Alpine-scale 3D geospatial modeling: Applying new techniques to old problems

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ABSTRACT

The investigation of geologically complex settings in Alpine or mountainous terrains is still dominated by traditional data collection and analytical techniques. The application of computer-aided geometric design and three-dimensional (3D) visualization and interpretation is rarely applied to such settings, despite its significant benefits. This contribution uses the Gosau Muttekopf Basin (Eastern Alps, Austria) to demonstrate that the application of 3D geospatial models can both provide new insights into our understanding of such settings and result in a more robust and reproducible synthesis of a complex region.

The objective of studying the Muttekopf Basin is to investigate the 3D structural control on the deposition of the deepwater sedimentary basin fill. Data for the investigation only consist of that which would be collected in a traditional field study (e.g., structural mapping, stratigraphic logging, and data localities derived from hand-held GPS [global positioning system]). The 3D basin configuration is initially derived using traditional analysis techniques (e.g., cross-section construction, photo-panel mapping, block diagrams, etc.). Using these analysis techniques, significant thickness variations are observed in the basin fill and are related to temporal and spatial variations in displacement of the controlling structure on the southern basin margin. However, there are significant limitations to this approach. In particular, because of the uncertainty in projection and spatial positioning, these techniques can only be used in an illustrative or qualitative fashion. To overcome these limitations, a 3D geospatial model is constructed from the same input data and illustrates that 3D geospatial modeling is a powerful technique for understanding complex geological settings. Integration of map data, stratigraphic section data, photographic images, structural data, and rock property data (gamma ray) into a single geospatial model maximizes the constraints of the limited data set. It also facilitates a deeper data analysis by significantly decreasing the time involved in generating multiple surfaces required for isopach generation.

The use of the isopach maps in the Muttekopf Basin provides significant insights into the basin’s evolution. In the Schlenkerkar section, the isopach maps reveal: (1) there was very little sediment thickness variation across the basin during the early basin fill; (2) the intermediate episode was characterized by a very thick accumulation in the basin’s axis with significant thinning onto the southern uplifted margin; and (3) a northward migration of accumulation occurred during the late stage of the basin fill. Overall, the isopach maps suggest that the structure on the southern margin was the primary control on accommodation space creation and that it was most active during the intermediate basin-fill episode. Using similar observations from isopach maps for the entire basin reveals that the change in structural style of the southern margin from a fold- to a fault-dominated system plays a significant role both on internal deformation of the basin as well as the sedimentology of the syngrowth basin fill.

Geospatial models, therefore, provide a more robust technique for analyzing and interpreting data within a 3D environment. In addition, they enable analysis that would be impossible with traditional techniques, such as probabilistic geocellular model construction and input models for 3D structural restorations.

Keywords: Alpine geology, geospatial models, structural reconstructions, geocellular models, structure sediment interactions

1. INTRODUCTION

Over the past decade there has been an increase in the application of computer-aided...
integrates both structural and stratigraphic com-

odology of generating a 3D volume model that
basin. We then discuss the workfl ow and meth-

iques for data analysis, we present an overview
to compare “traditional” and 3D geospatial tech-
tions, generation of geocellular models, etc.).

1.1. Utilization of Multimedia in This Contribution

Given the inherently 3D nature of this contribu-
tion’s topic, a number of methods are utilized to
portray the data and illustrate the 3D geospa-

tional (3D) visualization (Mallet, 1992; Jessell

and valentα, 1996; Mallet, 1997; Mcgaughy

and Vallée, 1997; de Kemp, 1998, 1999; Jes-
sell, 2001; Pringle et al., 2004). Coupled with
this are recent technological advances that pro-
vide affordable technology for digital imagery and
data collection, including high-resolution sat-
ellite imagery, digital elevation models (DEMs),
high-resolution surveying, and light detection and
ranging (lidar) (Bellian, et al., 2002, 2005; Jones
et al., 2004; Clegg et al., 2005). The integration of both CAGD software
and digital imagery/data collection has proved
to be an invaluable tool in addressing a num-
ber of research questions ranging from fracture
mechanics and the orientation of joint sets, to
the stacking of stratigraphic channel elements,
to mineral deposits and the development of
Archean greenstone belts (e.g., de Kemp, 2000;
Maerten et al. 2001; Ahlgren and Holmlund,
2003; Hasson and Mugiier, 2003; Pringle et al.,
2004; Wilson et al., 2005; Rawling et al., 2005).
Despite these developments in digital data col-
lection and analysis, there remains a signifi cant
disconnect between the use of such technology
and its common application to fi eld-based geo-
logical problems. In particular, when addressing
basin-scale problems in Alpine or mountainous
lands, most studies still rely upon traditional
techniques for both data collection (e.g., bed-
ding dip and strike, mapping, stratigraphic log-
ing, photo-mosaic mapping, etc.) and analysis
(e.g., structural or stratigraphic maps, cross-section
construction, and stratigraphic correlation
panels). We pose the question, therefore, “can
the application of digital technology and CAGD
advance our understanding of basin-scale prob-
lems in mountainous terrains?”

We use the Muttekopf Basin in the Austrian
Alps, in which there is a complex interaction
between structural confi guration and stratig-
graphic basin fi ll both spatially and temporally,
to address the question. Data in this study have
been collected using traditional field techniques
(e.g., bedding dip and strike, stratigraphic log-
ing, photomosaic mapping, etc.) and are spa-
tially located using topographic maps, aerial
photographs, and hand-held GPS units. In order
to compare “traditional” and 3D geospatial tech-
niques for data analysis, we present an overview
of the basin using standard techniques (e.g., sec-
tions, photo panels, and block diagrams) and
discuss the limitations of these in a structur-
ally and stratigraphically complex sedimentary
basin. We then discuss the workflow and meth-
odology of generating a 3D volume model that
integrates both structural and stratigraphic com-
ponents and demonstrate the application of such
3D techniques in improving our understanding
of geological complexity and basin evolution.
Finally, we compare and contrast the under-
standing of the Muttekopf Basin derived from
traditional and 3D geospatial model techniques
and illustrate that the geospatial approach not
only enables us to analyze data more effi ciently
(e.g., generation of true cross sections and thick-
ness maps), but we can also undertake analysis
that previously would have been impossible
(e.g., volume balanced 3D structural reconstruc-
tions, generation of geocellular models, etc.).

