

## Austria: New Insights from 3D Seismic Data

## Deep Marine Sedimentation and Gas Reservoir Distribution in Upper Austria

By M. J. DE RUIG\*

**A**bstract

The Oligo-Miocene deepwater foreland deposits of the Puchkirchen and basal Hall Formations contain the main gas reservoirs of Upper Austria. Due to recent acquisition and post-stack merging of 3D seismic surveys, RAG now has nearly continuous 3D seismic coverage over large areas of the Upper Austrian Molasse Basin. This has allowed new insight into the deepwater depositional processes and reservoir distribution within the Puchkirchen Trough.

Regional 3D seismic attribute maps, calibrated by nearly 200 wells, reveal that the Puchkirchen and Base Hall clastic reservoirs are associated with a deep marine, axial channel belt that runs approximately parallel to the Alpine thrust front. The channel belt is 3–5 km wide and of low sinuosity. The channel fill consists predominantly of coarse-grained conglomeratic debris flow and turbidite deposits, whereas overbank areas are characterised by fine-grained turbidite sands. Different architectural elements, such as channel thalweg, levee/ overbank, crevasse splays, tributary channels and slope fan deposits, as well as large-scale slumps and olistolith fields can be recognised on seismic and compared to depositional facies and reservoir quality in core and wireline log data.

The 3D seismic architectural element analysis provides a framework for reservoir prediction in both producing gas fields as well as undrilled exploration targets. Further calibration by core studies and the integration of production data will provide a useful tool to characterise reservoir architecture and production performance in the various deepwater facies.

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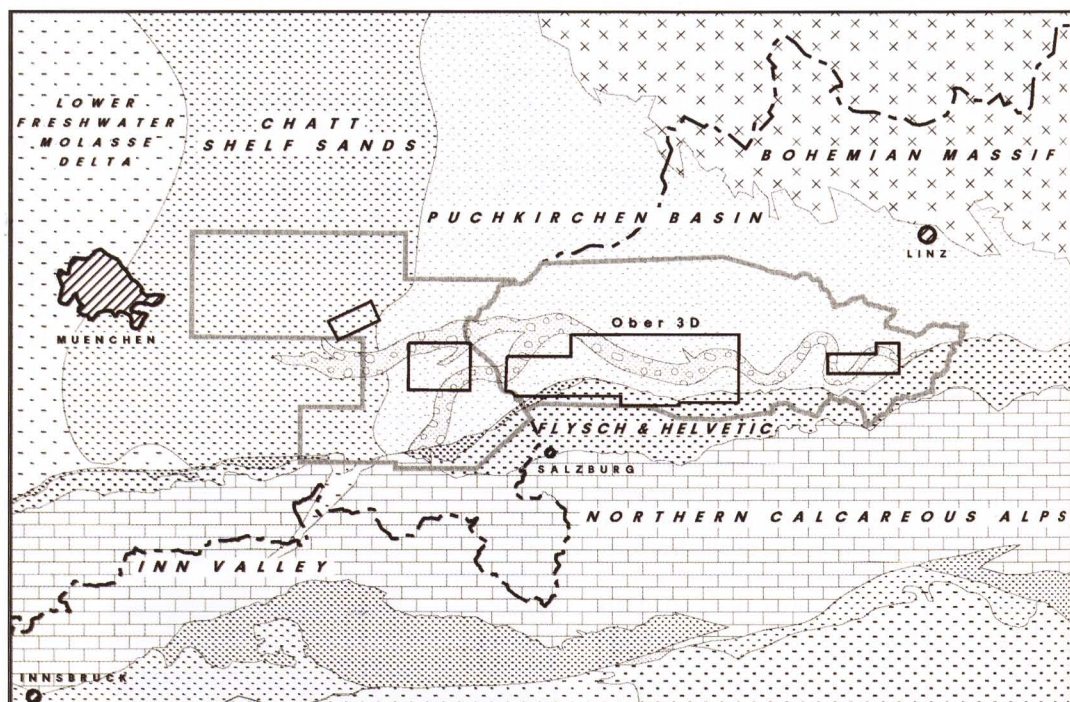


Fig. 1 Map of the Upper Austrian Molasse, showing the location of the main Oligocene paleogeographic zones, the Puchkirchen channel belt and the Ober 3D seismic survey area

