science for a changing world

Digital Mapping Techniques ‘10

Association of American State Geologists

United States Geological Survey

Digital Mapping Techniques ‘10—Workshop Proceedings

May 16–19, 2010
Sacramento, California

Convened by the
Association of American State Geologists
and the
United States Geological Survey

Hosted by the
California Geological Survey

U.S. Geological Survey Open-File Report 2012–1171

U.S. Department of the Interior
U.S. Geological Survey

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Edited by David R. Soller

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2012

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U.S. Geological Survey

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Introduction

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The Digital Mapping Techniques ‘10 (DMT‘10) workshop was attended by 110 technical experts from 40 agencies, universities, and private companies, including representatives from 19 State geological surveys (see Appendix A). This workshop, hosted by the California Geological Survey, May 16-19, 2010, in Sacramento, California, was similar in nature to the previous 13 meetings (see Appendix B). The meeting was coordinated by the U.S. Geological Survey’s (USGS) National Geologic Map Database project. As in the previous meetings, the objective was to foster informal discussion and exchange of technical information. It is with great pleasure that I note that the objective was again successfully met, as attendees continued to share and exchange knowledge and information, and renew friendships and collegial work begun at past DMT workshops.

At this meeting, oral and poster presentations and special discussion sessions emphasized (1) methods for creating and publishing map products (“publishing” includes Web-based release); (2) field data capture software and techniques, including the use of LiDAR; (3) digital cartographic techniques; (4) migration of digital maps into ArcGIS Geodatabase format; (5) analytical GIS techniques; and (6) continued development of the National Geologic Map Database.

Acknowledgments

My sincere appreciation is offered to the California Geological Survey (CGS), and especially to George Saucedo, who was the principal CGS organizer for this meeting. George was assisted by Margaret Hyland, Milind Patel, Chris Wills, and Karen Saucedo; together they provided the meeting attendees with a most enjoyable venue for learning and exchanging technical information. I also thank the California Geological Survey (CGS) and the Director and State Geologist, John Parrish, for hosting this meeting, and for encouraging his staff to participate; in the first seven papers of these Proceedings the mapping science and digital techniques of the CGS are highlighted. Last, but not least, I thank all attendees for their participation; their enthusiasm and expertise were the primary reasons for the meeting’s success.

Presentations and Posters

The workshop included 21 oral presentations, 3 discussion sessions, and 24 posters. Many are supported by a paper contained in these Proceedings. The papers describe technical and procedural approaches that currently meet some or all needs for digital mapping at the respective agency. There is not, of course, a single “solution” or approach to digital mapping that will work for each agency or for each program or group within an agency; personnel and funding levels, and the schedule, data format, and manner in which we must deliver information to the public require that each agency design its own approach. However, the value of this workshop and other forums like it is through their roles in helping to design or refine these agency-specific approaches to digital mapping and to find applicable approaches used by other agencies. In other words, communication helps us to avoid having to “reinvent the wheel.”

During the course of the 14 annual DMT meetings, it has been my pleasure to meet, and work with, the many talented people who have authored papers in these Proceedings. As the subjects addressed by the DMT meetings have become even more essential to the Nation’s geological surveys, the demands placed on them have risen to the point where many authors scarcely have time to address their work fully. Predictably, less time is then available to compose written summaries of their work; I am sure the readers (or at least other editors) can sympathize with this predicament. Therefore, I include with this Introduction a list of all presentations and posters (Appendix C). If the reader finds an interesting title that isn't recorded in these Proceedings, I encourage the reader to contact the authors directly. Further, some presentations and related information are available for download at *http://ngmdb.usgs.gov/Info/dmt/DMT10presentations.html*.

The Next DMT Workshop

The 15th annual DMT meeting will be held in the spring of 2011 in Williamsburg, Virginia. Please consult the Web site (*http://ngmdb.usgs.gov/Info/dmt/*) for additional information about this and other DMT meetings.

Appendix A. List of Workshop Attendees

[Grouped by affiliation]

Alaska Division of Geological and Geophysical Surveys
Jennifer Athey

American Institute of Professional Geologists
William Siok

Arizona Geological Survey
Ryan Clark

Arkansas Geological Survey
William Hanson

British Geological Survey
Jeremy Giles

California Department of Toxic Substances Control
Richard Fears
John Karachewski

California Department of Water Resources
Jonathan Mulder

California Geological Survey
John Clinkenbeard
Milton Fonseca
Carlos Gutierrez
Chris Higgins
Terilee Mc Guire
Timothy McCrink
Robert Moskovitz
John Parrish
Milind Patel
Ante Perez
Charles Real
Pete Roffers
Anne Rosinski
George Saucedo
William Short
James Thompson
Barbara Wanish
Chris Wills

Colorado State University – a NPS Cooperator
James Chappell
Heather Stanton
Stephanie O'Meara

Engineering/Remediation Resources Group, Inc.
Mark Rogers

ESRI, Inc.
Larry Batten
Peter Becker
Janel Day
Charles Frye
Willy Lynch

Geological Survey of Finland
Hannu Idman

Idaho Geological Survey
Jane Freed
Collette Gantenbein
Loudon Stanford

Kentucky Geological Survey
Matthew Crawford

Maine Geological Survey
Robert Marvinney

Minnesota Geological Survey
Harvey Thorleifson

Montana Bureau of Mines and Geology
Paul Thale

National Park Service
Bruce Heise
Georgia Hybels

Natural Resources Canada-Geological Survey of Canada
Christine Deblonde
Vic Dohar
David Everett
Andrew Moore

Nevada Bureau of Mines and Geology
Heather Armeno
Heather Green
Jordan Hastings
P. Kyle House
Gary Johnson
Jennifer Mauldin
Matthew Richardson

New Mexico Bureau of Geology and Mineral Resources
Adam Read
Peter Scholle
Shannon Williams

Nova Scotia Department of Natural Resources
Brian Fisher

Ohio Geological Survey
James McDonald

Oregon Department of Geology and Mineral Industries
Rachel Lyles
Jed Roberts

South Carolina Geological Survey
Erin Koch

University of Alabama
Douglas Behm

University of Tennessee
Andrew Wunderlich

University of the Pacific
Kurtis Burmeister
Luke Crawford
Shoko Yamamoto

U.S. Department of Energy
Susan Gregersen

U.S. Environmental Protection Agency
Randall Ross

U.S. Forest Service
James Cloyd
Andrew Rorick

U.S. Geological Survey
Stafford Binder
Sky Bristol
Stephanie Brown
Ernest Crider
Tamara Dickinson
Jennifer Dieck
Mary DiGiacomo-Cohen
Carolyn Donlin
Christopher Garrity
Linda Gundersen
Ralph Haugerud
Theresa Iki
Linda Jacobsen
Donna Knifong
Richard Koch
Taryn Lindquist
Peter Lyttle
Jeremy McHugh
Kathryn Nimz
Randall Orndorff
Carol Ostergren
Lydia Quintana
Mark Reidy
Larry Robinson
Lisa Rukstales
Darlene Ryan
David Soller
Nancy Stamm
Frederic Wilson
Jan Zigler

Utah Geological Survey
Kent Brown

Washington State Department of Natural Resources
Robert Berwick

West Virginia Geological and Economic Survey
Keri Wilson

Western Washington University
Elizabeth Schermer

Wisconsin Geological and Natural History Survey
Peter Schoephoester

Wyoming State Geological Survey
Allory Deiss
David Lucke
Phyllis Ranz

Appendix B. Previous Digital Mapping Techniques Workshops

1997:
Hosted by the Kansas Geological Survey, Lawrence, Kansas, June 2-5. 73 technical experts attended, from 30 State geological surveys, the USGS, and the Geological Survey of Canada.

Soller, D.R., ed., 1997, Proceedings of a workshop on digital mapping techniques: Methods for geologic map data capture, management, and publication: U.S. Geological Survey Open-File Report 97-269, 120 p., *http://pubs.usgs.gov/of/of97-269/*.

1998:
Hosted by the Illinois State Geological Survey in Champaign, Illinois, May 27-30. More than 80 technical experts attended, mostly from the State geological surveys and the USGS.

Soller, D.R., ed., 1998, Digital Mapping Techniques '98—Workshop Proceedings: U.S. Geological Survey Open-File Report 98-487, 134 p., *http://pubs.usgs.gov/of/of98-487/*.

1999:
Hosted by the Wisconsin Geological and Natural History Survey in Madison, Wisconsin, May 19-22. 91 selected technical experts from 42 agencies, universities, and private companies attended, including representatives from 30 State geological surveys.

Soller, D.R., ed., 1999, Digital Mapping Techniques '99—Workshop Proceedings: U.S. Geological Survey Open-File Report 99-386, 216 p., *http://pubs.usgs.gov/of/of99-386/front.html*.

2000:
Hosted by the Kentucky Geological Survey in Lexington, Kentucky, May 17-20. 99 technical experts from 42 agencies, universities, and private companies attended, including representatives from 28 State geological surveys.

Soller, D.R., ed., 2000, Digital Mapping Techniques '00—Workshop Proceedings: U.S. Geological Survey Open-File Report 00-325, 209 p., *http://pubs.usgs.gov/of/of00-325/*.

2001:
Hosted by the Geological Survey of Alabama, in Tuscaloosa, Alabama, May 20-23. 108 technical experts from 48 agencies, universities, and private companies attended, including representatives from 31 State geological surveys.

Soller, D.R., ed., 2001, Digital Mapping Techniques '01—Workshop Proceedings: U.S. Geological Survey Open-File Report 01-223, 248 p., *http://pubs.usgs.gov/of/2001/of01-223/*.

2002:
Hosted by the Utah Geological Survey, in Salt Lake City, Utah, May 19-22. More than 100 technical experts from 40 agencies, universities, and private companies attended, including representatives from 30 State geological surveys.

Soller, D.R., ed., 2002, Digital Mapping Techniques '02—Workshop Proceedings: U.S. Geological Survey Open-File Report 02-370, 214 p., *http://pubs.usgs.gov/of/2002/of02-370/*.

2003:
Hosted by the Pennsylvania Geological Survey, in Millersville, Pennsylvania, June 1-4. Nearly 90 technical experts from 36 agencies, universities, and private companies attended, including representatives from 22 State geological surveys.

Soller, D.R., ed., 2003, Digital Mapping Techniques '03—Workshop Proceedings: U.S. Geological Survey Open-File Report 03-471, 262 p., *http://pubs.usgs.gov/of/2003/of03-471/*.

2004:
Hosted by the Oregon Department of Geology and Mineral Industries, in Portland, Oregon, May 16-19. Nearly 100 technical experts from 40 agencies, universities, and private companies attended, including representatives from 22 State geological surveys.

Soller, D.R., ed., 2004, Digital Mapping Techniques '04—Workshop Proceedings: U.S. Geological Survey Open-File Report 2004-1451, 220 p., *http://pubs.usgs.gov/of/2004/1451/*.

2005:
Hosted by the Louisiana Geological Survey, in Baton Rouge, Louisiana, April 24-27. More than 100 technical experts from 47 agencies, universities, and private companies attended, including representatives from 25 State geological surveys.

Soller, D.R., ed., 2005, Digital Mapping Techniques '05—Workshop Proceedings: U.S. Geological Survey Open-File Report 2005-1428, 268 p., *http://pubs.usgs.gov/of/2005/1428/*.

2006:
Hosted by the Ohio Geological Survey, in Columbus, Ohio, June 11-14. More than 115 technical experts from 51 agencies, universities, and private companies attended, including representatives from 27 State geological surveys.

Soller, D.R., ed., 2007, Digital Mapping Techniques '06—Workshop Proceedings: U.S. Geological Survey Open-File Report 2007-1285, 217 p., *http://pubs.usgs.gov/of/2007/1285/*.

2007:
Hosted by the South Carolina Geological Survey, in Columbia, South Carolina, May 20-23. More than 85 technical experts from 49 agencies, universities, and private companies attended, including representatives from 27 State geological surveys.

Soller, D.R., ed., 2008, Digital Mapping Techniques '07—Workshop Proceedings: U.S. Geological Survey Open-File Report 2008-1385, 140 p., *http://pubs.usgs.gov/of/2008/1385/*.

2008:
Hosted by the Idaho Geological Survey, in Moscow, Idaho, May 18-21, 2008. More than 100 technical experts from 39 agencies, universities, and private companies attended, including representatives from 19 State geological surveys.

Soller, D.R., ed., 2009, Digital Mapping Techniques '08—Workshop Proceedings: U.S. Geological Survey Open-File Report 2009-1298, 217 p., *http://pubs.usgs.gov/of/2009/1298/*.

2009:
Hosted by the West Virginia Geological Survey, in Morgantown, West Virginia, May 10-13, 2009. About 90 technical experts from 42 agencies, universities, and private companies attended, including representatives from 24 State geological surveys.

Soller, D.R., ed., 2011, Digital Mapping Techniques '09—Workshop Proceedings: U.S. Geological Survey Open-File Report 2010-1335, 260 p., *http://pubs.usgs.gov/of/2010/1335/*.

Appendix C. List of Oral and Poster Presentations, and Discussion Sessions

Oral Presentations (listed in order of presentation)

Building a National Archive – Standards development and the National Geologic Map Database
By David R. Soller and Nancy R. Stamm (U.S. Geological Survey)

I came, I digitized, I posted: An existential look back over twenty years of digital mapping in Idaho
By Loudon R. Stanford (Idaho Geological Survey)

Opengeoscience: meeting the U.K.'s geospatial data requirements in geoscience
By P. Bell, R. Hughes, K. Westhead, and J. Giles (British Geological Survey)

From data collection to publishing maps on the Web: the Nova Scotia experience
By Brian E. Fisher, Jeff C. Poole, Jeff S. McKinnon, and Angie L. Ehler (Nova Scotia Department of Natural Resources, Mineral Resource Branch)

The geological map flow process – How the Geological Survey of Canada is streamlining map compilation and delivery
By Andrew Moore (Geological Survey of Canada)

Automation in ArcGIS 10: Understanding changes in methods of customization and options for migration of legacy code
By Andrew L. Wunderlich (University of Tennessee – Knoxville)

Update on ESRI cartographic representations for the FGDC digital cartographic standard for geologic map symbolization
By Charlie Frye and Janel Day (ESRI)

A plan and plea for increasing communication about digital geologic field mapping
By Jennifer E. Athey (Alaska Division of Geological & Geophysical Surveys)

The Nevada Digital Dirt Mapping Project: An experiment in supervised crowd-sourcing for rapid geologic map development with ArcSDE
By P. Kyle House and Heather Green (Nevada Bureau of Mines and Geology), and Abbey Grimmer (Department of Geography, University of Nevada)

Derivative maps from geologic maps: hazard mitigation and resource planning
By Chris Wills (California Geological Survey)

Discussion Session — "Recommended citations for unpublished GIS files"
Moderated by Dave Soller (U.S. Geological Survey). Increasingly, unpublished GIS files and related information are being derived from pre-existing publications. Soon thereafter, or perhaps many years in the future, these files are used in new publications. How can we try to ensure that not only the unpublished GIS file, but also its source(s) of information, are informatively cited in new publications? It's critical to our science that years from now, the original and authoritative source of all cited information can be found. This brief session introduced the challenge and offered some suggestions.

Discussion Session — "Acquiring high-quality digital base maps"
Moderated by Randy Orndorff, Allen Crider, and Dave Soller (USGS).
Geologic mapping projects depend on high quality digital base maps. With the move away from paper topographic maps and mylar hard copies, significantly more effort is now needed to acquire a usable base map. There are many sources for digital base maps, many methods of creating them, and uneven quality. Easy access to standardized, high-quality digital base map layers (perhaps including, but not limited to, LiDAR) is a critical requirement of geologic mapping projects. This session addressed required elements and technical requirements of products to be developed by The National Map and other sources, and attempted to formalize guidance to management.

We have a dream
By Holger Kessler, Andy Hughes, Jeremy Giles, and Denis Peach (British Geological Survey)

Building a surficial geology data model for mapping projects
By Christine Deblonde (Geological Survey of Canada)

National Park Service Geologic Resources Inventory: Data model concepts and implementation, and a programmatic approach to digital map production
By Stephanie O'Meara, James Chappell, Heather Stanton, and Ron Karpilo (Colorado State University and the National Park Service)

NCGMP09 – Draft standard format for digital publication of geologic maps
By National Geologic Map Database Project and Pacific Northwest Geologic Mapping Project (U.S. Geological Survey)

What's coming in ESRI ArcGIS 10 for better, faster, more efficient geologic maps, map production, and map serving
By Willy Lynch (ESRI)

Mapping regulatory floodplains with Lidar and USGS StreamStats
By Jed Roberts and John English (Oregon Department of Geology and Mineral Industries)

Digital mapping of potential mineral hazards in California: Naturally occurring asbestos, radon, and highway corridor mapping
By John P. Clinkenbeard, Ronald K. Churchill, and Chris T. Higgins (California Geological Survey)

Image data management and use with ESRI ArcGIS
By Peter Becker (ESRI)

Application of geologic maps and resources to support regulatory review of environmental sites
By Rick Fears and John Karachewski (California Department of Toxic Substances Control)

Producing geologic maps and GIS products supporting the Geological Map Flow Project
By Vic Dohar (Natural Resources Canada)

A window to the National Geologic Map Database (NGMDB) Map Catalog via ArcGIS Image Server – Wyoming pilot project
By Christopher P. Garrity, David R. Soller, and Mark E. Reidy (U.S. Geological Survey)

Discussion Session — "Cartographic Design and Map Production"
An informal time to show maps and discuss map design and preparation techniques.

Poster Presentations (listed alphabetically, by author)

Seamless bedrock geology of Finland – A new map service at *http://www.geo.fi/en/*
By Niina Ahtonen, Hannu Idman, Jyrki Kokkonen, Jukka Kousa, Jouni Luukas, Mikko Nironen, and Jouni Vuollo (Geological Survey of Finland)

An Interactive session on the National Digital Catalog of Geologic and Geophysical Data: questions, answers, and feedback
By R. Sky Bristol and Richard E. Brown (U.S. Geological Survey)

Radon in California
By Ron Churchill (California Geological Survey)

The National Geothermal Datasystem: Geothermal data in the U.S. Geoscience Information Network
By Ryan Clark, Steve Richard, and Wolfgang Grunberg (Arizona Geological Survey)

Naturally occurring asbestos in California
By John Clinkenbeard (California Geological Survey)

Assessing early stages of landslide inventory
By Matthew M. Crawford and William M. Andrews, Jr. (Kentucky Geological Survey)

Integrating style files and carto representation into the geological map flow process (the GSC's implementation of the FGDC geologic symbology)
By Dave Everett and Vic Dohar (Natural Resources Canada)

Map production: Software tools, tricks, and stratagems
By Jane Freed and Collette Gantenbein (Idaho Geological Survey)

Update on ESRI cartographic representations for the FGDC Digital Cartographic Standard for Geologic Map Symbolization
By Charlie Frye and Janel Day (ESRI)

Assessing erosion potential and *Coccidioides immitis* probability using existing geologic and soils data
By Will Harris and Peter Roffers (California Geological Survey)

Development of digital-map products of potential mineral and mining-chemical hazards along selected highway corridors in northern California
By Chris T. Higgins, Ronald K. Churchill, Cameron I. Downey, and Milton C. Fonseca (California Geological Survey)

Using digital geologic maps to assess alluvial fan flood hazards
By Jeremy T. Lancaster, Thomas E. Spittler, and William R. Short (California Geological Survey)

Coal basin, Pitkin County, Colorado – An example of NGMDB data capture, conversion, and 3D editing in ArcGIS 10
By Willy Lynch (ESRI)

GIS-based digital photogrammetry for geologic and hazard mapping
By Timothy P. McCrink and Florante G. Perez (California Geological Survey)

Evaluating mine subsidence using a GIS software application
By James McDonald (Ohio Division of Geological Survey)

Cenozoic geology of the Sacramento Valley
By Jonathan Mulder (California Department of Water Resources)

Building a National Archive – Standards development and the National Geologic Map Database
By The National Geologic Map Database Project (U.S. Geological Survey)

A window to the National Geologic Map Database (NGMDB) Map Catalog via ArcGIS Image Server – Wyoming pilot project
By Christopher P. Garrity, David R. Soller, and Mark E. Reidy (U.S. Geological Survey)

NCGMP09 – Draft standard format for digital publication of geologic maps
By National Geologic Map Database Project and Pacific Northwest Geologic Mapping Project (U.S. Geological Survey)

California Geological Survey zones of required investigation for earthquake-induced landslides – Livermore Valley, California
By Florante G. Perez, Wayne D. Haydon, and Mark O. Wiegers (California Geological Survey)

The New Mexico Bureau of Geology and Mineral Resources geologic data model, a comparison with other existing models
By Adam S. Read, Geoff Rawling, Daniel J. Koning, Sean D. Connell, J. Michael Timmons, David McCraw, Glen Jones, Mark Mansell, and Shannon Williams (New Mexico Bureau of Geology and Mineral Resources)

Digital mapping techniques used for preparation of State of California Seismic Hazards Zones Maps
By Anne Rosinski (California Geological Survey)

A draft structure for Minnesota Geological Survey information systems
By Harvey Thorleifson, Rich Lively, Bob Tipping, and Tim Wahl (Minnesota Geological Survey)

Utility of combined aerial photography and digital imagery for fault trace mapping
By Jerome A. Treiman, Florante G. Perez, and William A. Bryant (California Geological Survey)

Derivative Maps from Geologic Maps: Hazard Mitigation and Resource Planning

By Chris J. Wills

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Abstract

The California Geological Survey (CGS) uses digital mapping techniques to prepare products for a wide variety of users, who range from geologists to engineers to local government planners and the public. In California, almost all land-use planning and building decisions are made at the local level, and few local governments have the geologic expertise to interpret geologic maps and glean from them the information on geologic hazards and resources that are of interest to them. California law requires CGS to prepare several products specifically for use in hazard and resource evaluation by local government. Those maps are derivatives of geologic maps and contain only the information needed by land-use planners and decision-makers.

This paper briefly describes examples of digital mapping techniques in use at CGS to create maps for an audience that includes geologists, who want all the details of our geologic observations, and for other audiences who want only the information that directly affects their projects. It serves as an introduction to papers in this volume by Treiman and others, Perez and others, Rosinski, Lancaster and others, Clinkenbeard and others, and Harris and Roffers, who provide additional detail on specific CGS map products. Those descriptions and the additional examples below illustrate the range of digital map products developed by CGS and the range of users served.

Introduction

Pascal wrote, "I would have written a shorter letter, but I did not have the time." Actually what he wrote is closer to "I made this [letter] very long, because I did not have the leisure to make it shorter," but editors and translators have found it useful to have a quote from some famous person on the difficulty and time involved in being brief and to the point. Even famous quotes about brevity can be edited for brevity. In producing geologic hazard maps, brevity and clarity are vitally important so that the important message gets through. CGS has found that a simple hazard zone map requires the development of extensive and detailed geologic, geotechnical, and seismological data. All of those intermediate data can be shown on maps, but the "shorter letter" that delivers the message without all the potentially confusing detail requires much care and effort to produce.

This paper serves to introduce CGS's efforts to produce derivative maps, the "shorter letters" that deliver only a key message about geologic hazards or resources. First, of course, a detailed analysis of the geologic data is needed to prepare as complete a description of the hazard as possible. Then, we must take into account an even more basic rule for authors: "know your audience." In making hazard or resource maps for use by non-geologists, knowing the audience should lead us to produce derivative maps that have reduced the geologic content to simple, readily understandable concepts.

CGS has found that the geologic hazard format that leads to concrete changes in a community's resilience to geologic hazards is the "Zone of Required Investigation." Those zones are established based on extensive analysis of a hazard, but once they are drawn, any location is either inside the zone or outside it. California state law provides the authority for CGS to draw the zones, and it is the local government's duty to enforce the laws under which the zones are established. Where California law does not call for a "Zone of Required Investigation," derivative maps showing the level of a hazard may be effective in conveying the amount of information needed for land-use planning decisions.

Mapping of Active Faults and Other Geologic Hazards

Credible geologic hazard maps for planners and decision-makers require detailed mapping and analysis of those hazards. Treiman and others (this volume) describe some of the remote sensing techniques used to map active faults. Detailed remote sensing, particularly LiDAR, has become increasingly common for mapping of active faults, particularly in California where there has been a concerted effort to acquire LiDAR surveys along the major active faults. LiDAR is strictly a topographic tool, however, and although LiDAR surveys depict fault geomorphology in unprecedented detail, they do not show other features of active faults that are visible in other types of remote sensing. Recent studies by Treiman and others (2010, and this volume) have focused on determining which additional forms of remote sensing (aerial photographs, multi-spectral or thermal scanning) add the most additional detail.

Detailed mapping of landforms is also a key aspect of recognizing and mapping landslides. For many years, CGS has prepared maps of existing landslides based on interpretation of aerial photographs. More recently, this traditional approach has been supplemented with interpretation of LiDAR and interpretation of stereo digital imagery. CGS has found that landslide-related landforms are more quickly and accurately mapped from bare earth LiDAR DEM’s than from aerial photographs, especially in heavily forested areas. In some areas, however, so many more landslide-related landforms are visible in the LiDAR topography that mapping them all requires more time per area than interpretation of aerial photographs of the same area. The resulting map is much more complete and accurate, but takes just as long to produce as using “traditional” methods (Falls and others, 2006).

Developing Derivative Maps

CGS is charged by the Alquist-Priolo Earthquake Fault Zoning Act of 1972 and the Seismic Hazards Mapping Act of 1990 with determining areas where further investigation of surface fault rupture, liquefaction, or seismically induced landslide hazards is required before construction of “structures for human occupancy.” The maps that are produced by CGS show “Zones of Required Investigation” where additional studies by geologists are required. These zone maps incorporate all of the detail described by Perez and others (this volume) for seismically induced landslides and by Rosinski (this volume) for liquefaction. As described in those papers, the detailed geologic and seismic data are condensed to answer a single question: Are further geologic studies required? The final maps are given to local agencies, which are required to enforce the provisions of the acts.

Alquist-Priolo Earthquake Fault Zone Maps (“AP maps”) show faults that are “sufficiently active and well-defined as to constitute a potential hazard to structures from surface faulting or fault creep” (Public Resources Code Chapter 7.5, section 2622) (fig. 1). Determining which faults meet those criteria involves detailed mapping and evaluation of the neotectonic geomorphology along faults. The evaluation of which faults are “sufficiently active and well defined” is of interest to geologists, but the basic product of the program is the AP map, which only shows the faults that meet the criteria and the regulatory zones around them. A local planner only needs to be able to read a map to determine if a property is inside or outside the “AP zone.” If a property is within a zone, a CGS publication (Bryant and Hart, 2007) describes in detail the responsibilities of the property owner, the permitting agency (usually local), and the state.

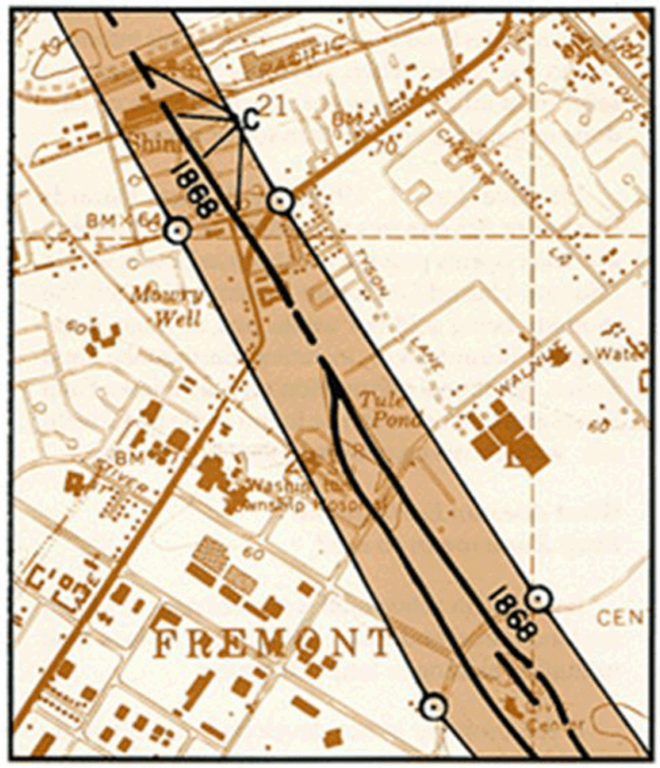

Figure 1. Part of Alquist-Priolo Earthquake fault zone in Fremont, California, showing faults, dates of surface rupturing earthquakes, and zone boundaries.

The process of making AP maps began in 1974, long before digital mapping techniques were available. As more sophisticated remote sensing data have become available, CGS has incorporated those into our analysis. Currently, designation of a fault as “sufficiently active and well defined” requires clear evidence of Holocene surface rupture along with a fault trace that can be accurately mapped at the surface. As described by Treiman and others (this volume), a wide variety of remote sensing techniques provide some information about the location of faults.

The Seismic Hazards Mapping Act of 1990 was modeled after the Alquist-Priolo Earthquake Fault Zoning Act. Like the AP Act, it requires the California Geological Survey to prepare maps showing “zones of required investigation” for particular seismic hazards, and it requires other agencies to ensure that additional studies are done to determine the severity of the hazard before development is allowed within those zones. Rosinski (this volume) and Perez (this volume) describe the process of assembling the geologic and geotechnical data required to define the zones of required investigation. Once the seismic hazard zones maps are prepared, agencies that oversee land use and construction use them to ensure that the potential hazards are evaluated and, if necessary, mitigated before construction. Detailed guidelines for the evaluation of these hazards and review of these reports are provided in a CGS publication (CGS, 2008).

Other geologic hazards that should be considered in making land-use decisions include flood potential and dangers due to naturally occurring hazardous materials. In contrast to Seismic Hazard Zones, there are no statutory requirements for CGS to prepare maps or for permitting agencies to use maps showing areas that may be subject to these hazards. Information is needed by agencies with regulatory authority over these types of hazards, however, and derivative products based on geologic maps can help focus effort on areas where they may occur. CGS prepares derivative maps using digital mapping techniques for these hazards, but these derivative maps do not result in “zones of required investigation.” In southern California, CGS is preparing maps of relative flood potential on alluvial fans, from information found on geologic maps. Traditional floodplain models may not accurately portray flood potential on alluvial fans, and usually do not account for the changing location of alluvial fan flooding with time. As described by Lancaster and others (this volume) geologic maps that emphasize the different ages of alluvial fan deposits can greatly assist users who are planning development projects by showing areas where alluvial fan flooding has occurred in the past. These maps can use the same polygons as on a geologic map, simply by including additional attributes related to alluvial fan flooding potential.

As described by Clinkenbeard and others (this volume), CGS has prepared maps showing areas that may contain naturally occurring asbestos, radon, or other potentially hazardous geological materials. These maps are designed to show local planning departments and other agencies the extent and severity of these hazards. Harris and Roffers (this volume) provide a similar analysis for a different hazard: the potential for spores of a pathogenic fungus in Tertiary sedimentary rocks and soils derived from those rocks. Like AP or Seismic Hazard Zones Maps, maps showing potential for naturally occurring asbestos, radon, or *Coccidioides immitis* spores must be based on detailed geologic mapping and analysis. Like alluvial fan flood potential maps, the polygons from a geologic map, with additional attribution, can form the basis for these maps.

Mineral resources can be shown on maps derived from geologic maps in much the same way as geologic hazards. In California, the Surface Mining and Reclamation Act requires CGS to prepare maps showing areas of potentially valuable mineral resources. Although California is known for gold production, the most valuable resources in recent years are construction materials, particularly sand and gravel. Maps showing where regionally important natural resources are most likely to occur are provided to local agencies so that they can consider them in making land use decisions. The maps show areas where construction aggregate exists in the region, and accompanying reports provide estimates of the volume of these resources (fig. 2). The potential resources are compared with the current permitted resources (reserves), and projected demand is estimated for the region, thereby allowing local agencies to consider future resource availability when they make a land use decision.

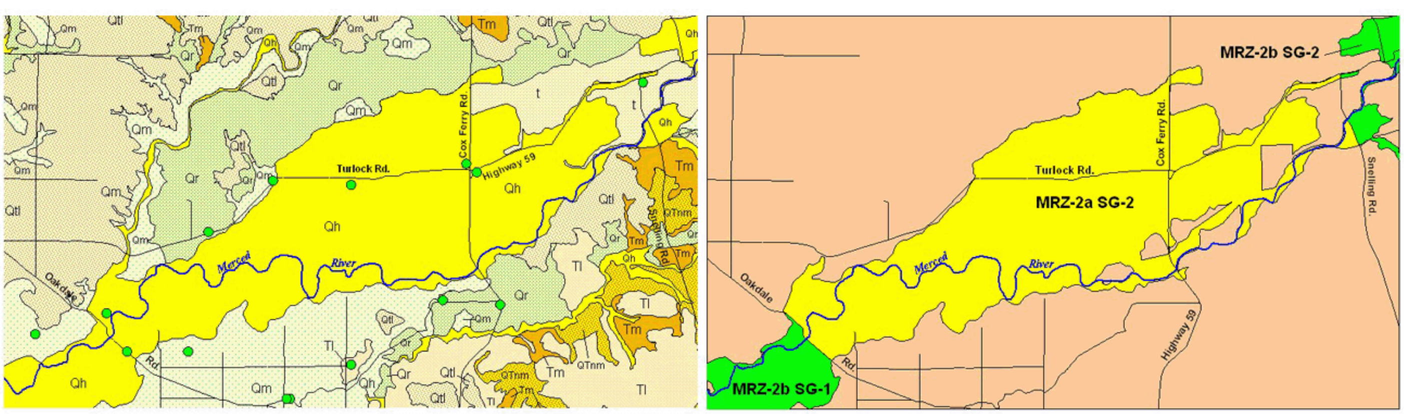

Figure 2. Geologic map (left) and mineral resource zones map (right) of part of Merced County, California. Mineral resource zones correspond to Holocene alluvial deposits (Qh); MRZ-2a in yellow shows where the material is well characterized, and MRZ-2b in green where similar geologic material is less well tested. Note that areas where existing surface mines have removed the resources are not included in MRZ-2a.

Conclusions

Most potential users of geologic information do not have the training to interpret geologic maps. Therefore, it is vital to produce derivative maps that are based on thorough geologic mapping and analysis but focus on the critical factors that might constrain land use or other societal decision-making. The California Geological Survey has developed several types of derivative maps for different purposes. The concept of a "zone of required investigation" is the most effective at focusing on an area where a more detailed site-specific study must be completed so that geologic hazards can be considered before structures are built. Derivative maps showing other geologic hazards or resources maps can be developed from geologic maps. All derivative maps are intended to convey geologic information to an audience of non-geologists. To keep these maps simple, they should show a limited number of categories (such as high, moderate, or low) describing the range of a hazard and not try to show too much information on the same map.

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Utility of Combined Aerial Photography and Digital Imagery for Fault Trace Mapping in Diverse Terrain and Vegetation Regimes

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Introduction

Various types of aerial imagery have long been recognized for their value in fault trace mapping. Most recently, the value of LiDAR imagery to "see through" vegetation has been recognized for forested areas. In this study we compared the effectiveness of shaded relief imagery derived from high-resolution LiDAR digital elevation models to standard aerial photography and to digital multi-spectral imagery for identifying and mapping active faults in moderate to sparsely vegetated terrain in southern California. The digital imagery included recently acquired stereo imagery. We also compared LiDAR-derived imagery to several combinations of draped or fused digital imagery. Additionally, we looked at the use of accurately georeferenced digital imagery for the registration of interpreted data from older, non-registered aerial photography. The study areas spanned varying terrain and geology.

A detailed discussion of the original mapping, imagery preparation and processing, image visualization and analysis, and results of this study can be found in the USGS final technical report (Treiman and others, 2010).[4]

Purpose

This study was intended to compare the utility of various imagery types in the identification of active surface faults. We have done comparative mapping of recently active surface traces of the San Andreas Fault in southern California using conventional aerial photography, digital elevation models (DEMs) from LiDAR (Light Detection and Ranging, also known as Airborne Laser Swath Mapping), recently acquired digital imagery (stereo and ortho-images), and satellite multi-spectral imagery.

[4]Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 08HQGR0096.

Current methods of fault interpretation from aerial imagery, individually, have certain strengths and weaknesses. Vintage aerial photos provide stereo viewing and show the landform prior to extensive human modification but commonly lack color and have limitations in accuracy of location due to lack of georeferencing and the inherent distortions in the medium. LiDAR terrain data have high spatial resolution and accuracy that can reveal subtle geomorphic features, can be viewed as detailed shaded-relief images illuminated from any direction, and have the capability of removing vegetation (in a virtual sense). But this type of imagery is limited to the modern landscape, does not easily differentiate vegetation and cultural features from geologic features, and is relatively costly to acquire for new (not previously flown) areas. High resolution digital stereo imagery often can differentiate lithology, soil moisture content, and vegetation that can be useful for mapping the surface trace of active faults; however, as with traditional aerial photos, the ground surface can be obscured by vegetation. Multi-spectral imagery from several sources at varying resolutions makes advantageous use of single and multiple wavelengths of the electromagnetic spectrum but is also limited to the current landscape and requires considerable processing.

The value of LiDAR in areas with a tall, obscuring vegetation canopy has already been well demonstrated (Prentice and others, 2004; Whitehill and others, 2009). This study evaluates the relative value of LiDAR data in somewhat less densely vegetated terrain relative to several other types of imagery (photographic and digital). One objective of this study is to use the geographic precision of the digital imagery, especially LiDAR, to more accurately locate fault traces interpreted from vintage aerial photography and other imagery (typically plotted on 7.5-minute topographic base maps). A second objective is to merge the high-resolution LiDAR shaded relief with multi-spectral imagery, adding detailed topographic information to the unique surface information contained in spectral reflectance. By using several different types of imagery, we will judge which are more suitable for various field conditions.

Setting and Methodology

Two test areas of contrasting terrain and vegetation conditions were selected for this study. These two areas, shown on figure 1, are along the San Andreas Fault near the cities of Indio and Yucaipa, in southern California. The Indio area has very little vegetation, and so the surface morphology and character are visible in most imagery types. Strands of the fault lie partly along the abrupt southwest front of the Indio Hills and project southward beyond the hill front into more subdued desert terrain. Some of this area has been significantly modified by human activity. Secondary fault strands lie within the uplifted terrain of the Indio Hills. Geologic variation within the area is limited, with the main contrast

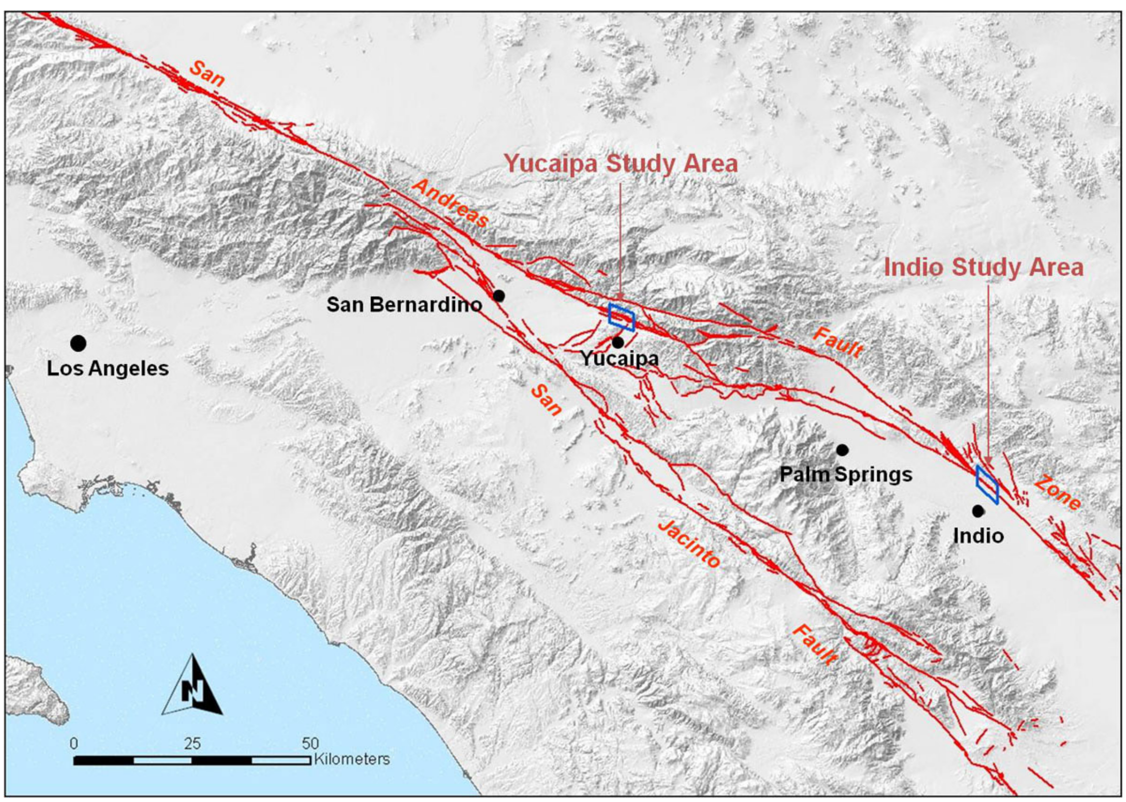


Figure 1. Index map of San Andreas Fault and the two study areas in southern California.

corresponding to the topographic front. The Yucaipa area differs from the Indio area in several aspects, most evident of which is the amount of vegetation growing on the slopes and associated thicker soil, which masks many of the finer fault features. Also, the faults in the Yucaipa area lie largely within uplifted terrain, with greater local relief than the Indio area. The underlying earth materials vary considerably, from bedrock to landslide to alluvium.

Several types of imagery were acquired and interpreted. These included standard black and white aerial photography, modern digital color imagery, and LiDAR-derived DEMs. Stereo viewing of the study areas was possible with standard aerial photography as well as with ADS40 (Aerial Digital Sensor) Stereo imagery. A three-dimensional (3D) view was effected with the LiDAR DEM (shaded relief) imagery. Each image type, alone and in selected combinations, was independently interpreted by a geologist for lineaments and other geomorphic features that could be associated with faulting. Interpretation was performed at a variety of scales to detect both large- and small-scale features.

The features interpreted from these types of imagery were compiled on separate map layers. A composite map was then prepared in order to consolidate into a best-fit location those features that were evidently the same. Faults interpreted from vintage aerial photos were not included in the composite map but were used to evaluate the completeness and accuracy of the composite fault map and served as a guide for subsequent field reconnaissance. Many “features” were plotted that did not correspond to any known faults. Features that were consistently observed across the various imagery types suggested the location of previously unmapped faults, or corroborated and helped to relocate other faults.

Limited field reconnaissance and mapping helped to further refine the baseline fault map, confirming or refuting some interpreted faults. In some field locations, additional geomorphic evidence of faulting was recorded that had not been observed in any of the imagery.

Two baselines of data are needed to compare the utility of the various imagery types. First is a baseline of the faults as previously mapped and presented in the published literature (figs. 2A and 2B). Improvements in fault mapping are judged against this base. Second is a map of revised fault locations. These maps were derived from the previous mapping, as revised to correspond with the more definitive evidence from this study (including both image interpretation and field reconnaissance). This second baseline fault map is used to judge the efficacy of each of the individual imagery types.

Assuming that the final revised fault locations are the best approximation of the actual fault pattern, we then measured how many linear meters of the fault traces had been identified using each imagery type. Conclusions were drawn from comparison of the relative utility of each imagery type for interpreting faults in a variety of terrain and vegetation conditions.

Remote Sensing Imagery

Six different types of imagery were acquired for this study: standard black and white aerial photographs, LiDAR digital elevation models, ADS40/NAIP color ortho-image, ADS40/ISTAR color-infrared ortho-image, ADS40 Stereo imagery, and ASTER imagery. These imagery types as well as their properties and characteristics are summarized in table 1.

In order to undertake a comparative analysis of the suitability of the different imagery for fault trace mapping, it is imperative that they are in a format that can be displayed, overlaid, analyzed, and digitized in a Geographic Information System (GIS) environment. It is essential therefore that the various imagery have the same areal extent or have some overlap, are georeferenced and co-registered, and have compatible file formats. Since the imagery acquired for this study was in a variety of file formats, pixel sizes, areal coverages, and coordinate systems, considerable preparation and processing had to be undertaken. Additionally, derivative imagery was extracted from the acquired imagery, and combination imagery was also generated by data fusion. Data fusion requires resampling, contrast stretching, and reprojection (Carter, 1998).

The processed and derived imagery used in the actual fault interpretation and evaluation is summarized in table 2.

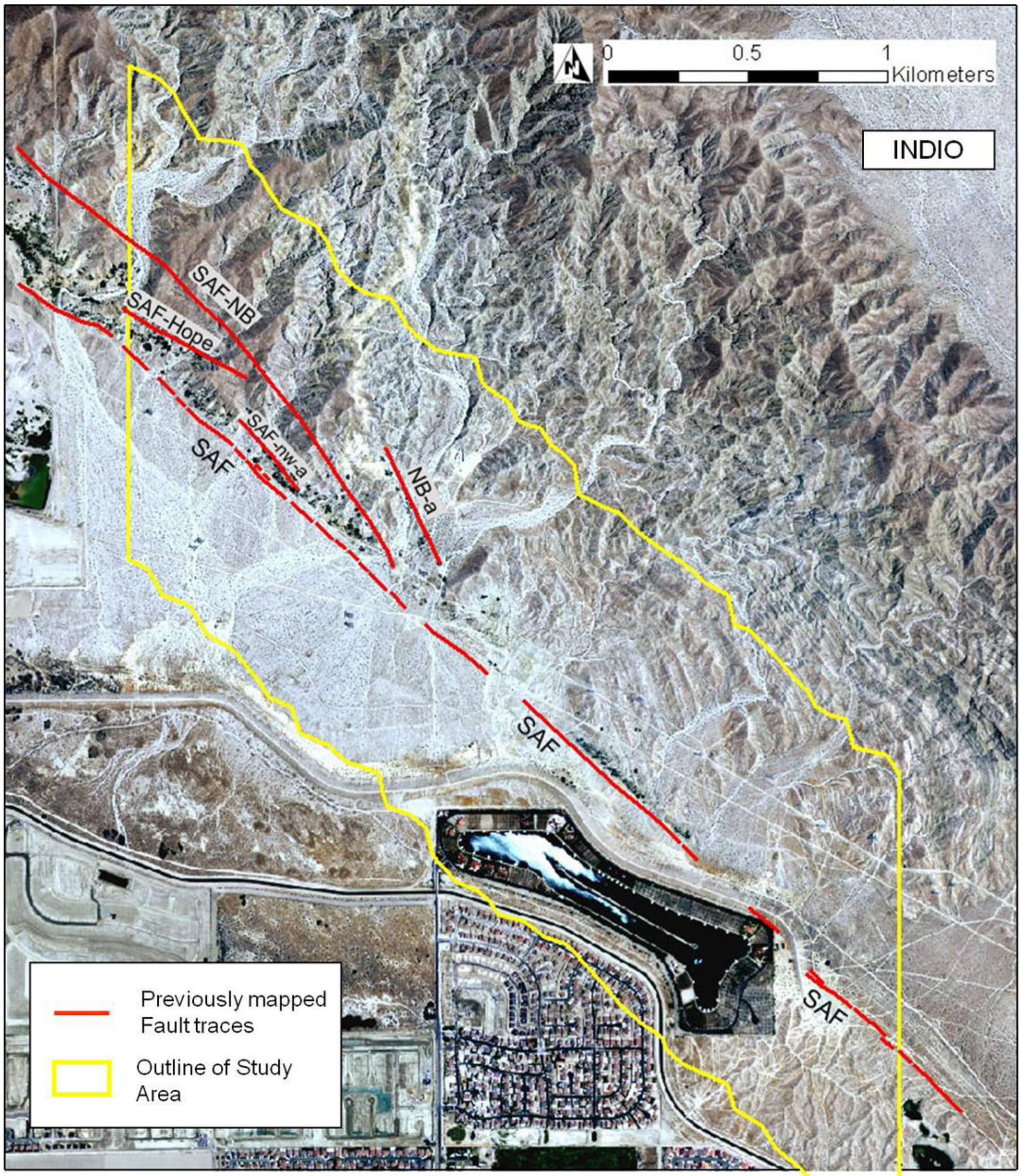


Figure 2A. Indio study area showing previously mapped fault traces. "SAF" refers to the San Andreas Fault; see Treiman and others (2010) for explanation of other identified fault traces.

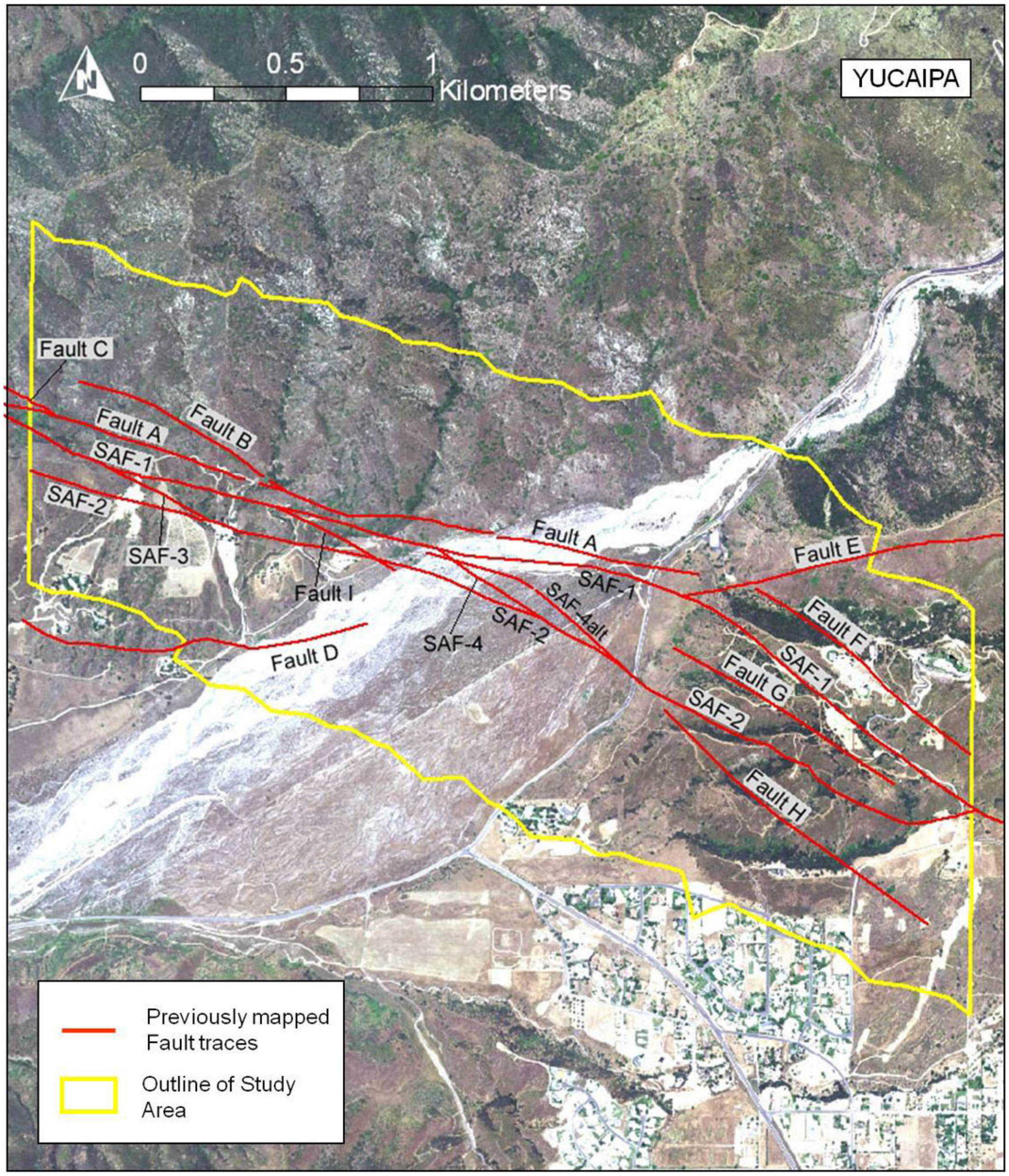


Figure 2B. Yucaipa study area showing previously mapped fault traces. “SAF” refers to the San Andreas Fault; see Treiman and others (2010) for explanation of other identified fault traces.

Table 1. Summary of properties and characteristics of the acquired imagery.

[RGB, red-green-blue; pan, panchromatic; NIR, near infrared; VNIR, very near infrared; SWIR, short wave infrared; TIR, thermal infrared; m, meter; cm, centimeter]

	IMAGERY (Acquisition Date)	Format/ Coverage	Scale/pixel resolution	Stereo	Rectified	Geolocated	Estimated/Stated Horiz. Accuracy	Spectral Bands	Unique Characteristics	File Format	Projection/ Datum
1	**Aerial Photos** (1930, 1953/54)	B&W Film/Paper 9 inch	~ 1:18000 ~1:20000	yes	no	no	same as warped imagery	1	pre-development photos, familiar character, sub-meter resolution in stereo.	paper JPEG TIFF	UTM, z11N NAD-83
2	**LiDAR DEM** (2005)	Digital Swath = 0.8 mi Variable length	0.5 m	no	yes	yes	10-20 cms	1	very high resolution topo with foliage penetration, 3D view, variable source of illumina-tion.	ADF	UTM, z11N WGS-84
3	**ADS40/NAIP** (2005)	Digital Quarter Quads ~16 mi²	1.0 m	no	yes	yes	5-10 m	3 (R,G,B)	synoptic coverage, natural color, vegetation and cultural features.	ADF, TIFF	UTM, z11 NAD-83
4	**ADS40/ISTAR** (2003)	Digital ~3 mi² tiles	0.5 m	no	yes	yes	1.5 m	3 Pan 4 RGB/NIR	visible and near infrared, veg-etation type, soil saturation.	FLT, ADF, TIFF	UTM, z11N NAD-83
5	**ADS40 Stereo** (2005)	Digital 5 mi x 100 mi (stereo subsets can be extracted using Leica GPro)	1.0 m	yes	partial	yes	6.0 m	5 (Pan,R.G.B, NIR)	rapid imagery interpretation with feature collection and attribution in stereo, variable vertical exaggeration.	TIFF	LSR Anchored WGS-84
6	**ASTER** (2006)	Digital ~38 mi²/scene	15 m 30 m 90 m	yes no no	no no no	yes yes yes	~25 m	3 VNIR 6 SWIR 5 TIR	spectral information can be transformed into other forms or space.	HDF, TIFF	UTM, z11N WGS-84

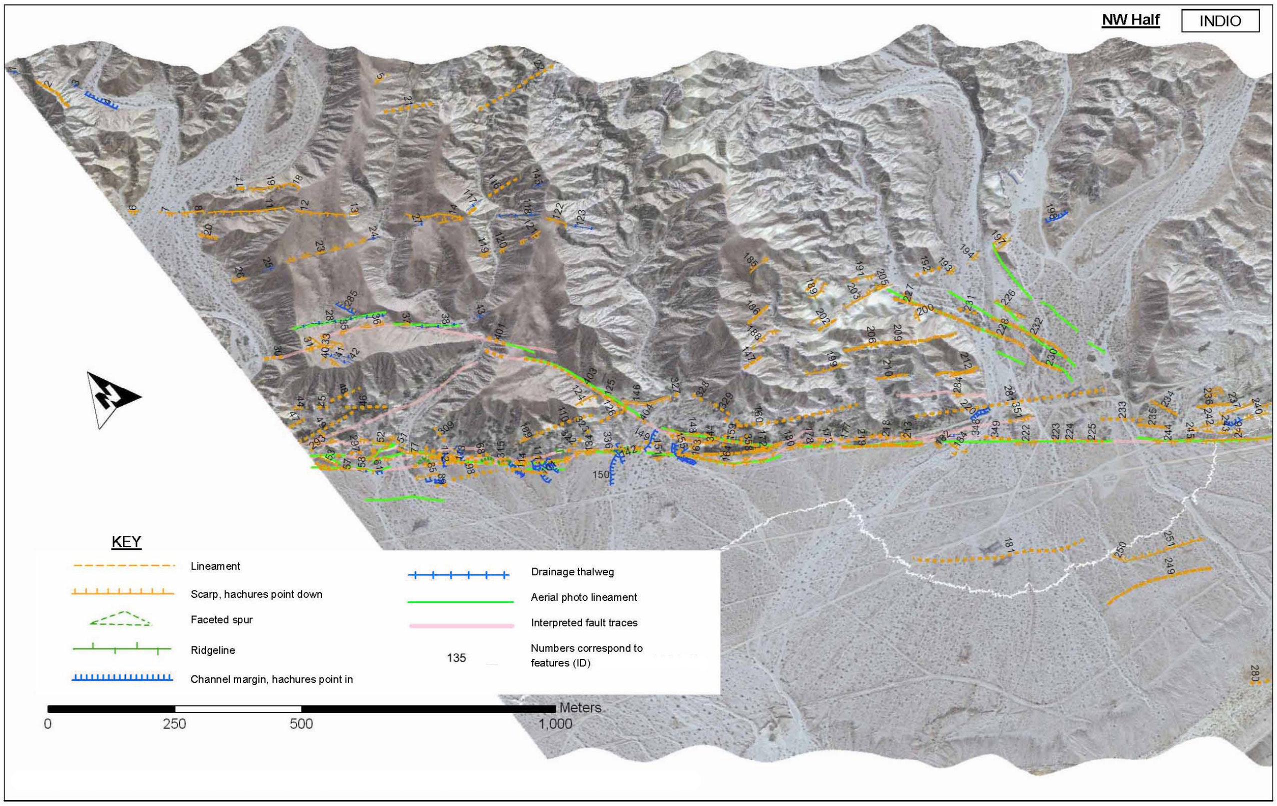
Table 2. Summary of the various image processing techniques used to generate the processed and derived imagery.

[TCC, True Color Composite; FCC, False Color Composite; VNIR, very near infrared]

ACQUIRED UNPROCESSED IMAGERY	IMAGERY PROCESSING / TRANSFORMATION														DERIVED / PROCESSED IMAGERY		
	Scan	Mosaic	Warp	Georeference	Subset	Resample	Re-Project	Enhance	Contrast Stretch	Band Order	Topo Modeling	Layer Stacking	Data Fusion	Slice - GPro	Single	Combination: Draped over LiDAR DEM Shaded Relief	Combination: Fused with LiDAR DEM
Aerial Photos	x	x	x	x	x		x	x							Digital Aerial Photos		
LiDAR DEM		x			x			x			x				LiDAR DEM Shaded Relief		
ADS40/NAIP					x	x	x	x	x		x	x	x		ADS40/NAIP TCC	ADS40/NAIP TCC	ADS40/NAIP TCC
ADS40/NAIP					x	x	x	x	x	x	x	x	x		ADS40/NAIP FCC	ADS40/NAIP FCC	ADS40/NAIP FCC
ADS40/ISTAR					x		x	x	x		x	x	x		ADS40/ISTAR TCC	ADS40/ISTAR TCC	ADS40/ISTAR TCC
ADS40/ISTAR					x		x	x	x	x	x	x	x		ADS40/ISTAR FCC	ADS40/ISTAR FCC	ADS40/ISTAR FCC
ADS40Stereo								x						x	ADS40 Stereo		
ASTER					x	x		x	x	x	x	x	x		ASTER VNIR	ASTER VNIR	ASTER VNIR

Results

Figures 3A and 3B present a consolidated plot of all of the geomorphic features interpreted for each study area. These features were used, along with previous mapping and field reconnaissance, to refine the previous fault trace locations and, in some instances, infer newly mapped traces. Many of the features were observed in more than one image, in which case a judgment was made as to the best representation for the consolidated plot.



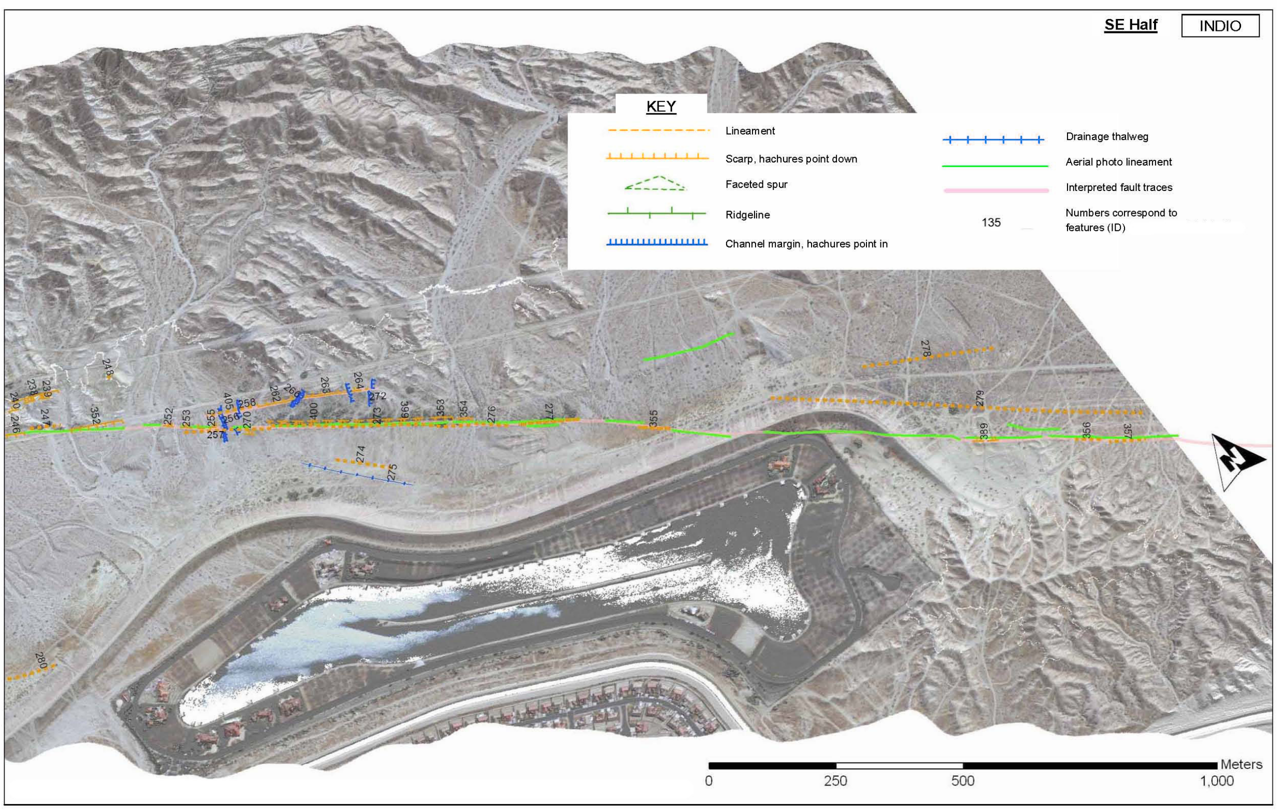


Figure 3A. Consolidated plot of fault-related geomorphic features interpreted in the Indio study area (upper figure is northwest half, lower figure is southeast half).

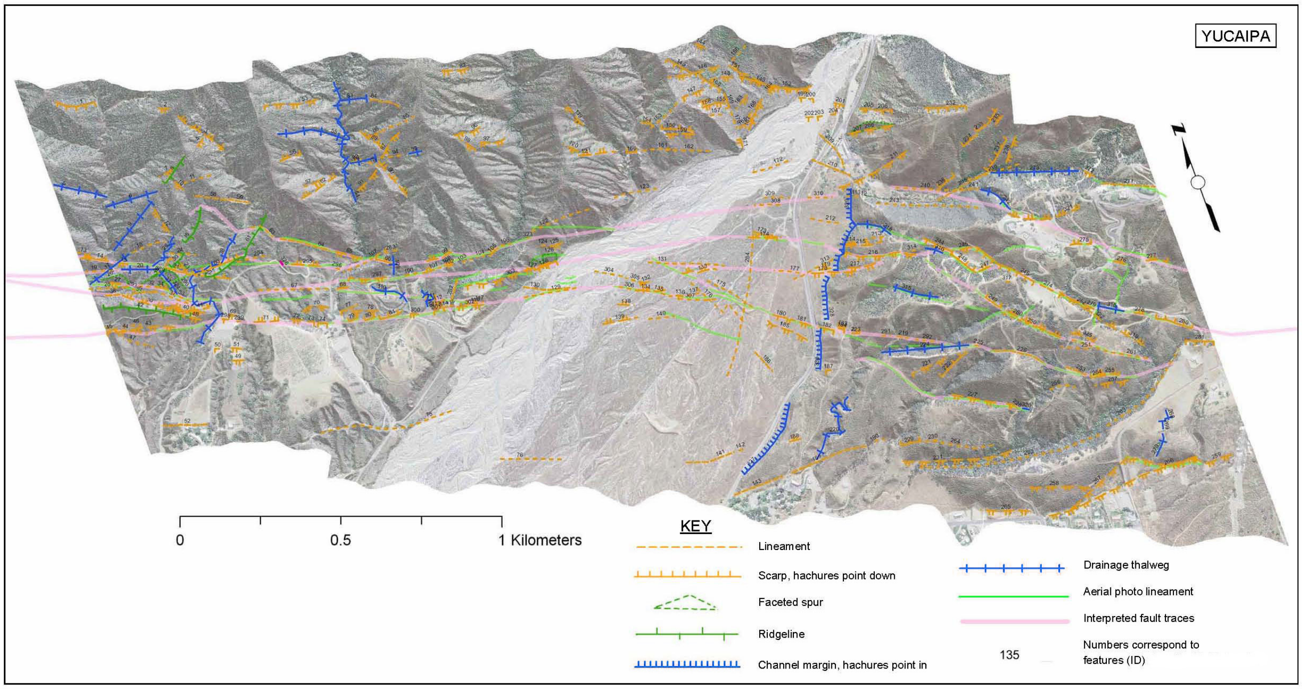


Figure 3B. Consolidated plot of fault-related geomorphic features interpreted in the Yucaipa study area.

Figures 4A and 4B show the reinterpreted faults used in this study, for the comparison of the different imagery types. Tables 3A and 3B-D show the raw numbers indicating the percent of the presumed fault trace lengths interpreted using each imagery type, for each of the two study areas. The totals for each area show that black and white stereo aerial photographs were most effective for mapping faults in either area, identifying 54 percent (Indio) to 50 percent (Yucaipa) of the accepted faults. In the sparsely vegetated Indio area, ADS40 Stereo imagery was nearly as effective (53 percent) whereas in the chaparral-covered Yucaipa area LiDAR was the next most effective imagery (40 percent). However, these are gross comparisons and more can be learned by focusing on sections of faulting that share common characteristics. The discussion below is confined to the most useful imagery. The results from the other imagery are compiled in the tables.

While the numbers in the tables provide some simplistic comparisons, they do not highlight whether the different imagery types were revealing more or less of the same traces or whether each had their own strengths, detecting fault segments not seen in other imagery. A more careful assessment of the results, considering area characteristics (geology, topography, and vegetation) and looking at each mapped fault trace revealed some trends but no overwhelmingly stark contrasts. Imagery types are ranked (based on percent of fault detected) for each fault segment, in tables 4A-D. For most areas, true stereo imagery (photographic or digital) detected the most fault traces. The character of the underlying geology does not appear to have a systematic impact that was detectable in this limited study.

Figure 4A. Interpreted fault traces in the Indio area.

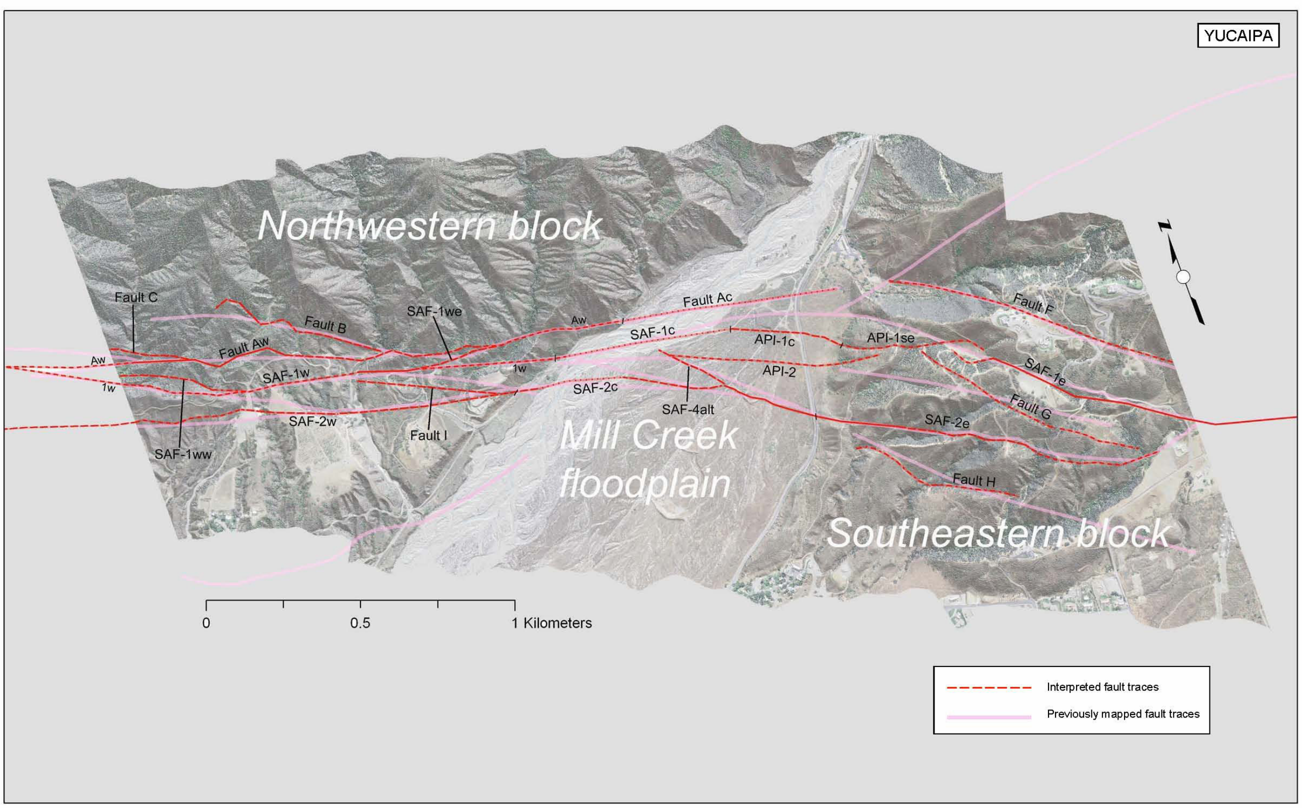


Figure 4B. Interpreted fault traces in the Yucaipa area.

Table 3A. Interpreted faults in the Indio study area showing the proportion of fault traces identified in each imagery type.

