GeoMap: Understanding Geological Structure from Remote Sensing Data

All Lab Lecture February 25, 2004

Exploration Systems Autonomy Section 367
Data Understanding Systems Group
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The GeoMap Initiative

▪MSSS/JPL/NASA MOC image

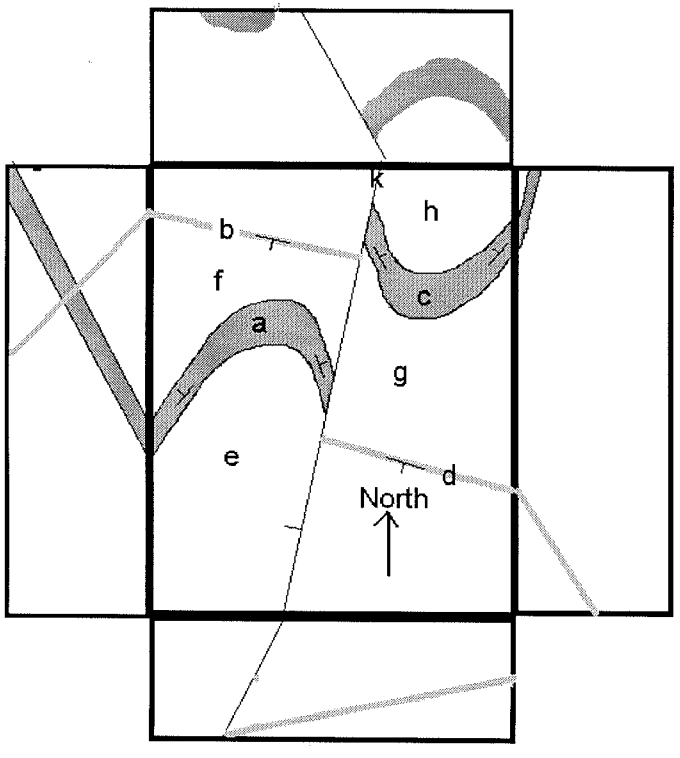
- We want a 4D geological model of Mars, Earth, and other solid bodies.
- We have (and are now collecting) much relevant data.
- We just need an automated way to extract the desired knowledge.

GeoMap Benefits

- Granite Peak Geologic Map and cross section

- **Mars**:
  - Aid site selection
  - Interpretation of in-situ missions in context of a much more complete background understanding.
  - Ease of integration and comparison of new data with existing data
- **Earth:**
  - Understand and protect our home planet

GeoMap Solution

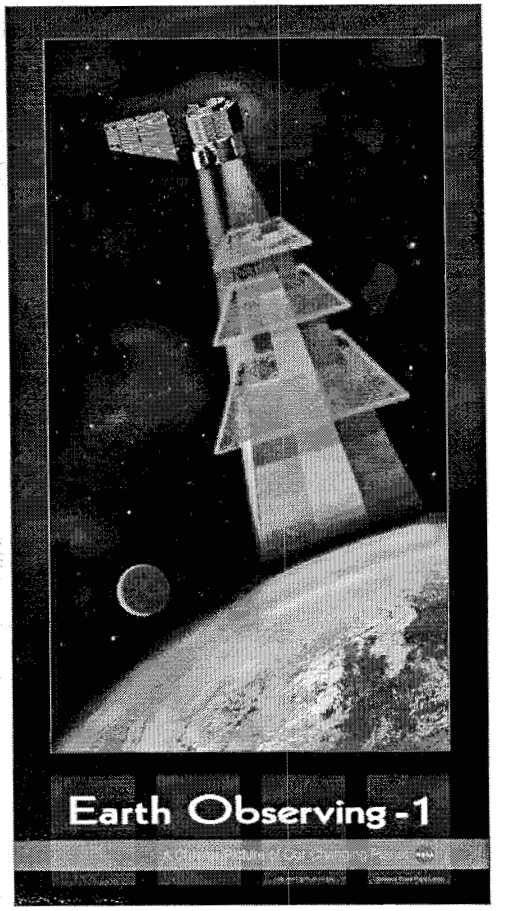


- Ingest high-resolution image, hyperspectral, topographic, and in-situ data
- Identify lithologic units based on clustering of texture and mineralogy
- Recognize patterns in lithologic units.
- Interpret these patterns in terms of 3D structure
- Infer a relative chronology of events to create 3D structure
- Enter into a database

Outline of the rest of the talk

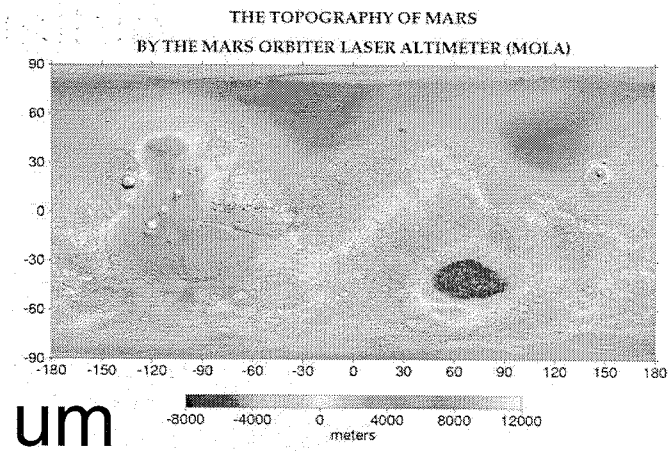
- Review remote sensing data
- Demonstrate plausibility of identifying lithologic units based on mineralogy and texture
- Digital Geologic Map Data Model
- Demonstrate how to infer 4D from 2D by hand
  - Review prior art
  - Proposed Parameterized Stochastic Grammar approach

Existing data - Earth

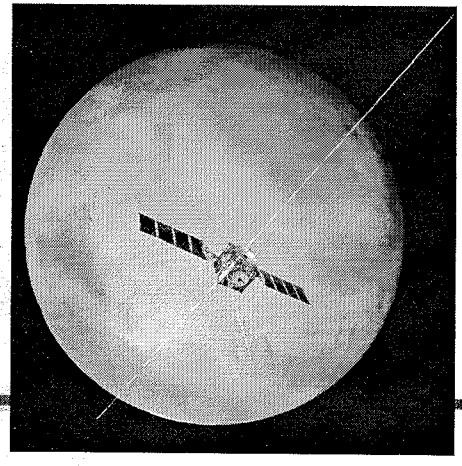


- HYPERION - EO1, 30 m pixel, Mineral ID, 220 bands 0.4-2.5 um
- ASTER – Terra, 14 bands, 0.5-12 um
- AVIRIS & HYDICE – Airborne Visible Infrared Imaging Spectrometer
- SRTM – 30 m pixel topography
- Ikonos – sub-meter pixel, visible
- Landsat – 30 m pixel 8 bands
- Others …

