Potential of the International Space Station for imaging Earth: Lessons from MOMS-2P aboard Mir

Robert J. Stern Geosciences Department, University of Texas, Dallas, P.O. Box 830688, 2601 North Floyd Road, Richardson, Texas 75083-0688, USA
Michael Beyth Geologic Survey of Israel, 30 Malkhei Yisrael Street, Jerusalem 95501, Israel
Johan Bodechtel University of Munich, Institute of General and Applied Geology, Luisenstrasse 37, Munich, Germany
Hans-Ulrich Wetzel GeoForschungsZentrum (GFZ), Telegraphenberg A17, Potsdam, Germany

ABSTRACT

Digital multispectral imagery collected by using two systems of similar spectral and angular resolution were compared to assess the potential of the International Space Station as an Earth-observing platform. Folds and faults associated with the Neoproterozoic Mai Kenetal synform in northern Ethiopia were imaged with the Modular Optoelectronic Multispectral Stereo Scanner (MOMS-2P) on the Russian space station Mir and the free-flying Landsat Thematic Mapper (TM) system. The most important difference between MOMS-2P and Landsat TM is the much lower altitude of the former (380 km versus 705 km), so that MOMS-2P has a significantly smaller ground-resolution cell, which reveals details not apparent from TM imagery over the same area. Corresponding improvements in spatial resolution can be expected if any of the free-flying imaging systems (ASTER, SPOT, *Hyperion*), which fly at altitudes of 700 to 820 km, were mounted on the ISS, which orbits at 380 km. The ultralow orbit of the ISS presents an outstanding, but currently underutilized, opportunity for observing Earth.

Keywords: remote sensing, International Space Station, Ethiopia, Neoproterozoic.

INTRODUCTION

The International Space Station is a prodigious technological undertaking and a natural next step in the manned exploration of space. Because it orbits at an unusually low altitude and will be continuously occupied for the foreseeable future, the International Space Station is an extremely valuable platform for studying Earth below it, as it orbits between 51.6°N and S latitudes. The fact that there are no plans to install and operate state-of-the-art multispectral (in the broadest sense) Earth-imaging systems on the International Space Station should be of concern to geoscientists, and the issue needs to be discussed broadly within the earth science community. In the hope of stimulating this discussion, we present results from the multispectral-imaging system aboard the Mir (''peace'') Space Station and use these results to show how the low Earth orbit occupied by the International Space Station (and formerly by Mir) offers significant advantages for imaging geologic features. We illustrate this potential by comparing images of the same area produced by the Modular Optoelectronic Multispectral Scanner (MOMS-2P, stationed on the Mir) and by the unmanned satellite Landsat Thematic Mapper (TM). These are comparable imaging systems positioned at different heights above Earth (MOMS-2P, 380–405 km; Landsat TM, 705 km). Comparison of folded and faulted Neoproterozoic sedimentary rocks in northern Ethiopia shows that the MOMS-2P image reveals these structures much better than does the Landsat TM image. We conclude that better images of Earth can be obtained from the International Space Station than can be obtained by using the same instrument mounted on a free-flying satellite such as Landsat.

MOMS-2P AND LANDSAT TM IMAGING SYSTEMS

MOMS-2P is the only Earth-imaging multispectral system that has tested the potential of the unusually low Earth orbit associated with a manned space station. The development of the MOMS sensor was discussed by Bodechtel and Zilger (1996) and Bodechtel et al. (1998). MOMS-2P was launched in March 1996 as part of the Priroda (''nature'') Module and docked on the USSR–Russian Mir Space Station, which orbited Earth from 1986 to 2001. Detailed information about the MOMS-2P sensor and data can be found in D.A.R.A. (1997). The MOMS-2P sensor has two imaging systems: (1) a nadir-looking system that utilizes four narrow multispectral bands in the visible and VNIR region of the electromagnetic spectrum with 16.9–18.0 m ground resolution, and (2) a multilook (21.6° fore, 21.6° aft, and nadir) panchromatic system for acquiring stereoscopic data. Because the MOMS-2P multispectral system is similar to the first four bands of the Landsat TM, we only compare images from these systems.

