senzora za snimanje iz satelita (EROS, 1996).

Nominalna rezolucija je bila oko 500 DPI (*dots per inch* - točaka po inču), a veličina nastalih datoteka je varirala između 5 i 10 Mb. Originalna rezolucija Shuttle-ovih fotografija bila je neizbježno reducirana tijekom ovog procesa. Glavni ograničavajući faktor bili su stativ i optičke karakteristike Limhof kamere.

Podaci su zatim pohranjeni na prenosivi tvrdi disk i preneseni u Texas Christian University Center for Remote Sensing and Energy Research na obradu.

2.3. RADARSKI SNIMCI

SIR-C/X-SAR (Spaceborne Imaging Radar-C/X-Synthetic Aperture Radar - Slikovni radar za snimanje iz svemira-C/X-radar sa sintetičkom antenom) kombinira dva zasebno razvijena radarska uređaja SIR-C i X-SAR te prima "quad" polarizirane (L, C kanali) impulse kao i VV polarizirane (X-kanal) impulse (FREEMAN, 1996). Ovaj instrument je bio korišten tijekom dvije Shuttle-ove misije u 1994. Godini, a rezolucija prikupljenih podataka varira između 10 i 50 metara (EVANS & PLAUT, 1996).

Crvena, zelena i plava komponenta na SIR-C/X-SAR umjetnoj kolor snimci zapravo predstavljaju različite kombinacije radarskih kanala i polarizacija signala (JPL, 1996).

Radarska snimka (scena) koja je korištena u ovoj studiji presnimljena je preko mreže s JPL-ove Space Radar Images of the Earth web stranice (http://www.jpl. nasa.gov/radar/sircxsar/). Ondje je predstavljeno 150 SIR-C/X-SAR snimaka (umjetni - kolor), klasificiranih u osam tematskih kategorija s navedenim geografskim lokalitetima. Svaki snimak može biti kopiran preko WWW kao JPEG datoteka s niskom rezolucijom (oko 140 Kb) ili visokom rezolucijom (oko 10 Mb).

2.4. PROCESIRANJE SNIMAKA I ANALIZA LINEAMENATA

Snimke su obrađene u Texas Christian University Center for Remote Sensing and Energy Research, na Power Macintosh 9500/132 računalu s 50 Mb RAM-a. Dimple program za obradu snimaka korišten je za relativnu rektifikaciju Shuttle fotografija spram SIR-C/X-SAR snimaka. Primijenjen je linearni transformacijski model i metoda "najbližeg susjeda" (*nearest neighbour*). Geografski smjer sjevera utvrđen je na svim snimcima, a kako su oni bili ili geometrijski ispravljeni (radar) ili prilično nedeformirani (Shuttle), precizno geografsko poboljšanje nije rađeno jer je tijekom ovog istraživanja bio značajan samo relativan položaj morfoloških i drugih elemenata spram struktura nastalih djelovanjem meteorita.

Aplikacija Adobe Photoshop je korištena za poboljšanje snimaka. Tako je kontrast podešen na svim Shuttle fotografijama, a primijenjena su i četiri filtra za pojačanje linearnih elemenata. Smjerovi njihove iluminacije su bili sjever, istok, sjeverozapad i jugozapad. Originalni snimak i četiri izvedene filtrirane snimke pohranjene su kao aplikacijski slojevi u jedinstvenom Adobe Illustrator dokumentu.

Lineament se definira kao jednostavni ili kompleksni linearni element čiji su dijelovi raspoređeni pravocrtno ili blago zakrivljeno i koji se bitno razlikuje od susjednih struktura (O'LEARY et al., 1976). Opaženi lineamenti su izvučeni na dodatnim aplikacijskim slojevima u sklopu Adobe Illustratora. Rezultati dobiveni pomoću različitih filtera su uspoređeni pa su linearni elementi uzrokovani ljudskim aktivnostima ili nejasnog podrijetla bili odstranjeni kad god je to bilo moguće.

Mapict program (dr A. BUSBEY, Texas Christian University) korišten je prilikom digitalizacije lineamenata koji su zatim unešeni u aplikaciju "Rosy" za izradu rozetnih dijagrama.

3. REZULTATI I DISKUSIJA

Snimci više meteoritskih kratera pronađeni su u Shuttle-ovoj bazi podataka te su odabrani oni najprikladniji za obradu (tablica 4, sl. 5). Promjeri istraživanih struktura variraju između 1,2 i 100 km, a zastupane su različite veličinske kategorije meteoritskih kratera na Zemlji.