**1** Introduction

Oil and gas exploration in the Upper Austrian Molasse Basin has been ongoing since 1956, when the Puchkirchen-1 exploration well struck oil in Upper Eocene sandstones. Since the late 1960's, industry focus has been on gas production, and more than 40 gas fields have so far been discovered in the area between Linz and Salzburg (Fig. 1). The majority of these gas fields are reservoirised in the Oligo-Miocene sandstones and conglomerates of the Puchkirchen and Hall Formations. Although the Upper Austrian Molasse Basin is a mature basin, with close to 700 wells drilled so far, new gas fields are still being found. During the past 10 years, Rohöl-Aufsuchungs A.G. (RAG) has sustained a continuing 3D seismic acquisition campaign with the aim of securing continued exploration success and enhancing gas recovery from existing fields. This made possible the discovery of the Haidach gas field in 1997, which is the largest gas field in Upper Austria to date. More recently, the merging together of several separate 3D seismic sur-

veys has for the first time allowed 3D seismic imaging of the Upper Austrian Molasse on a regional scale. This has allowed new insight into the reservoir distribution and geological processes responsible for clastic reservoirs within the Puchkirchen Basin. Based on regional 3D seismic attributes and architectural element analysis, a new geological model has been developed that provides a framework for improved reservoir prediction in both producing gas fields and undrilled exploration targets.

**2** Geological Setting

The Upper Austrian Molasse Basin forms part of the North Alpine Foreland Basin, which extends to the west into Bavaria and Switzerland, and east into the Carpathian foredeep. The Austrian Molasse Basin is a classical asymmetric foredeep, bordered in the north by the Bohemian Massif and in the south by the main overthrust of the Alpine orogenic front (Figs. 1, 2). It is filled with predominantly clastic sediments of

Tertiary age, reaching a thickness of up to 4500 m in front of the Alps. Tertiary Molasse deposits are known from seismic and well data to dip to the south and to extend up to 40 km underneath the Alpine nappes [1].

The general depositional history and tectonic evolution of the Tertiary Molasse Basin in

Upper Austria and Bavaria is well documented [2, 3, 4, 5]. The Molasse Basin was formed as a result of the collision between the Apulian continental microplate and the North European craton [6, 7]. During the latest Eocene and Early Oligocene, thrust loading by the advancing Alpine nappes caused flexural downbending of the European margin, resulting in a rapid deepening of the Molasse Basin [8]. Flexure of the foreland crust was accompanied by the development of a dense network of tensional faults and the reactivation of older fault systems. After an initial stage of deep marine sediment-starved basin conditions, clastic detritus from the rising Alps started to fill the Molasse Basin from mid Oligocene time onwards. In Bavaria, a thick succession of shallow marine and deltaic sediments developed (Lower Freshwater Molasse), whereas deep marine conditions persisted in Upper Austria until Early Miocene time.

The deep marine trough in Upper Austria is known as the Puchkirchen Basin, which is characterized by a thick succession of gravity flow deposits, comprising the Oligocene-Early Miocene Puchkirchen Formation and the basal parts of the Miocene Hall Formation. These deposits represent a time interval of roughly 10 million years (ca. 28 to 18 Ma). Sediments of the Puchkirchen Formation were first recognised as deep-water deposits in the late 1970s, based on paleontological and sedimentological data [9, 10]. Water depth of the basin is considered to have been in the order of 1000 to 1500 m based on foraminiferal assemblages [11, 12]. Total thickness of the turbiditic formations reaches up to 2000 m locally.

The Oligocene-Early Miocene geometry of the Puchkirchen Basin is characterized by a deep basin axis close to the front of the Alps, a steep and tectonically active slope in the south, and a wide, stable slope in the north (Fig. 2). The northern margin of the Puchkirchen Basin onlaps the crystalline basement of the Bohemian Massif. Between the northern basin margin and the Puchkirchen clastic belt lies the 30 to 50 km wide Northern Slope, a stable, relatively gentle submarine slope that is almost entirely mud-prone. The southern margin of the

