The First Quarter: A 25 Year History of Mineral Exploration Remote Sensing 1989 - 2014

Dan Taranik
Exploration Mapping Group, Inc.

GRSG Annual Meeting
London, December 17, 2014

www.ExplorationMapping.com

The First Quarter: A 25 Year History of Mineral Exploration Remote Sensing

- **Setting the Stage for 1989**
- **Timeline of Key Developments**
- **The Road Ahead**

EXPLORATION MAPPING

Setting the Stage

Pioneering Work:

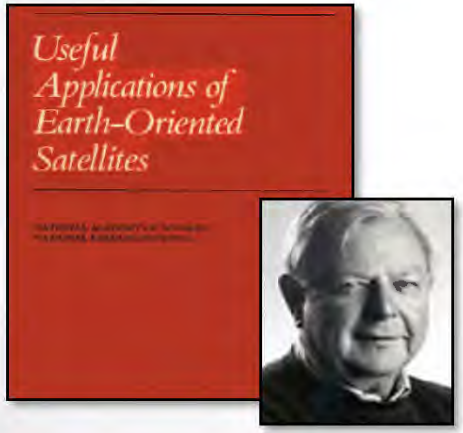
Eisenhower's **'Freedom of the Skies'**

"The principal fields of applied geology [for Earth-oriented satellites] are exploration for minerals, oil and gas and engineering construction" Ron Lyon, 1969

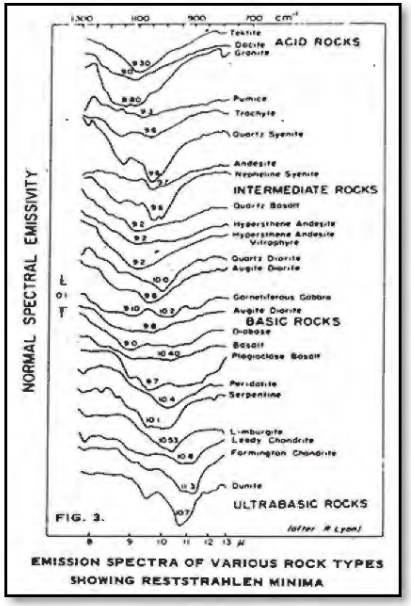
USGS Geologists

William Pecora

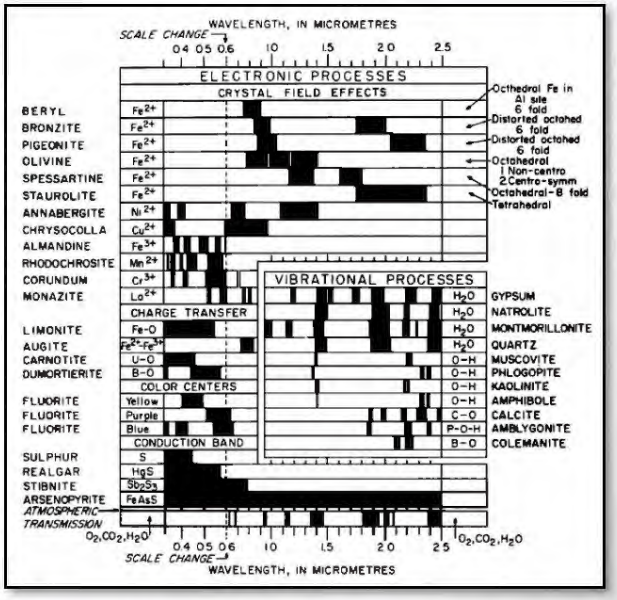
William Fisher



Ron Lyon



Lyon, 1965
Economic Geology



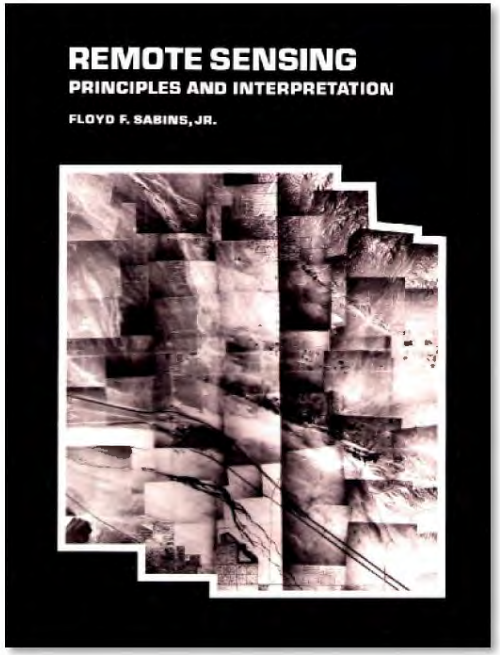
Hunt and Salisbury, 1970

EXPLORATION MAPPING

Setting the Stage
1978

First Textbook:

Remote Sensing: Principles and Interpretation, (Sabins,1978)



Floyd Sabins

Landsat Color Ratio Composite Goldfield, Nevada Courtesy L.C. Rowan USGS/JPL

During 37 years with Chevron, Dr. Sabins

- introduced remote sensing to Chevron leading to the first **oil discoveries in Sudan and Papua New Guinea**
- his programs for digitally processing Landsat images ***discovered the world-class Collahuasi and Ujina, Chile copper deposits,*** earning him the coveted Chevron Chairman's Award

EXPLORATION MAPPING

Setting the Stage
1970s - 1980s

***Field Spectrometers*:**

- **Portable Field Reflectance Spectrometer (PFRS)** 1974

- **Portable Instantaneous Display and Analysis Spectrometer (PIDAS)** 1984

- **Early Spectrometer** collection at Yerington, Nevada, left to right
  - Chris Elvidge, PIDAS
  - Ron Lyon, Daedalus prototype
  - Chuck Stanich, Spectrafax
  - Tod Rubin, Exotech

EXPLORATION MAPPING

Setting the Stage
1980s

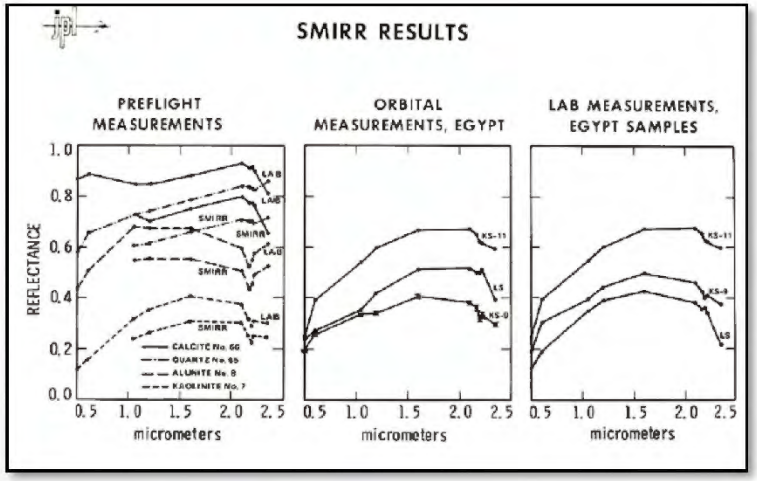
The Space Shuttle:

- Space **Shuttle Multispectral Infrared Radiometer** (SMIRR) and **Shuttle Imaging Radar-A** (SIR-A)

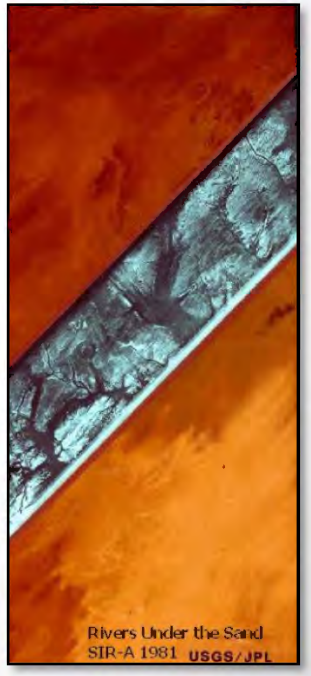
"'…first direct identification of a surface mineral from orbit."
(Goetz, 1982)