[Qal, younger alluvium and fan deposits; Qo, Ocotillo conglomerate; Qp, Palm Spring Formation; "/", indicates one unit faulted against the other; T, True Color Composite; F, False Color Composite]

Indio study area

INTERPRETED FAULTS			PROPORTION (Length and Percentage) OF FAULT TRACES IDENTIFIED IN EACH IMAGERY TYPE															
Fault Trace	Geology	Length meter (m)	Aerial Photo		LiDAR DEM		ADS40/NAIP		ADS40 Stereo		ASTER		Draped on LiDAR		Fused with LiDAR DEM			
													ADS40/NAIP		ADS40/NAIP T		ADS40/NAIP F	
			m	%	m	%	m	%	m	%	m	%	m	%	m	%	m	%
SAF-nw	Qp/Qal	2425	970	40%	820	34%	860	35%	1260	52%	915	38%	480	20%	575	24%	620	26%
SAF-c	Qp/Qal	1735	1155	67%	925	53%	905	52%	1180	68%	1050	61%	960	55%	615	35%	795	46%
SAF-se	Qal	1245	1050	84%	105	8%	180	14%	365	29%	845	68%	180	14%	165	13%	185	15%
SAF-NB(r)	Qo, Qp	555	210	38%	75	14%	0	0%	175	32%	0	0%	140	25%	205	37%	0	0%
SAF-nw-a	Qo, Qp	845	425	50%	285	34%	190	22%	660	78%	150	18%	185	22%	135	16%	85	10%
SAF-Hope(r)	Qp	330	0	0%	0	0%	90	27%	15	5%	0	0%	0	0%	0	0%	0	0%
NB-a	Qal	345	225	65%	0	0%	300	87%	325	94%	295	86%	335	97%	225	65%	235	68%
Sum	%	7480	4035	54%	2210	30%	2525	34%	3980	53%	3255	44%	2280	30%	1920	26%	1920	26%

Table 3B. Interpreted faults in the Yucaipa study area showing the proportion of fault traces identified in each imagery type.

[Qyf, younger alluvial fan deposits; Qof, older alluvial fan deposits; gg, gneissic basement rock; "/", indicates one unit faulted against the other; T, True Color Composite; F, False Color Composite]

Yucaipa, Northwest area – bedrock terrain

INTERPRETED FAULTS			PROPORTION OF FAULT TRACES (Length and Percentage) IDENTIFIED IN EACH IMAGERY TYPE																			
Fault Trace	Geology	Length meter (m)	Aerial Photo		LiDAR DEM		ADS40/NAIP		ADS40/ISTAR		ADS40 Stereo		Draped on LiDAR				Fused with LiDAR DEM					
													ADS40/NAIP		ADS40/ISTAR		ADS40/NAIP T		ADS40/NAIP F		ADS40/ISTAR	
			m	%	m	%	m	%	m	%	m	%	m	%	m	%	m	%	m	%	m	%
SAF-1w	gg/Qof, Qyf	1410	275	20%	650	46%	125	9%	0	0%	115	8%	345	24%	325	23%	90	6%	50	4%		
SAF-1ww	gg	415	330	80%	180	43%	0	0%	0	0%	240	58%	245	59%	0	0%	0	0%	190	46%		
SAF-1we	gg	275	280	102%	205	75%	125	45%	0	0%	215	78%	160	58%	0	0%	0	0%	35	13%		
SAF-2w	Qof, Qyf	1250	610	49%	450	36%	0	0%	0	0%	455	36%	375	30%	450	36%	540	43%	440	35%		
Fault Aw	gg, Qyf	1685	1200	71%	815	48%	470	28%	0	0%	840	50%	520	31%	105	6%	160	9%	215	13%		
Fault B	gg	600	240	40%	390	65%	150	25%	135	23%	330	55%	370	62%	180	30%	0	0%	0	0%		
Fault C	gg	270	145	54%	150	56%	0	0%	0	0%	0	0%	0	0%	0	0%	120	44%	0	0%		
Fault I	Qof, Qyf	455	340	75%	150	33%	0	0%	0	0%	0	0%	35	8%	85	19%	0	0%	25	5%		
Sum	%	6360	3420	54%	2990	47%	870	14%	135	2%	2195	35%	2050	32%	1145	18%	910	14%	955	15%	0	0%

Table 3C. Interpreted faults in the Yucaipa study area showing the proportion of fault traces identified in each imagery type.

[Qal, young and modern stream channel deposits of Mill Creek; Qoal, older flood plain and channel deposits of Mill Creek]

Yucaipa, Central area – alluvial flood plain of Mill Creek

INTERPRETED FAULTS			PROPORTION OF FAULT TRACES (Length and Percentage) IDENTIFIED IN EACH IMAGERY TYPE																					
Fault Trace	Geology	Length meter (m)	Aerial Photo		LiDAR DEM		ADS40/NAIP		ADS40/ISTAR		ADS40 Stereo		Draped on LiDAR				Fused with LiDAR DEM					
													ADS40/NAIP		ADS40/ISTAR		ADS40/NAIP T		ADS40/NAIP F		ADS40/ISTAR	
			m	%	m	%	m	%	m	%	m	%	m	%	m	%	m	%	m	%	m	%
SAF-1c	Qal	585	0	0%	380	65%	0	0%	0	0%	30	5%	50	9%	0	0%	0	0%	0	0%		
API-1c	Qoal	370	175	47%	0	0%	0	0%	0	0%	0	0%	140	38%	0	0%	0	0%	0	0%		
SAF-2c	Qal, Qoal	1000	730	73%	200	20%	90	9%	135	14%	410	41%	175	18%	80	8%	100	10%	100	10%	170	17%
Fault Ac	Qal, Qoal	710	0	0%	0	0%	0	0%	0		175	25%	0		0	0%	0	0%	0	0%		
Fault-API-2	Qoal	690	0	0%	220	32%	190	28%	255	37%	0	0%	325	47%	0	0%	275	40%	250	36%		
SAF-4alt	Qoal	240	190	79%	0	0%	65	27%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%		
Sum	%	3595	1095	30%	800	22%	345	10%	390	11%	615	17%	690	19%	80	2%	375	10%	350	10%	170	5%

Table 3D. Interpreted faults in the Yucaipa study area showing the proportion of fault traces identified in each imagery type.

[landslide deposits derived from Mill Creek Formation]

Yucaipa, Southeast area – landslide disturbed bedrock terrain

INTERPRETED FAULTS			PROPORTION OF FAULT TRACES (Length and Percentage) IDENTIFIED IN EACH IMAGERY TYPE																					
Fault Trace	Geology	Length meter (m)	Aerial Photo		LiDAR DEM		ADS40/NAIP		ADS40/ISTAR		ADS40 Stereo		Draped on LiDAR				Fused with LiDAR DEM					
													ADS40/NAIP		ADS40/ISTAR		ADS40/NAIP T		ADS40/NAIP F		ADS40/ISTAR	
			m	%	m	%	m	%	m	%	m	%	m	%	m	%	m	%	m	%	m	%
SAF-1e	landslide	840	725	86%	590	70%	170	20%	0	0%	565	67%	280	33%	0	0%	240	29%	370	44%		
API-1se	landslide	470	250	53%	420	89%	0	0%	0	0%	245	52%	115	24%	0	0%	260	55%	140	30%		
SAF-2e	landslide	1140	525	46%	535	47%	280	25%	40	4%	385	34%	410	36%	0	0%	405	36%	500	44%		
Fault F	landslide	960	340	35%	0	0%	0	0%	0	0%	125	13%	70	7%	0	0%	0	0%	175	18%		
Fault G	landslide	780	555	71%	350	45%	255	33%	0	0%	460	59%	190	24%	185	24%	445	57%	320	41%		
Fault H	landslide	570	510	89%	210	37%	195	34%	0	0%	210	37%	165	29%	205	36%	255	45%	275	48%		
Sum	%	4760	2905	61%	2105	44%	900	19%	40	1%	1990	42%	1230	26%	390	8%	1605	34%	1780	37%	0	0%

Table 4A. Imagery types with rankings of effectiveness for mapping each fault trace. Effectiveness is based on the percentage of lineal fault length identified in each imagery type.

[Qal, younger alluvium and fan deposits; Qo, Ocotillo conglomerate; Qp, Palm Spring Formation; "/", indicates one unit faulted against the other; T, True Color Composite; F, False Color Composite]

Indio study area

Fault Trace	TERRAIN / FIELD Conditions				Imagery Type							Best Imagery
	Slope	Vegetation	Geology	Remarks	AP	LiDAR	NAIP	STEREO	Draped	Fused		
									NAIP	NAIP T	NAIP F	
SAF-nw	low to moderate	light to moderate	Qp/Qal	multiple traces that are close together	4	4	4	3	5	5	5	STEREO with AP, LiDAR, NAIP
SAF-c	low to moderate	light	Qp/Qal		2	3	3	2	3	4	4	AP or STEREO
SAF-se	low	light	Qal	modified landscape	1		5	4	5	5	5	AP
SAF-NB(r)	low to mod to steep	light	Qo, Qp		4	5		4	5	4		AP, f-NAIP with STEREO
SAF-nw-a	low to moderate	low to moderate	Qo, Qp	parallel traces, oases	3	4	5	1	5	5	5	STEREO
SAF-Hope(r)	low to moderate	light to moderate	Qp	truncated old fans, oases			4					Field
NB-a	low	sparse	Qal, Qp	contrasting lithology	2		1	1	1	2	2	Color Imagery (NAIP,d-NAIP or STEREO)

Range	1	2	3	4	5
Percent range	75-100	60-74	50-59	26-49	10-25

Table 4B. Imagery types with rankings of effectiveness for mapping each fault trace. Effectiveness is based on the percentage of lineal fault length identified in each imagery type.

[Qyf, younger alluvial fan deposits; Qof, older alluvial fan deposits; gg, gneissic basement rock; "/", indicates one unit faulted against the other; T, True Color Composite; F, False Color Composite]

Yucaipa study area – northwest block

Fault Trace	TERRAIN / FIELD Conditions				Imagery Type									Best Imagery
	Slope	Vegetation	Geology	Remarks	AP	LiDAR	NAIP	ISTAR	STEREO	Draped		Fused		
										NAIP	ISTAR	NAIP T	NAIP F	
SAF-1w	moderate to high	moderate to dense	gg/Qof, Qyf	separates geologic units	5	4				5	5			LiDAR
SAF-1ww	moderate	moderate	gg/Qof, Qyf	faceted slopes	1	4			3	3			4	AP
SAF-1we	moderate	light to moderate	gg	alignment of features	1	1	4		1	3			5	AP or Stereo, LiDAR
SAF-2w	moderate to low	light to moderate	Qof, Qyf		4	4			4	4	4	4	4	all together
Fault-Aw	moderate to high	moderate	gg, Qyf	offset streams, ridges	2	3	4		3	4			5	AP with STEREO, LiDAR
Fault B	high to moderate	light to moderate	gg		4	2	4	5	3	2	4			LiDAR
Fault C	moderate to high	light to mod to dense	gg	hillslope features	3	3						4		AP or LiDAR
Fault I	moderate	light to medium dense	Qof, Qyf	manmade structures	1	4					5		5	AP

Range	1	2	3	4	5
Percent range	75-100	60-74	50-59	26-49	10-25

Table 4C. Imagery types with rankings of effectiveness for mapping each fault trace. Effectiveness is based on the percentage of lineal fault length identified in each imagery type.

[Qal, young and modern stream channel deposits of Mill Creek; Qoal, older flood plain and channel deposits of Mill Creek; T, True Color Composite; F, False Color Composite]

Yucaipa study area – central block

Fault Trace	TERRAIN / FIELD Conditions				Imagery Type									Best Imagery
	Slope	Vegetation	Geology	Remarks	AP	LiDAR	NAIP	ISTAR	STEREO	Draped		Fused		
										NAIP	ISTAR	NAIP T	NAIP F	
SAF-1c	low	light	Qal	modern, active channels		2								LiDAR
API-1c	low	moderate	Qoal	older inactive channels	4	4				4				AP, LiDAR, d-NAIP
SAF-2c	low	moderate	Qal, Qoal	modern, active channels	2	5		5	4	5		5	5	AP
Fault-Ac	low	light	Qal, Qoal	modern, active channels					5					Stereo
Fault-API-3	low	moderate	Qoal	older, inactive channels		4	4	4		4		4	4	NAIP or ISTAR and d-NAIP or f-NAIP
SAF-4alt	low	moderate	Qoal	older, inactive channels	1		4							AP

Range	1	2	3	4	5
Percent range	75-100	60-74	50-59	26-49	10-25

Table 4D. Imagery types with rankings of effectiveness for mapping each fault trace. Effectiveness is based on the percentage of lineal fault length identified in each imagery type.

[landslide deposits derived from Mill Creek Formation; Qoal, older flood plain and channel deposits of Mill Creek; T, True Color Composite; F, False Color Composite]

Yucaipa study area – southeast block

Fault Trace	TERRAIN / FIELD Conditions				Imagery Type									Best Imagery
	Slope	Vegetation	Geology	Remarks	AP	LiDAR	NAIP	ISTAR	STEREO	Draped		Fused		
										NAIP	ISTAR	NAIP T	NAIP F	
SAF-1e	moderate to high	moderate to dense	landslide	sag pond	1	2	5		2	4		4	4	AP STEREO/ LiDAR
API-1se	moderate to high	moderate to dense	landslide		3	1			3	5		3	4	LiDAR
SAF-2e	high to moderate	moderate to dense	landslide		4	4	4		4	4		4	4	LiDAR, AP or f-NAIP
Fault-F	moderate to high	moderate to dense	landslide		4				5				5	AP
Fault-G	moderate	moderate to dense	Qoal		2	4	4		3	5	5	3	4	AP
SAF-H	moderate	moderate to dense	landslide	sidehill bench	1	4	4		4	4	4	4	4	AP

Range	1	2	3	4	5
Percent range	75-100	60-74	50-59	26-49	10-25

Conclusions

Although there are no overwhelming trends, this study demonstrated that true stereo (ADS40 Stereo and vintage stereo photographs) was often the best imagery for identifying faults in terrain with topographic relief, whereas the LiDAR DEM offered advantages in terrain with moderate to heavy vegetation. If the clear advantage that vintage aerial photography has in areas that were subsequently modified is removed, ADS40 Stereo seemed to be the superior imagery for observing faults in areas of light vegetation. This advantage over vintage aerial photography is probably a result of the higher resolution of the digital imagery, with some additional benefit due to variable vertical exaggeration and adjustable brightness and contrast. In areas of heavier vegetation, LiDAR and vintage aerial photography were the more useful imagery.

There were always exceptions, and most other imagery or combinations certainly added fault elements not seen in the three principal platforms. However, these exceptions were often not clearly attributable to conditions of vegetation, relief, or geology, although the ability to see vegetation lineaments (using ISTAR and NAIP) proved advantageous in otherwise low-relief areas. Digital imagery (LiDAR or ADS40) with high resolution (1 m pixel or less) provides the best accuracy for fault location and is very useful for improving fault locations identified from either published mapping or aerial photo interpretation. Image types other than LiDAR had an advantage of sensing tonal differences, which often helps to define, connect, extend, or reinforce geomorphic lineaments. The low resolution of the ASTER data, even when fused with the LiDAR DEM shaded relief, seriously hampered its usefulness to a mapping effort at the scale made possible by the other imagery.

Ultimately, we believe that it was the use of multiple image types that allowed greater completeness of fault trace mapping in the areas studied, with an increase in accuracy of location dependent on the type of digital imagery available. Observation of a trace using several image types provided reinforcing evidence for fault interpretation. Even small fault elements, uniquely identified in one image type, when viewed in aggregate with other imagery, provided necessary continuity to lineament interpretation. Draped or fused imagery added value for some faults, but the additional processing involved in the fusion process may not be justified by the minimal improvements seen in this study. The identification of some strong lineaments that probably are not fault related also reinforced the need for ground truth in any geologic studies.

LiDAR data are freely available, but only along specific narrow swaths where data have already been collected (*http://www.opentopography.org*). This can be frustrating where unanticipated splay faults and local complications extend beyond the LiDAR coverage. ADS40 Stereo imagery currently exists for the entire State of California; wider availability is being considered. The results of this study show that investment in making these data more readily available and usable can have significant benefits for many mapping interests, including fault mapping.

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California Geological Survey Zones of Required Investigation for Earthquake-Induced Landslides – Livermore Valley, California

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Abstract

The California Geological Survey (CGS) recently released the official Seismic Hazard Zone Maps of the Altamont, Dublin, and Livermore 7.5-minute quadrangles including the Livermore Valley and surrounding hills (Livermore Valley Study Area). Areas that are most susceptible to seismically induced landslides are depicted on the maps as Zones of Required Investigation, where site-specific geotechnical investigations are required to be undertaken prior to development.

In establishing the landslide hazard zones, CGS used the best available terrain, geologic, geotechnical, and seismological data. These data are combined in a modified Newmark analysis to identify those slopes with the highest potential for earthquake-induced landsliding. For Dublin and Livermore quadrangles, 5-meter Digital Terrain Models (DTMs) are obtained from Interferometric Synthetic Aperture Radar (IfSAR) where vegetation, buildings, and other cultural features were digitally removed. The resulting bald earth topography is used in generating the slope gradient and slope aspect parameters, and also in updating the boundaries of the different geologic units and existing landslides. Geotechnical data, particularly shear strength, were collected to ascertain the rock strength of the geologic materials. In cases where shear strength data were insufficient to carry out a valid statistical analysis, data from adjacent quadrangles with similar lithology and depositional environment were used in the slope stability analysis.

The data collected and evaluated were transformed into primary and derived Geographic Information System (GIS) layers. Three of the 16 GIS layers—Geologic Materials, Landslide Inventory, and Landslide Hazard Potential—are considered stand-alone maps. In addition to the Seismic Hazard Zone Map, the Landslide Inventory layer is also being published as part of CGS's Landslide Inventory Map Series.

Introduction

Earthquake-induced landslide hazard maps are prepared by the California Geological Survey (CGS) using a GIS that allows the overlaying of various data layers. These data layers include terrain, geologic materials and structure, geotechnical data, mapped landslide features, slope parameters, rock-strength measurements, and probabilistic earthquake shaking estimates. Ground shaking inputs are based upon probabilistic seismic hazard maps that depict peak ground acceleration, mode magnitude, and mode distance with a 10 percent probability of exceedance in 50 years. City, county, and State agencies are required by the California Seismic Hazards Mapping Act (California Department of Conservation, 1997) to use the seismic hazard zone maps in their land-use planning and permitting processes. They must withhold building permits for sites being developed within Zones of Required Investigation until the geologic and soil conditions of the project site are investigated and appropriate mitigation measures, if any, are incorporated into development plans.

The Seismic Hazard Zone Maps of the Livermore Valley Study Area (fig. 1) covering the 7.5-minute quadrangles of Dublin and Livermore, and Altamont were officially released on August 27, 2008, and February 27, 2009, respectively. They cover the cities of Pleasanton, Dublin, and Livermore, portions of the city of Hayward, and unincorporated areas of Altamont County.

A more detailed discussion of the zoning procedures presented in this paper is included in the earthquake-induced landslide hazard evaluation reports of Perez (2008), Wiegers and Perez (2008), and Perez and Haydon (2009), which are available on the California Geological Survey's Internet page: *http://www.consrv.ca.gov/cgs/shzp/Pages/Index.aspx*.

Earthquake-Induced Landslide Hazard Zoning Workflow

Areas that are most susceptible to earthquake-induced landslides are steep slopes in poorly cemented or highly fractured rocks, sloped areas underlain by loose, weak soils, and areas on or adjacent to existing landslides or landslide deposits. These geologic and terrain conditions exist in many parts of California, including numerous hillside areas that have already been developed or are likely to be developed in the future. The opportunity for strong earthquake ground shaking is high in many parts of California because of the presence of numerous active faults. The combination of these factors constitutes a significant seismic hazard throughout much of California, including the hilly areas surrounding the Livermore Valley.

The earthquake-induced landslide hazard zone was derived from the landslide hazard potential map according to criteria developed in a CGS pilot study (McCrink and Real, 1996; McCrink, 2001) and subsequently adopted by the State Mining and Geology Board (California Department of Conservation, 2000). The data collected for the zoning were transformed into primary and derived GIS layers using commercially available software. These layers were combined or merged utilizing different algorithms to extract or generate the needed information or features.

The steps involved in generating the landslide hazard potential map are presented in a workflow diagram (fig. 2). At the top of the workflow diagram are four primary GIS layers: Digital Terrain Model (DTM), Bedrock Geology, Geotechnical Data, and PSHA (Probabilistic Seismic Hazard Assessment). Sixteen derived layers are generated or extracted from them and near the bottom of the diagram is the Landslide Hazard Potential map. This map is combined with the Landslide Inventory map to generate the Landslide Hazard Zone of required investigation.

The diagram illustrates the hierarchy and interrelation of the various GIS layers. For instance, slope parameters such as slope gradient and slope aspect are features or layers that can be extracted from the digital terrain model. Similarly, dip gradient and dip aspect layers can be extracted from the geologic structure, which in turn was derived from the bedrock geology. Subsequently, adverse bedding can be derived by combining and analyzing (grid overlaying) the categorized slope and dip parameters. A similar procedure is carried out for the other layers.

Figure 1. Location map of the Livermore Valley Study Area encompassing the 7.5-minute quadrangles of Dublin, Livermore, and Altamont, which were mapped for earthquake-induced landslide hazard zones.

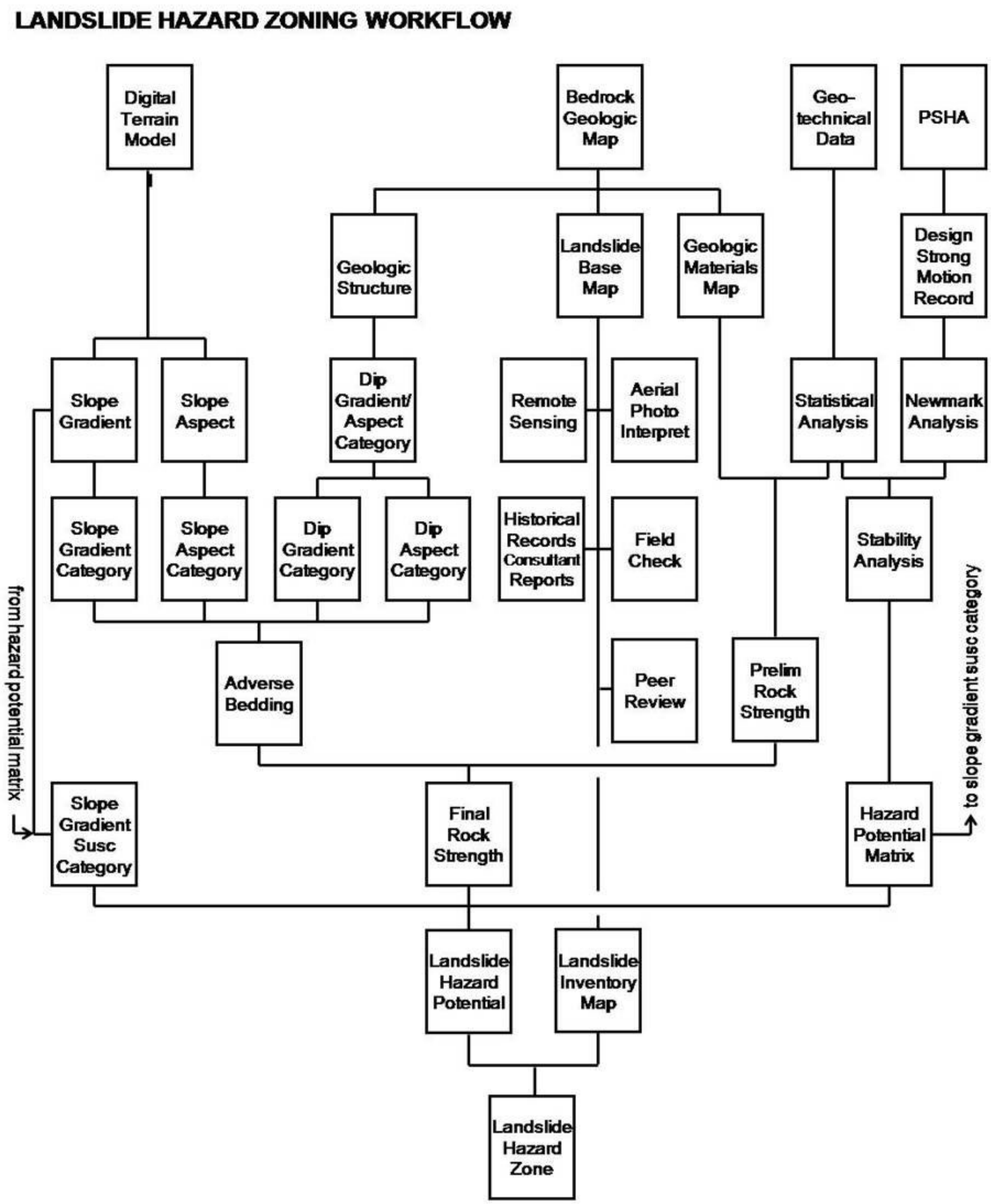

Figure 2. The Earthquake-Induced Landslide Hazard Zoning Workflow Diagram (modified from McCrink, 2001).

GIS Data Layers

The delineation of earthquake-induced landslide hazard zones of the Livermore Valley Study Area is based on the best available terrain, geologic, geotechnical, and seismological data. If unavailable or significantly outdated, new forms of these data were compiled or generated specifically for this area. The following were collected or generated for this zoning:

- Digital terrain data were collected or generated to provide an up-to-date representation of slope gradient and slope aspect in the study area.
- Geologic mapping was compiled to provide an accurate representation of the spatial distribution of geologic materials in the study area. In addition, a map of landslides, whether or not triggered by earthquakes, was prepared.
- Geotechnical laboratory test data were collected and statistically analyzed to quantitatively characterize the strength properties and dynamic slope stability of geologic materials in the study area.
- Seismological data in the form of CGS probabilistic shaking maps and catalogs of strong-motion records were compiled and used to characterize future earthquake shaking within the mapped area.

Terrain Data

The calculation of slope gradient is an essential part of the evaluation of slope stability under earthquake conditions. An accurate slope gradient calculation begins with an up-to-date map representation of the Earth's surface in the form of a digital topographic map. For both Dublin and Livermore quadrangles, DTMs were obtained from Intermap's Interferometric Synthetic Aperture Radar (IfSAR) system. The DTM (fig. 3) of the Dublin quadrangle was derived from the original radar data, available as a Digital Surface Model (DSM). Vegetation, buildings, and other cultural features were digitally removed using the company's proprietary software, TerrainFit (Intermap, 2003). These terrain data, which were acquired in 2003, present elevations at 5-meter postings with 2-meter root-mean-square error (RMSE) horizontal positional accuracy and 1-meter vertical positional accuracy. Furthermore, the DTM was resampled using a bilinear method in order to minimize the presence of false geometric artifacts in the radar data. A slope gradient map was generated from the DTM using a third-order, finite-difference, center-weighted algorithm (Horn, 1981). For the Altamont quadrangle, the DTM was derived from the USGS 10-meter Digital Elevation Model (DEM).

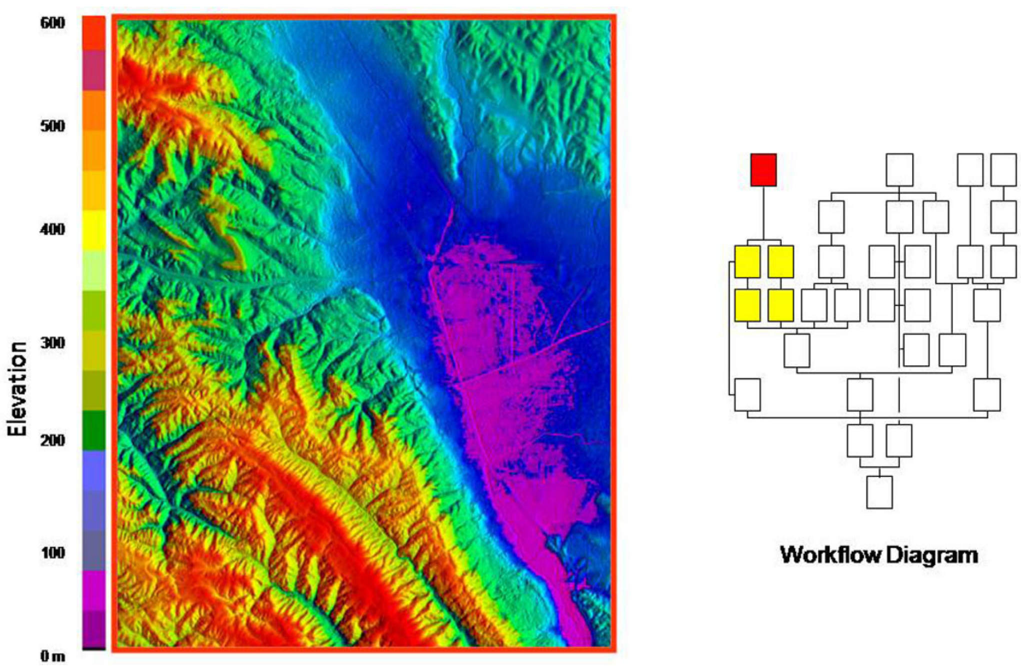

Figure 3. IfSAR DTM colorized hillshade of Dublin quadrangle (red box in the workflow diagram). Derived layers, such as slope gradient and slope aspect (yellow boxes in the diagram) can be extracted from the DTM primary layer.

Geologic Data

The primary sources of bedrock geologic mapping used in the slope stability evaluation of the Livermore Valley Study Area were obtained from U.S. Geological Survey Open-File Report 96-252 (Graymer and others, 1996), the 1:24,000-scale geologic map of the Livermore quadrangle (J.M. Sowers, USGS, unpub. data, 2006), and the geologic map of the Stockton 1:100,000-scale quadrangle (R.W. Graymer, USGS, unpub. data, 2004). Geologic mapping by Dibblee (1980) was also reviewed. The nomenclature of the Quaternary geologic units was based on U.S. Geological Survey Open-File Report 00-444 (Knudsen and others, 2000).

CGS geologists modified the digital geologic map in the following ways: (1) landslide deposits were deleted from the map so that bedrock formations and the newly created landslide inventory would exist on separate layers for the hazard analysis; (2) air-photo interpretation, digital orthophoto quarter-quadrangle review, satellite imagery review, and field reconnaissance were performed to assist in the remapping of contacts between bedrock and surficial geologic units; (3) contacts and distribution of alluvial deposits, as well as active gravel quarries, were modified to conform to 2006 topography as depicted on DigitalGlobe imagery (Google Earth, 2006) and Intermap's Ortho-rectified Radar Imagery (Intermap, 2003); and (4) the relation of the various geologic units to the development and abundance of landslides was noted. Figure 4 is an example of the bedrock geologic map (Graymer and others, 1996) used in the zoning.

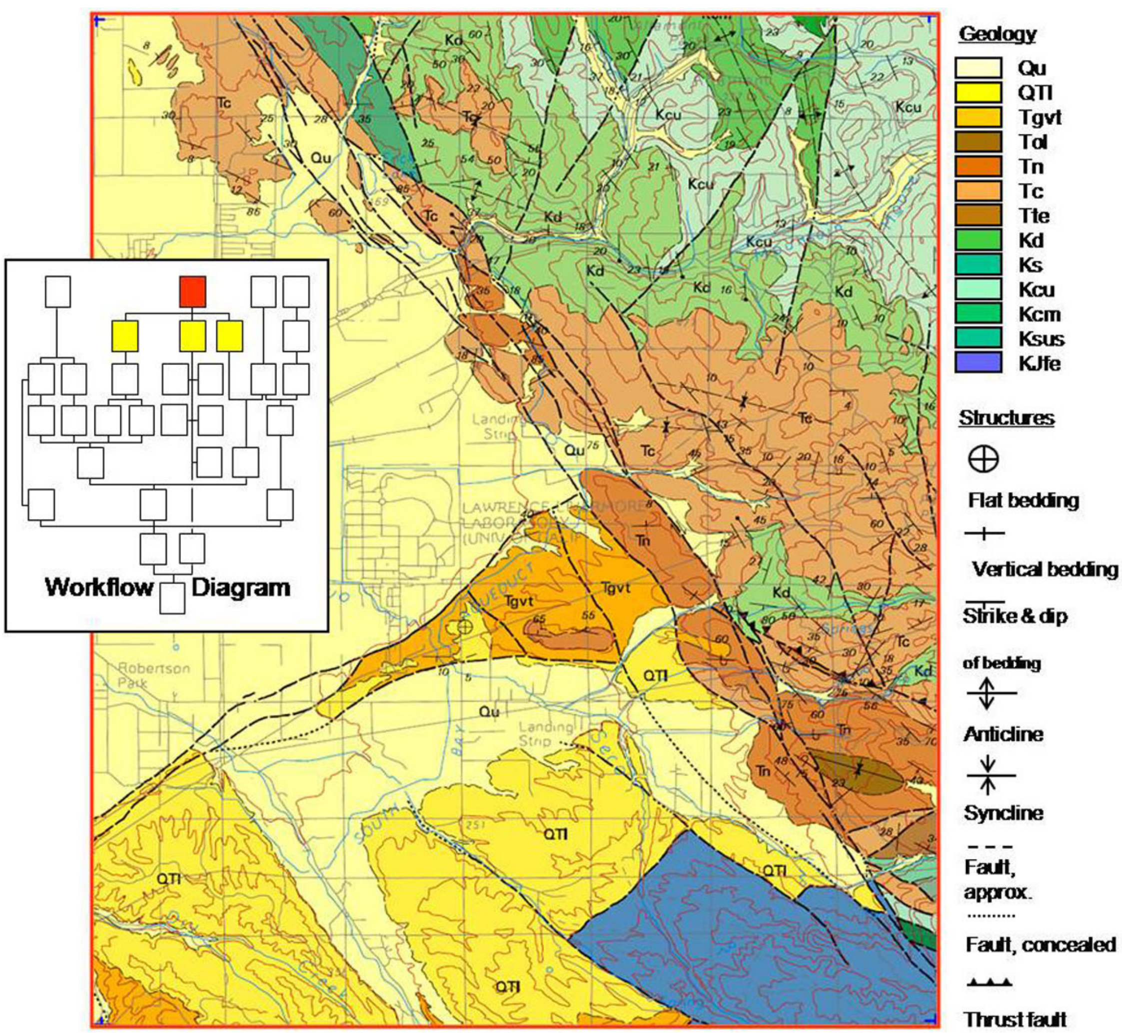

Figure 4. Bedrock geologic map of the Altamont quadrangle (red box in the workflow diagram) (Graymer and others, 1996). Derived layers such as geologic structure, landslide base, and geologic materials (yellow boxes in the diagram) are extracted and modified from this geologic map.

Geotechnical Data

To evaluate the stability of geologic materials under earthquake conditions, the geologic map units are ranked and grouped relative to shear strength. Generally, the primary source for shear-strength measurements is geotechnical reports prepared by consultants, which are on file with local government permitting departments. Shear-strength data for the units identified on the Livermore Valley geologic map were obtained from the cities of Livermore, Pleasanton, and Dublin, from the County of Alameda, and from CalTrans. The locations of rock and soil samples taken for shear testing within the Dublin quadrangle are shown on figure 5.

Shear strength data gathered from the above sources were compiled for each geologic map unit. Geologic units were grouped according to average angle of internal friction (average phi) and lithologic character. For each geologic strength group, the average shear strength value was then assigned to each map unit (table 1) in the Dublin quadrangle, and used in the slope stability analysis. A geologic material-strength map that provides spatial representation of material strength for use in slope stability analysis was developed based on these groupings.

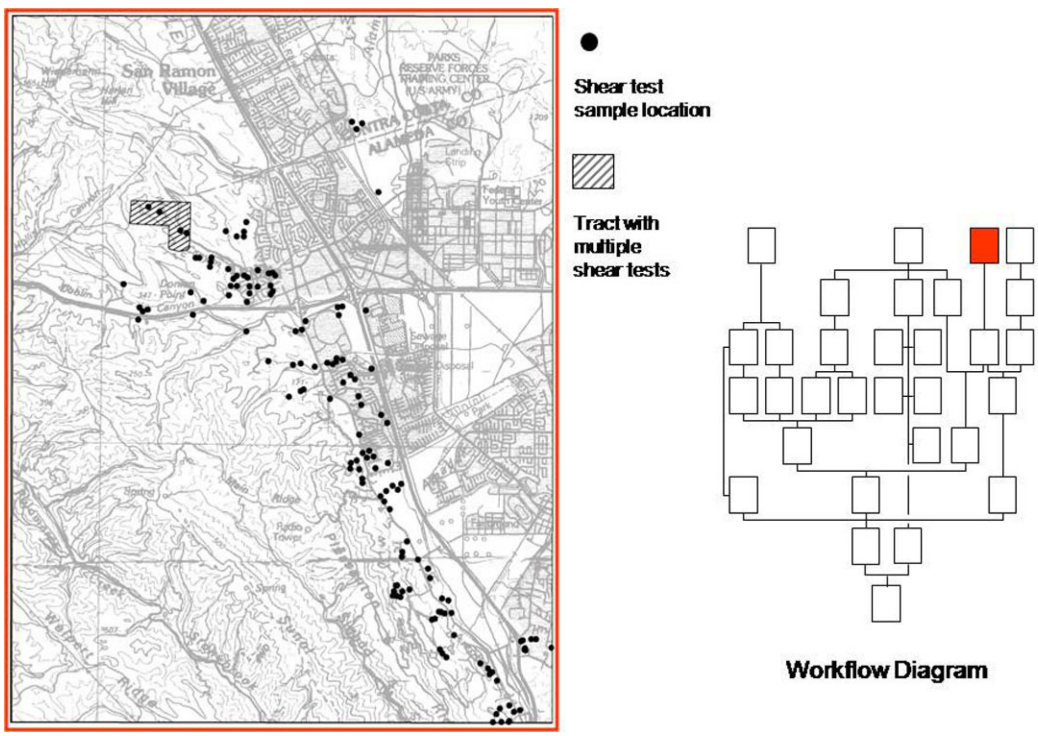

Figure 5. Location map of rock and soil samples where shear testing was undertaken for the Dublin quadrangle. A total of 161 shear tests were collected from the cities of Dublin and Pleasanton and the County of Alameda.

Table 1. Shear strength groups and map units in the Dublin quadrangle.

Group 1	Group 2	Group 3	Group 4	Group 5
Kc(fbc)	Kcv(abc)	KuII(fbc), Kcv(abc)	Kc(abc), Kull(abc)	Qls
Ko(fbc)	Tbr(fbc)	Tro(abc), Tt(abc)	Ko(abc), KsVII(abc)	
KsVII(fbc)	Tcs, Ts	Tn(abc), Tc(abc)	sp, Tbr(abc)	
Tbg(fbc)	Tro(fbc)	To(abc), QTl	Tbg(abc), Tusv	
Tbd	Tc(fbc)	Qpa, Qpf, Qoa2, Qoa1	Qoa, Qf, Qhb, Qhff	
Tbe	Tn(fbc)	Qa, Qha, Qhf, Qhc	Qht, Qhty	
Tbi	To(fbc), Tt(fbc)	Af, ac, alf	Qhly, Qhfy	

Seismological Data

To evaluate earthquake-induced landslide hazard potential in the study area, a method of dynamic slope stability analysis developed by Newmark (1965) was used. As implemented for the delineation of earthquake-induced landslide zones, the Newmark method necessitates the selection of a design earthquake strong-motion record ("design" refers to a representative record) to provide the "ground shaking opportunity." For the Livermore Valley Study Area, selection of a strong motion record was based on an estimation of probabilistic ground motion parameters for modal magnitude, modal distance, and peak ground acceleration (PGA) as depicted in figure 6. The parameters are based on the *2002 California Probabilistic Seismic Hazard Assessment (PSHA) Model* developed jointly by the CGS and USGS (Frankel and others, 2002; Cao and others, 2003) for a 10 percent probability of being exceeded in 50 years.

The strong-motion record selected for the slope stability analysis in the Altamont quadrangle is the Corralitos record from the 1989 magnitude 6.9 Loma Prieta earthquake (Shakal and others, 1989). This record had a source-to-recording site distance of 5.1 kilometers and a peak ground acceleration (PGA) of 0.64. The selected strong-motion record was not scaled or otherwise modified prior to its use in the analysis.

Slope Stability Analysis

A slope stability analysis was performed for each geologic material-strength group at slope increments of 1 degree. An infinite-slope failure model under unsaturated slope conditions was assumed. A factor of safety was calculated first, followed by the calculation of yield acceleration from Newmark's equation: $a_y = (FS-1)\ g \sin \alpha,$ where *FS* is the Factor of Safety, *g* is the acceleration due to gravity, and *α* is the direction of movement of the slide mass, in degrees measured from the horizontal, when displacement is initiated (Newmark, 1965). For an infinite slope failure, that is, failure plane is parallel to the ground surface, *α* is the same as the slope angle.

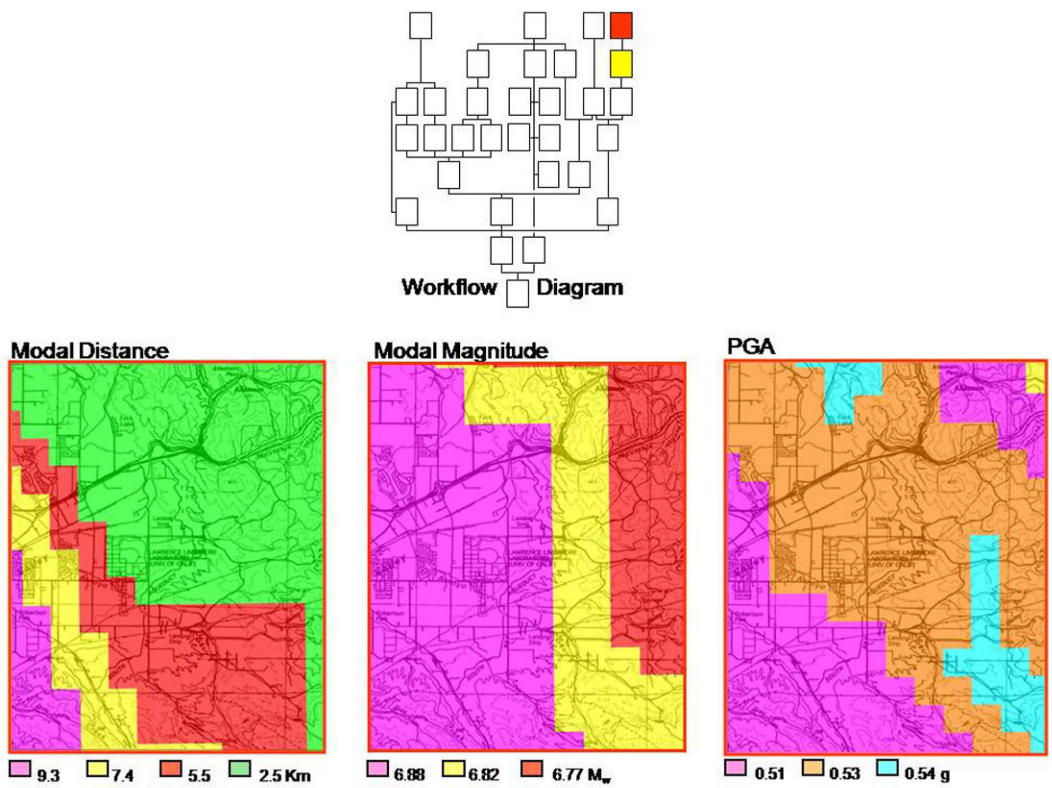

Figure 6. The probabilistic ground motion parameters for modal distance, modal magnitude, and peak ground acceleration (PGA) used in establishing the strong motion record for Altamont quadrangle.

In the examples given in figure 6, the parameters used in the record selection are:

Modal Distance	2.5 to 9.9 km
Modal Magnitude	6.8
PGA	0.49 to 0.54 g

The yield accelerations resulting from Newmark's equations represent the susceptibility to earthquake-induced failure of each geologic material-strength group for a range of slope gradients. Based on the relationship between yield acceleration and Newmark displacement, hazard potentials were assigned as follows:

1. If the calculated yield acceleration was less than 0.086 g, a Newmark displacement greater than 30 centimeters (cm) is indicated, and a HIGH hazard potential was assigned.
2. If the calculated yield acceleration fell between 0.086 g and 0.133 g, a Newmark displacement between 15 cm and 30 cm is indicated, and a MODERATE hazard potential was assigned.
3. If the calculated yield acceleration fell between 0.133 g and 0.234 g, a Newmark displacement between 5 cm and 15 cm is indicated, and a LOW hazard potential was assigned.
4. If the calculated yield acceleration was greater than 0.234 g, a Newmark displacement of less than 5 cm is indicated, and a VERY LOW potential was assigned.

Table 2 summarizes the results of the slope stability analyses. The earthquake-induced landslide hazard potential map (fig. 7) was prepared by combining the geologic material-strength map and the slope map according to this table.

Table 2. Hazard potential matrix for earthquake-induced landslides in Livermore quadrangle.

Geologic Material Strength Group (Average Phi)	HAZARD POTENTIAL SLOPE (Degrees)			
	Very Low	Low	Moderate	High
1 (32)	0 to 20	21 to 25	26 to 27	>28
2 (26)	0 to 15	16 to 18	19 to 20	>21
3 (23)	0 to 10	11 to 15	16 to 18	>19

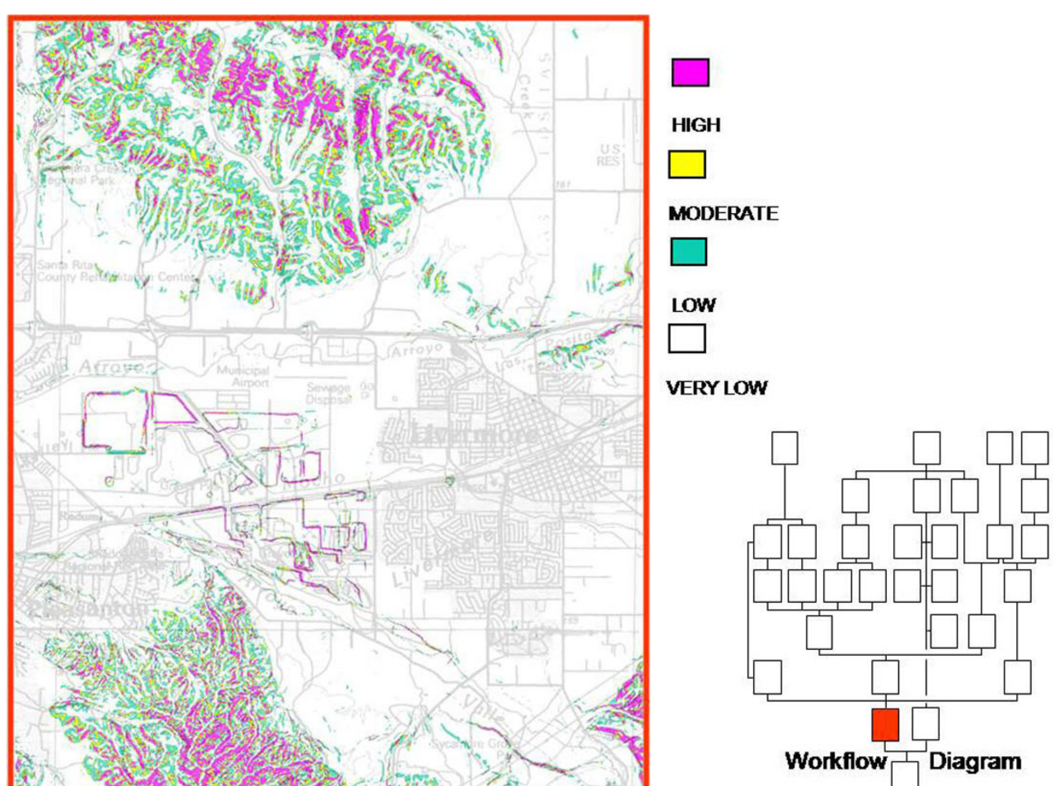

Figure 7. The landslide hazard potential map of Livermore quadrangle showing the different levels of hazard potential (from Very Low to High).

Hazard Potential Analysis

Based on the conclusions of a pilot study performed by CGS (McCrink and Real, 1996; McCrink, 2001), CGS designates earthquake-induced landslide hazard zones that encompass all areas that have a High, Moderate, or Low level of hazard potential (see table 2). This would include all areas where the analyses indicate Newmark earthquake displacements of 5 cm or greater. Areas with a Very Low hazard potential, indicating less than 5 cm displacement, are excluded from the zone.

Using table 2 as an example, all areas characterized by the following geologic strength group and slope gradient conditions are included in the earthquake-induced landslide hazard zone:

1. Geologic Strength Group 3 is included in the zone for all slopes greater than 11 degrees.
2. Geologic Strength Group 2 is included for all slopes greater than 16 degrees.
3. Geologic Strength Group 1 is included for all slopes greater than 21 degrees.

Based on the preceding discussions, table 3 summarizes the different "geologic strength group-slope gradient" combinations (listed by quadrangle) that fall within the earthquake-induced landslide hazard zone.

Zones Of Required Investigation

The landslide hazard potential map (fig. 7) is combined with the landslide inventory map to generate the landslide hazard Zones of Required Investigation (fig. 8). Figure 9 shows an example of the Official Seismic Hazard Zone Map (Livermore Quadrangle). The summary of this paper, presented as a poster at the DMT meeting, is shown in figure 10.

Table 3. Hazard potential matrix and percent of land area per quadrangle that are included in the earthquake-induced landslide hazard zone in Livermore Valley.

Quadrangle	Geologic strength group	Slope (Degrees)	Percent of quadrangle within the hazard zone
Dublin	Gp 4	> 11	33%
	Gp 3	> 19	
	Gp 2	> 21	
	Gp 1	> 24	
Livermore	Gp 3	> 11	19%
	Gp 2	> 16	
	Gp 1	> 21	
Altamont	Gp 3	> 12	22%
	Gp 2	> 17	
	Gp 1	> 22	

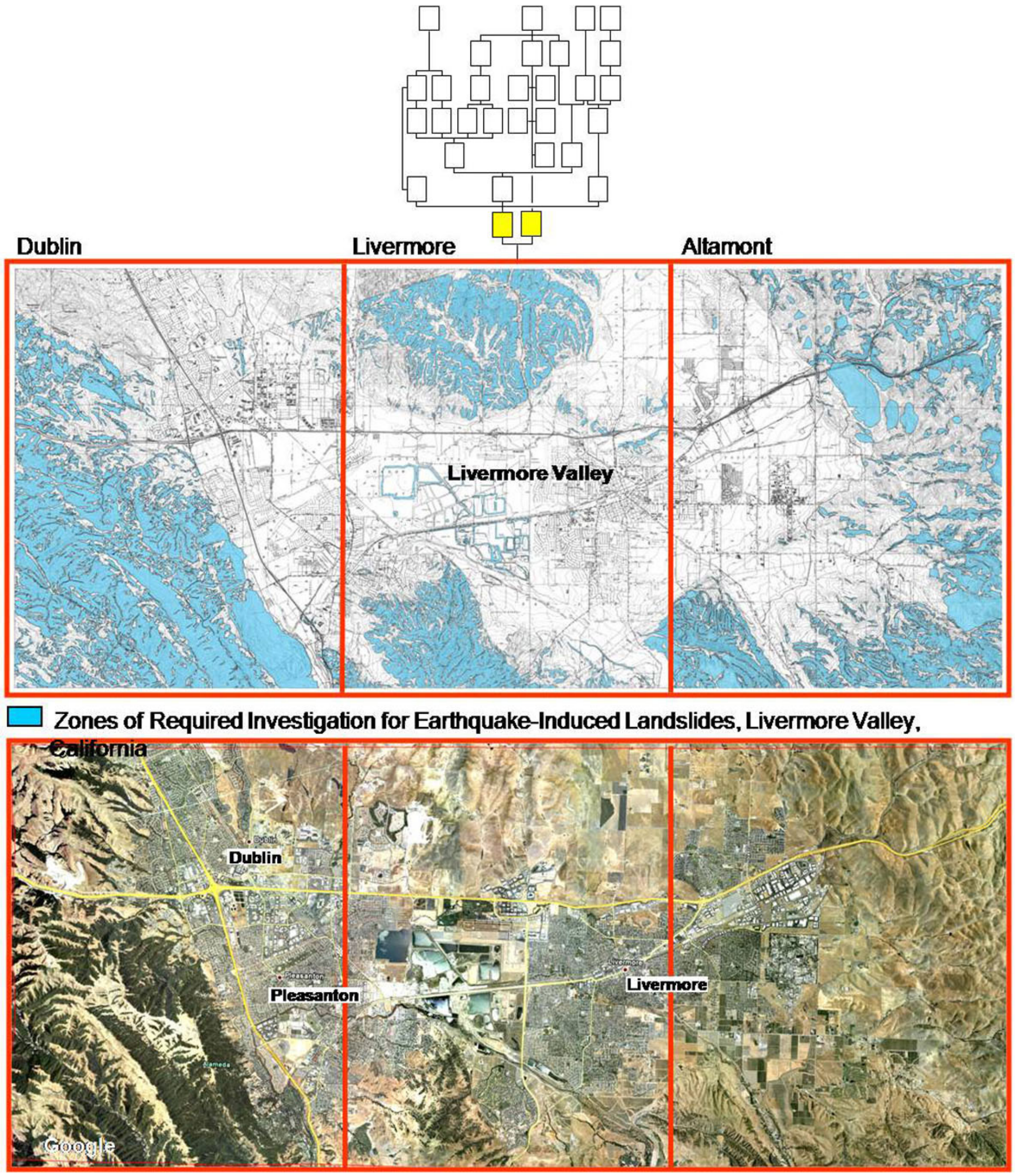

Figure 8. The mountainous and hilly areas surrounding Livermore Valley fall within the zone of earthquake-induced landslide hazard (depicted in blue in the upper image) and represent 32.7 percent of the entire land area of the three quadrangles. The Google image (lower image) shows the relative location of highway corridors (yellow lines) and built-up areas (cities of Dublin, Pleasanton, and Livermore).

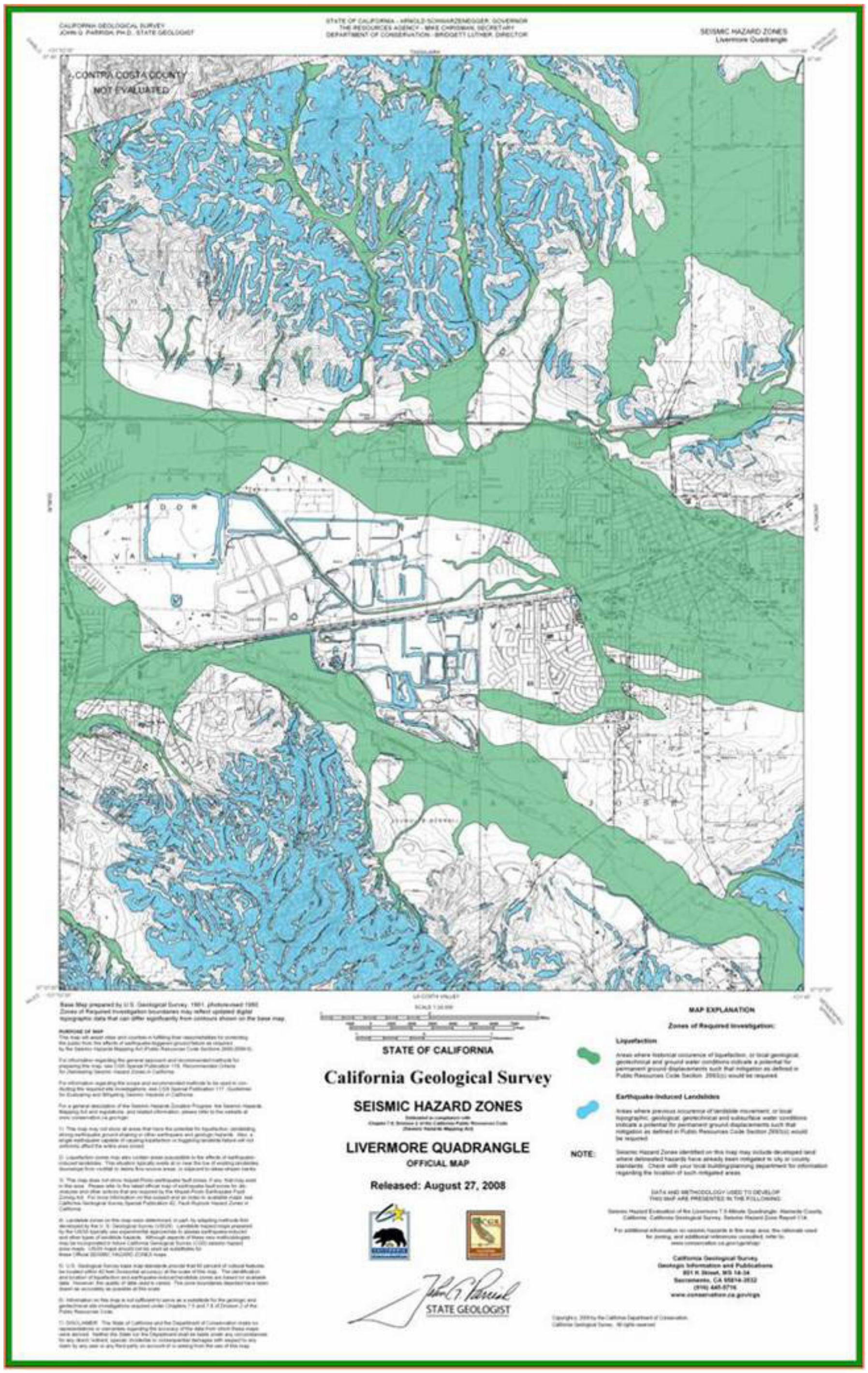

Figure 9. The Seismic Hazard Zone Map of Livermore quadrangle shows both liquefaction (green) and earthquake-induced landslide (blue) Zones of Required Investigation.

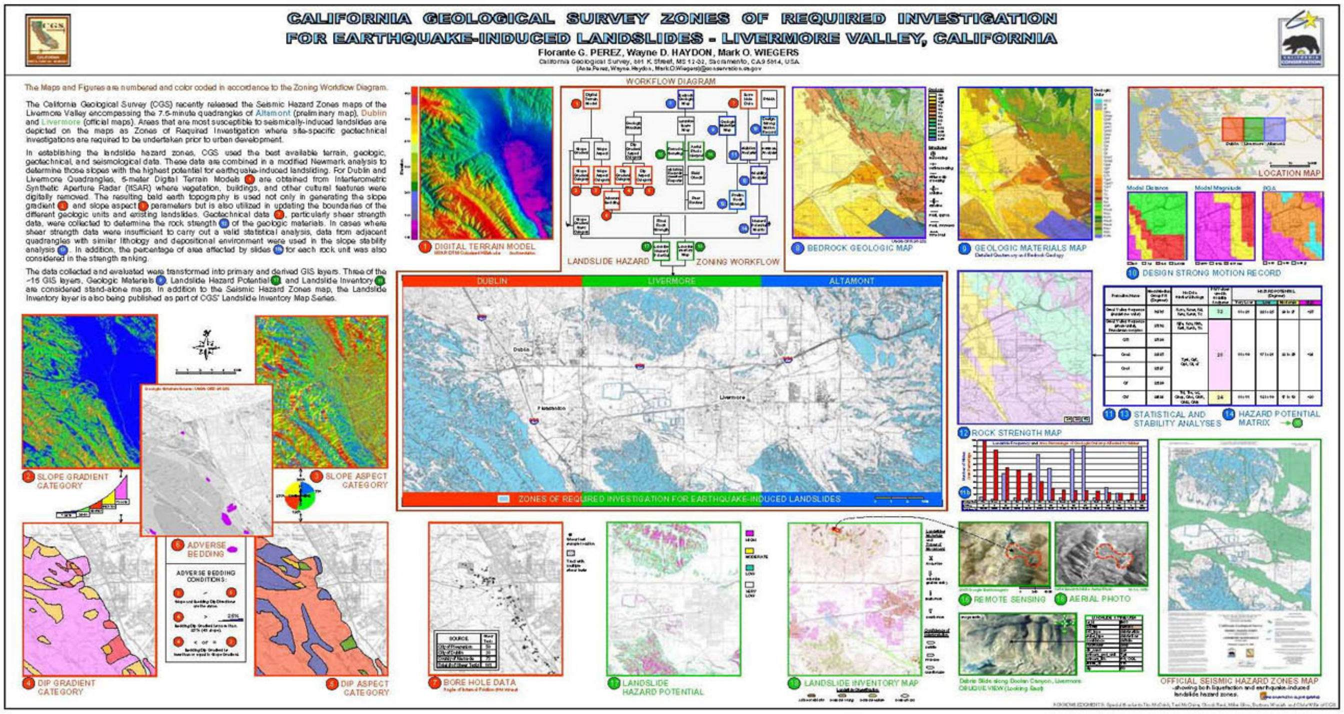

Figure 10. California Geological Survey Zones of Required Investigation for Earthquake-Induced Landslides - Livermore Valley, California (presented as a poster; see full-resolution image at *http://ngmdb.usgs.gov/Info/dmt/docs/1perez10.pdf*).

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California Geological Survey Zones of Required Investigation for Liquefaction – Livermore Valley, California

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Abstract

Official Seismic Hazard Zone Maps of Dublin, Livermore, and Altamont 7.5-minute quadrangles (1:24,000 scale) show areas that may be susceptible to earthquake-induced liquefaction. The maps are the result of the three-dimensional integration of geotechnical and geological data. Approximately 450 geotechnical borehole logs were collected, analyzed, entered into a geotechnical Geographic Information System database, correlated with surficial geologic units, and evaluated for the susceptibility of deposits to liquefaction. In addition, a map showing depth to historically highest groundwater level was prepared. The continuous relocation over the years of temporary water-filled pits associated with gravel mining in central Livermore Valley has caused localized changes to permeability, resulting in variable groundwater conditions.

The boundary for the Zone of Required Investigation (ZORI) is in most places defined by the contact of Holocene deposits with late Pleistocene deposits or with bedrock, and extends along the base of the foothills surrounding the Livermore Valley. Near Hacienda Drive and Central Parkway, sediment mapped as late Pleistocene to Holocene alluvial fan deposits (Qf) is included in the ZORI. Although the age of the unit suggests that the sediment has had sufficient time to consolidate, thus rendering it unlikely to liquefy, subsurface data indicate the deposit includes a greater abundance of silt, and lower penetration resistance, compared to occurrences of Qf mapped in other portions of the western margin of the Livermore Valley. Near the intersection of Hopyard Road and Arroyo Mocho, an area once known as "Willow Swamp" is excluded from the ZORI. Groundwater is within 10 to 20 feet of the ground surface throughout much of this area; however, the area is underlain by Holocene basin sediments (Qhb) locally composed of approximately 32 percent clay. Although soft soil failures are possible in young clay sediments, liquefaction is unlikely.

Introduction

Liquefaction-induced ground failure historically has been a major cause of earthquake damage in northern California. During the 1989 Loma Prieta and 1906 San Francisco earthquakes, significant damage to roads, utility pipelines, buildings, and other structures in the San Francisco Bay area was caused by liquefaction-induced ground displacement.

Localities most susceptible to liquefaction-induced damage are underlain by loose, water-saturated, granular sediment within 50 feet (ft) of the ground surface. These geological and groundwater conditions are widespread in the San Francisco Bay Area, most notably in some densely populated valley regions and alluviated floodplains. In addition, the potential for strong-earthquake ground shaking is high because of the many active faults in the region. The combination of these factors constitutes a significant seismic hazard for areas in the Livermore Valley.

This paper summarizes the methods and sources of information used to prepare the Seismic Hazard Zone Maps prepared in the vicinity of the Livermore Valley, including the Dublin, Livermore, and Altamont 7.5-minute quadrangles in Alameda County, California. For more detailed information regarding topics discussed in this paper, please see the official Evaluation Report for Liquefaction Hazard in these quadrangles (Rosinski, 2008a, b, c). The quadrangles cover a total of approximately 180 square miles in eastern Alameda and Contra Costa Counties at a scale of 1 inch = 2,000 ft and display the boundaries of preliminary *Zones of Required Investigation* for liquefaction. The areas subject to seismic hazard mapping include parts of the cities of Livermore, Pleasanton, and Dublin. A total of approximately 11 square miles in the Livermore and Altamont quadrangles falls within Contra Costa County, and was not included in this study.

About 19 square miles within the Alameda County part of the Livermore quadrangle, 10 square miles of land in the Dublin Quadrangle, and 9 square miles of the Altamont quadrangle are designated as *Zones of Required Investigation* for liquefaction hazard. These zones encompass about two-thirds of the Livermore Valley and most of the stream valleys and canyons that originate in the surrounding hills. Borehole logs of test holes in alluviated areas indicate the widespread presence of near-surface soil layers composed of saturated, loose sandy and silty sediments. Geotechnical tests conducted downhole and in soil labs indicate that these soils generally have a moderate to high likelihood of liquefying, given the levels of strong ground motion expected for this region.

Seismic hazard maps are prepared by the California Geological Survey (CGS) using geographic information system (GIS) technology, which allows the manipulation of three-dimensional data. Information analyzed in these studies includes topography, surface and subsurface geology, borehole log data, recorded groundwater levels, and probabilistic earthquake shaking estimates. Ground shaking inputs are based upon probabilistic seismic hazard maps that depict peak ground acceleration, mode magnitude, and mode distance with a 10 percent probability of exceedance in 50 years.

Methodology

CGS's evaluation of liquefaction hazard and preparation of Seismic Hazard Zone Maps requires the collection, compilation, and analysis of various geotechnical information and map data. The data are processed into a series of GIS layers using commercially available software. The following principal tasks are completed to generate a Seismic Hazard Zone Map for liquefaction hazard:

- Compile digital geologic maps to delineate the spatial distribution of Quaternary sedimentary deposits
- Collect geotechnical borehole log data from public agencies and engineering geologic consultants
- Enter boring log data into the GIS
- Generate digital cross sections to evaluate the vertical and lateral extent of Quaternary deposits and their lithologic and engineering properties
- Evaluate and digitize historically highest groundwater levels in areas containing Quaternary deposits
- Characterize expected earthquake ground motion, also referred to as ground-shaking opportunity
- Perform quantitative analyses of geotechnical and ground motion data to assess the liquefaction potential of Quaternary deposits
- Synthesize, analyze, and interpret above data to create maps delineating *Zones of Required Investigation* according to criteria adopted by the State Mining and Geology Board (SMGB) (California Department of Conservation, 2004).

Geology

Geologic units that generally are susceptible to liquefaction are limited to late Quaternary alluvial sedimentary deposits and artificial fill. To evaluate the areal and vertical distribution of Quaternary deposits in the Dublin, Livermore, and Altamont quadrangles, recently completed geologic maps of the nine-county San Francisco Bay Area showing Quaternary deposits (J.M. Sowers, USGS, unpublished photo-interpretation map, 2006; Knudsen and others, 2000; Witter and others, 2006) and bedrock units (R.W. Graymer, USGS, unpublished digital database of geologic mapping of the Stockton 1:100,000-scale quadrangle, 2004; Wentworth and others, 1999; Graymer and others, 1996) were obtained from the U.S. Geological Survey in digital form. The GIS maps and layers covering the Dublin, Livermore, and Altamont quadrangles were combined, with minor modifications along the bedrock/Quaternary contact to form a single 1:24,000-scale *geologic materials map* for each quadrangle that displays map unit polygons only (no faults, fold axes, or point data). This map can be used later in compilation of a new geologic map of the area. The distribution of Quaternary deposits on these maps was used in combination with other data, discussed below, to evaluate liquefaction susceptibility and to develop the Seismic Hazard Zone Maps (fig. 1).

Air photos were used, and limited field reconnaissance was conducted, to confirm the location of geologic contacts, map recently modified ground surfaces, observe properties of near-surface deposits, and characterize the surface expression of individual geologic units. In addition, digital data, including Intermap Digital Terrain Model (DTM) at 5-meter resolution (2003) and Google Digital Globe Color Imagery at a 1-meter resolution (2006) were used extensively to validate minor modifications to bedrock/Quaternary contacts in the Livermore quadrangle.

Figure 1. Excerpt of the map showing Zones of Required Investigation for Liquefaction of the Dublin 7.5-minute quadrangle in the vicinity of the intersection of Hopyard Road and Arroyo Mocho.

Engineering Geology

Groundwater

Saturated soil conditions are required for liquefaction to occur, and the susceptibility of a soil to liquefaction varies with the depth to groundwater. Saturation reduces the effective normal stress of near-surface sediment, thereby increasing the likelihood of earthquake-induced liquefaction (Youd, 1973). Current and historical groundwater data were compiled by CGS to identify areas presently or potentially characterized by near-surface, saturated soils. For purposes of seismic hazard zonation, “near-surface” means groundwater at a depth less than 40 ft.

During the course of this study, groundwater conditions were investigated for alluvial basins within the Dublin, Livermore, and Altamont quadrangles. The evaluation was based on first-encountered (shallowest), unconfined water noted in geotechnical borehole logs acquired from the cities of Dublin and Livermore, Alameda County, and the California Department of Transportation (CalTrans). Additional data were collected from the State Water Resources Control Board (SWRCB), and the Alameda County Flood Control and Water Conservation District Zone 7 Water Agency (Zone 7 Water Agency). Natural hydrologic processes and human activities can cause groundwater levels to fluctuate over time. Therefore, it is impossible to predict depths to saturated soils when future earthquakes strike. One method of addressing time-variable depth to saturated soils is to establish an anticipated high groundwater level based on historical groundwater data. Thus, in this study a contour map was developed to depict the highest level of groundwater anticipated within a land-use planning interval of 50 years (fig. 2). It is important to note that the contour lines on the map do not generally represent present-day conditions as usually presented on typical groundwater contour maps. Also, large-scale, artificial recharge programs, such as the ones already established in Livermore Valley, could significantly affect future groundwater levels. In such cases, CGS will periodically evaluate groundwater impact relative to liquefaction potential and revise official Seismic Hazard Zone Maps if necessary.

The Zone 7 Water Agency, which is responsible for managing both surface and groundwater supplies in the Livermore Valley basin, has been monitoring groundwater levels for over 30 years. Well data span the period from 1900 through 2005 and show significant fluctuation in overall water depth during that period. It is the practice of the Zone 7 Water Agency to use water levels measured in 1983-1984 as the historical maximum groundwater level for basin management purposes (Jones and Stokes Associates, Inc., 2006).

In this study, the groundwater elevation map prepared by Zone 7 Water Agency was digitized, and, by converting it and

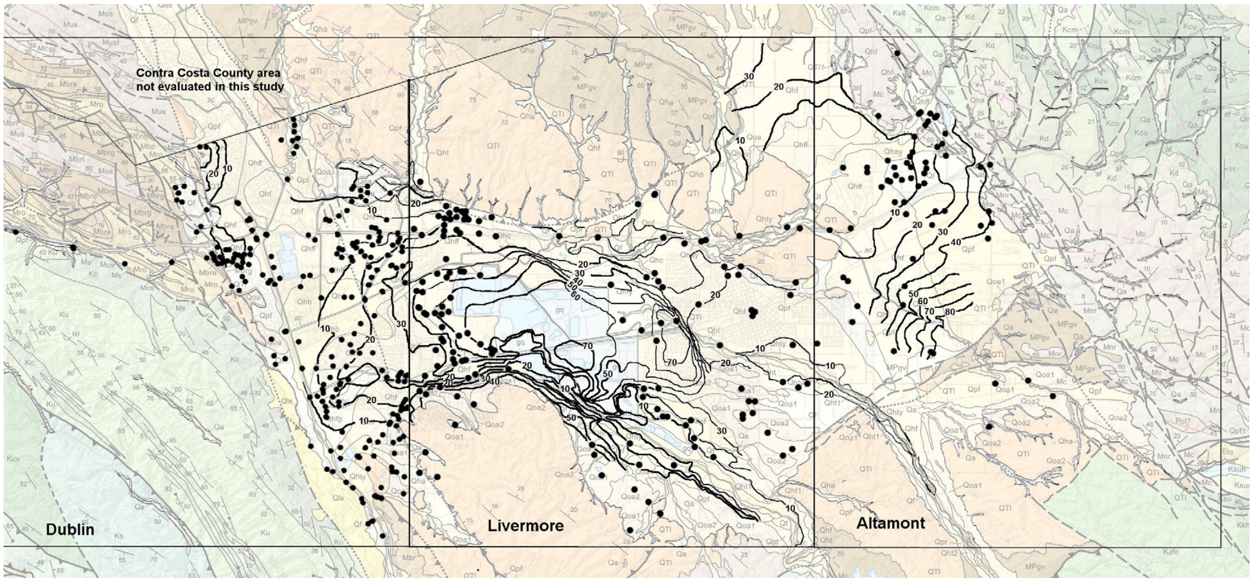

Figure 2. Locations of subsurface data and groundwater depth contours for the Dublin, Livermore, and Altamont quadrangles. Geologic base map from E.E. Brabb and others (USGS, unpub. map data, 2009), which includes revised mapping for Quaternary units in the Livermore Valley from seismic hazards zoning studies described here.

a digital elevation map (DEM) to grid maps, a third grid map showing depth to historically highest groundwater throughout the basin was produced. These values were then compared to the water-depth measurements recorded on geotechnical boring logs collected from the agencies referred to above. For the most part, water depths from individual boring and well logs correlate well with historically highest groundwater elevations shown on the 1983-1984 contour map prepared by the Zone 7 Water Agency.