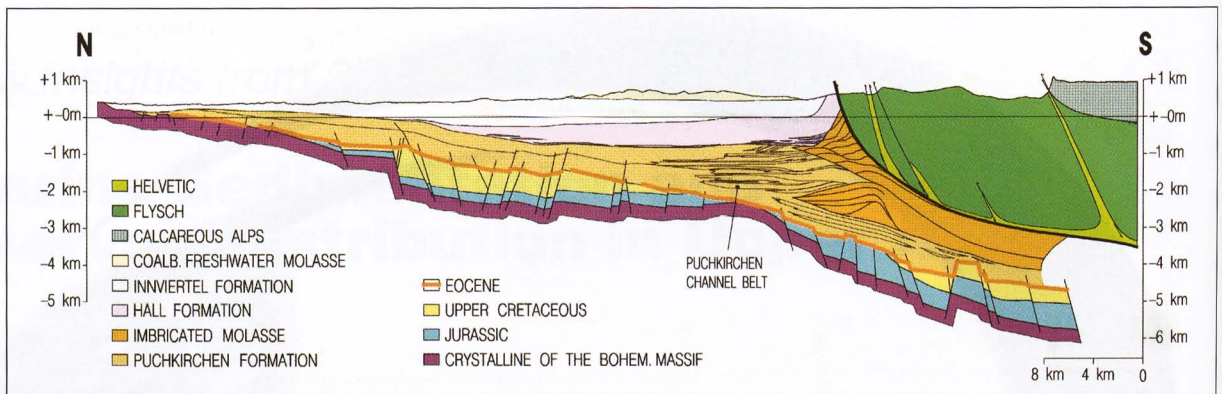


Fig. 2 Regional Geological Cross Section of the Upper Austrian Molasse Basin (modified after Kollmann, Wagner & Zimmer, 1987).

Puchkirchen Basin is a steep, tectonically active slope that is bounded in the south by the thrust complexes of the Helvetic Zone, the Rhenodanubian Flysch and the Northern Calcareous Alps. Sections of the Puchkirchen foreland deposits have been incorporated in the Alpine thrust wedge and form an imbricated stack of thrust sheets along the southern basin margin, known as the Imbricated Molasse.

### 3 Stratigraphy and Depositional Facies

The stratigraphy of the Puchkirchen Basin has traditionally been subdivided into four stratigraphic units; these are the Rupelian Sands, the Lower and Upper Puchkirchen Formation and the basal Hall Formation. The Rupelian Sandstones represent the first coarse clastic influx in the deep marine Puchkirchen Basin, and generally consist of fine to medium-grained sandstones separated by thicker mudstone intervals. The largest part of the Rupelian deposits have been subsequently overthrust by the advancing Alpine thrust sheets, and have not been studied in detail. The Lower Puchkirchen Formation is of Chattian age and is traditionally only subdivided in a Sand-Gravel Group (»Sand-Schotter Gruppe«), which overlies the mudstones of the »Liegende Tonmergel« and is locally overlain by the »Hangende Tonmergel«. The Upper Puchkirchen Formation is of Aquitanian age and is separated from the Lower Puchkirchen by a semi-regional erosional unconformity. On the basis of seismic and log correlation, the Upper Puchkirchen is subdivided into four units (Upper Puchkirchen A1 to A4). The basal Hall Formation unconformably overlies the Upper Puchkirchen Formation, and contains channelised deepwater deposits similar to the Puchkirchen Formation. The upper part of the Hall Formation consists of northward prograding, muddy prodelta deposits, which do not form part of the Puchkirchen turbidite system.

The deposits of the Puchkirchen Basin contain a wide range of clastic lithologies, ranging from clast-supported sandy conglomerates, muddy matrix-supported conglomerates, massive and pebbly sandstones to

fine-grained sandstones and siltstones. These sediments were deposited by a variety of gravity flow processes, such as turbidity currents, debris flows, submarine slides and slumps. The lithofacies units are commonly organised in stacked fining and thinning-upward sequences, varying in thickness from cm-scale to more than 20 m.

The gravel in the Puchkirchen conglomerates has a mature composition, with well-rounded pebbles consisting of a wide range of durable lithologies such as gneiss, granite, phyllite, quartzite, quartz, chert, dark grey and brown dolomites and limestones. Most of this material is derived from the Central Alps to the southwest of the Puchkirchen Basin [1, 13]. The coarse clastic deposits occur only in an elongate, ca. 15 km wide belt directly in front of the Alpine overthrust. Further north, the deposits of the Austrian Molasse Basin are dominated by marly claystones (»tonmergel«) and siltstones.

The accepted depositional model for the Puchkirchen clastics is that of a series of lobate submarine fans which were fed by erosion of the advancing Alpine thrust front [9, 14]. In this model, clastic sediment was fed into the deep marine Puchkirchen trough by a series of intramontane streams cutting through the narrow, tectonically unstable southern shelf. The sediments accumulated in front of the thrust front, where various submarine fans overlapped to form a belt of amalgamated turbidite fans, locally disturbed by slumps and submarine slides from both the southern and northern slopes. Sediment supply was thought to be predominately from south to north, although sediment reworking by an axial deepwater bottom current was postulated by Wagner [1, 5]. In a seismic stratigraphy study based on 2D seismic, Robinson and Zimmer [12] recognised that part of the submarine fan complex was channelised, and they interpreted these channel geometries as proximal feeder channels of the fan complex.