2. GOSAU BASIN OVERVIEW

The Upper Cretaceous Gosau Group is a syn-
"rogenic, carbonate-siliciclastic sedimentary
succession that crops out within the Northern
Calcareous Alps of the Eastern European Alps.
This study focuses on the outcrop in the Mutte-
kopf Basin of western Austria (Fig. 1A). The
Gosau Group strata in the basin are preserved
within a major syncline in the hanging wall of
the Inntal Nappe (Fig. 1B), which is composed
of the Hauptideolomite Triassic carbonate shelf.
Internally, the nappe is deformed by km-scale,
northward-directed, thrust imbricates that detach
onto the underlying thrust. Some of these thrusts
have been demonstrated to be synsedimentary
with respect to the Gosau Group and are asso-
ciated with growth fold structures within the
deepest water sedimentary basin fi ll (Ortner, 2001,
2006, 2007). Younger thrust structures associ-
ated with post-Gosau Group Alpine shortening
deform both the southern and northern margins
of the basin (Eisbacher and Brandner, 1996).
The Muttekopf outcrop consists of an elongate
basin that is ∼12 km long by a maximum of 4
km wide (Fig. 1C; Wagreich and Faupl, 1994).
Erosional unconformities (e.g., kerkar unconfor-
mity). The Schlenkerkar unconformity (Fig. 1
C). Structural confi nement for these sediments
occurs on both the southern and northern mar-
gins, although the nature of this confi nement
changes signifi cantly along the length of the
basin and through the basin’s evolution.

The most western section of the basin (Kogel-
seeispitz; Fig. 2A) is characterized by a narrow
Gosau outcrop width (∼1000 m) that contains
asymmetric growth strata with a steeply dipping
southern margin and a shallower dipping northern
margin. Sedimentologically, this area has some
of the most proximal facies in the basin and is
dominated by stacked and amalgamated channels
and conglomerate bodies (Plink-Bjorklund et al.,
2007). In addition to the Gosau growth strata, the
section highlights the structural complexities,
such as box folds and faults that are present within the pre-growth Hauptdolomite north of the Gosau outcrop.

The basin width increases significantly from ~1000 m to >1800 m east of Kogelseespitze over a distance of ~1000 m, as demonstrated by the Schlenkerkar section (Fig. 2B). At the Schlenkerkar outcrop, the thickness of preserved growth strata increases from 150 m to 800 m. Associated with this increase in thickness are steeper dipping fold limbs on the southern margin and significantly more faulting within the northern margin. The strata on the southern margin demonstrate the most obvious lateral thickness variation associated with syn-depositional structural growth and bedding in the Lower Gosau strata, and the Gosau-Hauptdolomite contact is locally overturned (Ortner, 2001; Paton et al., 2007). A similar structurally controlled stratigraphic thickness variation is observed in the northern margin, although there is a high degree of deformation that significantly disrupts bedding and hence stratal geometry.

Farther down the basin axis toward the east (Fig. 2C), the basin configuration is dominated by a 3-km-wide syncline that is oriented along the axis of the basin. The northern margin of the syncline is relatively undeformed, although there is significant erosion of the uplifted margin and within the axis of the syncline. The erosion within the syncline at Rotkopf corresponds to the unconformity between Sequences 2 and 3. The south limb of the syncline is highly deformed with complex faulting and folding. The southern margin, which is not visible from the perspective of Figure 2C, is defined by thrust faulting that dissects the growth strata (Fig. 2 inset map).

The most easterly section across the basin (Fig. 2D) is characterized by a similar northern margin with erosion and moderate but consistent southern dip. The same central syncline seen at Rotkopf is evident and gently plunges toward the east. The southern margin is complex with at least two major thrust faults—one within the basin fill, causing localized folding and complex deformation. The second fault is part of a much larger thrust fault system that emplaces a thrust sheet from the south.

2.2. Data Collected

The outcrops in this basin indicate a significant structural control on basin-fill evolution;
Figure 2. This representation of the Muttekopf Basin comprises four, north-south–oriented sections that are located along the major valleys within the basin; arranged from west (A) to east (D) with the locations shown on the inset map. These sections provide excellent exposures of the Cretaceous growth strata and highlight the along-trend variation in structural-stratigraphic interaction (see text for discussion). The sections also, however, illustrate some of the difficulties inherent in working in mountainous settings such as access, correlation between section, and parallel projection of data onto a common plane.
therefore, the following data were collected to constrain this structural/stratigraphic interaction further (a representative sample of the data collected is shown in Fig. 3). In addition, the data collected in this study supplement published geological maps, stratigraphic sections, and structural data (bedding and fault orientations; Ortner, 2001, 2006). The data collected consisted of:

• 12 stratigraphic sections that were logged to investigate proximal-distal and axis-margin changes;

• 3500 m of section of grain size and facies data at cm-scale resolution;

• paleocurrent directions throughout each section;

• bedding attitude throughout;

• structural data (bedding attitude, faults, and fold axes) that were collected in sections and at basin margins (including pre-growth areas);

and

• photographic and GPS mapping of section locations that enabled the recognition of lateral facies changes, key stratigraphic units, and structural geometry.

2.3. Limitations of Investigating Basin Configuration Using Traditional Techniques

In the Muttekopf Basin, the overall basin configuration can be summarized as follows: the west of the basin (proximal) is structurally confined by a large growth fold structure on the southern margin and complex deformation on the northern margin. Structural deformation increases toward the east (distal), generating significantly greater accommodation space that results in both a deepening of the basin and an increase in basin width (from ~0.5 to 3 km). This interaction of structure, basin configuration, and stratigraphy has been outlined in Section 2.1 primarily using 2D basin-scale cross sections (Fig. 2) integrated with geological maps (Fig. 1). The inherently 3D configuration of the basin can be illustrated through the integration of regional sections and block diagrams (e.g., Barnes, 1981; Barnes and Lisle, 2004; Hatch, 1994; Ragan, 1985); such techniques can reveal variations in basin configuration (Fig. 4).