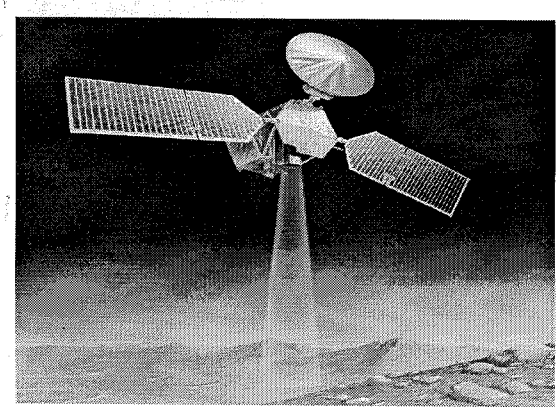
Existing data - Mars



- MOLA - MGS
- TES – MGS 3 km pixel, 6-50 um
- MOC – 1 m pixel
- THEMIS – Mars Odessy, 15 bands
- MARSIS – Mars Express, several Km sub-surface radar
- OMEGA – Mars Express, 100m mineral mapping spectrometer

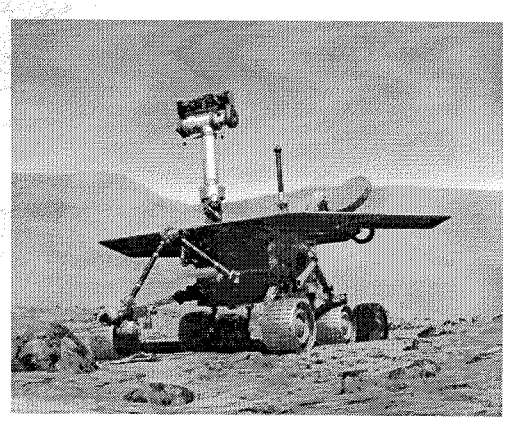


Future MRO mission

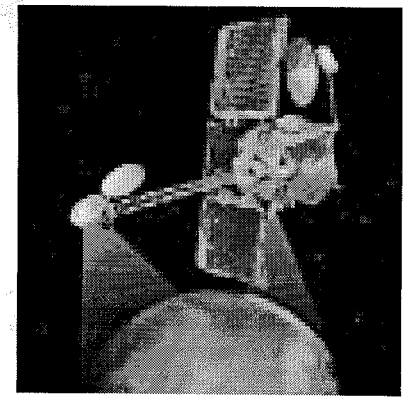


- HiRISE – MRO 0.25-0.5 m pixel, stereo, visible
- CRISM – MRO mineral ID spectrometer, 0.4-4 um, 560 bands, 18 m pixel
- SHARAD – MRO Up to 1 km sub-surface, 15 m vertical resolution, 0.3-3 km pixel

Complementary data

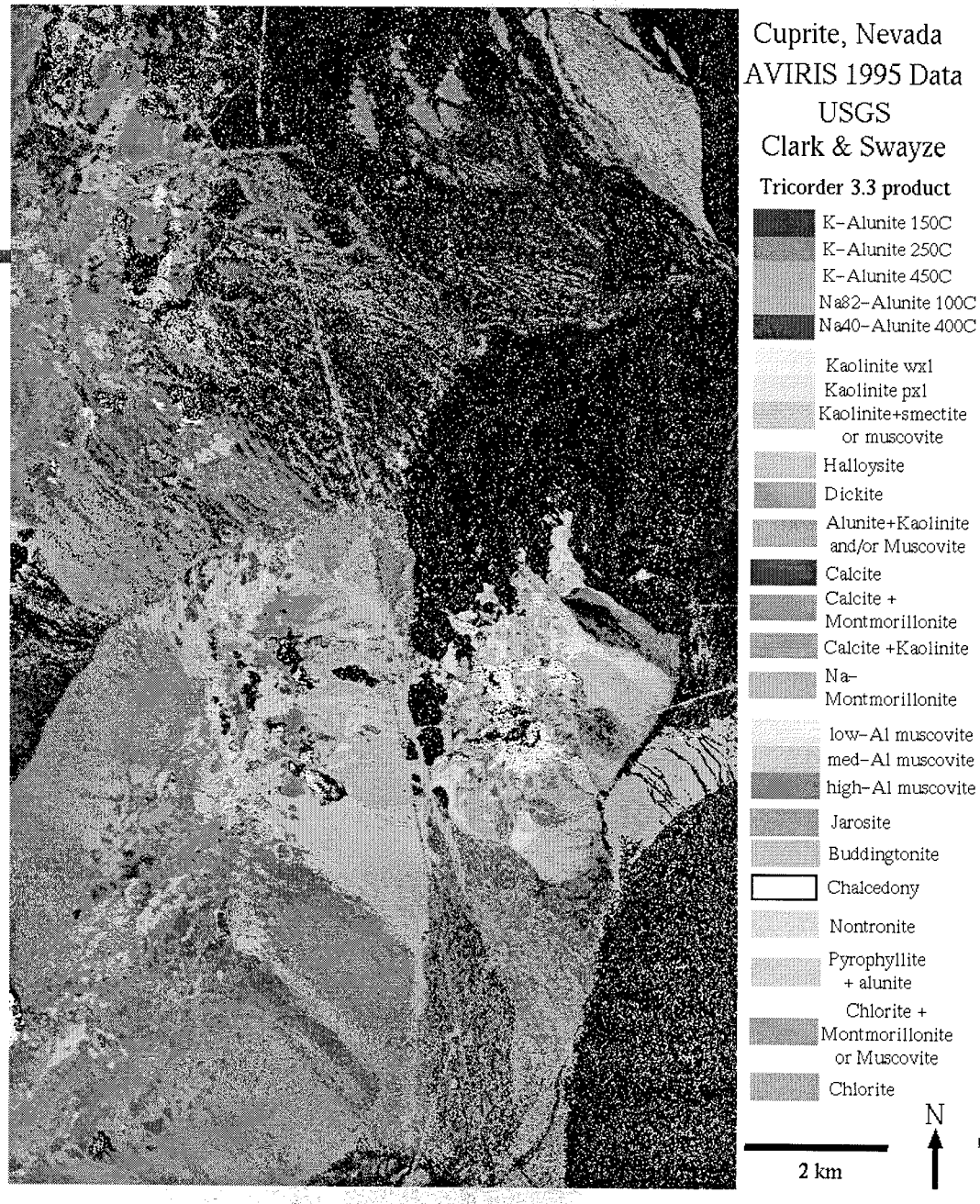


- Some observations are easy on the surface:
  - Small scale nature of a contact
  - Cliffs
- Some observations are easy from orbit:
  - Large scale morphology and context
    - Note: Spectral data from orbit can be sensitive to crystal/grain size



Mineral ID

- AVIRIS (Airborne Visible-Infrared Imaging Spectrometer)
- Processed to identify OH-, CO3-, and SO4- minerals