With the advent of 3D seismic in the past 10 years, it has become increasingly clear that the turbidite fan lobe model of the Puchkirchen system is inaccurate. Recent work by Linzer [15] has shown that the

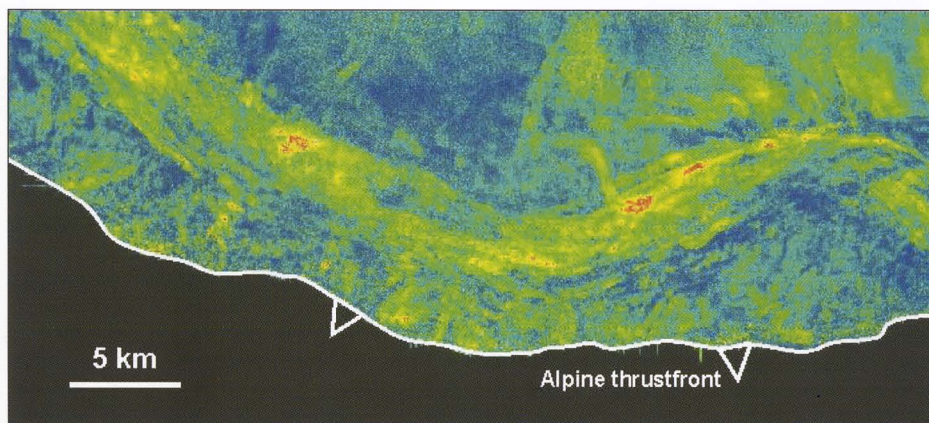


Fig. 3 Example of an RMS seismic amplitude map at the level of the Upper Puchkirchen A2 unit. Note the west-east trending high amplitude channel belt with small tributary channel (centre) and crevasse splay or overbank lobes on the outer bend of the main channel (top right).

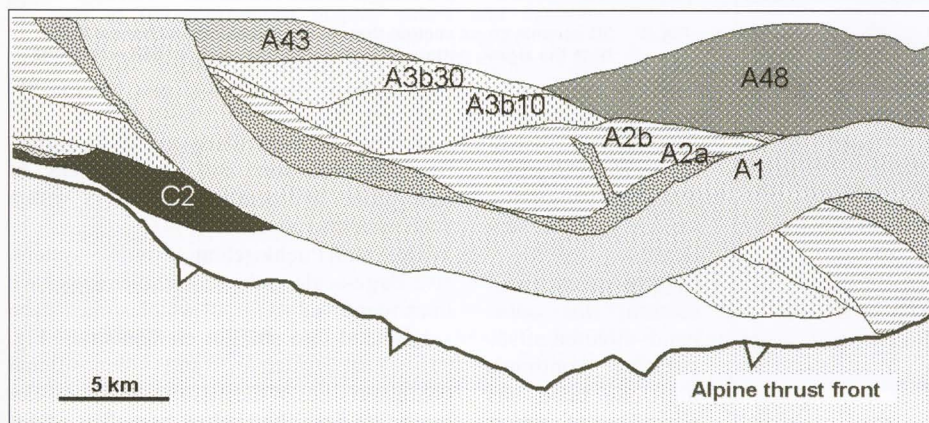


Fig. 4 Superposed outlines of the Puchkirchen channel belt at successive stratigraphic levels, from the Lower Puchkirchen Formation at the base to the Upper Puchkirchen A1 unit at the top. Numbers denote successive stratigraphic levels.

Puchkirchen system is characterized by a broad, roughly west-east trending, axial channel complex (Fig. 3). There is no evidence for the lobe geometries of the 'classical' turbidite fan model sensu Walker [16]. This new insight has important implications for the reservoir distribution in the Puchkirchen gas province, and provides a valuable contribution to the geological understanding of deepwater deposits in foreland basins.

#### 4 Database and Methodology

The study area is covered by six separate seismic surveys that have been acquired between 1992 and 2000. The data were acquired in a N-S direction on 480 channels with a sweep of 14–102 Hz. Nominal fold is 12 and bin size 25 m. In 2001, the six surveys have been combined by a post-stack merge into a single regional 3D seismic volume, the Ober 3D survey, which covers more than 900 km<sup>2</sup> (see Fig. 1 for location). All the seismic mapping for this study was performed on the Ober 3D time migrated seismic volume. A separate coherency filtered 3D volume was also produced, which highlights discontinuities such as faults and sedimentary features in uninterpreted 3D data by using a correlation coefficient

that expresses the (dis)similarity of adjacent seismic traces.