Given the structural complexity, coupled with difficulty in accessing much of the basin, there are significant difficulties in constraining the present-day basin geometry (Table 1). Problematic analyses include: the non-parallel projection of data onto cross sections; the correlation of horizons between outcrop sections; the correlation of horizons between outcrop sections;
derivation of stratigraphic correlation panels in a consistent basin location; and mislocation of nonspatially oriented photo panels that are used to construct the block diagrams. The following are three examples of the limitations of traditional techniques when applied to the Muttekopf Basin:

(1) There are abrupt changes in basin configuration, style and magnitude of controlling structure, and nature of the basin fill along the basin’s length. The distance over which change in basin configuration occurs is shorter than the spacing between the outcrop sections. That is to say it is spatially aliased. The use of the photo panels alone would, therefore, be akin to investigating a complex subsurface basin with limited 2D seismic profiles where the line spacing is greater than the change in basin configuration.

(2) The non-parallel projection of data is important in a number of the sections. In the Schlenkerkar area, an important issue is how preserved sediment thickness changes through time as an indication of variations in structure and basin fill. In particular, where the outcrop represents a non-ideal oriented section through a plunging basin, it is difficult to determine the true geometry. Constructing a correctly projected section is essential to understand growth of the structure.

(3) In the Muttekopf area (Fig. 4C), a north-facing exposure of the syncline and the controlling structure to the south is not available. Thus, significant projection of data is required across a particularly structurally complex area (Fig. 4D).

How can we overcome these limitations of using traditional field mapping techniques to understand a complex geological setting? High-resolution 3D data (e.g., lidar, high-resolution DEM) and visualization techniques have been used in a number of geological studies (e.g., Husson and Mugnier, 2003; Pringle et al. 2004; Wilson et al., 2005; Rawling et al., 2006; Pringle et al., 2006). These techniques have their strengths but are not universally practical or useful. In this study, for example, acquisition of lidar images of each cliff face is impractical and would not add significant constraint on the gross-scale basin geometry. The approach taken in this study is to generate a 3D geospatial model for the basin that integrates previous work (maps and structural data) with data collected to enable us to address the structural/stratigraphic interaction research question. The utilization of this technique does not require the use of digital data collection, although the methodology addresses the limitations of traditional data analysis discussed above.

3. DEVELOPING A 3D MODEL OF THE MUTTEKOPF BASIN

Various commercially available CAGD software packages exist that are suitable for the generation of 3D geological models, including Maptek’s Vulcan, Midland Valley’s 3D Move, and Schlumberger’s Petrel. This study uses Paradigm/Earth Decision’s GOCAD software because of its flexibility for surface generation.

Figure 4. Using traditional techniques of data analysis, a useful method for portraying 3D variation in settings such as the Muttekopf Basin is the construction of block diagrams that utilize the regional-scale sections (Fig. 2). Although such diagrams are illustrative, they cannot be used in a quantitative way.
<table>
<thead>
<tr>
<th>Issue/application</th>
<th>Limitation of traditional techniques in the Muttekopf Basin</th>
<th>Solution using 3D geospatial model*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatially correct representation of geology in 3D space</td>
<td>Generation of block diagrams from photo panels and sections that are not spatially correct because they are 2D representations of a 3D outcrop. The use of photomapping of non-spatially located panels is limited to qualitative impressions, not quantitative results.</td>
<td>Generation and visualization of 3D surface model in proper space</td>
</tr>
<tr>
<td>Correlation of horizons between outcrop sections</td>
<td>In mountainous settings, it can be problematic to correlate between outcrop sections. This problem is compounded when sections are dissected by ridge lines that cannot be easily observed on a single photo panel. For example, in the Muttekopf Basin the western outcrop of the basin axis syncline (Fig. 2C) cannot be extended to the south to include the southern thrust fault because of the location of topographic ridges.</td>
<td>Correlations can be traced using spatially positioned photographs, maps, etc. There may still be limitations where there are no outcrops or the photo images are poor.</td>
</tr>
<tr>
<td>Data that are not located on a section or photo panel require projection onto a 2D plane</td>
<td>Although the outcrop sections in Figure 3 are approximated to be a 2D plane, in reality there is a &gt;500-m variation in horizontal distance. The projection of data (e.g., strike, dip, facies, etc.) from their proper 3D spatial position onto a 2D plane is nontrivial and can lead to significant error. This is particularly important in areas such as the Schlenkerkar section (Fig. 2B), where the change in bedding attitude occurs within the area of projection.</td>
<td>The 3D model that encompasses geological surfaces and stratigraphic variations can be cut by 2D vertical planes and accurately represent the spatial and bedding geometries.</td>
</tr>
<tr>
<td>Geological complexity within inaccessible outcrops</td>
<td>Although the complexities can be observed, it is difficult to obtain a true perspective or spatial positioning of them.</td>
<td>Images of the complexity can be draped onto the DEM and incorporated into the geological interpretation.</td>
</tr>
<tr>
<td>Understanding stratigraphic variations across the basin</td>
<td>Sections through the entire Gosau stratigraphic thickness can be obtained; however, in order to find accessible and suitable outcrop, it may require traversing from axis to margin to axis positions in a single section. It is therefore problematic to construct a stratigraphic column that is consistently in the same depositional position of the basin (e.g., center of the basin axis).</td>
<td>A stratigraphic column can be obtained by extracting a pseudo-well from the model through a consistent depositional position of the basin.</td>
</tr>
<tr>
<td>Collection and integration of data at a number of scales (e.g., basin-scale location and geometry of controlling faults; stratal geometry of individual conglomerate beds)</td>
<td>In this study, the structural-stratigraphic interaction is to be investigated at both a basin scale (500 m-km) as well as at a bed scale (m). It can be difficult to evaluate data at multiple scales without an integrated model.</td>
<td>The geospatial model can be constructed at multiple scales, and the results can be integrated into a unified model.</td>
</tr>
<tr>
<td>Determining the quality and accuracy of the collected data</td>
<td>Without proper spatial positioning of data this can be problematic. An example is the integrating field localities with stratigraphic logged sections and photo-panel mapping of specific beds.</td>
<td>The geospatial model enables these data to be plotted together, and therefore the relative accuracy in position of each of them can be determined.</td>
</tr>
<tr>
<td>Determination of uncertainty and multiple scenarios; statistical approach to data interpolation</td>
<td>It is difficult and time consuming to generate multiple model solutions and determine uncertainty using traditional 2D map and 1D section techniques. The interpolation of data from regions of hard constraint using statistical methods is very time consuming.</td>
<td>The generation of multiple surfaces from the same data set is relatively simple; therefore, multiple scenarios can be constructed. In addition, the interpolation of data to areas of uncertainty can be done using statistical methods and is therefore reproducible and more robust.</td>
</tr>
</tbody>
</table>