Mineral ID

- AVIRIS (Airborne Visible-Infrared Imaging Spectrometer)
- Processed to identify Fe2+, Fe3+ minerals

Cuprite, Nevada
AVIRIS 1995 Data
USGS
Clark & Swayze

Tricorder 3.3 product

- amorphous iron oxides
- nano–Hematite
- Fine–grained to medium–grained Hematite
- Large–grained hematite
- Goethite
- Lepidocrosite
- Jarosite
- Fe^{2+}–bearing minerals + Hematite
- Fe^{2+}–bearing minerals
- Fe –bearing minerals: broad absorptions

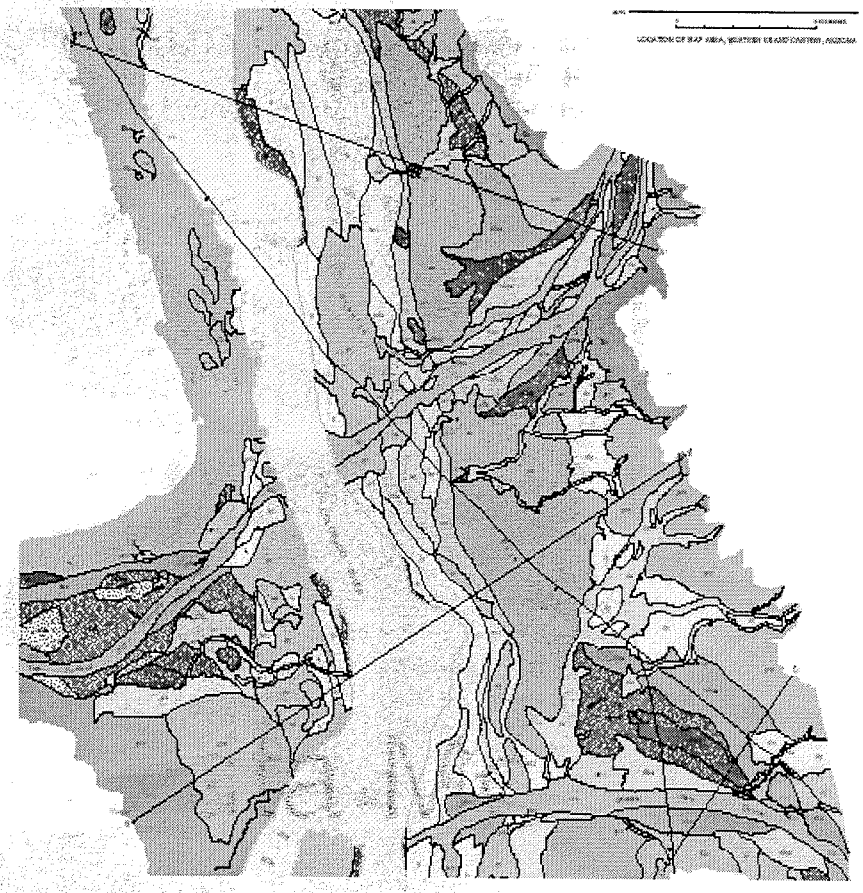
Note Fe^{2+}–bearing minerals are mainly muscovites and chlorites

N

2 km

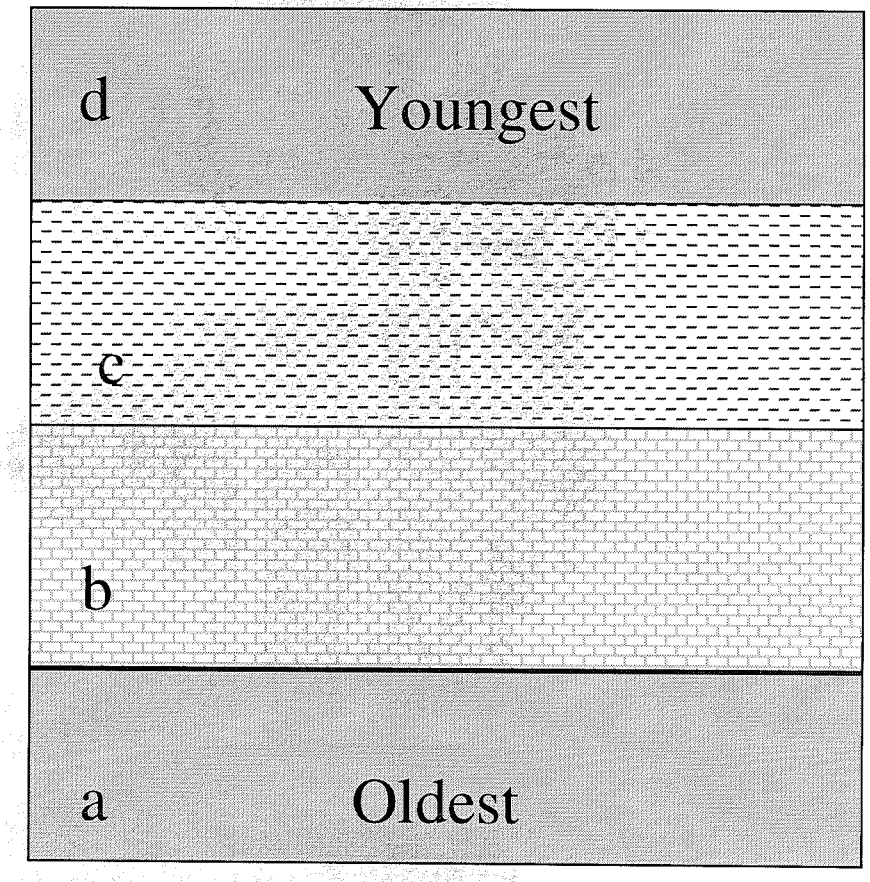
Digital Geological Data Model

- Under development by State Geologists and USGS
- Digital Data Model for building a database containing the information in a Geological Map
- http://geology.usgs.gov/dm