The Landsat TM was the pioneer and continues to be a workhorse for terrestrial remote sensing. A brief history of the Landsat program along with details about how the instrument operates can be found in Landsat 7 (2001). Landsat 5 and 7 operate today, using the TM instrument on Landsat 5 and Enhanced Thematic Mapper Plus (ETM+) on Landsat 7. The primary performance-related change of ETM+ over TM is the addition of the panchromatic band (with 15 m spatial resolution). For the purpose of this study, there is no significant difference between TM and ETM+, and the image we use was collected by Landsat 5 TM.

The four multispectral bands of MOMS-2P have locations on the electromagnetic spectrum similar to the first four bands of the Landsat TM; however, the former have significantly narrower wavelength intervals (35–60 nm wide) compared to the latter (60–140 nm wide). Spatial resolution is reported as the size of the ground-resolution cell (GRC), determined by the product of the instantaneous field of view (IFOV) of the instrument and the altitude. MOMS-2P (45.45 μradians) and Landsat TM (42.5 μradians) have very similar IFOVs. The much lower orbit of the Mir (380–405 km) compared to Landsat TM (705 km) results in a much smaller GRC for the former, in spite of the slightly better IFOV of the latter (Fig. 1). MOMS-2P multispectral bands 1–4 have GRCs between 15.9 and 18.0 m. This is approximately three times better than Landsat TM data, which have 28.5–30.0 m GRCs.

Landsat TM bands 1 to 4 and MOMS-2P multispectral bands are very similar. Band 1 (TM, 450–520 nm; MOMS-2P, 440–505 nm) covers the shortest wavelength visible part of the electromagnetic spectrum (blue) and coincides with the short-wavelength chlorophyll-absorption feature of vegetation as well as the minimum reflectance of iron-bearing rocks and soils. Band 2 (TM, 520–600 nm; MOMS-2P, 530–575 nm) is centered about the visible reflectance peak (green) of vegetation and with the charge-transfer part of iron-bearing rock and soil spectra. Band 3 (TM, 630–690 nm; MOMS-2P, 650–685 nm) covers the red visible part of the electromagnetic spectrum and coincides with the long-wavelength visible absorption feature of chlorophyll as well as the elevated reflectance of iron-bearing rocks and soils. Band 4 of MOMS-2P (770–810 nm) covers part of the infrared reflectance-maximum

---

Geology; September 2002; v. 30; no. 9; p. 851–854; 3 figures; Data Repository item 2002091.

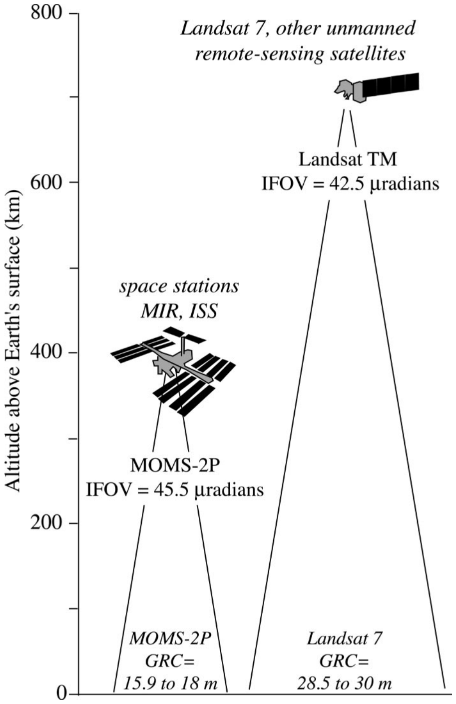

Figure 1. Comparison of altitudes and spatial resolutions of imaging systems like Modular Optoelectronic Multispectral Stereo Scanner (MOMS-2P) on manned space stations and those like Landsat Thematic Mapper (TM) on unmanned remote sensing satellites. Note that MOMS-2P and Landsat TM imaging systems have similar angular resolving power (instantaneous field of view, IFOV), but MOMS-2P, being much closer to Earth, yielded images with better ground-resolution cells (GRC). Note that GRC comparison between MOMS and Landsat 7 systems is only for multispectral data. ISS—International Space Station.