*Many of these solutions assume that the 3D geospatial model accurately represents the true geological volume. Given the density of hard-constrained data within the model, this is a simplification; however, the geospatial model can be used to determine uncertainty.
and model construction, its ability to create geologically realistic objects such as channels, and to populate the derived model with multiple properties to reflect facies or other rock property variations. The following sections outline the workflow undertaken for the development of the Muttekopf model (Fig. 5). Prior to the construction of any model, it is imperative that the rationale behind its generation is well defined because this will influence the model design including the selection of appropriate resolution and extrapolation strategies. These issues will be discussed in the following sections.

3.1. Resolution at Which Model is Generated

The resolution of the model is determined by the question that the model will address. The model must have sufficient resolution to answer the question but not so high that an unnecessary time effort is spent on its construction. Coupled to the resolution issue is the constraining data density, given that commonly data are sparse compared to the volume of interest (Sprague and de Kemp, 2005). Depending upon the questions, the model can be multi-resolution such that various questions can be addressed. In this study, we want to address the following: (1) the influence of the basin’s structural configuration on basin depositional architecture (~0.1–5 km scale); and (2) the stratal geometry and variation of sedimentology on a bed scale (0.5–1 m scale). The Muttekopf Basin model, therefore, consists of multiple resolutions (Fig. 6). At a basin scale (0.1–5 km), the large-scale features such as sequence distribution are considered, and features such as faults and stratigraphic variations on a bed scale are not considered (Fig. 6A). In contrast, a model for stratal geometry

![Figure 5. Workflow of the technique used in this study to generate a 3D geospatial model of the Muttekopf Basin.](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/3/6/527/854465/i1553-040X-3-6-527.pdf)

Figure 5. Workflow of the technique used in this study to generate a 3D geospatial model of the Muttekopf Basin.

![Figure 6. An important consideration at the inception of any model is the scale at which the model should be generated. In this study, both the overall basin configuration (500 m to km scale) and a detailed understanding of stratigraphic variation at the Schlenkerkar section (meter scale) are required. The model presented, therefore, accounts for both scales and comprises a high- and low-resolution component.](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/3/6/527/854465/i1553-040X-3-6-527.pdf)

Figure 6. An important consideration at the inception of any model is the scale at which the model should be generated. In this study, both the overall basin configuration (500 m to km scale) and a detailed understanding of stratigraphic variation at the Schlenkerkar section (meter scale) are required. The model presented, therefore, accounts for both scales and comprises a high- and low-resolution component.
Figure 7. (A) The initial digital elevation model (DEM) is generated from hand contouring a 1:25,000-scale topographic contour map and fitting a surface to it using GOCAD’s Discrete Smooth Interpolation function. Having generated the DEM, various data can be draped over the surface, including geological maps (B) and aerial photography (C). See Animations 1 and 2.

Animation 1. This movie demonstrates the generation of the digital elevation model and draping of additional data, such as geological maps and aerial photography onto it. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00093.S1, or the full-text article on www.gsajunctions.org to view Animation 1.

Animation 2. This 3D digital elevation model consists of the topographic surface draped with the basin-wide aerial photographs. It enables the user to interact with the model, including model rotation and zooming when viewed through Acrobat 7. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00093.S2, or the full-text article on www.gsajunctions.org to view Animation 2.

and bed-scale variations must consider faults with minor (m-scale) throws and stratigraphic variations on the m scale. The scale at which the model is generated also has implications for the confidence with which surfaces can be extrapolated beyond data-rich areas (Fig. 6C).

If the model is to be used as the basis of further modeling, then the final product resolution
also must be considered. If the resulting model, for example, is to be the framework for a cellular model for fluid-flow simulation, then the number and size of individual cells will be determined by the simulation tools. Addressing questions such as these prior to the construction of the geospatial model is essential.

3.2. Input Data for 3D Geospatial Model

Having defined the research questions that the model will address and having determined the resolution at which the model will be constructed, the next step is the generation of a digital elevation model (DEM; Fig. 7). Although there is global coverage of digital elevation data for most of the Earth’s continental surface, the resolution is commonly too low to represent high-resolution geologic field studies at an appropriate scale. For this study, a DEM has been generated by digitizing available 1:25,000-scale topographic maps using 20-m vertical contour interval. These data are tied to ridge-line locations by GPS data (Fig. 7A). A surface that corresponds to the areal extent of the study area is created within GOCAD and fitted to the digitized topographic curves and point data (see Section 3.3 for discussion on surface construction) using GOCAD’s Discrete Smooth Interpolation (DSI; Mallet, 1992, 1997) to generate a smoothed surface topography, or DEM. In order to generate an accurate high-resolution DEM, detailed data processing and uncertainties should be considered (e.g., Carrara et al., 1997; Jaakkola and Oksanen, 2000; Bonin and Rousseaux, 2005). Although this method of DEM generation is relatively simplistic, it has resulted in a model appropriate for the basin-scale study; however, in areas where a higher resolution model is required, a more rigorous DEM construction technique may be more appropriate (e.g., Carrara et al., 1997; Jaakkola and Oksanen, 2000; Bonin and Rousseaux, 2005). Having generated a topographic surface, it is then possible to drape onto the surface available data such as satellite, aerial and field photography, and geological data including localities, structural data, and stratigraphic logs (Figs. 7B–7C, 8, and 9). The photographic data can be imported as voxets (2D grids) located with appropriate coordinates. Stratigraphic section data are imported into the model through the generation of pseudo-wells (Fig. 9; Borer et al., 2003; Borer, 2005; Bellian et al., 2005). The well path is defined by GPS points collected in the field during section measurement and projected onto the DEM surface. The sedimentologic data are represented in the drafted section by a curve for the grain size, and the facies are represented by different predefined colors. The sedimentologic data are digitized at a regular interval resulting in a text file with three numeric columns: thickness, grain size, and facies. The data are then imported into the model and become logs for the pseudo-well; in addition, stratigraphic markers (e.g., sequence...
Figure 9. The integration of stratigraphic data into geospatial model is achieved through the creation of pseudo-wells in model space. Stratigraphic sections obtained from field data (A) are computer drafted with grain size documented by a curved line (increasing grain size to the left) and facies represented by color (B). The section is then digitized, in this case every 25 cm, and this forms the input for the pseudo-well. The location of the pseudo-well is generated from GPS field localities, and its path is plotted onto the digital elevation model (DEM) (D). In addition to the well path, the digitized grain-size and facies information are also plotted. Colored circles indicate stratigraphic cycle tops.
boundaries) are constructed to constrain appropriate surfaces.