Depth to groundwater near the center of the Livermore 7.5-minute quadrangle map is strongly influenced by temporary water-filled pits associated with gravel mining activities. The continuous relocation of the pits over the years has resulted in localized changes to permeability that affect the ability of water to seep into and flow through the soil, resulting in groundwater contours that are not reliable and (or) do not reflect conditions found under more natural conditions. For this reason, for zoning purposes the groundwater contour and grid maps have been simplified to reflect an estimate of groundwater conditions prior to the existence of the gravel pits.

As defined by the Zone 7 Water Agency, historically highest groundwater depths in the Livermore Valley range from approximately 0 to 170 ft (fig. 2). Historically highest groundwater levels are generally deepest toward the center of the basin, ranging in depth between 40 and 90 ft and becoming progressively shallower toward the basin's boundaries. Measured depth to groundwater for many of the borings located in the foothills outside of the groundwater basin is greater than 60 ft.

Soil Testing

A total of 442 borehole logs were collected for this investigation from the files of Alameda County, CalTrans, the Division of the State Architect, and the cities of Livermore, Dublin, and Pleasanton (fig. 2). Data from these borehole logs were entered into a CGS geotechnical GIS database.

Lithologic descriptions and soil test results reported in geotechnical borehole logs provide valuable information regarding subsurface geology, groundwater levels, and the engineering characteristics of sedimentary deposits. Of particular value in liquefaction evaluations are logs that report the results of downhole standard penetration tests (SPT) in alluvial materials. The SPT provides a standardized measure of the penetration resistance of soil and, therefore, is commonly used as a tool to index soil density. For this reason, SPT results are also a critical component of the Seed-Idriss Simplified Procedure, a method used by CGS and the geotechnical community to quantitatively analyze liquefaction potential of sandy and silty material.

Of the 442 geotechnical borehole logs analyzed in this study, most include blow-count data from SPTs or penetration tests that allow reasonable blow count conversions to SPT-equivalent values. Few of the borehole logs collected, however, include all of the information (for example, soil density, moisture content, sieve analysis) required for an ideal analysis using the Seed-Idriss Simplified Procedure. For boreholes having acceptable penetration tests, liquefaction analysis is performed using recorded density, moisture, and sieve test values or averaged test values of similar materials.

Liquefaction Hazard Assessment

Mapping Techniques

Liquefaction may occur in water-saturated sediment during moderate to great earthquakes. When this occurs, sediment loses strength and may fail, causing damage to buildings, bridges, and other structures. Many methods for mapping liquefaction hazard have been proposed. Youd (1991) highlights the principal developments and notes some of the widely used criteria. Youd and Perkins (1978) demonstrate the use of geologic criteria as a qualitative characterization of liquefaction susceptibility and introduce the mapping technique of combining a liquefaction susceptibility map and a liquefaction opportunity map to produce a liquefaction potential map. Liquefaction susceptibility is a function of the capacity of sediment to resist liquefaction, whereas liquefaction or ground shaking opportunity is a function of potential seismic ground shaking intensity.

Liquefaction Susceptibility

Liquefaction susceptibility reflects the relative resistance of a soil to loss of strength when subjected to ground shaking. Physical properties of soil such as sediment grain-size distribution, compaction, cementation, saturation, and depth from the surface govern the degree of resistance to liquefaction. Some of these properties can be correlated to a sediment's geologic age and environment of deposition. With increasing age, relative density may increase through cementation of the particles or compaction caused by the weight of the overlying sediment.

Grain-size characteristics of a soil also influence susceptibility to liquefaction. Sand is more susceptible than silt or gravel, although silt of low plasticity is liquefiable. Cohesive soils generally are not considered susceptible to liquefaction. Such soils may be vulnerable to strength loss with remolding and represent a hazard that is not specifically addressed in this investigation.

Soil characteristics that result in higher measured penetration resistances generally indicate lower liquefaction susceptibility. In summary, soils that lack resistance (susceptible soils) typically are saturated, loose, and granular. Soils resistant to liquefaction include all soil types that are dry, cohesive, or sufficiently dense.

CGS's inventory of areas containing soils susceptible to liquefaction begins with evaluation of geologic maps and historical occurrences, cross sections, geotechnical test data, geomorphology, and groundwater hydrology. Soil properties and soil conditions such as type, age, texture, color, and consistency, along with historical depths to groundwater, are used to identify, characterize, and correlate susceptible soils. Because Quaternary geologic mapping is based on observable similarities between soil units, liquefaction susceptibility maps commonly are similar to Quaternary geologic maps, depending on local groundwater levels.

Ground Shaking Opportunity

Ground shaking opportunity is a calculated measure of the intensity and duration of strong ground motion normally expressed in terms of peak horizontal ground acceleration (PGA). Ground motion calculations used by CGS exclusively for regional liquefaction zonation assessments currently are based on the 2002 California Probabilistic Seismic Hazard Assessment (PSHA) Model developed jointly by the CGS and USGS (Frankel and others, 2002; Cao and others, 2003). The model is set to calculate ground motion hazard at a 10 percent in 50 years exceedance level. CGS calculations of probabilistic peak ground acceleration deviate slightly from the model by incorporating additional programming that weights each earthquake's estimated ground shaking contribution by a scaling factor derived as a function of its magnitude. The function is simply the inverse of the liquefaction threshold-scaling factor used in the Seed-Idriss Simplified Procedure, the quantitative analysis method used by CGS to generate Seismic Hazard Zone Maps for liquefaction. The result is a magnitude-weighted pseudo-PGA that CGS refers to as *Liquefaction Opportunity* (LOP). LOP is used to calculate cyclic stress ratio (CSR), the seismic load imposed on a soil column at a particular site. This approach provides an improved estimate of liquefaction hazard in a probabilistic sense, ensuring that large, infrequent, distant earthquakes, as well as smaller, more frequent, nearby events are appropriately accounted for (Real and others, 2000).

Calculated LOP for alluviated areas in the Livermore Valley range from 0.33 to 0.57 g (standard gravity or acceleration due to free fall). These values were obtained by applying the NEHRP corrections (FEMA, 1994; Table 3.1) to the firm-rock LOP values derived from the CGS liquefaction application of the 2002 probabilistic ground motion model. In the Livermore and Altamont quadrangles, the calculations are based on an earthquake moment magnitude ranging from approximately 6.6 to 7.0 with a modal distance of 3 to 15 kilometers (km). In the Dublin quadrangle, the calculations are based on an earthquake moment magnitude of approximately 6.75 with a modal distance of 0 to 14.5 km.

Liquefaction Analysis

CGS performs quantitative analysis of geotechnical data to evaluate liquefaction potential using an in-house computer program based on the Seed-Idriss Simplified Procedure (Seed and Idriss, 1971; Seed and others, 1983; National Research Council, 1985; Seed and others, 1985; Seed and Harder, 1990; Youd and Idriss, 1997; Youd and others, 2001). The procedure first calculates the resistance to liquefaction of each soil layer penetrated at a test-drilling site, expressed in terms of cyclic resistance ratio (CRR). The calculations are based on SPT results, groundwater level, soil density, grain-size analysis, moisture content, soil type, and sample depth. The procedure then estimates the factor of safety relative to liquefaction hazard for each of the soil layers logged at the site by dividing their calculated CRR by the pseudo PGA-derived CSR described in the previous section.

CGS uses a factor of safety (FS) of 1.0 or less, where CSR equals or exceeds CRR, to indicate the presence of potentially liquefiable soil layers. The liquefaction analysis program calculates an FS for each geotechnical sample where blow counts were collected. Typically, multiple samples are collected for each borehole. The program then independently calculates an FS for each non-clay layer that includes at least one penetration test using the minimum normalized blow count [$N_{1(60)}$] value for that layer. The minimum FS value of the layers penetrated by the borehole is used to calculate the liquefaction potential for each borehole location. The reliability of FS values varies according to the quality of the geotechnical data. In addition to FS, consideration is given to the proximity to stream channels, which accounts in a general way for factors such as sloping ground or free face that contribute to severity of liquefaction-related ground deformation.

Liquefaction Zonation Criteria

Areas underlain by materials susceptible to liquefaction during an earthquake are included in liquefaction zones using criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the SMGB (California Department of Conservation, 2004). Under those guideline criteria, liquefaction zones are areas meeting one or more of the following: (1) areas known to have experienced liquefaction during historical earthquakes; (2) all areas of uncompacted artificial fill that are saturated, nearly saturated, or may be expected to become saturated; (3) areas where sufficient existing geotechnical data and analyses indicate that the soils are potentially liquefiable; and (4) areas where existing subsurface data are not sufficient for quantitative evaluation of liquefaction hazard.

Within areas where sufficient subsurface data are not available, zones may be delineated by geologic criteria, primarily deposits likely to contain loose, granular materials that are saturated because of near-surface groundwater. Those conditions, along with the strong ground motions expected to occur in the region, combine to form a sufficient basis for designating areas underlain by these types of deposits *Zones of Required Investigation* for liquefaction. The criteria are considered as follows: (1) areas containing soil deposits of late Holocene age (current river channels and their historical floodplains, marshes and estuaries), where the M7.5-weighted peak acceleration that has a 10-percent probability of being exceeded in 50 years is greater than or equal to 0.10 g and the anticipated depth to saturated soil is less than 40 ft; (2) areas containing soil deposits of Holocene age (less than 11,000 years), where the M7.5-weighted peak acceleration that has a 10-percent probability of being exceeded in 50 years is greater than or equal to 0.20 g and the anticipated depth to saturated soil is less than 30 ft; or (3) areas containing soil deposits of latest Pleistocene age (11,000 to 15,000 years), where the M7.5-weighted peak acceleration that has a 10-percent probability of being exceeded in 50 years is greater than or equal to 0.30 g and the anticipated depth to saturated soil is less than 20 ft.

Results: Delineation Of Liquefaction Hazard Zones

Upon completion of a liquefaction hazard evaluation for a project quadrangle, CGS applies the above criteria to its findings in order to delineate *Zones of Required Investigation*. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Maps for the Dublin, Livermore, and Altamont 7.5-minute quadrangles.

Areas of Past Liquefaction

There is no known documentation of historical surface liquefaction or paleoseismic liquefaction in the Livermore or Altamont quadrangles. In the Dublin quadrangle, Lawson and others (1908) reported one instance of historical liquefaction in association with the 1906 earthquake. The incident recorded occurred near the northeast corner of the intersection of Santa Rita Road and State Highway 580, along the east bank of Tassajara Creek. Lawson and others (1908) reported "…several somewhat crescentic cracks along which the ground had slipt down and toward the creek from 1 to 3 inches. These cracks extended farther south, according to local settlers, and crost the road" (Lawson and others (1908) cataloged and mapped by Youd and Hoose (1978) and Knudsen and others (2000)).

Areas with Sufficient Existing Geotechnical Data

Most of the subsurface data evaluated for this study represent boreholes drilled into the sediments at the surface of Livermore Valley. Collectively, the logs provide the level of subsurface information needed to conduct a regional assessment of liquefaction susceptibility with a reasonable level of certainty. Analysis of blow count values and other soil property measurements reported in the logs indicates that most of the boreholes penetrated one or more layers of liquefiable material whose CSR is greater than the soil's CRR. Accordingly, all areas covered by Holocene alluvium that is saturated within 40 ft of the surface are designated *Zones of Required Investigation*.

The majority of boundaries for the *Zones of Required Investigation* are defined by the contact between Holocene and late Pleistocene deposits and (or) bedrock, and extend along the base of the foothills that surround Livermore Valley. Although the groundwater conditions in the center of the

Livermore Valley have been complicated by gravel mining operations, groundwater elevations increase by tens of feet toward the center of the valley. Analysis of blow count values and other soil property measurements reported in the logs of borings drilled inside the zone boundary indicate that most of the boreholes penetrated one or more layers of liquefiable material having a CSR greater than the soil's CRR.

Along the northern margin of the valley within the Dublin quadrangle, in the vicinity of the intersection of Hacienda Drive and Central Parkway, sediment mapped as late Pleistocene to Holocene alluvial fan deposits (Qf) is included in the *Zones of Required Investigation*. Although the age of the unit suggests that the sediment has had sufficient time to consolidate, thus rendering it unlikely to liquefy, subsurface data indicate that the deposit in question includes a greater abundance of silt and lower penetration resistance compared to occurrences of Qf mapped in other portions of the Dublin quadrangle; it therefore is included in the *Zones of Required Investigation*.

Further, an area in the Dublin quadrangle near the intersection of Hopyard Road and Arroyo Mocho, which was once occupied by what was known as "Willow Swamp," is excluded from the *Zones of Required Investigation*. Although groundwater is within 10 to 20 ft of the ground surface throughout much of this area, it is underlain by Holocene basin sediments (Qhb) locally made up of approximately 32 percent clay. According to the geologic model of the Livermore basin developed by the California Department of Water Resources (DWR) in the early 1970's (California Department of Water Resources, 2003; 2007), "Up to 60 feet of clay was deposited in this lake [swamp] that now forms a clay cap referred to as the upper aquiclude." CGS analysis of borehole data in the vicinity of the lake shows that the shallowest liquefiable layers are overlain by a minimum of 35 ft of sediment and are less than approximately 5 ft thick. Therefore, even if these sediments were to liquefy, they likely would not produce surface deformation. An exception is a small Holocene basin deposit (Qhb) near the intersection of State Highway 680 and the Western Pacific Rail line, in the southeastern corner of the Dublin quadrangle. This area is included in the *Zones of Required Investigation* because the underlying sedimentary deposits contain a significantly smaller percentage of clay than Holocene basin deposits (Qhb) elsewhere in the Dublin quadrangle.

Areas with Insufficient Existing Geotechnical Data

Adequate geotechnical borehole information is lacking for most parts of canyons in the hilly to mountainous terrain surrounding Livermore Valley. Along with other isolated deposits of Holocene and undifferentiated Holocene alluvium (Qha), Holocene alluvial fan (Qhf) in upland areas, as well as the narrow bands of Holocene deposits in the Livermore quadrangle associated with active stream channels, are likely to be young, loose, granular, and saturated. Those conditions, along with the strong ground motions expected for the region, combine to form a sufficient basis for designating areas underlain by these types of deposits as *Zones of Required Investigation* for liquefaction.

Engineering Geology Characteristics of Livermore Valley Sediments

The Livermore Valley is divided among three quadrangle maps, but because it represents one geologic region, the liquefaction potential of soils in the Dublin, Livermore, and Altamont quadrangles was analyzed in one basin-wide investigation. Tables 1 and 2 summarize the frequency of soil sampling and the number of layers with a minimum $N_{1(60)}$ value less than 15 basin-wide for all textures and for liquefiable textures only, respectively. This range of $N_{1(60)}$ values represents an important input parameter for empirical models for predicting lateral spread displacements, a variety of liquefaction-induced ground failure. Soil sampling data from more than 440 boring logs collected for this investigation show that Holocene sediment in the Livermore Valley is composed primarily of clays and silts with interbedded layers of loose sands and gravels. Locally however, the general composition of the same geologic units mapped within each quadrangle may differ from average basin-wide composition for the same unit. For example, of the samples collected in the Livermore quadrangle for modern stream channel (Qhc), Holocene alluvial fan (Qhf), Holocene stream terrace (Qht), and late Pleistocene alluvial, undifferentiated (Qpf) deposits, they appear to be somewhat less clay rich than the basin-wide average. On the other hand, of the samples collected for latest Holocene alluvial fan (Qhfy), Holocene alluvial fan (Qhf), Holocene stream terrace (Qht), and late Pleistocene to Holocene alluvial fan (Qf) deposits, they appear to be somewhat more silt rich than the basin-wide average. It should be noted that the apparent change in the relative abundance of the various lithologic materials might simply reflect an increase or decrease in the frequency that the material was sampled, rather than a change in the actual abundance of the material.

Table 1. Summary of borehole data for all textures of sediments in the Livermore Valley.

Stratigraphic Age of Layer	Thickness (feet)		Thickness of Saturated Layers (feet)		Number of Layers		Number of Layers with a Penetration Test		Number of Layers with a Minimum $N_{1(60)} < 15$	
All	13457	100.0%	6570	48.8%	2170	100%	1551	100.0%	690	44.5%
Historical	1199	8.9%	272	2.0%	233	10.7%	141	9.1%	56	3.6%
Latest Holocene	752	5.6%	351	2.6%	132	6.2%	94	6.1%	69	4.4%
Holocene	6572	48.8%	3553	26.4%	965	44.4%	706	45.5%	422	27.2%
Latest Pleistocene to Holocene	2514	18.7%	1363	10.1%	489	22.5%	362	23.3%	113	7.3%
Latest Pleistocene	1159	8.6%	607	4.5%	169	7.9%	119	7.7%	20	1.3%
Early to Late Pleistocene	578	4.3%	64	0.5%	100	4.7%	65	4.2%	8	0.5%
Pre-Quaternary	683	5.1%	359	2.7%	82	3.8%	64	4.1%	2	0.1%

Table 2. Summary of borehole data for liquefiable textures only for sediments in the Livermore Valley.

	LIQUEFIABLE TEXTURES ONLY									
Stratigraphic Age of Layer	Thickness of Liquefiable Textures (feet)		Thickness of Saturated Liquefiable Textures (feet)		Number of Layers with Liquefiable Textures		Number of Layers with a Penetration Test		Number of Layers with a Minimum $N_{1(60)} < 15$	
All	6824	50.7%	2922	21.7%	1230	56.4%	853	55.0%	364	23.5%
Historical	1049	7.8%	192	1.4%	200	9.2%	129	8.3%	52	3.4%
Latest Holocene	432	3.2%	160	1.2%	81	3.7%	58	3.7%	48	3.1%
Holocene	2735	20.3%	1272	9.5%	469	21.5%	326	21.0%	192	12.4%
Latest Pleistocene to Holocene	1173	8.7%	651	4.8%	268	12.3%	197	12.7%	56	3.6%
Latest Pleistocene	693	5.2%	404	3.0%	103	4.7%	69	4.4%	9	0.6%
Early to Late Pleistocene	338	2.5%	27	0.2%	62	2.8%	38	2.5%	5	0.3%
Pre-Quaternary	405	3.0%	216	1.6%	47	2.2%	36	2.3%	2	0.1%

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Using Digital Geologic Maps to Assess Alluvial-Fan Flood Hazards

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Introduction

The factors that make alluvial fans desirable for development—relatively planar slopes, good surface drainage characteristics, and excellent views—are the result of natural processes such as floods and debris flows, which can negatively affect lives and property. Currently, alluvial-fan floodplains are mapped by the Federal Emergency Management Agency (FEMA), in coordination with local flood control agencies where communities participate in the National Flood Insurance Program (NFIP). However, FEMA mapping is rarely conducted in undeveloped areas, and therefore, alluvial-fan flood-hazard information is often unavailable for long-term planning.

The California Geological Survey (CGS) served as a technical consultant to the Alluvial Fan Task Force (AFTF), an interagency, multidisciplinary effort that provided planning and flood control departments with guidelines for minimizing loss of life and property while also preserving beneficial resources on alluvial fans. As part of this effort, CGS proposed an approach for land-use planners that may be used to establish a preliminary site assessment in the absence of FEMA flood hazard data. The approach includes integrating digital Quaternary geologic map data with first-order alluvial-fan flood-hazard assessments, resulting in derivative maps showing (1) areas underlain by Quaternary sediments that may include alluvial fans and (2) the relative magnitude of alluvial-fan flooding hazards. The flood hazard map is supported by a proposed methodology for determining the relative hazard. These two map products are designed to assist landowners, developers, regulators, and the public in identifying those areas where quantitative studies are likely to document an alluvial-fan flood hazard. By characterizing potentially hazardous areas, the maps are intended to promote best practices in land use and floodplain management.

Background

Alluvial-Fan Flooding

Alluvial fans form where streams emerge from mountain fronts onto relatively flat valley bottoms. Within a mountain range, particularly in areas experiencing tectonic uplift, a stream is often steeply inclined and confined to a single channel by narrow canyon walls. Once a stream reaches the mountain front, its gradient typically flattens and waters may spread into a distributary network of channels below the apex of the fan, both of which reduce the depth and velocity of stream waters and reduce size and volume of sediment that the stream is capable of carrying. It is this change in gradient and confinement that result in conditions where sediment builds up into the characteristic fan-shaped pattern of an alluvial fan. During a major flood, water can entrain sediment as a hyperconcentrated flood (debris flood; Pierson and Costa, 1987), where roughly 20 to 60 percent of the volume is sediment and debris. Flood waters may also evolve into a debris flow, where over 60 percent of the flow volume is sediment and debris. The interplay between these processes is exacerbated by channel instability, where banks between adjacent channels (interfluves) are relatively low and are susceptible to failure by (1) the rise in the channel base from sediment deposition from hyperconcentrated floods and debris flows (aggradation) and (2) by overland flow on adjacent surfaces that create small side channels heading into these unstable areas (Field, 2001). These processes lead to avulsion—the sudden cutting off of an existing channel, and the formation of new channel that diverts part or all of the flow. On relatively lower gradient fans, such as those in Arizona that have been used to characterize avulsive processes (Field, 2001), a relatively longer time may be required for these processes to occur than for higher gradient and geomorphically active fans common in southern

California that are dominated by debris flow processes (NRC, 1996; Pelletier and others, 2005). This is because on a debris fan, a single debris flow deposit may block a shallowly incised channel after one rainfall event, so that in subsequent events flow is immediately diverted to a new channel. In contrast, multiple events may be required to sufficiently raise a channel base on a water-flood dominated fan or to cause side channel incision into a main channel such that avulsions occur in the next rainfall event.

After numerous flooding events on alluvial fans resulting in repetitive losses to life and property, FEMA sought to better define the hazard as "…flooding occurring on the surface of an alluvial fan or similar landform which originates at the apex and is characterized by high-velocity flows; active processes of erosion, sediment transport, and deposition; and, unpredictable flow paths" (FEMA, 2003). FEMA has formally recognized that modeling this type of flooding is significantly different than riverine-type flooding and requires a cooperative effort between geologists and engineers.

Types of Alluvial Fans

The type of alluvial fan and mode of deposition, whether it is built up from hyperconcentrated flows, debris flows, or both, will differ with geologic setting. Factors that influence the mode of deposition are rainfall frequency/intensity, tectonic activity, upland watershed relief, channel slope, vegetation, and lithology and structure (erodibility) of bedrock in the upland watershed that is the source of sediment. For assessment purposes, alluvial fans are subdivided into three types based on their principal style of flooding and sedimentation: streamflow fans (fig. 1), debris flow fans (fig. 1), and composite fans (Bull, 1977; and NRC, 1996). These are discussed below.

Streamflow fans – Alluvial fans that were built up through successive water floods with sediment by volume concentrations that may reach into hyperconcentrated thresholds. Slopes on streamflow fans are generally less than 3-4 degrees, which is considered to be the threshold between streamflow fan deposition and debris flow deposition (Jackson and others, 1987). Stream channels on streamflow fans have large width-to-depth ratios and are typically braided. Erosion and deposition can alter channel flow during a single flood event (NRC, 1996) where deposition occurs as bars along the margins or center of the channel.

Debris flow fans – Alluvial fans that were built up through successive hyperconcentrated, transitional, and debris flow events (Keaton and Lowe, 1998; Staley and others, 2006). Slopes on debris flow fans may be as steep as 6 to 8 degrees (or greater) and may have terminal lobes, marginal levees, and trapezoidal or U-shaped channels with relatively low width-to-depth ratios. Deposition is episodic, and rapid aggradation or plugging may occur in much deeper channels than is the case for streamflow fans. Even channels that appear to be stable during flood events may be subject to avulsion during or after debris flow, and this contributes to the uncertainty in down-fan flow direction typical for alluvial fans.

Composite fans – Alluvial fans that were built up through water floods, hyperconcentrated flows, transitional flows, and debris flows and contain features found on both stream debris flow fans and debris flow fans. Slopes on composite fans typically range from 4 to 8 degrees (Jackson and others, 1987). In general, the proximal portions of the fan consist of coarse debris flow deposits that are interlayered with hyperconcentrated flow deposits. Stratified finer grained flood deposits are distributed randomly but with higher concentrations at the distal portions of the fan. Proximal areas typically contain rough surfaces as are apparent on aerial photographs and detailed topographic maps (Giraud, 2005).

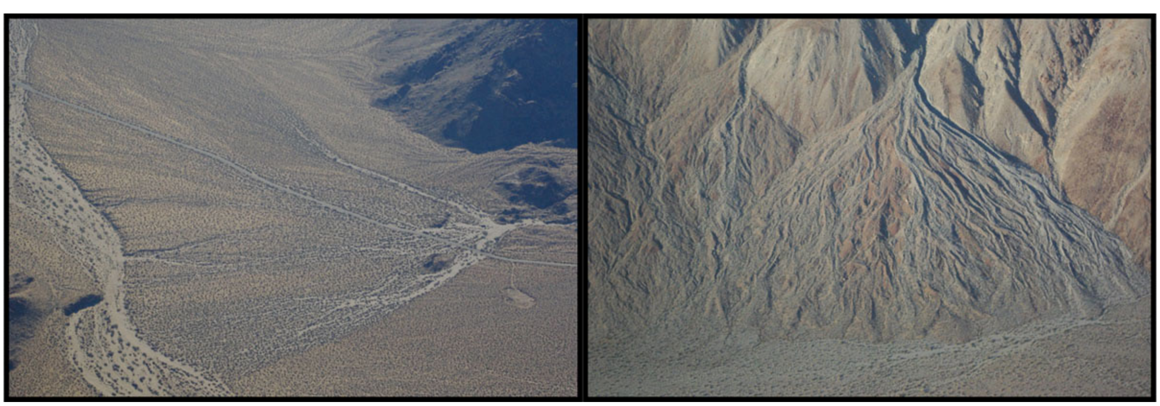

Figure 1. Left side shows a streamflow fan in Riverside County, California. Right side shows a debris flow fan in San Diego County, California.

AFTF Derivative Digital Geologic Map Products

Alluvial Fan Footprint Advisory Map: An Alluvial Fan Screening Tool

For the benefit of the land-use planner, maps that indicate areas underlain by alluvial-fan sediments (fig. 2) provide information about the potential for a proposed development to be located where alluvial-fan flooding may occur, indicating a need for additional studies. These advisory maps of Quaternary alluvial-fan deposits are based on digital surficial geologic maps by the CGS and the U.S. Geological Survey (USGS) and are being compiled at 1:100,000 scale (100k) for the 10-county southern California AFTF region (Kern, Los Angeles, San Diego, Santa Barbara, San Luis Obispo, San Bernardino, Riverside, Imperial, Orange, and Ventura).

Derivation of Alluvial-Fan Footprint based on Existing Digital Data

Areas underlain by Quaternary alluvial fans that may be subject to alluvial-fan flooding are produced by using a Geographic Information System (GIS) to select bedrock/Quaternary alluvial-fan contacts and Quaternary alluvial-fan/undifferentiated Quaternary sediment contacts, and then combining the Quaternary alluvial-fan units into a single alluvial-fan unit (the “footprint”). Bedrock units are combined into a single non-alluvial-fan-bedrock map unit. The axial valley deposits, including (among others) peralic, eolian, and stable channel fluvial deposits, are likewise combined to form a map unit depicting undifferentiated Quaternary sediments (figs. 3A-D). The primary concern is to show the alluvial-fan footprint at 100k, as part of the AFTF Integrated Approach planning manual (Longville, 2010).

Digital Mapping of Alluvial-Fan Footprint

Where digital information is not available for an individual 100k quadrangle, manual “heads-up” digitization at a screen scale of approximately 1:24,000 is necessary to complete the advisory map. The areas are mapped by observing alluvial-fan geomorphic features and following National Research Council (NRC) and FEMA guidelines for identifying the presence of alluvial fans; these are:

Composition – Is the area underlain by Quaternary alluvium?

Morphology – Is the geomorphic expression of the landform fan-shaped on topographic maps or DEM?

Location – Is the landform located adjacent to a topographic break?

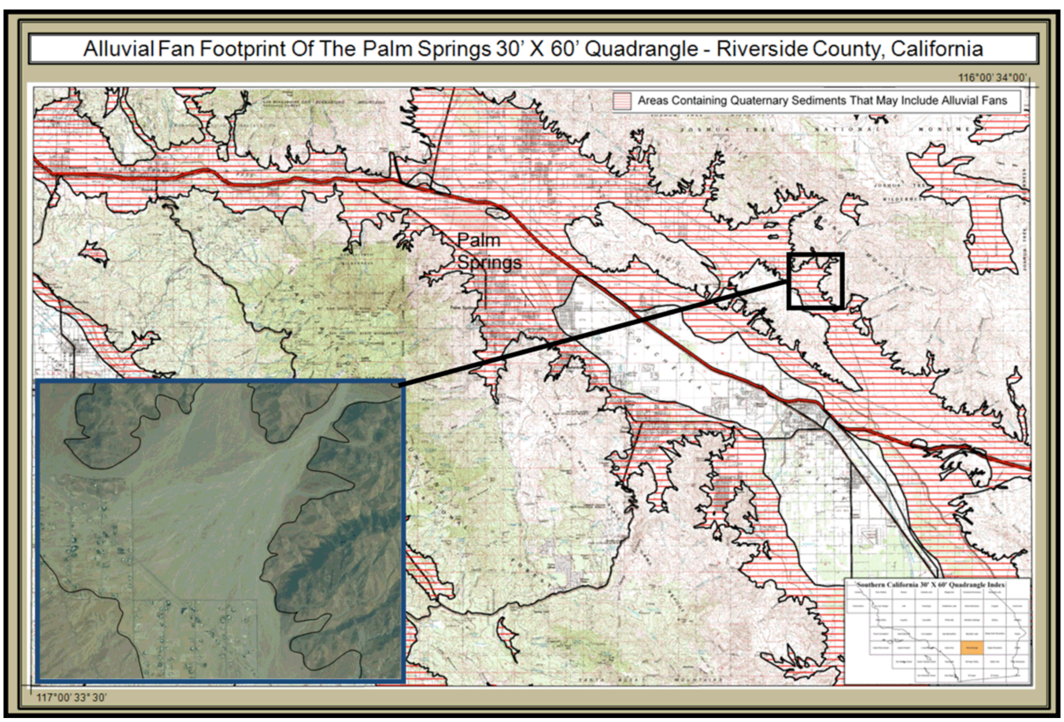

Figure 2. Alluvial fan footprint advisory map of a portion of the Palm Springs 1:100,000-scale quadrangle. Inset figure shows digitized extent of Quaternary alluvial-fan deposits drawn on 2005 National Agriculture Imagery Program (NAIP) imagery.

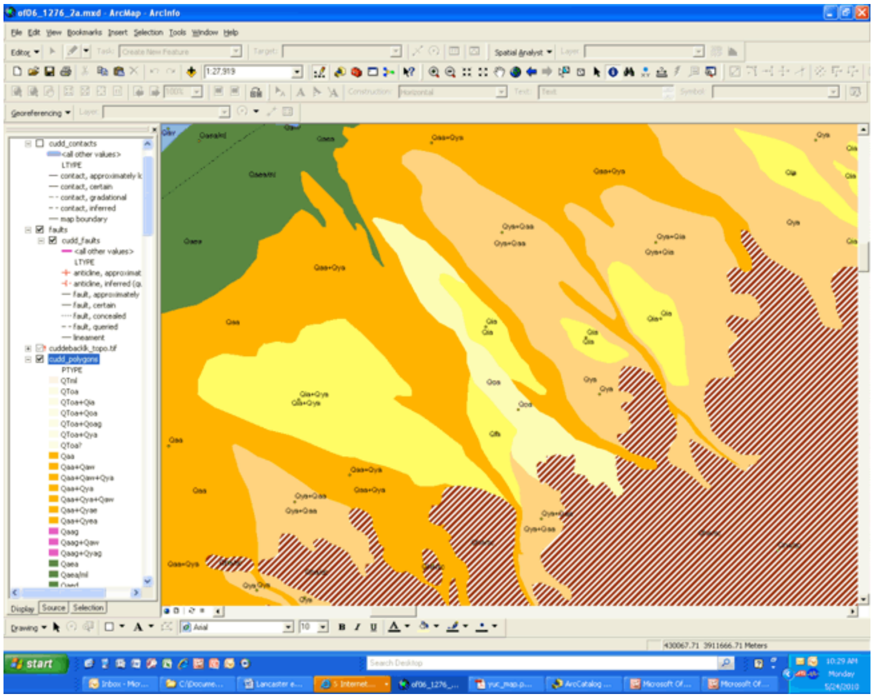

Figure 3A. Digital representation of the Surficial Geologic Map of the Cuddeback Lake 1:100,000-scale quadrangle (data taken from Amaroso and Miller, 2006). Green and blue colors represent Quaternary eolian and axial valley deposits; orange, yellow, and tan colors represent Quaternary alluvial-fan deposits; red hachured unit represents metamorphic bedrock.

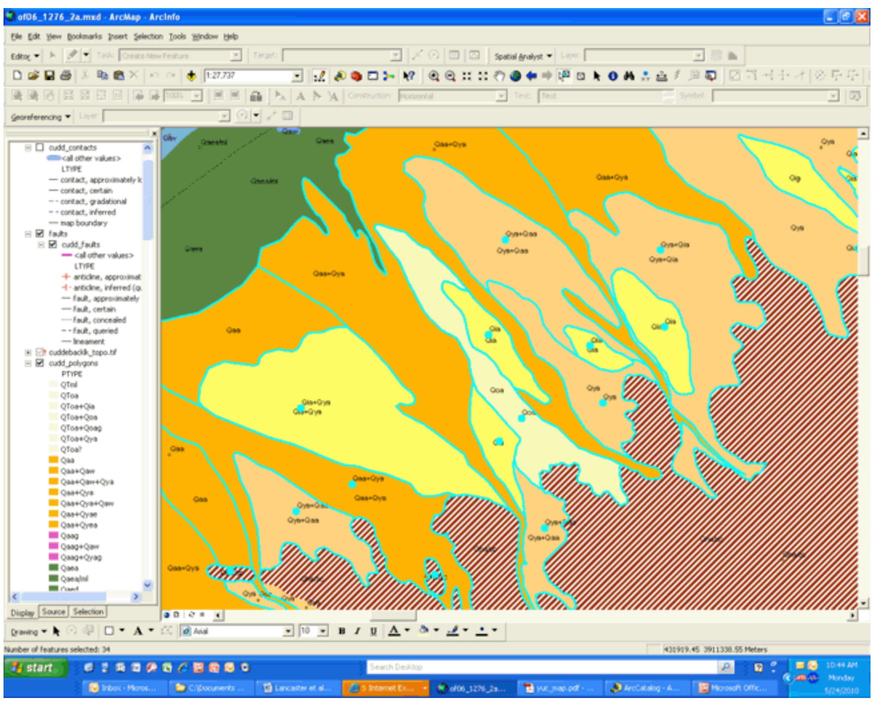

Figure 3B. Selection of all Quaternary alluvial-fan units.

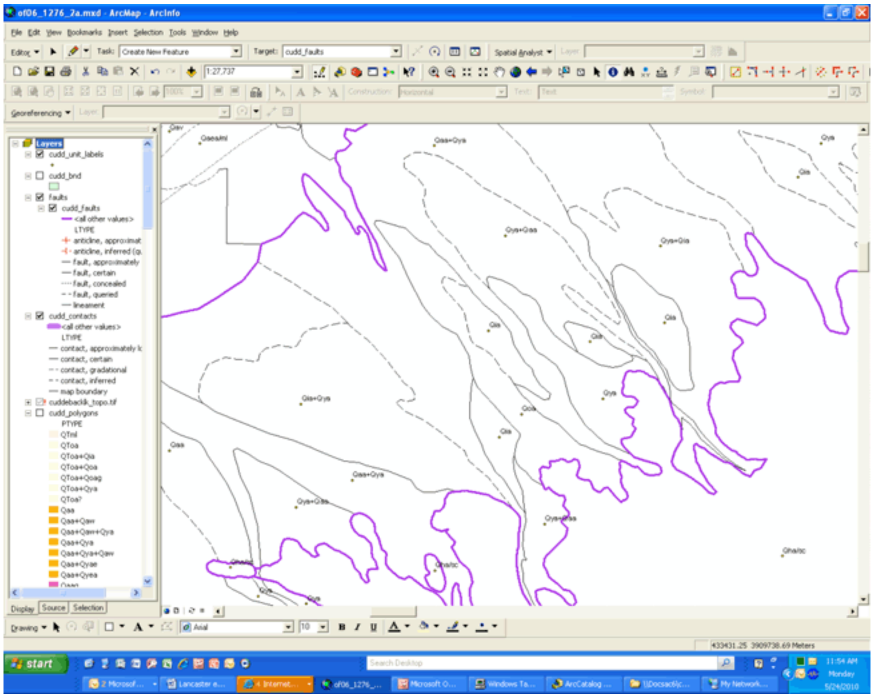

Figure 3C. Merged units (Quaternary alluvial-fan unit shown between the purple lines).

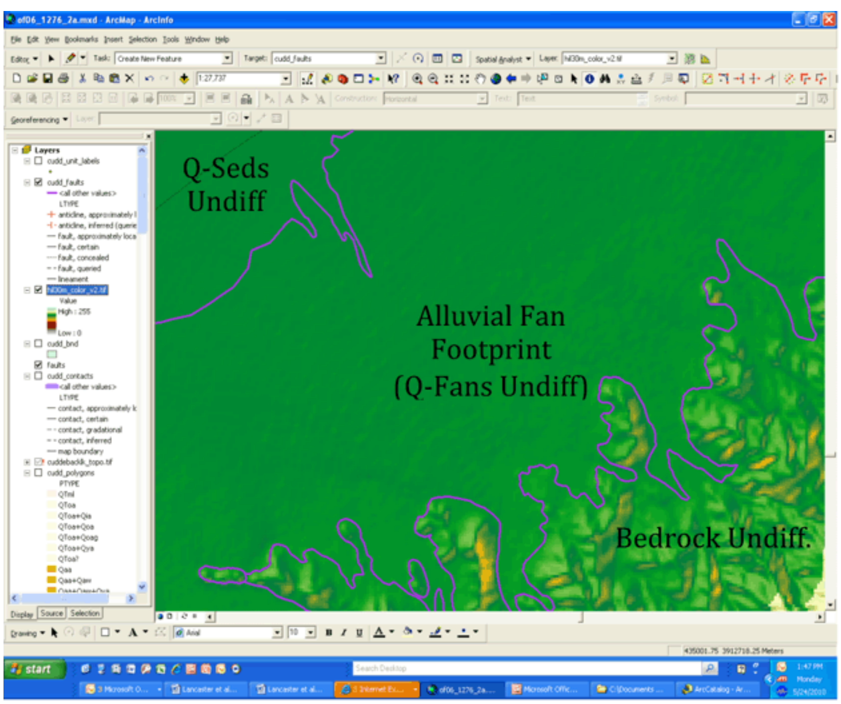

Figure 3D. Representation of the final derivative alluvial fan footprint advisory map showing bedrock, Quaternary alluvial fan, and undifferentiated Quaternary sediment polygons.

Digital data available for this type of mapping are many and varied; the most common sources are digital raster graphics (DRGs) such as 7.5-minute USGS topographic maps, 2005 and 2009 1-meter (m) resolution NAIP imagery, and USGS 10-m DEM (from the National Elevation Dataset). Variations to these data include slope and hillshade maps derived from DEM, and color infrared NAIP. These data provide a means to approximate both the bedrock/alluvial-fan contact, and the alluvial-fan/undifferentiated Quaternary sediment contacts.

Deriving Relative Hazard Information From Surficial Geologic Maps And Site Assessments

The Role of Surficial Geologic Maps In Assessing Alluvial-Fan Flooding

Surficial geologic maps of alluvial fans provide a record of the long-term flooding history; the fans are a function of tectonic processes, climate change, and various feedback mechanisms (Pelletier and others, 2005; Bull, 2007). The use of surficial geologic maps and geomorphology in flood hazard analyses on alluvial fans was formally recognized by the National Research Council (NRC, 1996) and by FEMA in their Guidelines and Specifications for Mapping Partners (2003). FEMA guidelines must be followed in all cases, yet the areal extent of FEMA mapping on alluvial fans is limited to where there is community participation in NFIP.

Planning departments and developers, up to this time, have had little available map-based communication of the hazard on alluvial fans other than Flood Insurance Rate Maps (FIRM), which are not available for most undeveloped alluvial-fan areas. To address these issues, the California Geological Survey has developed an engineering geologic approach for land-use planning, using surficial geologic maps and site assessments to determine the general distribution of alluvial fans and the relative potential for alluvial-fan flooding.

The Relative Potential of Alluvial-Fan Flooding

The recent work in Clark County Nevada, by House (2005, 2007) and Robbins and others (2008) identifies that the relative potential for alluvial-fan flooding is a function of the age and geomorphic position of alluvial-fan surfaces. Surficial geologic maps identify areas with flood and debris flow deposits of various ages, including modern drainage systems, their flow paths, and drainage divides (Robbins and others, 2008). As a part of the AFTF work products, CGS developed a similar approach to use surficial geologic maps to address the types and relative ages of alluvial-fan deposits for preliminary assessment of the relative potential for alluvial-fan flooding. CGS also identified additional information from site assessments, such as the potential for avulsion and debris flows, which should be considered in the assessment of alluvial fans. These preliminary studies may be conducted for pre-project assessment or for entire fan regional planning. Based on this approach, surficial geologic maps coupled with site assessments may be used to develop a preliminary ranking of an area as:

Relatively High (for alluvial-fan flooding) – Channels and washes (latest Holocene, <500 years or so), debris flow hazard areas, or entire fan areas subject to historical and future migration of flow paths.

Relatively Moderate – Alluvial-fan terraces that are moderately incised and raised above surrounding latest Holocene channels and washes. These areas are considered to have a moderate hazard. Fan terrace surfaces that are narrow interfluves surrounded by, or interwoven with, latest Holocene channels should be included with the Relatively High areas.

Relatively Low – Relict fans, or adjacent surfaces of deeply entrenched fan heads, containing well-developed soils that are elevated above active washes.

Debris Flow Hazard Area – Areas where Holocene debris flow deposits have been mapped based on geomorphic and geologic evidence, or where debris flows are anticipated.

Uncertain due to Disturbance – Areas where disturbances to natural flow patterns have occurred, and so the relative hazard cannot be reliably mapped at or below the disturbed areas.

These relative hazards designations are illustrated on both an oblique aerial photograph of the north slope of the Santa Rosa Mountains near Travertine Point, Riverside County, Calif. (fig. 4) and a geomorphic profile using surficial geologic map designations (fig. 5).

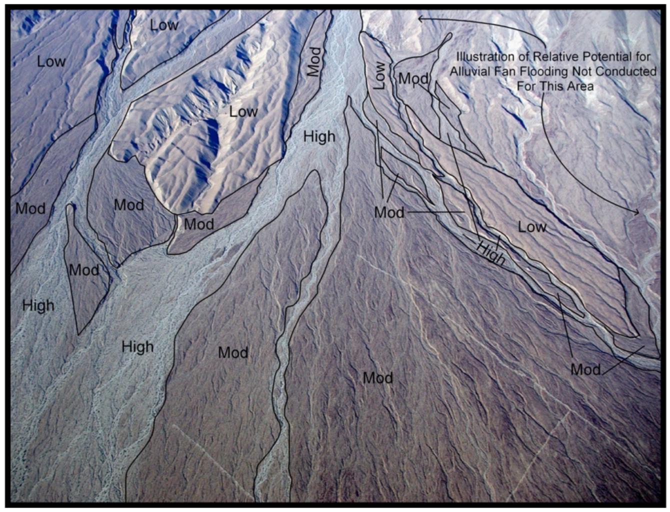

Figure 4. The relative hazard to alluvial-fan flooding in the Santa Rosa Mountains, Riverside County, California. High areas include latest Holocene alluvial-fan and wash deposits; moderate areas include Holocene abandoned alluvial-fan surfaces with faint-to-strong desert varnish development; low areas are relict alluvial-fan surfaces dissected with tributary drainage patterns.

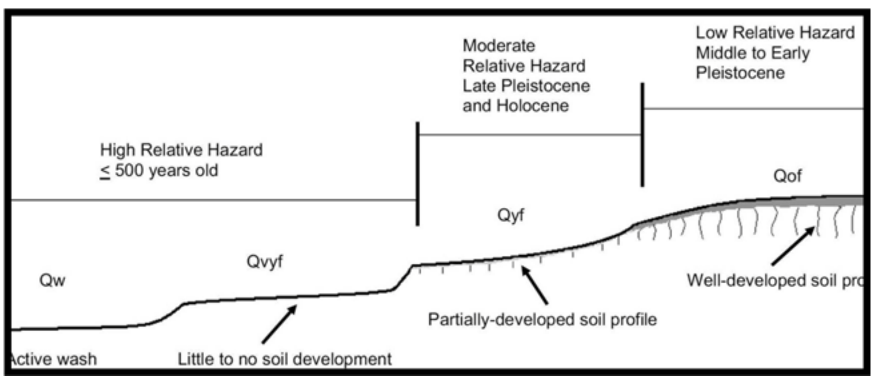

Figure 5. Illustrative geomorphic profile of the relative hazard to alluvial-fan flooding. Surficial units are classified as: Qw, active wash; Qvyf, latest Holocene alluvial fan; Qyf, late Pleistocene and Holocene alluvial fan; Qof, Pleistocene alluvial fan. Surficial mapping nomenclature based on J. Matti and P. Cossette (USGS, unpub. data, 2010).

Assessing the Potential for Debris Flow

The debris flow hazard on alluvial fans is a complex problem, and whereas quantitative site-specific studies may utilize probabilistic analyses, for planning purposes, identifying Holocene debris flow fans provides a preliminary indication of the susceptibility of areas where debris flow may occur (figure 6). This is because Holocene debris flow deposition is indicative of active processes occurring under the current climate regime (Giraud, 2005).

For preliminary indication of the potential for debris flow on an alluvial fan, the focus of study should be to identify the dominant mode of alluvial deposition—streamflow, debris flow, or composite, and then to identify where debris flow deposition has occurred in the Holocene Epoch. From a long-term planning, or pre-project standpoint, this information may then be used as the impetus for quantitative analysis of debris flow volumes during design phase analyses.

The geomorphic expression of debris flows has been documented by many workers in the field. Whipple and Dunne (1992) found that the roughness of alluvial-fan surfaces dominated by debris flow processes is controlled by the viscosity of debris flows. Fan apices and proximal areas tend to contain rougher surfaces expressed as channels with boulder-lined levees, terminal snouts, and boulder fields, due to higher viscosity debris flows (see fig. 7). Lower viscosity flows tend to smooth the lower fan surfaces by depositing less viscous debris farther downfan in low-lying areas and channels.

Assessing the Potential for Fluvial Avulsion

Fluvial avulsion may occur on alluvial fans that are dominated by water floods or flooding that is hyperconcentrated with sediment. They tend to occur at channel bends, where channels have high width-to-depth ratios (Field, 2001), and in areas that are aggrading, thereby causing channel bed elevations to increase relative to channel banks. They may also occur due to stream piracy, where overland flow causes incision and headward erosion into active channels, thus causing a redirection, or redistribution of flow on the fan. Figure 8 shows the process of avulsion via stream piracy.

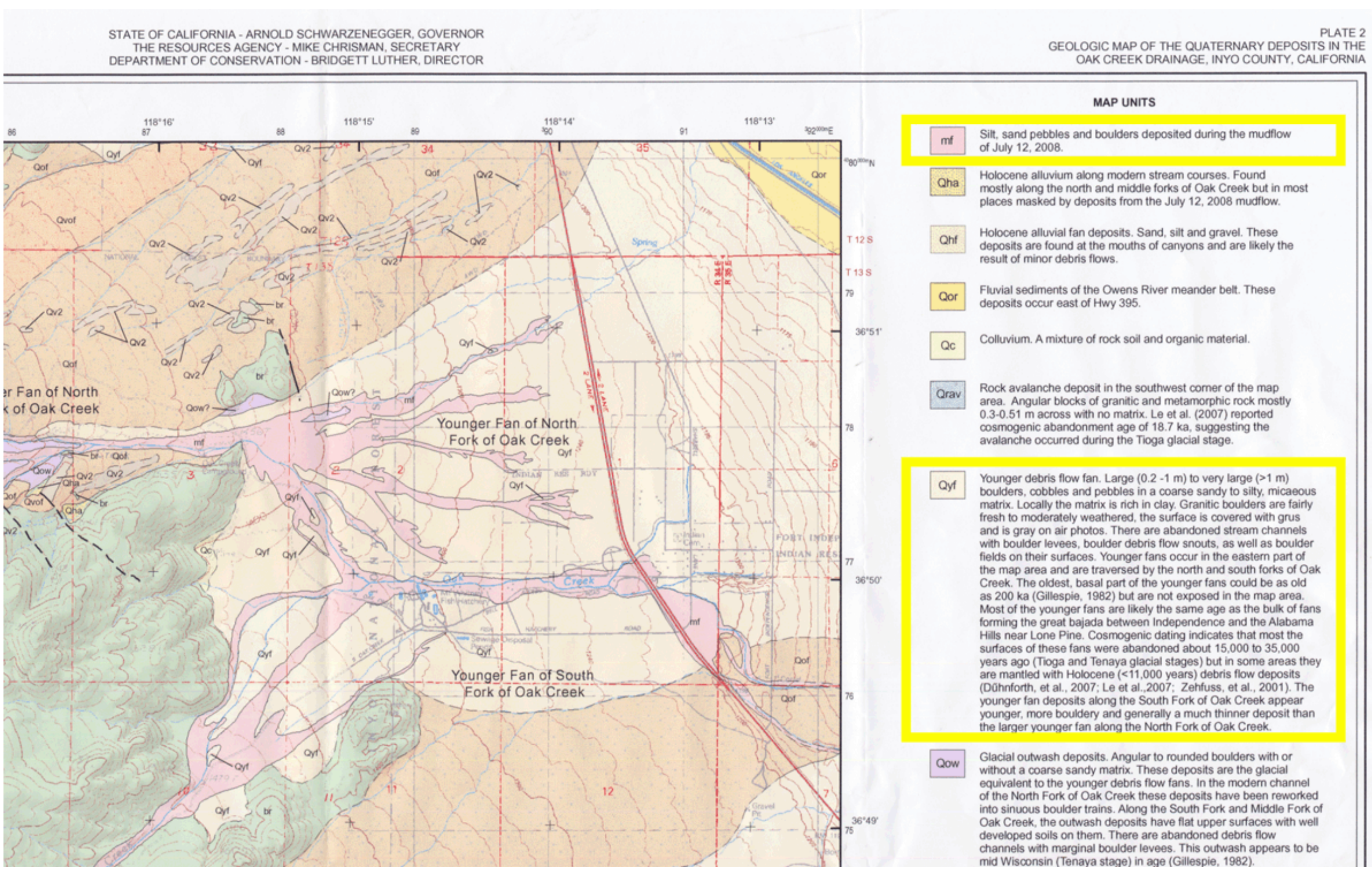

Figure 6. Draft Quaternary geologic map of the Oak Creek alluvial-fan system (Wagner and others, in press), showing the location of historical debris flow deposits, and the designation of Holocene debris-flow deposits. Highlight boxes drawn around the mapped debris-flow deposit of July 2008 and around the mapped Holocene debris fan deposits.

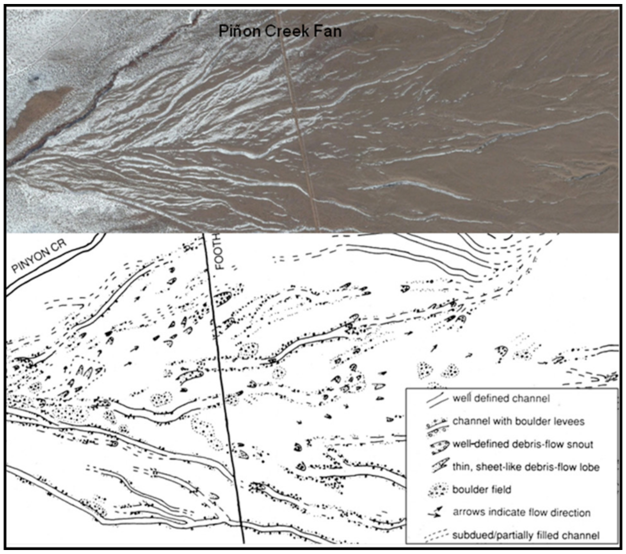

Figure 7. Upper part of figure shows NAIP aerial photograph of the Pinon Creek debris flow fan. Lower part shows map depicting the character and location of debris flow features.

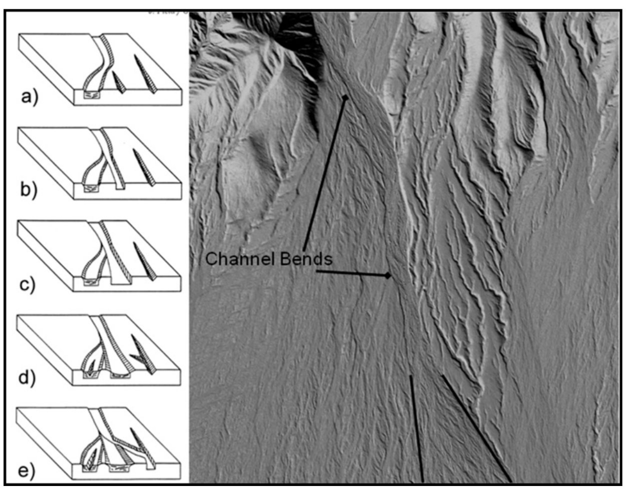

Figure 8. Schematic drawings of the channel processes that lead to fluvial avulsion on alluvial fans (left) (from Field, 2001), and LiDAR shaded DEM illustrating channel bends, where avulsion may occur on alluvial fans (right).

Assessing the Potential for Debris Flow Avulsion

Alluvial fans that are dominated by debris flow processes commonly have incised channels due to more frequent (for example, annual event) fluvial erosion processes. These channels may lead an investigator to falsely conclude that the channels are stable and that, therefore, the hazard is low. However, these channels serve as pathways where debris flows may travel for a limited distance until the channels are overtaxed by the sheer volume of flow. As with fluvial avulsion, debris flow avulsion tends to occur at channel bends but can occur much more frequently at the fan apex and proximal portions of the fan. Figure 9 shows a debris flow that occurred on an alluvial fan in Inyo County, Calif.

Summarizing the Derivative Products

For land-use planning, alluvial-fan footprint maps derived from digital geologic map data provide advisory information on general distribution of alluvial fans and indicate where detailed studies of alluvial-fan flooding potential may be necessary. Where proposed development sites are located within the Quaternary alluvial-fan hazard areas, additional assessments of the relative hazard to alluvial-fan flooding may be conducted by accessing digital geologic map data, analyzing the age and topographic position of geomorphic surfaces, and performing field assessments of the potential for avulsion and Holocene debris flow deposition. Following this approach, derivatives of geologic maps produced by CGS indicate the relative hazard to alluvial-fan flooding as relatively low,

Figure 9. Upper part of figure shows oblique aerial photograph of debris flow on the Oak Creek alluvial fan, Inyo County, California (July 2008, photograph by Ken Babion). Lower part shows aerial photograph of Oak Creek alluvial-fan debris flow, weeks after the event, showing where the debris flow avulsions occurred at the channel bends (photograph by Caltrans, 2008).

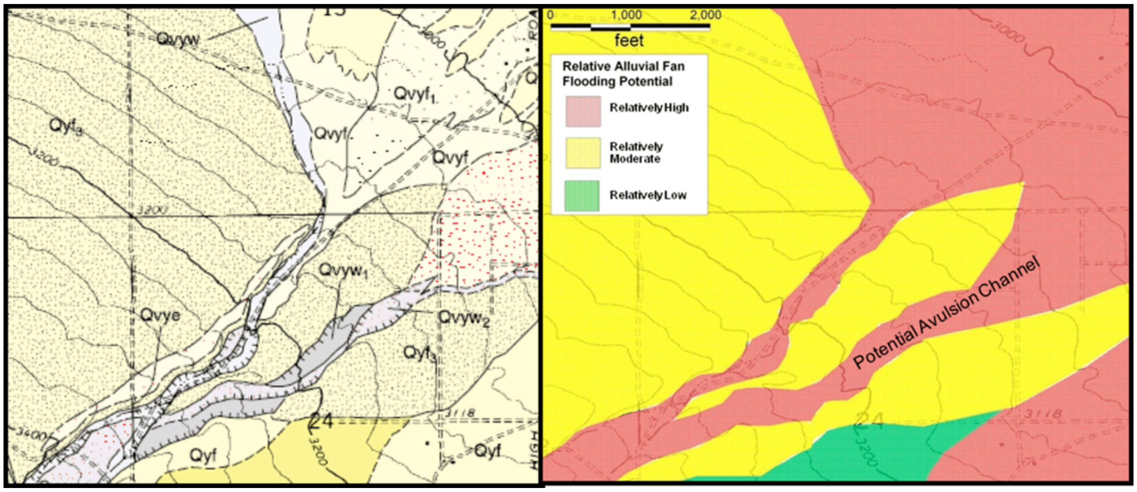

Figure 10. A portion of the geologic map of the Fifteenmile Valley 7.5' quadrangle (left) (Miller and Matti, 2001), and identification of relative alluvial-fan flood-hazard areas for the same area (right).

relatively moderate, relatively high, and the designation of areas susceptible to debris flow (fig. 10). These maps may be used by planners, developers, and homeowners to avoid development of hazardous areas and to design for proper flood and debris flow management facilities.

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Digital Mapping of Potential Mineral and Geochemical Hazards in California: Examples for Naturally Occurring Asbestos, Radon, and Highway Corridor Mapping Projects

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Introduction

Over the last two decades, the California Geological Survey (CGS) has increasingly received requests for environmental geology/mineralogy/geochemistry information from State and local agencies, consultants, industries, and the public. These requests have led to projects to identify and map potential mineral hazards such as naturally occurring asbestos, heavy metals, and radon. In these projects, digital mapping technology is used to compile, evaluate, and interpret data from a variety of sources and to develop associated products. The information and advice provided by the CGS are used by State and local government agencies and the public to protect the life and safety of California citizens, to protect the health of the environment, and to raise public awareness of these hazards.

This paper discusses three different types of mineral-hazard studies and the use of Geographic Information System (GIS) tools in their preparation. The complexity of these studies, both in geologic and GIS context, varies depending on the amount, type, and format of data involved as well as the intended use, audience, and format of the final products. These vary from relatively simple derivative maps based on geological information and intended for use by non-geologists to more complex maps and datasets combining data from varied sources and intended for multiple user groups with wide-ranging technical backgrounds. The reports accompanying all of these studies describe and document the study methodology, data sources, methods of analysis, interpretive conclusions, and limitations of the products.

Mapping Of Naturally Occurring Asbestos In California

Asbestos is classified as a known human carcinogen by State, Federal, and international agencies. In California, chrysotile and tremolite-actinolite asbestos are the most common types of naturally occurring asbestos (NOA) found, but occurrences of all six regulated asbestos minerals (chrysotile, tremolite, actinolite, anthophyllite, crocidolite, and amosite) have been reported. Currently, all six types of asbestos are considered hazardous and may cause lung disease and cancer. Fibrous richterite and winchite (currently unregulated) have also been reported. NOA is most commonly associated with serpentinite, serpentinized ultramafic rocks, and associated soils in California, but may also be found less commonly in other rocks or soils. It may also be more common in fault or shear zones in certain rock types or at geologic boundaries (Clinkenbeard and others, 2002; Van Gosen, 2007). Reported occurrences of asbestos minerals, fibrous amphiboles, or ultramafic rock/serpentinite are known in 53 of California's 58 counties.

Government agency and general public concerns about potential public health impacts from NOA exposure over the last two decades have resulted in State and local regulations to minimize the public's exposure to asbestos by requiring work practices that minimize dust emissions from various activities. In California, these regulations govern construction, excavation, and mining activities in areas that may contain NOA, and place restrictions on the use of aggregate materials containing NOA for surfacing applications. With these concerns and regulations, there has been a growing demand for information on where NOA is likely to be encountered in California. The CGS has been assisting various Federal, State, and local agencies by providing geologic information about NOA in the State since the late 1980s. Over the last decade, products have included a statewide map of ultramafic rocks (Churchill and Hill, 2000); guidelines for geologic investigations of naturally occurring asbestos in California (Clinkenbeard and others, 2002); county maps showing the relative likelihood for the presence of naturally occurring asbestos in western El Dorado (Churchill and others, 2000), Placer (Higgins and Clinkenbeard, 2006a), and eastern Sacramento (Higgins and Clinkenbeard, 2006b) Counties; and a collaboration with the U.S. Geological Survey (USGS) to perform a preliminary evaluation of a remote-sensing instrument, the Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS), as a potential tool for mapping the occurrence and distribution of asbestos-bearing rocks (Swayze and others, 2004; 2009).

The first county NOA study, western El Dorado County, was a pilot project prepared in response to a recommendation by a multi-agency asbestos task force formed in the late 1990s to advise government officials and the general public of the distribution, potential health risks, and possible mitigations for NOA in the county. Subsequent NOA studies in Placer and eastern Sacramento Counties were requested and funded by local Air Pollution Control Districts (APCDs). The CGS NOA maps are intended to provide information to local, State, and Federal agencies and the public about where NOA is more likely to be found in a region. The maps, while not regulatory, may be used to help determine where agencies wish to consider actions to minimize generation and exposure to dust that may contain NOA. They do not indicate whether NOA is present or absent in bedrock or soil on a particular parcel of land. Determination of the actual presence or absence of NOA at a particular site requires a site-specific examination of the property and sampling and analysis for NOA.

The NOA maps are derivative maps intended for use by non-geologists. Rather than showing conventional geologic units, they show the relative likelihood of areas to contain NOA (see figure 1). GIS tools are used for data management in compiling geologic maps, soil maps, and geologic or other information related to NOA and for aiding in the analysis of the spatial distribution of these elements as they apply to the potential occurrence of NOA.

Geology is compiled at an appropriate scale, typically 1:100,000, from a variety of sources, both electronic and hard-copy, to create a digital geologic map of the area being studied. Soil reports are reviewed to identify those soil units associated with ultramafic rock/serpentinite parent materials. Because of the characteristics of serpentine soils and their vegetation, they stand out in some types of remote-sensing imagery, potentially making such imagery useful in mapping areas of serpentinite and related soils. The boundaries of serpentine soils are added to the digital database for comparison to the geology. Information on known natural asbestos occurrences in the region is compiled, and information on the occurrence of other mineral deposits typically associated

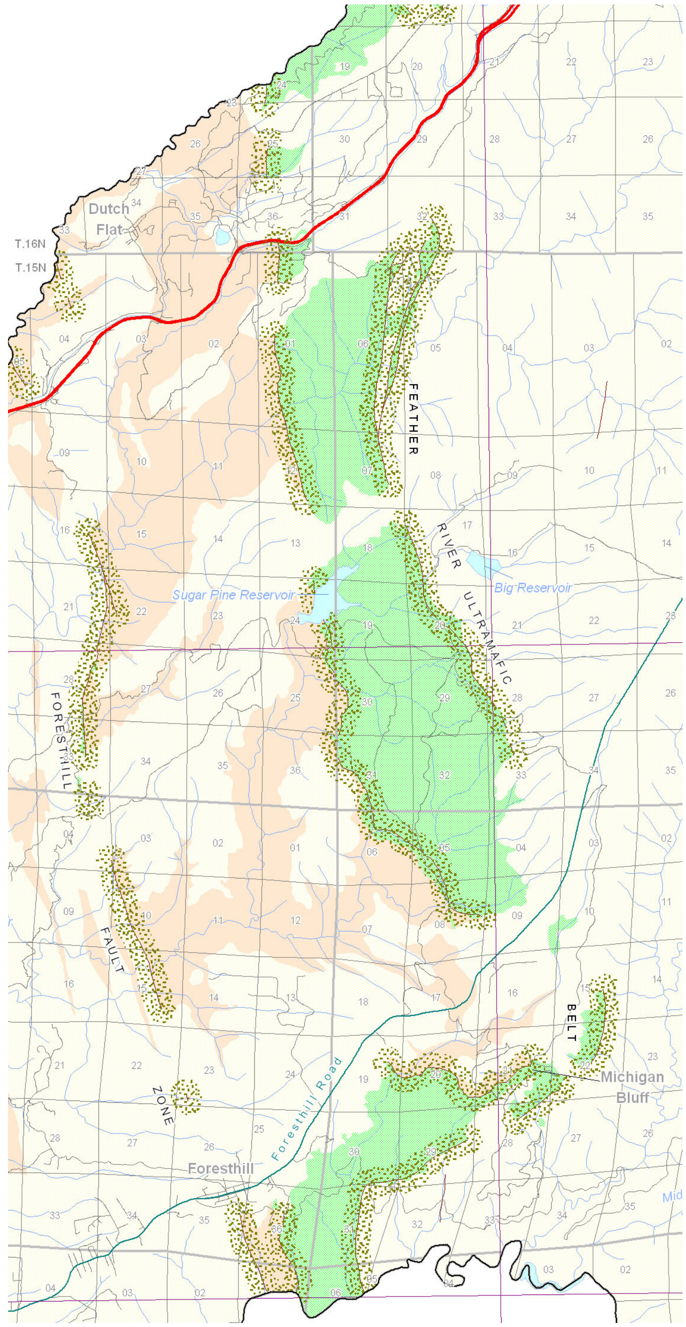

Figure 1. Part of map showing the relative likelihood for the presence of naturally occurring asbestos (NOA) in Placer County, California. Green = Areas Most Likely to contain NOA; buff = Moderately Likely; cream = Least Likely. Stippled pattern indicates areas of faulting or shearing that may locally increase the likelihood for NOA within or adjacent to areas moderately or most likely to contain NOA. Solid brown lines within stippled areas represent mapped traces of faults or shear zones. Original scale 1:100,000.

with ultramafic rock or serpentinite is also evaluated. These deposits include chromite, magnesite, mercury, nickel, and talc. Fieldwork is conducted to observe and verify the character of rocks and structures in the major rock units, evaluate the accuracy of the geologic boundaries of previously mapped areas, and collect samples for analysis.

Once the various data have been compiled, the information is interpreted and used to identify areas where NOA is most likely to occur, moderately likely to occur, and least likely to occur based on the likelihood of asbestos occurrence in different geologic environments. Areas determined most likely to contain NOA typically are underlain by ultramafic rocks, serpentinite, and associated soils. Areas identified as moderately likely to contain NOA typically are underlain by metamorphosed mafic volcanic rocks, metamorphosed igneous intrusive rocks, gabbroic rocks, and structurally complex units of mixed metamorphic rocks of different origins. Examples of rock types that underlie areas identified as least likely to have NOA include metamorphosed felsic volcanic rocks, granitic rocks, volcanic rocks, and glacial deposits.

Published California Geological Survey NOA maps and companion reports are available for viewing or downloading on the CGS NOA Web page, at *http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/asbestos/Pages/Index.aspx*.

Radon Hazard Mapping In California

Radon is a radioactive gas present in soil, rocks, water, and the atmosphere. It is produced by radioactive decay of small amounts of uranium and thorium naturally present in rocks and soil. Radon is not normally a health issue under ambient conditions. However, under certain conditions, radon may concentrate in the indoor air of homes and other buildings to the point where long-term exposure to such air significantly increases an individual's lung-cancer risk. The U.S. Environmental Protection Agency (EPA) estimates over 21,000 lung cancer deaths occur annually in the United States from radon exposure. A preliminary EPA estimate suggests about 1,700 radon-related lung-cancer deaths occur annually in California, which exceeds the State's annual number of deaths related to drunk driving.

Maps accurately predicting indoor-radon concentrations in specific buildings are not possible because of the number of variables involved, many of which vary from building to building. However, it is possible to construct maps indicating areas with higher or lower likelihood of buildings having indoor-air concentrations exceeding the 4 picocuries per liter (pCi/L) EPA recommended action level. Such "radon-potential" maps commonly are advisory, not regulatory. Government agencies and non-profit organizations can use them to target their radon public outreach and education campaigns for the greatest benefit. These maps also identify areas where radon-resistant building practices for new construction should be considered. Additionally, individuals contemplating home purchases in California are increasingly interested in obtaining information about the likelihood of indoor-radon problems in areas where they are considering purchases.

Simple radon-potential maps are constructed by displaying indoor-radon data means, medians, or percentages of data exceeding the EPA recommended action level for specific areas. Areas defined by county boundaries, Zip Code zone boundaries, and grid boundaries (for example, square kilometers or miles) can be used for radon maps. However, such maps often fail to identify the relatively small- to medium-sized radon "hot-spot" areas typical in California. Approaches using grid areas could identify small or medium-sized radon hot-spot areas, provided the grid area sizes are similar to or smaller than hot-spot areas and sufficient indoor-radon data are available for each grid cell. However, a grid cell approach is not viable at this time in California because of low indoor-radon sampling density.

Another radon mapping approach groups indoor-radon measurements and other radon related data by geologic unit. This approach has several advantages. First, because geologic units vary in physical and compositional character within relatively narrow limits by definition, occurrences of a unit without data often have radon potentials similar to occurrences of that geologic unit with data. One cannot assume the radon potential of a Zip Code area or county lacking indoor-radon data, on the basis of the radon potential of an adjoining Zip Code area or county. Second, certain lithologic types are more prone to indoor-radon problems than others. In California, organic-rich siliceous marine shale and mudstone and certain granitic and volcanic rocks, which typically have higher background uranium contents than many other rock types, are examples of units with higher radon potential. Such units deserve higher priority for indoor-radon surveys. Using a geologic-unit approach to radon potential mapping, the CGS has successfully identified a number of small- to moderate-sized high-radon potential areas in California not identified by county-wide or Zip Code area approaches.

In 1995, the CGS produced its first radon-potential maps (Santa Barbara and Ventura Counties), for the California Department of Health Services (CDPH) Radon Program. Since 2004, the CGS has had cooperative agreements with CDPH to produce radon maps. All CGS radon-potential maps have utilized GIS for data management, analysis, and cartographic design. These maps display radon-potential areas according to five categories: Very High, High, Moderate, Low, and Unknown (fig. 2). These categories correspond to the percentage of indoor measurements equal to or exceeding 4 pCi/L as follows: Very High (≥ 50 percent); High (20 to 49.9 percent); Moderate (5 to 19.9 percent), Low (< 5 percent), and Unknown (insufficient data to estimate radon potential).