James Taranik

Space Shuttle Columbia



SMIRR Kaolinite Identification



SIR-A Radar Sahara Sand Penetration Courtesy NASA/JPL

EXPLORATION MAPPING

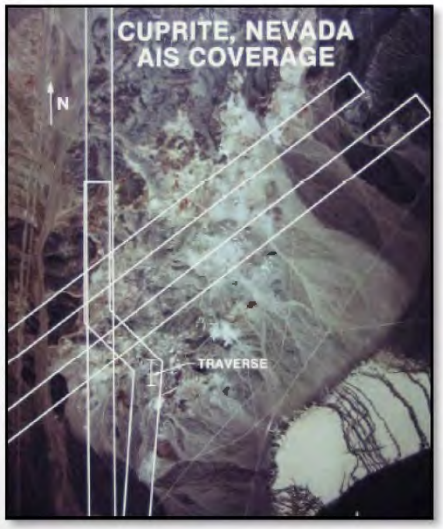
Setting the Stage
1980s

Alex Goetz

Imaging Spectrometry :

- **1982** *Deadalus Airborne Thematic Mapper*
- **1983** *AIS flight over Cuprite, Nevada*
- **1983** *Remote Sensing for Exploration: An Overview, Econ Geology*
- **1984** *Buddingtonite discovery at Cuprite, Nevada*
- **1985** *Hyperspectral Science paper, Goetz, et al.*
- **1985** *GeoScan AMSS MKI*
- **1986** *GER Imaging Spectrometer*
- **1987** *AVIRIS*

First mention of the term "hyperspectral"



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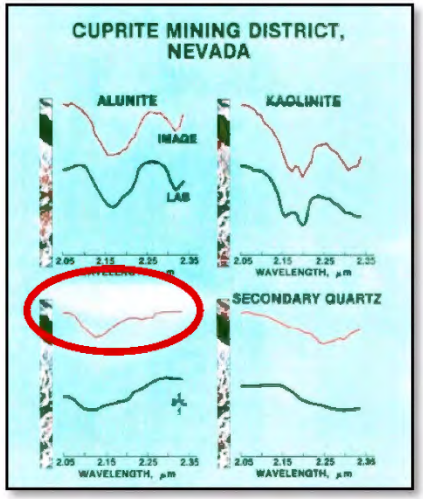
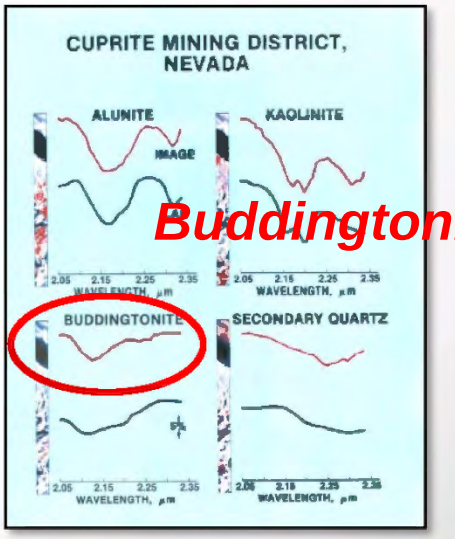




Buddingtonite!

Goetz, A., Vane, G., Solomon, J., Rock, B. 1985

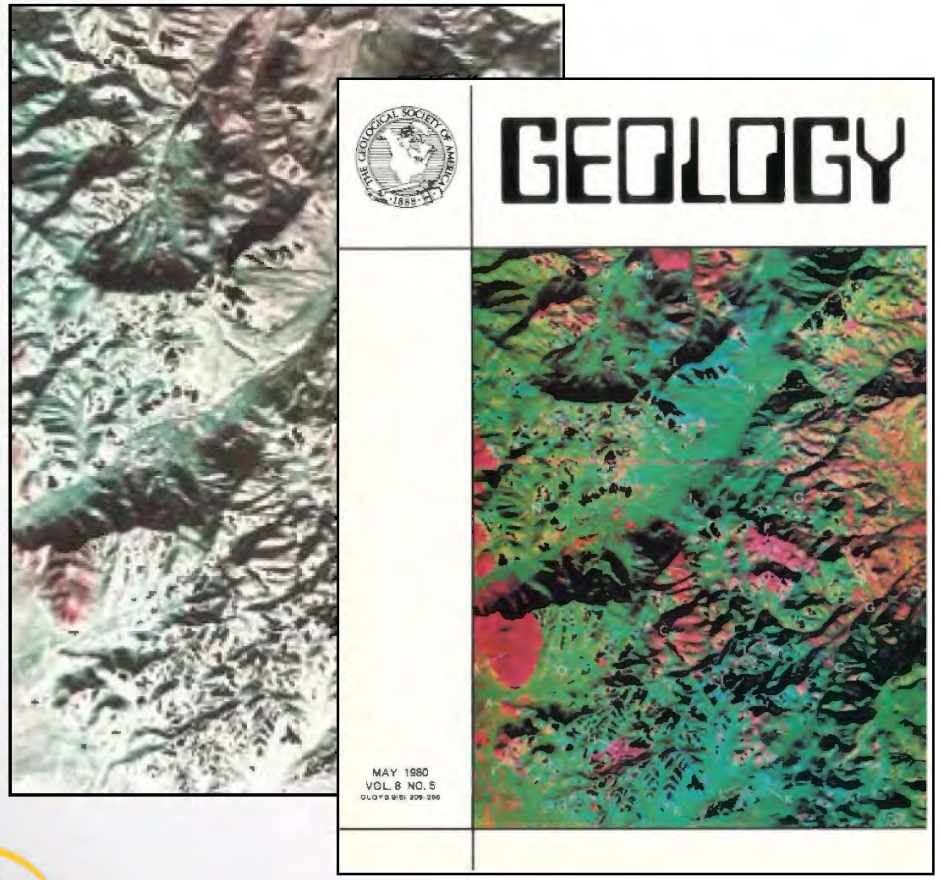
EXPLORATION MAPPING

Setting the Stage
1980s

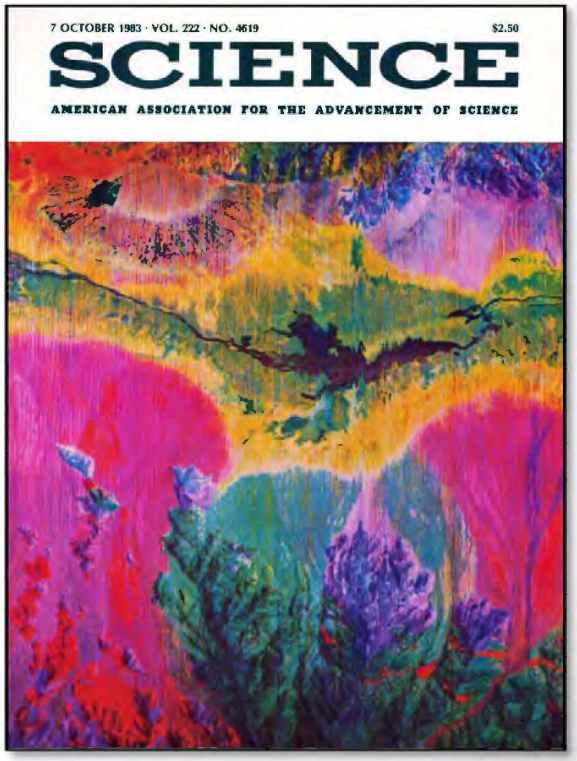
Anne Kahle

***Thermal Infrared Scanning*:**

- **Thermal Infrared Multispectral Scanner** (TIMS)



