An Innovative Approach Using Digital Photogrammetry to Map Geology in the Porcupine Hills, Southern Alberta, Canada

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Abstract

Digital and analog air photographs and field observations have been used to map resistant sandstones within the Porcupine Hills Formation in southern Alberta. The traces of these beds were plotted in three dimensions using a digital stereoplotter. The procedure permits correction of plotting errors made by the geologist who could previously use only a few ground points recognizable in the field to locate sandstone beds on the digital topographic base map. Digital orthophotos and elevation data were then used to calculate three-point solutions of the strike and dip of sandstone ridges. These procedures allowed the geologist to improve his geological interpretation and to validate the digital transfer of line work by the photogrammetrist. Photogrammetrically calculated bedding measurements augmented those measured in the field and allowed the geologist to delineate several previously unrecognized folds.

Introduction

In the last decade, digital technology applied to geological cartography has moved out of the domain of a few dedicated specialists and has become a successful technique to compile, manage, and analyze geological information. In contrast, the crucial step of geology data acquisition and mapping is, to a large degree, still dependent on field surveys. Digital techniques have been adopted by only a limited number of geologists. The technique of deriving some of the features of a detailed geology map from digital stereo plotting is still at an experimental stage, with only a few studies published (Lang *et al.*, 1987, Lang and Paylor, 1994; McGuffie *et al.* 1989; Berger *et al.*, 1992; McMahon and North, 1993; Larouche *et al.* 1994; Ellis, 1995; Jones and Oehlers, 1995).

The purpose of this paper is to describe an example of the use of digital orthophotos to map the geology of the southern part of the Porcupine Hills of Alberta, Canada (Brocket area, NTS 82H/12), an area of moderate relief and shallow bedrock dips. Researchers of the Geological Survey of Canada's Southeastern Cordillera NATMAP project (1993-1998; Lebel, 1994) have been mapping the area, together with adjacent areas of the Rocky Mountain Foothills foreland thrust and fold belt, to reach a better understanding of the bedrock and surficial geology, to support land planning, and water, mineral, and petroleum exploration.

Outline of the Porcupine Hills Physiography and Geology

The Porcupine Hills is an area of moderate relief (1000-m to to 1850-m range in elevation) situated southwest of Calgary, Alberta (Figure 1). The area is vegetated with spruce and pine interspersed with prairie meadows. Bedrock geology consists of sedimentary rocks of the Porcupine Hills Formation of Paleocene age, exposed in a broad syncline (Alberta Syncline) situated at the eastern edge of the Rocky Mountain Foothills deformed belt. Surface exposures comprise fine- to medium-grained sandstone beds that are amalgamated in sandstone-dominated units varying in thickness from a few metres to a few tens of metres. These units are interstratified with recessive and rarely exposed shale-dominated units. Sandstone units form cliff exposures, up to several tens of metres high. The cliffs are common in many areas of the Porcupine Hills. These geomorphologic features were used for hunting by early natives at sites such as Head-Smashed-In Buffalo Jump (Provincial Historic and World Heritage sites), northwest of Fort Macleod (Figure 1). A veneer of glacial till and more recent surficial sediments, up to 30 m in thickness, covers the broad valleys of the area.

The Problem of Evaluating the Structure of the Porcupine Hills

Although the bedrock structure of the area is simple, being only broadly folded, the dip orientation and the location of regional folds within the Porcupine Hills are extremely difficult to assess. Dips in bedding range from horizontal to only 5 degrees (Figure 2). Field measurements of bedding attitudes are often ambiguous because sandstones are channelized and heavily cross-bedded. These sedimentary structures obscure the paleohorizontal position of the beds. However, dips of beds can be measured across the numerous valleys that dissect the hills, using the trace of the resistant top of sandstone beds as key horizons, representing roughly the paleohorizontal. The triangulation of these horizons across these wide valleys using a surveying transit-theodolite instrument is, however, enormously expensive if carried throughout the area. An alternative method is to use aerial photographs to trace the position of these sandstone units and then plot them accurately on a map. This method is also prohibitively expensive because it requires the use of an analog stereoplotter. The use of digital orthophotos to do the same exercise is a cheaper alternative.

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Photogrammetric Engineering & Remote Sensing, Vol. 65, No. 3, March 1999, pp. 281–288.