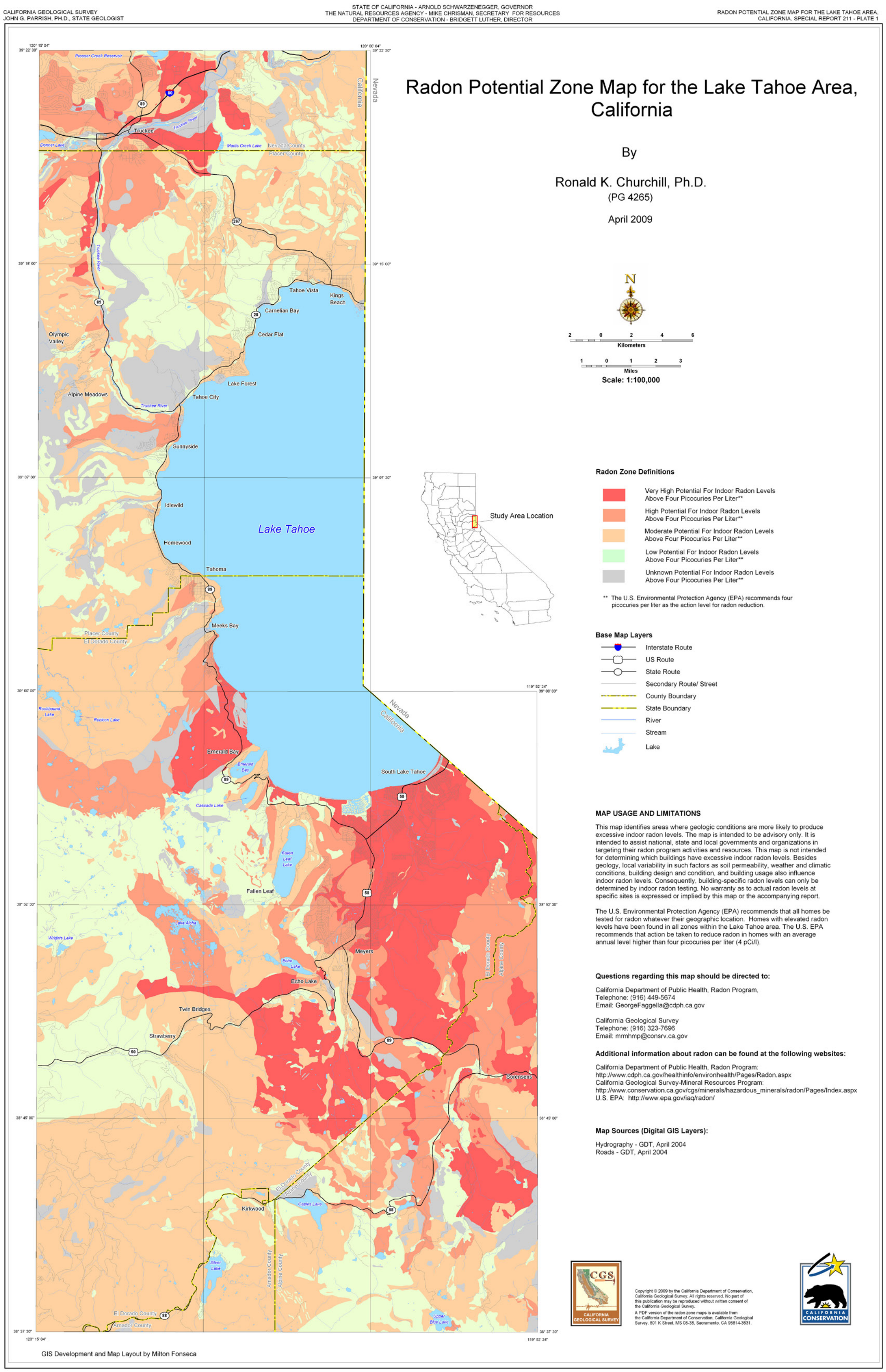

Figure 2. Radon Potential Zone Map for the Lake Tahoe Area, California. Original scale 1:100,000.

The CGS uses GIS for four principal activities to develop radon-potential maps:

1. Compilation of homeowner mailing lists for counties or areas selected by CDPH for indoor-radon surveys,
2. Preparation of a digital geologic layer,
3. Management and evaluation of indoor-radon and other data needed to classify radon potential and identify radon-potential zone areas, and
4. Design and production of the final map.

Because indoor-radon measurements are inexpensive and easy for homeowners to perform, CDPH usually can enlist some local homeowners to participate in a home survey program in support of the radon mapping process for a county or area. Using homeowner-occupied house address lists obtained by CDPH from commercial vendors or county governments, the CGS geocodes the addresses and selects a subset of homeowners to receive a CDPH letter requesting participation in the indoor-radon survey. Except in low population counties or areas, only some residents in a survey area are solicited for survey participation because the number of homeowner-occupied homes exceeds the CDPH mailing and radon-detector budgets. (Homeowner survey participation rates usually range between 3 and 8 percent of the solicitation letters mailed.) Additionally, the CGS attempts to ensure that a minimum of 20 to 25 measurements are collected from homes associated with geologic units known or suspected to have radon problems, on the basis of previous work. Experience has shown that this is the minimum number of measurements required for a high likelihood of proper radon potential categorization of a geologic unit. At this point, available 1:100,000- or 1:250,000-scale vector or raster geologic maps are used to provide geologic-unit location information. Given a worst-case survey participation rate of 3 percent, between 667 and 833 addresses are randomly selected from those associated with geologic units that have potential radon problems. If fewer than 667 addresses are available, all addresses receive a survey solicitation letter. After addresses associated with suspected high-radon geologic units have been identified, the remaining survey quota is filled by selecting homes from other parts of the survey area so that some indoor-radon measurements are obtained from as many geologic units as possible. For geologic units with high population densities, GIS queries that randomly select one of every three or four addresses have been used for mailing list development.

A digital (vector) map of geologic units at 1:100,000 scale is utilized for radon data evaluation and for final radon-zone map development. Experience has shown that 1:100,000-scale or more detailed geologic mapping is needed for radon potential mapping. At these scales geologic units tend to be more homogeneous in physical and chemical characteristics than geologic map units developed at less detailed map scales. Only some parts of California currently have digital 1:100,000-scale geologic maps available. In other areas, such maps need to be compiled from scanned paper geologic maps of more detailed scales. Once the digital geologic map layer is developed, indoor-radon measurements and additional radon data (discussed below) are compiled for each geologic unit through queries linking data from these layers with geologic unit areas on the geologic map layer. Next, the percentages of 4 pCi/L or higher measurements are calculated for each geologic unit, other available radon-related data are evaluated, and radon potentials are assigned to each geologic unit. Geologic units with similar radon potentials are grouped into the radon potential zones shown on CGS radon maps.

As mentioned, when available, additional data related to radon concentration and movement in the upper several meters of the subsurface are compiled into GIS layers and data are assigned to geologic units. These data may include:

1. Airborne gamma-ray spectral data collected during the National Uranium Resource Evaluation (NURE) project in the 1970s and 1980s,
2. NURE uranium-abundance data for soil and sediment samples,
3. Non-NURE uranium-abundance data for rock, soil, and sediment,
4. Surface gamma-ray spectral data, and
5. Near-surface soil-gas radon measurements.

The additional data sometimes support a “provisional” radon-potential ranking for geologic units with few or no indoor-radon measurements. Otherwise, units with few or no indoor data will be assigned to the “unknown” radon-potential category. Units assigned to the unknown radon-potential category become potential targets for future radon surveys if they underlie any homes.

Although not used directly in determining geologic unit radon potentials, soil permeability, soil shrink-swell characteristics and, in some cases, depth to bedrock and depth to water table data are compiled from U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) and U.S. Forest Service (USFS) soils reports and added to the attributes for indoor-radon measurements. Comparison of trends between these data and indoor-radon data, in combination with other previously listed radon and uranium data, have led to valuable insights and conceptual models for radon problem areas.

After the geologic units are classified for radon potential (Very High, High, Moderate, Low, or Unknown), all occurrences of units with the same classification are combined, forming one or more polygons. A single GIS layer is then created that contains all of the radon potential classes. All of the polygons for the geologic units in a category now represent the spatial distribution of that category. For example, if units A, B, and C met the criteria for high radon potential, and their presence in the study area is represented by 10 polygons, 4 polygons, and 7 polygons, respectively, then the high radon potential portion of the study area is represented by the 21 polygons of these units. Note that out of seven CGS radon potential maps completed to date, only one has “Very High” radon potential areas present.

The next step is to check the resulting radon potential categories for statistical validity. This check is done as follows:

1. Compile indoor radon data for each radon potential category.
2. Compare resulting data populations using the Mann-Whitney rank-sum (non-parametric) statistical test to confirm that each layer is significantly different from the others.

Typically the populations are confirmed as being different, and no further adjustments of the radon potential category polygons are made. On the rare occasion when two unit radon populations are not statistically different, then one of the following approaches should be chosen:

- The two categories may be combined into one. For example, the High category is not statistically different from the Moderate category, so all of the High category polygons will be reclassified as Moderate, and in this example the final map will not have any high radon potential areas.
- Polygon boundaries of the different categories may need to be adjusted to produce statistically different radon populations for the radon potential categories. For example, in California there are some areas where landslides have developed in portions of a high radon potential unit, and this material has moved down slope and now overlies the lower radon potential units. Because the thickness of the displaced higher radon material is at most a few tens of feet, these displaced areas were not mapped as the high radon potential unit. By adding buffer zones of 0.1 or 0.2 miles to the down-slope sides of the high radon unit polygons, these displaced high-radon unit areas can be removed from the lower radon potential group and, more properly, included with the high radon potential polygons. If a statistical comparison of the adjusted radon populations for the high and lower radon potential units now confirms that they are statistically different, then no further adjustments are needed.

Estimates of the number of individuals living in residences where indoor radon levels exceed the EPA recommended action level are made for each radon potential zone and for the entire map area. These estimates are included in the final report that accompanies the radon potential map, in order to put the significance of radon risk for a county or area into perspective. To make these estimates, radon potential zone layers are compared with U.S. Census data (TIGER) GIS layers for census tracts and census blocks. The populations for each radon potential zone are estimated by summing the tract or block populations contained within the areas of each zone. Where individual tracts or blocks include more than one radon potential zone, populations are divided between the zones proportionally by the area of the track or block within each zone. Once the total population for each radon potential zone is estimated, the total is multiplied by the percentage of indoor radon measurements for that zone that equaled or exceeded the EPA recommended action level to obtain the population at risk for radon exposure.

To complete the radon potential map, the radon potential layers are overlain on a 1:100,000-scale base map showing streets and highways, water features, and parks, which serve as points of reference. Individual city blocks can be resolved on the base map at this scale. This is usually sufficient information to allow most people to locate a point of interest on the map and determine its radon potential. Information about map use and limitations is included in the map margins. A PDF version of the final map and accompanying report is placed on the CGS Radon Web Page for viewing and downloading/printing by interested parties. Because paper copies of these maps and reports are requested by some users, a small number are available for purchase through the CGS Publications Office.

Published CGS radon potential maps and their companion reports completed to date are available for viewing or downloading on the CGS Radon Web Page at *http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/radon/Pages/Index.aspx*.

Mineral-Hazard Maps For Highway Corridors

Through a cooperative agreement with the California Department of Transportation (Caltrans) Division of Environmental Analysis, the CGS has prepared maps of potential environmental geology/mineralogy/geochemistry hazards along portions of two state-highway corridors (SH128 and SH299) in northern California. These products differ somewhat from the previously described studies in that they are intended for internal use by Caltrans and are not intended for use by the general public. These maps, reports, and digital datasets are designed to assist district staff in planning and conducting more detailed hazardous materials evaluations where regulatory compliance may be required, where frequent maintenance is needed, or where health and safety or public relations related to mineral hazards may be a concern along these highway corridors. The CGS employed standard digital mapping techniques to prepare the maps and related products for both corridors. The SH128 project was a pilot study to establish the process of mapping the potential for mineral hazards along highway corridors. The SH299 project expanded this process to a segment that is much longer and more geologically and mineralogically complex than the SH128 corridor.

All products were developed and generated using a commercial GIS and related software. The final products were designed based on two important needs of Caltrans: (1) presentation of information about potential mineral hazards in a fairly direct way that could be used by staff with a range of backgrounds (engineers, planners, maintenance workers) and (2) accommodation of users with different levels of computer experience or available computer resources. Correspondingly, the CGS provided Caltrans with products that ranged from paper maps, which can be used by Caltrans staff not familiar with GIS software or techniques, to digital products such as shapefiles and PDF files, which can be integrated into internal Caltrans GIS packages and other software for staff that routinely use such resources.

To evaluate and understand potential sources of mineral hazards that might affect these two highway corridors and associated operations along them, many base- and technical-data layers and ancillary data were needed. Geology is the essential foundation layer for interpretation of potential for mineral hazards; it was compiled for each corridor from existing digital geologic maps prepared by the CGS, USGS, USFS, and California Department of Water Resources. Gaps in the digital coverage were filled by digitizing and edge-matching of scanned paper copies of geologic maps. The geologic layer for each corridor was then reinterpreted to generate a "lithologic" layer, which established a consistent set of rock groups (polygons) that were categorized based on their geochemical and mineralogical characteristics rather than their ages or stratigraphic groupings. Interpretation of geochemical and mineralogical characteristics of each polygon is important because it gives some indication whether or not the lithology might contain particular minerals or metals in concentrations that exceed those established or proposed by governmental agencies as being hazardous to human health or the environment. Each lithologic polygon was then assigned to one of three layers of physical features: bedrock, alluvial deposits, and landslide deposits. Also from the geologic compilation, a separate layer of faults was developed for each corridor. Faults can be sites of anomalously high concentrations of different types of mineralization. Technical layers prepared for other physical features included mines and prospects, sediments along small streams (represented by a stream layer), and, along the SH299 corridor, areas of metal-sulfide mineralization. Mines and prospects are important because (1) they can indicate where anomalous concentrations of minerals or metals may be present and (2) they may be sites where contaminants were possibly produced by mining and mineral processing. They were mainly obtained from the USGS Mineral Resources Data System (MRDS), with supplemental information from CGS files. MRDS is not a "clean" database and can be locally misleading especially concerning locations of mines and prospects. For example, a given mine may be represented by two or three separate records in the database, each of which may have very different assigned locations for the mine. Consequently, we researched the records to help eliminate multiple records and improve the accuracy of locations. Stream locations also are important because they may transport harmful materials eroded from bedrock and mine sites upstream from the highway corridors and deposit them locally within the corridors.

All physical features described above are represented by points, lines, or polygons and thus were easily assigned attributes that provide Caltrans staff with information on each feature's potential for mineral hazards. Within each corridor, the physical features were evaluated and rated for their potential as sources of mineral hazards. With the exception of the areas of sulfide mineralization along SH299, each feature was rated as High (1), Medium (2), or Low (3) for its potential to contain naturally occurring asbestos (NOA) and to locally equal or exceed regulatory threshold concentrations for each of 17 metals that Caltrans routinely evaluates as possible sources of toxicity in earth materials. Referred to as the "CAM17" list, this group of metals can be hazardous to human health or the environment. Among these metals are copper, lead, zinc, cadmium, mercury, chromium, and nickel; these seven metals were the ones of most concern along the SH299 corridor, while chromium and nickel were of most concern along the SH128 corridor. The ratings for the physical features were assigned by a process that combined qualitative geological and semiquantitative geochemical evaluation with simple digital algorithms applied to the vector features. For example, because serpentinite commonly hosts naturally occurring asbestos, all bedrock polygons labeled as serpentinite in both the SH128 and SH299 corridors were digitally assigned a rating of "High" (1) for their potential to contain NOA. For evaluation of the CAM17 metals, baseline concentrations of each of the CAM17 metals were estimated for each bedrock polygon, based on the prevalent rock type of that polygon. Because there are very few available chemical analyses for CAM17 metals for rocks in the corridors, most of the baseline estimates are from generic rock types judged to be similar to those that comprise the polygons. For alluvial and landslide deposits, potential for NOA and CAM17 metals in them was based on estimates of the original upstream sources (bedrock, mining, and so on) from which the deposits are assumed to have been derived.

Finally, each physical feature along the highway corridors was ultimately assigned a single "overall" rating for its potential to contain mineral hazards. This approach was developed mainly so that the paper copies of the corridor maps would be simpler and therefore easier to use by Caltrans staff as initial screening tools for such hazards. Based on the geochemical and mineralogical characteristics of the feature, the overall rating combines the individual potential ratings for both NOA and each CAM17 metal and is shown on the final corridor maps by color coding. It represents the highest expected potential for a mineral hazard to be present in a physical feature. For example, given a specific bedrock polygon, if NOA is rated Low and the highest rating for any one of the CAM17 metals is High (for example, copper and zinc are High, but all other metals are Low), the polygon is assigned an overall rating of High and thus colored red on the corridor map. Furthermore, additional information about individual features is available to staff as attributes in the digital files that accompany the paper maps.

Mines and prospects were also evaluated as potential sources of mining chemicals. They were not rated, however, because of generally insufficient historical information about mining and processing activities at these sites as well as the additional time needed to research this information. Instead, estimates of types or degrees of ore processing are presented for most mines and prospects. Actual ore-processing operations, if any, may be determined in some cases by literature searches on individual mines and prospects. Correspondingly, on the digital layer of mines and prospects, a list of references is included as one of the attribute fields for Caltrans staff who wish to research individual mines or prospects.

To further assist Caltrans staff, several digital base-data layers that show terrain and hydrography were displayed on the paper maps to help visualize and interpret potential movement of hazardous materials related to mineralization and mining from upstream sources to the highway corridors. These layers included shaded relief from digital elevation models, topographic contour lines, watershed boundaries, and stream flowlines. As an alternative, the CGS advised Caltrans that its staff could view the various digital layers with Web-based image viewers or simple GIS freeware, which allow three-dimensional perspectives of the layers superimposed on underlying color imagery of the corridors. Examples of the mineral-hazard maps for SH128 and SH299 corridors are shown in figures 3 and 4.

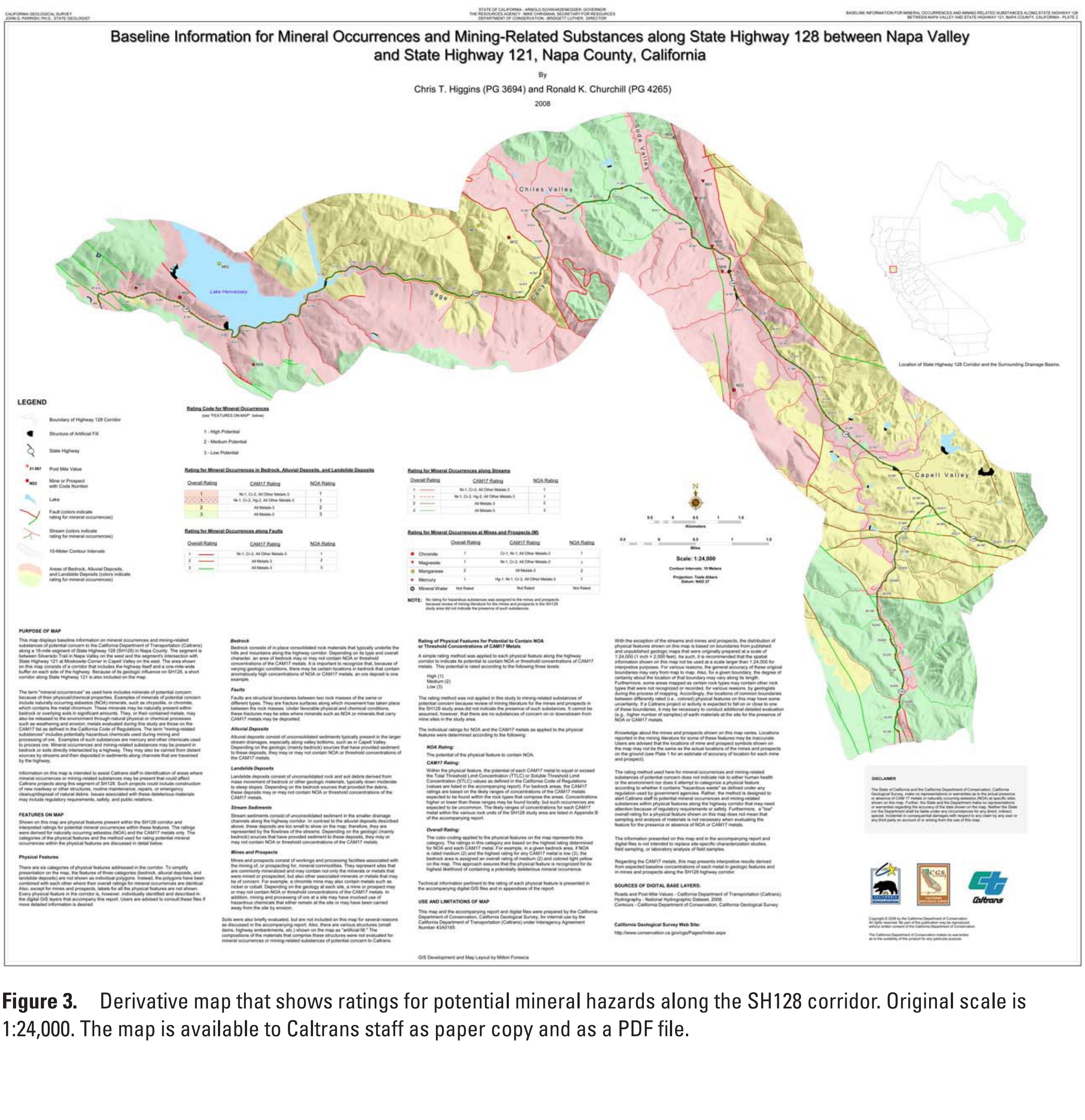

Figure 3. Derivative map that shows ratings for potential mineral hazards along the SH128 corridor. Original scale is 1:24,000. The map is available to Caltrans staff as paper copy and as a PDF file.

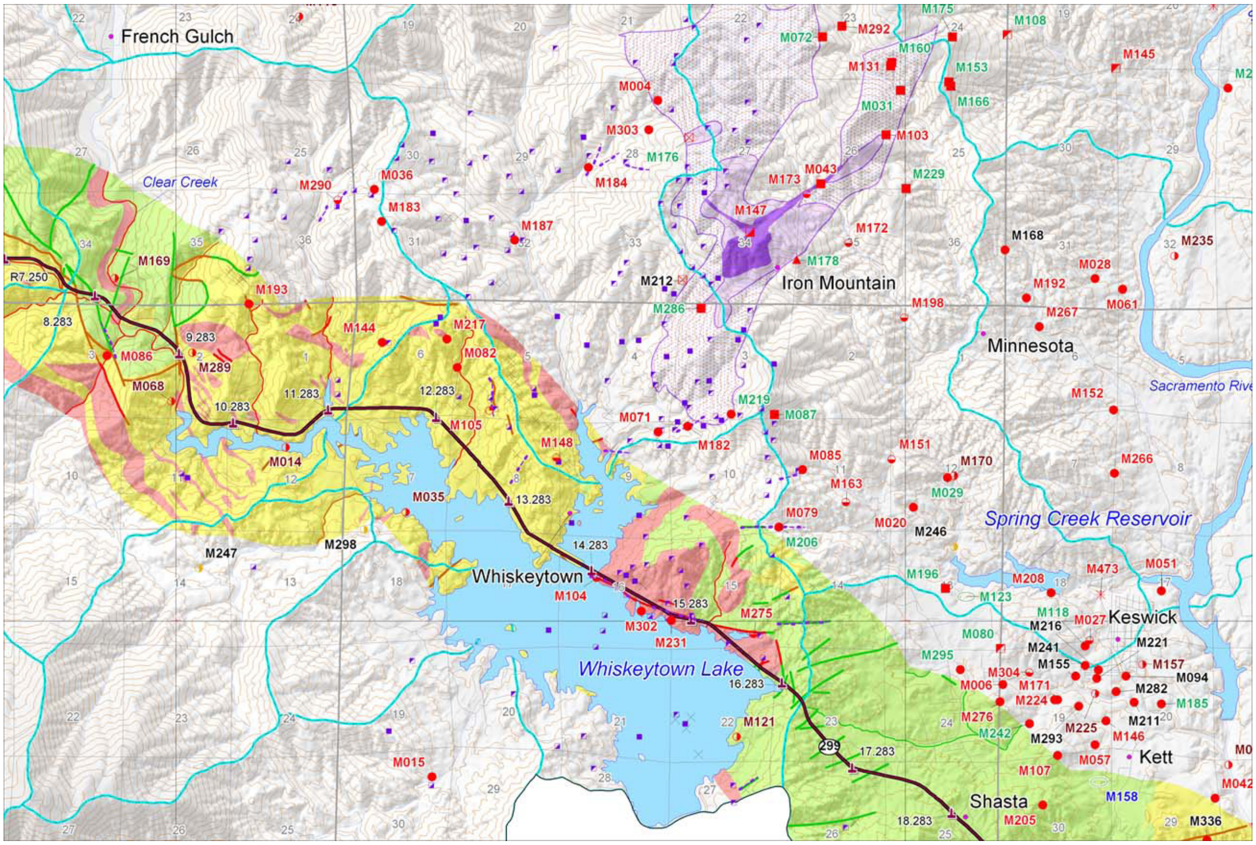

Figure 4. Part of map that shows potential for mineral hazards along the SH299 corridor. Original scale is 1:62,500. Accompanying attributed digital layers provide additional technical information for use by Caltrans staff. Colored areas in the highway corridor represent ratings for mineral occurrences in bedrock and alluvial deposits: red = high potential, yellow = medium potential, green = low potential. Colored symbols with labels represent locations of mines and prospects; color of labels indicates type of known or possible ore processing at site. Thick colored lines in corridor represent faults. Thin colored lines in corridor represent streams. Purple symbols and areas represent localities of hydrothermal alteration and mineralization. Light blue lines represent watershed boundaries.

The processes described above for mapping potential for mineral hazards along highway corridors are not necessarily in final form. Modifications and improvements to the processes will likely be made in the future as the CGS receives suggestions from Caltrans staff and researches and employs more rigorous quantitative methods to assign ratings of potential for mineral hazards. For example, a raster, rather than vector, approach could allow cell- or grid-based rankings of geochemical and mineralogical characteristics of physical features. In turn, such rankings might enable further refinement or discrimination of the potential for specific mineral hazards in certain areas. Nonetheless, any improvements in processes will be limited by the quality, consistency, and completeness of the original data used for each project.

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Assessing Erosion Potential and *Coccidioides immitis* Probability Using Existing Geologic and Soils Data

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Introduction

One of the primary benefits of a geographic information system (GIS) is its ability to analyze multiple overlapping layers of spatial data and create new derivative products that provide needed information or answer questions of interest. This new information can then be presented in a clearly understandable way for use by decisionmakers as well as the general public.

An example of this type of process is an assessment conducted by the California Geological Survey (CGS, 2006) on a property in the Bakersfield area that was being considered by the California State Parks Off-Highway Motor Vehicle Recreation Division as a possible State Vehicle Recreation Area (SVRA).

The property is located within a region that has an elevated incidence rate of coccidioidomycosis, or valley fever. Valley fever is caused by inhalation of spores of the pathogenic fungus *Coccidioides immitis*. The spores exist in soils in certain parts of the Southwestern United States, northern Mexico, and a few other areas in the Western Hemisphere. Valley fever contracted by mammals typically produces flu-like symptoms and in some cases causes chronic pulmonary infection and (or) disseminated infections in soft tissue and bones (CDC, 2005; NIH, 2006).

The purpose of this study was to utilize existing geologic, soils, hydrologic, vegetation, and topographic data layers and a GIS modeling approach based on a published erosion hazard rating system to assess both the erosion hazard potential of soils found within the site and the relative likelihood that spores of the *Coccidioides immitis* fungus exist in the soils. The findings would then need to be conveyed in a simple and effective manner to resource managers, political representatives, and the general public.

Methods

The methods used in this study are discussed in two sections, the first describing the modeling process for erosion hazard potential, and the second describing the assessment used to evaluate the relative likelihood of *Coccidioides immitis* spore presence across the project area. Data layers that were used as input for the GIS modeling process include existing data on geology, soils, hydrology, vegetation, topography, and physiography.

Erosion Hazard Potential

Erosion hazard potential was assessed using the Erosion Hazard Rating (EHR) System presented in the Soil Conservation Guidelines/Standards Off-Highway Vehicle Recreation Management (Division, 1991) and preliminary soil survey data provided by the Natural Resources Conservation Service (NRCS, not dated).

The EHR assessment method is described in detail in the Soil Conservation Guidelines/Standards (Division, 1991). The method utilizes information on soil type, vegetation cover, slope, and precipitation to derive an EHR. The assessment for the site was conducted in accordance with the Division (1991) method and utilized a model developed in ArcGIS to prepare data for EHR calculations.

The EHR method determines the relative risk of surficial erosion from runoff drainage on an existing soil-covered surface. It provides a first measure of erosion risk, thereby enabling land managers to assess baseline soil-erosion conditions, as well as to evaluate, design, and plan soil-disturbing activities so that erosion hazard risk is minimized.

Table 1. Soil units in the project area (from National Resources Conservation Service).

Unit	Soil Unit Name	Soil Texture
138	Hesperia	Sandy loam, fine sandy loam
174	Xeric Torriorthents-Calcic Haploxerepts Association	Silt loam, silty clay
187	Trigo-Chanac Association	Fine sandy loam
193	Chanac-Pleito Complex	Sandy clay loam
201	Pleito-Chanac-Raggulch Complex	Sandy clay loam, loam, sandy loam, weathered bedrock
205	Pleito-Trigo-Chanac Complex	Sandy clay loam, fine sandy loam, loam
261	Blasingame-Arujo-Cieneba Association	Sandy loam, sandy clay loam
265	Arujo Sandy Loam	Sandy loam, sandy clay loam
267	Cieneba-Vista-Rock Outcrop Complex	Sandy loam, granite
277	Feethill-Vista-Walong Association	Sandy loam, sandy clay loam
297	Walong-Blasingame-Rock Outcrop Association	Sandy loam, sandy clay loam, granite
302	Feethill-Cibo-Cieneba Complex	Sandy clay loam, clay loam, sandy loam
305	Chanac-Pleito-Premier Association	Loam, sandy clay loam, clay loam
306	Xerofluvents, Occasionally Flooded-Riverwash Complex	Sand, gravel, clay
313	Landfill	

The NRCS-assigned soil unit names, soil unit numbers, and soil texture are provided in table 1. To calculate EHR, soil textures are assigned values which depend on the slope steepness. Other NRCS factors used in the EHR calculation include infiltration and permeability ratings, and depth to restrictive layer (that is, bedrock).

Six-hour precipitation intensity, soil cover, and slope length are also factored into the EHR rating. The precipitation intensity value was based on data obtained from a weather station in Glennville, approximately 20 miles northeast of the site. The Glennville weather station data were used to provide somewhat conservative precipitation information. Glennville is at a higher elevation than the site, and precipitation there is generally greater than in the lower elevations of the southern San Joaquin Valley.

Soil vegetative cover was assumed constant throughout the site. The assigned cover value was based on a mix of groundcover vegetation, exposed soil, and shrub and tree canopy.

The slopes at the site are generally smooth. There is little significant microrelief and organic debris such as logs and large branches that may act to disrupt surface-water flow. Accordingly, the slope length value was held constant in the ArcGIS model, which utilized a 10-meter digital elevation model (DEM) to illustrate the topography of the site and surroundings. To more accurately reflect the topography represented by the 10-meter DEM, the slope length range value used in the EHR assessment was based on slopes greater than 50 feet in length. The results of the EHR assessment for the site are illustrated in figure 1.

Assessment of *Coccidioides immitis* Spore Presence

The soils in the southern San Joaquin Valley, particularly uncultivated native soils on the valley flanks, are known to contain *Coccidioides immitis* spores (F.S. Fisher, U.S. Geological Survey, retired, oral commun., 2006); NIH, 2006). Research conducted by others indicates that within a region known to have the spores, there are variables which increase or decrease the likelihood that the spores may be present at a given locality within the region (Bultman and others, 2005; F.S. Fisher, U.S. Geological Survey, retired, oral commun., 2006).

A general ArcGIS-based assessment was made of the site using several of these variables to rate the relative likelihood that *Coccidioides immitis* spores are present in the different soils on the site. To do this, a simplified scoring system was used. Variables were weighted with points ranging from one

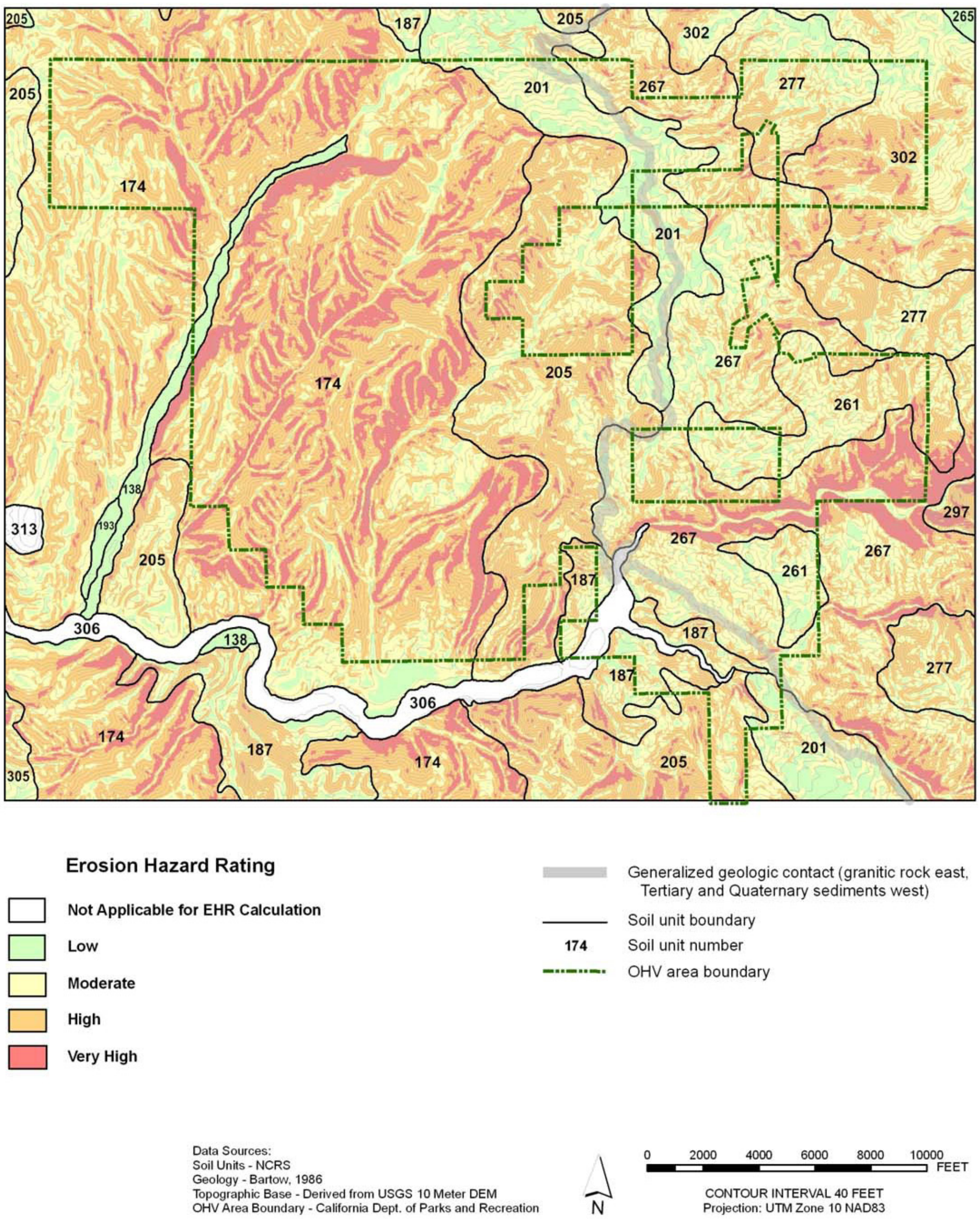

Figure 1. Erosion Hazard Rating map.

to three. Generally, each variable represents a characteristic of the soil type (for example, soil texture) or the physiography of the area (for example, seasonal drainage along a canyon bottom). These variables were given values of one or two. If the variable corresponds with a percent content, such as clay content, or a range, such as pH, the value given ranged from one to three, depending on percent content or range. This methodology is derived from work presented by Bultman and others (2005), and based on discussions with F.S. Fisher (U.S. Geological Survey, retired, oral commun., 2006). Higher values were given for conditions that would promote the growth of the spore, such as soils in a wash, which is subject to wetting and drying. Lower values were given for ground where the spore is unlikely to propagate, such as a granite outcropping on ridgeline. The results of the *Coccidioides immitis* spore presence assessment are illustrated in figure 2.

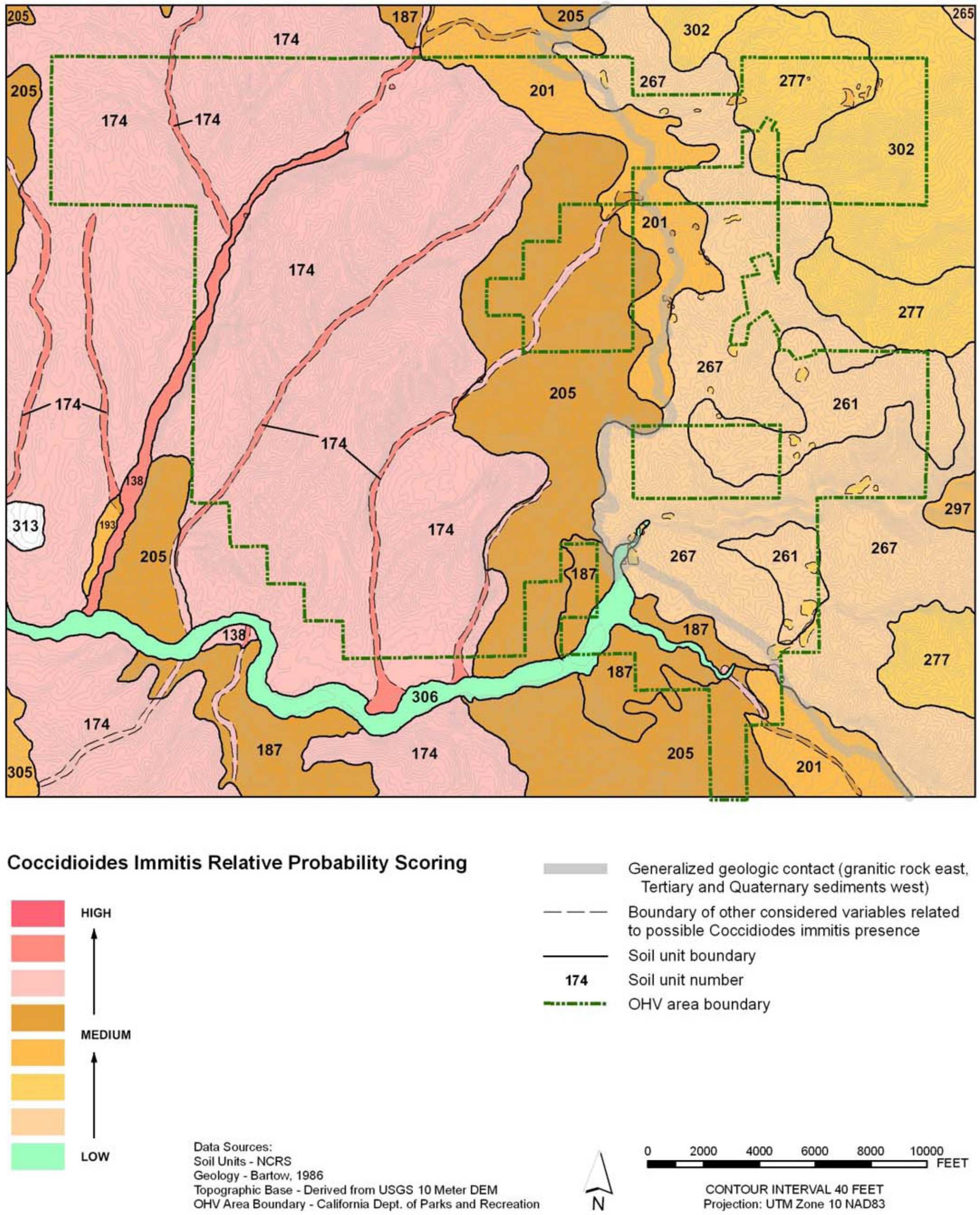

Figure 2. *Coccidoides immitis* relative probability map.

FINDINGS

Erosion Hazard Potential

Soils derived from Tertiary sediments, especially soil unit 174 (see table 1), appear to be the most susceptible to erosion as measured by the applied EHR method (fig. 1). These soils cover approximately the western two-thirds of the site, with soil unit 174 covering most of that area. An analysis of EHR values assigned to pixels within soil unit 174 shows that the EHR for this soil is Very High when it drapes a slope of 25 degrees (50 percent) or more. Correspondingly, this area, which consists of rolling hills and incised drainages, is mostly shaded orange and red, indicating an EHR risk of High and Very High (fig. 1).

Soils derived from the granitic bedrock on the east, which is mostly soil unit 267, appear to be comparatively less susceptible to erosion. This is due to the less varied topography of the granitic terrain; steep slopes are generally limited to the flanks of Poso Creek, which can be traced trending east to west along the lower half of figure 1. Elsewhere, slopes in the terrain are rarely steeper than 25 degrees. An analysis of EHR values calculated for soil unit 267 shows that the EHR for this soil is Very High when it is on slopes of 30 degrees (57 percent) or more, which is only 5 degrees steeper than the soil unit 174 discussed above.

Assessment of *Coccidioides immitis* Spore Presence

As illustrated in figure 2, soils west of the granitic bedrock have a greater likelihood of containing *Coccidioides immitis* fungal spores. These soils are mostly derived from Tertiary sediments. Again, soil unit 174 is the focus. This soil stands out because its silt and fine sand content, salinity, and favorable clay content and a corresponding water holding capacity are favorable for the growth of the fungus. Additionally, four prominent seasonal drainages run through the terrain covered by soil unit 174. Because these drainages provide a seasonal routine of wetting and drying the underlying soil, the likelihood that *Coccidioides immitis* fungus is in the soil is increased (F.S. Fisher, U.S. Geological Survey, retired, oral commun., 2006).

The likelihood that the *Coccidioides immitis* fungus is present in the fluvial sediments of Poso Creek (soil unit 306) is considered relatively low because this area is densely vegetated and the creek typically flows year-round; both of these factors inhibit the establishment and propagation of the fungus (F.S. Fisher, U.S. Geological Survey, retired, oral commun., 2006).

Discussion And Conclusions

The Tertiary sediments that underlie the soils in the western two-thirds of the site consist of fine sandstones, siltstones, and claystones (CGS, 2006), are generally soft, and are susceptible to erosion from concentrated runoff. Short of prohibiting OHV travel on the slopes in this area, reducing the erosion hazard risk to an acceptable level would be a significant mitigation effort. The soils in the western two-thirds of the site also have the highest relative likelihood of containing the *Coccidioides immitis* fungal spores (fig. 2).

It is unclear how to mitigate against the inhalation hazard of *Coccidioides immitis* spores when considering OHV recreation in this area. Dust suppression by spraying water on trails is ill-advised, as the frequent wetting and drying of soil may promote fungal growth and spore production (F.S. Fisher, U.S. Geological Survey, retired, oral commun., 2006).

In summary, this study provides an example of how existing geospatial data can be utilized in conjunction with known modeling factors to generate valuable information and potentially gain new insights. Through the proper use of such techniques, it is possible to distill a variety of related factors into an easily understood product to inform decisionmakers as well the layperson without any specialized GIS knowledge. In this case, the modeling process made use of existing data related to geology, soils, hydrology, vegetation, topography, and physiography, and provided information that assisted natural resource management and disease-mitigation efforts.

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Automation in ArcGIS 10: Understanding Changes in Methods of Customization and Options for Migration of Legacy Code

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Abstract

Important changes to how customizations and automations are created have been included in the latest update to Esri ArcGIS software, version 10. Microsoft has dropped support for Component Object Model (COM)-based programming languages Visual Basic 6 and Visual Basic for Applications (VBA) and is emphasizing a shift to Java- and .NET-compliant languages. As a result of this change, Esri is following suit by removing the familiar VBA development environment from their products, discontinuing its support, and promoting new scripting and application development alternatives. This paper seeks to describe the process of making the change from COM to .NET by (1) clarifying the reasons for the change, (2) discussing the leading vendor-supported, alternative scripting methods, (3) explaining the new Add-in model for customizing the ArcGIS interface, and (4) describing the most common and important differences between VBA and VB.NET code that are encountered during a conversion from previous versions of ArcGIS to version 10.

Introduction

With the release of ArcGIS 10, Esri has implemented many new features and updated components to their popular GIS software package. One of the most significant changes for power users is the way in which scripting, automations, and customizations to the user interface are handled. At the DMT'09 meeting in Morgantown, W.Va., I gave a presentation entitled "Improving ArcGIS workflow: Automation using Visual Basic for Applications (VBA)" in which I described using VBA to customize the ArcMap 9.x interface (Wunderlich, 2010). Since that time, the automations I described and posted to the Esri ArcScripts Web site have been downloaded over 1,600 times collectively, and I have received many emails regarding that presentation and the scripts described within it. Clearly, there is still a great interest in VBA applications, but as support for these applications is waning, it is now necessary to update these applications to work in the new customization framework of ArcGIS.

Since the debut of the ArcGIS suite (v. 8.0) more than 10 years ago, Visual Basic for Applications (VBA) has been its supported, integrated scripting language. In ArcGIS 10, support for the Microsoft Component Object Model (COM)-based VBA has been dropped, and a shift to Java- and .NET Framework-compliant programming languages is being emphasized. Customizations to the ArcGIS interface now require new methods of developing and debugging applications and scripts. Scripts, tools, and user interfaces developed using VBA will have to be converted to a compliant scripting language (such as Python) or converted to Java or .NET.

Customizing ArcGIS 10

One of the great advantages of the ArcGIS framework is that it is open for users to create customizations at any level of expertise, across the entire spectrum of the software's functionality. The most common forms of customization in ArcGIS 10 remain fundamentally the same as they were at 9.x, but with some notable differences, as explained below:

- Layer files, styles, representations, and templates in ArcMap documents
- Model Builder for creating geoprocessing workflows
- Python scripting (now with ArcPy) for advanced geoprocessing and map production
- Custom buttons and user interfaces (Add-ins) are created with Java, VB.NET, or C# *outside* ArcGIS using Microsoft Visual Studio (or Eclipse).

The first two items in this list remain relatively unchanged from 9.x. The more significant changes are the increased support for Python scripting and the deprecation of VBA and adoption of the Add-in component model, which uses the .NET development environment. The remainder of the discussion in this paper regarding customizations will focus on the latter two forms of customization.

Python Scripting and the New ArcPy Site-Package

With the launch of ArcGIS 10, Esri has fully embraced Python as its scripting language of choice for geoprocessing and automation of map production. Python is an open-source, cross-platform scripting language that has been in extensive use since the early 2000s. Some of the advantages of Python include its gentle learning curve, highly readable code structure, and runtime interpretation (no compilation or system registration is necessary). The ability to use Python for scripting has existed within the ArcGIS framework since version 9.0, mainly for creating geoprocessing scripts for use within ArcToolbox. Until now, Python was rather limited in functionality because many components of the ArcGIS framework were not exposed to Python. To improve the functionality of Python, Esri created the ArcPy site-package and added a command-line Python scripting window to all ArcGIS applications in order to allow scripts to be loaded and run on-the-fly within the individual applications (for example, in ArcMap and ArcCatalog). The ArcGIS Help describes ArcPy as an add-on to Python that "…provides access to geoprocessing tools as well as additional functions, classes, and modules that allow you to create simple or complex workflows quickly and easily" (ArcGIS Resource Center, 2011a).

Esri states that ArcPy has five major organizational groups: tools, environments, functions, classes, and modules (ArcGIS Resource Center, 2011a). ArcPy tools expose all available Toolbox tools, depending on your license level. This includes basic tools such as Buffer, Copy, Append, and Dissolve, and additional tools that are exposed by ArcEditor or ArcInfo license levels (for example, Densify, Snap), plus any tools exposed by licensed extensions such as the Hillshade tool in Spatial Analyst. Environments allow you to modify the tool's parameters that are used while executing, including: snapping tolerance, cell size for raster analysis, and input and output workspaces. Functions are general-use with no license dependence. They are used to do basic things such as checking for the existence of an object, querying feature class parameters such as the spatial reference, and refreshing the map view. Classes are "helpers" that aid the creation of objects (also known as instances) such as a spatial reference, a coordinate pair (point), or a cursor to store a set of features to be processed iteratively. These "instances" of objects can be referenced as often as needed during the execution of a script. Modules are groups of classes, used for referencing a specific set of functions related to a particular aspect of ArcGIS. For example, the Mapping module gives the user access to functions that open map documents, manipulate layers, and export or print maps. For more information about using Python and ArcPy in ArcGIS, see the ArcGIS Desktop Help topic "*What is ArcPy?*"

Using the Python window and utilizing the functions exposed by ArcPy, one can create some very powerful automations to aid in speeding up repetitive geoprocessing and map creation tasks. Consider the following example of a workflow that could be scripted with Python:

> An organization making an atlas is trying to create a graphical index of the atlas pages that shows the extent of each larger scale regional map on a small-scale map of the world. The process to do this manually would go something like this:
>
> - Open the ArcMap document of the atlas page.
> - Create a feature class to store a polygon that represents the spatial extent of the page.
> - Query the extent of the map and draw the corresponding polygon.
> - Create fields and calculate values in the polygon feature class attribute table that identify the map name and map scale.
> - Close the atlas page map document.
> - Open the map document that represents the graphical index.
> - Add the polygon feature class created in the previous steps.
> - Set the layer properties to label the polygon with the map name.
> - Save and close the graphical index map document.

Each step in this scenario can be accomplished by accessing various ArcPy modules and their classes: open and close map documents, create feature classes, query the map extent, create a feature based on the extent, add fields to the attribute table, calculate values based on map parameters queried from the document, add layers to map documents, and set map layer-labeling parameters. The user could additionally make the process iterative, whereby the script opens each map page, carries out the process of creating the extent polygon, and adds it to the graphical index map document in turn. If you or your organization has handled this type of process with a VBA script in the past, then a Python script will probably work very well for you in ArcGIS 10. Automation of repetitive processes that do not require a lot of user interaction are prime candidates for Python scripting.

Limitations of Python

The example presented in the previous section is one that is well suited to a Python solution. Many other tasks, such as generating empty databases from a template, validating database structures, and automated export of maps, are all perfect candidates for Python scripting solutions. However, as a development environment, Python has two major shortcomings when compared to more robust development environments such as Microsoft Visual Studio .NET (or even VBA). First, not all components of ArcGIS are exposed to Python. Geoprocessing tools and many functions for creating and interrogating datasets and map documents are available, but customizations to tool functions, or building new tools, is really not possible because access to the full library of ArcObjects is not available. Second, the editing and debugging capabilities of Python are limited. Third-party editors for Python, such as PythonWin (which is included with the ArcGIS 10 application suite), improve the readability and editability of the code, but do not have the power to debug and validate code as Visual Studio can. These are minor shortcomings and should not prevent users from developing scripts with Python. It is, after all, a *scripting* language, not an application development environment.

This brings us to the discussion of where the usefulness of Python gives way to more robust programming solutions. Python is not unlimited in capability and it is not appropriate for some important types of customizations that were accomplished with VBA in the past. Python's *most* important limitations compared to VBA or .NET are (1) it cannot listen for or respond to events within the ArcGIS application framework and (2) you cannot create any custom user interfaces that are tied directly to the application framework, such as buttons, toolbars, or user forms. If you have custom buttons, toolbars, combo boxes, editor extensions, or interactive forms that you need to function in ArcGIS 10, they will have to be recreated in the new system of customizations that Esri has implemented; these are called Add-ins.

Goodbye, VBA! Introducing Add-ins for ArcGIS

The Add-in model for customizing ArcGIS is a new feature, added at version 10. Add-ins have taken the place of VBA as the method for extending the user interface of Microsoft Windows-based applications that support customization. According to the ArcGIS Resource Center, the Add-in model "provides you with a declaratively-based framework for creating a collection of customizations conveniently packaged within a single compressed file" (ArcGIS Resource Center, 2011b). A more detailed discussion of the components of an Add-in for ArcGIS is presented in the next section. As for VBA, Esri has decided to continue support in a *very* limited fashion to facilitate the changeover. By default, VBA is not installed with ArcGIS 10, but it can be installed separately. If you choose to install VBA, a special license keycode must be requested from Esri to make it work, as if it were an extension such as Spatial Analyst. Esri is strongly discouraging any development using VBA and suggests that users migrate code to a supported language such as VB.NET, C#, C++, or Python. After version 10.0, VBA will be completely removed from ArcGIS and users will need to use the Add-in model for customizations to the user interface.

Overview of Add-ins

Add-ins are written in either a .NET or Java development environment. Major development packages that are supported by Esri include Eclipse and Microsoft Visual Studio (MSVS) 2008 and 2010, including the MSVS 2008 Express edition, which can be downloaded free of charge *from Microsoft*. [Note: As of this writing, only the *2008* version of MSVS *Express* is supported by the ArcObjects software development kit (SDK) for the Microsoft .NET Framework. See the SDK *system requirements* page for more information.] The ArcObjects SDK includes a wizard that integrates into these development environments to easily build new projects. The wizard handles the creation of all the required components of the Add-in. These components consist of the .NET or Java class (the code) and an XML file that describes the Add-in to ArcGIS, as well as any icons or picture resources required by the Add-in. When a new Add-in is created with the wizard, the user can name it, describe it, and specify its type. Then the required components are created and opened in the Solution Explorer of MSVS for the user to add the custom code.

There are many types of Add-ins available for ArcGIS when using the wizard:

- Buttons
- Tools
- Combo boxes
- Menus and context menus

- Multi-items
- Toolbars
- Tool palettes
- Dockable windows
- Application extensions
- Editor extensions

For more information about each type, and help in choosing the right one for your needs, see the article "*Building add-ins for ArcGIS Desktop*" in the ArcGIS Resource Center. The most common customizations are buttons, tools, combo boxes, toolbars, and editor extensions. Also, customizations that display information or accept input from the operator may present the user with a Windows user form, which can easily be added to button and tool projects.

Once an Add-in is created and custom code is written or converted from an existing VBA or VB6 project, it can be built and registered for use in ArcGIS. One of the advantages to the new system of Add-ins is that the user no longer has to paste code or load forms into the VBA editor manually or run an installation program to enable the Add-in to be recognized by ArcGIS. Simply building the project in MSVS will automatically register the Add-in on the computer used to develop it, and the .ESRIAddin file created during that process can be distributed to others and registered for use in ArcGIS simply by double-clicking the file and following the prompts.

Common Issues Encountered when Migrating Code

The purpose of this paper is not to step through a conversion of code from VBA to .NET, as there are many articles and resources available on the Web to help with specific details about the process. It is also difficult in a concise paper to explain *all* the nuances of conversion, so I have compiled some helpful resources for conversion, as well as links to articles that describe specific conversion tasks. Instead, I want to emphasize major differences between developing in .NET (specifically Visual Basic .NET) and in the VBA environment, including some of the most common errors you will encounter and some of the key differences in properties and syntax.

One consideration when beginning the conversion is the software environment in which you will be redeveloping your VBA projects. If you choose to use the freely available MSVS Express (VB.NET or C#), keep in mind that only the 2008 version is currently compatible with the ArcObjects SDK. The new project wizard will not be available if you use any 2010 Express edition (the wizard is available in all full versions of MSVS, 2008 and 2010). Also, one of the most helpful components of the SDK is the ArcGIS Snippet Finder, which is only available with full versions of MSVS and will not be available in any Express edition. Snippet Finder allows you to search for bits of code already written in .NET that can be inserted into your project.

Importing VBA Code to an Add-in

The first step for most code conversions is simply to import or copy/paste code from a VBA project to a new add-in project, in Visual Studio. In ArcGIS 9.x and earlier, code is commonly stored in the ThisDocument class of the "Normal" template of the application being customized (for example, in ArcMap or ArcCatalog). The code in that class can be exported to a file, typically called ThisDocument.cls. When you begin a new project in Visual Studio, you can import the contents of ThisDocument.cls to a new class in your project. Then you can take advantage of some of the error correction features of Visual Studio, which are far more advanced than the VBA editor's debugging capabilities. Depending on how many custom buttons and functions are stored in the ThisDocument class, you will probably need to split the code among several new classes and (or) several add-ins.

Once the code you need is imported into your project, notice the zigzag underlines on certain parts of the code. These denote errors in the code. The MSVS Error List inventories all the errors in the code, and by stepping through each error and either making the suggested correction or reworking the syntax, errors can be quickly identified and corrected. If you find that some of the errors are repetitive (as some of the errors undoubtedly will be) you can use the "Find All References" command from the context menu that pops up when right-clicking on an object in the code window. This command returns, to the Find Symbol Results window, all instances of a particular property or function within your project and gives you important information such as the object definition and line and character number of the occurrence (fig. 1). This is very helpful when you need to edit all instances of a reference or property *consistently*. Hovering the cursor over an error brings up a small exclamation point with a dropdown arrow that gives suggestions to correct errors (fig. 2), but be careful, the suggestions are based on the currently loaded references and might not always have the correct solution!

Another invaluable tool when working through a code conversion is the MSVS Object Browser. Once the ArcObjects SDK is installed, the Object Browser has access to every class object, interface, and property or method that can be accessed programmatically in your customization. This is especially helpful when an error description in the code informs you that a particular method is not associated with the object that it is referencing, or that a previously recognized class type is not defined and needs an object reference. By using the Object Browser's search function, you can search for the method and see which objects support it; this generally helps you find the correct object reference and fix the error (fig. 3).

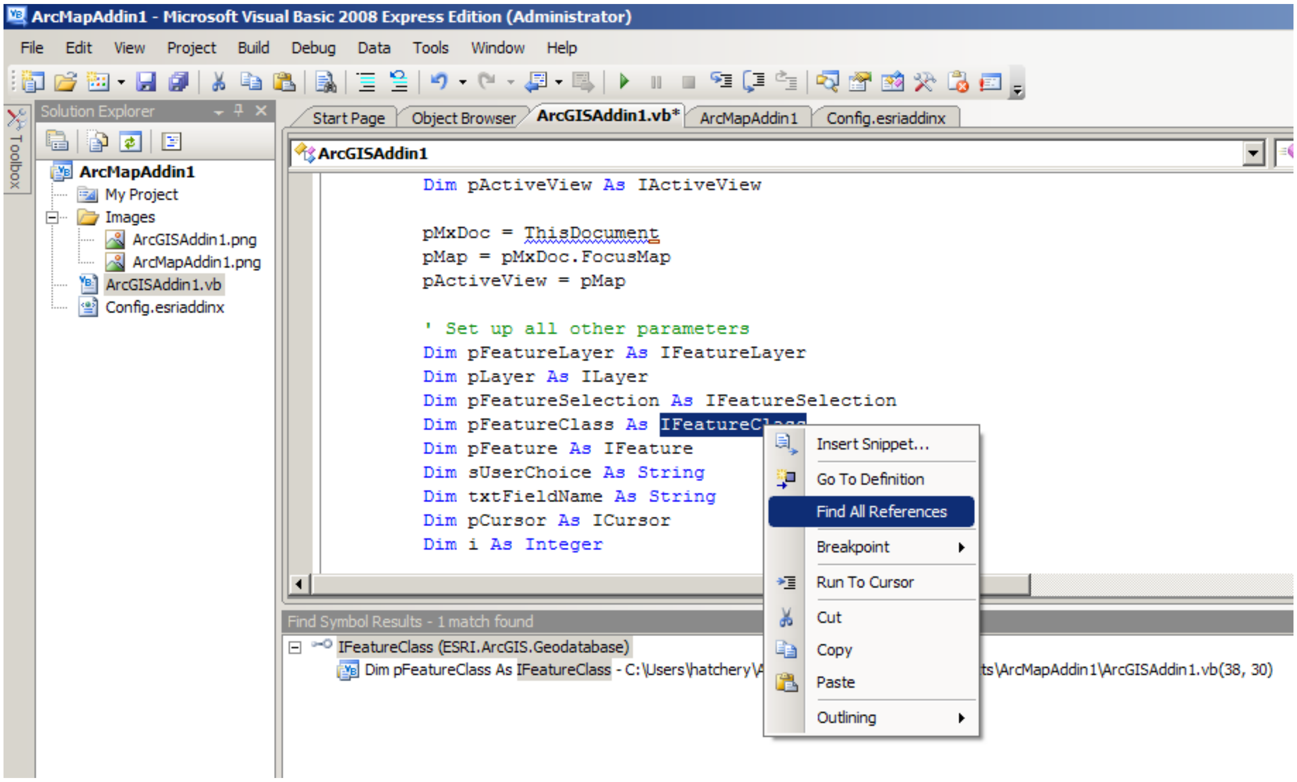

Figure 1. Use the "Find All References" command to identify all instances of a particular code object.

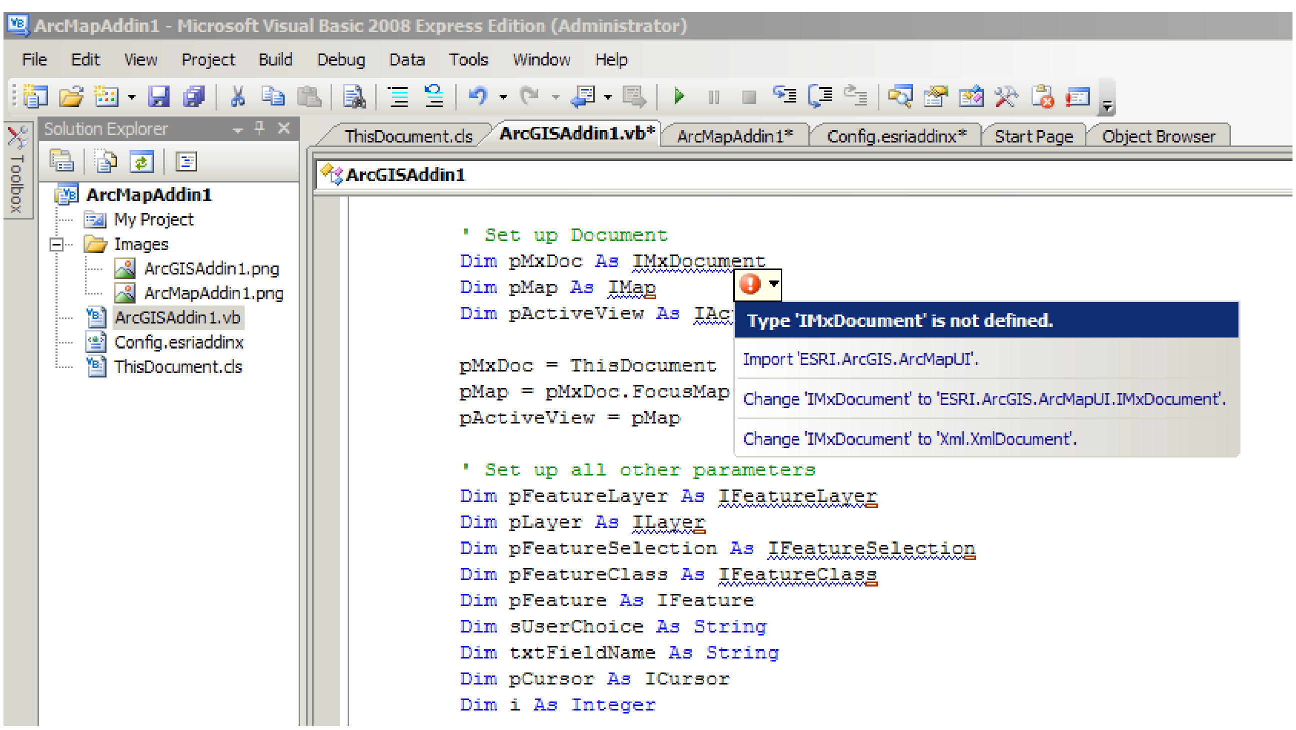

Figure 2. Context-sensitive error suggestions can be helpful to quickly correct errors. In this case, MSVS recognizes that in order for the "IMxDocument" interface to work properly, a reference to 'ESRI.ArcGIS.ArcMAPUI' must be added to the code. Unfortunately, not all reference errors are recognized automatically and will require the user to search the Help or Object Browser for a solution.

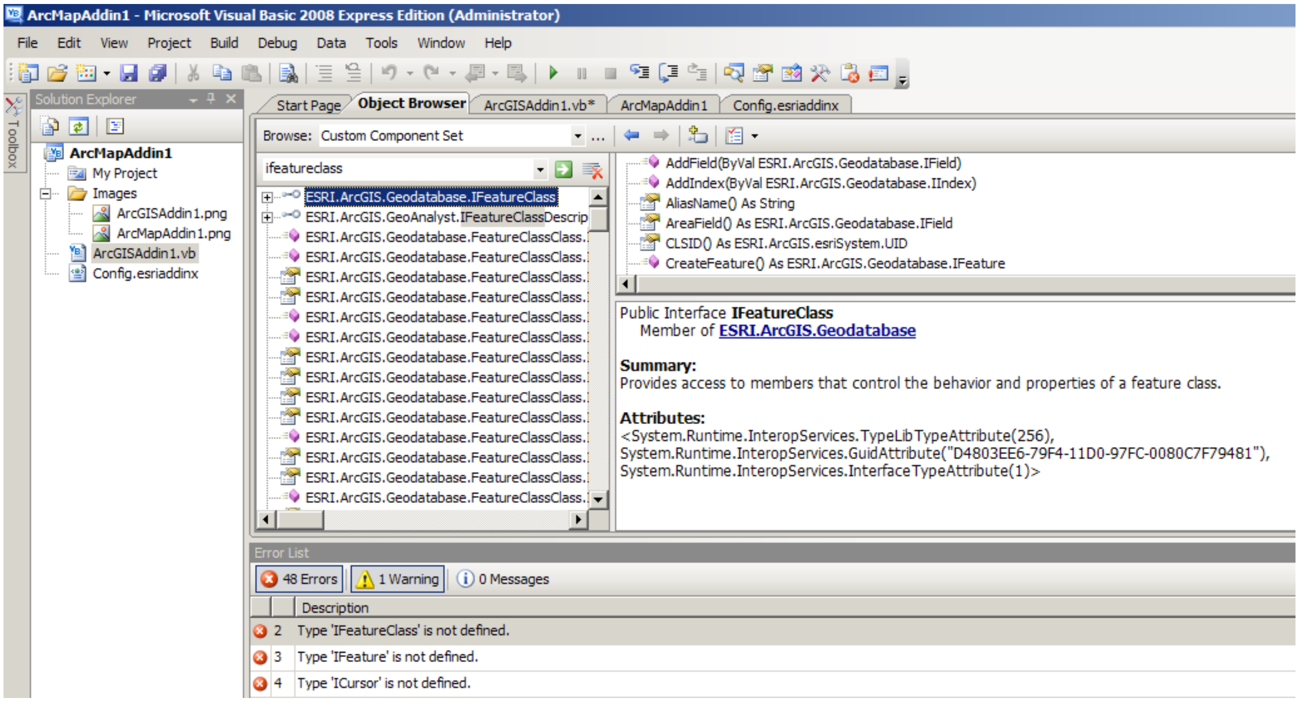

Figure 3. The Error List shows that "IFeatureClass" is not defined. Search the Object Browser for interfaces that are not recognized by the context-sensitive error handling. A search for "IFeatureClass" returns information about its functions, and a reference to its parent member "ESRI.ArcGIS.Geodatabase", to which a reference must be added for the interface to be accessible by the current project.

Fixing Some Common Errors

Errors in code that has been imported from VBA to VB.NET are inevitable, with varying levels of complexity when it comes to identifying and correcting their causes. In the process of unifying the SDK for ArcGIS, Esri has necessarily updated and changed some components within ArcObjects, which will in turn create errors in your code where before there were none. While this paper is not intended to be a comprehensive troubleshooting guide, it does discuss some very common errors that have simple solutions, which may be helpful to anyone making the transition from VBA to VB.NET.

Before trying to correct your code, remember that Add-ins and VB.NET are fundamentally different from VBA customizations in many ways but that the most important thing to do when converting code is to determine which object class references your project will need. In VBA, objects could be referenced implicitly; that is, every object that VBA could possibly access was exposed and could be called without adding references to specific classes of ArcObjects. In VB.NET (and others), object class references are always explicit and you will need to expose the object classes you plan to use in your project. These references must be assigned to your project in two ways: (1) at the project level and (2) in the code. It is important to understand the need for both sets of references. At the project level, the references are needed for the MSVS code editor to give context-sensitive help and debugging and to properly register the Add-in within the application framework when it is built (compiled). In the code, "Imports" statements provide hooks for the editing environment so that functions within each imported class are available implicitly within the current project, eliminating the need for additional syntax to make them explicit:

With an "Imports" statement placed *before* the first "Class" statement:

```
Imports ESRI.ArcGIS.Carto
```

… dimensioning can be done *implicitly*:

```
Dim pFeatureLayer As IFeatureLayer
```

… *instead* of explicitly:

```
Dim pFeatureLayer As ESRI.ArcGIS.Carto.IFeatureLayer
```

One of the most common errors that will appear in the converted code for a button or tool is the reference that most VBA projects use to hook into the open, currently active ArcMap document. Typically dimensioned as "pMxDoc" or similar, this reference was set to be equal to "ThisDocument." Since VBA was integrated into the application framework, this and other references to the active or open application window or document were coded without an explicit object reference. The fix for this is very easy. Simply change "ThisDocument" to "My.ArcMap.Document" and your project will have the correct, explicit reference to the parent application and its currently active document:

```
Dim pMxDoc As IMxDocument
Set pMxDoc = ThisDocument
```

…becomes:

```
Dim pMxDoc As IMxDocument = My.ArcMap.Document
```

Also note the slight change in syntax between the old and new references: the "Set" statement has been dropped and the lines are combined into one statement that simultaneously defines and assigns a value to the object "pMxDoc." This is due to a minor but important change in the syntax of assigning values to variables, which leads us to the next most common error: "Set" statements.

In VBA and VB6, many objects had a default property. This required that the "Set" statement be used in order to differentiate between the definition of the object *reference* and the *default property* of the object. With the removal of default properties of objects in VB.NET, the use of "Set" statements has become obsolete, and so too the need for a separate line to "set" a reference to an instance of an object. In most cases, simply going through your code and deleting all instances of the "Set" keyword should correct most errors, but some will persist in situations where the default property was used. This will require the removal of the "Set" statement as well as the addition of an explicit property keyword:

```
Dim lbl1 As Label, lbl2 As Label
lbl1 = "Label 1"     ' Assign value to lbl1's default property (Caption)
lbl2 = lbl1          ' Replaces lbl2's default property with lbl1's
Set lbl2 = lbl1      ' Replace lbl2 with an object reference to lbl1
```

…becomes:

```
Dim lbl1, lbl2 As New Label        ' Both become type Label
lbl1.Text = "Label 1"       ' EXPLICITY define the Text property
lbl2.Text = lbl1.Text       ' Copy Text property from lbl1 to lbl2
lbl2 = lbl1                 ' Copy object reference, "Set" not required
```

In a way, the object reference itself is now the default property, with all other properties becoming explicit.