In order to use oriented data, such as bedding planes or paleocurrents, in a more useful way, strike/dip or plunge/azimuth are converted to a 3D unit vector that represents either the normal to bedding or the direction of the lineation (Fig. 8B; Sprague and de Kemp, 2005). This vector has the advantage of being easier to visualize and can be used as a local constraint for surface generation.

3.3. Construction of Geological Surfaces

Input data in this study include field localities, bedding data vectors, and curves that correspond to the intersection of geological surfaces (in this case, sequence boundaries) and topography. The surfaces that are generated from the input data comprise a triangulated mesh (Mallet, 1992, 1997), and the location of mesh nodes between data are interpolated using (DSI) (Mallet, 1997).

3.3.1. Structural Ribbons

A common problem in 3D model generation is that data tend to be sparse, and where there is little or no constraint, interpolation is required. It is important, however, during this interpolation, that the differentiation between data and interpretation is maintained. A useful technique to overcome this problem is to construct structural ribbons (Sprague and de Kemp, 2005), which are surfaces that are narrow in extent and are locally well constrained.

In this study, the location of structural ribbons is constrained by the intersection between a geological surface and topography (Fig. 10). The dip of the ribbon is defined either by the 3D unit vector of a data point or by a dip domain. Dip domains are defined as regions that have a similar dip and, therefore, at the resolution of the model, can be considered planar (Fig. 10B). The advantage of dip domains compared to 3D unit vectors is that variations in dip that occur below the desired model resolution (e.g., through local folding or faulting) can be filtered out, and a statistically valid mean dip and strike can be used.

3.3.2. Extrapolation of Ribbons to the Subsurface

In order to investigate the structural configuration of the Muttekopf Basin, it is useful, as in many 3D models, to extrapolate the structural ribbons beyond the well-constrained area and into the subsurface. The interpolation of surfaces beyond data constraints (i.e., out with the structural ribbons) requires some further geological input, if the surface is to be geologically realistic. As an example, in the Schlenkerkar section, the Intra-sequence 2 surface is constrained by the structural ribbons (Fig. 11A). An initial surface for the syncline is generated that corresponds to the structural ribbons, resulting in a very shallow dipping surface with a subhorizontal fold axis (Fig. 11B). However, the fold axis is derived from outcrop data (Fig. 11B) and plunges toward the east at a high angle to the fold axis of the initial scenario. Scenario 2 (Fig. 11B) is constrained by the same structural ribbon as the first scenario; however, it is constrained by extrapolating the outcrop fold axis into the subsurface. Because this second scenario incorporates more field data, it is considered to be more realistic. This example also demonstrates that a noncylindrical geometry can be incorporated into the model, such as fold axes that are noncylindrical as the plunge changes along azimuth.

During the generation of multiple surfaces, it is important to consider the generation of one surface in context of the other surfaces. In this example, the best constrained surface was generated first. Then, additional surfaces were generated using some a priori knowledge (Fig. 11)—for example: (a) the sequences are present across the basin; therefore, unconformities are not relevant; (b) packages broadly thicken toward the east; and (c) they are also influenced by a similar fold axis for which the plunge and trend are known. To ensure that surfaces follow similar trends established by the first surface, the subsequent surfaces should be based on isopach maps generated between the known surface and the new surface, or generated from copies of the original surface.

3.3.3. Uncertainty in Surface Generation

Any geological model in which surfaces are extrapolated beyond hard constraints (i.e., the structural ribbon) has inherent uncertainty. The interpolation of data should use a statistical method—for example, a least-squares fit—to generate a surface in a rigorous and reproducible fashion. This process, however, using traditional techniques such as hand contouring of depth maps or structural contour construction is exceptionally time consuming and is commonly not undertaken. In contrast, the construction of surfaces is a relatively simple process within a geospatial model and, more importantly, is not only reproducible but various interpolation algorithms can be evaluated. A further technique to address the uncertainty in the geometry of the surface is the construction of multiple scenarios that use the same constraint (e.g., structural ribbons) and have different subsurface extrapolations (e.g., Fig. 11). The creation of multiple permutations of the same surface by hand is very time consuming and is unlikely to be undertaken. In contrast, as with the interpolation, this is a relatively simple process with the geospatial model and is, therefore, more likely to be carried out.

3.4. Integration of Stratigraphic Data into the Model—Use of Geocellular Models

The purpose of generating a geocellular model is to populate the volume between surfaces in the 3D model with properties such as facies, porosity, permeability, or density. Although this stage of model generation is not always required (e.g., in a purely structurally focused research area), when addressing stratigraphic variability, it is an important consideration. The geocellular model is generated by creating a volume between two surfaces; the volume has cell dimensions that are a function of the resolution of the research question (see Section 3.1). The Muttekopf Basin model is populated with grain size and facies data to assess stratigraphic variation in response to structural activity (Borer, 2005). The population of the model cells with properties requires both hard conditioning data such as the grain size along a measured stratigraphic section or photo panel and soft conditioning that uses a probabilistic approach to determine cell properties. Hard conditioning is achieved by plotting the trace of a pseudo-well through the geocellular model and transferring the property (e.g., grain size) from the well into the cell that the well intersects.