Due to the strong lateral variations in lithology, only the top and base of the Puchkirchen sequence form regionally continuous seismic markers (Top Eocene Lithothamnium Limestone and Base Hall Formation Unconformity, respectively). In order to study the regional lithology distribution within the Puchkirchen sequence, eight structurally conformable horizons were mapped throughout the survey area to guide the seismic attribute mapping. Various seismic attributes, such as amplitude and frequency, were then extracted from successive 40 millisecond time windows (ca. 60–70 m of stratigraphy) above and below each regional horizon. The most useful seismic attributes for regional stratigraphic information in the Puchkirchen system are the Root Mean Square (RMS) of amplitude and the RMS of coherency.

There are nearly 200 wells within the Ober 3D survey area, of which 76 wells penetrate the entire Puchkirchen sequence. All the wells have at least a basic set of wireline log data (Gamma Ray or SP, Sonic and Resistivity) and many have dipmeter or borehole imaging data over key intervals. Furthermore, a total of approximately 1500 m of conventional core is available from a variety of

lithofacies in the Puchkirchen and Base Hall Formations, allowing a direct correlation between seismic facies and sedimentary facies.

#### 5 Seismic Stratigraphy of the Puchkirchen Depositional System

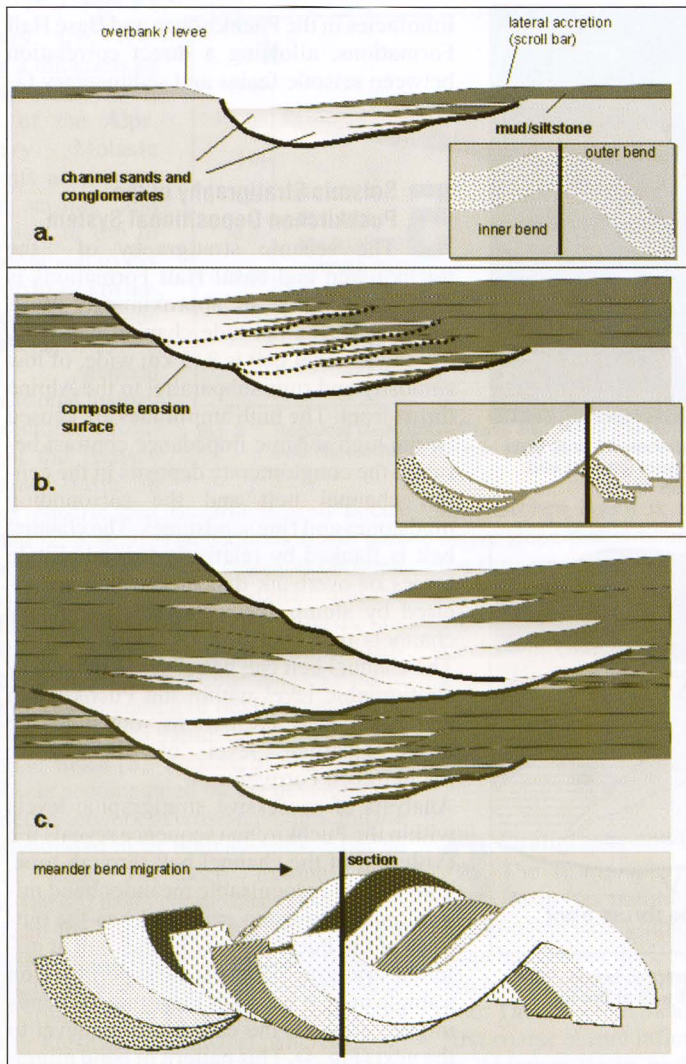
The seismic stratigraphy of the Puchkirchen and basal Hall Formations is characterized by an approximately W-E trending high amplitude channel belt (Fig. 3). The channel belt is 3–5 km wide, of low sinuosity and runs subparallel to the Alpine thrust front. The high amplitudes are caused by the high seismic impedance contrast between the conglomerate deposits in the central channel belt and the surrounding mudstones and fine sandstones. The channel belt is flanked by relatively low amplitude levees or overbank deposits, which are incised by slump scars and small tributary channels that feed into the main channel. The channel belt can be recognised at every stratigraphic level within the Puchkirchen and basal Hall Formations, down to the Early Chattian level of the Lower Puchkirchen Formation.

Analysis of successive stratigraphic levels within the Puchkirchen sequence reveals the evolution of the channel belt through time, with clearly recognisable meander bend migration and avulsion events. When the outlines of the Puchkirchen channel belt at different stratigraphic levels are superposed on a single map, it becomes clear that the bends migrate towards the east from one level to the next (Fig. 4). This pattern of bend migration in the Puchkirchen channel belt occurs without significant increase in bend size or curvature. Similar bend migration patterns can be observed in confined fluvial systems, where previous topography prevents further bend growth [17]. Bend migration normally occurs in a downstream direction [18], suggesting that the main sediment transport direction in the Puchkirchen channel belt was from west to east.