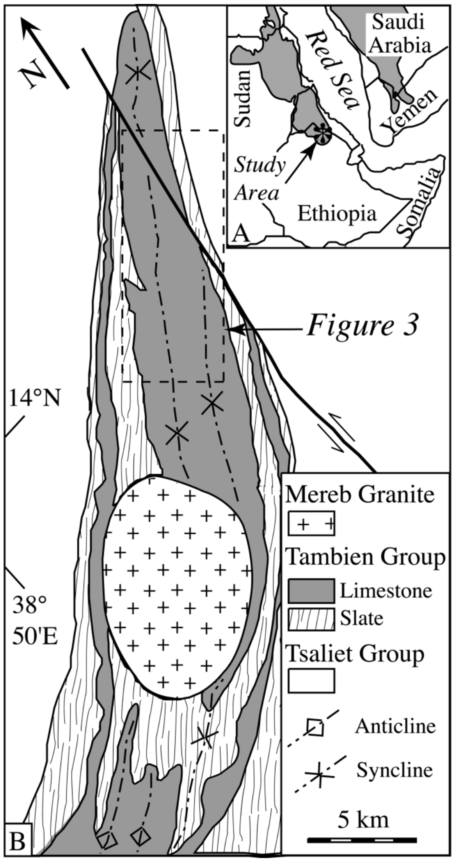

Figure 2. A: Locality map of Arabian-Nubian Shield (gray); asterisk marks location of Mai Kenetal synclinorium. B: Geological interpretation of Mai Kenetal synclinorium. Dashed rectangle shows detailed study area of Figure 3.

plateau of vegetation, whereas the wider Landsat TM band 4 (760–900 nm) covers the entire plateau. Hence, data acquired by MOMS-2P and Landsat TM bands 1–4 over the same area should have very similar spectral characteristics.

The MOMS-2P image used here was acquired at approximately 12:30 p.m. local time on December 18, 1996, whereas the TM image was acquired just before 10:30 a.m. local time May 30, 1984. The study area is close to the equator, so illumination conditions are quite similar for the two scenes. MOMS-2P and Landsat TM images were produced using ENVI image-processing software, assigning the color red to band 4, green to band 3, and blue to band 1 (4-3-1). The images were enhanced by simple linear stretching. Unsupervised classification was performed on portions of the images for purposes of quantitative comparison, following the IsoDATA procedure of Jensen (1996).

GEOLOGY OF THE STUDY AREA

The study area is in northern Ethiopia (Fig. 2A) within the East African orogen, which extends from Mozambique to the Mediterranean. The East African orogen formed when parts of East and West Gondwana collided in late Neoproterozoic time, ca. 600 Ma (Unrug, 1997). Deformed older rocks of the southern East African orogen—also known as the Mozambique belt—transition northward into juvenile Neoproterozoic crust of the Arabian-Nubian Shield. The Arabian-Nubian Shield is made up of convergent margin volcano-sedimentary and plutonic assemblages (arc terranes) sutured together and intruded by granitic plutons (Stern, 1994; Abdelsalam and Stern, 1996). The southern part of the East African orogen, known as the Mozambique belt, is dominated by high-grade metamorphic assemblages and reworked older crust and was the locus of the most intense collision (Stern, 1994). The southern East African orogen is also dominated by steep, north-trending structures—tight, upright folds and east- or west-directed thrusts—that die out northward; these are the shortening zones of Abdelsalam and Stern (1996).

The basement of northern Ethiopia is in the transition between the northern and southern parts of the East African orogen. It is compositionally similar to juvenile Arabian-Nubian Shield crust, but the structure is dominated by north-south–trending shortening zones. Tsaliet Group arc assemblages are unconformably overlain by weakly metamorphosed and deformed shales and shallow-water carbonates of the Tambien Group (Beyth, 1972). Sequences in Eritrea similar to the Tsaliet Group yield zircon ages of 854 ± 3 Ma (Teklay, 1997). The age of the Tambien Group as well as the timing of its deformation are not known, but both must be younger than the Tsaliet Group and older than the posttectonic Mareb granite, which yield zircon evaporation ages of 606 and 614 Ma, respectively (Sacchi and Kröner, 2001, personal commun.).