3.1. MANICOUAGAN KRATER

Manicouagan krater u Kanadi (sl. 5 i 6) smješten je u istočnom dijelu poluotoka Labrador. Starost mu je procijenjena na 214 milijuna godina (FLORAN & DENCE, 1976). Ovo područje pripada Grenville provinciji kanadskog štita te su u okolici kratera Manicouagana utvrđene različite petrološke Grenville jedinice (sl. 6), zastupane metagabrima, metaanortozitima i granitskim gnajsovima (ORPHAL, 1978). Dugotrajna izloženost procesima erozije i glacijacije znatno je promijenila ovu strukturu (FLORAN & DENCE, 1976).

Analiza kratera Manicouagan metodama daljinskih istraživanja pokazuje tipični sustav anularnih (kružno raspoređenih) rasjeda koji definiraju poligonalni oblik kompleksnih udarnih struktura (sl. 7). Orijentacija spomenutih rasjeda koincidira s najzastupljenijim pravcima lineamenata na ovom području, sjeveroistok-jugozapad i sjever-jug, što podupire

Struktura	Veličina	Mjesto po vel.
Manicouagan (Kanada)	100 km	5
Aorounga (Čad)	17 km	40
Roter Kamm (Namibija)	2.5 km	119
Meteor Crater (Arizona)	1.2 km	130
Moguća struktura u Južnoj Koreji	13 km	-

Tablica 4 Promjer i mjesto po veličini analiziranih meteoritskih struktura.

pretpostavku koju su iznijeli FLORAN & DENCE (1976) da je njihov postanak bio uvjetovan strukturama i zonama slabosti koje su na terenu postajale prije meteoritskog udara. Radijalni sustav površinskih tokova i druge karakteristike tipične za takve strukture (centralno uzdignuće, kružna depresija) su također identificirani na snimku.

3.2. AOROUNGA STRUKTURA

Aorounga stuktura (sl. 5, 8 i 9) smještena je u blizini Tibesti masiva u Borkou regiji istočnog Čada (BECK-GIRADUON et al., 1992). Promjer joj iznosi oko 17 km (JPL, 1996), a starost strukture je procijenjena na temelju pokrovnih sedimenata kao kasnodevonska (OCAMPO, 1996).

Shuttle fotografija ove strukture je analizirana i uspoređena sa SIR-C/X-SAR (sl. 9) snimkom koja je preuzeta preko mreže s JPL-ove Internet stranice. Reljefne forme tipične za meteoritske strukture na krateru Aorounga su dobro izražene i uočavaju se na oba korištena snimka.

Na Shuttle fotografiji pijeskom prekrivena područja su svijetlije obojena, dok je otkrivena stijena tamno siva. Svi elementi strukture, rub, prsten i centralno uzdignuće su jasno prepoznatljivi. Centralno uzdignuće može se identificirati na snimci kao tamna mrlja otkrivene stijene u središtu strukture.

Radarski zraci prodiru kroz nekoliko stopa suhog pijeska (McHONE et al., 1996), te se spomenuti tipični elementi izvrsno uočavaju. Dva izvora podataka, korištena tijekom ovog istraživanja (Shuttleove RGB fotografije i SIR-C/X-SAR snimci) međusobno su se nadopunjavali. Pri tome je digitalizirana RGB fotografija dala kvalitetnu informaciju o tonalnim karakteristikama materijala na tlu, a na radarskom su snimku morfološki elementi strukture bili bolje izraženi.

Usporedbom rezultata analize lineamenata utvrđeno je da ih je veći broj detektiran na radarskoj snimci, te da je na njoj veća zastupljenost lineamenata sa pravcem sjever-jug. Veliku je poteškoću pri obradi predstavljalo razlučivanje između lineamenata koji su vezani uz udarnu strukturu i eolskih pojava (orijentacija jugozapad-sjeveroistok). Ovi maskirajući efekti pješčanog pokrova bili su snažnije izraženi na Shuttle fotografiji, pa se time mogu objasniti i razlike u analizama dvaju snimaka.

3.3. KRATERI ROTER KAMM I METEOR CRATER

Roter Kamm (slika 5) udarni krater nalazi se u južnom dijelu pustinje Namib, Namibija (FUDALI, 1973). Ovaj relativno mali krater ima promjer 2,5 km, a starost mu je procijenjena na oko 3,7 milijuna godina (GRIEVE et al., 1995).

Meteor Crater (sl. 5) je smješten u području kanjona Diablo, sjeverne-centralne Arizone (SAD) (SHOEMAKER, 1977). Udar meteorita prije približno 49 tisuća godina uzrokovao je nastanak te strukture čiji promjer iznosi oko 1.220 m (GRIEVE et al., 1995).

Na Shuttle-ovim fotografijama navedenih manjih struktura, smještenih u aridnom području, bilo je moguće registrirati samo poligonalni rub i nekoliko lineamenta. Glavni problem su predstavljali mala veličina strukture, niska rezolucija fotografija i pješčani pokrov.