The previous example also highlights another common source of errors; those brought about by the elimination of default properties. When converting from VBA, since default properties were allowed, your code probably contains at least a few of these errors. You might also find that some properties have changed name or been eliminated. See the following examples:

In VBA, this code worked:

```
'--- Define the unique identifier for geofeature layers
pGFL_UID = "{E156D7E5-22AF-11D3-9F99-00C04F6BC78E}"
```

… but in VB.NET, a warning is issued about type conversion:

"Runtime errors might occur when converting 'String' to 'ESRI.ArcGIS.esriSystem.UID'."

… because the object "pGFL_UID" needs its "Value" property set explicitly:

```
pGFL_UID.Value = "{E156D7E5-22AF-11D3-9F99-00C04F6BC78E}"
```

In VBA, the "Caption" property was a default property for several objects related to the construction of user forms. This property has been eliminated and replaced by the "Text" property. Labels on forms that were defined, even explicitly, will need to be corrected:

```
lbl1 = "Label 1"                    ' Throws an error...
lbl1.Caption = "Label 1"   ' So does this...
lbl1.Text = "Label 1"               ' This one works!
```

In the same vein, you may get a warning that there is an object "passed by reference before it has been assigned a value. A null reference exception could result at runtime." To avoid this error, you can set an object reference equal to "Nothing" until it is time to define it properly in your code:

```
Dim m_pEnumGxObject As IEnumGxObject            ' Gives a warning
```

… whereas:

```
Dim m_pEnumGxObject As IEnumGxObject = Nothing ' No warning!
```

This type of error rarely results in the code not functioning correctly. It is merely good practice to get in the habit of assigning object references explicitly in your code.

New Methods of Error Handling

With the potential for the number of errors being high in the initial conversion, it is very helpful not only to use the MSVS Error List to help find errors and correct them but also to update the error handling in your code. In VBA, it was common to use the "On Error GoTo …" statement to catch errors in code. This code construct is no longer supported, so you will need to update your error handling. The "Try…Catch…Finally" construct is now the preferred method for error handling. It has the advantage of being able to deal with unhandled (unexpected) errors while also allowing you to decide what errors to handle explicitly with customized error messages and actions:

```
Public Sub Example()

 Try
 ' Code to try and set a value for pObject goes here, then check it

       If pObject Is Nothing Then
         ' Handle this object definition error explicitly
         ' Pass this message to the "Catch" statement
       Throw New Exception("Error defining pObject.")
       Else : End If

 ' If all is well with pObject, code continues here...

 Catch ex As Exception      ' This catches all errors
       ' If the exception was handled, displays message you created
       MsgBox("An exception has occurred: " & ex.Message)
 Finally
       ' Put more code here to execute after error is handled
 End Try

 End Sub
```

This is a very simple example of an extremely powerful code construct. For additional information regarding the "Try…Catch…Finally" statement, see the *MSVS help*.

Implementing User Forms Within an Add-in

Many customizations to ArcGIS require a user form to get input from, or display information to, the user. User forms in .NET have some very different behavior than they did in VBA. One major problem when upgrading VBA user forms to .NET is that, unlike code modules, a form's design/layout module is not importable and will need to be reconstructed in MSVS. But, since much of the functionality and code has to be "rewired" anyway, redesigning the form is just a necessary inconvenience. Depending on the complexity of the form that is being upgraded, or if your customization uses several linked forms, recreating the functionality and behavior can be tricky in .NET. In these cases, see the Help and Resources section below; there are many Web resources for help in making the switch if you are facing a more complicated scenario. However, there are several basic behavioral and code-related issues with forms in .NET that are important to understand in order to make it easier to use a form in your Add-in.

The most significant difference between user forms in VBA and .NET is that in VBA the form object was implicitly referenced throughout the project; that is, once the form was created in the VBA project, it could be called upon without further dimensioning or instantiation. As with other objects in .NET, the form object must be instantiated and defined *explicitly* in order to function correctly. Because of this change, the way in which forms are handled and referenced across the project is also quite a bit different, especially if there are multiple forms that must interact with one another. MSVS help has an excellent article on using forms in VB.NET, how to use multiple forms, and how to upgrade form-calling syntax used in VBA and VB6 (see *http://msdn.microsoft.com/en-us/library/aa289529(VS.71).aspx*).

User forms in VBA were "modal" by default. Modal forms are displayed to the user with the execution of code following the call effectively paused until the form is hidden or closed. A form within an Add-in created in .NET has much more flexibility in its use, display options, and behavior. If your application's form must be modal as it would have been in VBA, you will need to be specific when displaying the form using the "FormName.ShowDialog" construct. Another useful option in the form properties is the "FormName.TopMost" switch. This option allows the form to ride above all other forms, while giving the user the ability to access other parts of the application without closing the form. A common example of a form of this type is a Find and Replace tool window. More information about displaying forms in Add-ins and VB.NET can be found in the MSVS help topic *Form Class*.

Conclusion

It is my hope that this article will be helpful to those beginning the transition from VBA to the new Add-in model for customizing ArcGIS. By adopting the Add-in model, Esri has greatly expanded the ability of users to customize their products with tools and user interfaces that were not previously available. While this article focuses on the VB.NET approach, there are many resources for developing in all the major languages available from Esri and Microsoft. Below, I provide some links to the most important online resources, but do not forget that a little creative Web searching can also provide answers to your questions. Chances are, someone has had the same problem or asked the same question you are currently pondering!

Help and Resources for Customizing ArcGIS 10

These resources will aid in converting VB6/VBA code to VB.NET (or other languages), as well as help you create customizations to ArcGIS 10 using add-ins. I have also included links to legacy topics. Much of the information stored on the legacy sites can still be quite useful:

ArcGIS 10 Web Help:
- Searchable help for all aspects of the ArcGIS 10 software package.
http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html

Esri Resource Center:
- ArcGIS 9.3 (and later) resources for developers. Includes information on configuring the user interface, using Python for geoprocessing, writing add-ins for ArcGIS Desktop, and the use of the comprehensive ArcObjects library for developing custom software and extensions.
http://resources.arcgis.com/content/arcgisdesktop/10.0/customizing

- ArcObjects .NET API Code Gallery – successor to ArcScripts.
http://resources.arcgis.com/gallery/file/arcobjects-net-api

Esri Support Center:
- Search for help with solutions to automation problems. User can create a free Esri Global Account and post questions, watch threads, and post solutions to others' problems. The Global Account also provides access to free webinars and other exclusive training materials relating to ArcGIS. Highly recommended!
http://support.esri.com

MS Visual Studio Help (2008):
- Links to topics relating to all things MSVS.
http://msdn.microsoft.com/en-us/library/52f3sw5c(VS.90).aspx

Legacy Help Sites (ArcGIS 9.3 and earlier)

Esri Developer Network:
- Home page for licensing developer tools, resource center, and developer community pages. Links to version 9.2 and prior development resources still available here.
http://edn.esri.com

- Code Exchange – find code samples and documentation for ArcGIS 9.2 and earlier.
http://edn.esri.com/index.cfm?fa=codeExch.gateway

Getting started with VBA:
- "Getting started with VBA" in the ArcGIS 9.3 Desktop Help.
http://webhelp.esri.com/arcgisdesktop/9.3/index.cfm?TopicName=Getting_started_with_VBA

- "Sample VBA Code" in the ArcGIS 9.3 Desktop Help.
http://webhelp.esri.com/arcgisdesktop/9.3/index.cfm?TopicName=Sample_VBA_code

- "Customizing ArcGIS [9.3] Desktop with VBA".
http://resources.esri.com/help/9.3/arcgisdesktop/com/vba_start.htm

Esri ArcScripts:
- Home page for user community script posting and exchange. This site has been closed to new postings since April 2010, but all content is still searchable and downloadable. Many useful scripts for version 9.3.1 and earlier. Search with keyword "Wunderlich" to find my scripts from the DMT'09 presentation.
http://arcscripts.esri.com

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Integrating Style Files and Carto Representation into the Geological Map Flow Process
(The GSC's implementation of the FGDC geologic symbology)

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Abstract

This poster presents the process of creating Federal Geographic Data Committee (FGDC) and Geological Survey of Canada (GSC) symbols for an ESRI style file and Cartographic (carto) Representation. Additionally, a master Excel spreadsheet is used to generate domains for feature coding and symbolizing geologic features and to maintain harmony between the FGDC style item codes and carto representation rule IDs. The procedures below are in sequence and show as an example how fold feature symbols are managed. These procedures are integrated in the GSC's Geological Map Flow project to assist cartographers in map production.

Symbol Reference and Requisition

The FGDC Digital Cartographic Standard for Geologic Map Symbolization is used as the base point for the standard style file and carto representations that will be used in the Geological Map Flow process. The entire library of symbology has been created except for those that limitations in the ArcGIS software would not allow. Some of the map elements, such as state location maps, bar scales, and declination arrows, were not created. The Geological Map Flow project has other means to create these map surround elements.

If the author cannot find a suitable symbol in the FGDC standard (either because it does not exist in the standard or the author strongly feels that a second option is needed), the author fills out a Symbol Creation Form (fig. 1). On this form one states the type of symbol needed, colour, whether the symbol is based on an existing one, a description for its use in the legend, notes on the symbol's usage, and a detailed drawing of the symbol (giving as many dimensions as possible). This form is then passed on to a Legend Review Committee. This committee reviews the request and decides if an existing standard symbol should be used instead or if the new symbol should be created. This committee also fills out the second page of the form, which provides the database designers with the information needed to incorporate the new symbol into the bedrock or surficial data models. These data models store and manage geologic features from which the maps are derived. Once approval is given, the form is passed to the Symbol Steward, who then creates the symbol in the standard style file and as a carto representation.

Font Creation

Each point symbol or line decoration is drawn to scale in CorelDraw (fig. 2). A template has been set up with a 420-millimeter (mm) by 420-mm bounding box which has been determined to be the optimal dimension, comparable to specifying the size of the symbol in an ArcGIS style file. After the symbol is drawn to scale, it must be determined to be a single object, and all lines must be converted to outlines. Once this is achieved, the symbol is centered on the template and scaled to 420 mm in its largest dimension with "keep aspect ratio" turned on. It is then exported to a TrueType font under the next available character number (available numbers are 33 to 126 and 161 to 255; others are system reserved).

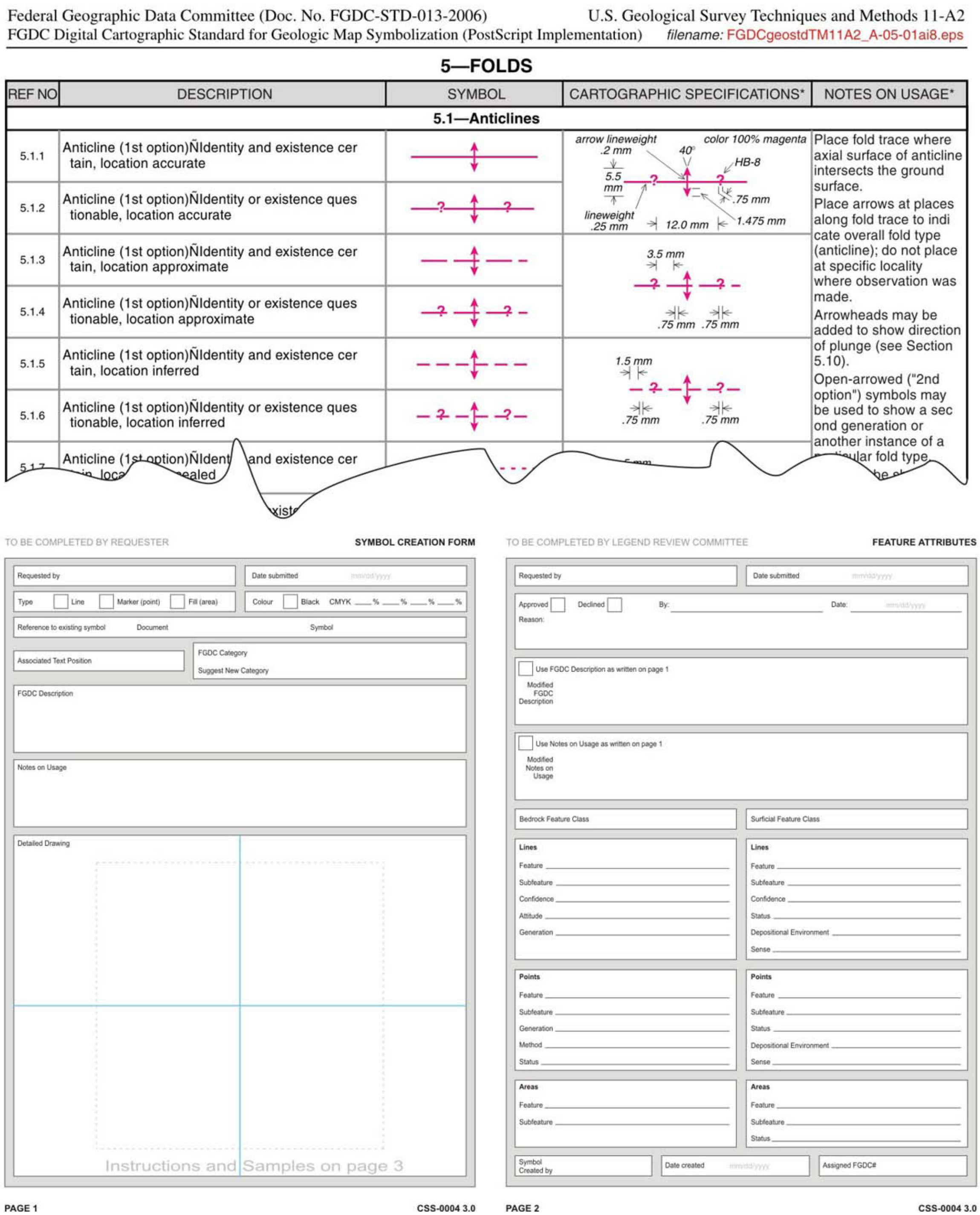

Figure 1. Symbol reference and requisition. The top portion of the figure depicts a piece of the FGDC standard from which authors can choose symbology (FGDC, 2006). If a symbol does not exist, the forms depicted on the bottom are used to draw and describe the new symbol for a Legend Committee to approve. The second page of the form is used to fill out information needed about the new symbol so the database designers can add it to the standard geodatabase.

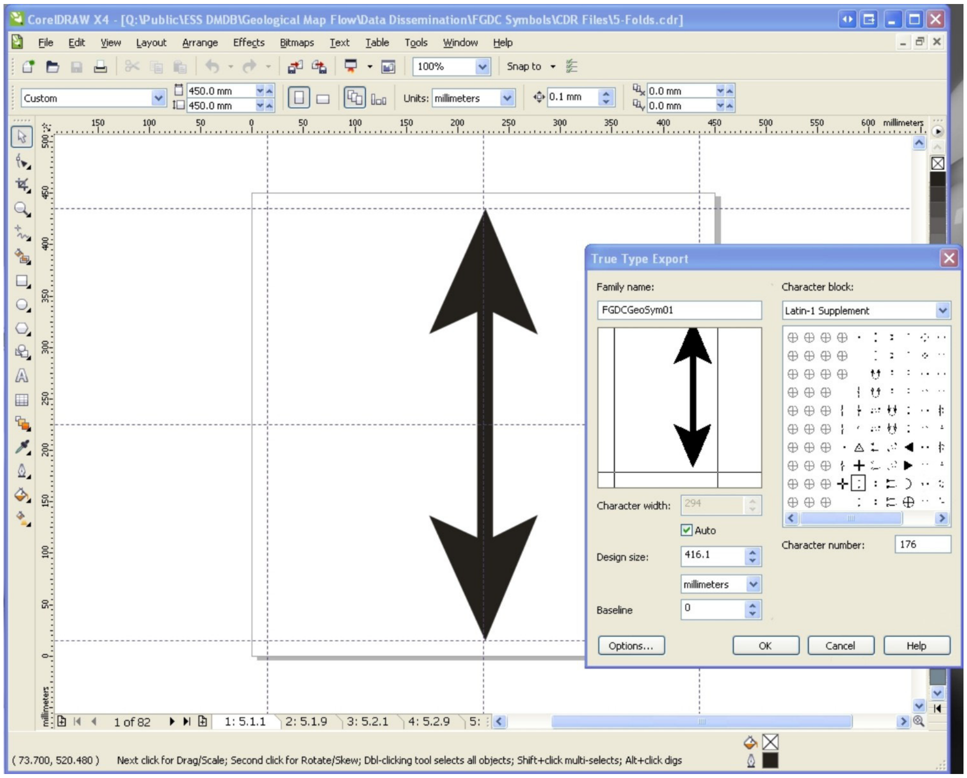

Figure 2. Font creation in Corel Draw.

Create Style Item and Check Symbol

Once the TrueType font has been updated, the complete symbol is created using the ArcGIS Style Manager (fig. 3). Each layer of the symbol is built to specifications provided on the Symbol Creation Form (for example, mark/gap line pattern, size of marker, colour). The new symbol is categorized according to which FGDC category it best fits and given a style item number that matches the FGDC standard. The newly created symbol is then brought into an ArcGIS .mxd and checked for sizing, orientation, and point of origin. Sizes may have to be adjusted to achieve specified dimensions, and offset values may have to be applied to point symbols so the point of origin occurs in the correct location.

Generate Carto Representation

All symbols in the style file are imported/converted into carto representation rules and stored in a master geodatabase template under the appropriate representation that corresponds to a feature class in the geodatabase (fig. 4). Each representation rule is checked to ensure that sizing and spacing accuracy was maintained after the conversion. A master Excel spreadsheet exists to aid in maintaining the sequence of carto representation RuleIDs. It contains a worksheet for each feature class that has the FGDC reference number and description, the style file number for “match to style,” and the assigned RuleID. These fields are critical in the following steps, where domains are created and a consistent relationship exists between style number and the RuleID.

Convert Table to Domain

The fields STYLE_NO and STYLE_DESC_EN in each Excel worksheet are used to create a coded value domain for each feature class in the project geodatabase (fig. 5). This procedure is required to be applied to each feature class in the geodatabase. In the future, a geoprocessing tool could be created to automate this process.

Assign Domain

In ArcCatalog, each of the domains is then assigned to the SYMBOL field in each of the corresponding feature classes (fig. 6). The SYMBOL field is then used in ArcMap, to render the feature on the map using “Match to Symbols in a Style.”

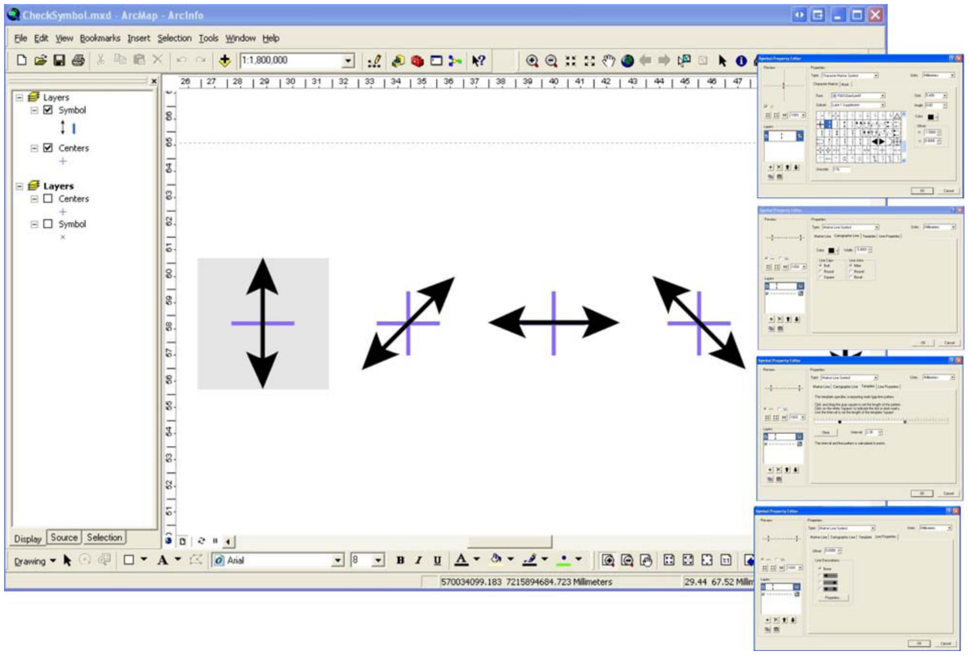

Figure 3. Creating the style item and checking the symbol in ArcGIS.

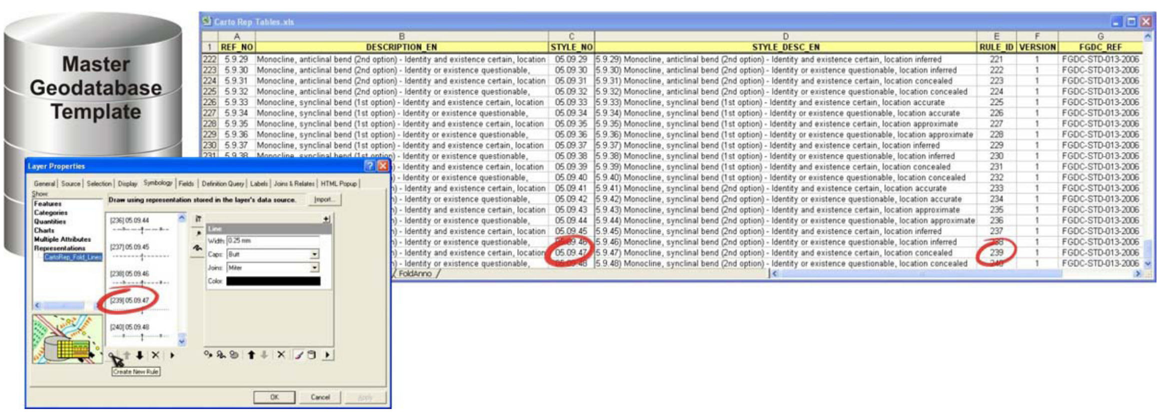

Figure 4. Generating the carto representation. This gives a view of the master spreadsheet that is maintained to keep correlation (circled in red) between the carto representation RULE_IDs that are stored in a master geodatabase template and the Symbol number stored in the standard style file.

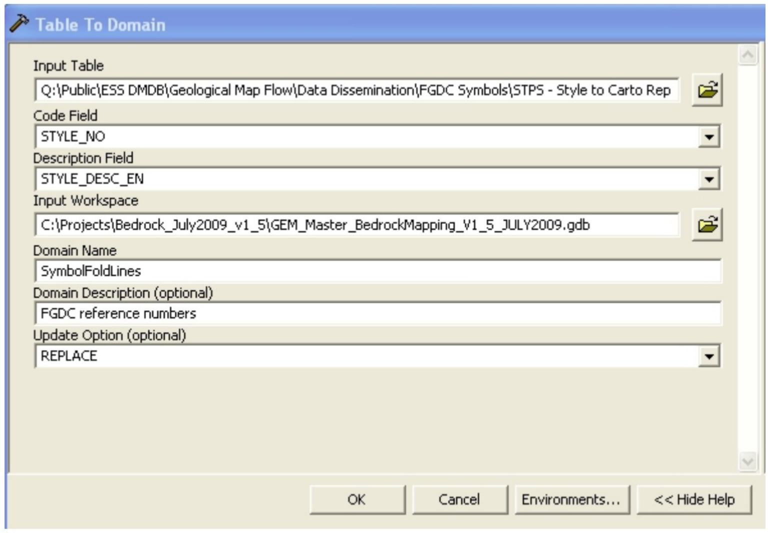

Figure 5. Converting symbols in the table to domains.

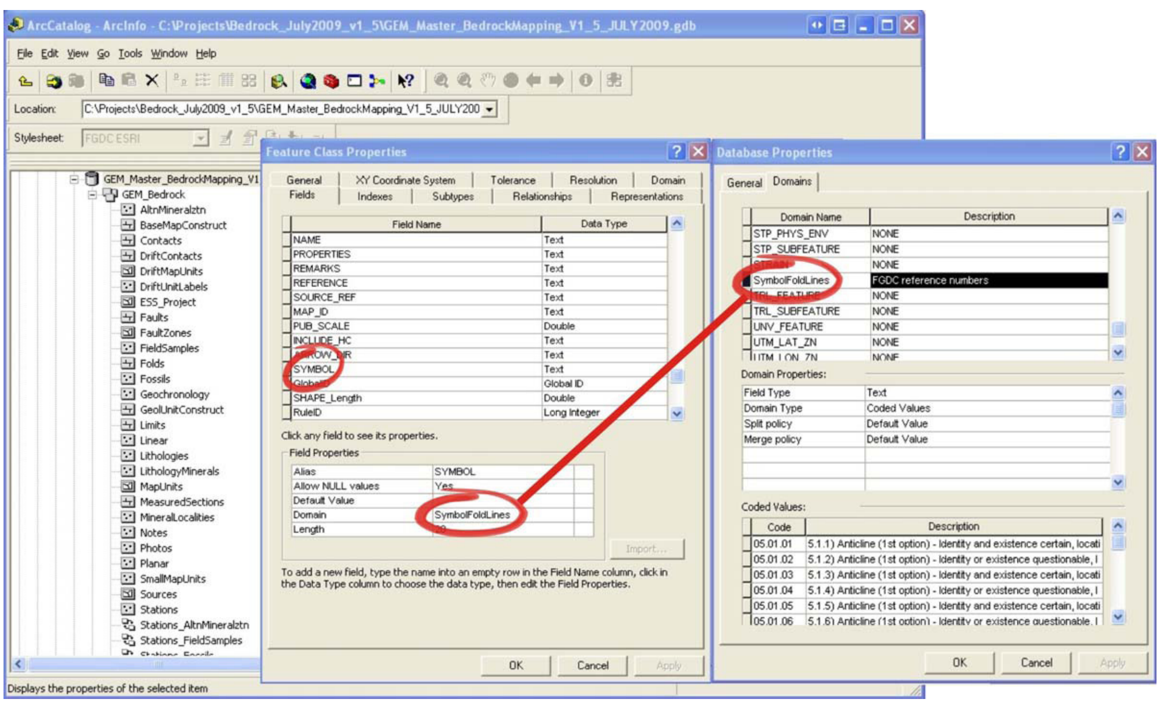

Figure 6. Assigning domains to the feature's Symbol field.

Copy Carto Representations

Using the Capture Representation Tool (Clark, 2009), copy the carto representation rules from the master geodatabase template for each feature class in the project geodatabase. Browse to the desired feature class in the master geodatabase and supply a name for the new representation class (fig. 7). This tool ensures that the RuleID number sequence is maintained as listed in each Excel worksheet.

Join Table

In ArcMap, join each individual Excel worksheet to the layer's attribute table in order to calculate the RuleID field (fig. 8). The join is based on the SYMBOL value in the layer and the STYLE_NO in each Excel worksheet (many to one).

Feature Coding

An FGDC symbol from the domain description (for example, "5.1.2 – Anticline (1st option). Identity or existence questionable, location accurate") is assigned to the SYMBOL field (fig. 9). The coded value domain (05.01.02) is actually used in the "Match to Style." This provides a simple method for geologists to symbolize features during map compilation as well as providing some standardization.

With the Excel worksheet joined to the layer attributes, the RuleID can be calculated to equal the value of the RULE_ID field in the joined Excel worksheet. This will ensure that the carto representation rule ID matches the FGDC symbol stored in the SYMBOL field.

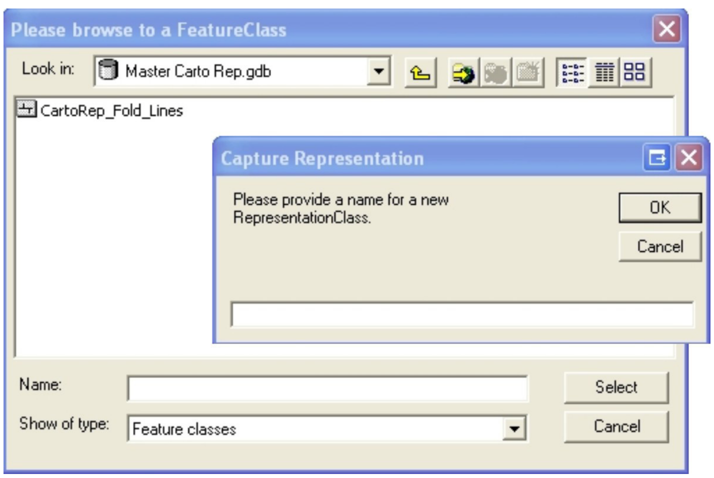

Figure 7. Copying carto representation rules for each feature class from the master geodatabase template to the project geodatabase.

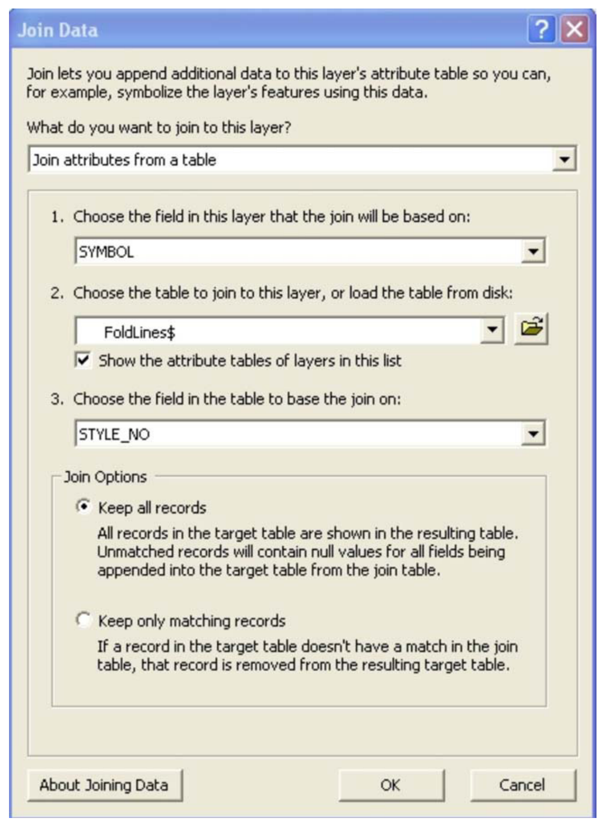

Figure 8. Joining attributes in the master Excel spreadsheet to each feature class attribute table.

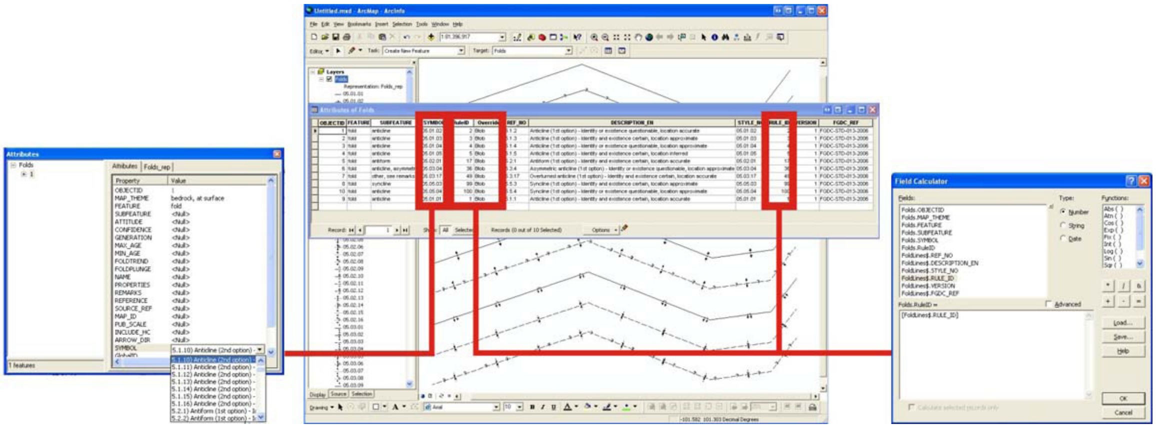

Figure 9. Feature coding. The left side depicts assigning an FGDC symbol (with domain description) to the Symbol field of the feature class. The coded value of the domain (which is the style file symbol number) is used to render the feature using “Match to Symbol in a Style.” The right side depicts assigning the RULE_ID value from the joined master spreadsheet to the carto representation RULE_ID of the feature class.

References

Clark, Ryan, 2009, Arizona Geological Survey, Capture representations: An ArcScript available as a download from ESRI Support Center, *http://arcscripts.esri.com*.

Federal Geographic Data Committee [prepared for the Federal Geographic Data Committee by the U.S. Geological Survey], 2006, FGDC Digital Cartographic Standard for Geologic Map Symbolization: Reston, Va., Federal Geographic Data Committee Document Number FGDC-STD-013-2006, 290 p., 2 plates, *http://ngmdb.usgs.gov/fgdc_gds/*.

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Creating Shaded Relief for Geologic Mapping using Multiple Light Sources

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Introduction

While symbols and colors on a geologic map give insight to the geology of a region, it is the shaded relief that reveals the geomorphology of the terrain. Creating a true-to-form image of a landscape's terrain has been a challenge for cartographers for centuries. Portraying three-dimensional surfaces on a flat piece of paper can only be done by tricking the eye (Thelin and Pike, 1991). This can be done with careful and suitable positioning of a light source. By introducing just the right position of a light source and the height in which light strikes the landscape, the illusion of depth in the terrain is created.

However, in applying a light source against elevation data, the generated shadow effects of shaded relief can be troublesome when adding colored thematic maps such as geologic maps. Detail in the shaded relief is defined by shadows, resulting in dark hues of gray and black pockets in ridges of mountains that will alter any color that is overlain. For example, Quaternary geologic map units that are typically shades of yellow appear muddy and greenish when placed over a highly detailed image of shaded relief. All colors are directly affected by the shaded relief, making them appear darker than their original hue. The challenge is to create shaded relief that retains detail through shadows and light application yet is faint enough to overlie a geologic map without misrepresenting the true hue of the geologic map units.

To enhance the shaded relief while preserving the original colors, the Idaho Geological Survey has developed a process for creating shaded relief from Digital Elevation Models (DEM). We developed a semi-standardized method using ESRI ArcMap (*http://www.esri.com*) and Adobe Photoshop (*http://www.adobe.com*) to create crisp hillshades to add detailed shaded relief to our geological maps without compromising the colors of the units.

Early Trials

Before establishing a new method of generating shaded relief, we decreased the opacity of the hillshade image in Adobe Illustrator during the layout process of map production. This gave us the results we were looking for in regards to matching the colors on the map to the geologic map units but presented us with yet another problem. Simply making the image more transparent faded the detail of the shaded relief. In another effort to lighten the hillshade, the brightness and contrast of the image were altered in Adobe Photoshop but resulted in the same faded appearance. It became apparent that more steps were needed in order to generate the hillshade in ArcMap, before the shaded relief was brought into the layout stage of map production. The idea was to create a single shaded relief image with multiple light sources to bring in more detail and reduce the saturation of dark shadows.

A New Method of Building Shaded Relief

Hillshades

The first step of the new process begins with creating three new hillshades from the DEM file in ArcMap, each with a different origin of light. The hillshades are created using the *Hillshade* tool found in the extension *Spatial Analyst* toolset, under the *Surface Analysis* menu. The light source is determined by the azimuth and altitude; azimuth is the illumination direction, and altitude is the illumination angle. The azimuth is a measurement between 0 and 360 degrees in which 0 is north, 90 degrees is east, 180 degrees is south, and 270 degrees is west. Light sources coming from the east and south will cause topography to look reversed. Values that are more northerly and (or) westerly are preferred. The altitude is a measurement in degrees of the light source position relative to the horizon. With an altitude value of 0 degrees, the light source is set at the horizon, whereas a value of 90 degrees sets the light source directly overhead. Using an altitude from directly overhead will make flat regions appear like an overexposed photograph, eliminating any detail in flatter regions, while using values closer to the horizon will make the landscape extremely dark, casting large black shadows around any topographic feature with significant elevation. Another important factor in creating the hillshade is the vertical exaggeration, which enhances the appearance of depth in the terrain. This is determined by the z factor, which is a multiplier of the z values (elevation). The higher the z factor, the more exaggerated the depth of the terrain will appear.

After experimentation with different azimuth, altitude, and z factor values, we have developed a suggested value set for creating hillshades. The transparencies of the three hillshades we create are then each adjusted individually. Varying the transparency values of the three hillshades allows the different topographic details accentuated by each hillshade to be seen in one image. Dark shadows that exist in a single hillshade are compromised by the presence of light in another hillshade. The hillshades that have darker shadows are made to be slightly more transparent than those with lesser shadows. The result is a more balanced image (fig. 1). An example of the values for the azimuth, altitude, and transparency we use is shown in table 1. The order in which the hillshades are layered is determined by the light and dark qualities of the hillshades. The hillshade with the lightest qualities are placed on top. When the transparencies are set, the image is ready to be exported from ArcMap. The image is saved as a tiff file so that it can be opened in Adobe Photoshop for the next steps of the process.

It is important to keep in mind that each DEM file needs its own special attention to bring out the detail desired by the cartographer. Different terrain types may benefit from alternate light sources and therefore these values used by the IGS should be considered as a guideline. It is also a good practice to experiment with different transparency levels for each hillshade.

Adobe Photoshop

Although the shaded relief created by layering the three hillshades in ArcMap does result in an image with fewer dark shadows, more can be done to improve the detail of the image and make it even lighter. In Photoshop there are several tools to manipulate the image to modify the highlights and shadows within the terrain. These tools can be found in the Image menu under Adjustments.

Shadows and Highlights Tool

We start with the *Shadows/Highlights* settings to further modify the shaded relief. The *Shadows/Highlights* settings lighten and darken the image on the basis of the surrounding pixel values. This property of the tool allows the cartographer to highlight details by emphasizing feature characteristics separately, as the shading that is applied is based on the individual pixel values rather than application of uniform shading to the entire image. The *Shadows/Highlights* dialog box uses sliders to make the adjustments and has a preview option so that the values applied can be seen immediately in the image.

The first setting in the dialog box is *Shadows*, which will alter the dark areas of the image (fig. 2). We set the slider in the higher percentage range, between 75 and 90 percent. The dark shadows added can be modified using the Tonal Width and Radius sliders. The Tonal Width adds a control on the adjustments being applied by setting a range to restrict how much modification occurs. We set the Tonal Width to a high value, between 80 to 95 percent, thereby restricting the adjustments to lighten just the darker regions. The Radius setting determines the extent of how many surrounding pixels will be affected by the adjustments. We set the Radius of the shadows setting between 35 and 200 pixels. The radius of the shadow setting is dependent on the diversity of elevation in the hillshade. Areas with lower elevations should get higher radius values to capture the small details of terrain features, whereas hillshades dominated by higher elevations should get lower values to ensure that fewer pixels are included in the adjustments, in order to prevent the addition of too many dark shadows.

Table 1. Example values for azimuth, altitude, and transparency for building hillshades. Each hillshade is given the same vertical exaggeration value (z factor=2).

Hillshade Layer Sequence	Azimuth	Altitude	Transparency
Top	350°	70°	65%
Middle	15°	60°	50%
Bottom	270°	55°	70%

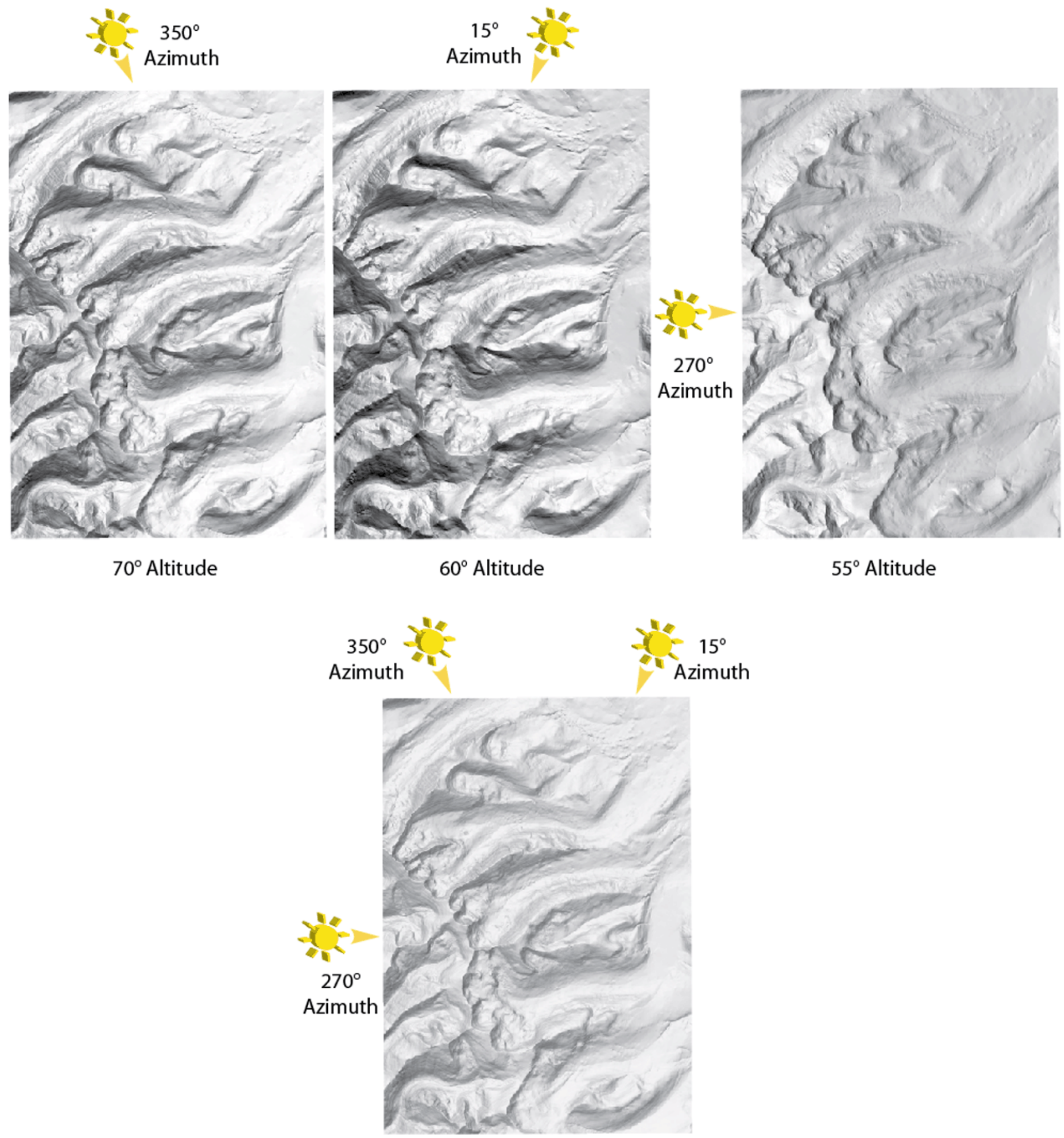

Figure 1. The three hillshades shown on the top row were created in ArcMap with different light sources. Their azimuths and altitudes are typically used by the IGS for these applications. The image on the bottom displays the three hillshades layered together, with their transparency settings optimized.

The Highlight settings complement the Shadows settings by processing only the light regions of the image. Increasing the percentage of the Highlight setting will darken the image, thereby showing more detail by accenting low-relief features. This is especially important in the lower elevations, where detail is harder to see in the original image. Adjusting the highlights also gives the shaded relief a smoother appearance. We typically keep our Highlight setting low to prevent the image from getting too dark. We set the Highlight between 5 and 20 percent. The Tonal Width of the highlight settings works the same as the Tonal Width of the Shadow settings, but on the opposite spectrum. We set the Tonal Width in a lower range from 5 and 20 percent, to lighten the image. The Radius of the Highlight settings is set to the same value as the Radius of the Shadow settings.

The last options in the *Shadows/Highlights* dialog box are the Brightness and Midtone Contrast. Changing the brightness and contrast too much can result in a loss of the detail created by the previous steps. We only brighten the image slightly and decrease the contrast slightly when working through the *Shadows/Highlight* adjustment tool. We typically set the brightness to about +15 and the contrast to -5.

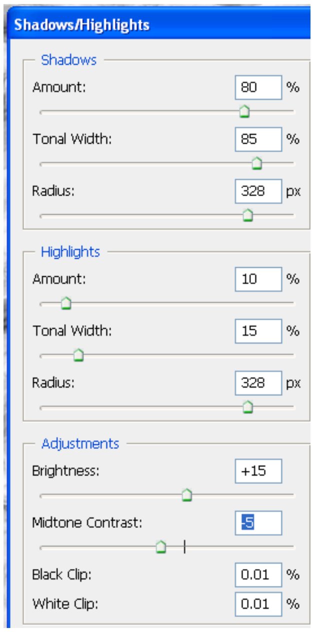

Figure 2. Dialog box for the *Shadows/Highlights* tool in Adobe Photoshop, showing the slider values used to adjust the image.

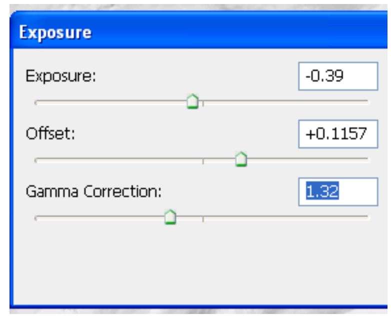

Figure 3. Dialog box for the Exposure tool in Adobe Photoshop, showing the slider values used to adjust the image.

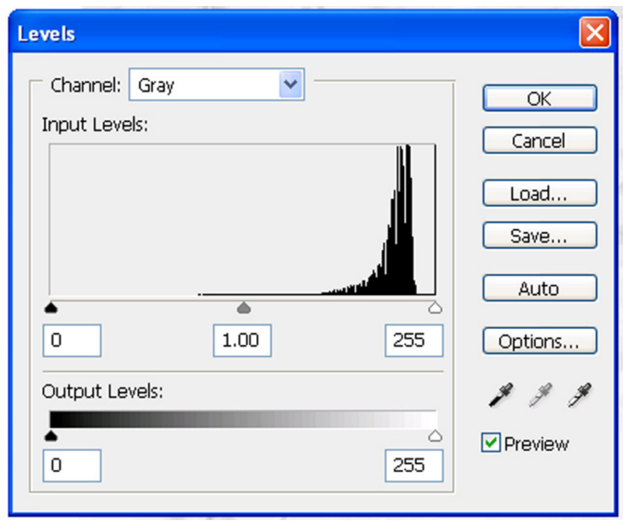

Figure 4. Dialog box for the Levels tool in Adobe Photoshop, showing the slider values and grayscale bell curve used to adjust the image.

Exposure

To lighten the image we use the *Exposure* tool found in the Image menu in the Adjustments drop down list (fig. 3). The *Exposure* tool allows more control in lightening the image than the Brightness and Contrast tools because it is based on calculations in the gamma spectrum. In the *Exposure* dialog box there are three values that can be specified—exposure, offset, and gamma. The exposure value adjusts the highlights of the image with very little effect on the shadows in the image. The offset value alters the shadows' midtones, with minimal effect on the highlights in the image. The gamma value uses a power function so that negative values are adjusted as if they were positive. To find the optimal adjustment, a sliding scale is used for each value. We set the exposure slightly toward the negative side, but no farther than -0.50. The offset is pushed toward the positive side, but no more than +0.30. We set the gamma to a value greater than 1, but no greater than 1.5.

Setting Levels

If the image still has dark areas even after using the *Exposure* tool, we use the *Levels* tool to change the grayscale of the shaded relief (fig. 4). The *Levels* tool is found under the Image menu in the Adjustments menu. In the *Levels* dialog box, the input and output values of the color ramp can be changed. The input values stretch the tonal range, which is defined by the output levels. As the default, the values are set to 0 for black and 255 for white. With the preview box checked, the value alterations can be seen in the image. To eliminate black areas in the image, the output value can be changed using a grayscale range from black (value of 0) to white (value 255). We usually set the black side of the range to a value from 20 to 80 in order to tone down the black values in the image.

To lighten the image even more, adjustments to the input levels can be altered, between 0 and 255. Three values that can be changed on the input grayscale—we set them to about 0, 1.40, and 215. The sliding scale under the input bell curve is helpful in finding the right balance of grayscale input values for the shaded relief. The image is then saved with a new name so that the original is not altered. Figure 5 shows the final results of creating shaded relief using multiple light sources and the Photoshop imagery tools, compared to our previous method of creating a single hillshade in ArcMap.

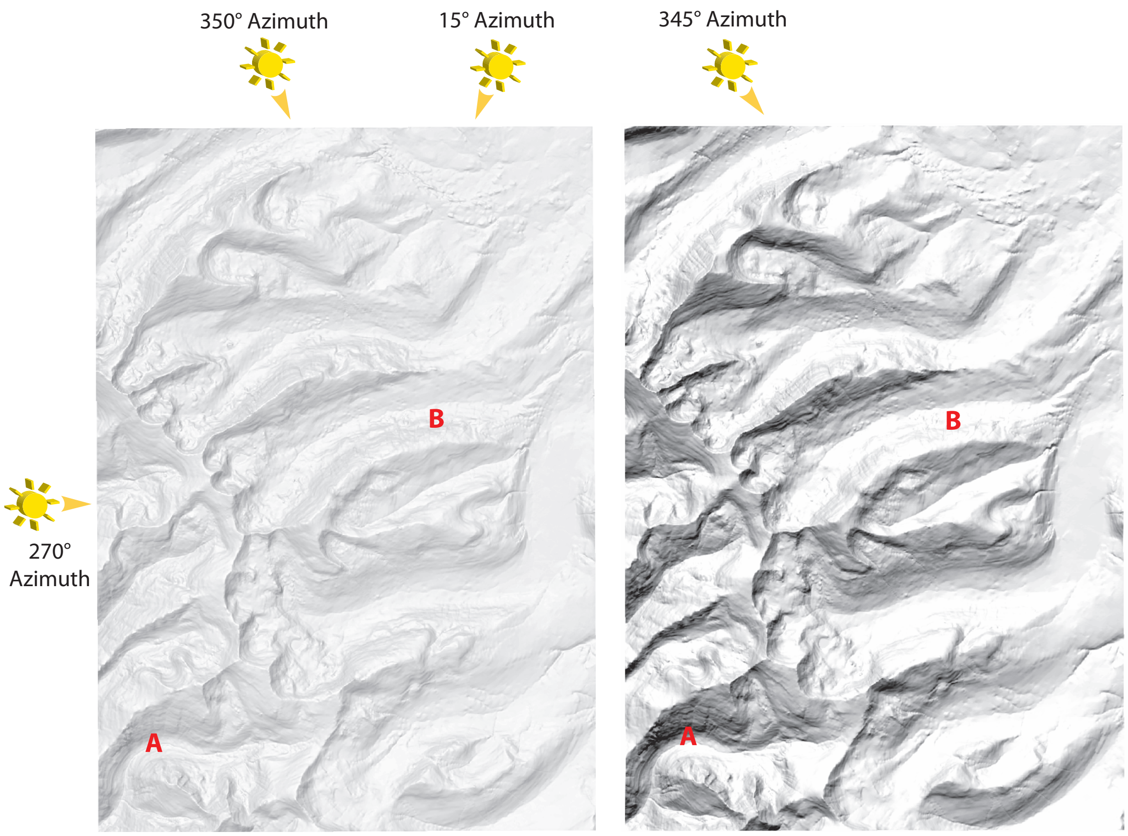

Figure 5. Imagery tools in Adobe Photoshop give the cartographer more control when modifying the highlights and shadows in a shaded relief image. With a combination of these toolsets and illumination from three different directions, the shaded relief created is still distinct in detail yet light in saturation. The image on the left is an example of our new method using multiple light sources and Photoshop imagery adjustment tools to produce shaded relief. The image on the right is an example of our previous method using one hillshade with one light source. The shaded relief on the right has more dark shadows and overexposed areas resulting in an image lacking in overall detail. The region labeled "A" is an example of how black shadows are reduced in Photoshop. The region labeled "B" demonstrates the loss of detail where features are overexposed to light using only one light source (right image), whereas the image with multiple light sources (left image) retains more detail.

Overlaying Color

The shaded relief image is now ready to be inserted into an Adobe Illustrator document, where the geologic map units will be combined with the shaded relief. The shaded relief should be inserted using the *Place* command located in the File Menu of Adobe Illustrator, into a new layer, under the geology color layer. Once the two images are overlain and aligned correctly, the colorized geology layer is set to *Multiply*. The *Multiply* option can be applied by selecting the entire geology layer and clicking on *Multiply* from the drop-down box in the Transparency window. The colored, and multiplied, geologic units over the shaded relief can be seen in figure 6, using both our previous method of generating shaded relief and the method described in this paper. If the shaded relief is still found to alter the color scheme of the map units, the Opacity can be changed to about 85 percent to lighten the image.

Creating shaded relief for geologic maps is an extremely difficult task. Finding the right angle and height for light sources is only the first hurdle. At the Idaho Geological Survey, we have been adding shaded relief to our geologic map publications for several years and are still working to find the quickest and most efficient way to present shaded terrain along with symbolization of data. Unfortunately, each DEM requires unique attention to its detail, in order to properly consider the position and physical characteristics of mountains, valleys, and other landscape features when changing elevation data to a three-dimensional image. All the values used in this paper should be considered as suggestions to begin the process. Although our process is a lot of work and requires many steps, the shaded relief created has allowed the colors of our geologic map units to retain their true hues.

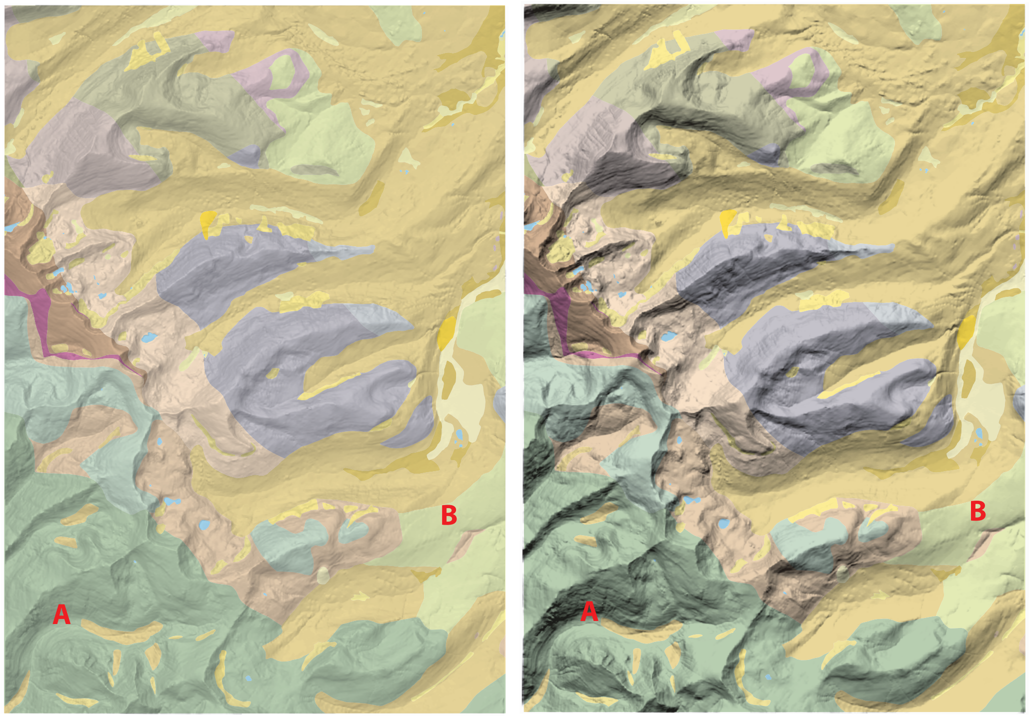

Figure 6. In these two images, the geology has been placed over the shaded relief that was created using our new method (image on the left) and our previous method (image on the right). In the image on the right, the geologic map unit colors have been altered by dark shadows. The area labeled "A" shows how dramatic this alteration is. The area labeled "B" is an example of how light unit colors are affected by the poor lighting. The light green appears more muddy and looks like a darker green than the original unit color. The image on the left shows these areas closer to the original map unit hue with only slight alterations caused by the light gray shadows of shaded terrain.

Reference

Thelin, G.P., and Pike, R.J., 1991, Landforms of the conterminous United States – A digital shaded-relief portrayal: U.S. Geological Survey Miscellaneous Investigations Series Map 2206, scale 1:3,500,000, *http://ngmdb.usgs.gov/Prodesc/proddesc_10187.htm*.

A Window to the National Geologic Map Database (NGMDB) Map Catalog via ArcGIS Image Server – Wyoming Pilot Project

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Introduction

The Association of American State Geologists-U.S. Geological Survey (AASG-USGS) National Geologic Map Database (NGMDB), through its Geoscience Map Catalog, provides access to >89,000 maps and reports by >630 publishers. More than 23,000 of these publications are geologic maps. Access to these geologic maps and other types of geoscience reports is provided via the Catalog's Product Description Pages (PDPs) and the links to sales offices, libraries, and Web servers where the products can be downloaded.

The NGMDB Web site was developed in 1996, initially as strictly a text-based system. In 2003, scanned maps began to be provided through the Catalog, viewable on-screen and downloadable (Soller and Berg, 2003). At that time, the available technology did not lend itself to efficiently and quickly displaying many maps simultaneously in the same view, and so maps were available only via a custom LizardTech ExpressServer-based image viewer linked from the PDPs. However, in 2009, we were introduced by Willy Lynch (ESRI) to their ArcGIS Server Image Extension, which enabled us to reconsider how to efficiently provide access to a set of maps within the same view, as a mosaic showing all available maps of an area. This idea was prototyped in cooperation with the Wyoming Geological Survey, and the preliminary results are presented here. The prototype will provide access to geologic maps for (1) users of ArcGIS, who can directly link to our Web Service (fig. 1) and (2) the general public, who will gain access via a map viewer in the NGMDB Map Catalog Web pages (fig. 2).

ArcGIS Server Image Extension

Image Extension is part of the ArcGIS Server family; it streamlines cataloging, processing, and disseminating large quantities of raster datasets. With Image Extension, raster processing is handled by the server, allowing client requests to be performed on the fly. This alleviates the need to create multiple preprocessed derivative datasets. Image Extension allows tiled raster datasets to be mosaicked seamlessly on the fly, thereby eliminating the need to process a single, static raster dataset. In most cases only the source imagery needs to be managed, thereby greatly simplifying data management and distribution. Image Extension allows authors to update datasets more efficiently because individual tiles in the image service can be revised without reprocessing the full mosaic. Image Extension supports multiple raster dataset formats (with varying compression types), including TIFF, JPEG, SDE Raster, and MrSID.

A noteworthy feature of Image Extension is that the client can manipulate a number of geometric (pixel location) and radiometric (pixel display) processes dynamically to the image service through what are called process chains. Process chains are essentially a list of actions, defined by the user, that are performed on the source data prior to mosaicking of the final image seen by the client. This enables the user to create multiple imagery products from a single raster dataset source. An example of a process chain might be to fuse a lower resolution Landsat ETM+ scene with a higher resolution panchromatic band (pan-sharpen process) and then reorder the bands (band-stack process) to produce a pan-sharpened true-color or near-infrared band combination.

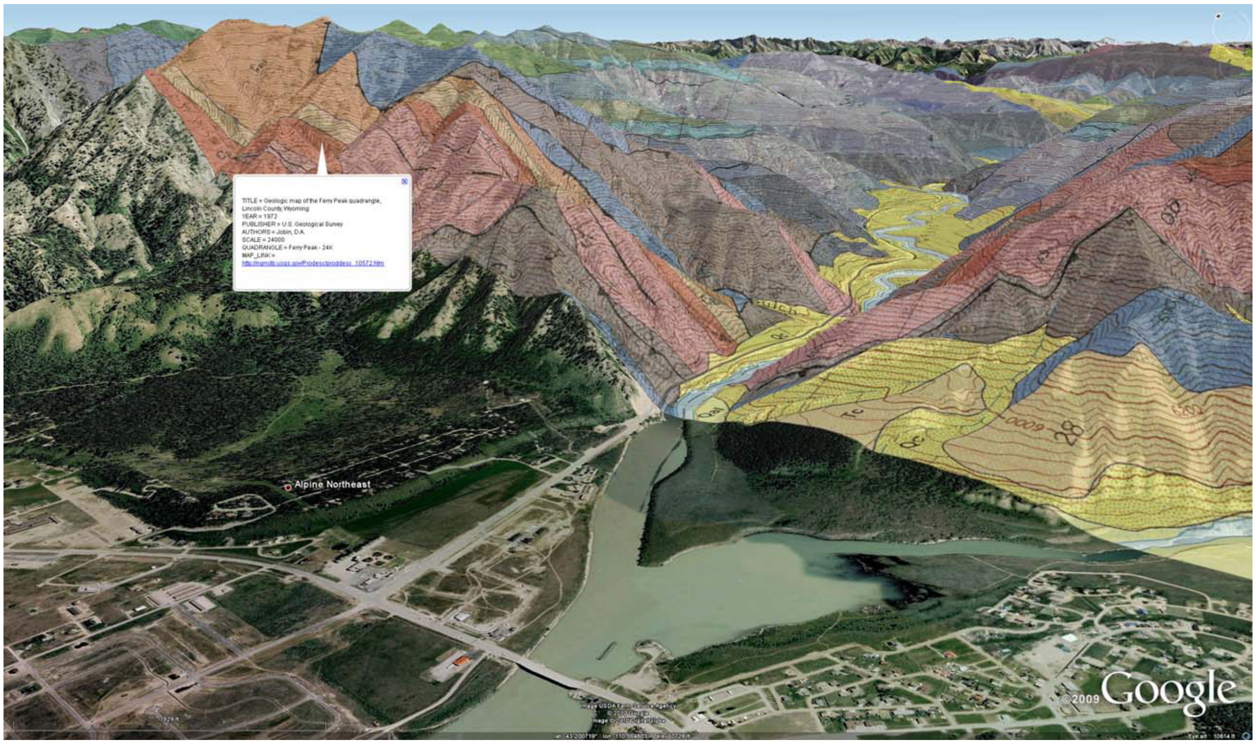

Figure 1. Geologic map Image Service, showing Geologic Map of the Ferry Peak quadrangle (USGS GQ-1027, 1:24,000 scale) draped along the Snake River near Alpine, Wyoming. Image Services published through ArcGIS Server can be consumed by Web clients that support OGC WMS/WCS or KML services, such as Google Earth. Metadata overlays link the client directly to the source data in the NGMDB Catalog (see white callout box) when the map area is clicked.

Figure 2. Image Server as a visual front-end, or "window," into the collection of geologic maps available through the NGMDB Map Catalog. In ArcGIS or in the Web client interface (left-hand image), when the user clicks on a map, a popup shows citation information and a link to the NGMDB Product Description Page (prototype page shown in center image). From that page, links are provided to the publisher, to downloadable files, and to the ImageViewer (right-hand image), where the entire map can be viewed.

In many cases, an image service will have raster tiles (for example, geologic maps) that overlap or will contain groups of tiles that are stacked. For these instances, Image Extension offers a method of controlling the stack order in which tiles are displayed through a user definable parameter called mosaic method. Mosaic method can be enabled to display imagery based on an author-defined attribute. For example, the client could sort by attribute “Time” to view the most recently acquired tile or by attribute “Map Type” to promote “bedrock” or “surficial” geologic maps.

To control unwanted pixel data (map collars, NoData values, and so on) authors can take advantage of a feature in Image Extension called the footprint layer. The footprint layer is a collection of polygons created when raster tiles are added to the image service. Each map tile has an associated polygon “footprint” to which pixels in the tile are clipped. By default, a footprint matching the spatial extent of the tile is created. Footprints can be modified by a variety of methods, including substitution with existing polygon feature class geometry. This is especially useful for removing unwanted collar information from maps when creating a seamless mosaic.

ArcGIS Image Extension distributes metadata about the image service through service-level metadata as well as individual, raster-level metadata (for example, for each geologic map in the service). When a client connects to the image service, the Image Service Properties dialog box can be opened to display an extensive list of the image service metadata that defines its source and accuracy. At any zoom level, the metadata for each input raster currently viewed on screen is transmitted to the client application and can be viewed from within the properties dialog or exported by the client to a file. Details of processes applied to the raster and the parameters for processes are also stored in the metadata. A view of the prototype is shown in figure 3.

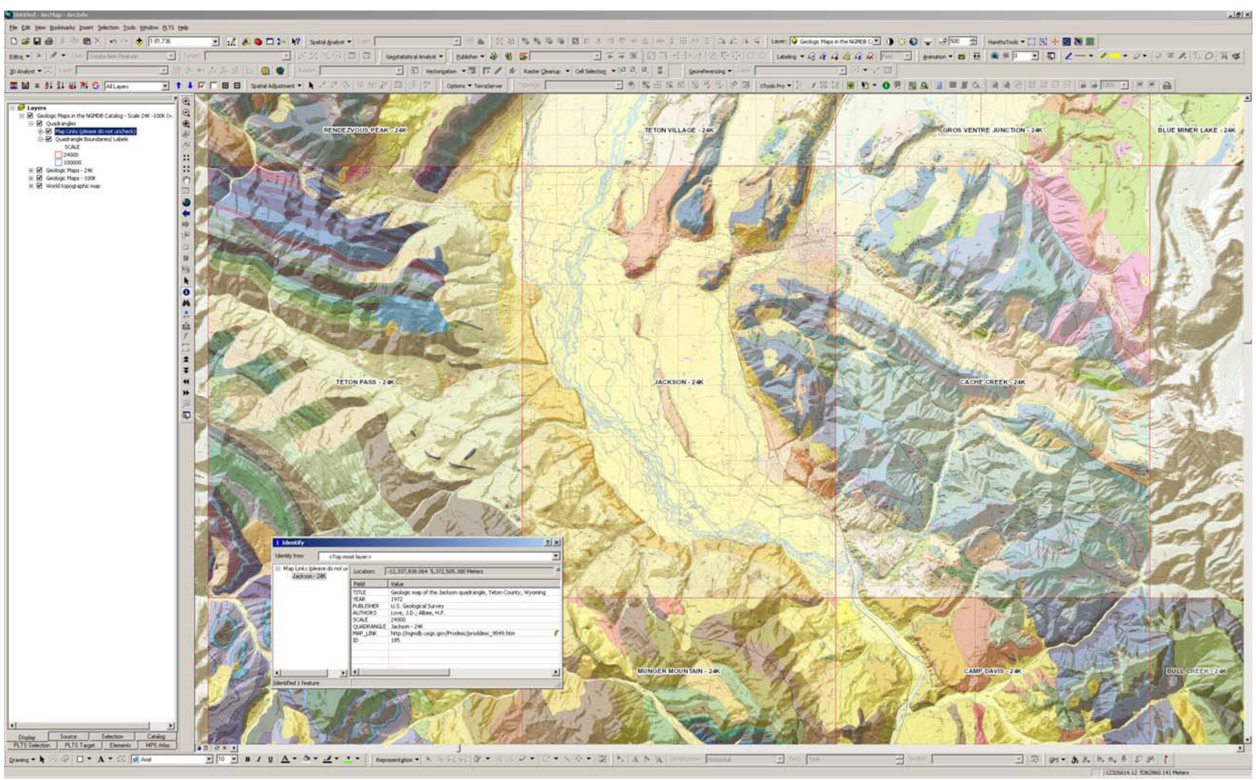

Figure 3. Screen capture of the Wyoming 1:24,000 geologic map Image Service in ArcGIS. The Image Service is bundled with a polygon footprint feature class and is served to ArcGIS clients as a layer (.LYR) file. The overlying footprint enables the user to hotlink to the source geologic map images in the NGMDB Catalog (see Identify pop-up). If desired, clients can export the Image Service raster layer directly from a data view to a local machine.

Workflow

To identify maps appropriate for this prototype, the NGMDB Catalog was queried for 24K to 250K geologic quadrangle maps that had already been scanned. From the candidate maps, each catalog record was quality-checked (for example, for image quality and correct coordinates) and prioritized for display in Image Server. Because only the topmost map in a "stack" is shown, the maps in a quadrangle were prioritized in order to list (1) the most current and comprehensive bedrock or surficial map and (2) older, and preliminary, maps of bedrock and surficial geology. The maps then were processed for Image Server application as follows:

1. Raw (uncompressed TIFF) geologic map scans were compressed using Open Source GDAL utilities and batch processed through Python scripting. The following compression and internal tiling parameters were applied, resulting in about 7X compression ratio:

   gdal_translate.exe -of Gtiff -co COMPRESS=JPEG -co JPEG_QUALITY=85 -co TILED=YES -co PHOTOMETRIC=YCBCR <in_tiff> <out_tiff>

   gdaladdo.exe -r average --config COMPRESS_OVERVIEW JPEG --config USE_RRD NO --config JPEG_QUALITY 85 --config TILED YES--config PHOTOMETRIC_OVERVIEW YCBCR <in_tiff> 2 4 8 16

2. Compressed images were georeferenced in the native UTM projection of the map using a second order polynomial transformation method. Sixteen-control point georeferencing was semi-automated using custom georeferencing software. Average time per map sheet was about 5-10 seconds.

3. An image service was created in a WGS 1984 Web Mercator (Auxiliary Sphere) projection. Geographic transformation (NAD 1927 to WGS 1984) was handled by adding an additional definition to the AISDatums.txt file. Images were added to the service in groups by UTM zone. The option to utilize internal tiling was activated upon image import.

4. Quadrangle boundary shapefiles were related to the footprint layer of the image service. A "clip by related geometry" (clipping mask) was performed to remove all map collar information, effectively creating a seamless geologic map service.

5. Service overviews (low resolution tiles, similar to a traditional map cache) were created for faster access to the image service at small scales.

6. Client-side compression was set to reduce transmission time to the client. A JPEG compression at 55 percent was set as default on the client side.

7. Raster level metadata was exposed through links to the footprint layer attribute table. Linked fields tagged as metadata in the Field Properties dialog appear in the Metadata tab.

8. Mosaic method was set to "By Attribute" to allow promotion of stacked images by map type. Attributes were linked to the footprint attribute table; map types included bedrock, surficial, and preliminary.

Web Client Interface

The ESRI ArcGIS Web application programming interface (API) uses the same ArcGIS Server services used by the ArcGIS desktop client. The API is offered in three different programming environments; we chose the ESRI ArcGIS Web API for Flex mostly for convenience. It offers rapid prototyping, cross-browser support, and a modern programming environment.

The ArcGIS Web API and the Adobe Flex framework favor an event-driven programming design in which the application's behavior is dictated by user interaction, as opposed to a series of operations performed in a predetermined order. In this case, the user interface consists of a user-selected base map, overlain with the 'footprint' and image layers mentioned above. User interactions include panning and zooming, switching of the base maps, changing layer opacity and visibility, and querying for the footprints of maps available through the NGMDB Catalog.

The ArcGIS Web API map 'object' provides the map functionality. The Adobe Flex framework provides the user interface needed to manipulate the map properties – map navigation controls offer panning and scale change, and a layer object has properties for visibility and opacity. By binding a Flex slider widget's current value to a layer's alpha property, the user can change the layer's opacity via the slider.

The query function, provided by the ESRI API, is called when the user clicks on the map. The map coordinates for the click location are sent as input, and the function returns a collection of features (maps) whose 'footprint' includes the coordinates passed. Feature attributes returned include Title, Publisher, Authors, and a URL to the feature's Product Description Page in the NGMDB Catalog.