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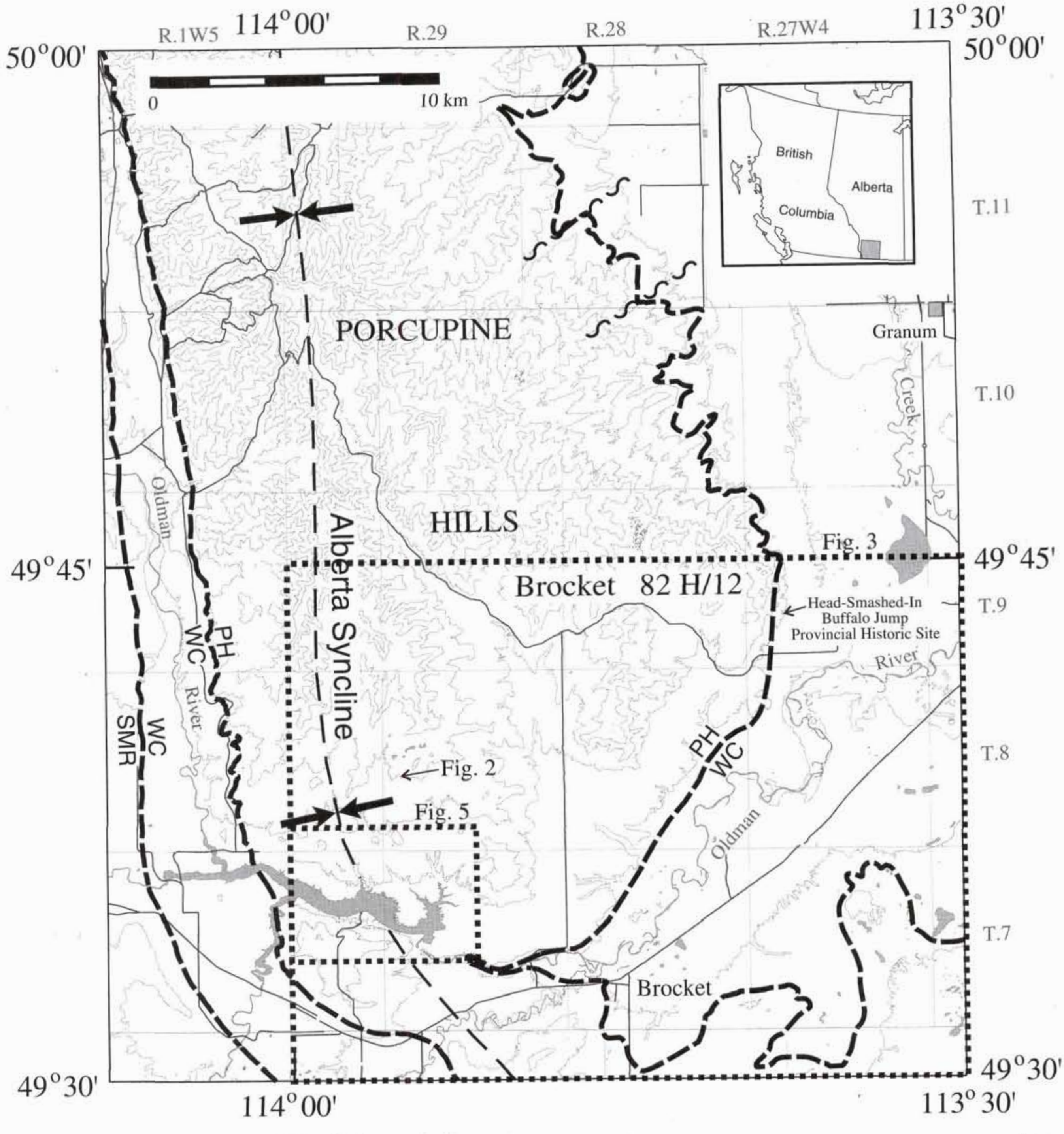


Figure 1. Location and geology of the study area in the southern part of the Porcupine Hills in southern Alberta. The eastern leading edge of Foothills thrust and fold belt follows approximatively the trace of the Alberta syncline. PH: Porcupine Hills Formation; WC: Willow Creek Formation; SMR: St. Mary River Formation. Figure adapted from McMechan and Stockmal (1996).

Using Digital Photogrammetry to Map the Porcupine Hills

Methodology

In order to map the geology of the Porcupine Hills in the Brocket area, digital and analog air photographs, and field observations were used to map more than ten resistant sandstone units within the Porcupine Hills Formation. The exact position of these sandstone units was traced in three dimensions using a digital stereoplotter, or in some cases using orthophotos with the assistance of a DEM. The locations of field stations and bedrock exposures were also plotted on a conventional digital NTS topographic map base using the same method. The result is one of the first geology maps of Canada compiled with the assistance of digital photogrammetry (Fig-