In most models, the density of the hard conditioning is very low in comparison to the model volume; therefore, if the remainder of the volume must be populated, it is accomplished through stochastic simulations (Fig. 12). These simulations rely on incorporation of both aerial horizontal and vertical trends as derived from the hard conditioning data. In the Muttekopf Basin model, horizontal facies maps reflect changes in sedimentation in response to the magnitude of margin uplift and regional sediment supply. Such an aerial facies map would reflect (Fig. 12): (a) slope-failure-derived gravel facies that have a high probability of being present adjacent to the uplifting southern margin with the probability decreasing away from the margin; and (b) the basin axis with a high probability of being composed of sandstone facies and the margins have a higher probability of being siltstone dominated. For vertical probability data, the measured sections reveal that between the mapped surfaces there is an overall
DIP DOMAINS

Figure 10. Generation of structural ribbons. (A) Aerial photograph-draped digital elevation model with the intersect between the topography and geological surfaces (Top Pre-growth, Top Sequence 1, and Intra-sequence 2) traced. Structural data are used to define dip domains—for example, fold limb dip/strike, and stereonets are used to determine statistical average values for each domain (inset). (B) The values derived for each domain are used in conjunction with local 3D vector units to control the local attitude of the structural ribbons, which are surfaces that are extrapolated a short distance (in this case, 40 m) below and above the topography/geological surface intersect. These ribbons correspond to narrow surfaces—in this case, 80 m wide—that are well constrained. See Animation 3.

Animation 3. Generation of structural ribbons using geological contacts and structural domains. These ribbons are then interpolated into the subsurface. Two scenarios for the Top Pre-growth surface are shown that are constrained by the same structural ribbon. Scenario 1 is derived through a simple interpolation constrained by the structural ribbon. In scenario 2, the fold axis derived from outcrop data is projected into the subsurface and used to constrain the alternative surface. Using a priori knowledge, in this case that the fold axes are parallel structures at depth with little change in vertical offset, subsequent surfaces can be generated from their respective structural ribbons. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00093.S3, or the full-text article on www.gsaajournals.org to view Animation 3.

fining upwards of grain size; therefore, grain size is a function of the stratigraphic height between the two surfaces. The lowest portion of the section, therefore, has a higher probability of being gravel compared to siltstone, but this probability decreases upsection. In both the horizontal and vertical dimensions, the actual values used for defining the probability are derived from the hard-conditioned well data.

The geocellular model is then stochastically populated utilizing the known data as hard-conditioning data and the vertical proportion curves and aerial trend maps as soft conditioning. Care must, of course, be taken in the derivation of input parameters for the soft conditioning to make them as geologically realistic based upon prior knowledge. In addition, the results of the modeling must be considered in the context of where the geocellular model is well constrained (i.e., at the location of the pseudo-wells or photo panels) versus where it is probabilistically derived.
Figure 11. Extrapolation of surfaces from structural ribbons (A) to areas of less certainty. (B) Two scenarios for the Top Pre-growth surface are shown that are constrained by the same structural ribbon. Scenario 1 is derived through a simple interpolation constrained by the structural ribbon. In scenario 2, the fold axis derived from outcrop data is projected into the subsurface and used to constrain the alternative surface. Using a priori knowledge, in this case that the fold axes are parallel structures at depth with little change in vertical offset, subsequent surfaces can be generated from their respective structural ribbons (C–E).
Figure 12. Generation of geocellular model to investigate stratigraphic data within one cycle of the Schlenkerkar high-resolution surface model. (A) The stratigraphic data from sections sampled from the pseudo-wells (Fig. 9) are used as hard conditioning for the model. The cell size for a surface (B) is user defined and is dependent upon the required resolution of the model. (C) Geocellular model conforms to the surfaces and generates a volume between the surfaces, the resolution of which is determined by cell-size surface. (D) The stratigraphic hard conditioning (A) is sampled into the geocellular model. Because this corresponds to a small proportion of the model volume, grain-size and facies data are populated through the volume using conditioning data or probability data (see text for discussion). The result presented in the figure is one realization of a stochastic simulation of grain-size distribution within a cycle along the Schlenkerkar outcrop that reflects the sand-rich axis and a gravel- and silt-dominated margin. The gravels correspond to localized slope instability, while the silt corresponds to the marginal component of the sand-rich axis.
3.5. Using Geospatial Models as a Data Analysis Tool

An integrated data set becomes a tool for data analysis. The ability to quickly and easily analyze data such as contours or other formats and compare this information to the distribution of another data type is one of the strongest arguments for making the effort to integrate the data sets. The following is an example of a data analysis technique that can be employed.

3.5.1. Use of Isopach Maps to Investigate Structural Controls on Basin Fill

In a structurally controlled basin, the use of isopach maps is a powerful technique to determine where tectonically controlled accommodation space was being created, because sediment thickness variation can be used as a proxy for fault displacement. This technique is commonly applied to subsurface studies (e.g., Schlishe and Anders, 1996; McLeod et al., 2000; Paton, 2006); however, it has not generally been used for field studies because it can require the generation of a 3D geospatial model. In the Muttekopf Basin, the isopach maps are used as a proxy for accommodation space on the assumption that sedimentation rate is broadly equivalent to tectonic subsidence for the studied interval. The isopach maps are generated by calculating the true stratigraphic thickness between two surfaces using vectors normal to the surface (Fig. 13) and can reveal both the temporal and spatial evolution of the basin fill.

3.5.2. Temporal Variations in Basin-Fill Evolution

The evolution of the basin fill at the Schlenkerkar section comprises three distinct episodes. These episodes are evident from the 2D section (Fig. 14); however, the limitations of section projection significantly inhibit our understanding of the variations in basin fill. In contrast, the generation of isopach maps from the 3D model is more revealing. Sequence 1 has a relatively uniform thickness, although there is a thinning toward the southern margins. The depositional bodies have a sheet-like geometry and are continuous with little variation in facies or bed thickness across the basin. This applies both to the conglomerates and interbedded heterolithic turbidite components of the basin fill. During the deposition of Sequence 2, therefore, the basin was moderately broad with only limited differential subsidence between the margins and axis. Although of a relatively small magnitude, the southern margin has the greater influence on basin fill compared to the northern margin. In contrast to this relatively uniform thickness distribution, the isopach map of Sequence 2 demonstrates significant thickness variation and most noticeably a prominent depositional axis (≈450 m thickness) in the center of the section. The unit thins onto both northern and southern margins, although it is most pronounced on the former (thickness of <50 m compared to ~150 m). The thickness variation demonstrated in the isopach maps is most evident in the heterolithic turbidite units with relatively constant thickness of conglomerates. In addition, the thinning observed onto the northern margin corresponds to a stratigraphic thinning of the package, while the thinning in the south reflects onlap of strata onto the southern margin. This observation reflects an overall increase in accommodation space during the deposition of Sequence 2B, which is principally being controlled by the structure on the southern margin, as demonstrated by the onlap geometry. During the deposition of Sequence 3, the depositional axis increases significantly in width with a much less pronounced channel axis. The thinning observed is approximately equivalent on both margins and corresponds to a stratigraphic thinning rather than onlap. This reflects a less tectonically dominant southern margin.