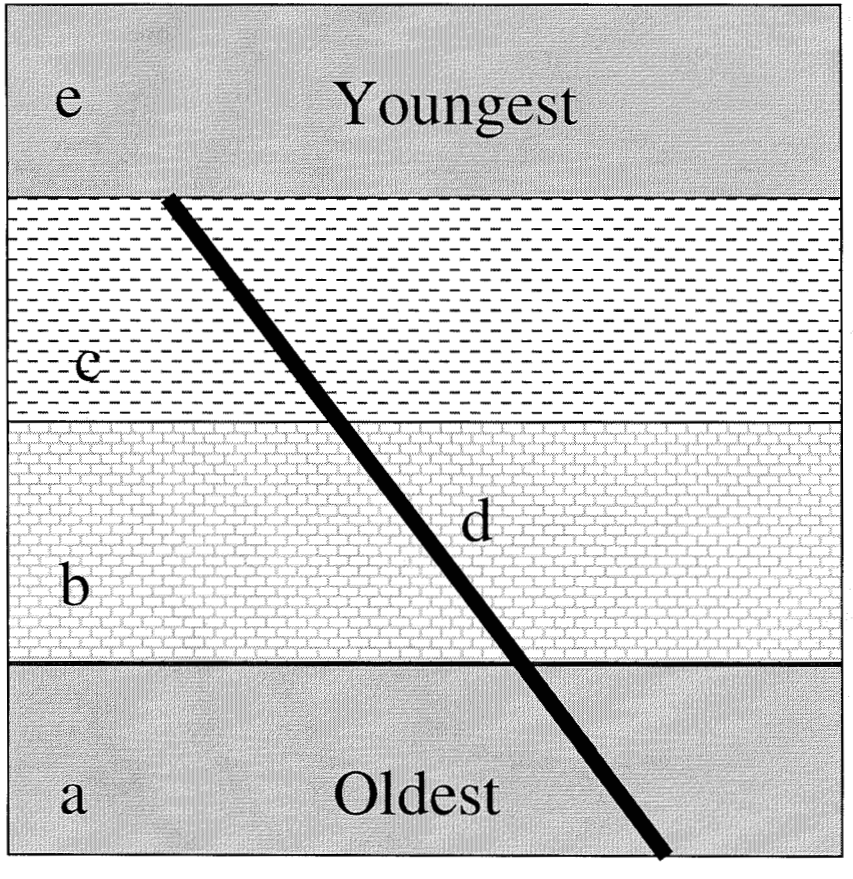


4D from 2D

- In geology, time and space are closely linked by the "Principle of Superposition"
  - First stated by Steno in 1669
- Younger sediments overlie older sediments unless the strata have been overturned.

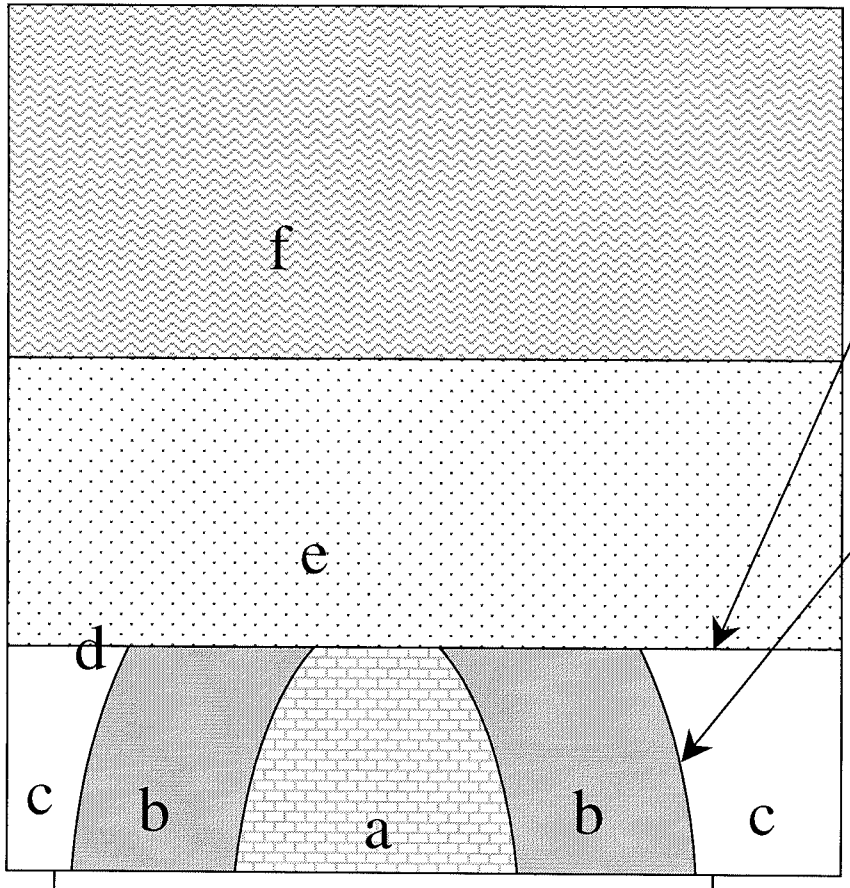


Corollaries 1



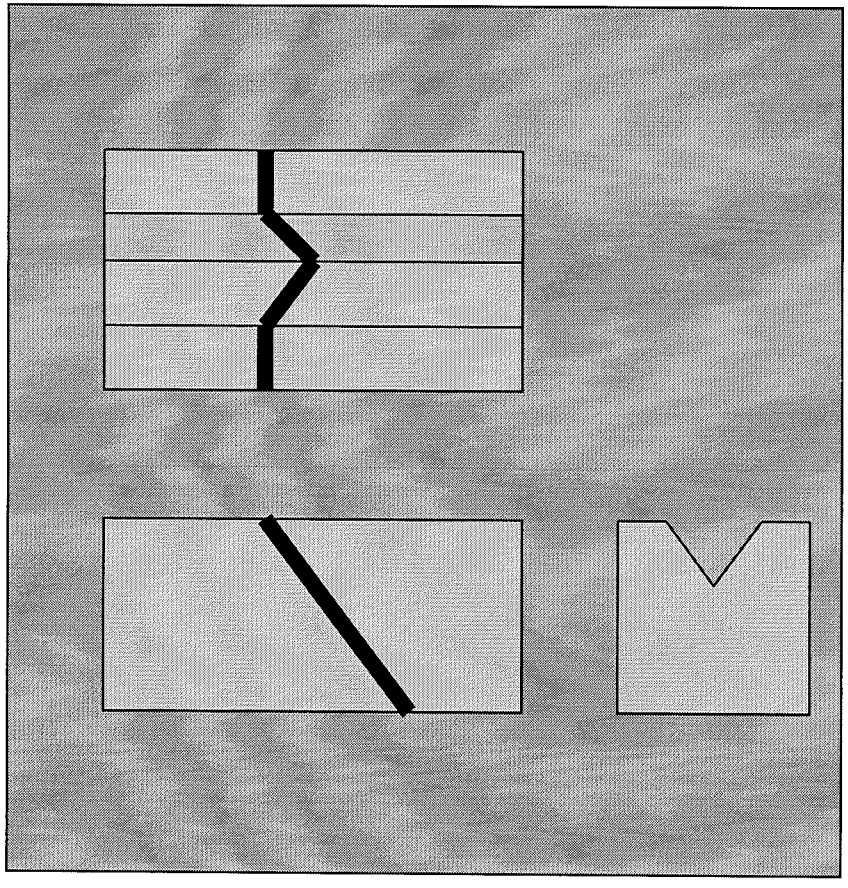
- Cross-cutting relationships
  - Younger events (rock units) cut across older events (rock units)
- Inclusion
  - Inclusions in sedimentary or igneous rocks are older than the surrounding rock unit