The study area is part of the north-northeast–south-southeast–trending Mai Kenetal synclinorium (Fig. 2B). This structure is ∼40 km long, 10 km wide, and is defined by sedimentary rocks of the Tambien Group that are folded, faulted, and overturned to the east. The synclinorium consists of three synclines and two anticlines with wavelengths of ∼2 km each (Beyth, 1972). Beds dip ∼25°NW on the eastern flank and ∼45°SE on the western flank. Dextral strike-slip faults trend ∼060° and have offsets of ∼250 m, whereas faults trending 310° are mostly sinistral. Faults of similar age and orientation elsewhere in the Arabian-Nubian Shield are interpreted to result from east-west shortening due to collision between East and West Gondwana (Abdelsalam and Stern, 1996). Shortening to form the Mai Kenetal synclinorium thus is suggested to have occurred ca. 610–630 Ma, strike-slip faulting occurring shortly thereafter.

The core of the synclinorium is occupied by black limestone, which appears greenish-yellow in the 4-3-1 MOMS-2P image (Figs. 2B and 3A). Slate surrounding the limestone core appears blue in the MOMS-2P image. The slate is succeeded to the east by a greenish limestone layer and then by more slate near the eastern contact with Tsaliet Group metavolcanic rocks. The south-central part of the synclinorium is intruded by an ∼8-km-diameter body of Mareb Granite (Fig. 2B).

COMPARISON OF MOMS-2P AND LANDSAT TM IMAGERY

To compare MOMS-2P and Landsat TM imagery, we used the northernmost part of the Mai Kenetal synclinorium because of its abundance of linear features. The MOMS-2P image (Fig. 3A) is much sharper, i.e., has a noticeably better spatial resolution, than the TM image (Fig. 3C). This difference is true for both units with discrete thickness (beds) as well as faults. The slate ridges (dark blue) on the east side can be identified in both images, but bedding and the northeast-trending dextral faults are much more distinct in the MOMS-