Kahle and Rowan ,1980



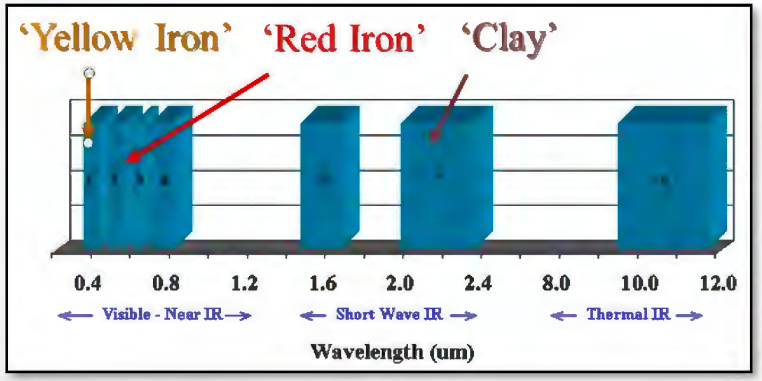
Kahle and Goetz,1983

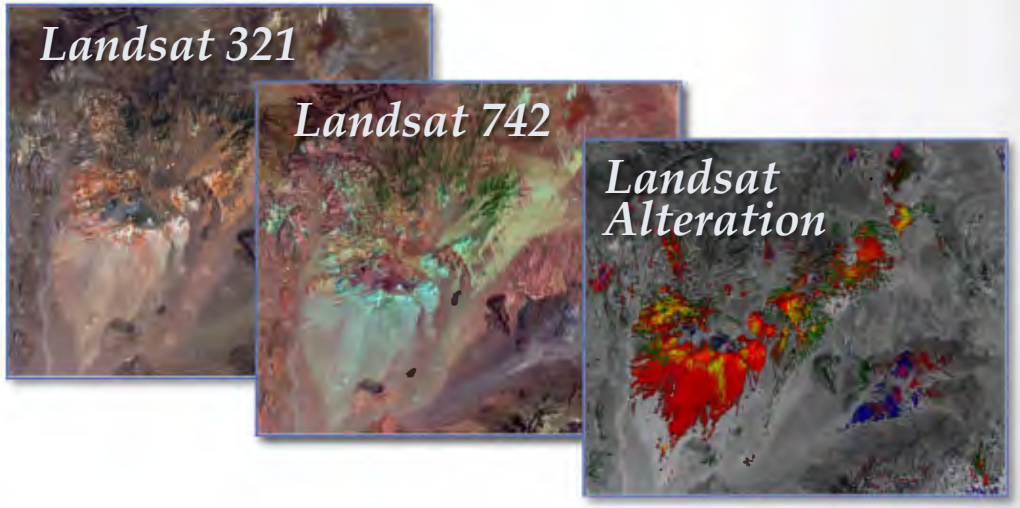
EXPLORATION MAPPING

Setting the Stage
1970s - 1980s

***The Satellites*:**

- **Landsat-1** 1972 (ERTS) with 4 image bands in the VNIR
- **Landsat 4 - Thematic Mapper**, launched July 1982, first to have Band 7 'Clay' band

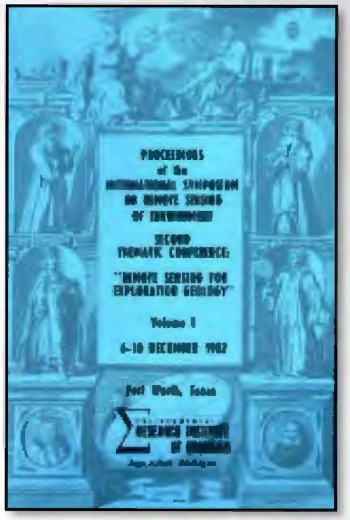




- French **SPOT-1** launched 1986, 10m pan, 20m multispectral
- Indian **IRS-1A** launched 1988, 72m 36m in the Visible

EXPLORATION MAPPING

Setting the Stage
1970s - 1980s



***Meetings and Publications*:**

- **Manual of Remote Sensing** – Reeves, 1975
- **Remote Sensing Image Processing** – Moik, 1980
- **Remote Sensing in Geology** – Siegal and Gillespie, 1980
- **ERIM Geological Remote Sensing Meetings** (1982-2000)
- **Joint NASA/Geosat Test Case** – Settle and Abrams, 1984
- **Numerical Recipes** – Vetterling et al, 1986
- **Image Interpretation in Geology** – Drury, 1987
- **Remote Sensing Principles and Interpretation 2nd Ed** – Sabins, 1987
- ***Limited Email, No Internet !***

EXPLORATION MAPPING

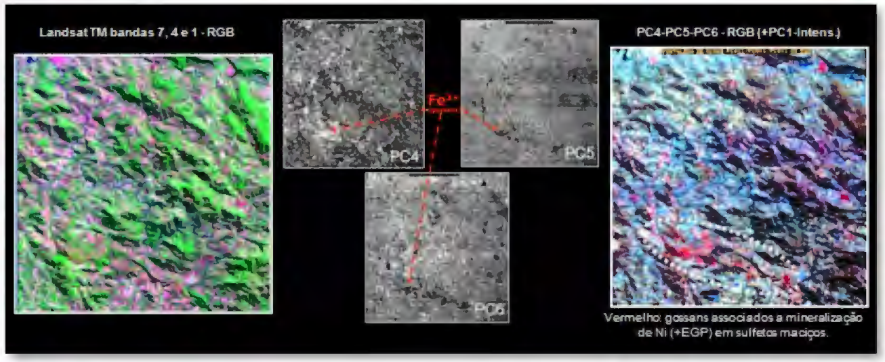
The First Quarter: A 25 Year History of Mineral Exploration Remote Sensing

- Setting the Stage for 1989
- **Timeline of Key Developments**
- **The Road Ahead**

EXPLORATION MAPPING

1989

- **Geological Remote Sensing Group (GRSG)** formed
- **Crosta** Landsat alteration mineral enhancement process first published



Alvaro Crosta

PIMA SP

- **PIMA spectrometer** developed at CSIRO by Terry Cocks, first units purchased by Anglo American
- First **Image Cube** constructed by Joe Boardman at University of Colorado Center for the Study of Earth from Space (CSES) using the SIPS software written in IDL pre-cursor to ENVI

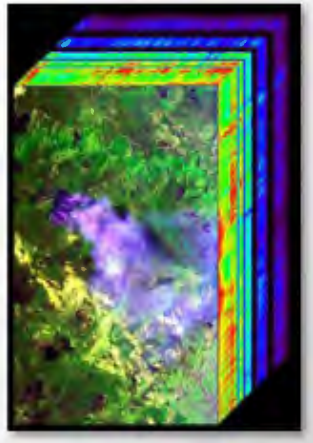


Image Cube

EXPLORATION MAPPING

1990

- First commercial **Compact Airborne Spectrographic Imager (CASI)** flown and sold by Canada's ITRES
- '**ATREM**' first atmospheric model-based reflectance correction developed University of Colorado
- The **WWW (World Wide Web)** created by Berners-Lee introducing concepts of HTML, HTTP, URL
- Australian Beta Release of PC-based **ER Mapper**
- **Analytical Spectral Devices** formed in Boulder, Colorado

Tim Berners-Lee

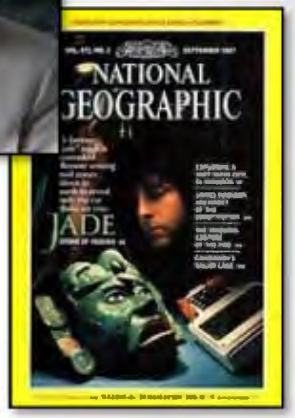
ASD's First Marketing Flyer

EXPLORATION MAPPING

1991

- **Analytical Spectral Devices** produces the Personal Spectrometer II (PSII)

Brian Curtiss

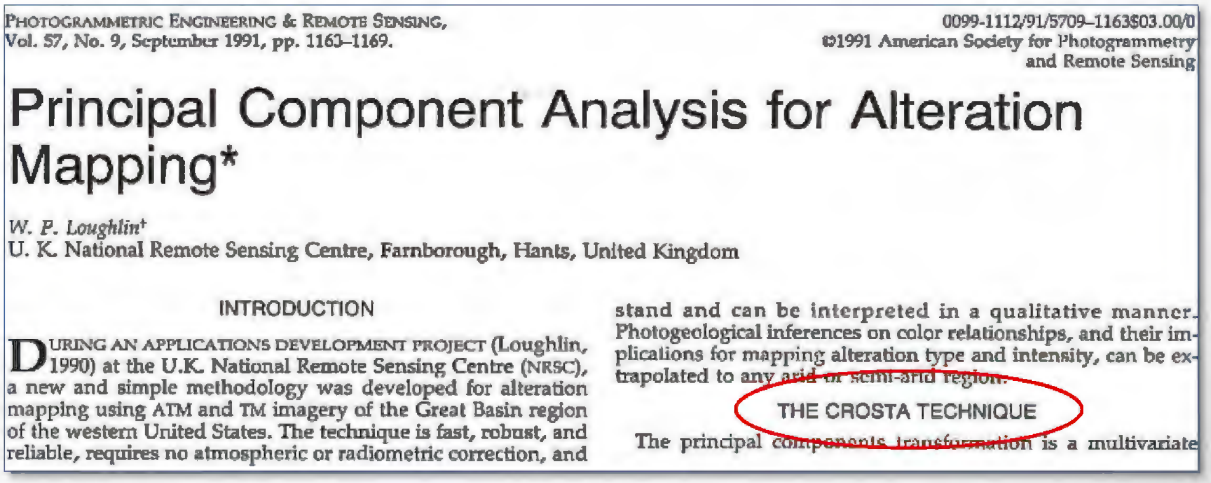


- **ERS-1,** European Radar Satellite-1 launched by European Space Agency, notable for C-band radar

Images courtesy Brian Curtiss, ASD and Fred Ward, National Geographic, 1987

- **Billy Loughlin** modifies Crosta's PhD thesis procedure for gold exploration and coined the term **'Crosta Technique'**

Billy Laughlin



PHOTOGRAMMETRIC ENGINEERING & REMOTE SENSING,
Vol. 57, No. 9, September 1991, pp. 1163–1169.