Corollaries 2



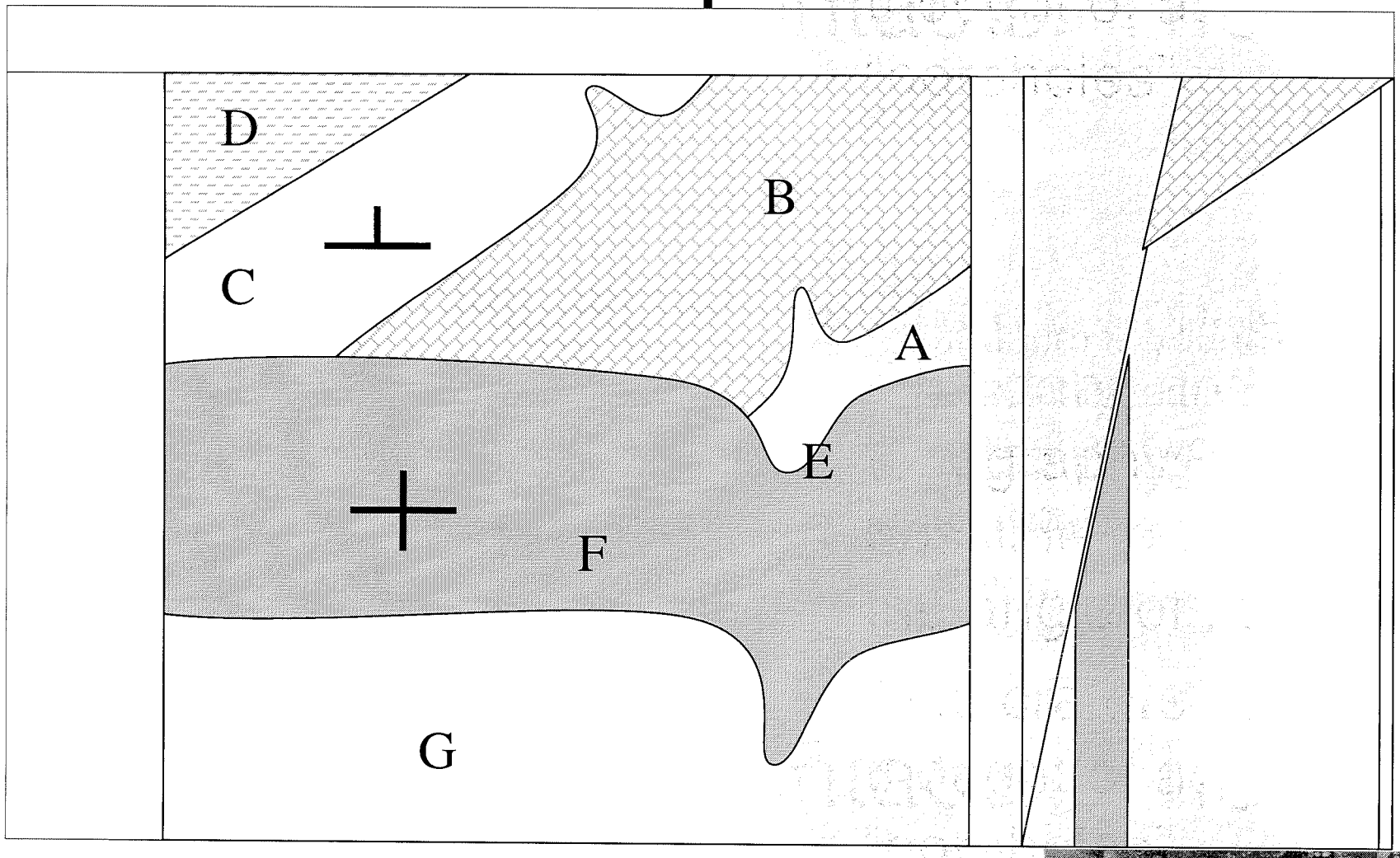
- Unconformities
  - An unconformity (erosional surface) is younger than the truncated rocks and older than overlying rocks
- Deformation
  - Deformation event is younger than deformed rocks
- Others….

Orientation of contacts: The Three point problem



- Given a dipping boundary, and some topography, it is possible to work out the angle of the dip.
- Also craters can be thought of as "boreholes"

Cartoon Example



Example: Harrisburg PA

A sampling of previous work

Algorithm for inferring time order of events from 2D map (Burns & Remfry 1976)

- Construct a matrix in which each bed is represented once on the rows and columns.
- Wherever a time relationship between two beds is known, make an entry in the matrix such that row is older than column.
- Triangularize the matrix by transposition of columns. Inability to triangularize indicates inconsistent information.
- Can then "fill in" much of rest of triangular matrix

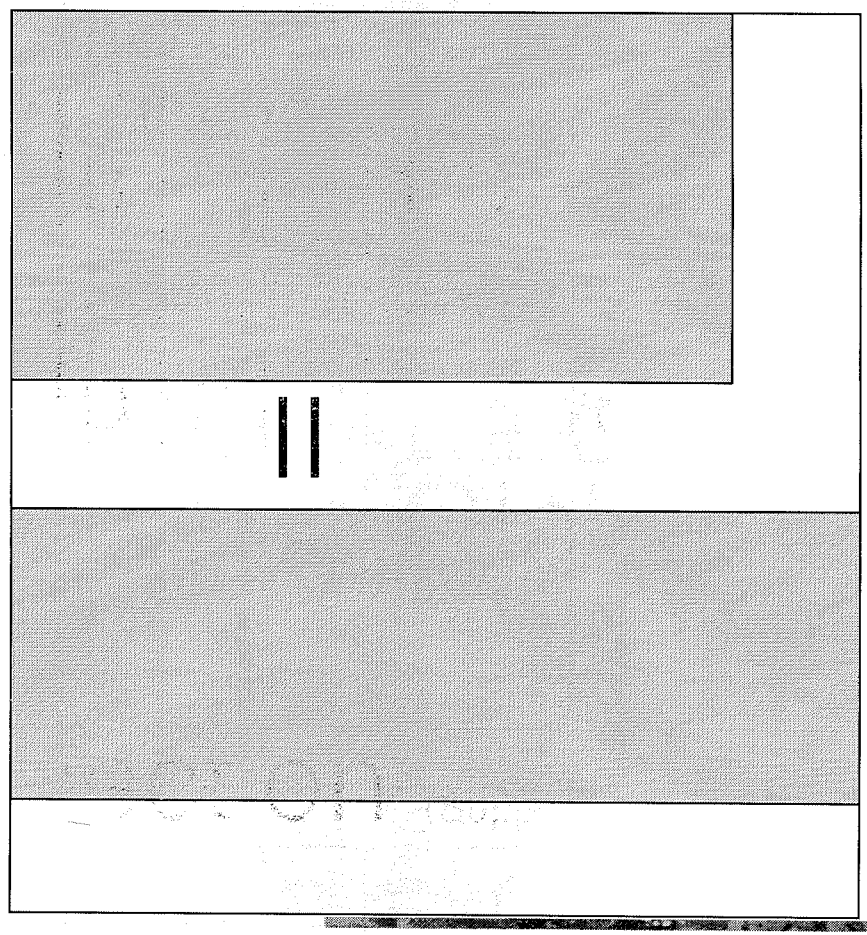
Pairwise relative age to Global Chronology