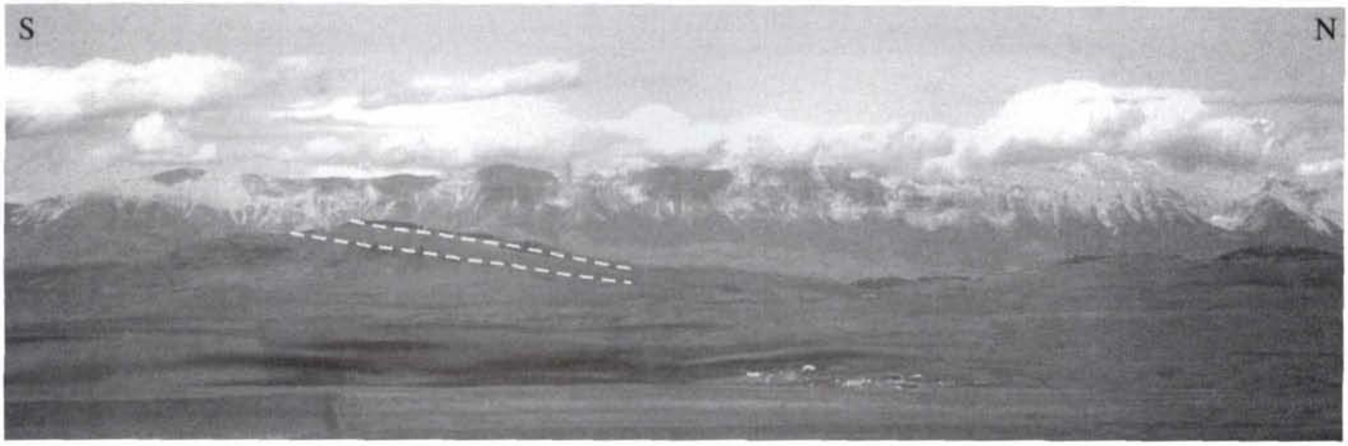


Figure 2. Panoramic view, looking west, of sandstone exposures in the southwest part of the Porcupine Hills. White line outlines the top and bottom of one of the mapped sandstone units. See Figure 1 for location.

ure 3)(Lebel, 1996). The method used to complete this map project is summarized in the eight steps described below.

Field Surveying and Plotting of Geology Data on Aerial Photographs and a Digital Base

During four weeks of the summer of 1995, geological fieldwork was conducted in the Porcupine Hills of the Brocket area. Fieldwork consisted in visiting 264 bedrock exposures and recording observations in a relational database at each field station. Recorded information included the lithological and sedimentological characteristics of the outcrop, the bedding thickness, structural measurements wherever possible, and handheld photography of geological features of the outcrop. Finally, the traces of the top and bottom of the resistant sandstone units were plotted with black china ink on black-and-white aerial photographs, acquired from Alberta Environmental Protection (AEP, formerly Map Alberta), at a scale of 1:30,000.

A preliminary map of geological contacts, field stations, and outcrop outlines was plotted on a 1:50,000-scale digital topographic map base acquired from the National Topographic Database (NTDB, Geomatics Canada). This procedure involved use of a digitizing tablet attached to a computer running Bentley's MicroStation V.5, a CAD program. Everyday, upon returning to field camp, a CAD built-in registration procedure (DIGITIZER SETUP) was used to tie the aerial photographs to the NTDB vector map through matching of features such as creek junctions, bridges, road intersections, and hill summits. This allowed for a rough "rubber-sheeting" of the distorted airphoto into the 2D UTM coordinate system of the NTDB map, and permitted a transcription of the geologist's notes.