Figures 4 and 5 show the interface at the time of presentation, and after revisions were made in late 2011, prior to publication of these Proceedings. The most significant change was in how the map files are managed – in order to improve display speed, all maps (regardless of scale) are now managed in a single image service.

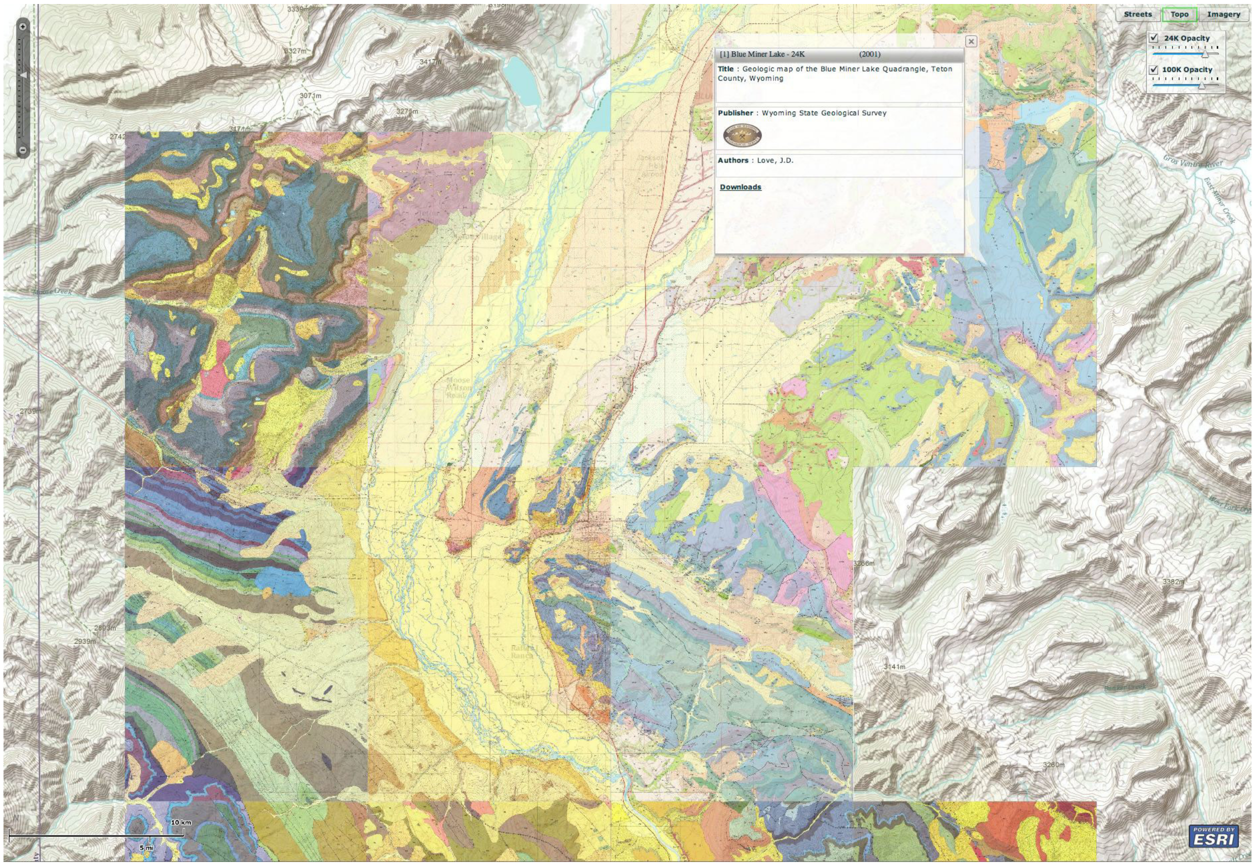

Figure 4. NGMDB map viewer prototype, circa 2010, as shown at the DMT'10 meeting. Maps of various scales (for example, 1:24,000 and 1:100,000) were managed in separate image services. Map area is northwestern Wyoming, near Jackson Hole, and display scale is roughly 1:150,000. Pop-up shows publisher information, with link to NGMDB Product Description Page.

Figure 5. The updated NGMDB map viewer, showing same area as in figure 4. All maps are managed in a single image service, with larger scale (for example, 1:24,000) maps "stacked" above smaller scale (for example, 1:250,000) maps. The default view shows the most detailed map of each area (in this view, all maps showing are 1:24,000 except in the extreme upper right, where the most detailed map is at 1:62,500 scale). In order to view maps of less detail (for example, 1:100,000), the slider (upper right) permits the user to "step" down through maps of lesser detail, eventually showing only the most regional maps such as those of 1:250,000 scale.

Acknowledgments

This work has been accomplished in collaboration with the Wyoming Geological Survey and ESRI, and we sincerely thank them. In particular, we thank Willy Lynch (ESRI) for helping to jump-start this process, and for his encouragement and support.

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The Geological Map Flow Process – How the Geological Survey of Canada is Streamlining Map Compilation and Delivery

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Transitioning Geological Mapping

The Geological Survey of Canada, Natural Resources Canada, has been producing geological maps since Sir William Logan was designated as the first Director of the Geological Survey of Canada (GSC) in April 1842. The compilation of a geological map has always involved considerably more than the cartographic work. Just as a topographic map compilation requires the surveying of the topographic features, a geological map requires the collection of remote and ground-based data from which the geologists will compile the map. But this work is not based completely on observational information; rather, the geologist takes on the role of a detective who, using vast knowledge and skills of interpretation, must piece together the most likely scenario of the geological history based on limited information that can be collected because most of the 'facts' are hidden by vegetation, water, sediment, and other rocks. Add to this the fact that the last glaciation of North America (about 20,000 years ago) smeared many of the clues across the landscape, and that in a geological context, this glaciation was a very recent event. You can get an idea of how difficult it is for these 'rock sleuths' to practise their trade.

Over time, the GSC developed an international reputation for the quality of its geoscience maps, from both a scientific and technical point of view. Much of the supporting information used for the compilation of the maps was then discarded or lost after the maps were published. However, times have changed and the GSC has had to adapt to the demands of users and technology. With the advent of Geographic Information Systems (GIS) and digital cartography, many enhancements in the way geological maps are produced have been made, but this has mainly focused on the cartographic component, and less so on the scientific components. Although technology has been applied to many of the scientific areas, it generally has been on an individual basis and (or) in support of scientific analysis, and not in the context of data management or as part of a standard methodology for making maps. Increasingly, the demand not only for the interpretation (published map) but also for the supporting data has compelled a rethinking of how the data are managed and used. The inherent value of this information, for example, the cost of collecting a rock sample on Ellef Ringes Island in Nunavut, includes not just the potential geological knowledge but also the cost of reacquiring that sample. The collected data, therefore, have a significant value and have become a government asset that needs to be properly managed and made available to Canadians.

New Requirements For Geological Mapping

Clearly, a more efficient and streamlined method to collect, manage, interpret, and disseminate these data, information, and knowledge was needed. A catalyst was necessary to effect this change. The Geo-mapping for Energy and Minerals (GEM) Program was announced in 2008 to provide the geoscience knowledge necessary for private sector exploration companies to guide investment decisions, as well as for local governments to make informed land-use decisions such as the creation of parks and other protected areas. GEM's focus is mainly on mapping the Arctic using modern geological methods and standards to identify the potential for energy and mineral resources. GEM has become the catalyst needed for the improved management of scientific information.

Additionally, GEM was mandated to deliver geoscience data and knowledge. The Geological Map Flow (GMF) project was initiated under GEM to address the need for a more consistent and efficient approach to geological mapping and managing the geological map data.

Approach

The approach taken by the GMF team was to define a complete process from project initiation to final output (publication), so that the data were controlled from the outset. It was also understood that this would be a significant cultural change for many geologists and so, without adequate preparation and training through a transitional period, this initiative would be painful. In order to mitigate this 'culture shock,' the team:

- identified and reviewed existing best practices and selected those methods that could be adapted to the GMF;
- developed new tools that mimicked 'traditional' methods where needed, so that the adoption of new technology followed conventional practices;
- defined roles and responsibilities so that the scientist can continue to focus on science;
- provided specific training for the different roles in a timely manner; and
- consulted continuously with geological staff throughout this process, in order to address challenges and to enhance the process when and where necessary.

The project was divided into four components, each addressing a key area in the GMF process: field preparation and collection, information management and compilation, map information dissemination, and training and delivery.

Field Preparation and Collection

The field preparation and collection component defines sources of information (for example, topographic data, geophysical information) for project planning and preparation and provides tools to extract this information from the sources where necessary. An enhanced version of GanFeld (Buller, 2004) was developed from an existing field data collection system for geoscience data, providing a seamless data flow into the project data management process while continuing to provide field projects with a level of scientific flexibility (figs. 1 and 2). By properly managing the data during the collection phase, we can also support and feed other corporate systems such as the Sample Management System, which catalogs all samples collected in the field including key information such as location and sample method.

Information Management and Compilation

This component supports the integration of data and information, both existing and new, and the interpreted geological map model within a structured project-level geodatabase. To support this, the following were developed:

- standard bedrock and surficial geology geodatabases using consistent fields and terminology while allowing for 'free text' descriptions at more detailed levels of the geologic model,
- tools and services to streamline the digital compilation of interpreted geologic map information (polygons, contacts, and so on),
- a legend compilation tool to facilitate the symbolization of preliminary maps,
- an intuitive interface for the geologist to view multiple layers of collected field and other information, facilitating the digital compilation of interpretations, and
- a service for the streamlined compilation of interpretations compiled on stereo-pair images.

The use of consistent geodatabase design and science language enables the integration of published project-level geodatabases into a corporate geological map database. This in turn provides the foundation for the dissemination of geological map information.

Map Information Dissemination

This component has a product preparation process that streamlines the delivery of print-ready and geographic information system (GIS) products directly from the geological databases. This process includes providing geomatics (that is, GIS-cartographic) support during the compilation steps and a more automated process for print-ready product preparation. The GIS-ready product is designed to facilitate immediate use in common GIS software and is released at the same time as the print-ready product. The GMF project team is working with GSC scientists and international agencies (U.S. Geological Survey, Federal Geographic Data Committee) to define a North American standard for the cartographic representation of geological information.

A key deliverable of GMF is a revised geoscience map output (print-ready and GIS-ready). The current Open File and A-Series map publications will be replaced by the new Canadian Geoscience Map (CGM) Series. The CGM can clearly show users that they are using a "preliminary map" and that a final version is pending. The final version will simply be a later edition of the same map in the CGM series. In addition, the geoscience map outputs (print-ready and GIS-ready) are derived from the same project geodatabase through a

Figure 1. Field geologists at a sample site (left) and digitally collecting information in the field (right).

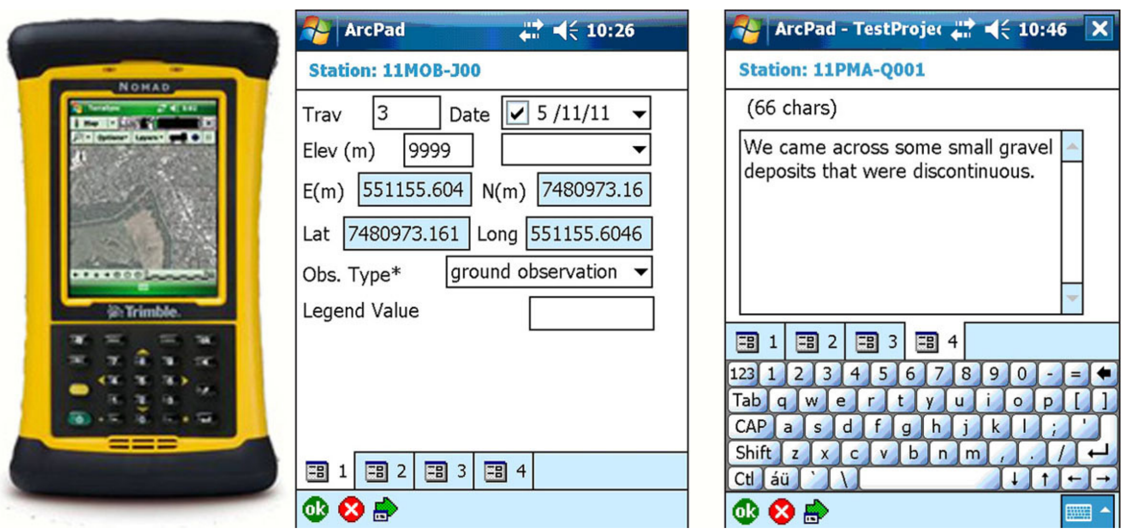

Figure 2. GPS/GIS-enabled field device (left) and data collection interface (right), which uses the GanFeld software (Buller, 2004).

semi-automated process (with defined procedures and tools), ensuring that both are delivered quickly and in a coordinated fashion (fig. 3).

Training and Delivery

In order to support and coordinate a sustainable implementation of GMF, clear and consistent documentation, appropriate and timely training for field parties, and clearly defined roles and responsibilities have been prepared. This component also provides support to key field geologists who will validate the work and direction of this project.

In summary, the Geological Map Flow process has gone from a purely cartographic and less standardized (not so GIS-ready) digital product to a coordinated and consistent collection of geoscience information. The former was characterized by nonstandard, inconsistent data collection, pen and ink compilation, and digital cartographic representation focused on a paper product. The new system offers data that are now fully managed in a central project database from project initiation, through the scientific compilation, to the delivery of print-ready and GIS-ready products.

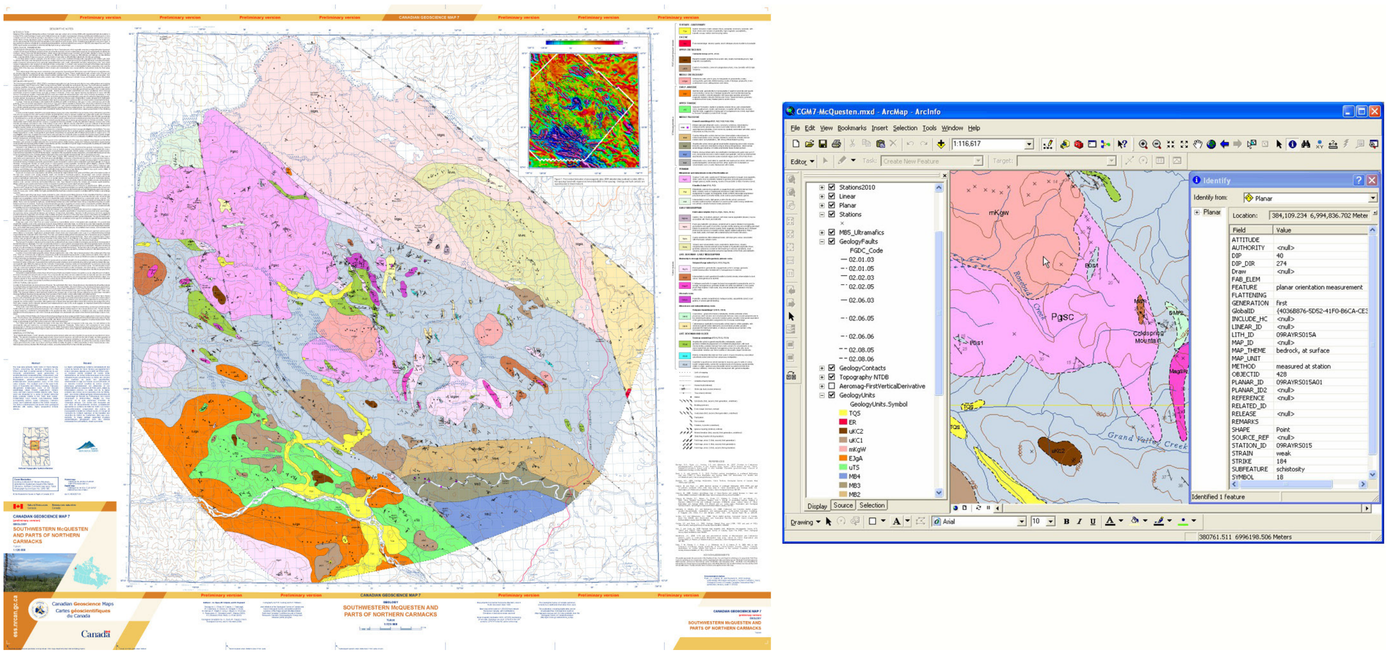

Figure 3. Canadian Geoscience Map Series (left) and corresponding GIS-ready data (right).

Results

As the GEM program nears completion and we look forward to GEM 2, the GMF system has evolved and has been adapted to overcome specific operational challenges and to mitigate the ‘culture shock’ effect associated with implementation of a new way of doing geological field work. To date, GEM has released new maps through this process and more are expected over the next 2 years. Not only has this process shown that it can accelerate the delivery of geological map information by providing more efficient and effective data management processes and tools but also it has shown GSC scientists and our key users alike the potential of this process in delivering supporting data in addition to the interpreted map.

Acknowledgments

The author would like to acknowledge the work of the Geological Map Flow team and the staff from Natural Resources Canada, Earth Sciences Sector: Kaz Shimamura, Stephen Williams, Guy Buller, Patty Zhao, Etienne Girard, Pierre Brouillette, Heryk Julien, Karen Fallas, Graham Lai, Larry MacDonald, Christine Deblonde, Vic Dohar, Dave Everett, Benoit Chagnon, Roger MacLeod, Robert Cocking, Peter Davenport, Natalie Morisset, Alison Weatherston, Evelyn Inglis, and Mike Sigouin. The author, Andrew Moore, is Program Manager for the Geo-mapping for Energy and Minerals (GEM), Knowledge Management component.

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What's Coming in ESRI ArcGIS 10 Desktop for Better, Faster, More Efficient Geologic Maps, Map Production, and Map Serving

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Introduction

Esri is planning a major release of the ArcGIS software platform in 2010 (fig. 1), which will have significant implications for geologic map making. The new release will allow for better, faster, and more efficient workflows for the desktop user, will enhance collaboration for office and field mappers, and will enhance map publication.

In ArcGIS10, there will be new editing tools based on templates, more complete Python scripting integration for workflows and automation, new 3D editing capabilities, major advances in image management-analysis, and new map production tools ("Data Driven Pages") to facilitate map production. Regardless of whether you are using ArcGIS in a desktop, mobile, or server environment, the new enhancements will improve how geographic information is leveraged

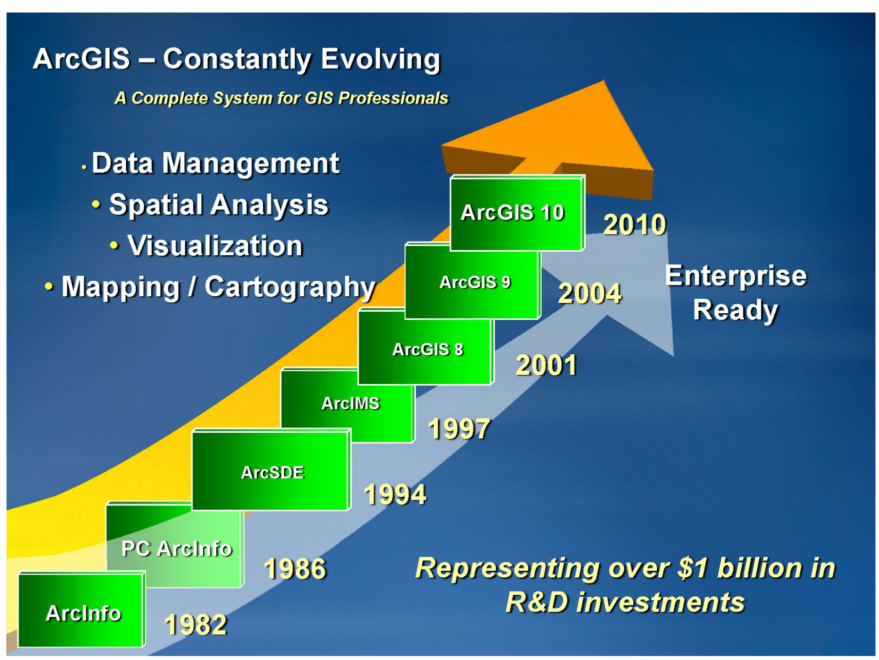

Figure 1. Esri's ArcGIS software is constantly evolving. From the release of ArcInfo in the early 1980s to the pending release of ArcGIS 10 in 2010, Esri's GIS software provides ever improving tools for data management, spatial analysis, visualization, and mapping.

throughout your enterprise. ArcGIS 10 will "transform the way you use GIS." ArcGIS 10 is expected to be available in June 2010.

GIS technology and its use for geologic map making is constantly evolving (fig. 2). The most current information about existing Esri GIS applications can be found at the Esri Web site *http://www.esri.com*, more information about training for mobile GIS can be found at *http://training.esri.com*, and current geoscience industry examples and case studies can be found at *http://www.esri.com/industries.html*. Please see *http://www.esri.com/software/arcgis/whats-new/new-features.html* for details on new features.

Demonstration

Live demonstrations of ArcGIS 10 using ArcMap, 3D Analyst Extension and ArcGIS Explorer were quickly presented during the DMT meeting (fig. 3). A video file of the demo is available directly from the author and is posted at the DMT 2010 Web site (*http://ngmdb.usgs.gov/Info/dmt/docs/DMT10_Lynch1.wmv*).

Acknowledgments

The author thanks Geoff Wade and Danny Spillmann (Esri) for their ongoing support of geology and natural resource industry activities at Esri, and Dave Soller (USGS) for all his tireless work with the DMT program.

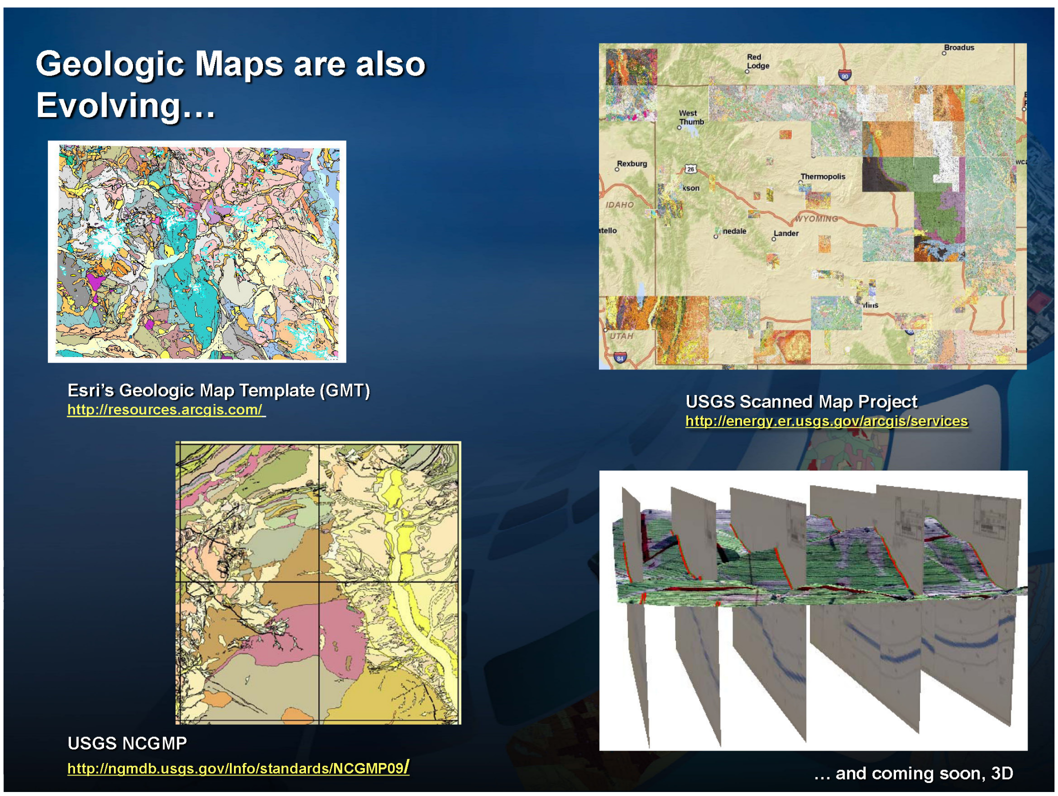

Figure 2. Geologic maps are also evolving from early paper maps of the USGS and State geological surveys to ongoing efforts such as Esri's Geologic Mapping Template (*http://resources.arcgis.com/gallery/file/map-templates/details?entryID=6AA281F3-1422-2418-8825-C44631AFA8EE*) and the USGS's "NCGMP09" geologic map standard database design (*http://ngmdb.usgs.gov/Info/standards/NCGMP09*) and scanned geologic map delivery effort (*http://energy.er.usgs.gov/arcgis/services*).

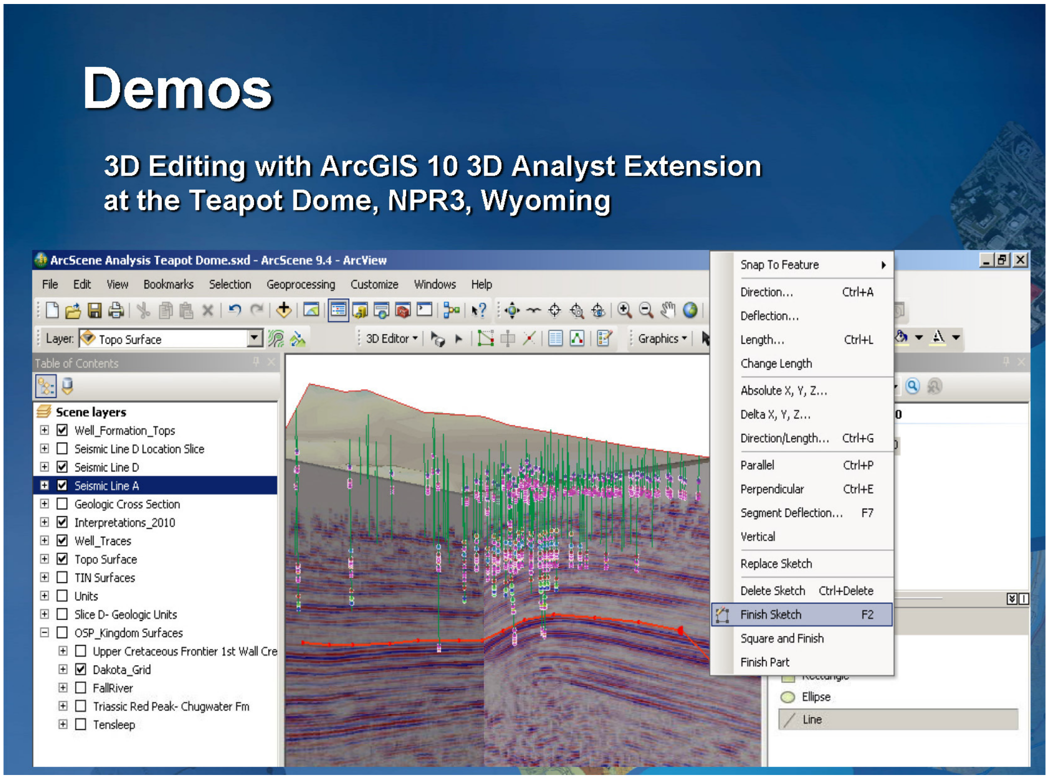

Figure 3. Screen capture of live demo of ArcGIS 10 3D Analyst extension with data from Teapot Dome, Natrona County, Wyoming. NPR3 is the Naval Petroleum Reserve #3 (*http://ludb.clui.org/ex/i/WY3148/*).

Coal Basin, Pitkin County, Colorado – An Example of NGMDB Data Capture, Conversion, and 3D Editing in ArcGIS 10

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Coal Basin is located in the Carbondale Coal Field near Redstone, Pitkin County, Colorado, and is perhaps best known for the April 15, 1981, coal mine disaster in the Dutch Creek Mine, which killed 15 miners. Geologic mapping and coal resource assessments were completed in the area in late 1970s by the USGS and were published as black and white open file maps (Kent and Arndt, 1980). These maps are cataloged and made available by the National Geologic Map Database (NGMDB) as scanned images and .djvu files. As a case study of new 3D functionality and digital mapping tools in ArcGIS10, the original map files were exported as .jpg images (multi-page), georeferenced, and digitized to capture the geologic data. The data were loaded into ESRI file geodatabase format using a field-oriented geologic data model, and 2D and 3D maps were created. Using newly available high resolution ESRI basemap maps and images (*http://www.arcgis.com/home/*), the digital data are now available to be easily edited and updated to better document coal seam outcrops and regional geology. At the DMT meeting, this information was presented as a poster (fig. 1) and as a live demo of the data.

Acknowledgments

The author thanks Geoff Wade and Danny Spillmann (Esri) for their ongoing support of geology and natural resource industry activities at Esri, and Dave Soller (USGS) for all his tireless work with the DMT program.

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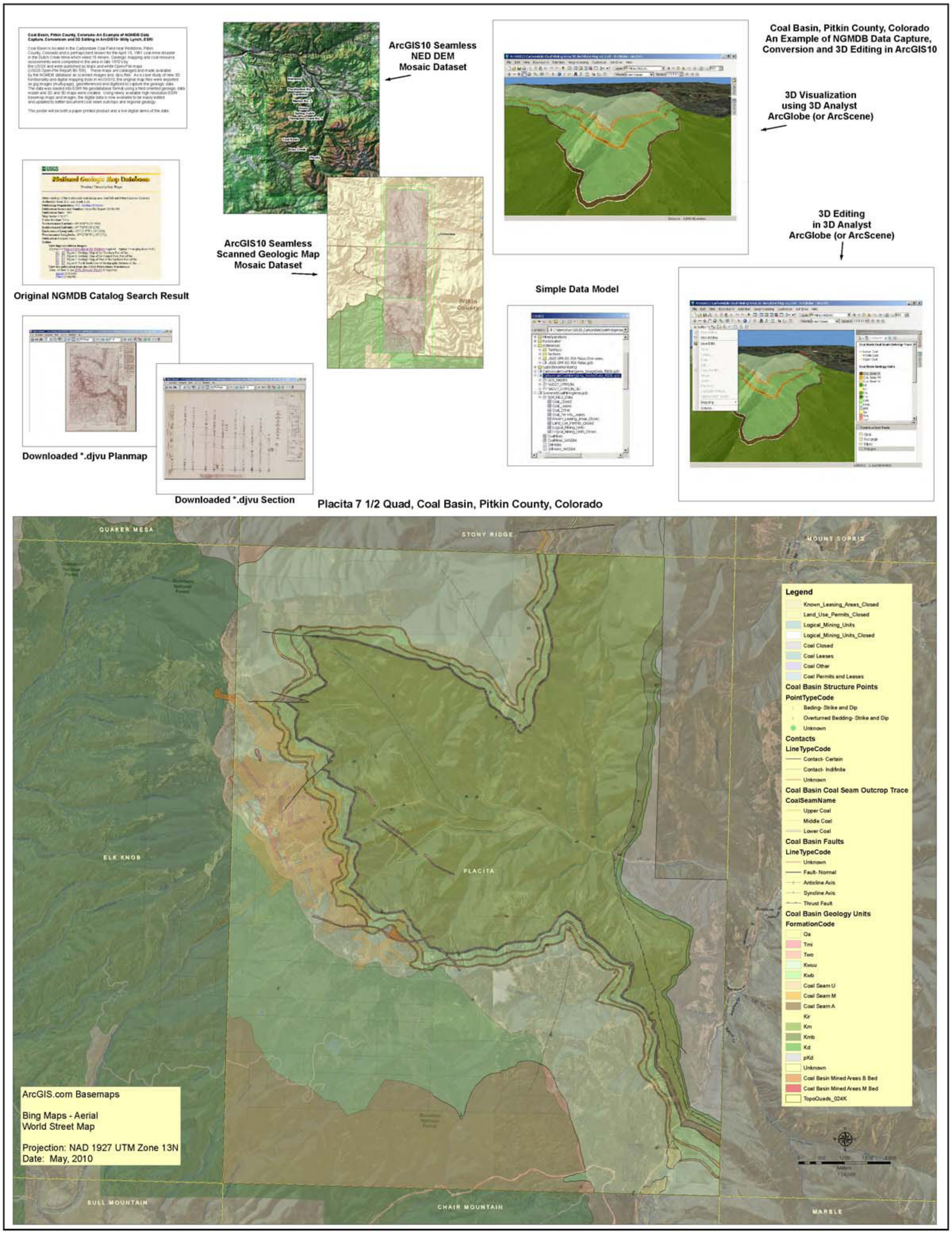

Figure 1. Using ArcGIS 10 and the 3D Analyst Extension for data capture, conversion, and 3D editing at Coal Basin, Pitkin County, Colorado (presented as a poster; see full-resolution image at *http://ngmdb.usgs.gov/Info/dmt/docs/DMT10_Lynch2.pdf*).

Evaluating Mine Subsidence Using a GIS Software Application

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Abstract

Subsidence due to the collapse of abandoned underground mines is a geologic hazard that can affect highways and buildings, potentially endangering lives and property. Damages from mine subsidence can cost millions of dollars. In 2008, the Ohio Department of Natural Resources (ODNR), Division of Mineral Resources Management invested more than $1.3 million to complete 32 projects related to abandoned underground mines. As of 2005, the Ohio Department of Transportation had spent approximately $14.3 million to repair highway damage caused by mine subsidence. The costs of mine subsidence will continue to rise as abandoned underground mines age and deteriorate and further development occurs across the Ohio landscape.

Homeowners are particularly at risk because most homeowner insurance policies do not cover cost of damages from mine subsidence. In Ohio, the Mine Subsidence Insurance Fund gives property owners the opportunity to purchase mine subsidence insurance. When officials from the Ohio Mine Subsidence Insurance Underwriting Association (OMSIUA) receive a claim from a property owner, the claim is forwarded to geologists at the ODNR Division of Geological Survey for further evaluation. Geologists use a geographic information system (GIS) application that automatically gathers all digital geologic maps and documents for the claim location. When all the digital geologic maps and documents are gathered into the GIS, geologists first evaluate the potential of an underground mine to underlie a property and then write a claim report that is submitted to a consulting engineering company for further evaluation and potential remediation. The OMSIUA GIS application provides easy access to digital geologic information for faster insurance claim processing and property remediation.

Introduction

Underground mining for coal in Ohio was first reported in 1800 (Crowell, 1995). The majority of the underground mining takes place in coal- and clay-mining areas of eastern and southern Ohio (fig. 1). Other commodities, such as salt, gypsum, limestone, shale, and even peat, have been mined underground in Ohio. Geologists have estimated that over 8,000 mines have been in operation over the last 200 years (DeLong, 1988). With such a large number of mines developed over a long period of time, there is an increasing probability that mines will collapse and subside as they age and deteriorate and as development occurs across the Ohio landscape.

In Ohio, mine subsidence has been a problem that has been recognized only in the last 40 years. In 1977, a mine shaft collapsed underneath a garage in Youngstown, Ohio (fig. 2). This incident led the ODNR Division of Geological Survey to map the detailed locations of abandoned underground mines (DeLong, 1988). Other prominent incidents have occurred throughout the state, such as the collapse of Interstate 70 (I-70) near Cambridge (fig. 3; Crowell, 1995), and the recent subsidence beneath a house in Sugarcreek (fig. 4). The costs associated with the remediation of abandoned mines are high. The repairs of the collapse of I-70 near Cambridge cost approximately $3.8 million (Crowell, 1995). As of 2005, the Ohio Department of Transportation had spent approximately $14.3 million to repair highway damage caused by mine subsidence. In 2008, the ODNR Division of Mineral Resources Management invested more than $1.3 million to complete 32 projects related to abandoned underground mines (Gordon, 2009). As abandoned underground mines age and deteriorate, the ODNR Division of Geological Survey expects remediation costs associated with abandoned mines to increase.

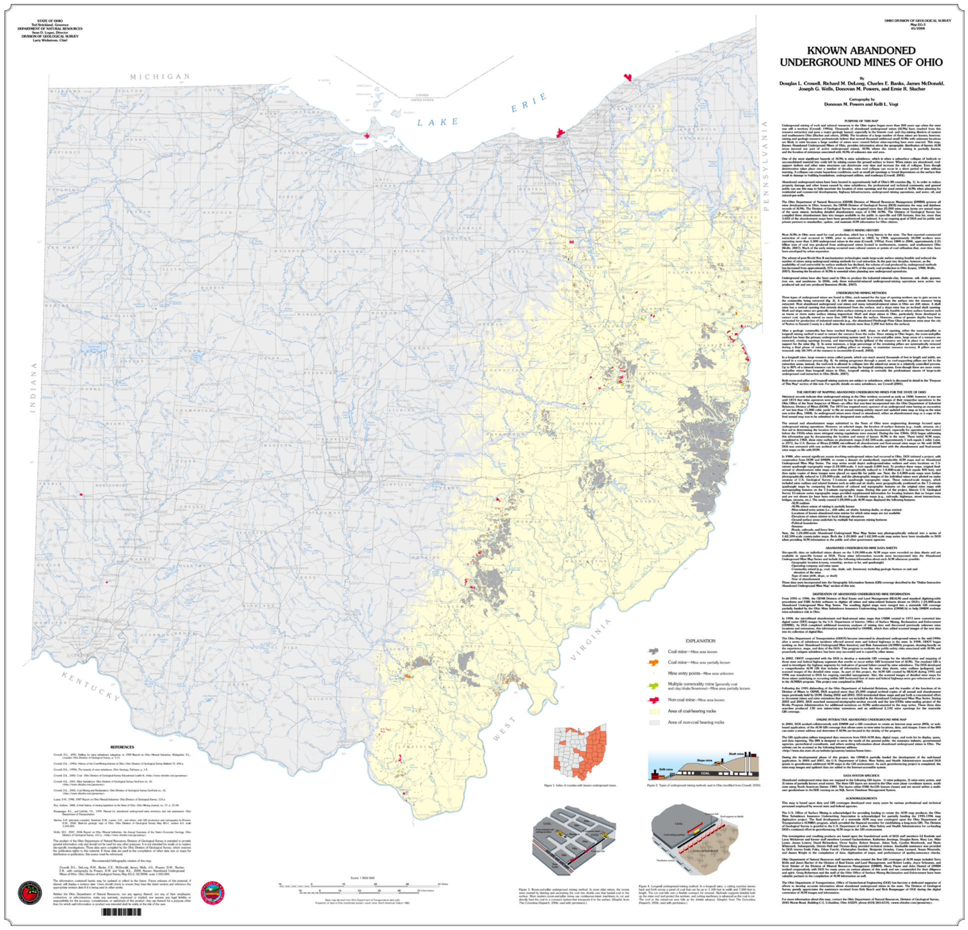


Figure 1. Known abandoned underground mines of Ohio (Crowell and others, 2008). The majority of abandoned underground mines are associated with coal and clay mining in eastern Ohio.

Figure 2. Aerial photograph showing location of mine subsidence. In 1941, a property was inventoried by Fuller and Sturgeon (1941) as containing an abandoned mine shaft of the Foster #1 mine, which was abandoned in 1884. In 1977, a garage collapsed into a mine shaft on a nearby property (Crowell, 1980; DeLong, 1988).

Figure 3. Collapse of Interstate 70, near Cambridge, Ohio, caused by mine subsidence (Crowell, 1995).

Figure 4. A home damaged by mine subsidence, in Sugarcreek Township, Tuscarawas County, Ohio.

Most homeowner insurance policies do not cover damages from mine subsidence. In Ohio, the Mine Subsidence Insurance Fund gives property owners the opportunity to purchase mine subsidence insurance. In order to assist the Ohio Mine Subsidence Insurance Underwriting Association (OMSIUA) with the evaluation of insurance claims, the ODNR Division of Geological Survey has entered into an agreement with OMSIUA to provide geologic information and preliminary evaluation of the validity of the mine subsidence claims. When OMSIUA officials receive a claim from a property owner, geologists at the ODNR Division of Geological Survey are given the claim for further evaluation. Geologists use a geographic information system (GIS) application that automatically gathers all digital geologic maps and documents for the claim location. When all the digital geologic maps and documents are gathered into the GIS, geologists first evaluate the potential of an underground mine to underlie a property and then write a claim report. The claim report is submitted to a consulting engineering company for further evaluation and potential remediation. The GIS application provides easy access to digital geologic information to speed up insurance claim processing and property remediation.

Data Archives, GIS Datasets, and Access

The ODNR Division of Geological Survey is the legally defined repository of geologic data in the State of Ohio and has been collecting geologic data since it was first organized in 1837 as the Ohio Geological Survey. In its archives, there are over 17,000 measured stratigraphic-measured sections (Carlton, 2001), over 4,000 core descriptions, and thousands of draft project maps and open-file maps. Starting in the mid-1980s, the division created project databases for individual projects. Systematic GIS dataset and database creation and data archiving started in 1996 with the creation of the oil- and gas-well GIS dataset (McDonald and others, 2005). The systematic conversion of the 1:24,000-scale bedrock geology and bedrock topography open-file maps was completed in 2003 (McDonald and others, 2003). Other datasets have been converted since 2003, as part of the various projects funded to map the locations of abandoned underground mines. These datasets include the scanning and georeferencing of low-resolution abandoned-mine maps, the scanning of abandoned-mine maps at high resolution, and the conversion of the bedrock-geology structure-contour maps to a GIS dataset. Currently, the division is in the process of digitally archiving all of the records and converting all of the spatially referenced information to GIS datasets, which can be accessed by the staff and eventually by the public.

One challenge inherent in creating digital archives of statewide GIS datasets is discovery and access of information at the desktop. Traditionally, with paper records at the ODNR Division of Geological Survey, identifying records and maps that contain information for a particular site involves searching through each collection, which could be organized by county/township/section or by U.S. Geological Survey quadrangle. Even if a staff member or member of the public is successful in examining the entire collection for information, other collections may be missed due to the person not knowing about them. These types of searches through paper records and archives are typically slow, taking days to weeks to undergo. As a mine subsidence report comes into the ODNR Division of Mineral Resources Management, a geologist will visit the Geologic Records Center (at the ODNR Division of Geological Survey) and will examine measured sections, core descriptions, 1:24,000-scale abandoned-underground mine maps, bedrock geology maps, and other records collections. Such searching and examination can take many hours to research a particular mine subsidence claim (Tim Jackson, ODNR Division of Mineral Resources Management, oral commun., 2010). Because the ODNR Division of Geological Survey is still in the process of scanning and digitizing all of its collections of paper records, allowing access to these digital data is difficult. If there are hundreds of different types of datasets, then knowing what relevant datasets to add to an analysis is a time-consuming task. More importantly, if there are written documents that support a GIS analysis, then adding these written documents to the project is almost impossible.

OMSIUA GIS Application

Application Design

Many different types of geologic information can be used for geologic-hazards analysis. Types of geologic information produced by geologists and engineers include published and open-file reports; miscellaneous documents, such as core descriptions and measured-stratigraphic section descriptions; published and draft working maps; and vector and raster GIS datasets representing digital geologic maps. All of these types of geologic information form a voluminous archive. In order to locate geologic information about a specific site, geologic maps and documents need to be scanned or digitized, digitally indexed, and spatially referenced. Indexing involves recoding within a database table the existence and location of a record on the computer network. Spatial referencing involves attaching geographic-location information to the geologic record. By associating with each geologic record the location on the computer network and the geographic location, a geologic record can be easily retrieved for any geographic location within a GIS.

The basic concept of the OMSIUA application is to easily locate all pertinent geologic records and maps and load them into the GIS for a user to evaluate the mine-subsidence potential of a site. The information that is then loaded into ESRI ArcMap is driven by reading records from multiple tables in a database. The basic information indexed into database tables can be categorized into vector GIS layers, scanned maps and digital orthophoto images, and scanned paper records. These database tables record the file name and the network path of the geologic information record, which provides the information necessary to locate the digital geologic record on the computer network. The tables also contain geographic information indexes describing the county, township, or U.S. Geological Survey 7.5-minute or 15-minute quadrangle in which the record is located.

The vector GIS layers are loaded by reading the records in the table that index the vector layers. The table contains attribute fields that record various types of information related to how the layer will be loaded into ArcMap (fig. 5). The attribute fields include the name of the layer, the location of the layer file, the group name in the ArcMap table of contents (TOC), the location of the group in the TOC, and the order in which both the layers in the groups, and the groups within the TOC, are loaded into ArcMap. For example, there are nine layers associated with abandoned underground mines. Each of the nine layers has a group-order attribute value and a TOC attribute value. These values determine where the group of abandoned-mine vector layers is loaded and displayed in the TOC in ArcMap. Inside the group, the order of the layers

Attributes of ODGSLAYERS

ID	LAYERNAME	PATH	GROUPORDER	GROUPNAME	GROUPTOCORDER	GROUPVISABLE	GROUPPDFEXPORT
1	BG Facies.lyr	S:\AUM\OMSIUA\Layer_Files	8	Bedrock Geology Layers	6	0	0
2	BG Mines Line.lyr	S:\AUM\OMSIUA\Layer_Files	6	Bedrock Geology Layers	6	0	0
3	BG Mines Ply.lyr	S:\AUM\OMSIUA\Layer_Files	10	Bedrock Geology Layers	6	0	0
4	BG Mines Pnt.lyr	S:\AUM\OMSIUA\Layer_Files	1	Bedrock Geology Layers	6	0	0
5	BG Misc Pnt.lyr	S:\AUM\OMSIUA\Layer_Files	2	Bedrock Geology Layers	6	0	0
6	BG Structure Line.lyr	S:\AUM\OMSIUA\Layer_Files	5	Bedrock Geology Layers	6	0	0
7	BG Structure Pnt.lyr	S:\AUM\OMSIUA\Layer_Files	3	Bedrock Geology Layers	6	0	0
8	BG Units Contacts.lyr	S:\AUM\OMSIUA\Layer_Files	9	Bedrock Geology Layers	6	0	0
9	BG Units Line.lyr	S:\AUM\OMSIUA\Layer_Files	7	Bedrock Geology Layers	6	0	0
10	BG Units Ply.lyr	S:\AUM\OMSIUA\Layer_Files	11	Bedrock Geology Layers	6	0	0
11	BG Units Pnt.lyr	S:\AUM\OMSIUA\Layer_Files	4	Bedrock Geology Layers	6	0	0
13	BT Contours.lyr	S:\AUM\OMSIUA\Layer_Files	2	Surface and Bedrock Topography Layers	5	0	0
14	BT Data Points.lyr	S:\AUM\OMSIUA\Layer_Files	1	Surface and Bedrock Topography Layers	5	0	0
15	Coal Geochemistry Samples.lyr	S:\AUM\OMSIUA\Layer_Files	2	Coal Layers	2	1	0
19	Directional drilled wellbore.lyr	S:\AUM\OMSIUA\Layer_Files	2	Oil and Gas Layers	4	1	0
20	DMRM Strip Mines.lyr	S:\AUM\OMSIUA\Layer_Files	4	Coal Layers	2	1	0
24	Mine Location - Extent Unknown.lyr	S:\AUM\OMSIUA\Layer_Files	5	AUM Layers	3	1	0
25	Mine Opening from Topographic Maps.lyr	S:\AUM\OMSIUA\Layer_Files	3	AUM Layers	3	1	0
26	Mine Opening.lyr	S:\AUM\OMSIUA\Layer_Files	4	AUM Layers	3	1	0
28	NCRDS_PTS.lyr	S:\AUM\OMSIUA\Layer_Files	1	Coal Layers	2	1	0
29	OGWELLS.lyr	S:\AUM\OMSIUA\Layer_Files	1	Oil and Gas Layers	4	1	0
36	Superimposed Underground Mine.lyr	S:\AUM\OMSIUA\Layer_Files	8	AUM Layers	3	1	0
37	Underground Mine - Extent Partially Unknown.lyr	S:\AUM\OMSIUA\Layer_Files	7	AUM Layers	3	1	0
38	Underground Mine.lyr	S:\AUM\OMSIUA\Layer_Files	9	AUM Layers	3	1	0
39	Wayne NF - Gob Piles and Spoil Points.lyr	S:\AUM\OMSIUA\Layer_Files	1	Wayne National Forest	7	0	0
40	Wayne NF - Mine Openings.lyr	S:\AUM\OMSIUA\Layer_Files	2	Wayne National Forest	7	0	0
41	Wayne NF - Mine Seepages.lyr	S:\AUM\OMSIUA\Layer_Files	3	Wayne National Forest	7	0	0
42	Wayne NF - Mine Subsidence Locations.lyr	S:\AUM\OMSIUA\Layer_Files	4	Wayne National Forest	7	0	0
43	Wayne NF - Parcel Ownership.lyr	S:\AUM\OMSIUA\Layer_Files	11	Wayne National Forest	7	0	0
44	Wayne NF - PH and Water Sampling Points.lyr	S:\AUM\OMSIUA\Layer_Files	6	Wayne National Forest	7	0	0
45	Wayne NF - Ponds.lyr	S:\AUM\OMSIUA\Layer_Files	7	Wayne National Forest	7	0	0
46	Wayne NF - Rubbish.lyr	S:\AUM\OMSIUA\Layer_Files	8	Wayne National Forest	7	0	0
47	Wayne NF - Slumps Associated with Mines.lyr	S:\AUM\OMSIUA\Layer_Files	9	Wayne National Forest	7	0	0
48	Wayne NF - Structures.lyr	S:\AUM\OMSIUA\Layer_Files	10	Wayne National Forest	7	0	0
49	Wayne NF - Surface Mine Highwall Locations.lyr	S:\AUM\OMSIUA\Layer_Files	5	Wayne National Forest	7	0	0
50	Bedrock Topography 500K.lyr	S:\AUM\OMSIUA\Layer_Files	5	Surface and Bedrock Topography Layers	5	0	0
51	Drift Thickness.lyr	S:\AUM\OMSIUA\Layer_Files	6	Surface and Bedrock Topography Layers	5	0	0
52	Water Wells.lyr	S:\AUM\OMSIUA\Layer_Files	1	Water Wells	1	1	0
53	Pittsburgh No. 8 Isopach.lyr	S:\AUM\OMSIUA\Layer_Files	2	Regional Coal Maps - Pittsburgh No. 8	8	0	0
54	Pittsburgh No. 8 Structure Contours.lyr	S:\AUM\OMSIUA\Layer_Files	1	Regional Coal Maps - Pittsburgh No. 8	8	0	0
55	Pittsburgh No. 8 Structure Grid.lyr	S:\AUM\OMSIUA\Layer_Files	3	Regional Coal Maps - Pittsburgh No. 8	8	0	0
56	Pittsburgh No. 8 Overburden Grid.lyr	S:\AUM\OMSIUA\Layer_Files	4	Regional Coal Maps - Pittsburgh No. 8	8	0	0
57	Upper Freeport No. 7 Isopach.lyr	S:\AUM\OMSIUA\Layer_Files	2	Regional Coal Maps - Upper Freeport No. 7	9	0	0
58	Upper Freeport No. 7 Structure Contours.lyr	S:\AUM\OMSIUA\Layer_Files	1	Regional Coal Maps - Upper Freeport No. 7	9	0	0
59	Upper Freeport No. 7 Structure Grid.lyr	S:\AUM\OMSIUA\Layer_Files	3	Regional Coal Maps - Upper Freeport No. 7	9	0	0
60	Upper Freeport No. 7 Overburden Grid.lyr	S:\AUM\OMSIUA\Layer_Files	4	Regional Coal Maps - Upper Freeport No. 7	9	0	0
61	Lower Freeport No. 6a Isopach.lyr	S:\AUM\OMSIUA\Layer_Files	2	Regional Coal Maps - Lower Freeport No. 6a	10	0	0
62	Lower Freeport No. 6a Structure Contours.lyr	S:\AUM\OMSIUA\Layer_Files	1	Regional Coal Maps - Lower Freeport No. 6a	10	0	0
63	Lower Freeport No. 6a Structure Grid.lyr	S:\AUM\OMSIUA\Layer_Files	3	Regional Coal Maps - Lower Freeport No. 6a	10	0	0

Record: 1 Show: All Selected Records (0 out of 86 Selected) Options

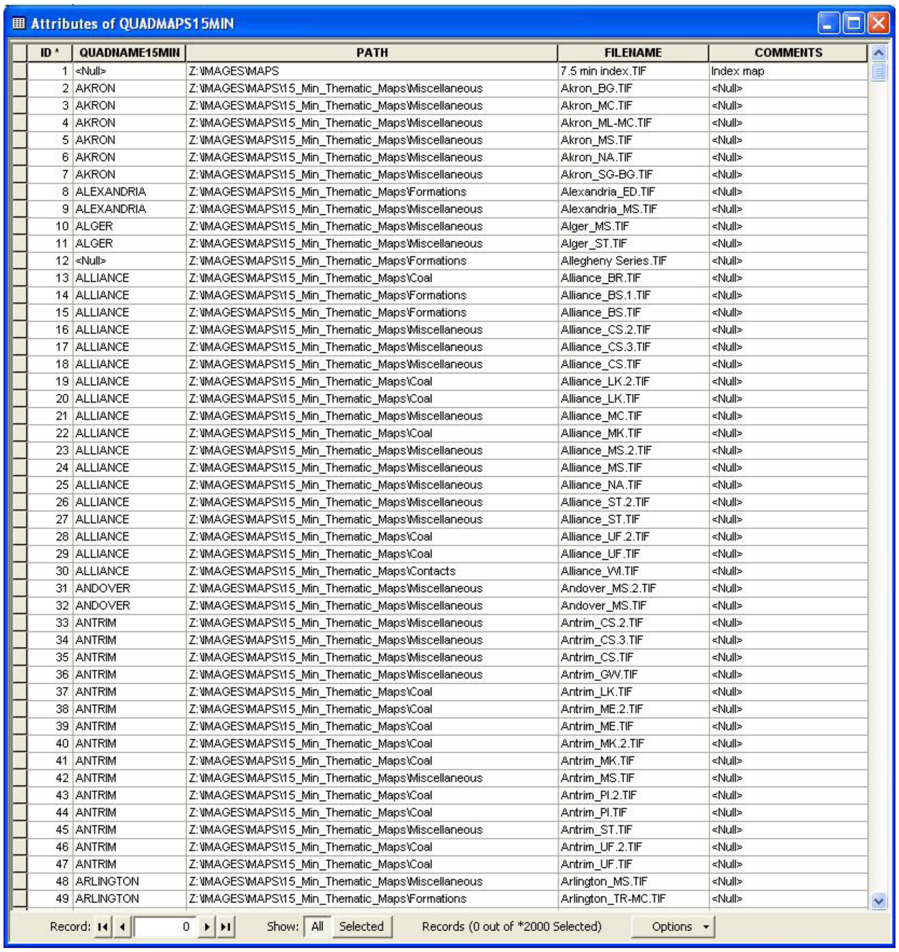
Figure 5. Portion of the table used for loading the vector layers into the ESRI ArcMap documents. The fields in the table contain information on the vector layers to be loaded into the table of contents (LAYERNAME), location of the layer file (PATH), the order in which the vector layer is loaded into the group layer (GROUPORDER), the group layer name (GROUPNAME), the location of the group layer in the table of contents (GROUPTOCORDER), whether the group layer display is turned on or off in the ArcMap (GROUPVISABLE), and whether the group can be exported into the PDF maps during the automated map production process (GROUPPDFEXPORT).

is specified using the TOC order attributes. All of the vector layers are loaded at the statewide level; the display of the vector layers is not limited to the zoomed-in area of interest.

The scanned paper maps, Digital Raster Graphic (DRG) maps, digital orthophoto images, and the scans of the abandoned-underground mine maps have the same type of table associated with them. The table contains the file name, the location of the file on the network drive and full path name (network location and file name), and an index location. The index location can be a county, civil township, U.S. Geological Survey 7.5-minute or 15-minute quadrangle name, or the identification number for the abandoned underground mine (fig. 6). In figure 6, the table contains information about the scanned 15-minute thematic geologic maps. These are maps that have been used to record geologic information, such as the locations of coal samples or the draft mapping of the bedrock geology for a particular 1:62,500-scale topographic quadrangle. The index location is the 15-minute quadrangle name.

In order to load the raster map images, a point location first must be identified. The point location, identified using a standard ESRI ArcObjects VBA function, is then passed along to a VBA class method that will process the location. A temporary half-mile, circular buffer is then applied to the point. Using the 15-minute thematic maps as an example, a spatial intersection is then performed between the buffer of the point and the 15-minute quadrangle map index feature class. The spatial intersection will identify all the 15-minute quadrangles that intersect the buffered point location. Once the list of 15-minute quadrangles is obtained, then a search is executed against the 15-minute quadrangle thematic maps table. All the georeferenced 15-minute quadrangle thematic maps selected from the table will then be loaded into the ArcMap application.

The application uses the similar table format for the 1:24,000-scale DRG topographic maps; the 1:1,200- and 1:600-scale digital-orthophotography images that are supplied from the Ohio Statewide Imagery Program (OSIP;



Attributes of QUADMAPS15MIN

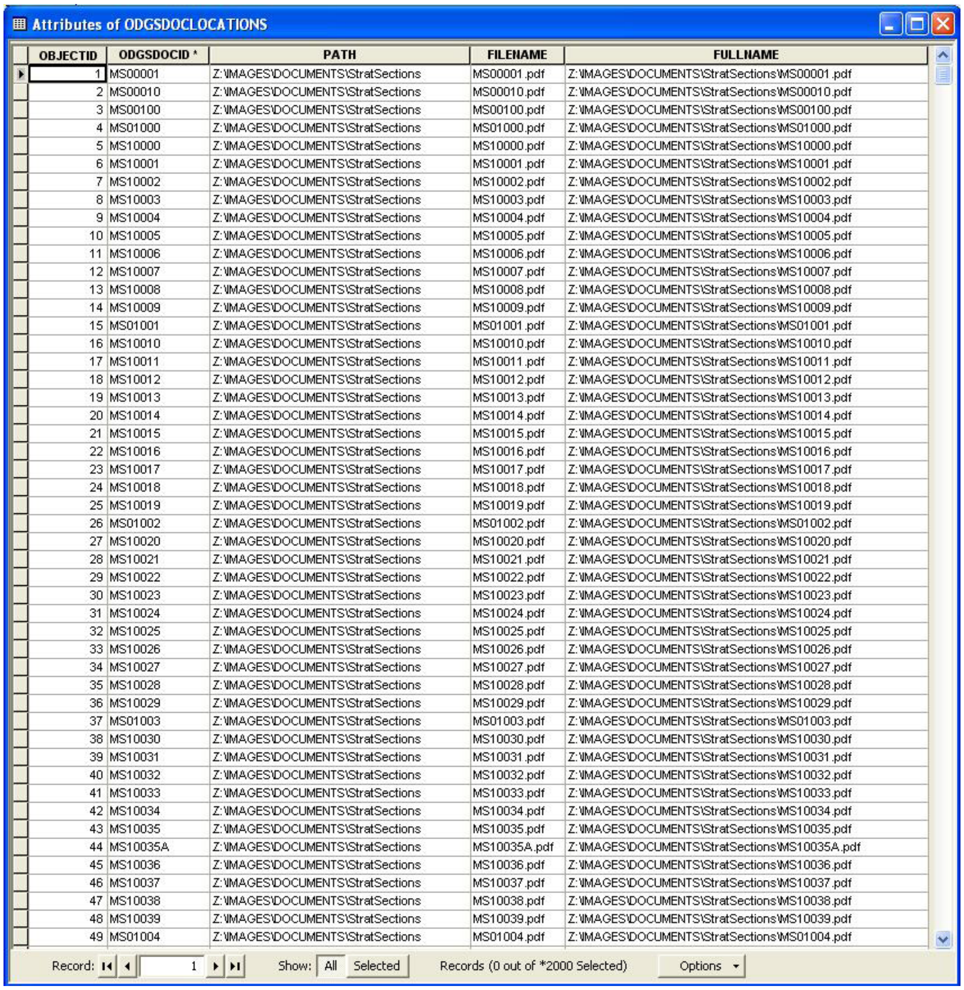
ID *	QUADNAME15MIN	PATH	FILENAME	COMMENTS
1	<Null>	Z:\IMAGES\MAPS	7.5 min index.TIF	Index map
2	AKRON	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Akron_BG.TIF	<Null>
3	AKRON	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Akron_MC.TIF	<Null>
4	AKRON	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Akron_ML-MC.TIF	<Null>
5	AKRON	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Akron_MS.TIF	<Null>
6	AKRON	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Akron_NA.TIF	<Null>
7	AKRON	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Akron_SG-BG.TIF	<Null>
8	ALEXANDRIA	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Formations	Alexandria_ED.TIF	<Null>
9	ALEXANDRIA	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alexandria_MS.TIF	<Null>
10	ALGER	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alger_MS.TIF	<Null>
11	ALGER	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alger_ST.TIF	<Null>
12	<Null>	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Formations	Allegheny Series.TIF	<Null>
13	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Alliance_BR.TIF	<Null>
14	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Formations	Alliance_BS.1.TIF	<Null>
15	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Formations	Alliance_BS.TIF	<Null>
16	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alliance_CS.2.TIF	<Null>
17	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alliance_CS.3.TIF	<Null>
18	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alliance_CS.TIF	<Null>
19	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Alliance_LK.2.TIF	<Null>
20	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Alliance_LK.TIF	<Null>
21	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alliance_MC.TIF	<Null>
22	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Alliance_MK.TIF	<Null>
23	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alliance_MS.2.TIF	<Null>
24	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alliance_MS.TIF	<Null>
25	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alliance_NA.TIF	<Null>
26	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alliance_ST.2.TIF	<Null>
27	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Alliance_ST.TIF	<Null>
28	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Alliance_UF.2.TIF	<Null>
29	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Alliance_UF.TIF	<Null>
30	ALLIANCE	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Contacts	Alliance_VM.TIF	<Null>
31	ANDOVER	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Andover_MS.2.TIF	<Null>
32	ANDOVER	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Andover_MS.TIF	<Null>
33	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Antrim_CS.2.TIF	<Null>
34	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Antrim_CS.3.TIF	<Null>
35	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Antrim_CS.TIF	<Null>
36	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Antrim_GW.TIF	<Null>
37	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Antrim_LK.TIF	<Null>
38	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Antrim_ME.2.TIF	<Null>
39	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Antrim_ME.TIF	<Null>
40	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Antrim_MK.2.TIF	<Null>
41	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Antrim_MK.TIF	<Null>
42	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Antrim_MS.TIF	<Null>
43	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Antrim_PI.2.TIF	<Null>
44	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Antrim_PI.TIF	<Null>
45	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Antrim_ST.TIF	<Null>
46	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Antrim_UF.2.TIF	<Null>
47	ANTRIM	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Coal	Antrim_UF.TIF	<Null>
48	ARLINGTON	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Miscellaneous	Arlington_MS.TIF	<Null>
49	ARLINGTON	Z:\IMAGES\MAPS\15_Min_Thematic_Maps\Formations	Arlington_TR-MC.TIF	<Null>

Record: 0 Show: All Selected Records (0 out of *2000 Selected) Options

Figure 6. Portion of the table used for loading the raster map images into the ESRI ArcMap documents. The fields in the table contain information on the index identification number for the file (QUADNAME15MIN), the location of the raster image (PATH), the name of the raster image (FILENAME), and a comments field (COMMENTS). The raster images listed in this table are for the 15-minute quadrangle thematic maps. The index identification numbers in this figure refer to the 15-minute quadrangle names.

OGRIP, 2006); and the low-resolution (72 dpi) abandoned-underground mine maps. These three types of index tables use different spatial indexing schemes. The U.S. Geological Survey DRG topographic maps and the OSIP imagery have been compiled into county-level tiles across the state. Therefore, these tables use a county index identifier for each record. The low-resolution abandoned-underground mine maps use the new 12-digit identifier that has been modified from the American Petroleum Institute identifier (API no.) for oil and gas wells. In order to load the DRGs and the OSIP imagery, ArcMap needs to contain an Ohio county index map feature class. In order to load the scans of the abandoned-underground mine maps, ArcMap needs to contain the abandoned-underground-mine polygon feature class. The same procedure is used to locate the index polygons, to find the index identifier, which is then used to select the records in the raster index table, and then to load the selected raster maps and georeferenced images into ArcMap.

The scanned records have a similar type of table schema as the raster maps tables (fig. 7). In the table, there is a unique identifier associated with each record, which could be a core description number or a measured stratigraphic section number. In addition, the file name for the document, the location of the file on the network, and the full path name for the file are included each as attribute fields for the record. The unique identifier is used to join the scanned records index table with the scanned documents GIS feature class. Currently, each document is located via a point location within a feature class. The feature class is loaded into ArcMap and the scanned records table is joined to the document feature class using an attribute table join. When the user wants to display the document for a particular location in ArcMap, the user uses the hyperlink tool to display the document. The full path and file name for the document are used for displaying the document as a hyperlink within ArcMap.



OBJECTID	ODGSDOCID *	PATH	FILENAME	FULLNAME
1	MS00001	Z:\IMAGES\DOCUMENTS\StratSections	MS00001.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS00001.pdf
2	MS00010	Z:\IMAGES\DOCUMENTS\StratSections	MS00010.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS00010.pdf
3	MS00100	Z:\IMAGES\DOCUMENTS\StratSections	MS00100.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS00100.pdf
4	MS01000	Z:\IMAGES\DOCUMENTS\StratSections	MS01000.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS01000.pdf
5	MS10000	Z:\IMAGES\DOCUMENTS\StratSections	MS10000.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10000.pdf
6	MS10001	Z:\IMAGES\DOCUMENTS\StratSections	MS10001.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10001.pdf
7	MS10002	Z:\IMAGES\DOCUMENTS\StratSections	MS10002.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10002.pdf
8	MS10003	Z:\IMAGES\DOCUMENTS\StratSections	MS10003.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10003.pdf
9	MS10004	Z:\IMAGES\DOCUMENTS\StratSections	MS10004.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10004.pdf
10	MS10005	Z:\IMAGES\DOCUMENTS\StratSections	MS10005.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10005.pdf
11	MS10006	Z:\IMAGES\DOCUMENTS\StratSections	MS10006.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10006.pdf
12	MS10007	Z:\IMAGES\DOCUMENTS\StratSections	MS10007.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10007.pdf
13	MS10008	Z:\IMAGES\DOCUMENTS\StratSections	MS10008.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10008.pdf
14	MS10009	Z:\IMAGES\DOCUMENTS\StratSections	MS10009.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10009.pdf
15	MS01001	Z:\IMAGES\DOCUMENTS\StratSections	MS01001.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS01001.pdf
16	MS10010	Z:\IMAGES\DOCUMENTS\StratSections	MS10010.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10010.pdf
17	MS10011	Z:\IMAGES\DOCUMENTS\StratSections	MS10011.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10011.pdf
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19	MS10013	Z:\IMAGES\DOCUMENTS\StratSections	MS10013.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS10013.pdf
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49	MS01004	Z:\IMAGES\DOCUMENTS\StratSections	MS01004.pdf	Z:\IMAGES\DOCUMENTS\StratSections\MS01004.pdf

Figure 7. Portion of the table used for loading and accessing the scanned records into the ESRI ArcMap documents. The fields in the table contain information on the index identification number for the file (ODGSDOCID), the location of the raster image (PATH), the name of the raster image (FILENAME), and the full path and name of the raster image (FULLNAME). The scanned records in this figure refer to the measured stratigraphic sections, and the index identification numbers refer to the measured stratigraphic section ID.

During an earlier project, GeoDecisions, Inc., created the initial database design for the abandoned-underground mines database. The attribute database for the abandoned underground mines includes a number of different tables, all of which are tied together using the new 12-digit identifiers (fig. 8). The primary table is the Abandoned Underground Mine polygon feature-attribute table, which is part of the abandoned-underground-mine polygon feature class. Associated with the primary table are a number of tables that record the attribute information concerning the underground mines. These tables include basic information on the underground mines (TBLMINES), information on the operator and the name of the mine (TBLOPERATOR), information on the location (TBLCOUNTY, TBLTOWNSHIP, TBLQUAD), information on the type of commodity being mined (TBLCOMMODITY), the name of the coal bed or geologic unit being mined (TBLSEAM), and general information about the mine (TBLCOMMENT). Some of the tables have a one-to-one relationship with the polygon feature-attribute table (for example, TBLMINES). Other tables have a one-to-many relationship with the polygon feature-attribute table. Examples of these types of relationships include the tables TBLOPERATOR and TBLSEAM. With the one-to-many relationship, a mine can have more than one record associated with those particular attributes. For example, a mine can have one or more owners over the life span of the mine. Or, a mine can produce coal from one or more coal beds. In order to display all of these attributes, relationships are set up in either the database or in ESRI ArcGIS between the polygon feature class and all the attribute tables.

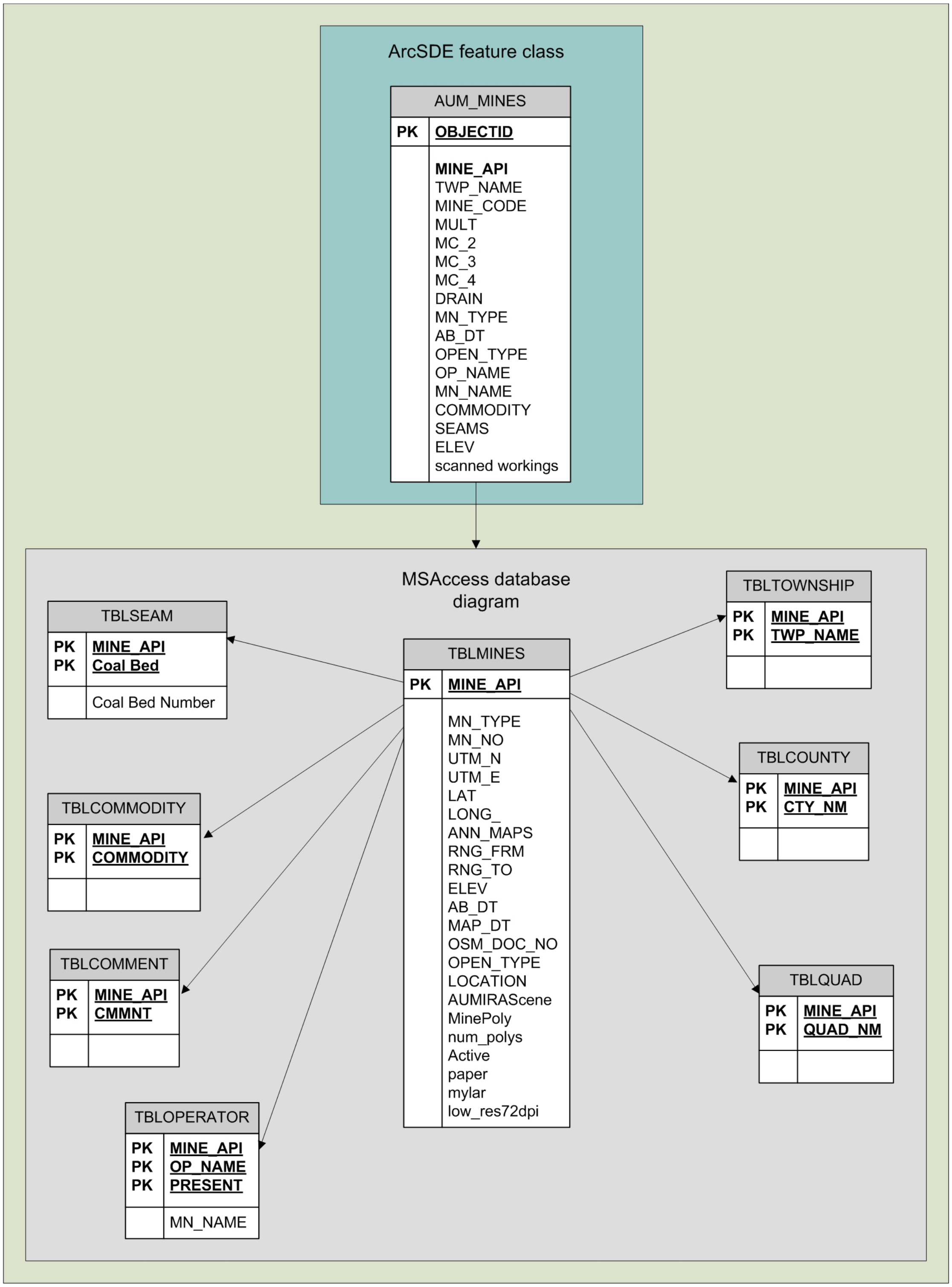


Figure 8. Entity relationship diagram of the Abandoned Underground Mines database. This diagram shows the relationships between all the tables describing the attribute information associated with the abandoned underground mines.