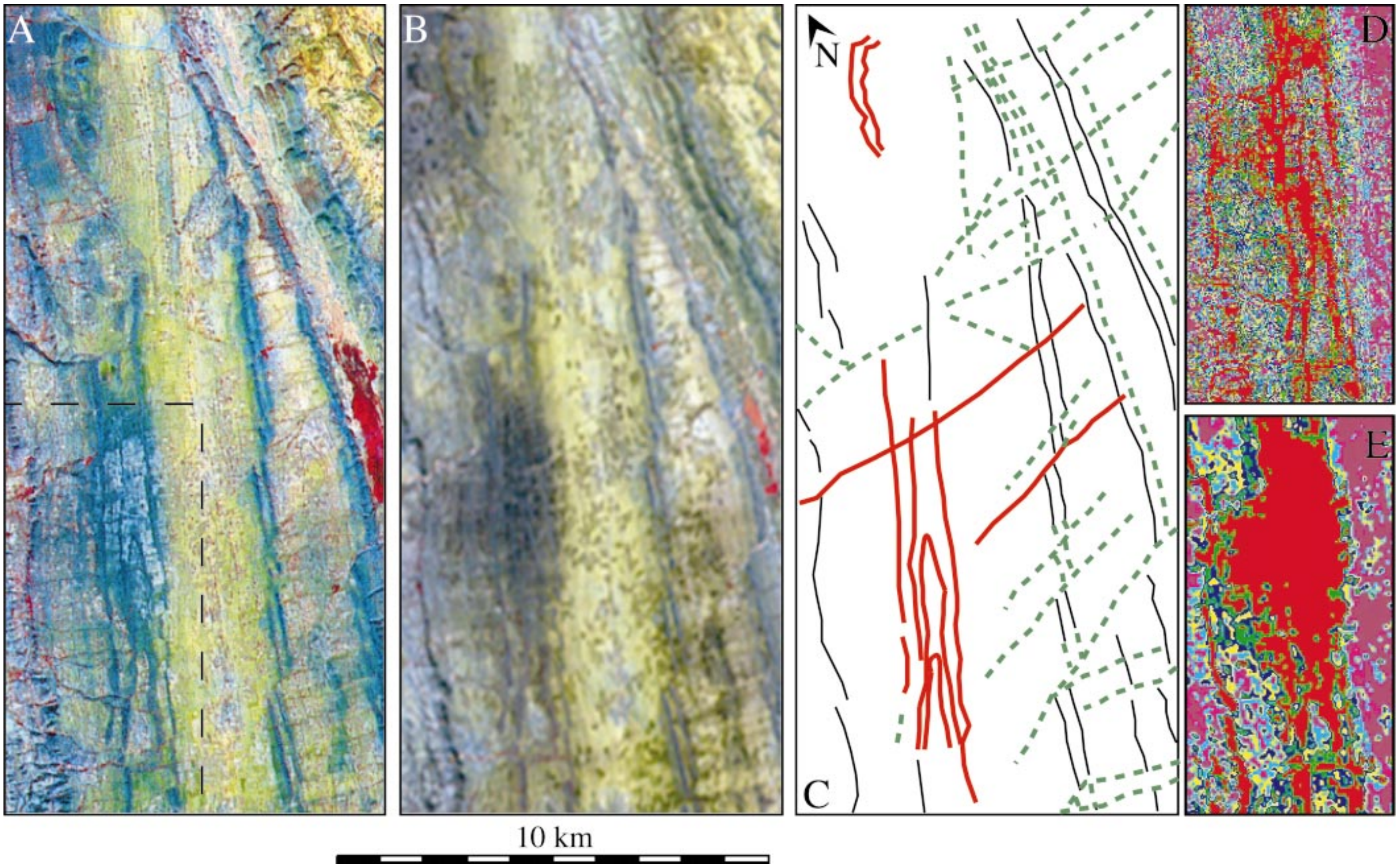

Figure 3. Comparison between 4-3-1 MOMS-2P and 4-3-1 Landsat TM images for northern part of Mai Kenetal synclinorium. (See Fig. 1 for abbreviations.) A: 4-3-1 MOMS-2P image: dashed rectangle in lower left shows location of D and E. B: 4-3-1 Landsat TM image. C: Structural interpretation of two images A and B. Thin black lines represent structural features visible in both images. Thick, dashed green lines represent structural features visible in both images but sharper in MOMS-2P image. Thick red lines represent structural features visible only in MOMS-2P image. D: IsoDATA unsupervised classification using bands 4, 3, and 1 to generate 5 classes for area shown in A on MOMS-2P image. E: Unsupervised classification of same area as D for Landsat TM image.

2P image. The easternmost slate belt is obvious on the MOMS-2P image but difficult to distinguish in the TM image. Tight folds in the slate are clear in the left center of the MOMS-2P image, but cannot be distinguished in corresponding parts of the TM image. The north-trending layering in the core of the Mai Kenetal synclinorium is deformed by a set of subvertical, few-kilometers-long, northeast-trending faults, many of which appear to be dextral strike-slip faults. This geometric relationship is best seen where the thin bluish slate layer sandwiched between the thick yellow limestone (right center) is used as a marker. The amount of apparent strike-slip separation does not exceed 500 m. The MOMS-2P image (Fig. 3A) reveals these faults better than the Landsat TM image (Fig. 3B).

An unsupervised classification exercise was carried out on part of the study area (dashed rectangle in Fig. 3A). This is an area where a tight fold can be seen on the MOMS-2P image but not on the TM image (Fig. 3, A, B, and C). The IsoDATA procedure of Jensen (1996) was employed, and the results show that much more detail over the folded area can be distinguished (Fig. 3, D and E). Given that the spectral properties of the two images are so similar, the difference must be due to the superior spatial resolution of the MOMS-2P image.

DISCUSSION

The earth sciences have played an important role in humankind's accelerating push into space. Space science has benefited tremendously from the perspective of geoscientists, especially for interpreting results from voyages of exploration to our moon and the terrestrial planets. Space exploration has returned the favor by giving us a new way to behold Earth, using astronaut photography or intelligent remote sensing and multispectral images acquired by unmanned satellites. These two modes of visualizing our planet have grown increasingly separate, most recently by the separation of the International Space Station imaging program—largely based on astronaut photography (Earth Science and Image Analysis, 2001)—from that of NASA's satellite-based Earth Observing System (2001). This division of Earth-imaging missions was done in part because the orbit of the International Space Station does not carry it over all parts of Earth's surface, but is limited to latitudes less than 51.6°.