Digitizing of Air Photographs

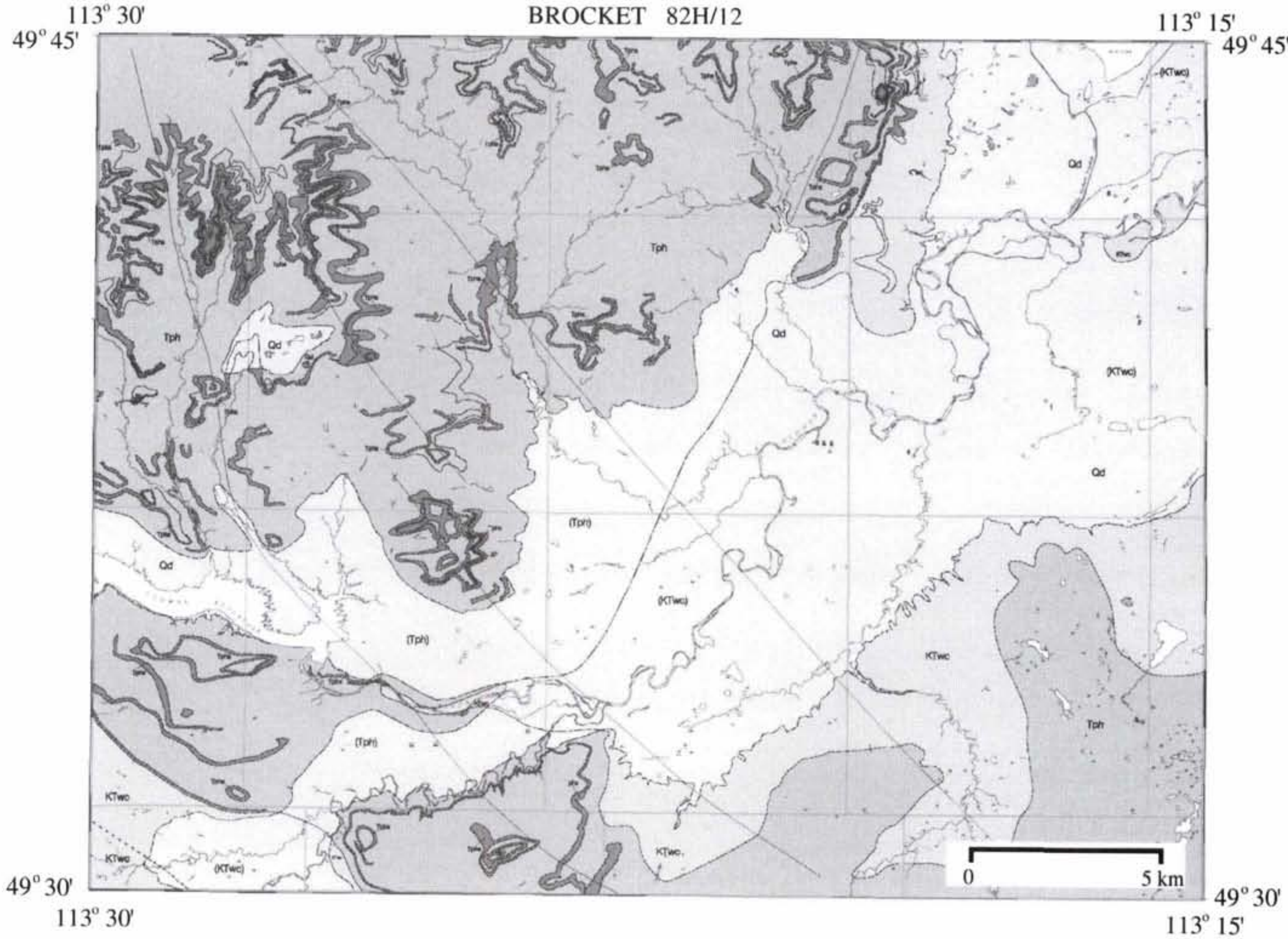
Upon return from field, the annotated aerial photographs were provided to the photogrammetrist for rasterization and vectorization. A network of tie, pass, and surveyed points was established and adjusted, after being extrapolated from the 1:50,000-scale NTDB digital map. This crude method of establishing control points produced higher values of residuals due to shift in registration between layers and the archaic analog method used for constructing the NTDB digital map. Ideally, control points should be acquired through more direct survey methods. In addition, a set of pug points, from a separate set of 1:60,000-scale aerial photo diapositives, with accurately known geographic coordinates were marked on each photograph to constrain the photogrammetric model. These points were provided by the Alberta Environment Protection organization and are derived from ground surveys and aerial triangulation.

The equipment available in-house for the rasterization process consisted of a Sharp JX-610 single-pass photogrammetric scanner, capable of optimal scans of 600 dpi by 600 dpi optically, 12 bits per channel (RGB) on an 11- by 17-inch flat scanning bed. Over time, measured produced positional accuracy for this scanner has consistently been close to an order of magnitude better than resolution (Δx, Δy = 1.5, 4.5 μm). Scanning of the 1992 set of 53 1:30,000-scale aerial photos (9- by 9-inch) at 600 dpi and 8 bits (256 grey scale) took 10 minutes per scan. Conversion of a digitized photo to the format required by the digital stereoplotter took an additional 3 minutes and produced a 42-Mb file, with a resolution of about 1.2 m (original photo scale is approximate).

Generation of Digital Stereopairs

Once the rasterization of the photographs was completed, the registration process was carried out by the photogrammetrist, using the in-house DiAP digital stereoplotter (Figure 4, acquired from International Systemap (ISM) Corporation of Vancouver, British Columbia). The apparatus consists of a hand- and foot-wheel positioning device in addition to a mouse, giving altogether six degrees of freedom. The photogrammetrist uses these positioning devices in parallel with a pair of stereo glasses (Crystal Eyes-Stereographic Corporation). The glasses are coupled with the computer monitor to provide a stereo visualization system. Coupling is accomplished with a field sequential electrostereoscopic display in which full screen left and right images alternate rapidly. Synchronized shutters in the active eyewear direct these images to the appropriate eye, creating a stereoscopic view. The DiAP system also provides a stereo raster rendition application running within the memory address of Bentley's MicroStation v.5 on the PC-DOS operating platform.