0099-1112/91/5709–1163$03.00/0
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and Remote Sensing

Principal Component Analysis for Alteration Mapping*

W. P. Loughlin†
U. K. National Remote Sensing Centre, Farnborough, Hants, United Kingdom

INTRODUCTION

DURING AN APPLICATIONS DEVELOPMENT PROJECT (Loughlin, 1990) at the U.K. National Remote Sensing Centre (NRSC), a new and simple methodology was developed for alteration mapping using ATM and TM imagery of the Great Basin region of the western United States. The technique is fast, robust, and reliable, requires no atmospheric or radiometric correction, and

stand and can be interpreted in a qualitative manner. Photogeological inferences on color relationships, and their implications for mapping alteration type and intensity, can be extrapolated to any arid or semi-arid region.

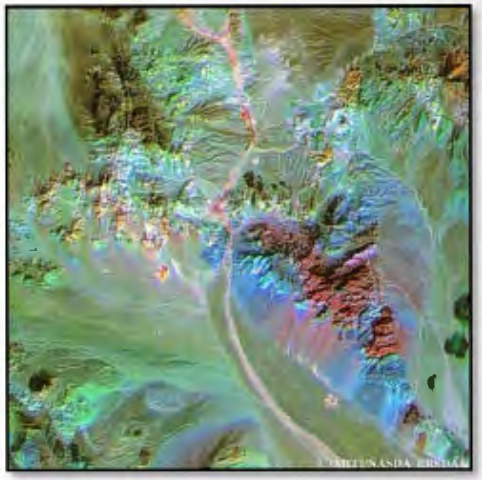
THE CROSTA TECHNIQUE

The principal components transformation is a multivariate

EXPLORATION MAPPING

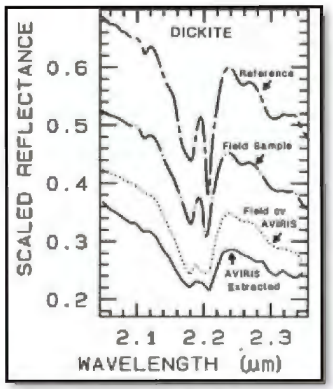
1992

- **SpecTIR** formed in California for US DOD using technology derived largely from the Hughes Aircraft Research Centers
- Japanese Earth Resources Satellite **JERS-1** radar launched for land use and exploration applications
- USGS first to discriminate **spectral solid solution series** of alunite and kaolin group minerals using AVIRIS at Cuprite. (Swayze et al., 1992; Clark et al., 1992)



JERS-1 Image courtesy MITII, NASDA, ERSDAC

Gregg Swayze



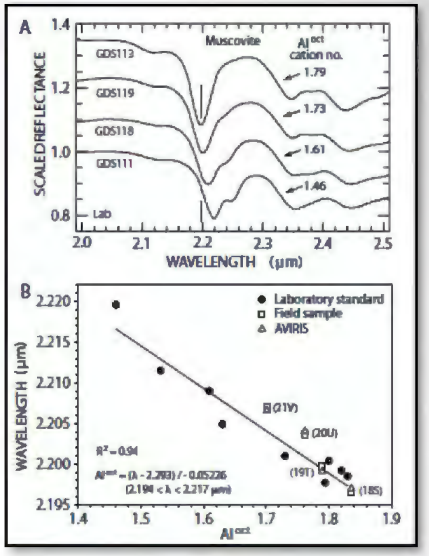
Dickite Ground Truth

Roger Clark

EXPLORATION MAPPING

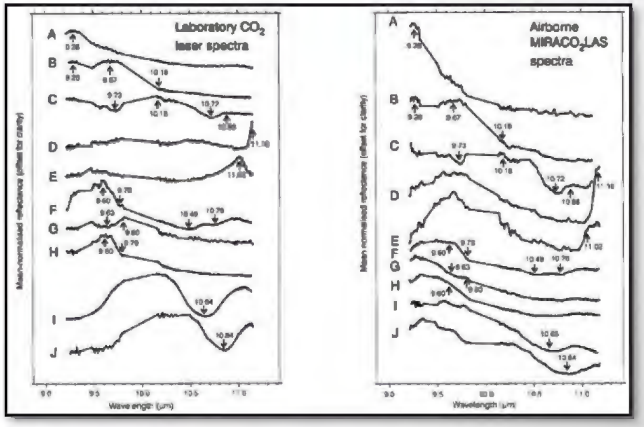
1993

- USGS first to post **Digital Spectral Library v1** on the primordial web
- USGS differentiates **white mica compositional series** (Swayze, 1993)
- **CSIRO MIRACO2LAS** fist airborne hyperspectral TIR developed in Australia



USGS Muscovite Compositional Mapping

MIRACO2LAS Images Courtesy CSIRO



Lab vs Airborne TIR Spectra Cudahy et al 1997

EXPLORATION MAPPING

1994

- **Environment for Visualizing Images (ENVI)** commercial software developed at Better Solutions Consulting, Boulder, Colorado (Kruse, Boardman, Lefkoff, Young and Young)

ENVI Approach

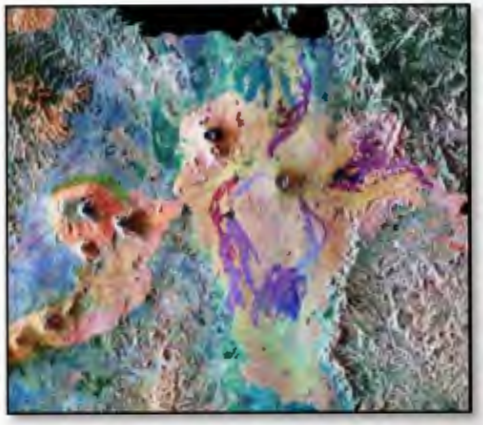
Fred Kruse

Bill Baugh

- Kruse and Baugh publishes first results on **hyperspectral core scanning** for minerals

PIMA Core Spectra and Unmixing Results Kruse and Baugh,1994

Integrated Spectronics PIMA



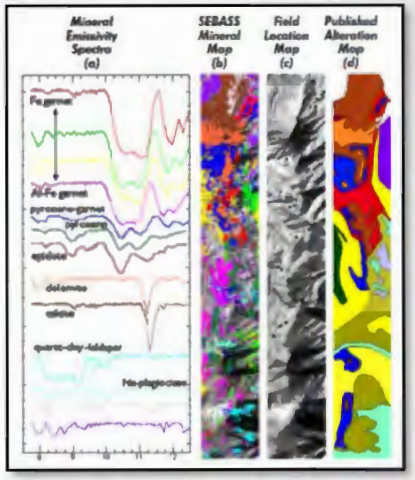
SIR-C/X-SAR color Central Africa 1994 NASA

- **SIR-C / X-SAR** space shuttle radar flown this year

EXPLORATION MAPPING

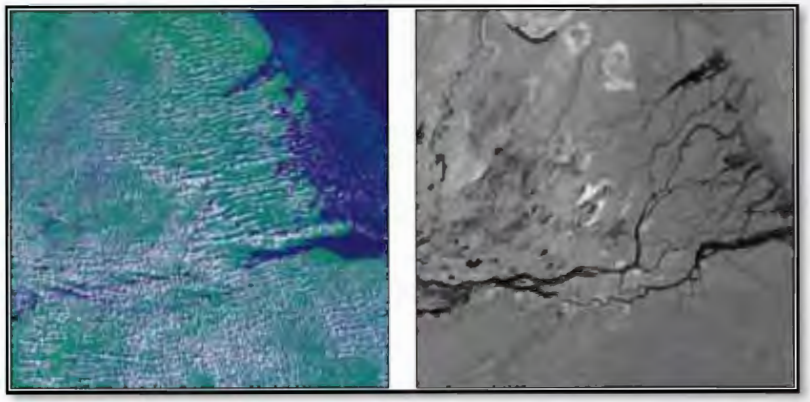
1995

- The airborne **Spatially Enhanced Broadband Array Spectrograph System (SEBASS)** commissioned in 1995, 128 bands 7.8-13.5um



Images Courtesy CSIRO

- Canada's first commercial earth-observation satellite **RADARSAT-1** launched by NASA for natural resource and climate change applications