	A	C	E	B	G	F	D
A				2			
C							3
E						5	
B		1					
G						2	
F				1	4		
D			8				

	A	B	C	D	E	F	G
A		2	X	X	X	X	X
B			1	X	X	X	X
C				3	X	X	X
D					8	X	X
E						5	X
F		1					4
G							

Balanced Cross-section (Suppe 1983)

- Deformed strata (folded and faulted) should occupy the same volume as they did in their original un-deformed state.
- Humans are not good at this – computers are.
- This is has been common practice for more than a decade.



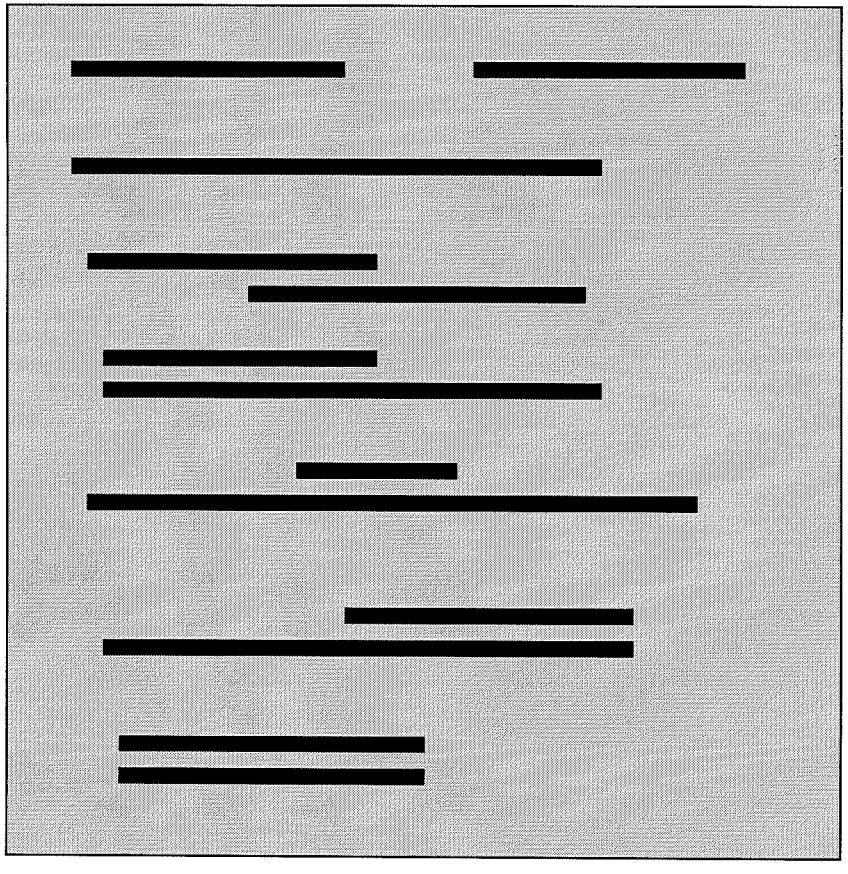
Geological time concepts

- Erosion introduces gaps
- Simultaneous events
- Finite duration events
  - Interval algebra (Allen 1984)

IGIS: Computer-Aided Photogeologic Mapping System (McGuffie et al 1989, Lang et al 1987)

- Characteristics
  - User traced contacts on LANDSAT image
  - Computer solved 3 point problem for orientation through combination with digital elevation model
  - Could combine with seismic profile data
  - Could generate cross-sections
- Part of NASA's Sedimentary Basins Analysis Task, using Multispectral Remote Sensing as a Geologic Tool

Geological time concepts (after Ady 1993, Allen 1984)



- A before B; B after A
- A meets B; B met-by A
- A overlaps B; B overlapped-by A
- A starts B; B started-by A
- A during B; B contains A
- A finishes B; B finished-by A
- A equals B

Spatiochronologic Reasoner (Ady 1993)

- Characteristics
  - Given a digitized geologic map
  - GIS interface
  - Qualitative temporal object representation based on Allen 1983
  - Knowledge base of spatio-temporal ordering principles
  - Inconsistency checker
  - Inference system for propagation of constraints

Frequently under-constrained

- Erosion removes part of the record of the history written in the rocks
- Sub-surface structure could be arbitrarily complex and still match 2D data.
- There is usually a “simplest” solution consistent with the data
- Grammars, especially parameterized stochastic grammars, are a promising tool

Stochastic Grammar

- Origin in natural language analysis
- Break down a sentence into sub-elements
  - Non-terminals – composed of other non-terminals and termanls (eg noun-phrase, verb-phrase)
  - Terminals
- Relationships between elements build up interpretation
- Relationships between elements may be probability rules, binary decision trees, complex physical models, or other

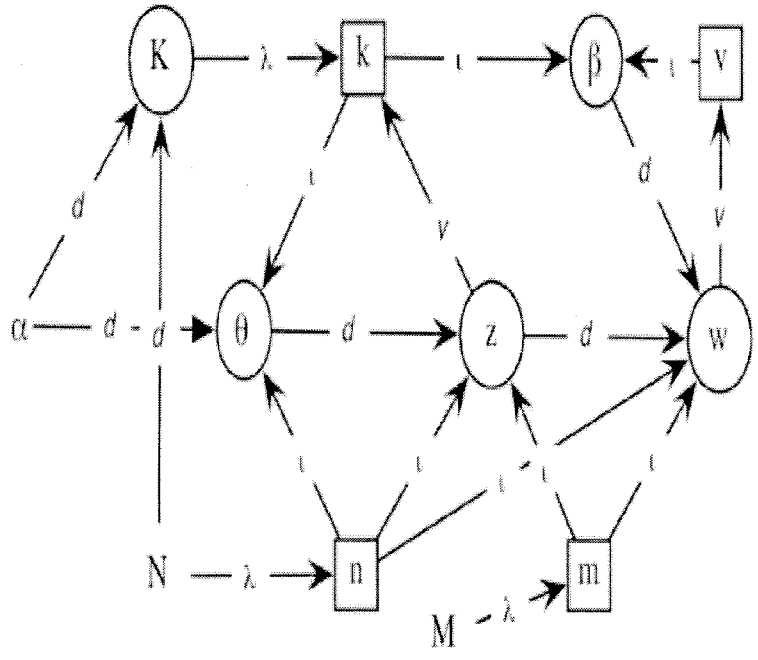
Grammar using a sentence

- The boy hit a ball.
- <sentence> → <noun-phrase> <verb-phrase>
- <noun-phrase> → <article><modified-noun>
- <verb-phrase> → <verb> <noun-phrase>
- <modified-noun> → <adjective><modified-noun>
- <article> → a | the
- <noun> → boy | ball
- <verb> → hit