A proportional distribution of control points was sought and used to generate the stereo model. These points, plus additional ground features from the NTDB digital map, provided a minimum of six points per stereo model. This was a tedious procedure, given the discrepancy in the age of the photos relative to the map (1992 versus 1971). Several roads and intersections were relocated between 1971 and 1992, and many other cultural features had to be discarded in order to achieve an exact registration of the photograph on the hypso-



QUATERNARY

PLEISTOCENE AND RECENT

Qd — *Till, alluvium, colluvium*

TERTIARY

PALEOCENE

Tph — *PORCUPINE HILLS FORMATION (undivided): Thick, cross bedded, fine- to medium-grained, buff-weathering, grey sandstone· cross bedded friable, medium to dark gre mud shale; minor fine-grained pedogenic limestone; (non marine)*

Tphs — *Resistant sandstone lithosome: Fine- to medium-grained sandstone, cliff-forming, typically 5 to 20 meter thick units; minor mud shale interbeds*

CRETACEOUS AND TERTIARY

UPPER CRETACEOUS TO PALEOCENE

KTwc — *WILLOW CREEK FORMATION: red, green, dark grey, and purple mud shale; limy caliche nodules in shale; fine- to medium-grained, cross-bedded buff -weathering, grey sandstone (non marine)*

CENOZOIC

MESOZOIC

Figure 3. Scaled reproduction of the geological map of the Brocket area (NTS 82H/12)(Lebel, 1996). Some features such as roads, structural measurements and outcrops have been removed here for clarity. See Figure 1 for location.

Figure 4. Digital stereoplotter installation at GSC Calgary. See text for explanation.

graphic and hydrographic layers. Some areas in the northwest part of the map were inaccurately compiled (egregious horizontal differences of up to 50 metres were noted where the map was rubber sheeted to coincide with adjoining map sheets) and the digital model was corrected accordingly. In other areas where the discrepancy was high, the digital vector map was corrected (see the next step, below). The process of registering each photo took 50 minutes on average after discounting the stated discrepancies.

Correction of the Base Map
The southern part of the Porcupine Hills is crossed by the Oldman River (Figure 1). Construction of the Oldman River irrigation dam started in 1985 and the flooding of the reservoir was completed by 1992. The 1992 set of aerial photographs, used for this project, displayed the reservoir in a state comparable to its present extent, and also with the addition of new bridges and surrounding roads. The older NTDB map was thus unsuitable to display the geology accurately. Thus, steps were taken to redo the cartography of the area of the reservoir, up to its upper reach in the Oldman River and in the Crowsnest and Castle river tributaries in the Blairmore map area (82G/9, Figure 5). This fourth step took about 120 hours.

Vectorization of Geological Line Work by Stereogrammetry
Geological contacts and outcrops plotted on the original aerial photographs by the geologist were vectorized in three-dimensional coordinates, using the DiAP stereoplotter. Some of these black ink markings were difficult to recognize because of their low contrast relative to the dark evergreen vegetation cover. However, in most areas barren of trees, the markings were relatively easy to trace. The process of vectorizing some 600 outcrop locations and 955 km of geological contacts took about 4 to 6 hours per model or 150 hours in total.

Generation of Digital Orthophotos and DEM
Once absolute orientation of each stereo pair was completed, the DiAP software was used to quickly produce an orthophoto out of the double neat model area. Twenty-one orthophotos were produced in this manner, which covered the northwestern two-thirds of the Brocket map area. Contour files obtained from the NTDB were combined with corrected elevation data acquired by redoing the cartography of the Oldman River dam, and a digital elevation model (DEM) was generated to assist the geologist in completing the geology map.