3.4. MOGUĆI METEORITSKI KRATER U JUŽNOJ KOREJI

Mogući meteoritski krater u Južnoj Koreji smješten je oko 20 km sjeverno od Seoula, kod grada Uijongbu u blizini demilitarizirane zone (JONES et al., 1995). Posada Space Shuttle-a Endaveor (STS-59) snimila je fotografije ove strukture tijekom jedne misije izvedene 1994. godine. JONES et al. (1995) su prvi opisali taj mogući meteoritski krater i raspravili njegov postanak.

Prema JONES et al. (1995) polukružni greben s promjerom od 13 km i centralno uzdignuće karakteriziraju krateru sličnu strukturu. Visinska razlika od dna do vrha grebena je veća od 400 m a struktura je smještena unutar jurskih granita, okruženih s 2 milijarde godina starim gnajsovima i šistovima. Rasjed Tongducheon s orijentacijom sjever-jug presjeca strukturu na dva dijela.

KANG et al. (1985) navode da je pucanje duž pukotine kružnog oblika tijekom hlađenja granitskog plutona uvjetovalo nastanak polukružne forme, međutim JONES et al. (1995) ne smatraju da je struktura magmatskog podrijetla te pretpostavljaju da se radi o ostatku meteoritskog kratera. Buduće studije uzoraka stijena iz kratera trebale bi dati relevantne informacije o njezinom podrijetlu.

Analiza navedene strukture je provedena na Shuttle fotografijama te Landsat TM i Spot HRV snimcima. Na sva tri snimka bilo je moguće podjednako dobro registrirati morfološke elemente pretpostavljenog meteoritskog kratera. Broj registriranih lineamenata bio je podjednak na Shuttle fotografijama i Landsatovim snimcima dok je bolja prostorna rezolucija SPOT snimka omogućila zapažanje nešto većeg broja lineamenata (osobito oni kraćeg pružanja).

Mogući rub kratera i centralno uzdignuće na snimcima se lako uočavaju, no istočni dio ruba kratera je znatno bolje ocrtan od njegove zapadne strane. Dva snažna lineamenta (jedan od njih odgovara Tongducheon rasjedu) jasno se uočavaju na snimci, a imaju pravac pružanja sjever-jug i sjeveroistok-jugozapad.

Osim dobro izraženih lineamenata ruba kratera, na snimkama su registrirani brojni kraći lineamenti s različitim orijentacijama. Oni se manifestiraju kao linearne doline i grebeni. Iako neki od njih imaju anularnu i radijalnu orijentaciju u odnosu prema strukturi, ovaj podatak nije značajan ako se uzme u obzir velika sveukupna disperzija pravaca ovih lineamenata. U nižim predjelima prekrivenim poljoprivrednim površinama identifikacija lineamenata nije bila moguća.

Razmatrana prstenasta struktura pokazuje neke tipične elemente identificirane na Shuttle-ovim fotografijama drugih dokazanih meteoritskih struktura (centralno uzdignuće i dio ruba kratera), no oni nisu potpuno razvijeni i rezultati analize ne daju definitivne argumente za bilo koju od hipoteza o njezinom postanku.

4. ZAKLJUČAK

Korištene Space Shuttle fotografije imaju ograničenu primjenu u daljinskoj analizi meteoritskih kratera. Ograničavajući faktori su relativno slaba prostorna rezolucija, nedigitalan oblik podataka i nepotpuno prostorno prekrivanje. Ipak, na analiziranim fotografskim snimkama sa Shuttle-a kao i na korištenim radarskim i satelitskim snimkama izvršena je analiza lineamenata, te je bilo moguće vrlo dobro registrirati elemente prstenastog oblika bilo meteoritskog ili drugog podrijetla.

Uspješna identifikacija snimaka s kraterima moguća je putem mrežnih (WWW) baza podataka i baza podataka na video diskovima. Tekstualno pretraživanje pomoću ključne riječi ili geografskog lokaliteta nabrži je put do traženih scena.

Tehnike poboljšavanja snimka i pojačavanja lineamenata su uspješno primijenjene na skaniranim Shuttle fotografijama. Neki morfološki elementi te karakteristični sustavi pukotina i rasjeda identificirani su na svim snimcima, no rezultati dobiveni na temelju snimaka kratera manjih od 2 km bili su bitno slabiji.

Bolja rezolucija snimaka, njihov digitalni format, te misija posvećena snimanju meteoritskih struktura bitno bi unaprijedili vrijednost fotografskih snimaka sa Shuttle-a pri istraživanju meteoritskih kratera.

Zahvale

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