The ability of the Earth Observing System and other unmanned remote sensing satellites to image Earth's entire surface is essential for a wide range of earth sciences. Our study demonstrates that installing multispectral imaging systems on the International Space Station would result in improved spatial resolution compared to that obtainable for the same instrument in an ~700 km orbit. Improvements in resolution are simple and predictable; because GRC = IFOV × altitude, an imaging system with a given GRC at 700 km altitude (a typical altitude for unmanned remote sensing satellites) will have a GRC at 380 km altitude that is ~54% that obtained at the higher altitude. Table 1 (see GSA Data Repository[1]) compares the spatial resolutions of a range of orbital sensors with the improvements that can be expected for these if they were mounted on the International Space Station orbiting at an

---

[1] GSA Data Repository item 2002091, Table 1, Spatial resolution data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

altitude of 380 km. These improvements would enable geologists using data from these instruments to do a better job of mapping surface features, finding mineral deposits, and monitoring natural and human hazards.

An important advantage of multispectral imagery over astronaut photography is the ability to acquire information about reflectance and emittance of wavelengths longer than those corresponding to very near infrared. These longer wavelengths contain valuable information about lithology, vegetation, or water properties (Arvidson et al., 1993). Because film is not sensitive to wavelengths longer than the very near infrared (800 nm, C. Evans, 2002, personal commun.), limited compositional information can be extracted from photographs. Furthermore, because the energy reflected or emitted from surfaces is limited and this energy decreases with the inverse square of the distance to the sensor, trade-offs between spatial and spectral resolution are routinely made during instrument design. Moving the imaging system closer to the target allows more energy to arrive at the sensor and requires less compromise between spatial and spectral resolutions.

Discussions about installing remote sensing equipment on the International Space Station should be enlarged to include imaging philosophy, for the purpose of capitalizing on the intelligent and highly trained humans onboard. It would be most advantageous to install a hyperspectral instrument like *Hyperion*, with 240 bands encompassing visible, near-infrared, shortwave-infrared, and thermal-infrared wavelengths. Digital imaging equipment could be mounted inside or outside the International Space Station. The U.S. Laboratory module has an optical quality window (the Window Observational Research Facility [WORF]; National Aeronautics and Space Administration, 2001) that is nadir viewing, and digital imaging equipment could readily be adapted for this. Installation of digital imaging equipment using the WORF would maximize the ability of the astronauts to adjust operating parameters, including trade-offs between spatial and spectral resolution of the instrument depending on the nature of the feature to be imaged. Alternatively, imaging equipment could be mounted outside the International Space Station, which would allow for the acquisition of oblique images. This would maximize the rapid response aspect, i.e., the ability to identify and photograph transient phenomena, such as eruptions, fires, and storms, that the astronaut photography program has demonstrated over the years (e.g., Kuchler and Jupp, 1988; Yoder et al., 1994; Evans et al., 2000). Consider a large, Plinian-type volcanic eruption, on the scale of Mount Peleé in 1902 or Mount St. Helens in 1980. An instrument that could be trained in any direction could be programmed to follow a volcano where an eruption was suspected to be imminent as it passed near it, perhaps measuring thermal infrared energy to monitor temperatures at likely eruption sites. When an eruption occurred, the instrument could use visible and near-infrared wavelengths to image the eruption cloud from many perspectives, alerting regional governments and air-traffic controllers. These images could also allow a three-dimensional representation of the cloud to be generated later, which would be useful for defining models of pyroclastic eruptions.

CONCLUSIONS

Because the MOMS-2P orbited closer to Earth's surface than the Landsat TM, it produced images that have superior spatial resolution and better allow for mapping of geologic features. This comparison demonstrates the great potential that manned space stations have for remote sensing the equatorial and mid-latitudes of Earth. It is clear that adding an advanced sensor as part of the International Space Station scientific payload would be a uniquely powerful and flexible addition to the growing constellation of orbital imagers now used to study Earth. Such a capability could also be uniquely powerful for studying a wide range of sudden Earth phenomena and natural hazards, including hurricanes, floods, tsunamis, and earthquakes. Installing multispectral imaging equipment on the International Space Station would also help bridge the widening chasm between astronaut photography and multispectral imaging by unmanned satellites.