To easily display all the attributes associated with an underground mine, a VBA form was created. When a mine is selected with the tool associated with the form, the 12-digit identifier is read from the polygon feature class. The identifier is then used to create SQL statements within the ArcObjects environment. The SQL statements are in turn applied to each of the related tables, gathering information about the selected mine. Finally, the information is presented in the VBA form for a user to examine.

The final portion of the application involves the creation of simple PDF maps from all the vector layer groups. A code snippet, in the VBA language, was downloaded from the ESRI Web site (*http://www.esri.com*) that exports PDF maps from ArcMap. The code snippet was modified to automatically generate many PDF maps, based upon the vector groups that had been loaded into ArcMap. The modified code reads the vector layers table and then creates a PDF map for all the groups specified in the vector layers table.

Application User Interface

The user interface of the OMSIUA GIS application features a number of toolbar tools, including native ArcGIS tools and tools custom-designed using VBA for ArcObjects (fig. 9).

To locate mine subsidence claims, two tools are used to zoom into the claim location and load all geologic maps and documents. The toolbar contains the native ArcGIS Find tool (fig. 10). This tool is used to locate insurance claims based upon the Address Locator function in the Find tool. The second tool on the toolbar is the mine-subsidence location Select Location tool (fig. 11). This tool will load all known digital geologic maps and all geologic GIS data into the ArcMap document for that location. Some of the GIS datasets include abandoned underground mines, permitted surface mines, the 1:24,000-scale bedrock geology, and the 1-foot-resolution digital orthophotography. One of the most important historical records is the set of 15-minute thematic geologic maps. The Select Location tool will identify all the scanned maps within a half-mile radius and load them into ArcMap (fig. 12).

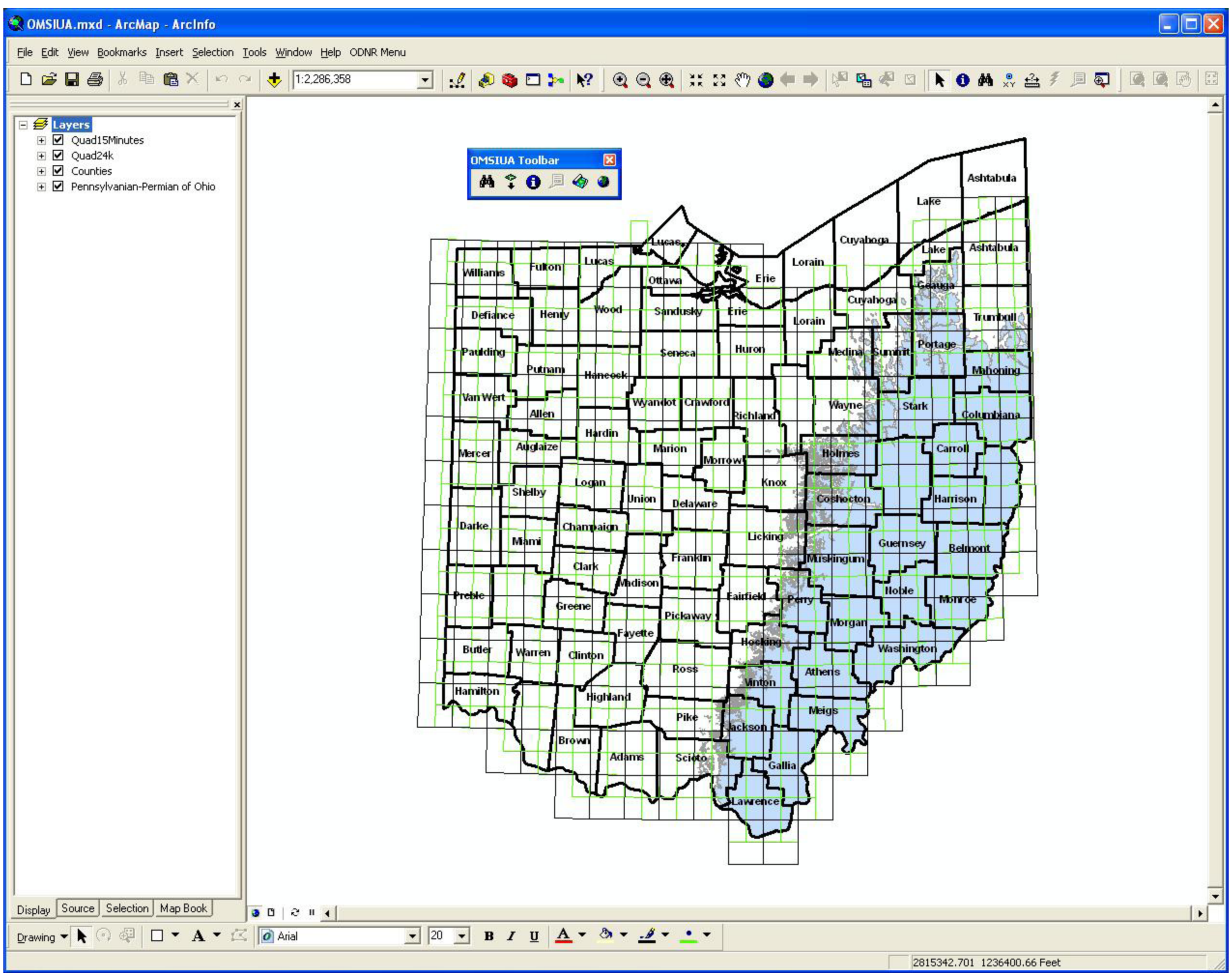


Figure 9. OMSIUA Toolbar. The toolbar, built using ESRI ArcMap customization tools, contains a set of native ArcMap commands and custom-built VBA commands.

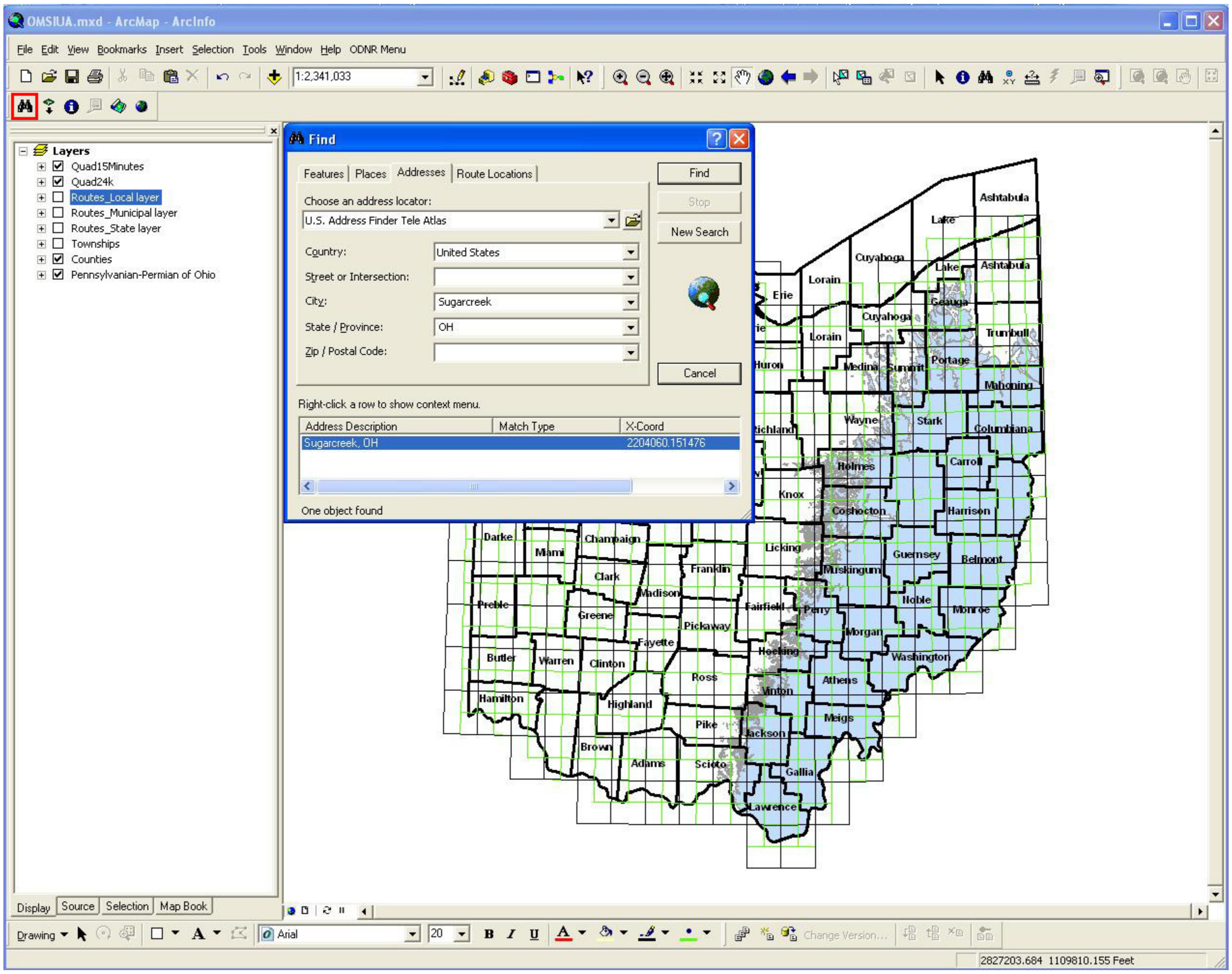


Figure 10. The "Find" tool on the OMSIUA Toolbar. This tool and the ESRI Address Locator are used to locate an insurance claim based upon the claim address. The "Find" tool is highlighted in RED on the OMSIUA Toolbar.

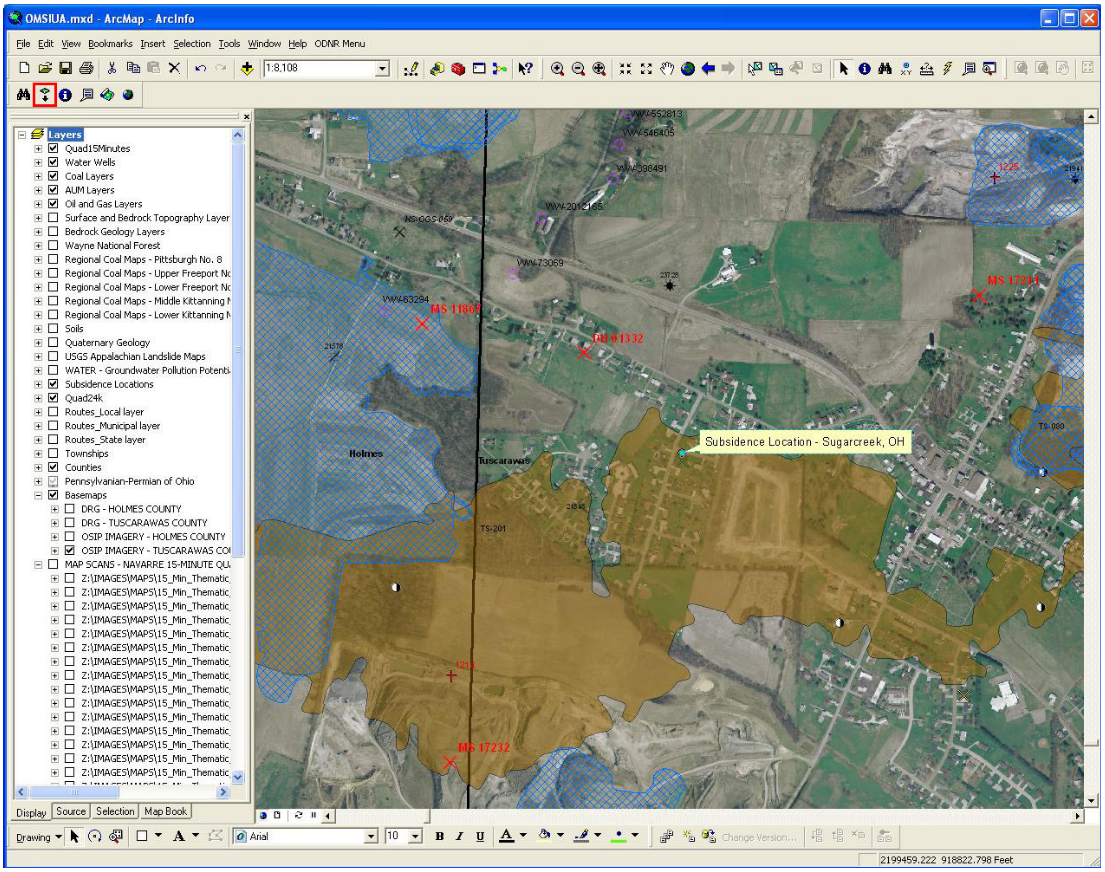


Figure 11. The "Select Location" tool on the OMSIUA Toolbar. All geologic information is loaded into ESRI ArcMap for the complainant location. The "Select Location" tool is highlighted in red on the OMSIUA Toolbar.

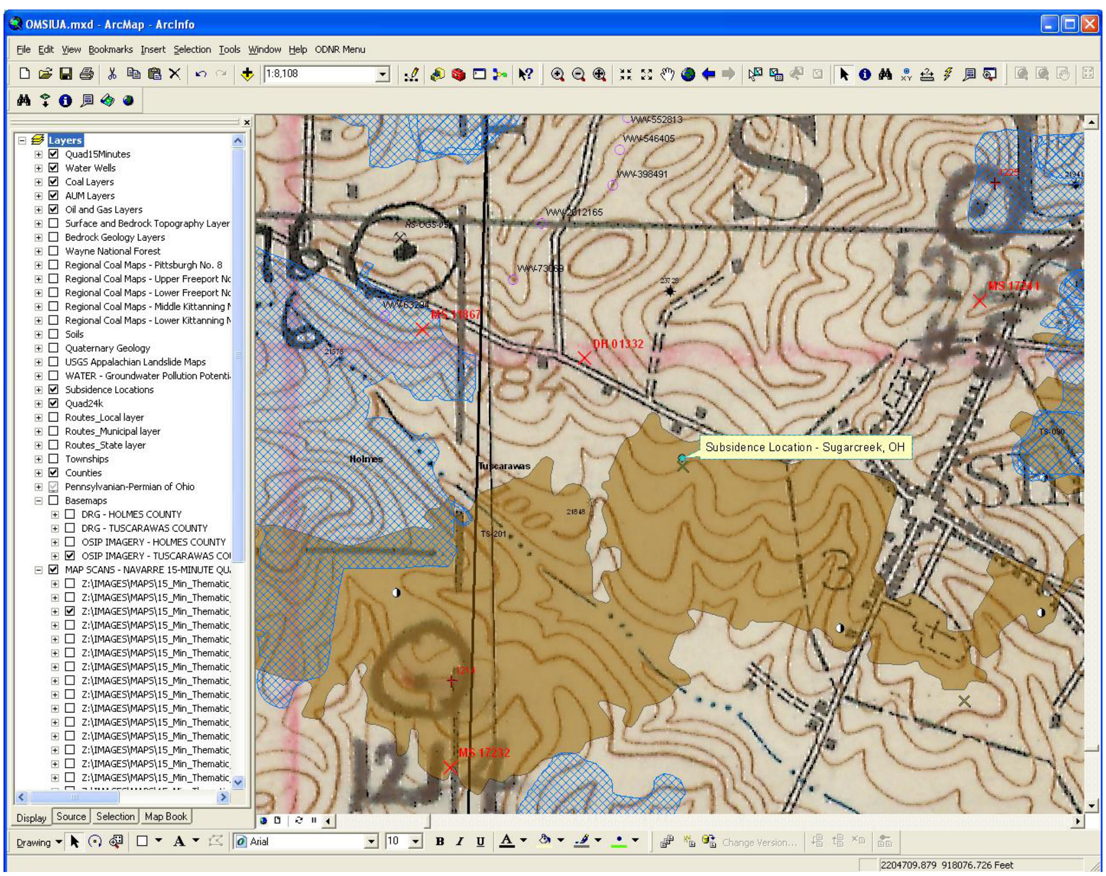


Figure 12. Historic thematic 15-minute topographic map as a base map. In the ArcMap TOC, 38 different thematic 15-minute topographic maps have been identified and loaded into the ArcMap project. The base map in this figure shows the coal sample locations mapped onto the thematic 15-minute topographic map.

Once the information is loaded, the geologist can conduct a preliminary mine-subsidence analysis. The Underground Mine Information Form (fig. 13A) will present the attribute information on abandoned underground mines. In addition, by using the form, the georeferenced abandoned mine maps can be loaded into ArcMap (fig. 13B). Documents can be accessed using the native ArcGIS Hyperlink tool (fig. 14). Some of the documents that can be accessed are measured stratigraphic sections, core descriptions, and oil- and gas-well completion cards. These three types of documents may contain a description of a coal bed, and possibly the notation that an underground mine is nearby.

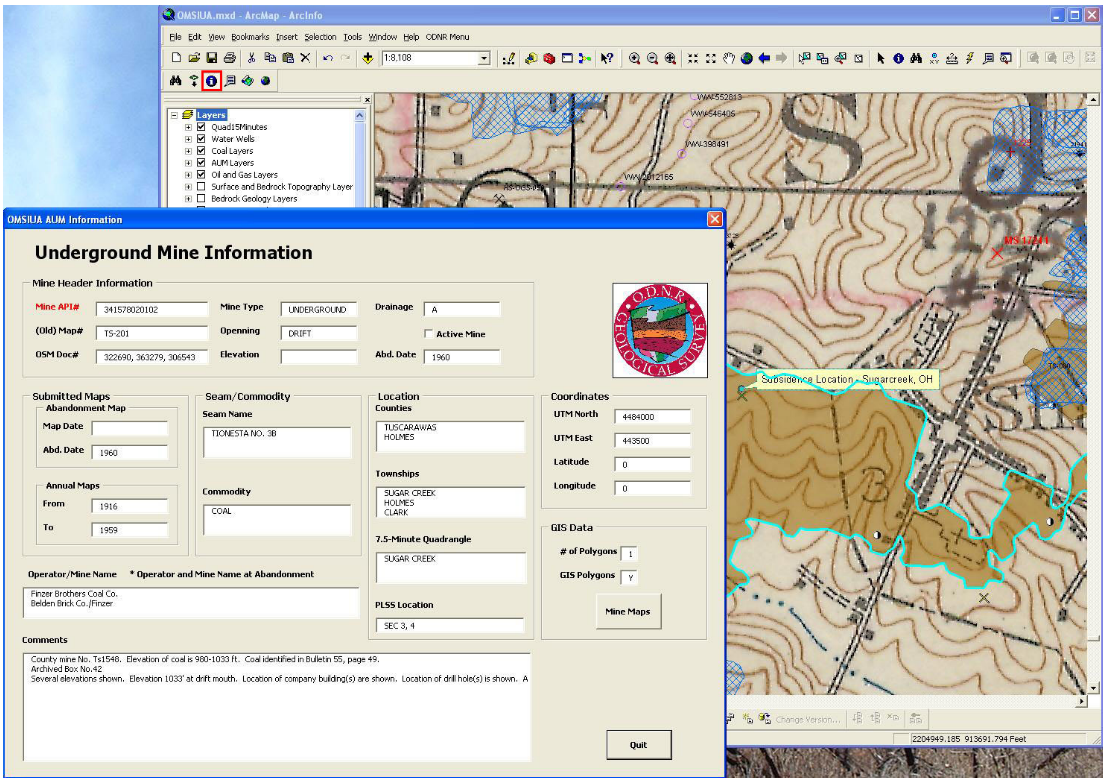


Figure 13A. Underground Mine Information Form. A VBA form was created that allows the selected mine attribute information to be loaded into the form for display. The Underground Mine Information Form is activated by selecting the "Underground Mine Information" tool on the OMSIUA Toolbar, which is highlighted in red.

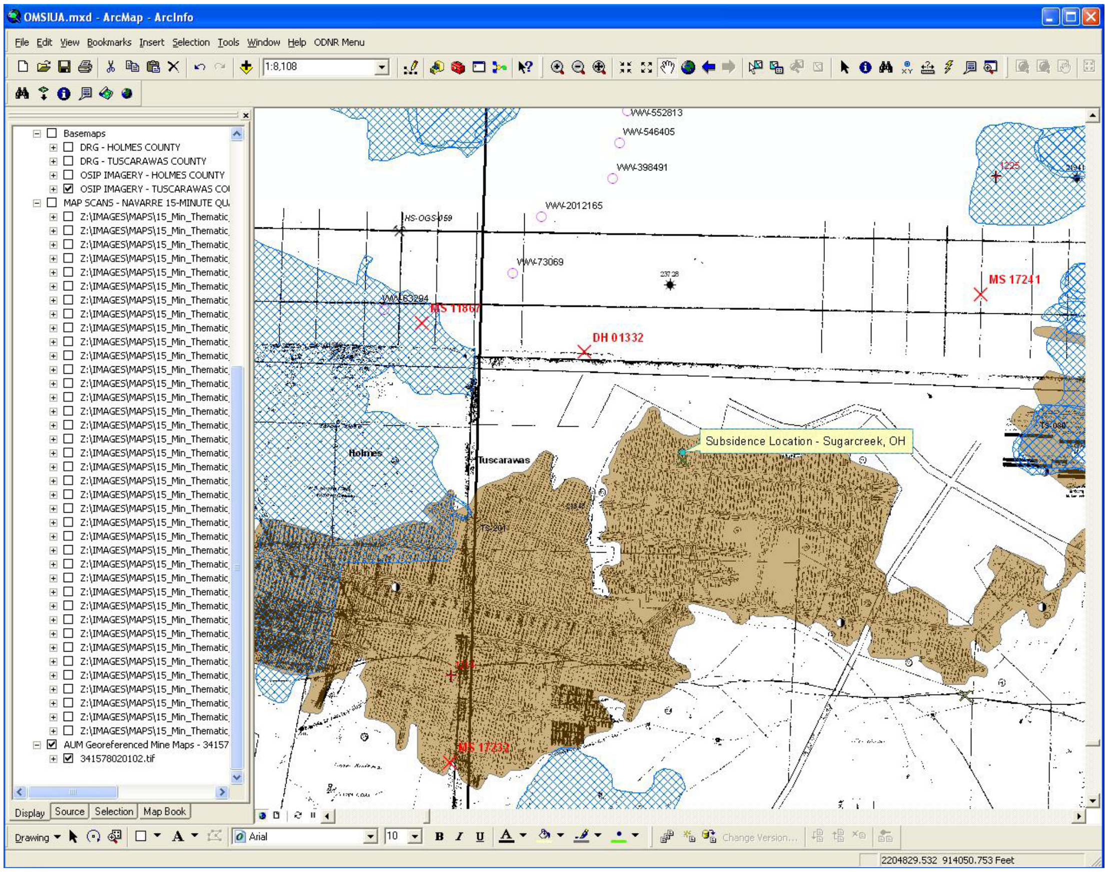


Figure 13B. Using the Mine Maps command on the Underground Mine Information Form, the georeferenced, detailed mine map can be loaded into ArcMap. The detailed mine maps show the room-and-pillar configuration within the abandoned underground mine.

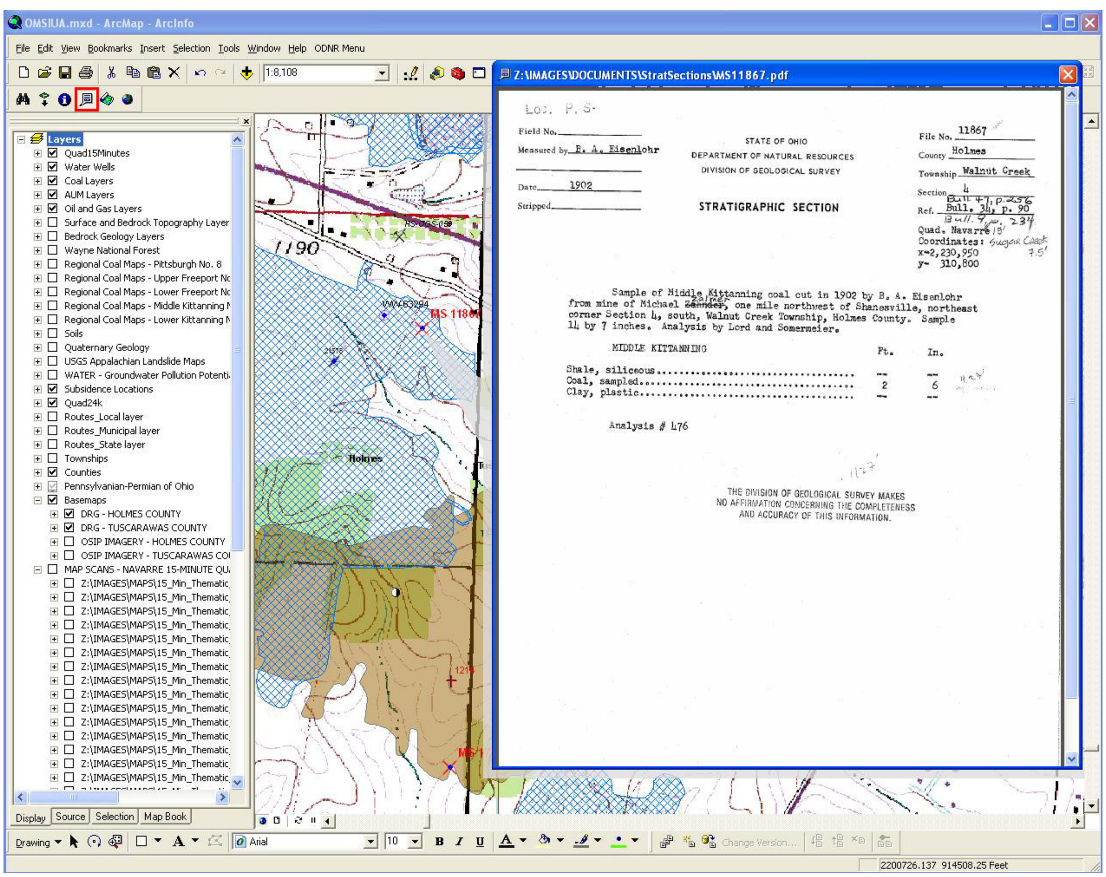


Figure 14. Example of using the ESRI ArcMap Hyperlink tool to access a scanned document. In this figure, the scanned document is a measured stratigraphic section. The ESRI ArcMap Hyperlink tool is highlighted in red on the OMSIUA Toolbar.

After the analysis is completed, portions of the preliminary mine subsidence report can be automated. A custom-designed tool will export thematic, page-sized PDF maps (fig. 15A). The page-size maps are generated with titles that are based upon the group layer names in the ArcMap TOC (fig. 15B). The PDF maps, along with all the geologic documents within a half-mile of the site, will be exported to a temporary directory (fig. 15C). The geologist can then compress the files and send them to the consulting engineering company for further analysis. These data allow the consulting engineering companies to have existing, publicly held geologic data about a site made available so that they arrive at the complainant's site with the appropriate data.

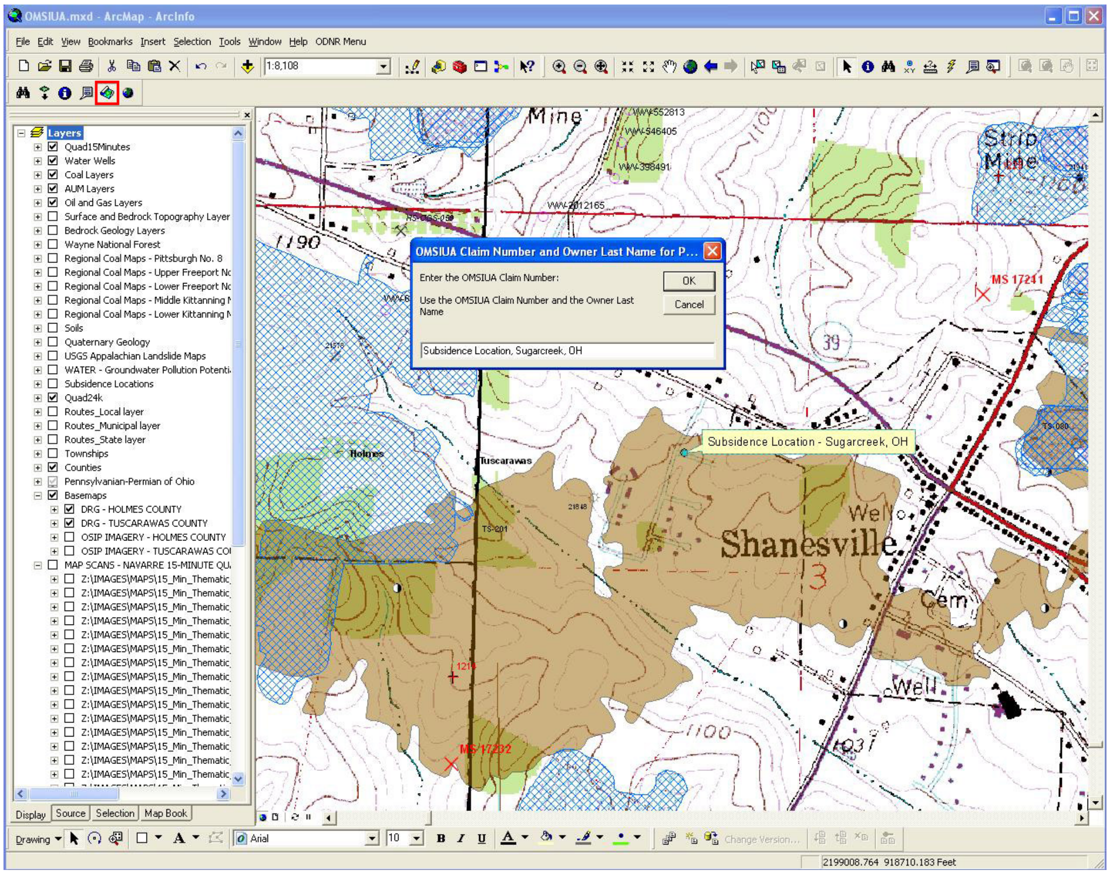


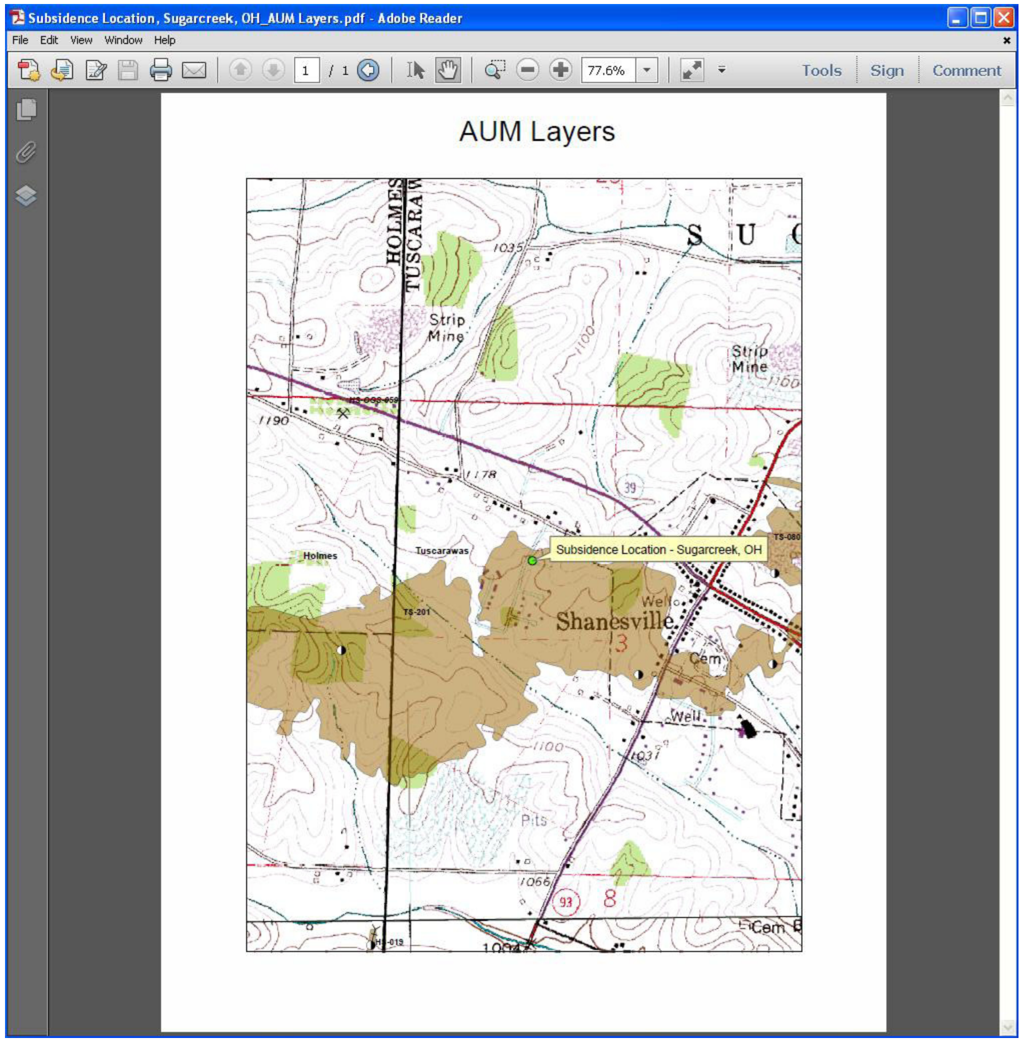
Figure 15A. The OMSIUA Toolbar contains a tool that automates exporting of PDF maps. The Export PDF tool is highlighted in red on the OMSIUA Toolbar.

Summary

The OMSIUA GIS application has proven to be extremely successful in its ability to gather all known geologic information for a specific location and present the information to GIS users within the ESRI ArcGIS Desktop environment. This application has significantly reduced the amount of time that a geologist takes to determine if the site of a mine subsidence claim is underlain by an abandoned underground mine. The application significantly speeds up the process of evaluating mine subsidence claims, thereby saving the State of Ohio and its citizens significant tax monies.

The application also proves to be very popular for nonsubsidence inquiries. Geologists have used the application to investigate potential karst sinkholes and the potential causes of landslides in Ohio. A modified version of the application has also been created to assist with the permitting of oil- and gas-well locations.

Figure 15B. Example of an automatically exported PDF map. Each automated PDF map is generated with a title based upon the group layer name in the ArcMap TOC.



Acknowledgments

The ODNR Division of Geological Survey thanks the Ohio Mine Subsidence Insurance Underwriting Association (OMSIUA) for providing funding to create the application and to perform the preliminary site assessments of mine subsidence insurance claims.

We also thank the many agencies that have allowed access to their GIS datasets for use in the OMSIUA GIS application. Within the Ohio Department of Natural Resources, the Division of Mineral Resources Management provides the surface-coal mine GIS datasets (MINEINFO dataset) and the Abandoned Mine Lands (AML) emergency locations, the Division of Soil and Water Resources provides access to the SSURGO soils GIS dataset and the DRASTIC GIS dataset, and the Office of Information Technology provides ESRI ArcSDE access and maintenance to the SURGO soils GIS dataset. The U.S. Department of Agriculture, Forest Service, provides access to the AIM dataset of abandoned-mine features located within Wayne National Forest.

The engineering consulting firms of Gannett Flemming and H.C. Nutting provide reviews of the output from the OMSIUA GIS application. These reviews provide information that makes the application more useful for mine-subsidence claim investigations. Finally, thanks to ODNR Division of Mineral Resources Management supervisor Tim Jackson and former chief John Husted for their support of the project.

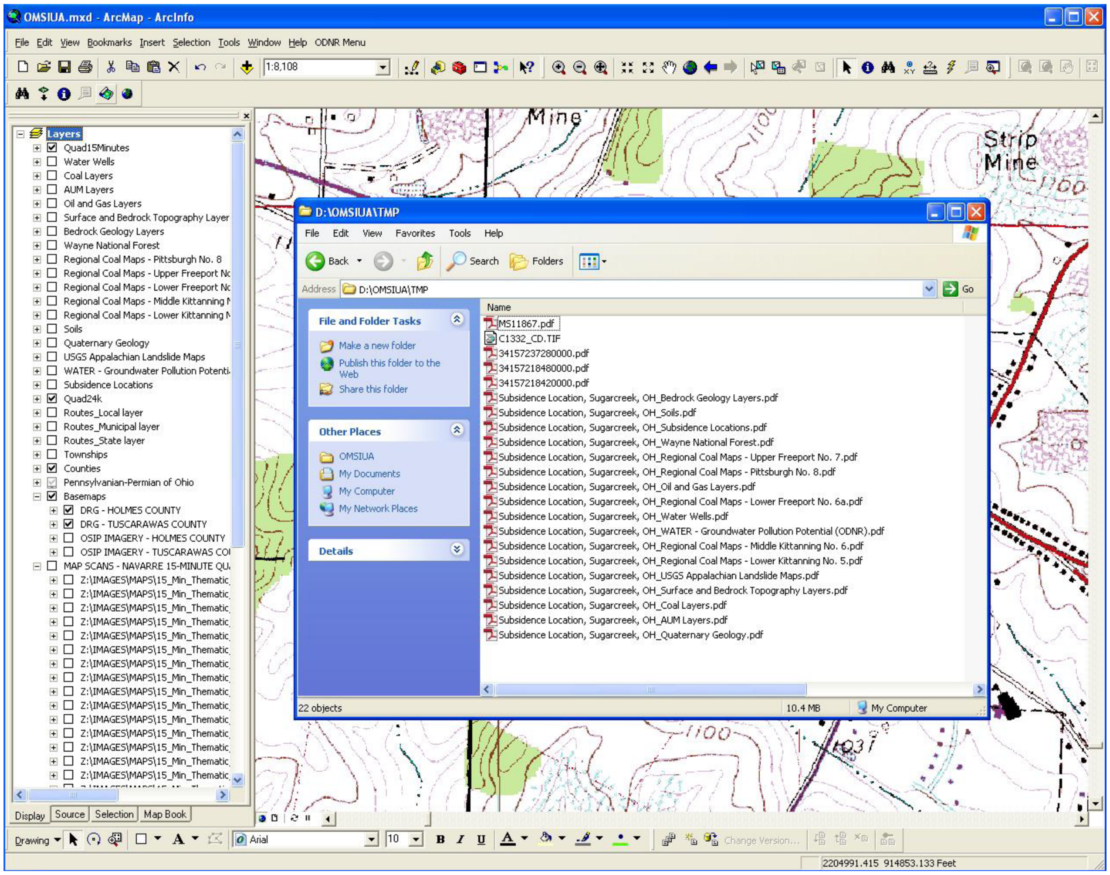


Figure 15C. Example showing the temporary directory that is specified to contain all the exported PDF maps and relevant scanned documents. The PDF figures and all documents within a half-mile radius are copied to this temporary directory, which then can be forwarded to the consultant for the site evaluation.

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Assessing Early Stages of a Landslide Inventory

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Introduction

The Kentucky Geological Survey (KGS) is actively collecting data for a statewide landslide inventory and database. Steep topography, variable bedrock geology, and surficial deposits have combined to result in several areas of Kentucky being highly susceptible to different styles of landslides. To better document the distribution and context of Kentucky's landslide problems, KGS has begun a landslide inventory program.

A landslide inventory that can address remediation and repair costs and ultimately reduce the risk of landslides is the primary goal. Incorporating vast amounts of data in an organized, effective manner is a challenge. The early stages of work consist of prioritizing data collection from a wide variety of sources of landslide locations, sources such as active field mapping, light detection and ranging (LiDAR) analysis, preexisting landslide maps, State and county agencies, and anecdotal information (fig. 1).

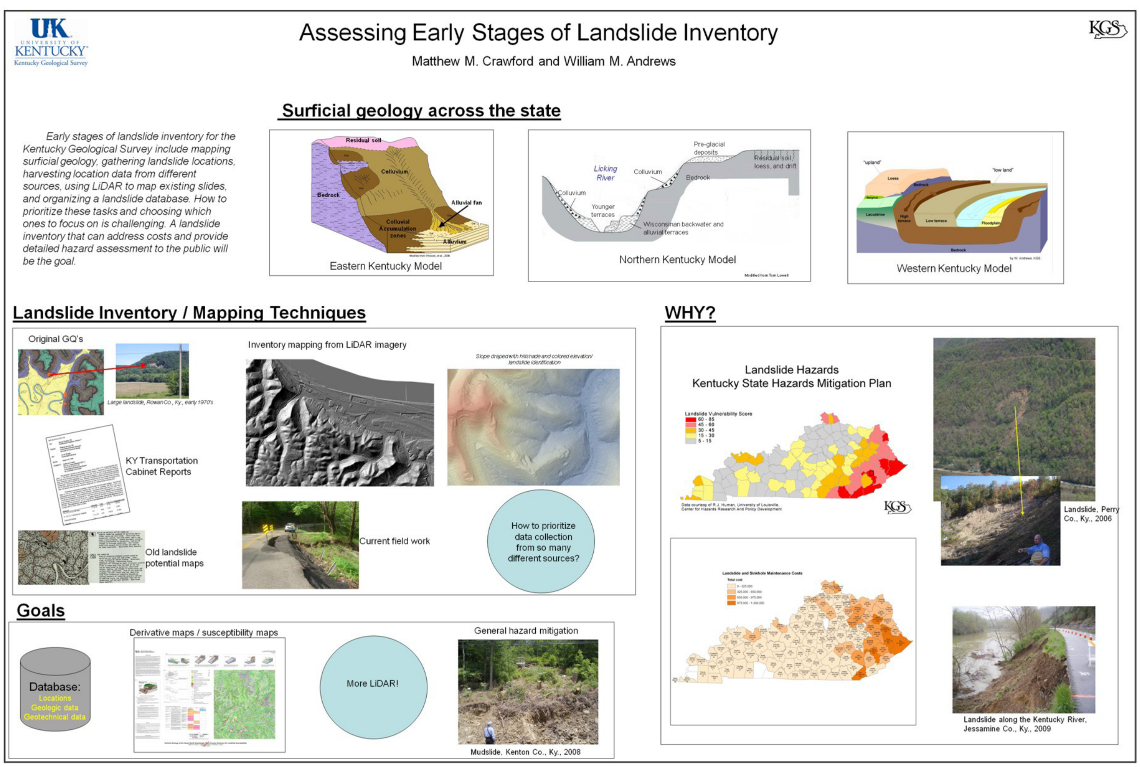

Figure 1. Page-size version of DMT '10 poster showing process of developing the KGS landslide inventory; see full-resolution image at *http://ngmdb.usgs.gov/Info/dmt/DMT10presentations.html*). Poster includes images modified from Wysocki and others (2000) and Potter (1996).

Purpose and Goals

Landslides are a major cause of property loss and infrastructure damage in Kentucky. The natural geology and soils combined with human activity put many places at risk, causing financial hardship for property owners and challenges for the government agencies that may be responsible for assisting. Since the early 1970s, the Kentucky Transportation Cabinet and the Kentucky Transportation Center have documented over 3,000 landslides (approximately 25 percent of those have geotechnical reports and are accurately located). Costs for repair of infrastructure damaged by these landslides exceed $2 million annually; however, there remain hundreds that are unreported, and many of these may not be related to transportation corridors. In addition, the Kentucky Office of Emergency Management spent $617,466 solely on acquisition of landslide-impacted homes from 2004 to 2007 (Kentucky State Hazard Mitigation Plan, 2007, p. 115).

An understanding of surficial deposits and the underlying bedrock is critical to the structure of the inventory and what data will be collected. Early construction of a database of landslide locations (their coordinates) is complete, and populating it with the associated geologic and geotechnical attributes is in progress. Because of a wide range of ages for these landslides and the limited time available for field checking, not all landslides in the database have a full set of attributes. In addition to the landslide inventory database, using the landslide locations, existing 1:24,000-scale geologic mapping, slope, and other datasets in a GIS, derivative maps or other products that the public can access will be created to address specific landslide issues.

Surficial Geologic Settings

Landslides occur statewide in Kentucky. All physiographic regions contain varying extents of steep slopes, bedrock lithology, and complex soils. For the purposes of understanding and mapping landslide potential, Kentucky can be broadly divided into three regions of distinctive surficial geologic conditions.

Eastern Kentucky

This large area lies east of the Cumberland Escarpment and within the Eastern Kentucky Coal Field of the Appalachian Basin. The topography is characterized by steep slopes with broad to very narrow valleys. Bedrock lithologies include sandstone, shale, siltstone, coal, and clay of variable thickness. The bedrock weathers to form complex surficial deposits of colluvium, alluvium, and residual soils (fig. 2). The steep slopes, heterogeneous bedrock lithologies, and variable thicknesses of the surficial deposits create a dynamic terrain highly susceptible to landslides.

Western Kentucky

Low-relief bedrock uplands are separated by broad alluvial valleys (Andrews and others, 2006). Bedrock lithologies include sandstone, shale, siltstone, coal, and clay of variable thickness. Surficial materials primarily consist of Pleistocene loess on the uplands and thick deposits of Pleistocene and Holocene alluvial and lacustrine sediment in the valleys. The

Figure 2. Photograph showing surficial geologic deposits typical in eastern Kentucky.

variable thicknesses and lithologies of the deposits create properties and behaviors that have a direct impact on slope stability. Areas where KGS has completed surficial geologic mapping primarily lie in the Green and Ohio River corridors of the Western Kentucky Coal Field of the Illinois Basin.

Northern Kentucky

The surficial deposits in this area are mainly glacial sediments, hillslope colluvium, residual soils, alluvium, and lacustrine deposits. The northern extent of this area is bounded by the glaciated Ohio River Valley, which served as an outlet for glacial meltwater, creating outwash deposits, slackwater sediment, and high-level terraces along the tributaries (Potter, 1996). Topographic relief averages approximately 500 feet, ranging from steep slopes along the Ohio River, gently sloping uplands, and broad dissected valleys. Shaly bedrock in the region weathers easily and produces thin to thick, clayey colluvial soils. Landslides typically occur within the colluvium or along the colluvial-bedrock contact.

Data Collection

Sources

Landslide locations came from a variety of sources: active field mapping, published geologic maps, LiDAR visualization, Kentucky Transportation Cabinet geotechnical landslide reports, the Natural Resource Conservation Service, Division of Natural Resources–Mine Reclamation and Enforcement, Division of Abandoned Mine Lands, media reports, and individuals.

Presently there are approximately 2,100 landslides with accurate locations inventoried across Kentucky. As resources permit, selected landslides are visited to collect key ground-condition information; to date, approximately 40 sites have been visited. For historic or other older landslides in the inventory that cannot be investigated in the field, the database will be populated with as many data as possible from a variety of information resources.

Attributes and Priority

The KGS landslide inventory database was designed on the basis of common attributes collected by other states with active inventories and landslide hazard assessment programs, as well as data fields necessary to collect and store information on recurrence and associated costs and losses. Landslide attributes have been devised to represent the conditions common to most of Kentucky's landslides and to capture information that is essential to hazard assessment.

Developing a comprehensive inventory of landslides in a state with widely varying geologic conditions is a challenge. Landslide hazards impact public infrastructure and lands as well as many private residences. Among the many landslide locations for which there is very little information, which ones should be focused on? Which of the many types of landslide inventory source records might be most amenable to field verification? For example, an old landslide related to a transportation route may have a good x,y location in the database, but it may not be identifiable in the field or may not have a geotechnical report available. The current data collection process includes converting the landslide locations from very different sources into one standardized database. Choosing the attributes (fig. 3) to focus on is important in order to gather as much information as possible while keeping in mind the goals and potential products. For example, would it be more effective for landslide susceptibility analysis to focus on a relatively few landslides that can be visited in the field in order to gather information for all the attributes? The emergence of LiDAR data across different parts of the state may dictate which areas to focus on. The availability of an inventory that has sufficient geologic and geomorphic information associated with landslides and that can address costs and ultimately reduce the landslide hazard risk is the ideal goal.

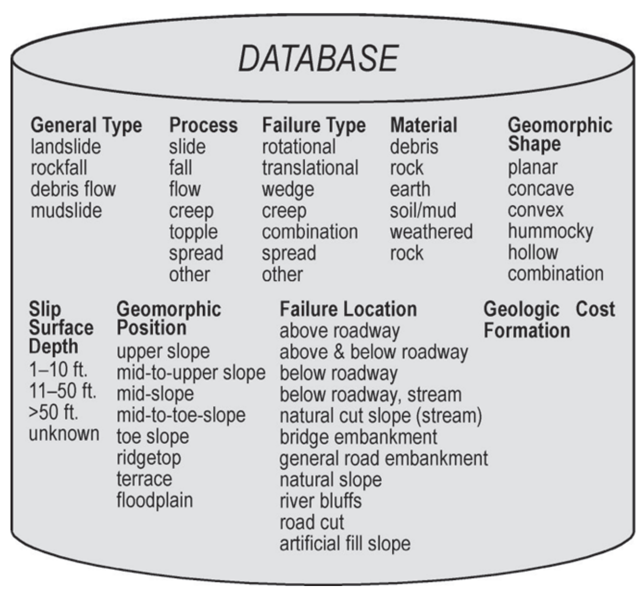

Figure 3. Selected attributes and values for landslides entered into the inventory database. Geologic formation and cost values are not listed.

Conclusion

The Kentucky Geological Survey is actively collecting data for a statewide landslide inventory and database. Constructing the database and collecting data associated with each slide is critical to successfully using an inventory to begin to analyze landslides for risk. The variety of sources of landslide locations, the age range for different landslides, the availability of information for each slide, and variable geologic conditions make this a difficult task. Once an inventory is constructed and data can be collected efficiently for landslide locations, new and old, then a wealth of information can become available in the form of maps, reports, or GIS files to address cost and ultimately reduce risk.

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A Plan and Plea for Increasing Communication about Digital Geologic Field Mapping

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Introduction

The Alaska Division of Geological & Geophysical Surveys (DGGS) collects, analyzes, and publishes geological and geophysical information to help inventory and manage Alaska's natural resources and mitigate geologic-hazard risks. In 2005, DGGS began investigating the potential of digital field mapping technology to streamline data collection and processing (Athey and others, 2009). Digital mapping is defined as using a computer or personal digital assistant (PDA) to display and record information that has traditionally been recorded on paper, whether on notecards, in a notebook, or on a map. To facilitate discussion in the geologic community regarding digital field mapping technology, DGGS implemented a three-pronged plan. In 2009, DGGS created a Wikipedia page for digital geologic mapping (*http://en.wikipedia.org/wiki/Digital_geologic_mapping*). In 2010, DGGS created an electronic mailing list (*http://list.state.ak.us/soalists/geomapping_technology/jl.htm*) that currently has more than 60 members, in the United States and abroad. DGGS also surveyed the geologic community regarding interest in digital geologic field mapping and the currently used technology. With the help of the American Geological Institute, the e-mail survey went out to more than 1,250 organizations (university geology departments, state and national geological surveys, and the private sector) with a ~13 percent response rate. Results of the survey are available at *http://ngmdb.usgs.gov/Info/dmt/docs/DMT11_Athey.pdf*.

Communication in the Geologic Community

Toward the goal of developing a workable digital field methodology, the biggest asset that geologists have is the experience of all the other geologists in the geologic community. Worldwide, geologists working for government surveys, universities, engineering firms, mining companies, and in other related occupations perform many of the same tasks and, consequently, have many of the same requirements for a digital field mapping system. Many digital mapping hardware and software options are available on the market, but it is cost prohibitive for one person or organization to evaluate a variety of different systems. Increased communication among geologists regarding successes and failures in digital mapping will provide a knowledge base to help them quickly select the system that best suits their needs. A knowledge base will spur new ideas and encourage growth of programs. As a collective voice, the digital geologic mapping community can have greater influence on the development of mapping-related technology.

Ideas and methodology in science are commonly exchanged through published papers, formal presentations at conferences, and person-to-person networking; however, these methods of communication are not ideal when discussing technology. By the time a formal paper is published, a manufacturer may already have moved on to the next generation of devices. By nature, conference presentations and personal networking reach only small, targeted audiences. Instead of these traditional methods, geologists can benefit from user-friendly online communication and social media to promote the exchange of information in a timely manner.

DGGS hopes to spur conversation in the geologic community on digital field mapping by maintaining this e-mail list and Wikipedia page on digital geologic field mapping. We chose these forums in part because they are manageable with our limited financial and staff resources. Electronic mailing lists facilitate fast communication, are easy to use, and membership is open to anyone. However, they also have disadvantages in that messages are easily overlooked and it is difficult to develop a target audience. Wikipedia is structured to ensure that the resource is easy to access and edit by anyone, the language is free of jargon or defined, and information is well documented. Wikipedia is excellent for recording the current state of digital geologic mapping but is far from ideal for the purpose of sparking conversation because posting original research or opinions violates two of its core content policies (*http://en.wikipedia.org/wiki/Wikipedia:Neutral_point_of_view*). Therefore, the geomapping_technology e-mail list is better suited for this purpose. In addition to DGGS's efforts, attendees of the Digital Mapping Techniques 2011 workshop are designing an additional online resource and discussion board for geologists, GIS specialists, and cartographers, which will include a section on computing in field geology. We anticipate that this new resource will be a virtual meeting place where ideas, opinions, successes, failures, methodology, tips, and tricks can be shared with the community.

Digital Geologic Mapping Survey, 2010

Many researchers are experimenting with and using digital geologic field mapping, while relatively few of these efforts are reported in publications or informally, online. To capture the experience and wisdom of these pioneers and take a snapshot of the technology, more than 1,250 organizations (university geology departments, State and national geological surveys, and the private sector) were surveyed in 2010 regarding their thoughts on and use of digital field mapping. Two basic categories were addressed in the survey: (1) general interest in using computing technologies as a field tool and (2) the current technology being utilized to conduct digital field mapping. The majority of respondents (82 percent) stated that they are interested in applying digital mapping to their field programs, although only half of them are currently using digital mapping. Comments indicate that, although the interest exists, expense and lack of a proven methodology (including hardware and software well suited to fieldwork) remain major hurdles to digital mapping becoming commonly used in the field.

In geologic education, the best role of digital field mapping is undetermined. A significant number of geology faculty at universities responded that digital mapping is inappropriate at the undergraduate level, when students are still learning the fundamentals of geology, but that it may be useful for graduate students and experienced researchers. However, a few universities do have successful undergraduate field programs with a digital mapping component, such as Bowling Green State University (*http://www.bgsu.edu/departments/geology/page58461.html*), University of Kansas (*http://www.geo.ku.edu/programs/tectonics/digitalmapping/mappingwebpage.shtml*), and University of Texas at El Paso (Pavlis, 2010).

In 2010, the most popular digital mapping device was the PDA, and Trimble brand devices in particular (*http://www.trimble.com/*). The most widely used software was ArcPad by ESRI (*http://www.esri.com/software/arcgis/arcpad/*). Mappers are collectively using a large number of hardware and software combinations, sometimes including traditional handwritten notes or paper maps. Around 40 percent of geologists are satisfied with the systems they have devised. Another 40 percent of geologists are willing to overlook minor annoyances and imperfections in their digital field systems for the convenience of taking digital notes and producing real-time digital geologic maps while on traverse.

Conclusions

The geologic community is still working the bugs out of methods for digital geologic field mapping. Many geologists are excited about the possibilities, but a simple, easy-to-use, cost effective, and robust system is not yet widely available. Increased communication on the successes and failures of computing in the field using various forms of online digital and social media will help this technology grow and improve more quickly to meet users' needs. Crowdsourcing, that is, "Many heads are better than one," is a viable option to design digital field mapping systems that meet the needs of the mapping community. The Wikipedia page "Digital geologic mapping" and the geomapping_technology e-mail list are currently available avenues of communication. The National Geologic Map Database Web site (*http://ngmdb.usgs.gov*) will have a link to the new digital geologic issues forum/wiki when it becomes available for online data sharing opportunities.

Acknowledgments

Thank you to the American Geological Institute (*http://www.agiweb.org/*) for sending the 2010 digital mapping survey out to its university geology department e-mail list and for providing comments on the survey content. Mention of specific brands or models of hardware or software in this article is for illustrative purposes only and does not imply endorsement by the author or the State of Alaska.

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National Park Service Geologic Resources Inventory: Data Model Concepts and Implementation, and a Programmatic Approach to Digital Map Production

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Introduction

The Geologic Resources Inventory (GRI) program is tasked with producing geologic information for 270 National Park Service (NPS) parks with significant natural resources. The program is funded by the NPS Inventory and Monitoring Division (IMD) and is administered by the NPS Geologic Resources Division (GRD). The GRI program relies heavily upon partnerships with Colorado State University (CSU), the U.S. Geological Survey (USGS), individual State surveys, and other organizations in developing its products.

In developing GRI products, CSU research associates work side-by-side with GRD staff, attending scoping meetings at parks to identify mapping needs and park-specific geologic issues, features, and processes. A scoping summary report is then produced. The geologic issues, features, and processes identified at scoping are then further explained in a geology report written for park resource managers. From the scoping plan, source geology maps, in paper, mylar, and (or) digital format, are acquired and evaluated, then processed into the GRI Geology-GIS Geodatabase Data Model (O'Meara and others, 2010), which is in ESRI's geodatabase format.

To facilitate the creation of a useful and high quality digital map product, good data model designs, as well as efficient map production processes, are needed. This paper presents prominent concepts and requirements considered in the design and implementation of the GRI data model and the approach utilized in streamlining digital map production.

Data Model Concepts and Design

In developing a geology-GIS data model, there are typically a number of design requirements that should be considered to ensure a well-developed working data model that effectively communicates geologic information to the intended data users and promotes the production of consistent quality data.

When designing the GRI Geology-GIS Geodatabase Data Model, several base design requirements, as well as factors such as geologic diversity across our national parks, variable source map scale, and map compilation considerations were addressed.

Fundamental Data Model Design Requirements

- Model is implementable in standard GIS software. The GIS software widely employed by the NPS is ESRI ArcGIS.
- Intended users of our data are park resource managers, most of whom are scientists but not geologists!
- Geologic information on source map is preserved and effectively communicated as GIS data (as features and tables) or as ancillary documents (as report text, metadata, or graphics).

Other Design Requirements and Challenges

- Geology across the land managed by the NPS is varied and diverse, with each geologic terrain often possessing its own set of geologic features and observations. Such geologic diversity requires a data model that is flexible and can accommodate new features.

- Map scale considerations: Features may vary in their spatial representation (polygon, line, or point) depending on map scale. In this case the data model needed to accommodate changes to the spatial representation of some features, as these can vary depending on the geologic feature’s spatial extent and the scale at which the feature was mapped. For example, on most maps a gravel pit is represented as a point locality; however, if the feature is of significant size and (or) the feature was mapped at a very large scale (for example, 1:12,000) the gravel pit would likely be an area (polygon) feature. This variation in spatial representation is present amongst a significant number of geologic features found on geologic maps of different scales.

- Map compilation considerations: Many GRI park maps are compiled from multiple source maps. This frequently results in the integration of geologic features not present on every source map. In these cases all features are incorporated into the compiled map (none are simply omitted), and in some cases this dictates that some features are given their own feature class (for example, the integration of two or more sets of different structure contour lines where each set is given its own feature class and is not simply merged into one structure contour line feature class).

Data Model Implementation

It was a fundamental design requirement that the GRI data model had to be implementable in ESRI ArcGIS software, which is the GIS software widely used within the NPS. The latest and most functional ESRI GIS format is the geodatabase. This format provides robust functionality that the GRI data model fully utilizes to store, attribute, and relate features. Characteristics of the GRI data model are described below.

GIS Data Format and Architecture

- Geologic-GIS data are implemented in an ESRI 9.x personal geodatabase.

- Feature class attribute tables comprise just those fields necessary to fully capture all applicable information.

- Geologic features commonly are grouped into data layers (feature classes) based upon the geologic processes that created them (for example, deformation/structural, volcanic, glacial), for ease of presentation to our intended users.

- We continue to evaluate a revision to an ESRI 9.x/10.x file-based geodatabase format.

GIS Building Blocks

The GRI data model employs much of the functionality inherent in the ESRI geodatabase format to depict, attribute, ensure spatial coincidence, and relate geologic features and observations to ancillary GIS tables.

- Geologic features are depicted as area (polygon), line, or points in discrete data layers referred to as feature classes.

- Only 25 data model attribute fields are employed for data model feature classes. Custom attribute fields also can be readily added, and both coded and ranged attribute domains are implemented (fig. 1).

- Geodatabase topology is implemented to ensure no gaps, no overlaps, and no dangles and to ensure feature coincidence between features where appropriate (fig. 2).

Field Name	Field Alias	Data Type	Allow Nulls	Implemented Domain	Precision	Scale	Length
OBJECT_ID*	NA	Object ID	–	–	–	–	–
SHAPE*	NA	Geometry	Yes	–	–	–	–
FUID	Unique Feature ID	Long Integer	No	–	0	–	–
GLG_SYM (2)	Unit Symbol	Text	No	–	–	–	12
SRC_SYM	Source Unit Symbol	Text	No	–	–	–	12
SORT_NO	Sort Number	Float	No	–	6	3	–
NOTES	Notes	Text	No	–	–	–	254
LBL	Label	Text	Yes	–	–	–	60
GMAP_ID (1)	Source Map ID	Long Integer	No	–	0	–	–
SHAPE_Length*	NA	Double	Yes	–	0	–	–
SHAPE_Area*	NA	Double	Yes	–	0	–	–

* Standard ESRI 9.X geodatabase feature class attribute field.
(1) Relationship class foreign key field to MAP table.
(2) Relationship class foreign key field to UNIT table.

Ranged Domain Value	Definition
1	minimum value
359	maximum value
999	not applicable (NULL) value

Figure 1. Geologic Units (GLG) feature class attribute table parameters, and Strike/Trend (STRIKE_ROTATION) Ranged Domain list (lower right).

- Ancillary GIS tables consistent of a Geologic Unit Information (UNIT) and a Source Map Information (MAP) table (fig. 3).
- Feature classes are linked to ancillary tables via relationship classes using a common key field.
- Additional GIS tables, if present in the source data, can be readily added as-is, or as custom table schema created for a specific map or, if needed, implemented for other (future) maps that will contain the same table.

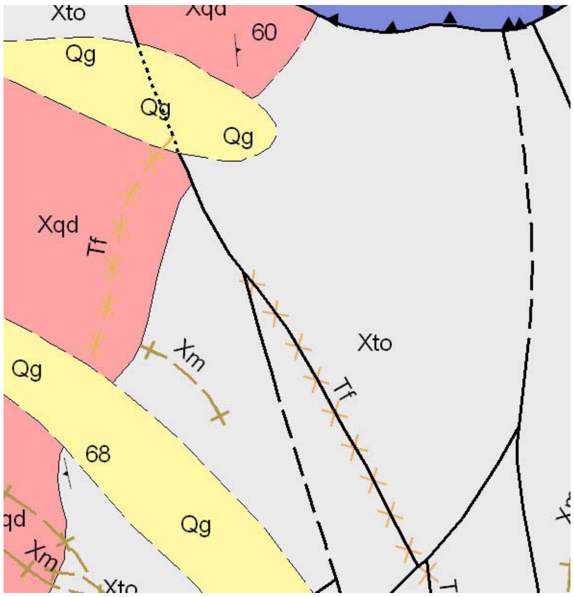


Figure 2. Dike intruded along a fault (fault is solid dark line, with dike shown diagrammatically as lighter colored X's and labeled Tf). Feature coincidence is maintained between the Linear Dikes (DKE) and Faults (FLT) feature classes via topology rules. If either the fault or dike feature is spatially edited using topology edit tools, then both features are edited.

Feature Class Implementation

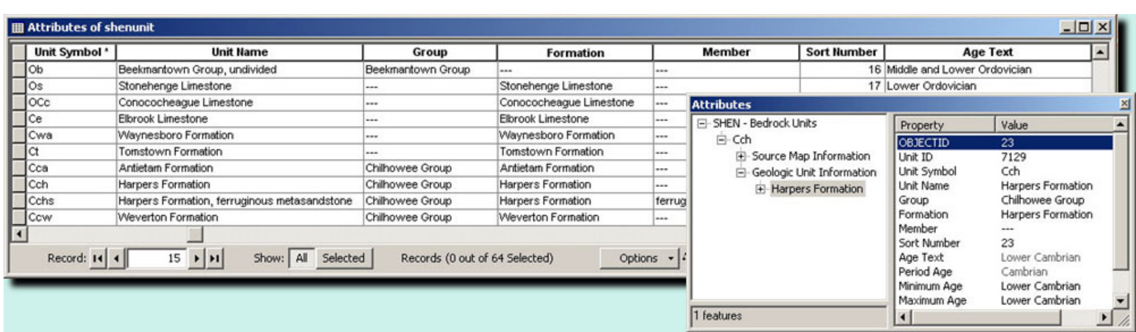
Many data model feature classes can be repeated if warranted (for example, for different structure contour lines or for different area hazards). To implement many feature classes, our data model employs the use of shared schema. Feature classes share the same schema when they have the same:

- Spatial geometry (polygon, line, or point).
- Attribute fields (the minimum required to fully attribute).
- Table-to-table relationships.
- Topological rules.

Shared data model schema are referred to as a "Template Feature Class Definition" in our data model. Seven template feature class definitions are employed to represent 44 of the 56 possible GRI data model feature classes (fig. 4).

Production Workflow and Development

Capturing geologic-GIS data can be a time-consuming process. Often the steps involved in digital data production introduce a component of human error due to the repetitive and sometimes complex processes involved in digital GIS data production. A task that is seemingly simple, like adding a set of data-model-defined topology rules, can be a repetitive and time-consuming process with little control over whether the rules were added correctly. By automating certain processes like adding data model topology rules, some tasks can be significantly streamlined and errors caused by manual processes eliminated. The GRI development team has identified tasks within the GRI GIS production workflow that can be automated through custom programming (fig. 5).



Unit Symbol *	Unit Name	Group	Formation	Member	Sort Number	Age Text
Ob	Beekmantown Group, undivided	Beekmantown Group	---	---	16	Middle and Lower Ordovician
Os	Stonehenge Limestone	---	Stonehenge Limestone	---	17	Lower Ordovician
OCc	Conococheague Limestone	---	Conococheague Limestone	---		
Ce	Elbrook Limestone	---	Elbrook Limestone	---		
Cwa	Waynesboro Formation	---	Waynesboro Formation	---		
Ct	Tomstown Formation	---	Tomstown Formation	---		
Cca	Antietam Formation	Chilhowee Group	Antietam Formation	---		
Cch	Harpers Formation	Chilhowee Group	Harpers Formation	---		
Cchs	Harpers Formation, ferruginous metasandstone	Chilhowee Group	Harpers Formation	ferrug		
Ccw	Weverton Formation	Chilhowee Group	Weverton Formation	---		

Property	Value
OBJECTID	23
Unit ID	7129
Unit Symbol	Cch
Unit Name	Harpers Formation
Group	Chilhowee Group
Formation	Harpers Formation
Member	---
Sort Number	23
Age Text	Lower Cambrian
Period Age	Cambrian
Minimum Age	Lower Cambrian
Maximum Age	Lower Cambrian

Figure 3. Shenandoah NP (SHEN) Geologic Unit Information (UNIT) Table and an ArcMap Information Window (lower right) showing UNIT table information related via a relationship class to a bedrock unit (Cch) polygon in the Geologic Units (GLG) feature class.

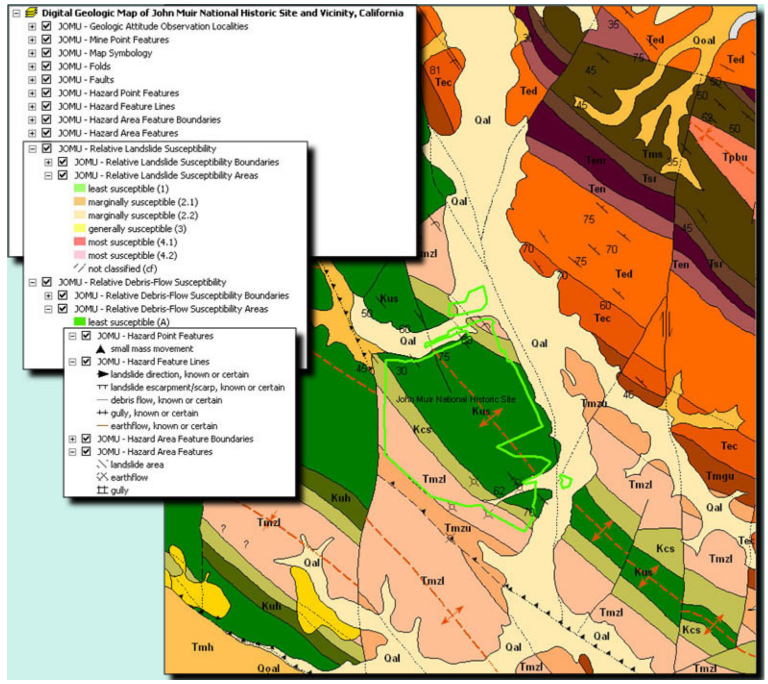


Figure 4. Partial extent of the GRI John Muir National Historic Site (JOMU) digital map (from Haydon, 1995) showing JOMU data model feature classes (upper left) and hazard feature classes (middle to lower left). Both area hazard susceptibility data layers, as well as the Hazard Area Features feature class, implement shared data model schema referred to as a template feature class definition in the GRI data model. The park is in the center of the figure.

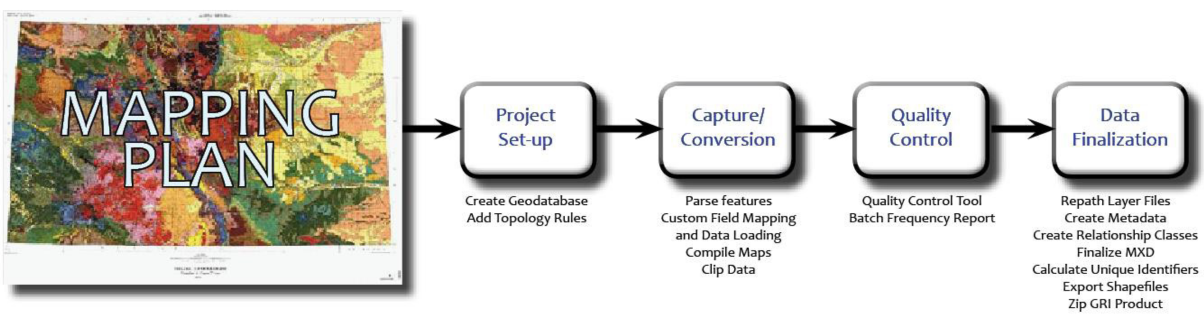


Figure 5. Overview of the GRI digital map production workflow, starting with a mapping plan for a specific park and ending with map finalization. These processes use automation tools and scripts (see captions for workflow steps) to provide efficiency and quality not possible with manual processing.