From the base to the top of the Puchkirchen Formation there is a modest but distinct trend towards greater sinuosity. The oldest channel levels in the Lower Puchkirchen Formation are relatively straight and broad (5–6 km) compared to the younger channel levels in the Upper Puchkirchen Formation (3–4 km). The increased sinuosity towards top of sequence is correlatable with a slight overall decrease in grain size and increase in mud content; the topmost Upper Puchkirchen A1 Unit and the basal Hall Formation are characterized by a very high mud content and the absence of coarse conglomerate deposits.

#### 6 Channel Margin Asymmetry and Bend Migration

In cross-section, the Puchkirchen channel system shows a distinct asymmetry



**Fig. 5** Depositional model for the asymmetry between the inner and outer bend of the Puchkirchen channel (a), the offset stacking with outer bend erosion (b), and the zigzag stacking pattern resulting from meander bend migration (c).

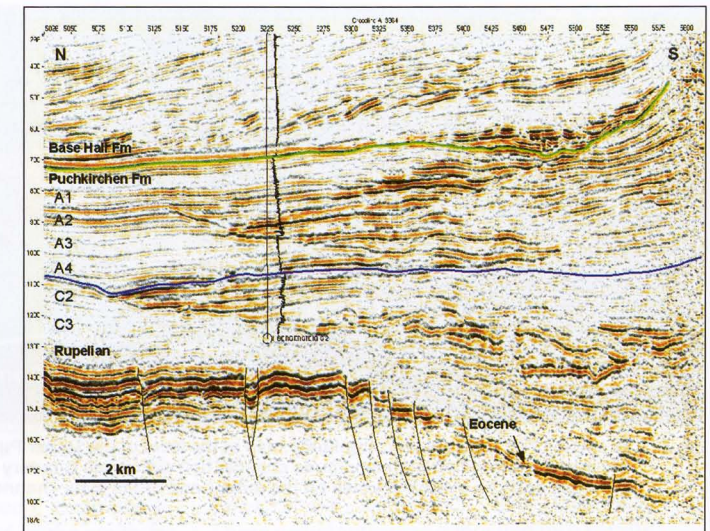
between inner bend and outer bend geometry, not unlike fluvial channel systems. The outer bend typically shows a steep, erosional channel margin with an abrupt transition between the coarse clastic deposits within the channel and the mudstone-dominated levee deposits (Fig. 5a). The inner bend generally has a much gentler gradient and is only weakly erosive or constructional. From the inner bend levee towards the channel axis, there is a more gradational grain-size transition from mudstone/siltstone to sands and conglomerates.

Successive channel fills show a pattern of lateral offset stacking, which is the product of vertical aggradation and bend migration (Fig. 5b). The erosive outer bend migrates further outward, thereby eroding older levee and overbank deposits. Simultaneously, the inner bend of the channel migrates by lateral accretion of relatively fine-grained sands and mud. As sediment accumulates by successive channel cut and fill events, an inclined composite erosion surface is formed along the outer bend of the channel system. In the inner bend, a stack of lateral accretion

and the channel margin asymmetry switch sides. The outer bend now starts eroding the lateral accretion deposits of the previous inner bend, and the inner bend starts building up sediment at the previously erosive outer bend. This process of channel aggradation and bend migration results in the typical zig-zag pattern that is seen in most seismic cross-section through the Puchkirchen channel belt (Fig. 5c, 6).

## 7 Architectural Element Analysis

The Puchkirchen channel belt can be subdivided into various components or »architectural elements« on the basis of their seismic character and their associated sedimentary facies. The concept of architectural elements is borrowed from fluvial sedimentology and was introduced to describe turbidite systems by Mutti and Normark [19]. Architectural elements are mainly large-scale features, such as channels, overbank deposits and lobes. Architectural element analysis attempts to link these various elements of a turbidite system to depositional processes,



**Fig. 6** 3D seismic cross section through the Puchkirchen channel belt. Note the zigzag pattern of high amplitude channel belt reflections

deposits or scroll bars is formed, punctuated by low-angle, weakly erosive surfaces.

In any given cross section, this outer bend-directed offset stacking continues until the bend has moved out of section due to downstream migration, or more abruptly when the channel changes course due to avulsion. At this stage in the vertical stacking pattern, both the offset stacking direction

which can be particularly useful in evaluating the location and development of sand-prone hydrocarbon reservoirs within such systems [20, 21].