LANDSAT (left) © EOSAT, RadarSat-1 (right) © Canadian Space Agency 1996

- Launch of **OrbView-1** the world's first commercial imaging satellite

EXPLORATION MAPPING

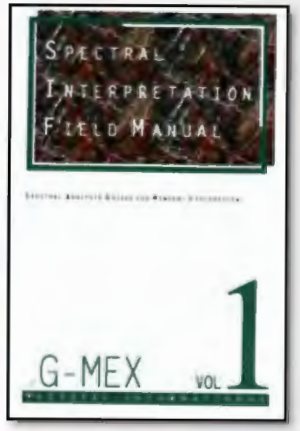
1996 - 1997

HyMap AMS
Images Courtesy DeBeers

- **Integrated Spectronics** built the first of the **HyMap** series of hyperspectral scanners – the **DeBeers AMS** 96 channels - for DeBeers / Anglo American

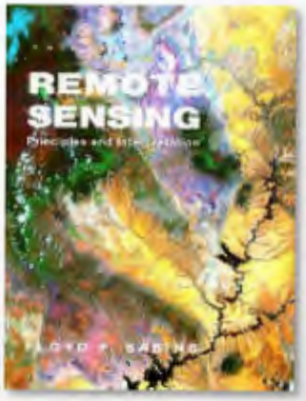
- Integrated Spectronics builds 2 more hyperspectral scanners for **Earth Search Sciences, Inc** (Probe-1 & Probe-2), ESSI leases Probel-1 to **Noranda** for large surveys in Arctic Canada

Sasha Pontual



- **The Spectral Geologist (TSG)** and **GMEX** mineral exploration spectral analysis software and guides published by AusSpec International Ltd.

- **Remote Sensing Principles and Interpretation** 3rd Edition – Sabins, 1997



EXPLORATION MAPPING

1998

- **SpecTIR** begins development of the HyperSpecTIR commercial airborne imaging spectrometers

Research Scanning Polarimeter (RSP)

HST #1

- Integrated Spectronics spin-off company **HyVista Corporation** formed to operate the third HyMap scanner

- **Google** founded by Stanford Ph.D. students Larry Page and Sergey Brin

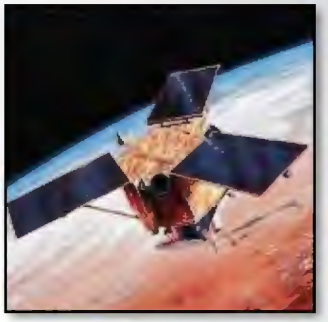
Google

1999

- **IKONOS**, Greek for ‘image’, built by US Lockheed Martin Corporation for Space Imaging EOSAT, first commercial high-resolution satellite 1- and 4-meter resolution panchromatic and multispectral imagery

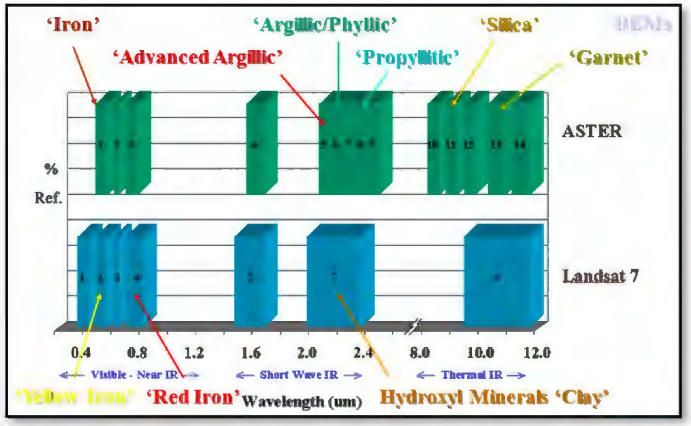
- **Landsat 7 ETM+** launches April 15 1999 primary advance was the 15m pan band

- **ASTER** (Advanced Spaceborne Thermal Emission and Reflection Radiometer) launches in December of 1990



IKONOS

Landsat 7



ASTER (top) vs Landsat Banpasses

ASTER – Escondida Mine, Chile
Courtesy NASA/Japan Space Systems

EXPLORATION MAPPING

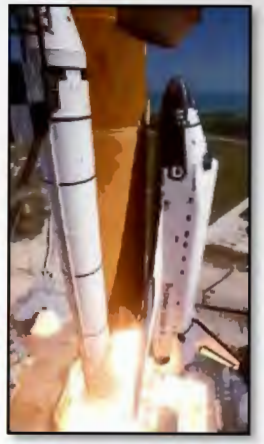
2000

- The **Shuttle Radar Topography Mission (SRTM)** launches February 2000 collecting topographic data and creating the first-ever global data set of land elevations in 10 days

- Early **UAV Technology** used for ASTER/Terra validation

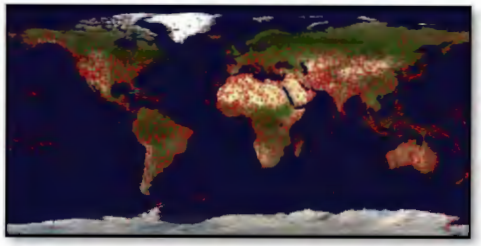
- The **Hyperion** hyperspectral satellite launches on NASA's EO-1, 220 spectral bands, 30m

- **Garnet-Skarn alteration mineralogy** mapped by Cudahy et al with SEBASS TIR at Yerrington, Nevada

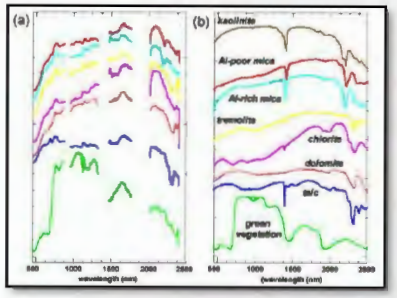


Space Shuttle Endeavour

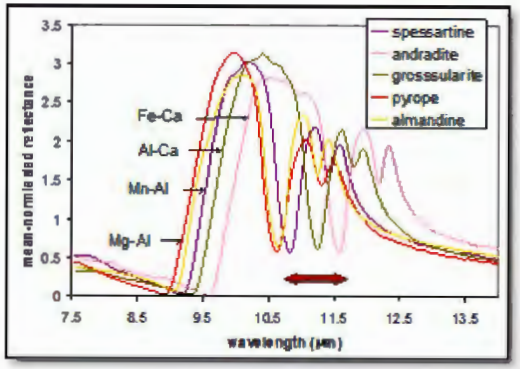
Courtesy Curtis Thome, Alfredo Huerte



Hyperion Global Coverage



First HYPERION SWIR Signatures CSIRO

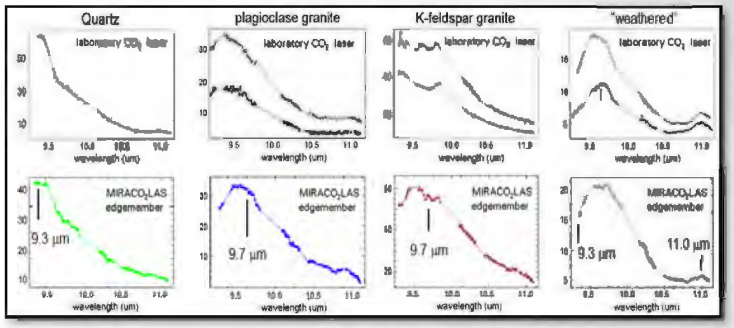


Garnet Spectra Courtesy CSIRO

Tom Cudahy

EXPLORATION MAPPING

2001



Spectra Courtesy CSIRO, ERSDAC

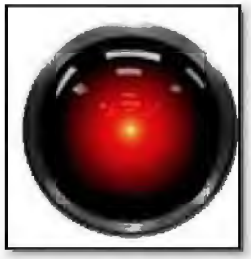
- **K-feldspar and Na-plagioclase feldspar** alteration mineral variations mapped using SEBASS TIR, Cudahy, Mt Fitton, Australia

- **Wikipedia** founded by Larry Sanger and Jimmy Wales to make a publicly-editable encyclopedia

- **Quickbird** satellite launched with 61cm pan and multispectral images at 2.4m with large image size (18km x 360km strips)

- **Keyhole Inc** founded with pioneering geospatial data visualization application **Earth Viewer**

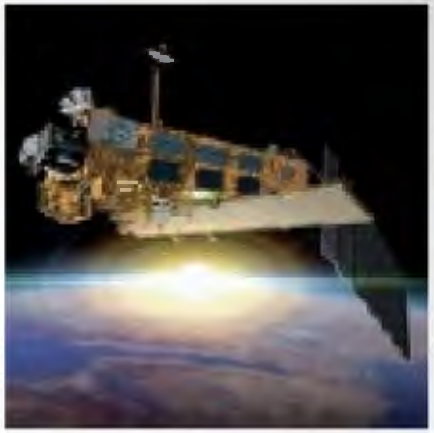
- **David Bowman** shuts down the **HAL 9000** while in orbit around Jupiter