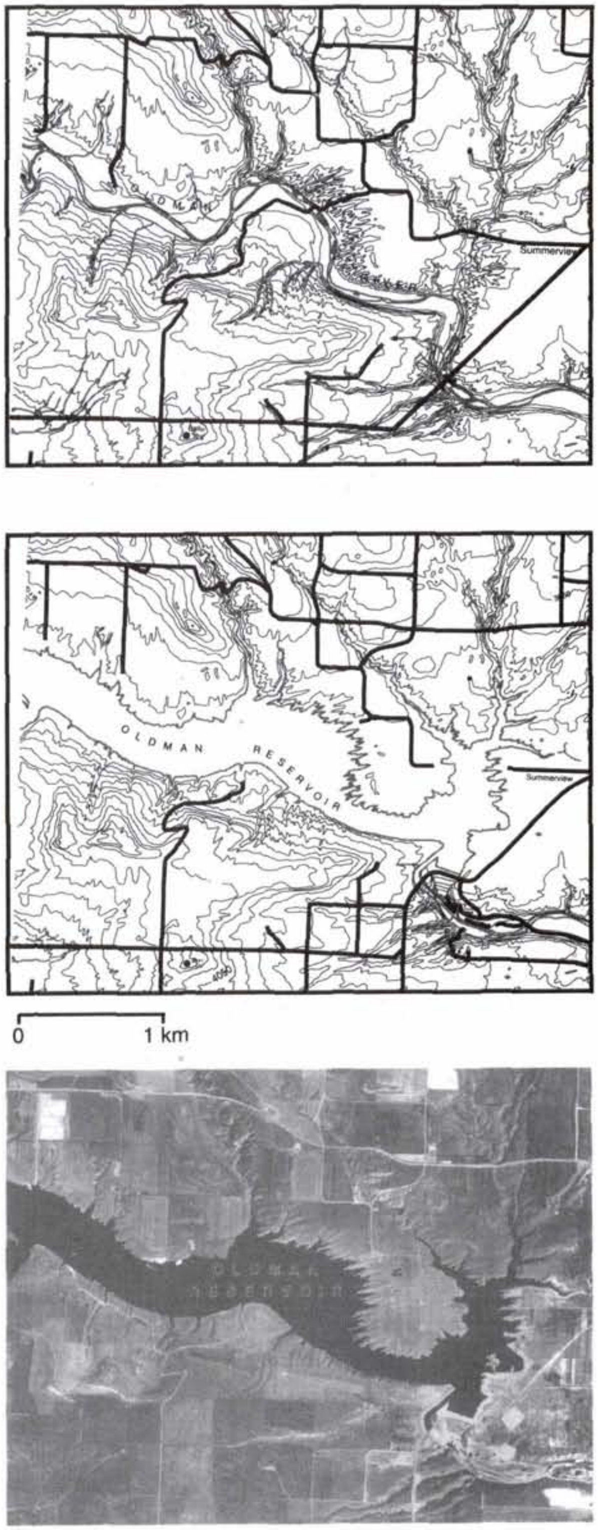


Figure 5. Comparison of the Oldman River area before and after topographic correction. See Figure 1 for location. Top: Original NTDB map of the Oldman River (1971 edition); Middle: Corrected map with new features (road, dam, reservoir) and orography; Bottom: Orthophoto covering the area remapped.

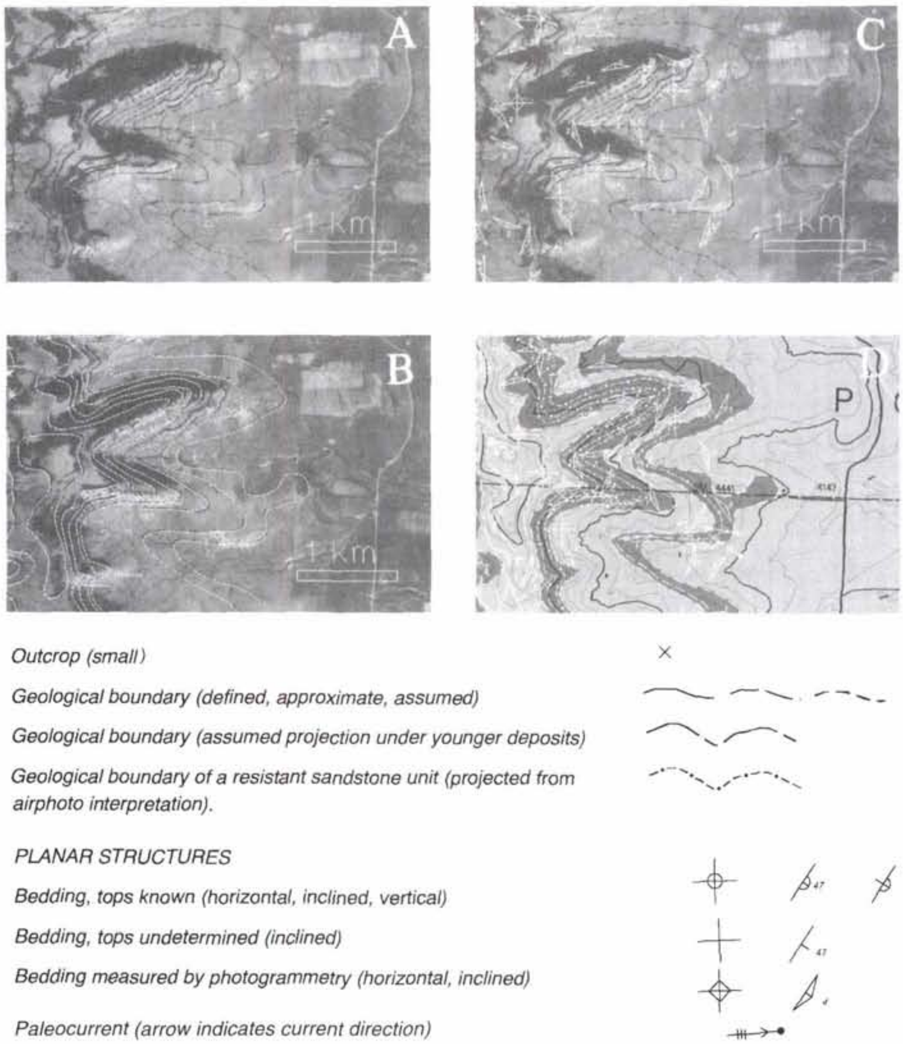


Figure 6. Illustration of the procedure used to map geology of the Brocket area using digital photogrammetry. Steps refer to the text: (a) Step 1 to 3: Field surveying and plotting of geology data on original aerial photographs, scanning and production of the stereopairs and orthophotos; (b) Step 5 and 7: Vectorization of geological contacts and outcrop locations over the orthophoto; (c) Step 8: Calculation of the beds strike and dip by solving three-point equation; (d) Final geological map with topographic base and field observations.