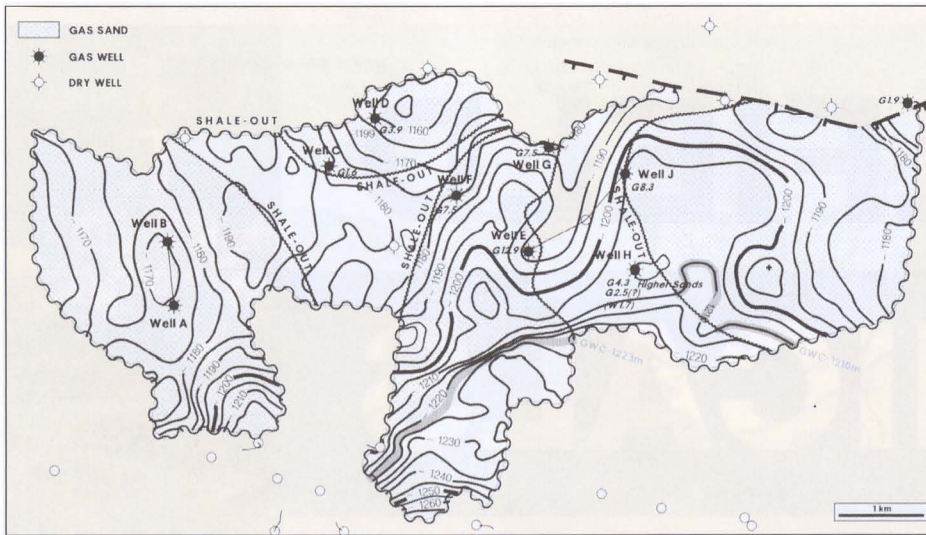
Within the Puchkirchen turbidite system, five large-scale architectural elements have been identified so far, of which some can be subdivided into smaller elements (see Fig. 7). The seismic and depositional characteristics of the main architectural elements are described below, as well as a brief qualitative description of the associated hydrocarbon reservoirs.

### 7.1 Channel belt facies

The central channel belt is generally characterized by high amplitude, high continuity seismic facies with a smooth, channelised appearance on amplitude and coherency maps. In cross section, the high amplitude channel reflections are subparallel, or show a broad, flat-bottomed channel geometry. The central channel belt probably does not represent a single, 3–5 km wide channel, but is the product of lateral amalgamation of multiple smaller channels. Within the central part of the broader channel belt, linear or arcuate terrace incisions can often be distinguished oblique or subparallel to the channel margins, suggestive of multiple channel cut-and-fill events. Locally, smaller meandering channels of up to 1 km wide can be recognised in the central axis of the channel belt (»channel thalweg«).

At most stratigraphic levels within the Puchkirchen channel belt, the smooth, high amplitude seismic character central of the channel belt is locally disrupted by irregularly shaped bodies with a chaotic appearance, highly variable amplitude and an uneven top surface. These bodies are often associated with high amplitude »blobs« of several tens to hundreds of meters in diameter. Well penetrations indicate that these high amplitude blobs correspond to olistoliths, which are rafted blocks of sandstone or





**Fig. 9** Contoured depth map of the Zell am Pettenfirst (Zapf) Gas Field (after Kreczy & Smuk 1997), with thin turbidite sheet sand reservoirs that have been deposited as overbank or crevasse lobes on the outer bend of the main channel.

**7.4 Slope fans**

Slope fans occur exclusively on the southern slope, directly in front of the Alpine thrust front or in piggy-back basins within the Imbricated Molasse Zone. They are seismically recognised as high amplitude lobes or aprons that are detached from the main channel system. They are relatively rare and areally limited in size (typically less than 5 km<sup>2</sup> to less than 1 km<sup>2</sup>). Seismic amplitude within these slope fans is unfortunately not a good indicator of reservoir presence. The prime example of a slope fan is the Haidach Field (Fig. 10), discovered in 1997 and to date the largest field in Upper Austria. The Haidach Field consists of a fan-shaped, northward dipping sand body that is sealed in the south by the Alpine thrusts. The reservoir consists of a 70–180 m thick sequence of stacked medium-coarse grained sandstone beds and breccias. The sandstones are very poorly sorted and consist entirely of re-worked Eocene sands and carbonates from the Helvetic Zone. The typical Central Al-

pine detritus of the Puchkirchen deposits is absent in the Haidach Field, indicating a local sediment source area directly to the south of the field. Due to the grain size and low mud content, the Haidach reservoir has exceptionally high permeability. Although the Haidach Field is an exceptional example, it does show several of the characteristics of slope fan reservoirs in the Puchkirchen Basin. They consist of thick, amalgamated sandstone beds with relatively few mudstone intervals. Because the slope fan sandstone bodies are encased in slope mudstone, and lack a connection to the main channel system, aquifer support is limited or absent. The vertical stacking of sandstone beds is likely to be the result of the rapid infilling of local accommodation space on the southern slope, such a slump scars or slope gullies.