ACKNOWLEDGMENTS

Extraordinary thanks to Mohamed Abdelsalam, without whose help this work would not have been done. We appreciate thoughtful reviews by C. Evans (Johnson Space Center) and J. Dehn (Alaska Volcano Observatory). Remote sensing data for this study were provided for through funds from the German Space Agency (to Bodechtel) and from the National Aeronautics and Space Administration (to Stern and Abdelsalam). The German-Israel Foundation is also acknowledged for supporting cooperation between the Geological Survey of Israel and GeoForschungsZentrum. This is University of Texas, Dallas, Geosciences contribution 978.

REFERENCES CITED

Abdelsalam, M.G., and Stern, R.J., 1996, Sutures and shear zones in the Arabian-Nubian Shield: Journal of African Earth Sciences, v. 23, p. 289–310.

Arvidson, R.E., Duncan, I., Green, G., Rivard, B., and Sultan, M., 1993, Geologic mapping using Landsat Thematic Mapper data over Oak-Hickory Forest, arctic, and hyperarid terrains, *in* Pieters, C.M., and Englert, P.A.J., eds., Remote geochemical analysis: Elemental and mineralogical composition: Cambridge, Cambridge University Press, p. 247–282.

Beyth, M., 1972, The geology of central western Tigre, Ethiopia [Ph.D. thesis]: Bonn, University of Bonn, 155 p.

Bodechtel, J., and Zilger, J., 1996, MOMS—History, concepts, goals: Proceedings of MOMS symposium, Köln, July 1995: EARSel Special Publication, p. 12–25.

Bodechtel, J., Lei, Q., and Beyth, M., 1998, Differentiation of lithologic units in arid regions using narrow band multispectral satellite data (MOMS-2P): Tenth Australasian Remote Sensing and Photogrammetry Conference Meeting, Sidney, 9 p.

D.A.R.A., 1997, Modular Optoelectronic Multispectral Stereo Scanner MOMS-2P, MOMS on PRIRODA: DLR, DFD, Germany: www.nz.dlr.de./moms2p/MOMS-2P Web site (January 2002).

Earth Observing System, 2001, NASA's Earth Observing System. NASA Goddard Space Flight Center: http://eospso.gsfc.nasa.gov/ (January 2002).

Earth Science and Image Analysis, 2001, The gateway to astronaut photography of Earth. Search for photos. Access to all photographs since 1961. Earth Science and Image Analysis, Johnson Space Center: http://eol.jsc.nasa.gov/sseop/ (January 2002).

Evans, C.A., Robinson, J.A., Wilkinson, M.J., Runco, S., Dickerson, P.W., Amsbury, D.L., and Lulla, K.P., 2000, The 1997–1998 El Niño: Images of floods and drought, *in* Lulla, K., and Desinov, L., eds., Dynamic Earth environments: Remote sensing observations from Shuttle-Mir missions: New York, John Wiley & Sons, p. 61–76.

Jensen, J.R., 1996, Introductory digital image processing: Englewood Cliffs, New Jersey, Prentice-Hall, 318 p.

Kuchler, D.A., and Jupp, D.L.B., 1988, Shuttle photographs capture massive phytoplankton bloom in the Great Barrier Reef: International Journal of Remote Sensing, v. 9, p. 1299–1301.

Landsat 7, 2001, Landsat 7 gateway: http://landsat.gsfc.nasa.gov/ (January 2002).

National Aeronautics and Space Administration, 2001, A window on the Earth: Earth Sciences from the International Space Station and The Window Observational Research Facility (WORF): http://eol.jsc.nasa.gov/worf/ (May 2002).

Stern, R.J., 1994, Arc assembly and continental collision in the Neoproterozoic East African Orogen: Implication for the consolidation of Gondwanaland: Annual Review of Earth and Planetary Sciences, v. 22, p. 319–351.

Teklay, M., 1997, Petrology, geochemistry and geochronology of Neoproterozoic magmatic arc rocks from Eritrea: Implications for crustal evolution in the southern Nubian Shield: Eritrea Department of Mines Memoir 1, 125 p.

Unrug, R., 1997, Rodinia to Gondwana: The geodynamic map of Gondwana supercontinent assembly: GSA Today, v. 7, p. 2–6.

Yoder, J.A., Ackleson, S.G., Barber, R.T., Flament, P., and Balch, W.M., 1994, A line in the sea: Nature, v. 371, p. 689–692.

Manuscript received March 27, 2002
Revised manuscript received May 24, 2002
Manuscript accepted May 31, 2002

Printed in USA