Geological Grammar building blocks

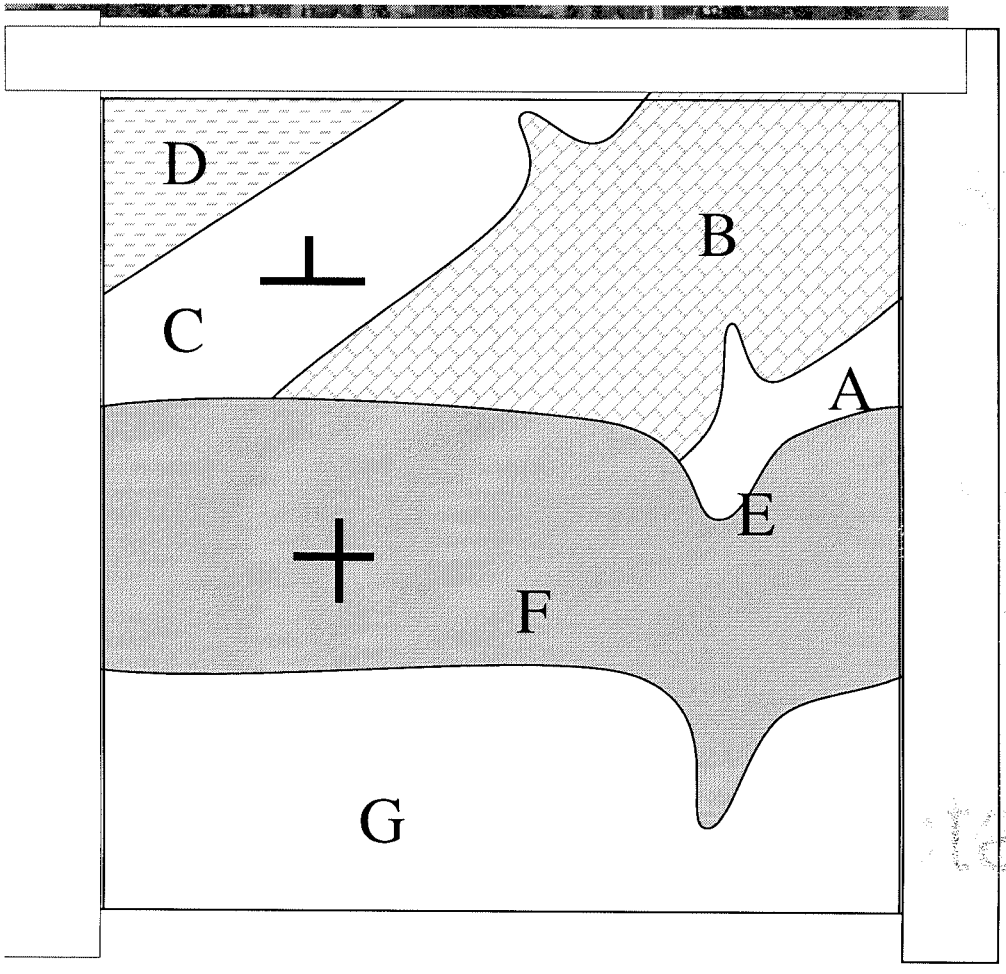
- <submergent phrase> Sequence going from sediment with pebbles in it through sandstone to mudstone
- <volcanic intrusive phrase> Igneous rocks surrounded by non-igneous. Surrounding rock contains minerals altered by hydrothermal fluids.
- Existing models are 1 or 2 dimensional (Duane 1996, 1999). We will need to generalize to 3 spatial dimensions and time.

Roadmap: Grammar



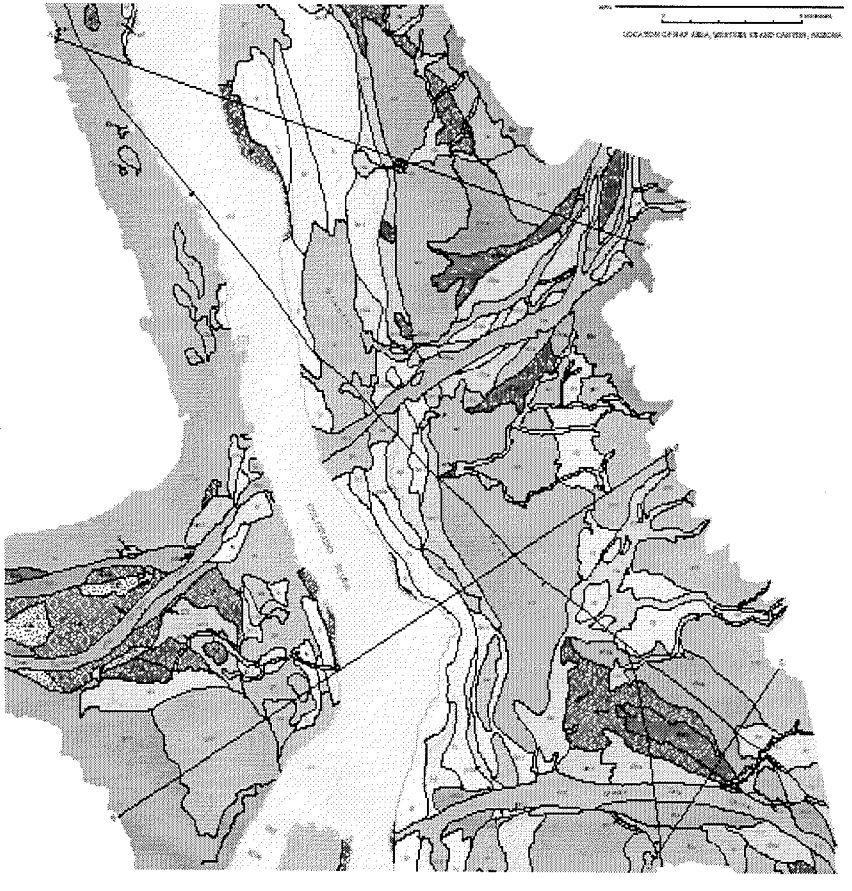
- Phase 1: Develop a Stochastic Grammar to infer the sub-surface structure and chronology of events from an annotated map or image. Will involve extension of Stochastic Grammar concept to deal with notions of 3D spatial relationships, orientation, and chronology.
- Chosen for phase 1 since we have limited prior art
  - Simmons 1983
  - Ady 1993
  - Duane 1996, 1999