The isopach maps, in particular, when integrated with sedimentological data, provide a valuable tool for understanding basin-fill evolution and elucidating variations in sediment accumulation. As the next section will illustrate, isopach maps are also useful for investigating spatial variations of basin fill.

3.5.3. Spatial Variations of Basin Fill

The spatial variation of basin fill and its association with the nature and position of the controlling southern margin structure can be investigated—in particular, the change from a fold to a fault domain (west to east) along the basin axis. In addition to generating isopach maps (Fig. 15B), the geological surfaces can also be restored to a horizontal datum to reflect the geometry of the basin fill at the time of deposition (Fig. 15C). This restoration uses a strain-minimization–based, map-surface restoration algorithm (Mallet, 2002).

In the west of the basin, the dominant structural style is a fold that uplifts and deforms the southern margin. The position of the basin axis is controlled by the fold, and there is little faulting of the basin fill; instead, the stratigraphic geometry is characterized by folding, progressive onlap, and thinning onto the margin. Furthermore, there is a very uniform thickness of ~450 m along the trend of the margin (Fig. 15B-I). The principal basin axis continues to the west into the Muttekopf area (Fig. 15B-II) and has a relatively consistent thickness of ~450 m, although the basin does become wider toward the northeast. The largest variation between Schlenkerkar and Muttekopf occurs along the southern margin. In contrast to the relatively narrow and folded southern margin in Schlenkerkar, at Muttekopf the basin has a significantly greater areal extent to the south (Fig. 15B-II) and is controlled by thrust faults. Two thrust faults are evident in the Muttekopf area—fault 1 is within the basin and forms an intrabasin, while fault 2 defines the southern extent of the basin fill. The intrabasin high only has ~30 m of sediment deposited onto it and defines the northern margin of subbasin that is not present at Schlenkerkar. The intrabasin high and corresponding thrust influences basin fill in two ways. First, because the dominant sediment transport direction is from the west, the principal Muttekopf Basin is a direct, along-basin continuation of the Schlenkerkar section, and correlation of sedimentary bodies between the two areas is possible. In contrast, the presence of the intrabasin high results in noncorrelative sedimentary bodies within the subbasin. Second, the fault that forms the intrabasin was active at the surface during deposition and results in thinning of sand bodies onto the high (Fig. 15C-II), subsequent displacement on the fault, significant local fracturing, and discontinuous beds (Fig. 15D-II).

4. DISCUSSION: A COMPARISON OF TRADITIONAL TECHNIQUES VERSUS GEOSPATIAL MODELS

A comparison of input data, techniques and model results between traditional methods (Section 2.3), and geospatial modeling is insightful (Table 2). In summary, although the gross-scale observations and conclusions can be the same using both techniques, and block diagrams (Fig. 16) can often prove to be very illustrative, there is an additional quantitative result gained from geospatial modeling rather than just the qualitative results of traditional methods.

The comparison can be considered in two categories (Table 2). The first contains processes that can be undertaken using traditional techniques, which are, however, generally so time consuming that they are commonly not undertaken. The second category consists of processes that could not be undertaken using traditional techniques. It is important to stress that the use of this geospatial technique does not require the collection of any data that would not normally be collected during a “traditional” field study; it is the method of integrating, visualizing, and analyzing the data that differs.

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4.1 Improvements of Traditional Analysis Techniques Using Geospatial Models

A number of limitations in the analysis of Alpine-scale terrains using traditional techniques were outlined in Section 2.3 (Table 1). Many of these limitations are overcome when the same input data are considered within the context of a 3D geospatial model, and the principal benefits of geospatial models are discussed in the following sections.

4.1.1. Cross Section Generation

Traditionally cross sections can be generated in two main ways. Sections can be joined by a zigzagging line that connects the data points, or alternatively, data can be projected into a straight dip or strike line. Both of these techniques may produce incorrect or deceptive surface geometry and require assumptions for the projection. For example, given the stratigraphic sections in the Schlenkerkar section (Fig. 17), it is difficult to represent appropriately the complex surface geometry and section orientations within a traditional 2D cross section. This problem can be overcome because cross sections taken as vertical slices through the model
Figure 14. The perspective of the field view of the Schlenkerkar section prevents a full investigation of the growth of the fold on the southern margin of the basin (A); however, isopach maps (Fig. 13) are a useful derivative of the 3D geospatial model. The evolution of the section consists of three tectonic episodes that have a significant influence on sediment thickness and distribution: (1) little basin confinement with slight thinning onto the basin margin; (2) relative uplift of the southern margin reflected in onlap of strata onto a tilted surface and thinning of the sequence toward the south (the basin axis is well defined); and (3) migration toward the north and widening of the basin axis accompanied with little facies variation across the section.
do not require data projection (e.g., Fig. 17). In the Muttekopf area of the basin, a specific limitation is that panoramic field views (e.g., Fig. 2C) cannot illustrate the interaction of the principal basin, the intrabasin thrust faults, and the southern subbasin. Although a cross section could be generated, it would require significant projections of data onto the line of section. In contrast, a slice through the 3D volume readily demonstrates this complex relationship and can be used to investigate the interaction of basin fill with structural configuration (Fig. 15).

4.1.2. Noncylindrical Nature of Structures

In many settings, geological features such as surfaces and fold axes are commonly noncylindrical. Using traditional techniques, trend-plunge variations would be used to define an irregular grid in present-day map view, and then cross sections would be constructed for each portion of the grid, resulting in a slow and time-consuming process. In the geospatial model, assuming that the noncylindrical geometry has been used to constrain the surfaces, the geometry will be evident within the appropriate 2D slice of the 3D volume. An example of this is the fold axis in the Schlenkerkar that was used to construct the surfaces within the model. Outcrop data were used to define the change in fold axis along its trend, and this was used to constrain the surface locally.