EXPLORATION MAPPING

2002 - 2003

- Launch of European Space Agency's **ENVISAT**
- GRSG conducts **ASTER Unveiled** Annual Meeting
- First **CubeSat** launched on designs made at Stanford and California Polytechnic to help universities to perform space science and exploration



ENVISAT
Courtesy ESA

Aerospace Corporation CubeSat
measures 10 by 10 by 10 centimeters, weighs 1 kg

EXPLORATION MAPPING

2004

- **HyVista** begins a campaign of airborne hyperspectral coverage of **Namibia** with the HyMap scanner, the first full-country coverage by a hyperspectral scanner

Namibia HyMap Coverage Courtesy Mike Hussey

- **DeBeers - SpecTerra Systems** begin trials of hyperspectral core logging by fitting a periscope lens to the HyMap instrument for <1mm pixels

DeBeers AMS/HyMap 96-channel scanner Configured for Core Scanning 2004

- **Google** acquires Keyhole, Inc. and it's virtual globe obtained from EarthSat's Landsat satellite imagery and high-resolution coverage of most major cities using Quickbird and aerial photography and Digital Elevation Model (DEM) from NASA SRTM

2005 - 2006

Mark Landers

- **SpecTIR** reorganizes to focus on airborne SpecIm Aisa Dual systems; Spatial, Spectral, Calibration, Pointing and especially no ITAR restrictions to respond to international demand
- **SpecTerra Systems** (Frank Honey with help of Mike Hussey, DeBeers) delivers first commercial prototype Hyperspectral Core Imager (HCI-1) instrument to Anglo Gold, scans one length of core

Prototype HCI-1
AngloGold

- Amazon Web Services provides commercial access to their computer systems, a key event in the development of **Cloud Computing**

- **Google Earth** program released to the public driving general public interest in remote sensing and related geospatial technologies
- Microsoft releases **Virtual Earth** in response to Google Earth
- **Joe Boardman** summarizes the history of hyperspectral software development at an IGARSS IEEE conference and publication

EXPLORATION MAPPING

2007

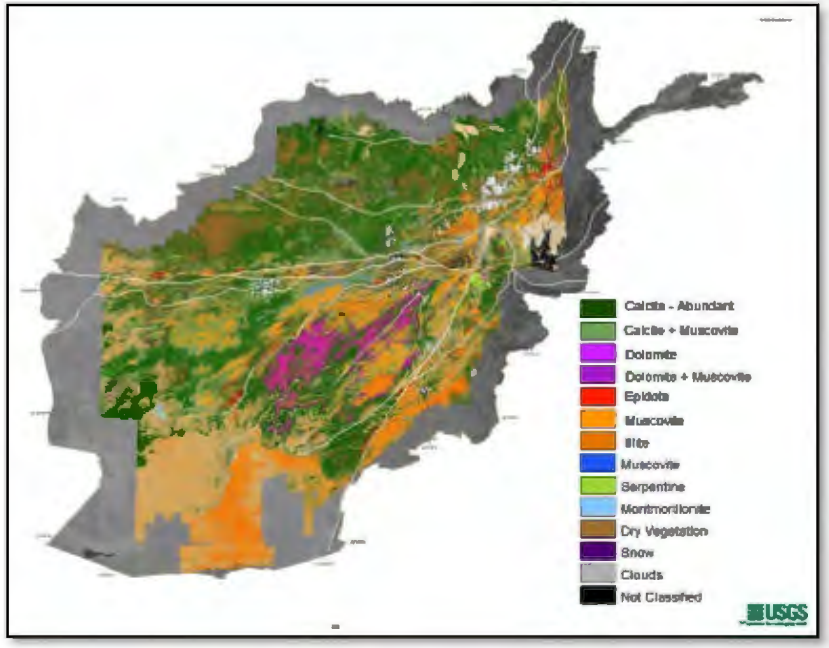
- Jon Huntington at CSIRO coordinates development of the **AusScope National Virtual Core Library (NVCL)** to build an Australian national online database of drillcore using HyLogging technologies

Awarded
Australia Prize 1995

Jon Huntington

- **WorldView-1** launches with 50cm panchromatic band

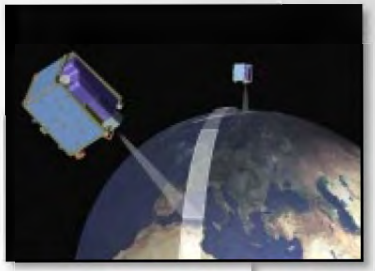
- **US Geological Survey** leases a HyMap scanner for virtually complete survey of **Afghanistan** in 43 days



Afghanistan HyMap Coverage
Courtesy Trude King, USGS

EXPLORATION MAPPING

2008 - 2009



- **RapidEye** established, the first commercial German satellites, a five-satellite constellation producing 5m colour imagery, capable of imaging any point on earth every day
- **Falcon-1** rocket launched by **SpaceX** in California, first successfully liquid-propelled orbital launch vehicle developed with private funding
- **EO-Miners** consortium forms to develop tools and methods to assess Environmental and Societal Impacts of Mining
- **CoreScan** founded by Frank Honey, developing purpose-built core scanner and analysis software
- First **Ore Sorting** paper published by Alex Goetz, *Rapid gangue mineral concentration measurement over conveyors by NIR reflectance spectroscopy, Minerals Engineering, v22, pp 490-499*
- **Micro-Hyperspec** commercial release by Headwall Photonics, 369 VNIR bands, weight less than 2.5kg

SpaceX Falcon-1

Micro-Hyperspec

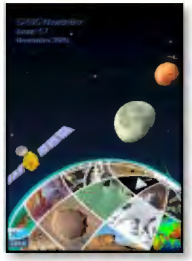
EXPLORATION MAPPING

2009

- Richard Bedell, Alvaro Crosta, Eric Grunski coordinate the **SEG**'s **Remote Sensing and Spectral Geology** publication covering a wide spectrum of exploration remote sensing case studies

Reviews in Economic Geology, v. 16, 2009

- **Hyperspectral Remote Sensing** historical reviews by;
  - Alex Goetz, Three decades of hyperspectral imaging of the Earth: A personal view, *Remote Sensing of Environment*, v113, S5-S16
  - Mike Hussey, Terry Cox An Australian perspective on commercial hyperspectral imaging, GRSG Issue 53,



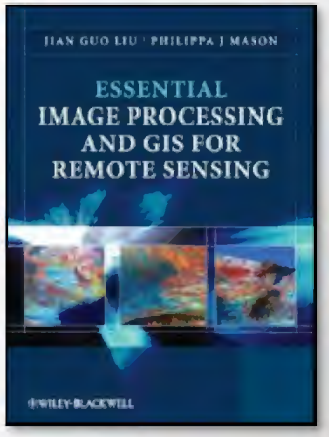
GRSG Issue 53, November 2009

Mike Hussey

- **Essential Image Processing and GIS for Remote Sensing** published by J.G. Liu and P.J. Mason

Jian Guo Liu

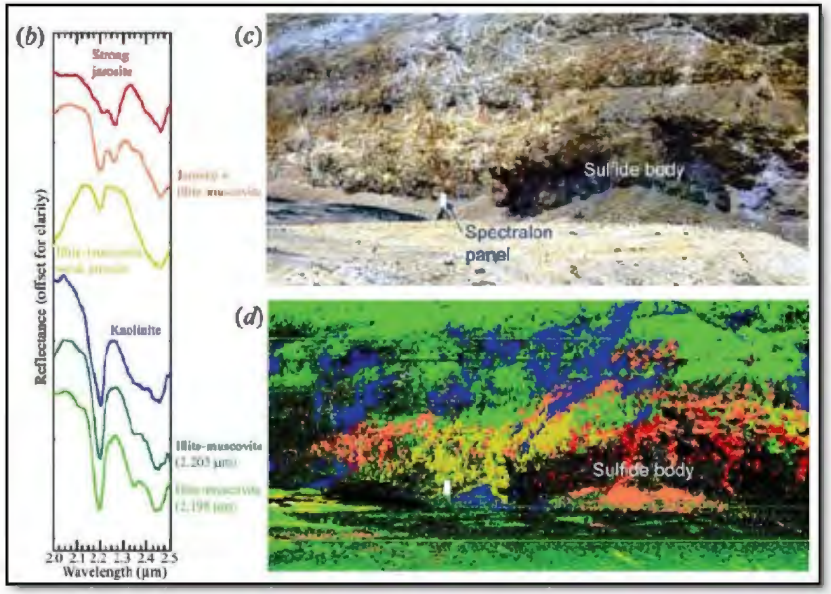
Philippa Mason



EXPLORATION MAPPING

2010

- **Mine-wall and Core Scanning** of Trinity Silver Mine, Nevada, paper published by Kruse et al, project and instrumentation sponsored by SpecTIR