Interpretation of Features and Completion of the Geological Map from Digital Orthophotos

The geological map was completed by the geologist using the set of orthophotos. Instead of using the digital stereoplotter, the geologist used a flat orthophoto display because of its ease of use and immediate availability (the single in-house stereoplotter is over subscribed by other projects). A raster display program (Sysidisp.ma or Sysimage viewer from ISM), running as an adjunct module to Microstation v.5, was used by the geologist to display the orthophotos in conjunction with the topographical base map and the geology dataset. An additional module (Autoz.ma, also from ISM) was used with the DEM to provide a three-dimensional ground-registered coordinate system. This program module forces any input on a top view (map view) to be located at a proper elevation by continuously searching the elevation in the DEM corresponding to the *x,y* coordinates of the cursor on the map view. The program is fast, allowing for the rapid three-dimensional digitization of features from the orthophotos. Work involved correcting misplaced or absent contacts and outcrops.

Calculating Bed Attitudes

Because a geological contact represents the trace of intersection between a relatively tabular rock body and the ground surface, the attitude of beds can be calculated by triangulation. A Microstation Basic macro program was written by the first author to calculate, by triangulation, the attitude of the relatively tabular sandstone bodies (Figure 6). This method is similar to a previously described method for triangulating structural data (Berger *et al.*, 1992), and uses elevation data along the trace of rock units, requiring three points situated at different geographic coordinates but in relatively close proximity (to evaluate the local dip). However, our procedure is different and more similar to that described by Lang *et al.* (1987), in that it uses elevation values provided by a draped DEM coordinate system rather than values from stereoscopic measurements. Although dependent on the availability of a precise and tight DEM grid, the procedure is quick and allowed for the calculation of some 690 bedding strike and dips in about 20 hours. Axial planes of folds were traced from the information provided by this dataset and the geological contacts. Given the uncertainties of structural measurements made in the field, the accumulation of photogrammetrically calculated bedding measurements has allowed the delineation of several previously unrecognized broad folds that parallel the axis of the Alberta Syncline.

Discussion

A comparison of the early vectorization made by the geologist (the first step) showed plotting errors in the range of 20 to 500 metres relative to the more precise digital stereo plotting (the fifth step). The initial procedure was difficult and inaccurate, given the photograph radial distortion and the relatively small number of ground features that could be used for the matching between the map and the photograph.

Stereo plotting by the photogrammetrist was accurate in most cases, except in areas of poor image contrast. The geologist corrected minor errors, completed the outline of missing geological contacts, and added linework that had been forgotten in the early interpretation. The geologist was not aware of the ability of the system to make three-dimensional projections of cliff faces using the orthoimage and draping it on the DEM, a feature that could have helped in drawing some of the more difficult geological boundaries. We have since learned that dramatic improvement in accuracy can be achieved with such oblique views, also achievable by using the surface rendering tools built within Microstation.

Only a few reliable bedding measurements were available from fieldwork, and they generally agreed with the photogrammetrically calculated ones. However, the accuracy of the photogrammetrically calculated bedding measurements has not been tested sufficiently with field measurements to assess its reliability in the case of very shallow dips. The precision of the method is dependent to a large degree on the precision of the DEM that is used and the resolution of the photographs. In the case of steeper dips, such as those encountered in the Front Ranges of the Rockies, the method has proven to be fairly accurate, within 5 degrees in strike and dip, or within the error range of the traditional compass and level method. This accuracy is equivalent to that reported by Lang *et al.* (1987), who used similar procedures with satellite pictures in a Wyoming study.

The ability to quickly correct the base map without the necessity of ground surveying is an additional advantage of the use of digital photography because once registered to the geology, the digital aerial photographs were also well suited for correcting the topographic base map.

Data storage is a concern for such a project, requiring at least 4 Gb to store the raw data and stereopairs, consisting in 56 original TIF files (1.27 m/pixel) and an equal number of DiAP-generated geographically located raster files (SIS files) of each airphoto, and some 280 Mb more for the 26 orthoimages (2.00m/pixel) and DEM. We found that writable CDROMs (CD-Rs) were a reliable and inexpensive means of archiving the data through the different steps of the project. Color, higher resolution, and larger map areas would all make the project files significantly larger.

Finally, the availability of a skilled photogrammetrist equiped with a stereoplotter workstation may be an additional concern for some organizations. From beginning to end (see above, the first three steps), the process of producing a single digital orthophoto takes at least 8 hours. The use of original photographs of a smaller scale to cover a given area substantially reduces the amount of work. Given the high geometric accuracy of present scanners, rasterization of 1:60,000-scale air photographs at 600 dpi (2.54 m/pixel) is good enough to achieve accurate 1:50,000-scale regional mapping. A newly acquired photogrammetric drum scanner now allows for 2000 dpi resolution and sub-metre accuracy (this is a limit given film grain size). Because the time needed to register a single photo is the same for any scale, the smaller the scale, the more efficient is the system. In fact, we have since found that aerial diapositives with embedded pug points (from AEP or Geomatics Canada) at 1:60,000-scale are a superior set because they hold important geometric information about specific point locations. This allows for a substantial acceleration of the registration process of the digital stereo photo pairs.