4.1.3. Map and Isopach Generation

Isopach map generation is a powerful tool both during surface construction and in the analysis of the basin evolution (Figs. 14 and 15). Using a similar process to that of surface
Figure 15 (continued). Through flexural slip restoration of the surfaces, the syndepositional geometry of both domains can be obtained (C). The results of the 3D modeling can explain the variations in strata geometry and basin fill that are observed between the two domains (D). See Animations 4 and 5.

Animation 4. Final 3D model of the Muttekopf Basin that illustrates the along-trend variation in basin configuration. The model from which these images are taken is included as Animation 5 in the 3D interactive model. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00093.S4, or the full-text article on www.gsaajournals.org to view Animation 4.

Animation 5. This 3D surface model consists of the three basin-scale surfaces that have been constructed (Top Pre-growth, Top Sequence 1, and Intra-sequence 2). The default view of the model is from above, although views from the west and east and cross-section view that illustrate the fold and thrust domains have been defined. This model illustrates the lateral change in basin configuration from fold domain in the west to a fault domain in the east. It enables the user to interact with the model, including model rotation and zooming when viewed through Acrobat 7. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00093.S5, or the full-text article on www.gsaajournals.org to view Animation 5.
generation, the traditional technique of generating isopach maps requires hand contouring, etc., and has the same problem of statistical reproducibility and determining uncertainty (Section 3.3); as discussed earlier, these problems are less of an issue within the geospatial model. In addition, if the isopach maps are to be used in an iterative fashion to help generate additional surfaces in areas with little constraint, this can become very time consuming using traditional techniques. In contrast, these processes can be undertaken with relative ease within the geospatial model, and, as with surface generation (Section 3.3), multiple scenarios can be constructed and tested. As discussed in Section 3.5, the integration of isopach maps with field data is a powerful technique for understanding the interaction of structures and sedimentology in settings similar to the Muttekopf Basin (Figs. 14 and 15). In this example, understanding the geometry of the sand-body pinch out is difficult with traditional mapping, whereas the 3D geometry of the pinch out can be established, and its implications within a basin context can be investigated using isopach maps.

4.2 New Techniques Only Achievable through Geospatial Models

There are numerous analytical techniques that could not be undertaken using traditional data analysis. This contribution has highlighted a few of these techniques, in particular the use of geocellular modeling, in which the property of one cell (where there is no hard conditioning) is soft conditioned through the probabilistic input parameters of the surrounding cells. Such modeling becomes even more useful when considered with a multivariate analysis context—for example, if the facies distribution maps (Fig. 12) were correlated with isopach thickness of the same sequence (Fig. 14). The results of such modeling can then form the basis of quantitative analysis—for example, the results of the multivariate analysis of facies and isopach maps could be used to determine the net-to-gross ratio of sand within a sedimentary unit as a function of bed thickness.

In addition, the derived 3D model, whether it is a surface model or geocellular model, can also be used as the input model for further basin analysis including structural reconstructions or hydrocarbon/hydrological fluid-flow modeling. An example of this is the use of the surfaces and isopach maps derived for Sequence 2b that are restored to their syndepositional geometry (Fig. 15C), which results in a better understanding of the structural control on the sedimentology of the basin fill (see Section 3.5).

5. CONCLUSIONS

Understanding the spatial and temporal variations in complex geological settings in mountainous Alpine settings has many problems, including inaccessible outcrops, photopanel mapping from non-ideal perspectives, difficulty in tracing geological boundaries between valley outcrops, etc. These problems have been illustrated in the Upper Cretaceous Muttekopf Basin, Austria. Although a qualitative analysis of the basin, and variations in its configuration, can be achieved through traditional cross-section construction and illustrative block diagrams, it is difficult, if not impossible, to use those techniques to analyze such settings in a quantitative way. We have illustrated the development of a robust, reproducible, and correctly spatially oriented geological model based on “traditional” field data. This process is significantly more time efficient than is possible using traditional analytical techniques and yet does not require advanced digital technology such as lidar or differential GPS. Three-dimensional geospatial models can also provide significant additional benefits that are not possible with traditional techniques, including an assessment of model uncertainty, true integration of diverse data sets through geocellular model construction, the ability to calculate multivariate statistics, and creation of models for additional modeling procedures, such as volume-conserved structural reconstructions and fluid-flow simulations.

In the introduction to this contribution we posed the question, can the application of digital technology and CAGD advance our understanding of basin-scale problems in mountainous terrains? We conclude that not only is the answer a resounding yes, but that the application of the new techniques associated with geospatial models, in particular to Alpine-scale geological complex settings, enables us to address old problems with new insights.

ACKNOWLEDGMENTS

This project is funded as part of the Chevron Center of Research Excellence’s “Structural controls on deepwater sedimentary systems” project. We would like to thank the following for discussions, support, and assistance in collecting field data: Jim Borger, David Pyles, Rob Amerman, Grace Ford, Estelle Mortimer, Piter Plink-Bjorklund, Martin Ritter, and Richard Wild. We would also like to thank Earth Decisions for releasing the GOCAD license and Frank Harris and Charlie Rourke for their continuing support of the project. We also thank Enrico Tavarnelli, an anonymous reviewer, and Jonny Imber for their constructive comments.
Figure 16. The use of block diagrams to convey variations in basin configuration is a very powerful tool (A); however, there are significant limitations such as a lack of a true geospatial positioning or absence of quantitative and reproducible result. Depending upon the research question that is being addressed, a more robust, testable and well-constrained result is obtained when the same field data are considered within a 3D geospatial model (B).

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Figure 17. One of the primary limitations of using traditional analytical techniques in complex mountainous study areas is the non-parallel projection of data. (A) First-order traditional approach limitation of using photo panels for projecting data and stratigraphic section. (B) View of the 3D model with the same perspective as the field photograph in (A); yellow surface corresponds to a vertical plane aligned along the top of the ridge. (C) Oblique view of the 3D model. See Animation 6.

Animation 6. Demonstration of the 3D nature of the Schlenkerkar section and the limitation of using a simple projection onto a 2D plane. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00093.S6, or the full-text article on www.gsaajournals.org to view Animation 6.