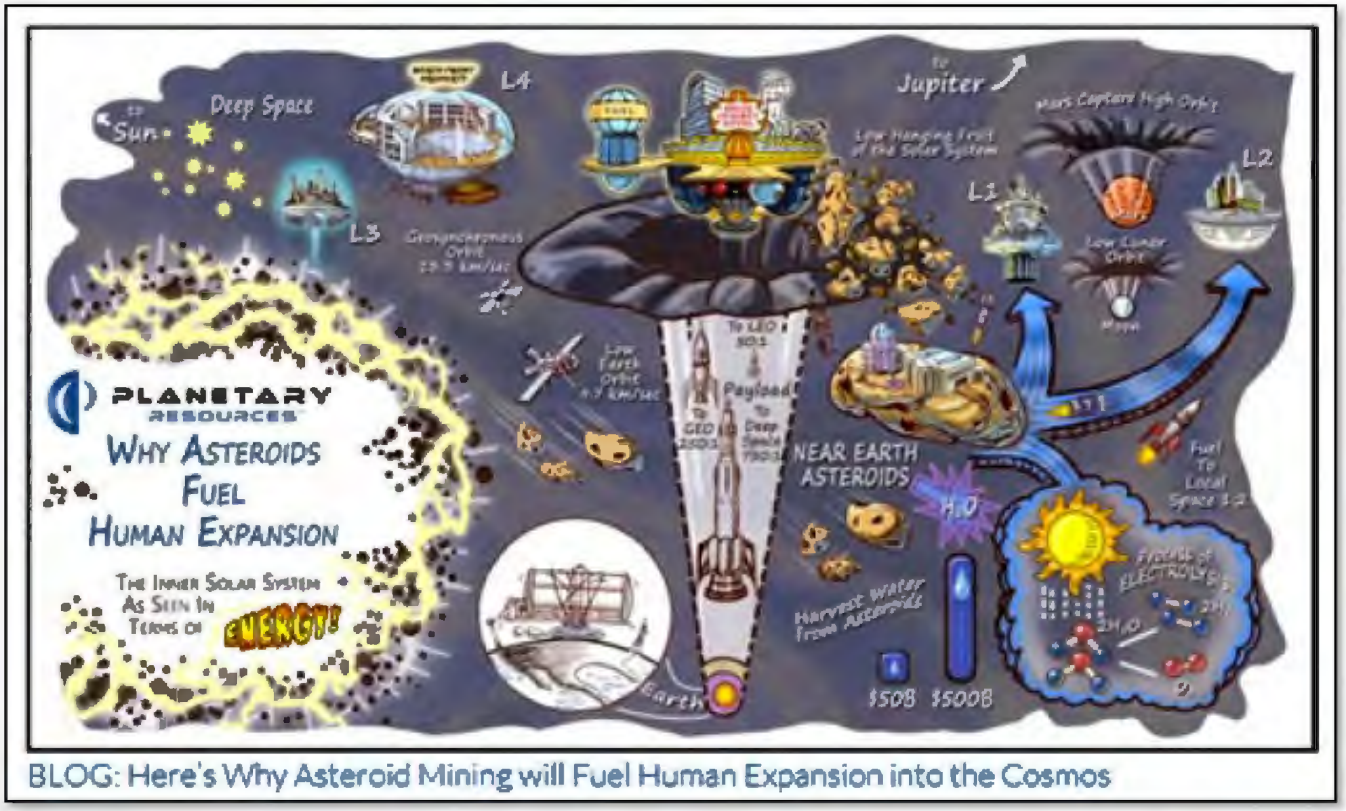
Trinity Silver Mine, Nevada

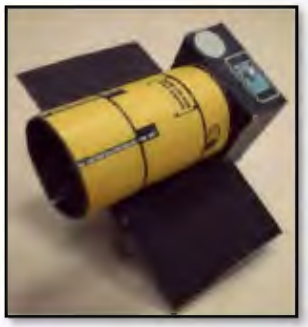
- **Geological Society of Nevada Remote Sensing Workshop** conducted in Reno, Nevada by R. Bedell, D. Coulter with broad support of GRSG leading to GRSG North American Chapter

EXPLORATION MAPPING

2011

- **Planetary Resources** encorporated in Seattle to commercially mine asteroids





ARKYD-1

Images Courtesy Planetary Resources

PLANETARY RESOURCES
THE ASTEROID MINING COMPANY

EXPLORATION MAPPING

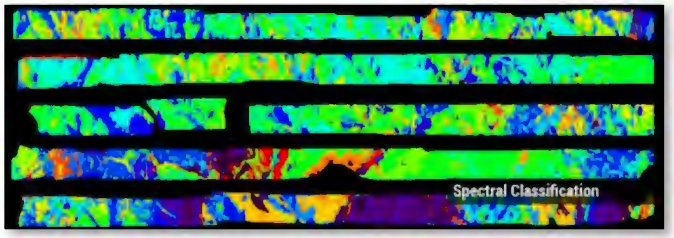
2012 - 2013

- **Geospectral Imaging** founded by Phil Harris, Neil Pendock and Michael Sears to provide drill core imaging and processing services

Phil Harris

Neil Pendock

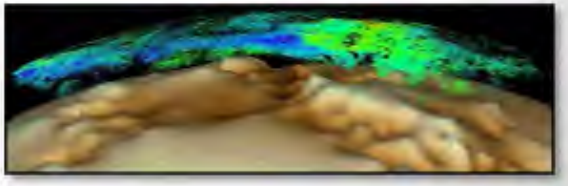
Michael Sears



- SpecTIR spins off **TerraCore International** (TCI), partnering with ALS, for hyperspectral drill core imaging

Conrad Wright with TerraCore, photo courtesy ALS

- **Landsat 8** launches with the longest record for continuous observation of the Earth's surface from space
- CSIRO completes first **Continental-Scale ASTER** SWIR/TIR alteration maps of Australia



CSIRO Australian ASTER geosciences maps

EXPLORATION MAPPING

2014

- **WorldView-3,** launched August 2014 to become DigitalGlobe's sixth satellite in orbit joining Ikonos, QuickBird, GeoEye and WorldView-1 and 2, 0.31m pan, 8-band multispectral with 1.24m resolution
- **Copernicus Sentinel-1,** radar launched by ESA in April 2014 is the first in a series of complimentary earth observation satellites

- **Advanced Argillic Alteration, Cuprite, Nevada,** G. Swayze, R. Clark et al, USGS, *Economic Geology*, August 2014

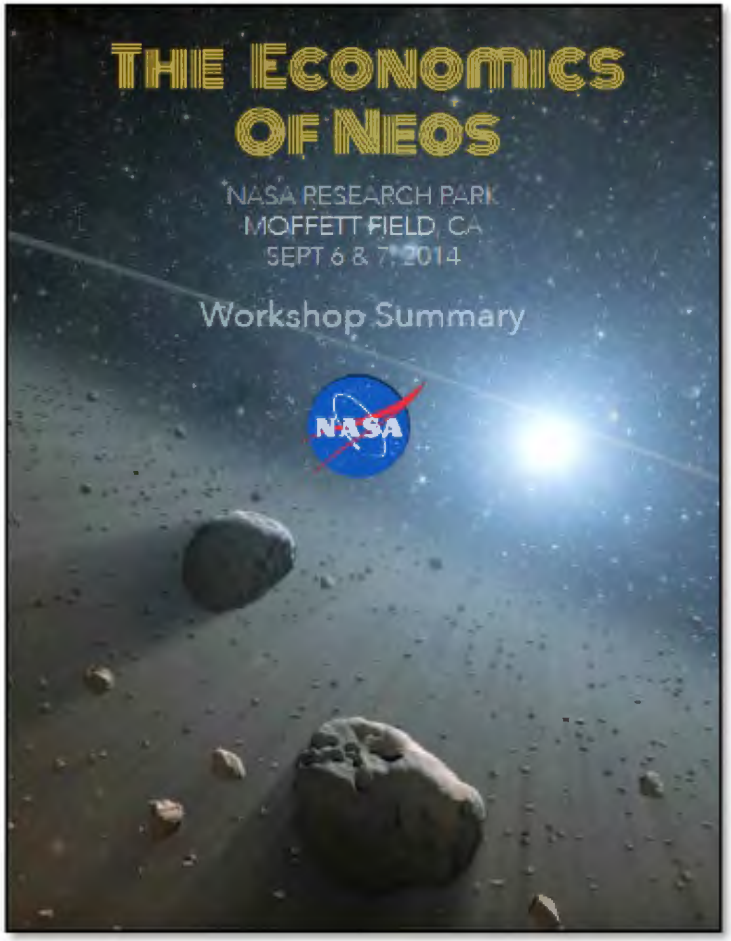
- **Nano-Hyperspec** commercial release by Headwall Photonics, 270 VNIR bands, weight less than 1.5lbs (0.68kg) designed for UAVs
- **HySpecIQ** >200 bands, AMIRA / Mining Company Consortium