Development Approach

The GRI development team comprises project managers who have programming ability but also have annual production responsibilities. Most programming, as a result, must be accomplished when it can be fit in with production tasks. Because GRI project managers are familiar with the production workflow, they are able to identify processes that are error prone, inefficient, or could be automated. To reduce the amount of programming, developer samples, snippets, starter code, and other applicable toolsets are acquired, evaluated, and utilized whenever possible. Newly developed GRI tools are tested on real data, refined, and then deployed to the GRI production team. The resulting production tools range from simple macros run in ArcToolbox to more complex scripts and applications utilizing ArcObjects and .NET. This simplistic approach to tool development enables the development team to get production tools into the general workflow quickly while significantly reducing development time.

Create GDB Tool

The CreateGDB tool (fig. 6) is a wizard-like tool, initially developed in VBA and later migrated to VB.NET, that enables a user to easily create a GRI data model-compliant geodatabase. It prompts the user to select applicable feature classes, create custom feature classes, and includes the option to generate ancillary data model GIS tables. Data model domains are associated with respective feature classes, and applicable topology rules are added to the final output.

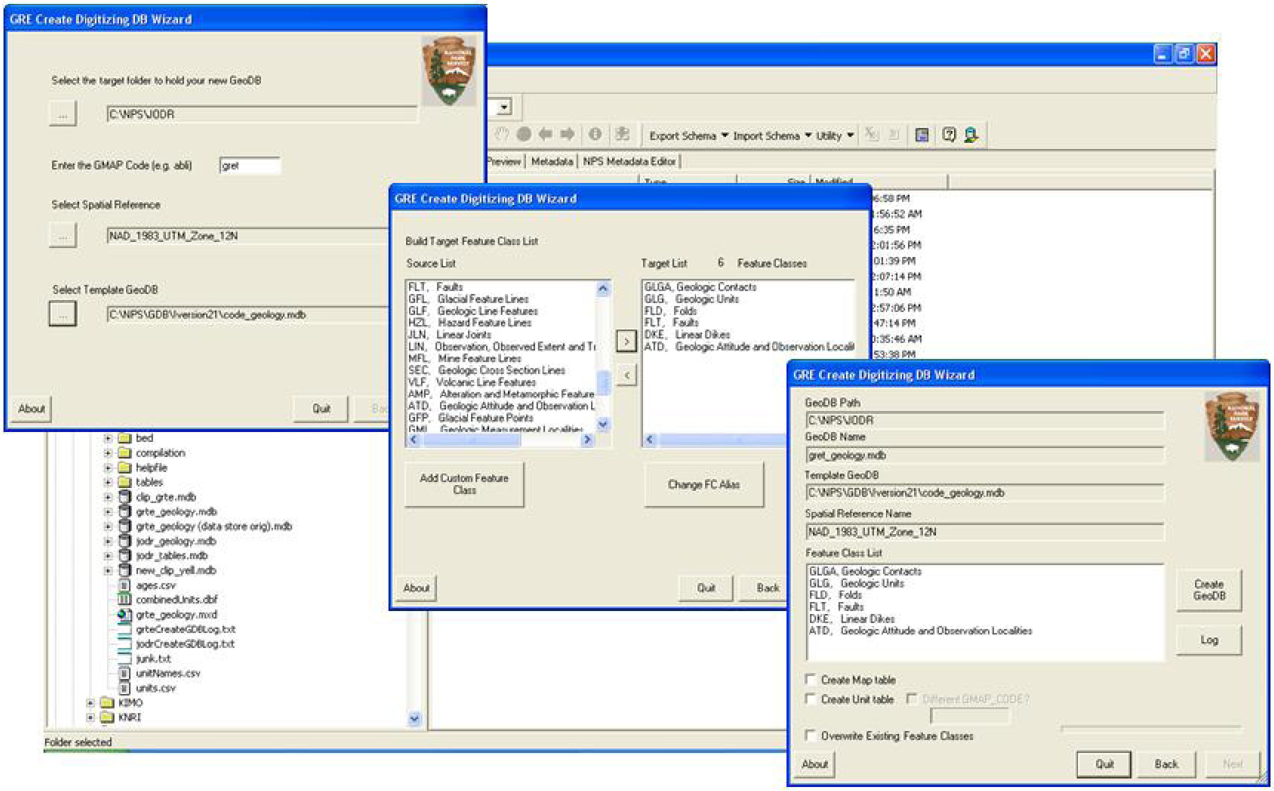


Figure 6. The CreateGDB tool. The first dialog (upper left) of the wizard prompts users for dataset name, location, spatial reference, and GRI template geodatabase. The second dialog (middle) allows users to select feature classes, create custom feature classes, and change feature class aliases, if desired. The third and last dialog (lower right) summarizes user defined parameters and provides option to create ancillary tables before generating the new geodatabase.

QC Tool

Designed in Python and later recoded in VB.NET, this tool prescribes spatial and attribute rules or tests based on feature classes present within a specified GRI data model geodatabase. For example, all water polygons must be bordered by shoreline, and contacts on the edge of the map must be attributed as map boundary. Run in ArcMap (fig. 7), the QC tool reports and graphically highlights errors while providing “zoom to” and selection options to aid in error resolution.

Summary

The GRI data model needed to be flexible and not too technical in design. Primary factors that influenced the design were (1) our anticipated data users are not geologists and their use of our data varies according to their backgrounds and the priorities established for the particular park; (2) the data model needed to preserve all source map information; (3) there is varied and diverse geology across the lands managed by the NPS; (4) we often use large-scale source maps; and (5) we frequently produce map compilations.

The GRI geology-GIS data model is implemented in an ESRI 9.x personal geodatabase and makes use of much of the functionality (attribute domains, topology, relationship classes) that this format provides. The GRI data model preserves all source map geologic information and presents this information in data layers and attribution that can easily be understood and manipulated by our users. As a result of our design and implementation methodology, our data model can accommodate the addition of new features, as well as new data layers as these are recognized. In addition, the data model is simplified by implementing many features classes using shared schema.

The GRI production workflow has been fine-tuned through the insertion of custom-programmed tools and scripts that increase production efficiency while yielding high quality and consistent GIS data. Because programming of these custom tools and scripts is completed by project managers, who are intimate with the production workflow, the time it takes to implement is greatly reduced.

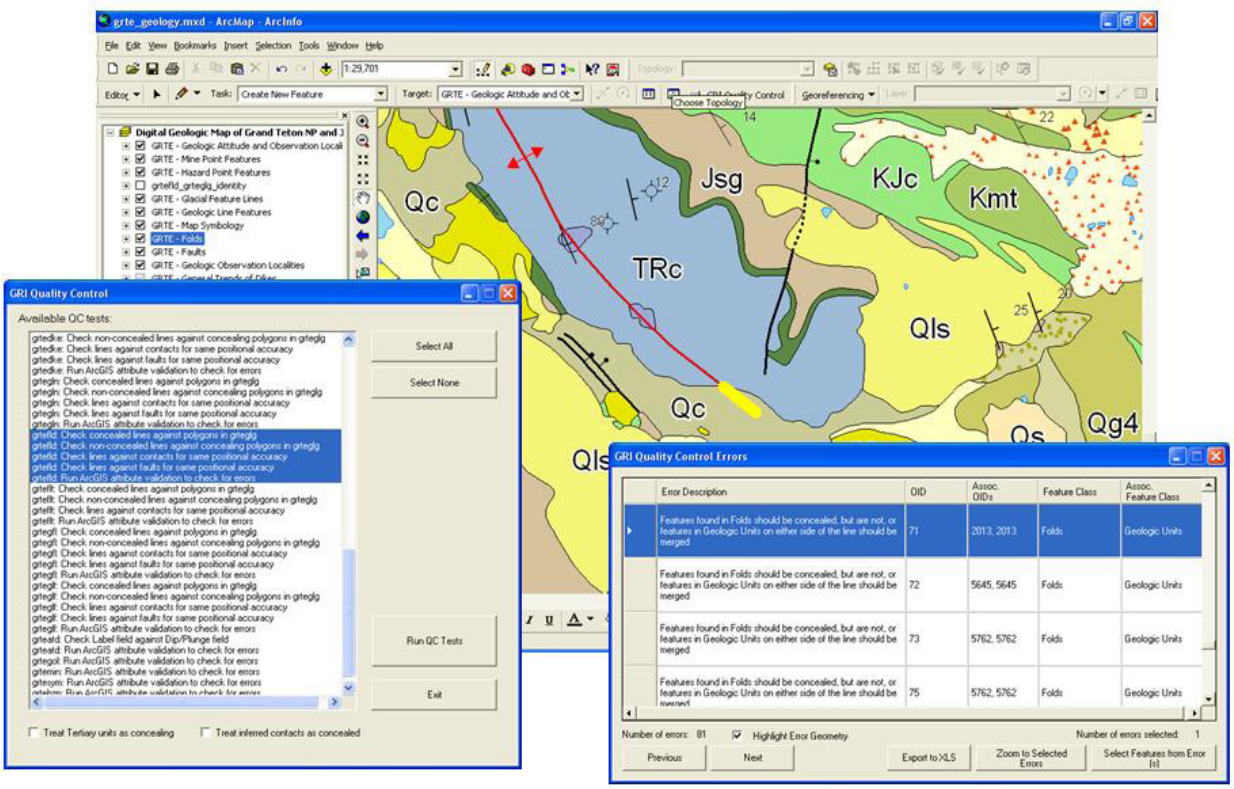


Figure 7. The QC tool. The dialog on the left shows tests prescribed for a specific collection of feature classes. The first test in the highlighted block of tests suggests checking fold axis positional accuracy with surrounding geologic unit polygons. For example, typically, most non-Quaternary linear features that have the same Quaternary unit on either side should be attributed as concealed. The dialog on the right shows results from that test. The highlighted test result shows that the feature highlighted in yellow on the map should be attributed as concealed but currently attributed as approximate.

GRI Products

GRI GIS data and report products are available for download at the NPS Natural Resource Information Reference Search Application: *http://nrinfo.nps.gov/Reference.mvc/Search*. Enter the search word "gri" into the search text, and select the park(s) from the units listed.

Geologic Resources Inventory Products: *http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.*

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The New Mexico Bureau of Geology and Mineral Resources Geologic Data Model, A Comparison with other Existing Models

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What is a Geology Data Model and Why Would I Want to Use One?

Like most mapping agencies, the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) has produced geologic maps for many years using a Geographic Information System (GIS). A GIS is essentially a geospatial database that stores information about the shape and position of mapped features as well as associated data. In order for GIS-based maps to be interoperable with other maps, their geospatial databases must be organized with a consistent structure. A data model is a standardized database structure (also called a database schema) that defines what features (or entities) are recorded, what their attributes are (often with a predefined set of possible values), and how they relate to one another.

Hasn't a Good Geology Data Model Already Been Created?

Yes and no—several comprehensive data models have been proposed, but none are in common use throughout the country or the world. Geologic maps are extremely complicated documents that attempt to record both geological observations and interpretations in four dimensions—through space and time. There are many reasonable approaches to encoding geological data and a lot of institutional inertia to keep using what has been working, albeit in some cases imperfectly, because it is painful to migrate existing data to a new schema. Adoption of new ways of doing things only occurs when old methods are either too difficult to continue using, and (or) newer methods have obvious benefits.

When we decided we needed a better data model, we looked at existing geologic data models at the time and found that they were either too complex to be practical, or otherwise did not fit our needs. Consequently, we chose to create our own model from scratch, borrowing useful ideas from other models. Since both field mapping and digitization of maps are already fairly labor-intensive, we did not want to add needless complexity to the process of producing maps. However, we did want the ability to create a fully attributed geologic map in a GIS. Other groups came to the same conclusion and independently produced their own geologic data models.

Model Comparison

Our model (fig. 1) was developed in tandem with the NCGMP09 (*http://ngmdb.usgs.gov/Info/standards/NCGMP09/*) model and ESRI's Geologic Mapping Template (*http://arcscripts.esri.com/details.asp?dbid=16317*) and shares several design features with both – but also has some important differences:

Feature Classes

Our model has more feature classes than the NCGMP09 model does and has a different structure than the ESRI Geologic Mapping Template. The benefit of many separate

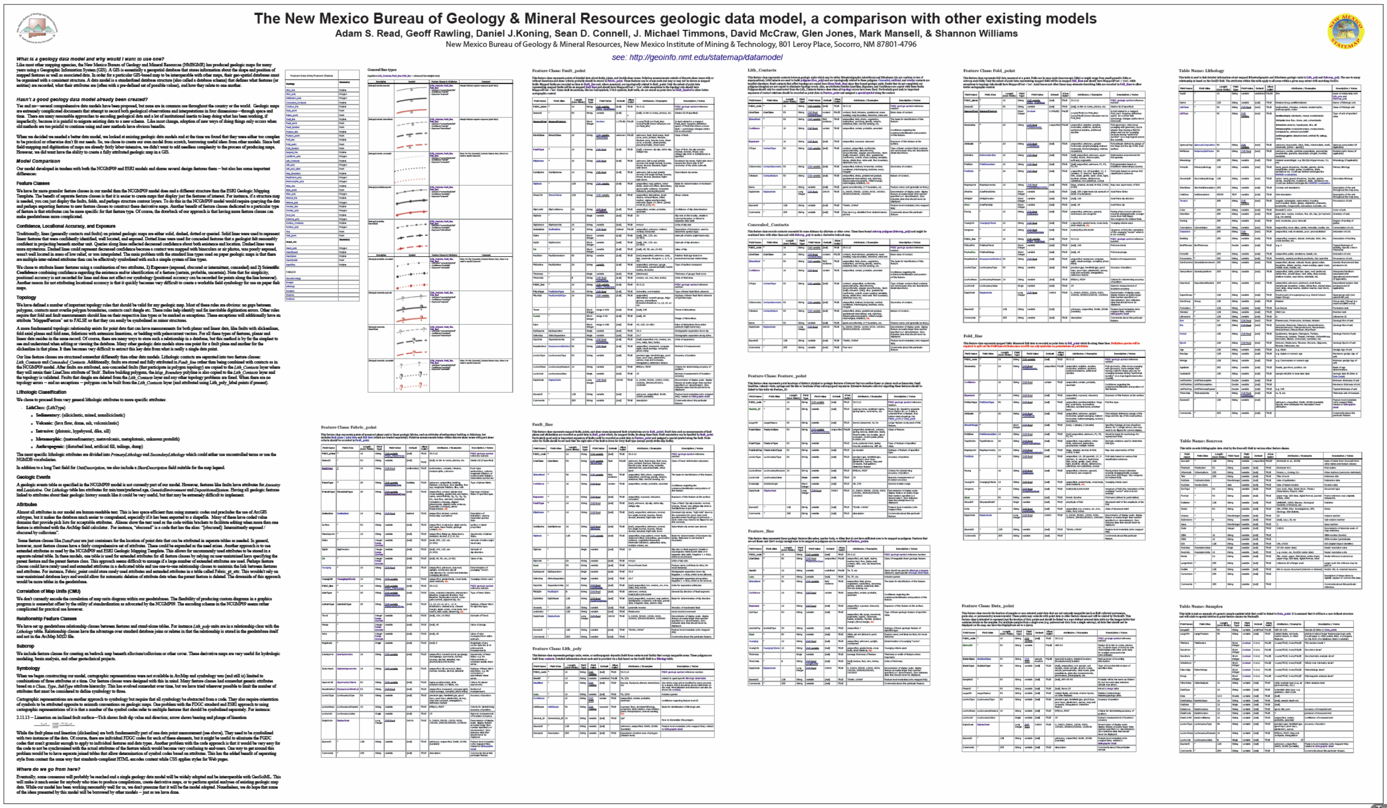

Figure 1. The New Mexico Bureau of Geology and Mineral Resources geologic data model (presented as a poster at the DMT meeting; (see full-resolution image at *http://ngmdb.usgs.gov/Info/dmt/docs/DMT10_Read.pdf*).

feature classes is that it is easier to create maps that display just the features of interest. For instance, if a tectonic map is needed, you can easily just display the faults, folds, and perhaps structure contour layers. To do this in the NCGMP09 model would require querying the data and perhaps exporting features to new feature classes to construct these derivative maps. Another benefit of feature classes dedicated to a particular type of feature is that attributes can be more specific for that feature type. This is particularly apparent with contacts and faults. Our model separates these into separate feature classes with attributes specific to each, whereas the NCGMP09 model does not. Of course, the drawback of our approach is that having more feature classes makes our geodatabases files somewhat larger.

Confidence, Locational Accuracy, and Exposure

Traditionally, lines (generally contacts and faults) on printed geologic maps are either solid, dashed, dotted, or queried. Solid lines were used to represent linear features that were confidently identified, well located, and exposed. Dotted lines were used for concealed features that a geologist felt reasonably confident in projecting beneath another unit. Queries along lines reflected decreased confidence about both existence and location. Dashed lines were more mysterious. Dashed lines could represent decreased confidence because a contact was mapped with binoculars or air photos, was poorly exposed, was not well located in areas of low relief, or was interpolated. The main problem with the standard line types traditionally used on paper geologic maps is that there are multiple interrelated attributes for linear geologic features that cannot effectively be symbolized with such a simple system.

We chose to base our symbolization of linear features on a combination of two required attributes, (1) exposure (exposed, obscured, or intermittent, concealed) and (2) scientific confidence combining confidence regarding the existence and (or) identification of a feature (certain, probable, uncertain). Note that for simplicity, positional accuracy is not recorded for lines and does not affect our symbology. Positional accuracy can be recorded for points along the line, however. Another reason for not attributing locational accuracy is that it quickly becomes difficult to create a workable field symbology for use on paper field maps. We also allow for the attribution of the identification method for lines, which provides an indication of the locational accuracy expected, but this attribute is generally not symbolized. To see how the combination of exposure and confidence might look on a geologic map, see *http://geoinfo.nmt.edu/statemap/datamodel/symbology/lines*.

Topology

We have defined a number of important topology rules that should be valid for any geologic map. Most of these rules are obvious: no gaps between polygons, contacts must overlie polygon boundaries, and contacts cannot dangle. These rules help identify and fix inevitable digitization errors. Other rules require that fold and fault measurements should lie on their respective line types or be marked as exceptions. These exceptions will additionally have an attribute "MappedFeature" set to FALSE so that they can be symbolized easily as minor structures.

A more fundamental topologic relationship exists for point data that can have measurements for both planar and linear data, like faults with slickenlines, fold axial planes and fold axes, foliations with extension lineations, or bedding with paleocurrent vectors. For all these types of features, planar and linear data reside in the same record. Of course, there are many ways to store such a relationship in a database, but this method is by far the simplest to see and understand when editing or viewing the database. Many other geologic data models store one point for a fault plane and another for the slickenline in that plane. It then becomes difficult to extract these key data from what is fundamentally a single data point.

Our line feature classes are structured somewhat differently from other data models. Lithologic contacts are separated into two feature classes: Lith_Contacts and Concealed_Contacts. Additionally, faults are stored and fully attributed in Fault_line rather than being combined with contacts as in the NCGMP09 model. After faults are attributed, non-concealed faults (that participate in polygon topology) are copied to the Lith_Contacts layer where they will retain their LineClass attribute of 'fault'. Before building polygons, the Map_Boundary polyline is also copied to the Lith_Contacts layer and the topology is validated. Faults that dangle are deleted from the Lith_Contacts layer and any other topology problems are fixed. When there are no longer any topology errors—or exceptions—polygons can be built from the Lith_Contacts layer (and attributed using Lith_poly_label points if present).

Lithologic Classification

We chose to proceed from general lithologic attributes to more specific attributes:

- **LithClass**: (LithType)
    - **Sedimentary** (siliciclastic, mixed, nonsiliciclastic)
    - **Volcanic** (lava flow, dome, ash, volcaniclastic)
    - **Intrusive** (plutonic, hypabyssal, dike, sill)
    - **Metamorphic** (metasedimentary, metavolcanic, metaplutonic, unknown protolith)
    - **Anthropogenic** (disturbed land, artificial fill, tailings, dump).

The most specific lithologic attributes are divided into *PrimaryLithology* and *SecondaryLithology,* which could use uncontrolled terms or the National Geologic Map Database (NGMDB) vocabularies. Note: these are no longer available online, but have been superseded by NCGMP09 vocabularies.

In addition to a long Text field for *UnitDescription*, we also include a *ShortDescription* field suitable for the map legend.

Geologic Events

A geologic events table as specified in the NCGMP09 model is not currently part of our model. However, features like faults have attributes for *Ancestry* and *LastActive*. Our *Lithology* table has attributes for min/max/preferred age, *GeneticEnvironment,* and *DepositionalSystem*. Having all geologic features linked to attributes about their geologic history sounds like it could be very useful, but that may be extremely difficult to implement – with any schema.

Extended Attributes

Some feature classes like *DataPoint* are just containers for the location of point data that can be attributed in separate tables as needed. In general, however, most feature classes have a fairly comprehensive set of attributes. These could be expanded as the need arises. Another approach is to use extended attributes as used by the NCGMP09 and ESRI Geologic Mapping Template. This allows for uncommonly used attributes to be stored in a separate related table. In these models, one table is used for extended attributes for all feature classes by relying on user-maintained keys specifying the parent feature and the parent feature class. This approach seems difficult to manage if a large number of extended attributes are used. Perhaps feature classes that have rarely used attributes could have extended attributes in a dedicated table and use one-to-one relationship classes to maintain the link between features and attributes. For instance, Fabric_point(s) could store rarely used attributes and extended attributes in a table called Fabric_pt_attr. This would not rely on user-maintained database keys and would allow for automatic deletion of attribute data when the parent feature is deleted. The downside of this approach would be a proliferation of tables in the geodatabase.

Relationship Feature Classes

We have set up geodatabase relationship classes between features and stand-alone tables. For instance *Lith_poly* units are in a relationship class with the *Lithology* table. Relationship classes have the advantage over standard database joins or relates in that the relationship is stored in the geodatabase itself and not in the ArcMap MXD file.

Subcrop

We include feature classes for creating a bedrock map beneath alluvium/colluvium or other cover. These derivative maps are useful for hydrologic modeling, basin analysis, and other geotechnical projects.

Symbology

When we began constructing our model, Cartographic Representations were not available in ArcMap, and symbology was (and still is) limited to combinations of three attributes at a time. Our feature classes were designed with this in mind. Many feature classes had somewhat generic attributes based on a *Class*, *Type*, *SubType* attribute hierarchy. This has evolved somewhat over time, but we have tried wherever possible to limit to three the number of attributes that must be considered to define symbology.

Cartographic Representations are another approach to symbology but require that all symbology be abstracted from a code. They also require orientation of symbols to be attributed opposite to azimuth conventions on geologic maps. One problem with the Federal Geographic Data Committee (FDGC) standard and ESRI approach to using cartographic representations of it is that a number of the symbol codes refer to multiple features that should be symbolized separately (see, for example, fig. 2).

While the fault plane and lineation (slickenline) are both fundamentally part of one data point measurement (fig. 2), they need to be symbolized with two instances of the data. Of course, there are individual FGDC codes for each of these elements, but it might be useful to eliminate the FGDC codes that are not granular enough to apply to individual features and data types. Another problem with the code approach is that it would be very easy for the code not to be synchronized with the actual attributes of the feature, which would become very confusing to users. One way to get around this problem would be to have separate joined tables that allow determination of symbol codes based on attributes. This has the added benefit of separating style from content the same way that standards-compliant HTML encodes semantic content, while CSS applies styles for display of Web pages.

Where Do We Go From Here?

Eventually, some consensus will probably be reached, and a single geology data model will be widely adopted and be interoperable with GeoSciML (*http://www.geosciml.org/*). This will make it much easier for anyone who tries to produce compilations, create derivative maps, or perform spatial analyses of existing geologic map data. While our model has been working reasonably well for us, we do not presume that it will be the model adopted. Nonetheless, we do hope that some of the ideas presented by this model will be borrowed by other models – just as we have done.

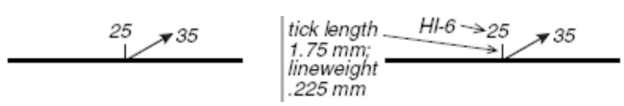

Figure 2. FGDC Geologic map symbol 2.11.13—Lineation on inclined fault surface—Tick shows fault dip value and direction; arrow shows bearing and plunge of lineation.

The National Geologic Map Database Project – 2010 Report of Progress

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Introduction

Development and management of science databases for support of societal decisionmaking and scientific research are critical and widely recognized needs. The National Geologic Mapping Act of 1992 (*http://ncgmp.usgs.gov/ncgmpabout/ngmact/ngmact1992*) and its subsequent reauthorizations stipulate creation and maintenance of a National Geologic Map Database (NGMDB, *http://ngmdb.usgs.gov*) as a national archive of spatially referenced geoscience data including geology, paleontology, and geochronology. The Act further stipulates that all new information contributed to the NGMDB should adhere to technical and science standards that are to be developed as needed under the guidance of the NGMDB project. Development of a national database and its attendant standards is a daunting task requiring close collaboration among all geoscience agencies in the United States, at the State and Federal levels. The Act, therefore, creates the environment within which the U.S. Geological Survey (USGS) and the Association of American State Geologists (AASG) can collaborate to build the NGMDB and also serve the needs of their own agencies.

The congressional mandate for State-Federal collaboration on the NGMDB has proven invaluable, facilitating progress on many technical issues that would otherwise have been much more difficult to achieve by separate efforts within agencies. The NGMDB's long record of accomplishment owes a significant debt to its many collaborators, and to the institutions with which it interacts (appendix A). At numerous meetings during the year, technical plans and progress are reported, and discussion and comment is requested; these activities are recorded each year by a progress report in the DMT Proceedings. In order to minimize repetition in this report, we have limited the background and explanatory information, which are contained in previous reports of progress (appendix B; in particular the 2005 report); however, some repetition is considered necessary here in order to provide background for first-time readers.

Strategy and Approach

From the guidance in the National Geologic Mapping Act, and through extensive discussions and forums with the geoscience community and the public, a general strategy for building the NGMDB was defined in 1995 (see Soller and Berg, 1995, 1997, in appendix B). Based on continued public input, the NGMDB has evolved from that concept to a set of resources that substantially help the Nation's geological surveys provide to the public, in a more efficient manner, standardized digital geoscience information.

The NGMDB is designed to be a suite of related databases, products, and services consisting of (1) a Map Catalog containing information and Web links for all paper and digital geoscience maps and related reports of the Nation, and images of many of these maps; (2) the U.S. Geologic Names Lexicon; (3) the Mapping in Progress Database; (4) nationwide geologic map coverage at intermediate and small scales; (5) an online database of geologic maps (predominantly in vector format; planned as a distributed system); (6) a set of Web interfaces to permit access to these products; and (7) a set of standards and guidelines to promote more efficient use and management of spatial geoscience information. The NGMDB system is a hybrid – some aspects are centralized and some are distributed, with the map information held by various cooperators (for example, the State geological surveys). Through a primary entry point on the Web, users can browse and query the NGMDB and obtain access to the information wherever it resides.

The project's success depends on the strong endorsement and collaboration of management and technical consultants in the USGS and AASG. This support is critical because (1) the project has responsibility for standards development, and standards cannot successfully be implemented until they are widely endorsed; (2) many of the various project tasks are at least partly conducted by collaborators rather than by funded project members; and (3) this project is national in scope and does not fit cleanly into the USGS regional organizational structure. The project therefore relies on USGS and AASG management to implement and maintain certain policies and standards that support NGMDB objectives and to help promote constructive interaction with new initiatives whose objectives may be similar (for example, the USGS National Geological and Geophysical Data Preservation Program; the NSF-funded U.S. Geoinformatics Network project).

Example "Outcomes"

In yearly proposals for project funding, the USGS requires that three examples of a project's impact and contributions be provided. They are included here.

1. On a monthly basis, the NGMDB Web site receives 90,000-100,000 visits from about 25,000 users (nearly all non-USGS). This high level of Web traffic spawns numerous user requests for information and assistance—these users vary widely in interest and background and include schoolchildren, homeowners, local government planners, and professional geologists. Most often they use the NGMDB data-discovery databases (Map Catalog, Geolex, Mapping in Progress) to find geoscience maps and publications. With many of these users we have personal contact by email to ensure they find what they need.

2. Public interest in two national map databases published by the NGMDB project in 2010 remains high. These are databases for (1) the Geologic Map of North America (GMNA; Garrity and Soller, 2009) and (2) surficial materials of the conterminous United States (Soller and others, 2009). In response to this interest, a resources page for the GMNA was developed (*http://ngmdb.usgs.gov/gmna/*) to provide access to the numerous file formats (for example, shapefiles, Google Earth) requested by users after formal publication in ESRI Geodatabase format. The resources page also addresses the emerging uses for the GMNA in various Web Mapping Services. Similar requests for the surficial materials database are being handled informally, but a resources page also may be developed.

3. For 14 years, the NGMDB project has organized annual workshops on "Digital Mapping Techniques." The workshops support the needs of State and Federal agencies for information exchange and for development of more efficient methods for digital mapping, cartography, GIS analysis, and information management. These workshops have been very successful and have significantly helped the geoscience community converge on more standardized approaches for digital mapping and GIS analysis. The workshop Proceedings are widely read and consulted for technological advances and trends. As a response to information learned at these workshops, agencies have adopted new, more efficient techniques for digital map preparation, analysis, and production. Examples are numerous; here is one from the first DMT meeting: "After attending the Digital Mapping Techniques '97 (DMT '97) conference in Lawrence, Kansas, we decided to model our digital cartographic production program after that of the Nevada Bureau of Mines and Geology ...[which] expedited our overall cartographic production. Months of trial-and-error digitizing and interaction between geologists and technicians were replaced by a single scanned image that could be quickly drafted. In about two weeks, the 1:24,000 Alameda geologic quadrangle went from an inked mylar to a multicolor plotted map sheet, complete with cross sections."

Project Organization

This project has been designed as a set of related tasks that will develop, over time, an NGMDB with increasing complexity and utility. This is being accomplished through a network of geoscientists, computer scientists, librarians, and others committed to supporting the objectives of the NGMDB. Since the project's inception, the plan for its design has been described in three phases. This approach has served to communicate the general plan, but as the project evolved in response to changing technology and to changing perceptions regarding its proper role in support of the U.S. geoscience community, the three-phase design became somewhat misleading. These three phases are now more accurately referred to simply as tasks, and are executed concurrently.

Task One (formerly Phase One) principally involves the building of a comprehensive Map Catalog of bibliographic records and online images of all available paper and digital maps, and book publications containing maps and related information, that adhere to the earth-science themes specified in the National Geologic Mapping Act of 1992. Development and maintenance of the U.S. Geologic Names Lexicon (Geolex) is an essential component of Task One, serving as a foundation for the Nation's geologic mapping science. This task also includes related activities such as design and maintenance of the Mapping in Progress Database. Task Two (formerly Phase Two) addresses development of standards and guidelines for geologic map and database content and format. Task Three (formerly Phase Three) is a long-term effort to develop a database (principally vector, GIS-compatible information) that contains national, regional, and detailed geologic map coverage managed according to a complex set of content and format specifications that are standardized through general agreement among all partners in the NGMDB (principally the AASG); this database will be integrated with the databases developed in Task One.

The NGMDB project's technology and standards development efforts also are coordinated with various related entities including: the Federal Geographic Data Committee, ESRI Inc., the USGS Geological and Geophysical Data Preservation Program, the NSF-funded Geoinformatics project (GIN), the North American Geologic Map Data Model Steering Committee, the International Union of Geological Sciences (IUGS) Commission on the Management and Application of Geoscience Information (CGI), the IUGS Commission on Stratigraphy, and the IUGS-affiliated Commission for the Geological Map of the World.

A full realization of the project's Task Three is not assured and will require a strong commitment among the cooperators as well as adequate technology, map data, and funding. The project will continue to assess various options for development of this database, based on realistic funding projections and other factors. During the development of the NGMDB, extensive work will be conducted to develop Web interfaces and search engines and to continually improve them, and to develop the data management and administrative protocols necessary to ensure that the NGMDB will function efficiently in the future. The NGMDB's databases and project information are found at *http://ngmdb.usgs.gov*.

Progress in 2010

Task One

A wealth of geoscience information is available in various paper and digital formats. With the emergence of the Internet and Web, the public has come to expect rapid, easy, and unfettered access to government data holdings. Geoscience data must therefore become widely available via the Web, and the concepts presented in its products must be readily understood by the public. If our information is more readily available to the public, and if tools are offered to help integrate and provide access to that information, its utility may be greatly increased.

However, providing effective public Web access to our products presents a real challenge for each geoscience agency because of new and rapidly evolving technology, restricted funding, and new types of demands from the user community. To help address these challenges, this task provides simple, straightforward access to a broad spectrum of geoscience information and forms the stable platform upon which the other NGMDB tasks and capabilities are based.

Specific accomplishments in 2010 include:

1. Began the first major redesign of all NGMDB databases and Web pages since the project began 15 years ago. This work was undertaken in order to reduce system maintenance and to provide users with greatly enhanced search and display options. As the first step in redesigning the NGMDB database and Web site, Map Catalog and Geolex citations were merged into a single Oracle database, to provide integrated search and reporting of publications, geologic names, and study area footprints. Citations were error-checked against USGS Publications Warehouse (PW) citations, and errors in both NGMDB and PW systems were corrected. The majority of citation revisions were completed, and the merged database is being prepared to serve the redesign's next step—enhanced database search and reporting capabilities.

2. Expanded the Map Catalog by ~6,700 records, to a total of ~89,500 records. Some 1,500 records are new publications, and 5,200 were added from Geolex when their citations lists were merged. The Catalog now includes 40,000 USGS publications, 31,600 state survey publications, and 17,900 by other publishers.

3. Engaged all states in the process of entering Map Catalog records. Processed ~658 new records for State geological survey publications.

4. In response to NCGMP and AASG requests, and in part to address NCGMP performance metrics required by the Office of Management and Budget, provided: (a) index maps showing areas in the United States that have been geologically mapped at various scales and time periods and (b) computations including the number of square miles geologically mapped at intermediate and more detailed scales (see Soller, 2005). Helped NCGMP to revise their metrics, to better measure annual and cumulative productivity in geologic mapping.

5. Collaborated with the USGS Publications Warehouse (PW) on publication-tracking, database-compatibility, and image-processing issues to minimize duplication of effort and to better integrate the two systems. Collected from various donors, organized, and shipped to the PW a pallet of USGS publications to be scanned and put online.

6. Continued to add to Map Catalog the Web links to online digital maps and reports. Forty-six percent of the publications (more than 41,000) now have at least one link. Many publications have multiple links, to individual map sheets. Contributed to the PW more than 3,000 links to online publications, to insert into their citation pages.

7. Scanned, processed, and loaded into the Map Catalog about 2,200 map images.

8. Public requests for map images in various formats prompted initial phase of development work on a complex set of methods to bulk-process thousands of images into: (a) TIFF, (b) PDF, containing metadata from the Map Catalog; (c) JPEG; and (d) MrSID.

9. Hand-assembled a high speed computer to replace the current image-processing machine, and maintained a 12-terabyte (TB) disk array for storage of map images. This computer will process all scanned maps into various formats.

10. Researched, acquired, and began configuring two servers and a 36-TB disk array. This upgrade of the computing infrastructure will permit significantly better services to be offered to the public (see image formats noted above).

11. Continued to revise existing records in Geolex. Given the many and disparate origins of this lexicon, revision of existing electronic records inherited from the last-published USGS listing of names (in USGS Digital Data Series 6) remains the focus of work. As time permits, critically important stratigraphic information (for example, type localities) is retrieved from the authoritative published USGS lexicons (for example, Bulletins 896, 1200) and integrated into Geolex. To support this work, Bulletins 896 and 1200 were scanned with Optical Character Recognition under contract.

12. Revised and reissued contract to scan the Geologic Name Committee's (GNC) master card file of geologic names (~220,000 cards, located in Reston, Va.). This collection will be a valuable supplement to Geolex, especially regarding relevant publications for geologic names. Continued to scan and process the USGS Menlo Park, Calif., collection of GNC cards, which are an invaluable complement to the Reston set.

13. With collaboration from the Wyoming Geological Survey and ESRI, developed a prototype application using ESRI's ImageServer, and demonstrated it at the DMT'10 meeting. This application provides a visualization of available geologic maps of Wyoming and links to the Map Catalog Product Description Page for each map. It provides a new means of access to the Catalog and will facilitate searching and downloading of map images in various formats. It is anticipated that this initiative will be greatly expanded in future years.

14. Continued to revise the Web statistics that identify the extent to which State geological survey publications are accessed via the Map Catalog. These statistics are now provided to each State geologist, via a password-protected site.

15. Customer service: completed several hundred productive interchanges with Map Catalog and Geolex users via the NGMDB feedback form and other mechanisms.

Task Two

Geoscience information increasingly is available in digital format. Within an agency, program, or a project, there are standard practices for the preparation and distribution of this information. However, widely accepted standards and (or) guidelines for the format, content, and symbolization of this information do not yet exist. Such standards are critical to the broader acceptance, comprehension, and use of geoscience information by the non-professional and professional alike. Under the mandate of the National Geologic Mapping Act, the NGMDB project serves as one mechanism for coordinating and developing the standards and guidelines that are deemed necessary by the U.S. and international geoscience community.

The NGMDB project leads or assists in development of standards and guidelines for digital database and map preparation, publication, and management. This challenging activity entails a lengthy period of conceptual design, documentation, and test-implementation. For example: (1) a conceptual data model must be shown to be implementable in a commonly available GIS such as ESRI's ArcGIS; (2) a data-interchange standard must be demonstrated to be an effective mechanism for integrating (for example, through the NGMDB portal) the many and varied data systems maintained by the State geological surveys, USGS, and others; and (3) a map symbolization standard must be implemented in, for example, PostScript or ArcGIS before it can be used to create a map product. Then, of course, each proposed standard must become widely adopted; otherwise, it isn't really a standard. Internationally, the NGMDB participates in venues that help to develop and refine the U.S. standards. These venues also bring our work to the international community, thereby promoting greater standardization with other countries.

The accomplishments listed below address a fundamental NGMDB goal—to propose a "core" set of standards and guidelines for endorsement by the Nation's geological surveys. Throughout the past decade and more, geological surveys have collaborated on geologic map database design, science terminology, and data interchange standards. Progress has been significant and was in part facilitated by long-term technical and funding support by the NGMDB project and by the 14 annual DMT meetings.

Specific accomplishments in 2010 include:

1. Organized and led the fourteenth annual "Digital Mapping Techniques" workshop. Developed the agenda, solicited presentations, and worked to prepare the workshop proceedings. Edited the workshop Proceedings from the previous year's meeting (DMT '09, Morgantown, W.Va.), and completed production of the DMT'08 Proceedings.

2. Continued to collaborate with the USGS Pacific Northwest project to design a database format suitable for digital publication of single, traditional geologic maps. This database design ("NCGMP09") attempts to balance the map-preparation and publication-workflow needs of a mapping project and the long-term, national need to archive standardized geologic map data from many projects (NCGMP, 2010). NCGMP09 is an ArcGeodatabase design supported by example map databases, standard vocabularies, documentation, and prototype tools such as error-checking scripts. In early- to mid-2010, extensive technical sessions were held with geologists and GIS specialists in USGS geologic mapping projects, in order to evaluate the design and solicit suggested changes. In this initial phase of development, the focus was limited to the geologic-map preparation requirements of NCGMP-funded projects in the USGS, with the intention to then hold discussion with the State geological surveys in order to further refine the database design. Revisions made to NCGMP09 after its introduction at the DMT'09 meeting were discussed at the DMT'10 meeting, specifically to begin to solicit comment from the State geological surveys.

3. Evaluated the draft set of NGMDB standard terminology lists, developed in past years, for their suitability to support the NGMDB project and NCGMP09. Began evaluating the IUGS CGI-sponsored GeoSciML terminology lists. This is an ongoing process, as these term lists evolve by consensus among various scientists and interest groups.

4. Continued collaboration with ESRI on an ArcGIS Geology Data Model compatible with NCGMP09. Discussed feasibility of developing a book in their ArcGIS database design series that focuses on geologic map database design.

5. Coordinated work on the FGDC geologic map symbolization standard. Made minor revisions to the standard and addressed all user comments, requests for materials, and technical questions.

6. Continued to work with ESRI on their implementation of the FGDC standard. Provided technical guidance on science and technical aspects, and on preferred workflows for creating well-symbolized products from legacy maps and new map databases. Worked with ESRI on details of adapting their implementation to more directly support the NCGMP09 design. Funded the continuing work by USGS staff to create technical specifications and to evaluate ESRI's implementation.

7. Served as committee Secretary and as member of the U.S. Geologic Names Committee.

8. Served as Chair of FGDC Geologic Data Subcommittee. Managed the Subcommittee's Web site.

9. Served as: (a) U.S. Council Member to IUGS Commission for the Management and Application of Geoscience Information (CGI); (b) U.S. representative to DIMAS, the standards body for the Commission for the Geological Map of the World; and (c) USGS technical representative to the OneGeology project.

Task Three

From the NGMDB project's origin in 1995 it has been the generally held vision, by users and colleagues alike, that the National Geologic Map Database would, principally, be a repository of GIS data for geologic maps and related information, managed in a complex system distributed among the USGS and State geological surveys. The system would offer public access to attributed vector and raster geoscience data, and allow users to perform queries online, create derivative maps, and download source and derived map data. Further, all information in the database would retain metadata that clearly indicates its source (that is, who created a particular contact, fault, or delineation of a map unit contained in the database, and how the feature or attributes were later modified by further study).

To realize this vision will require (1) full commitment and close collaboration among the partners; (2) a flexible and evolving set of standards, guidelines, and data management protocols; (3) a clear understanding of the technical challenges to building such a system; and (4) an adequate source of funding. This task is designed to foster an environment where the distributed database system can be prototyped while these requirements are being addressed by the partners.

This is a long-term effort whose fully realized form is, at this time, difficult to predict. It is a complex task that depends on data availability, technological evolution, skilled personnel (in high demand and, therefore, in short supply), and the ability for all participants to reach consensus on the approach. Bearing this in mind, the scope and details of this task have been systematically explored and developed through prototypes. Each prototype addressed aspects of the database design, implementation in GIS software (for example, ArcGIS), standard science terminologies, and software tools designed to facilitate data entry. Each prototype was presented to the participants and the public for comment and guidance. The focus of new prototypes is guided by the comments received.

For example, in FY01 the NGMDB project completed a major prototype in cooperation with the Kentucky Geological Survey, the Geological Survey of Canada, the University of California at Santa Barbara, and the private sector (Soller and others, 2002). The principal goal was to implement the North American Data Model (NADM; *http://nadm-geo.org/*) draft standard logical data model in a physical system and to demonstrate certain very basic, essential characteristics of the envisioned system. That prototype was demonstrated and discussed at numerous scientific meetings, and its data model contributed to development of the North American conceptual data model and GeoSciML (see Task 2).

We then considered plans to improve that system by adding more complex geologic data and software functionality. However, it would have required significant new funding at a time when technology and geoscience community ideas on database design were rapidly evolving. Therefore, a more limited approach was pursued in the next prototype, in which draft NGMDB science terminologies, a NADM-based database design, and data-entry tools were devised in order for the project to develop a Data Portal (*http://maps.ngmdb.us/dataviewer/* and see discussion in Soller, 2009). The prototype NGMDB Data Portal was publicly released in June 2009; it offered public access to a simplified view of GIS data held by various cooperating agencies. As with previous Task 3 prototypes, further development of this Data Portal based on more collaboration with these states, or others, depends on public response.

Status of this task in 2010 was as follows:

1. After developing the NGMDB Data Portal (*http://maps.ngmdb.us/dataviewer/*) sufficiently to make it available at a public Web site, we entered an evaluation phase. Further development of the Data Portal's interface, and additions to content, were temporarily halted in order to assess public reaction to the site and to solicit expressions of interest or concern from our partners in AASG. Public comment indicated that the Data Portal has some value as an entry point to the Map Catalog and that the science portrayed in the Portal is well expressed with the Data Portal's Dynamic Legend. Comments from the AASG were insufficient to indicate whether, if we proceed with further development, there could be a productive effort to integrate this Data Portal with similar GIS-based Web-mapping sites in the State geological surveys. Comment and guidance will continue to be solicited, in order to determine if, or how, this work will proceed. The two most probable actions are these: (a) the Data Portal will be significantly expanded, with new datasets and interface features; and (or) (b) concepts, software components, and (or) datasets will be used in other NGMDB applications (for example, to improve the Map Catalog's "Geographic Search" function). Given the nature of prototyping a system such as this, under conditions of rapidly changing technologies, it is entirely possible that only action "b" will be taken, and the Data Portal's technology would be absorbed into other parts of the project. This evaluation also will consider the appropriate role for NGMDB in providing GIS-based map information to the public. The evaluation will principally be based on guidance from the USGS and AASG.

2. ESRI's "Geology base map" (similar in purpose to the NGMDB Data Portal) also was publicly released this year and became a static entity that remains under evaluation. Scientific guidance and discussions continued with ESRI regarding possible collaboration and integration of their portal and NGMDB's.

3. Continued discussions with USGS Central Energy Resources Science Center (CERSC), regarding establishing collaborative computing and Web services in order to conserve funds and bring more map content to their system and the NGMDB. The initial focus, to set up an OGC-compliant Web service for the newly published database of the Geologic Map of North America (Garrity and Soller, 2009) was successful in linking this map database to the CERSC's global GIS interface for energy-related maps and information ("EnergyVision", *http://certmapper.cr.usgs.gov/data/envision/index.html*).

Acknowledgments

We thank the USGS National Cooperative Geologic Mapping Program (NCGMP) and the AASG Geologic Mapping Committee for their long-term support for the NGMDB project. We also thank the NGMDB project staff and collaborators for their enthusiastic participation and expertise, without whom the project would not be possible. In particular, we thank: Dennis McMacken, Michael Gishey, and Alex Acosta (USGS-Arizona; Web site and database management); Chuck Mayfield (USGS, Menlo Park; Map Catalog content); Robert Wardwell and Justine Takacs (USGS, Vancouver, Wash., and Reston, Va.; Map Catalog's Image Library); Sarah Jancuska (USGS, Reston; biostratigraphic database); Steve Richard (Arizona Geological Survey / USGS, Tucson, Ariz.; Phase 3 – data model and science terminology); David Percy and Morgan Harvey (Portland State University; Task Three – Data Portal). We also thank the many committee members who provided technical guidance and standards (appendix A).

References

Garrity, C.P., and Soller, D.R., 2009, Database of the Geologic Map of North America; adapted from the map by J.C. Reed and others (2005): U.S. Geological Survey Data Series 424, CD-ROM, *http://pubs.usgs.gov/ds/424/*.

NCGMP (USGS National Cooperative Geologic Mapping Program), 2011, NCGMP09—Draft standard format for digital publication of geologic maps, version 1.1, *in* Soller, D.R., ed., Digital Mapping Techniques '09 – Workshop Proceedings: U.S. Geological Survey Open-File Report 2010-1335, p. 93-146, *http://pubs.usgs.gov/of/2010/1335/pdf/usgs_of2010-1335_NCGMP09.pdf*.

Soller, D.R., 2005, Assessing the status of geologic map coverage of the United States—A new application of the National Geologic Map Database, *in* Soller, D.R., ed., Digital Mapping Techniques '05 – Workshop Proceedings: U.S. Geological Survey Open-File Report 2005-1428, p. 41-47, *http://pubs.usgs.gov/of/2005/1428/soller2/*.

Soller, D.R., 2009, A classification of geologic materials for Web display of national and regional-scale mapping, *in* Soller, D.R., ed., Digital Mapping Techniques '08 – Workshop Proceedings: U.S. Geological Survey Open-File Report 2009-1298, p. 105-121, *http://pubs.usgs.gov/of/2009/1298/pdf/usgs_of2009-1298_soller4.pdf*.

Soller, D.R., Brodaric, Boyan, Hastings, J.T., Wahl, Ron, and Weisenfluh, G.A., 2002, The central Kentucky prototype: An object-oriented geologic map data model for the National Geologic Map Database: U.S. Geological Survey Open-File Report 02-202, 38 p., *http://pubs.usgs.gov/of/2002/of02-202/*.

Soller, D.R., Reheis, M.C., Garrity, C.P., and Van Sistine, D.R., 2009, Map database for surficial materials in the conterminous United States: U.S. Geological Survey Data Series 425, scale 1:5,000,000, *http://pubs.usgs.gov/ds/425/*.

Appendix A. Principal committees and people collaborating with the National Geologic Map Database project

Geologic Data Subcommittee of the Federal Geographic Data Committee:
Dave Soller (U.S. Geological Survey and Subcommittee Chair)
Jerry Bernard (U.S. Department of Agriculture-Natural Resources Conservation Service)
Courtney Cloyd (U.S. Forest Service, Minerals and Geology Management)
Mark Crowell (Department of Homeland Security, Federal Emergency Management Agency)
Laurel T. Gorman (U.S. Army Engineer Research and Development Center)
John L. LaBrecque (National Aeronautics and Space Administration)
Lindsay McClelland (National Park Service)
Jay Parrish (State Geologist, Pennsylvania Geological Survey)
George F. Sharman (National Oceanic and Atmospheric Administration, National Geophysical Data Center)
Dave Zinzer (Minerals Management Service)

Map Symbol Standards Committee:
Dave Soller (U.S. Geological Survey and Committee Coordinator)
Tom Berg (State Geologist, Ohio Geological Survey)
Bob Hatcher (University of Tennessee, Knoxville)
Mark Jirsa (Minnesota Geological Survey)
Taryn Lindquist (U.S. Geological Survey)
Jon Matti (U.S. Geological Survey)
Jay Parrish (State Geologist, Pennsylvania Geological Survey)
Jack Reed (U.S. Geological Survey)
Steve Reynolds (Arizona State University)
Byron Stone (U.S. Geological Survey)

AASG/USGS Data Capture Working Group:
Dave Soller (U.S. Geological Survey and Working Group Chair)
Sheena Beaverson (Illinois State Geological Survey)
Scott McColloch (West Virginia Geological and Economic Survey)
George Saucedo (California Geological Survey)
Loudon Stanford (Idaho Geological Survey)
Tom Whitfield (Pennsylvania Geological Survey)

DMT Listserve:
Maintained by Doug Behm, University of Alabama

IUGS Commission for the Management and Application of Geoscience Information:
Dave Soller (U.S. Geological Survey, Council Member)

Conceptual model/Interchange Task Group (of the Interoperability Working Group of the IUGS Commission for the Management and Application of Geoscience Information):
Steve Richard (Arizona Geological Survey / U.S. Geological Survey, Task Group Member)

DIMAS (Digital Map Standards Working Group of the Commission for the Geological Map of the World):
Dave Soller (U.S. Geological Survey, Working Group Member)

NGMDB contact persons in each State geological survey:
These people help the NGMDB with the Geoscience Map Catalog and GEOLEX. Please see *http://ngmdb.usgs.gov/info/statecontacts.html* for this list.

These groups have fulfilled their mission and are no longer active:

NGMDB Technical Advisory Committee:
Boyan Brodaric (Geological Survey of Canada)
David Collins (Kansas Geological Survey)
Larry Freeman (Alaska Division of Geological & Geophysical Surveys)
Jordan Hastings (University of California, Santa Barbara)
Dan Nelson (Illinois State Geological Survey)
Stephen Richard (Arizona Geological Survey)
Jerry Weisenfluh (Kentucky Geological Survey)

AASG/USGS Metadata Working Group:
Peter Schweitzer (U.S. Geological Survey and Working Group Chair)
Dan Nelson (Illinois State Geological Survey)
Greg Hermann (New Jersey Geological Survey)
Kate Barrett (Wisconsin Geological and Natural History Survey)
Ron Wahl (U.S. Geological Survey)

AASG/USGS Data Information Exchange Working Group:
Dave Soller (U.S. Geological Survey and Working Group Chair)
Ron Hess (Nevada Bureau of Mines and Geology)
Ian Duncan (Virginia Division of Mineral Resources)
Gene Ellis (U.S. Geological Survey)
Jim Giglierano (Iowa Geological Survey)

AASG/USGS Data Model Working Group:
Gary Raines (U.S. Geological Survey and Working Group Chair)
Boyan Brodaric (Geological Survey of Canada)
Jim Cobb (Kentucky Geological Survey)
Ralph Haugerud (U.S. Geological Survey)
Greg Hermann (New Jersey Geological Survey)
Bruce Johnson (U.S. Geological Survey)
Jon Matti (U.S. Geological Survey)
Jim McDonald (Ohio Geological Survey)
Don McKay (Illinois State Geological Survey)
Steve Schilling (U.S. Geological Survey)
Randy Schumann (U.S. Geological Survey)
Bill Shilts (Illinois State Geological Survey)
Ron Wahl (U.S. Geological Survey)

North American Data Model Steering Committee:
Dave Soller (U.S. Geological Survey and Committee Coordinator)
Tom Berg (Ohio Geological Survey)
Boyan Brodaric (Geological Survey of Canada and Chair of the Data Model Design Technical Team)
Peter Davenport (Geological Survey of Canada)
Bruce Johnson (U.S. Geological Survey and Chair of the Data Interchange Technical Team)
Rob Krumm (Illinois State Geological Survey)
Scott McColloch (West Virginia Geological and Economic Survey)
Steve Richard (Arizona Geological Survey)
Loudon Stanford (Idaho Geological Survey)
Jerry Weisenfluh (Kentucky Geological Survey)

Appendix B. List of progress reports on the National Geologic Map Database, and Proceedings of the Digital Mapping Techniques workshops.

Soller, D.R., ed., 2011, Digital Mapping Techniques '09—Workshop Proceedings: U.S. Geological Survey Open-File Report 2010-1335, 260 p., *http://pubs.usgs.gov/of/2010/1335/*.

Soller, D.R., ed., 2009, Digital Mapping Techniques '08—Workshop Proceedings: U.S. Geological Survey Open-File Report 2009-1298, 216 p., *http://pubs.usgs.gov/of/2009/1298/*.

Soller, D.R., ed., 2008, Digital Mapping Techniques '07—Workshop Proceedings: U.S. Geological Survey Open-File Report 2008-1385, 140 p., *http://pubs.usgs.gov/of/2008/1385/*.

Soller, D.R., ed., 2007, Digital Mapping Techniques '06—Workshop Proceedings: U.S. Geological Survey Open-File Report 2007-1285, 217 p., *http://pubs.usgs.gov/of/2007/1285/*.

Soller, D.R., ed., 2005, Digital Mapping Techniques '05—Workshop Proceedings: U.S. Geological Survey Open-File Report 2005-1428, 268 p., *http://pubs.usgs.gov/of/2005/1428/*.

Soller, D.R., ed., 2004, Digital Mapping Techniques '04—Workshop Proceedings: U.S. Geological Survey Open-File Report 2004-1451, 220 p., *http://pubs.usgs.gov/of/2004/1451/*.

Soller, D.R., ed., 2003, Digital Mapping Techniques '03—Workshop Proceedings: U.S. Geological Survey Open-File Report 03-471, 262 p., *http://pubs.usgs.gov/of/2003/of03-471/*.

Soller, D.R., ed., 2002, Digital Mapping Techniques '02—Workshop Proceedings: U.S. Geological Survey Open-File Report 02-370, 214 p., *http://pubs.usgs.gov/of/2002/of02-370/*.

Soller, D.R., ed., 2001, Digital Mapping Techniques '01—Workshop Proceedings: U.S. Geological Survey Open-File Report 01-223, 248 p., *http://pubs.usgs.gov/of/2001/of01-223/*.

Soller, D.R., ed., 2000, Digital Mapping Techniques '00—Workshop proceedings: U.S. Geological Survey Open-file Report 00-325, 209 p., *http://pubs.usgs.gov/of/2000/of00-325/*.

Soller, D.R., ed., 1999, Digital Mapping Techniques '99—Workshop proceedings: U.S. Geological Survey Open-file Report 99-386, 216 p., *http://pubs.usgs.gov/of/1999/of99-386/*.

Soller, D.R., ed., 1998, Digital Mapping Techniques '98—Workshop Proceedings: U.S. Geological Survey Open-File Report 98-487, 134 p., *http://pubs.usgs.gov/of/1998/of98-487/*.

Soller, D.R., ed., 1997, Proceedings of a workshop on digital mapping techniques: Methods for geologic map data capture, management, and publication: U.S. Geological Survey Open-File Report 97-269, 120 p., *http://pubs.usgs.gov/of/1997/of97-269/*.

Soller, D.R., and Stamm, N.R., 2011, The National Geologic Map Database Project – 2009 Report of Progress, *in* Soller, D.R., ed., Digital Mapping Techniques '09 – Workshop Proceedings: U.S. Geological Survey Open-file Report 2010-1335, p. 147-156, *http://pubs.usgs.gov/of/2010/1335/pdf/usgs_of2010-1335_Soller1.pdf*.

Soller, D.R., and Stamm, N.R., 2009, The National Geologic Map Database Project – 2008 Report of Progress, *in* Soller, D.R., ed., Digital Mapping Techniques '08 – Workshop Proceedings: U.S. Geological Survey Open-file Report 2009-1298, p. 13-22, *http://pubs.usgs.gov/of/2009/1298/pdf/usgs_of2009-1298_soller3.pdf*.

Soller, D.R., 2008, The National Geologic Map Database Project – 2007 Report of Progress, *in* Soller, D.R., ed., Digital Mapping Techniques '07 – Workshop Proceedings: U.S. Geological Survey Open-file Report 2008-1385, p. 11-20, *http://pubs.usgs.gov/of/2008/1385/pdf/soller.pdf*.

Soller, D.R., 2007, The National Geologic Map Database Project: Overview and Progress, *in* Soller, D.R., ed., Digital Mapping Techniques '06 – Workshop Proceedings: U.S. Geological Survey Open-file Report 2007-1285, p. 7-13, *http://pubs.usgs.gov/of/2007/1285/pdf/Soller.pdf*.

Soller, D.R., Berg, T.M., and Stamm, N.R., 2005, The National Geologic Map Database Project: Overview and Progress, *in* Soller, D.R., ed., Digital Mapping Techniques '05 – Workshop Proceedings: U.S. Geological Survey Open-file Report 2005-1428, p. 23-40, *http://pubs.usgs.gov/of/2005/1428/soller1/*.

Soller, D.R., Berg, T.M., and Stamm, N.R., 2004, The National Geologic Map Database project: Overview and progress, *in* Soller, D.R., ed., Digital Mapping Techniques '04—Workshop Proceedings: U.S. Geological Survey Open-File Report 2005-1451, p. 15-31, *http://pubs.usgs.gov/of/2004/1451/soller/*.

Soller, D.R., and Berg, T.M., 2003, The National Geologic Map Database project: Overview and progress, *in* Soller, D.R., ed., Digital Mapping Techniques '03—Workshop Proceedings: U.S. Geological Survey Open-File Report 03-471, p. 57-77, *http://pubs.usgs.gov/of/2003/of03-471/soller1/*.

Soller, D.R., and Berg, T.M., 2002, The National Geologic Map Database: A progress report, *in* Soller, D.R., ed., Digital Mapping Techniques '02—Workshop Proceedings: U.S. Geological Survey Open-file Report 02-370, p. 75-83, *http://pubs.usgs.gov/of/2002/of02-370/soller2.html*.

Soller, D.R., and Berg, T.M., 2001, The National Geologic Map Database--A progress report, *in* Soller, D.R., ed., Digital Mapping Techniques '01—Workshop Proceedings: U.S. Geological Survey Open-file Report 01-223, p. 51-57, *http://pubs.usgs.gov/of/2001/of01-223/soller1.html*.

Soller, D.R., and Berg, T.M., 2000, The National Geologic Map Database--A progress report, *in* Soller, D.R., ed., Digital Mapping Techniques '00—Workshop Proceedings: U.S. Geological Survey Open-file Report 00-325, p. 27-30, *http://pubs.usgs.gov/of/of00-325/soller2.html*.

Soller, D.R., and Berg, T.M., 1999a, Building the National Geologic Map Database: Progress and challenges, *in* Derksen, C.R.M., and Manson, C.J., eds., Accreting the continent's collections: Geoscience Information Society Proceedings, v. 29, p. 47-55, *http://ngmdb.usgs.gov/info/reports/gisproc98.html*.

Soller, D.R., and Berg, T.M., 1999b, The National Geologic Map Database—A progress report, *in* Soller, D.R., ed., Digital Mapping Techniques '99—Workshop Proceedings: U.S. Geological Survey Open-file Report 99-386, p. 31-34, *http://pubs.usgs.gov/of/of99-386/soller1.html*.

Soller, D.R., and Berg, T.M., 1998, Progress Toward Development of the National Geologic Map Database, *in* Soller, D.R., ed., Digital Mapping Techniques '98—Workshop Proceedings: U.S. Geological Survey Open-file Report 98-487, p. 37-39, *http://pubs.usgs.gov/of/of98-487/soller2.html*.

Soller, D.R., and Berg. T.M., 1997, The National Geologic Map Database—A progress report: Geotimes, v. 42, no. 12, p. 29-31, *http://ngmdb.usgs.gov/info/reports/geotimes97.html*.

Soller, D.R., and Berg, T.M., 1995, Developing the National Geologic Map Database: Geotimes, v. 40, no. 6, p. 16-18, *http://ngmdb.usgs.gov/info/reports/geotimes95.html*.

Recommended Citations for Unpublished GIS Files – Summary of a Discussion Session

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Introduction

The DMT'10 meeting provided several opportunities for group discussion of technical and map publication-related issues. These sessions focused mostly on cartographic techniques and methods of data preservation, and were highly informal in nature – they were quite useful but did not lend themselves to a succinct and meaningful summary for these Proceedings. However, the narrow focus of this particular session, the spirited if inconclusive discussion, and the specific recommendations offered warrant the following summary. It is hoped that the notes presented below will be helpful to agencies and authors as they struggle to address the issue.

The Discussion Session introduction was this: "Increasingly, unpublished GIS files and related information are derived from pre-existing publications. Soon thereafter, or perhaps many years in the future, these files are used in new publications. How can we try to ensure that not just the unpublished GIS file, but also its source(s) of information, are informatively cited in new publications? It is critical to our science that, years from now, the original and authoritative source of all cited information can be found. This brief session will introduce the challenge and offer some suggestions."

In previous DMT discussion sessions on this topic (Berquist, 1999; Richard, 2000; Berquist and Soller, 2001), a wide range of opinion was expressed regarding how authors and technical contributors should be attributed, both in the formal citation and in the metadata. Most of those who spoke in these sessions used, or favored, similar approaches, but it was clear that "one size doesn't fit all." A prescriptive approach, while useful as a guide, cannot suit all agencies and types of publications. The examples and opinions in this document extend the discussion to unpublished information, and should be considered in that same light – they are suggestions based on personal experience that, I hope, will contribute to improvements in managing and documenting unpublished map data.

The Challenge

As noted above, it is critical to our science that, years from now, the original and authoritative source of all cited information can be found. Here is a hypothetical, but plausible, example of how knowledge of that source can be lost (fig. 1):

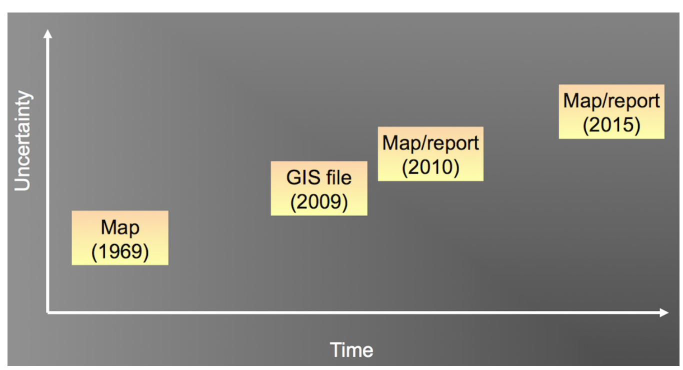

Figure 1. Four map products, described in the bulleted list below. All are derived from (at least in part) fieldwork done in preparation for publication of a geologic map in 1969. As products are subsequently produced and time elapses, the uncertainty of what constitutes the source information tends to increase.

1. In 1969, a geologist published a map. It was assigned to a geologic map series, given a series number, printed, and cataloged and archived by the organization's library.

2. In 2009, someone decided to digitize the map because it was needed in GIS format, in order to support new mapping and research. Because the person wants to share it with others, he or she posts it to a Web site or may simply ftp it to colleagues who request it. If the GIS file has been finalized (that is, it is not a preliminary version), the preparer, following conventional practice, indicates in the metadata that the map published in 1969 is the source. But because this GIS file is not published, it is not accorded the status of a publication and is not so managed and archived: (1) the library does not catalog it; (2) the agency's publications staff do not ensure that the URL and filename, and the Web page, are as informative as that expected for a publication; and (3) the information-management staff cannot be expected to archive it as part of their systematic backups.

3. In 2010, someone finds the GIS file online and downloads it. The person compiles and interprets it along with other information and formally publishes a new geologic map. In that product, the 2009 GIS file is cited, since it (and not the 1969 map) was directly used. At the time, the authors of the published map decide this is sufficient because the 2009 GIS file's metadata indicates that the 1969 map is the source.

4. In 2015, someone reads the 2010 map or paper and wants to use it for some new research or application. Let us assume that this person tries to find the source information, in order to get a better feel for the geologic interpretations and for the quality and density of observations and other data. However, the GIS file, posted to the Web in 2009, is no longer available. There is no agency record of it because it was not a publication, and so this person must rely on the information provided in the 2010 publication. In terms of the geology of the region in question, the 2010 publication must now be considered the authoritative source. With additional study, the true source (the 1969 map) could be inferred, and the field notes and supporting material perhaps accessed, but this process can be greatly facilitated by more detailed citations.

Suggested Citations

In 2004, I helped compile a national-scale map (Soller and Reheis, 2004; revised and republished as a GIS file in Soller and others, 2009) from a wide range of sources including published maps (paper and digital) and unpublished GIS files with various levels of documentation and completeness. The suggestions offered here are based for the most part on the citations devised for that map publication. They tend toward the verbose, in order to be informative but also to suggest the types of information that could be helpful in citations that you might devise. In the interest of completeness, I include citations to published GIS files. The citation types are:

- Published map
- Published GIS file that refers to the source map
- Published GIS file that does not refer to the source map
- Unpublished GIS file, from which a map was later printed
- Unpublished GIS file, digitized from a printed map, and later incorporated into a published GIS file
- Unpublished GIS file, digitized from a printed map, with some modification and later incorporated into a published GIS file
- Unpublished GIS file, later superseded by published GIS file
- Unpublished GIS file derived from an online database
- Descriptive notation that an unpublished GIS version of map was used
- Descriptive notation regarding modifications to published map prior to digitization and use

Suggested citation for published map:

Soller, D.R., and Reheis, M.C., 2004, Surficial materials in the conterminous United States: U.S. Geological Survey Open-File Report 03-275, scale 1:5,000,000, *http://pubs.usgs.gov/of/2003/of03-275/*.

Suggested citation for a published GIS file that refers to the source map (from Berquist and Soller, 2001):

Smith, A.B., and Digits, C.D., 2001, Geologic map of the XYZ Quadrangle, *adapted from* Doe and Smith 1999 map: The Geological Survey, Map D-31, one Adobe Acrobat (PDF) file, scale 1:24,000, available on CD-ROM or <URL, if any> [*adapted from* Doe, J.K., and Smith, A.B., 1999, Geologic map of the XYZ Quadrangle: The Geological Survey, Map M-123, scale 1:24,000].

Citation for a published GIS file that does not refer to the source map:

Green, G.N., 1992, The digital geologic map of Colorado in ArcInfo format: U.S. Geological Survey Open-File Report 92- 507, ArcInfo file, *http://pubs.usgs.gov/of/1992/ofr-92-0507/*. [Digitized from Tweto, Ogden, 1979, Geologic map of Colorado: U.S. Geological Survey, scale 1:500,000.]

Unpublished GIS file, from which a map was later printed. The extent to which the file was further modified by the authors, before printing the map, is unknown, as somewhat implied by the bracketed note:

Fullerton, D.S., Bush, C.A., and Pennell, J.N., unpublished, Surficial deposits and materials in the eastern and central United States (east of long 102° W.), *derived from* Quaternary Geologic Atlas of the United States: U.S. Geological Survey Geologic Investigations Series I-1420, one ArcInfo file, scale 1:2,500,000. [Printed map derived from this database is available as Fullerton, D.S., Bush, C.A., and Pennell, J.N., 2003, Map of surficial deposits and materials in the eastern and central United States (east of long 102° W.): U.S. Geological Survey Geologic Investigations Series I-2789, scale 6 1:2,500,000, *http://pubs.usgs.gov/imap/i-2789/*.]

Unpublished GIS file, digitized from a printed map, and later incorporated into a published GIS file. The bracketed note refers the user to the published GIS, with which it has some unspecified level of commonality:

Bedford, D.R., unpublished, Digital file showing geology of California, *digitized from* Jennings, C.W., Strand, R.G, and Rogers, T.H. comps., 1977, Geologic map of California: California Div. Mines and Geology Map GDM 2, scale 1:750,000. [Some information in this file is found in Bedford, D.R., Ludington, Steve, Nutt, C.M., Stone, P.A., Miller, D.M., Miller, R.J., Wagner, D.L., and Saucedo, G.J., 2003, Geologic database for digital geology of California, Nevada, and Utah—An application of the North American Data Model: U.S. Geological Survey Open-File Report 03-135, 35 p., *http://geopubs.wr.usgs.gov/open-file/of03-135/*.]

Unpublished GIS file, digitized from a printed map, with some modification ("adapted from") and later incorporated into a published GIS file. The bracketed note refers the user to the published GIS, with which it has some unspecified level of commonality:

Bedford, D.R., unpublished, Digital file showing geology of Utah, *adapted from* Hintze, L.F., Willis, G.C., Laes, D.Y.M., Sprinkel, D.A., and Brown, K.D., 2000, Digital geologic map of Utah: Utah Geological Survey Map 179DM, CD-ROM. [Information about modifications of the published map are found in Bedford, D.R., Ludington, Steve, Nutt, C.M., Stone, P.A., Miller, D.M., Miller, R.J., Wagner, D.L., and Saucedo, G.J., 2003, Geologic database for digital geology of California, Nevada, and Utah—An application of the North American Data Model: U.S. Geological Survey Open-File Report 03-135, 35 p., *http://geopubs.wr.usgs.gov/open-file/of03-135/*.]

Unpublished GIS file, later superseded by published GIS file (but not in time for published file to be used, so uncertain whether they are identical or different):

U.S. Geological Survey, unpublished, digital file showing geology of Oregon, *digitized from* Walker, G.W., and MacLeod, N.S., 1991, Geologic map of Oregon: U.S. Geological Survey, scale 1:500,000, *http://geology.wr.usgs.gov/docs/geologic/or/oregon.html*. [A digital version of this map was more recently published as Walker, G.W., MacLeod, N.S., Miller, R.J., Raines, G.L., and Connors, K.A., 2003, Spatial database for the geologic map of Oregon: U.S. Geological Survey Open-file Report 2003-67, scale 1:500,000, *http://pubs.usgs.gov/of/2003/of03-067/*.]

South Dakota Geological Survey, unpublished, digital file showing geology of South Dakota. [Contains map information later published in Martin, J.E., Sawyer, J.F., Fahrenbach, M.D., Tomhave, D.W., and Schulz, L.D., 2004, Geologic map of South Dakota: South Dakota Geological Survey Map 10, 1:500,000.]

Unpublished GIS file derived from an online database. Citation briefly notes the nature of the database query:

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