This project has also shown that a substantial amount of work could be shifted from the photogrammetrist to the geologist, during the step of vectorizing the geology. This is because the geologist is better trained to discard or add relevant geological information. Surprisingly to the photogrammetrist and the geologist, this last step does not require the help of the photogrammetrist if the computer interface is well designed and easily understood. In theory, given the availability of digital orthophotos and DEM from other sources, the entire process of compiling geology from digital photos could be done without the help of a stereoplotter or a photogrammetrist. However, given the fairly minimal orthophoto coverage presently available for the country and the need for high accuracy in the production of the orthophoto and DEM datasets, it appears that we will continue to produce orthophotos and DEMs in-house for some time. Upcoming availability of high-resolution satellite imagery may not change this situation quickly either because it may take some time before sub-10-metre resolution geometric corrections are well understood and possible. Although the services of a photogrammetrist added a substantial cost to this mapping project, it was balanced by substantial savings in time for the geologist for plotting geology, the benefits of a new accurate base map, a more accurate geology dataset, and mutual training in each field.

Conclusion

Digital photos provide an efficient base for plotting geological contacts and bedrock exposures. Base maps which are not up-to-date or are inaccurate can be quickly corrected. In comparison with methods that use airphotos registered on a digitizing tablet, our procedure reduces the risk of error significantly. We found that stereopairs and the use of the stereoplotter is not the most efficient base for vectorizing the geology. The use of orthophotos by the geologist was the most efficient tool for the level of accuracy required to complete the mapping of regional geology. Rapid calculation of bedding attitudes is a successful tool applied during this project.

Acknowledgments

Thanks to Chris Harrison and Christian Larouche who introduced D.L. to the digital stereoplotter technique. Steven Hinds prepared the figures presented here. Acknowledgments to reviewers H. Lang and anonymous. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not constitute or imply endorsement by the Government of Canada or Geological Survey of Canada. This is Geological Survey of Canada Contribution #1998007.

References

Berger, Z., T.H. Williams, and D.W. Anderson, 1992. Geologic stereo mapping of geologic structures with SPOT satellite data, *American Association of Petroleum Geologists Bulletin*, 76:101–120.

Ellis, J.M., 1995. Geological and environmental remote sensing for international petroleum operations (Abstract), *American Association of Petroleum Geologists Bulletin*, 79:1729.

Jones, R.E., and M. Oehlers, 1995. Successful integration of remote sensing and ground based exploration techniques in an arid environment, *Oil and Gas Journal*, 93(10):47–51.

Lang, H.R., S.L. Adams, J.E. Conel, B.A. McGuffie, E.D. Paylor, and R.E. Walker, 1987. Multispectral remote sensing as a stratigraphic and structural tool, Wind River/Bighorn Basin area, Wyoming, *American Association of Petroleum Geologists Bulletin*, 71:389–402.

Lang, H.R., and E.D. Paylor, 1994. Spectral stratigraphy: Remote sensing lithostratigraphic procedures for basin analysis, central Wyoming examples, *Journal of Nonrenewable Resources*, 3:25–45.

Larouche, C., J.A.R. Blais, and J.C. Harrison, 1994. Digital geological map production with a PC-based photogrammetric stereoplotter, *Proceedings, Canadian Conference on GIS*, Ottawa, Ontario, Survey, Mapping and Remote Sensing Sector, Natural Resource Canada and Canadian Institute of Geomatics and the Inter-Agency Committee on Geomatics (ed), 1:549–564.

Lebel, D., 1994. *Regional Geology of the Cardston Map Area, Alberta (82H/3)*, Geological Survey of Canada, Current Research 1994-A, pp. 231–236.

———, 1996. *Brocket (82H/12), Alberta-Geology* (preliminary), Geological Survey of Canada, Open File map 3289, scale 1:50,000.

McGuffie, B.A., L.F. Johnson, R.E. Alley, and H.R. Lang, 1989. IGIS-computer-aided photogeologic mapping with imaging processing, graphics and CAD/CAM capabilities, *Geobyte*, 4(10):8–14.

McMahon, M.J., and C.P. North, 1993. Three-dimensional integration of remotely sensed geological data: A methodology for petroleum exploration, *Photogrammetric Engineering & Remote Sensing*, 59:1251–1256.

McMechan, M.E., and G.S. Stockmal, 1996. Definition of a mappable contact between the Willow Creek and Porcupine Hills formations, southern Porcupine Hills, Alberta: A conformable boundary, *Current Research 1996-E*, Geological Survey of Canada, pp. 103–110.

(Received 01 December 1997; accepted 24 February 1998; revised 24 April 1998)