Courtesy Headwall Photonics

EXPLORATION MAPPING

2014

- NASA coordinates workshop **The Economics of NEOS (Near Earth Objects)** in the wake of swelling interest to commercially mine NEOs



NASA: The Economics of Near Earth Objects, September 2014 Workshop

EXPLORATION MAPPING

The First Quarter: A 25 Year History of Mineral Exploration Remote Sensing

- Setting the Stage for 1989
- Timeline of Key Developments
- **The Road Ahead**

EXPLORATION MAPPING

The Road Ahead

"***Heavier-than-air flying machines are impossible***" - Lord Kelvin, President of Royal Society, 1896

Lord Kelvin

"***There is nothing new to be discovered in physics now. All that remains is more and more precise measurement***." – Lord Kelvin, *President of the Royal Society*, 1900

Lee DeForest

"***Man will never reach the moon, regardless of all the future scientific advances***" - Lee DeForest , Inventor of Vacuum tube electronic Valve, 1957

"***There is no reason for any individual to have a computer in his home***" – Ken Olsen, Founder of DEC, 1977

Ken Olsen

EXPLORATION MAPPING

The Road Ahead

- Field and Airborne Instrumentation
- Data Search, Processing and Delivery
- Basic Research with Breakthrough Potential
- State-Sponsored and Commercial Satellites
- Space Ventures

EXPLORATION MAPPING

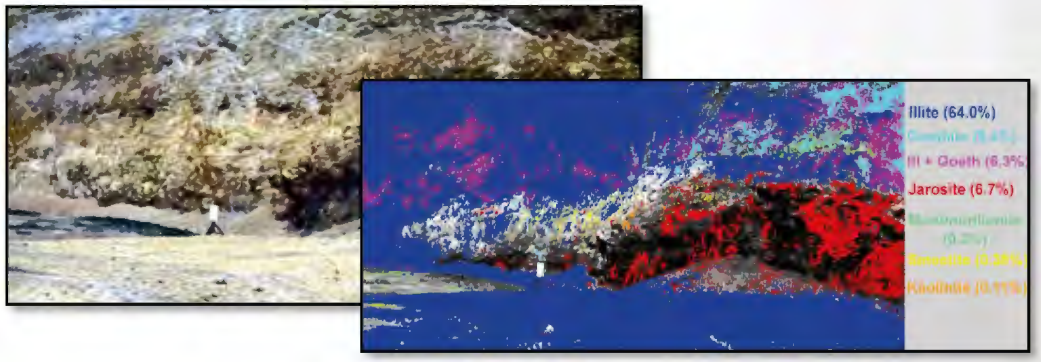
The Road Ahead

Field and Airborne Instrumentation

- Core imaging evolves to high-speed conveyor ore sorting using remote sensing VNIR, SWIR, TIR, XRF, EM

Courtesy SonicSampleDrill

- Portable hand-held imaging spectrometers



Courtesy SpecTIR

- UAVs smaller more sophisticated

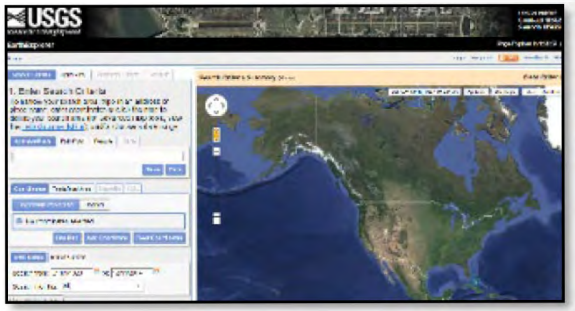
Courtesy QuarryDesign UK

EXPLORATION MAPPING

The Road Ahead

Data Search, Processing and Delivery

- **Software processing tools including**
  - **atmospheric corrections**
  - **Image mosaic and airborne data levelling tools**
  - **unmixing software to resolve similar minerals**
- **Spectral library development**
- **Improved image search tools across data sources**
- **Commercial web delivery and subscription models**



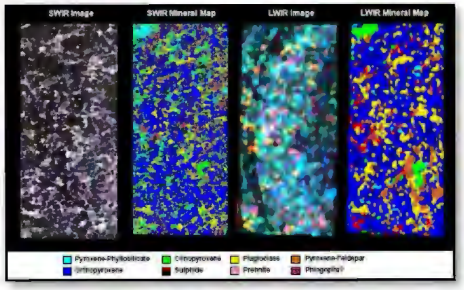
USGS Earth Explorer

Spatial on Demand

EXPLORATION MAPPING

The Road Ahead

Basic Research with Breakthrough Potential

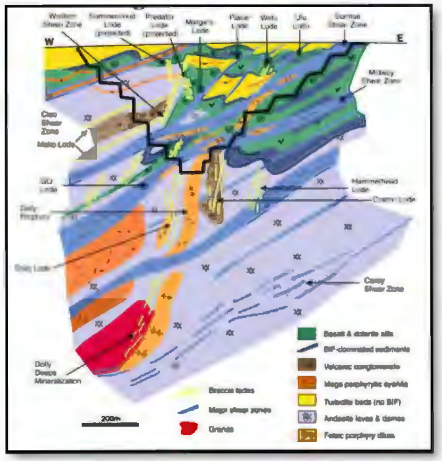


Harris, 2009

Exploration TIR Applications
midwave (3-5um) and longwave (7-12um)

Deposit Alteration Footprints

- Ultramafic PGE/Ni
- Iron Ore
- Sediment-hosted U
- Rare Earth Elements
- Green Rocks chlorite/epidote



Surface Expression Sunrise Dam Au, Western Australia, Baker, 2015

Huntsville Museum Collection

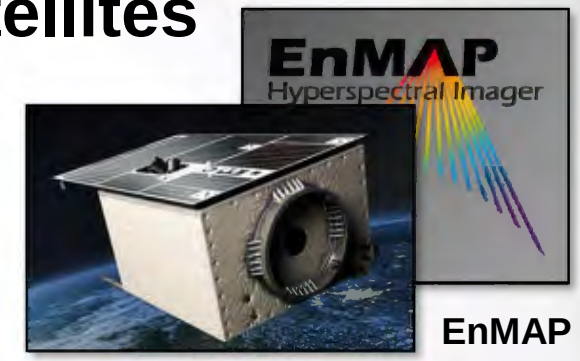
UV and Flourescence
Imaging

EXPLORATION MAPPING

The Road Ahead

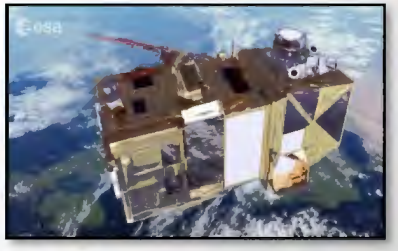
State-Sponsored and Commercial Satellites

- **DESIS Germany** 240 bands - 2016
- **ENMAP Germany** 218 bands - 2017?
- **Sentinel-2 ESA** 13 bands
- **PRISMA Italy** 237 bands
- **HISUI Japan** 185 bands - 2016?
- **HYPXIM France** >200 bands - 2019?
- **ECOSTRESS** USA (5 TIR) – 2018?
- **SHALOM Italy-Israel** >200 bands – 2020?
- **ChinaSAT HRS China** >220 bands – 2020?
- **HysplRI USA** >200 bands (8 TIR) - 2024?



EnMAP

PRISMA



ESA Sentinel-2

EXPLORATION MAPPING

Going Forward

The Road Ahead

Commercial Space Ventures – Space Mining

Image Credit: Artur Zima, Donald Goldsmith

EXPLORATION MAPPING

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Floyd Sabins, Chevron
Rhonda Stevenson, Space Mining Resources Coalition
Greg Swayze, USGS
Matt Zacharias, USAF

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EXPLORATION MAPPING

Thank You

EXPLORATION MAPPING