**7.5 Megaslides**

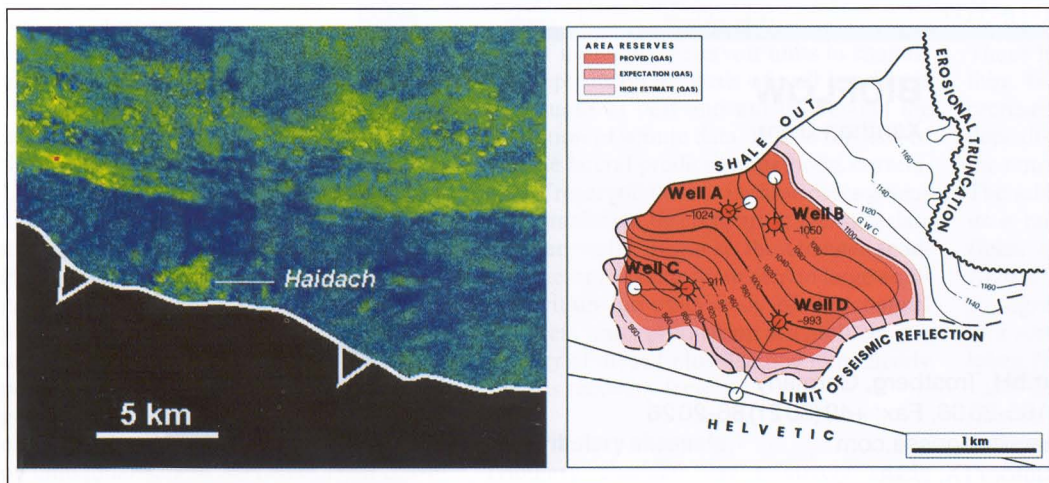
At several levels within the Puchkirchen and basal Hall formations, the zig-zag pattern of

the migrating channel belt is interrupted by large slide masses and rotated slump blocks. On seismic they are recognised as wedge shaped masses of chaotic and steeply inclined beds with highly irregular top surfaces. The base of the slide is semi-conformable, whereas overlying deposits onlap the top surface. These megaslides can be up to 250 m thick and cover areas of several tens of square kilometers. The megaslides are formed by gravitational collapse of sections of the southern slope, and were probably triggered by tectonic movements of the Alpine front [15]. Their lithology is dominated by southern slope mudstones and minor sandstones, but channel conglomerates and sandstones have locally been incorporated in the slide masses. Due to the extensive sediment deformation within the megaslides, any reservoir sands are prone to be faulted and compartmentalised. So far, no commercial quantities of gas have been found in megaslide deposits.

**8 Conclusions**

On the basis of regional 3D seismic and well data, a new geological model for the gas reservoirs of the Upper Austrian Molasse has been formulated. The Oligocene-Miocene gas reservoirs of the Puchkirchen and basal Hall Formations are associated with an approximately west-east trending, axial deepwater channel complex that runs subparallel to the Alpine thrust front. The recognition of different depositional elements in the Puchkirchen channel belt explains many of the complex lateral variations in reservoir quality and reservoir distribution that have been observed in the Austrian Molasse. As such, the new model provides a geological framework for subsurface interpretation. Using 3D seismic attributes, well log and core data, the model allows prediction of lithology and reservoir characteristics on the basis of the occurrence of a particular seismic character within a diagnostic depositional context, rather than seismic character alone.

The application of this methodology is still in its early stages, and much work still remains to be done. In particular, the sedimentary processes responsible for the complex architecture of the Puchkirchen turbidite system are not yet fully understood, and many questions still remain regarding sediment provenance. Also, the characterisation of reservoir properties has so far only been made in qualitative terms. However, the abundance of well data in this area and the production data from various fields should allow quantitative prediction of reservoir properties in the vari-



**Fig. 10** RMS seismic amplitude map and contoured depth map of the Haidach Gas Field (after A. Wagini, 2000). Haidach is a slope fan deposit, visible as an isolated sand apron on the southern slope.

ous depositional elements, providing a powerful new tool for continued gas exploration and production in Upper Austria.

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