Roadmap: Annotated Image



- Phase 2: Adapt and extend software to identify lithologic units, estimate their orientation, and annotate the image.
- Verification on Earth data
- Chosen for phase 2 because systems exist that can do pieces of this job:
  - Tetracorder (Clark & Swayze 1995)
  - MESMA (Carvalho 2002)
  - ENVI (RSI)
  - IGIS (McGuffie et al 1989)

Roadmap: Integration



- Phase 3: Integrate the results of Phase 1 and 2 to produce a prototype system ingesting raw image data, and producing a geologic map with 4D interpretation stored in a Digital Geologic Map Data Model database
- Verification on Earth data

Roadmap: Production

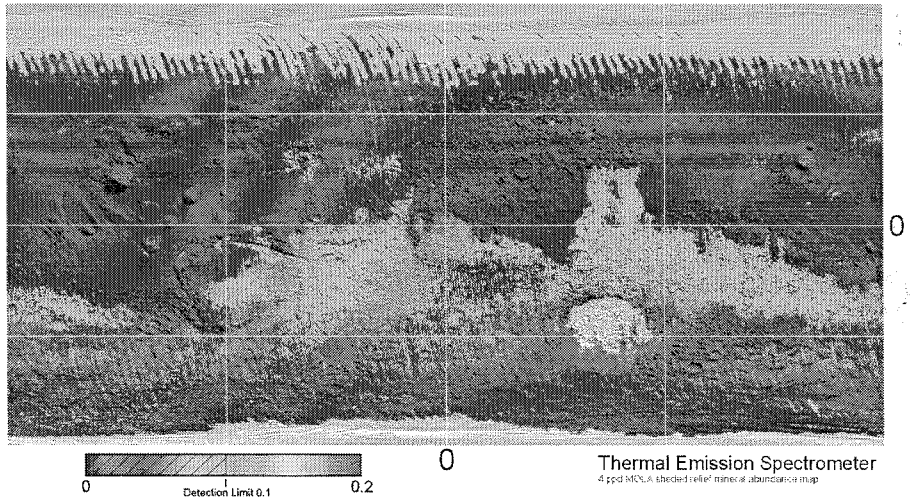
Akna Montes mountain belt, Venus, http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/mgn_c160n291_1.html

- Phase 4: Refine the system to be a production system and apply it to global data for Mars, Earth, and other solid planetary bodies.

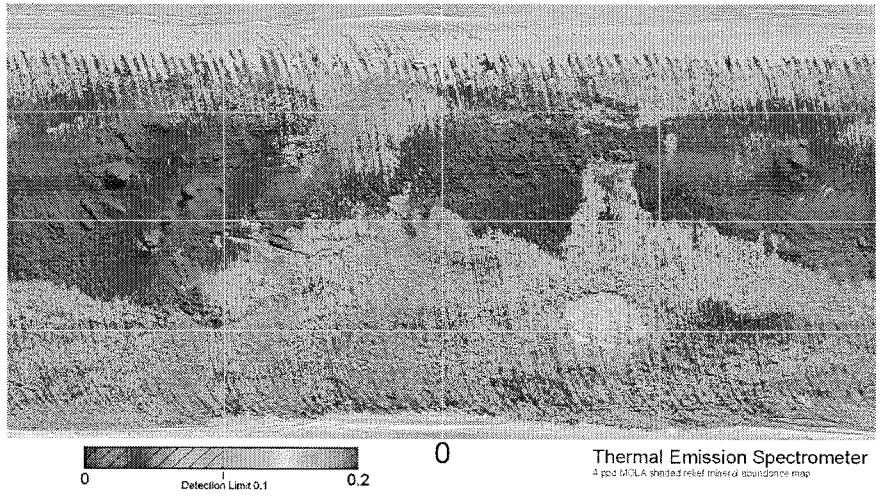
Summary

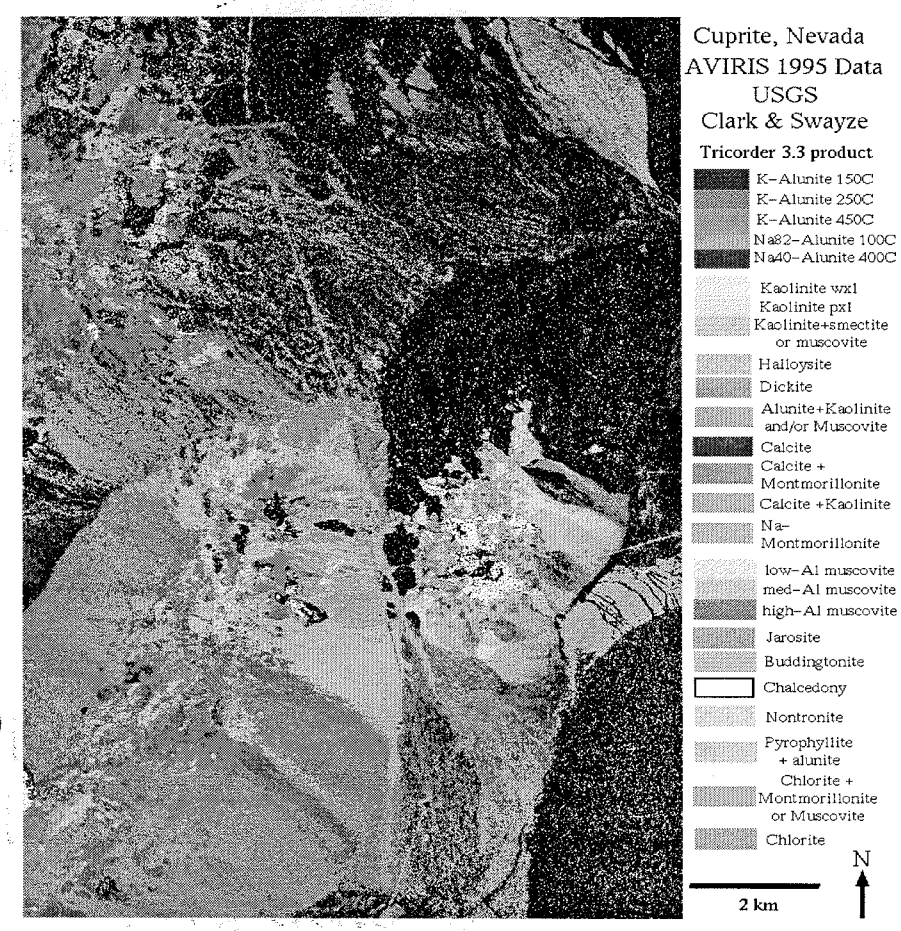
- There is enough data to “cut our teeth”
- We will soon have much more data
- There are promising methods that with appropriate development could yield a 4D interpretation of remote sensing data
- A 4D digital geological model would enable a new kind of integration of diverse datasets leading to greatly increased understanding of the planets

High-Ca Pyroxene



Plagioclase





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