Utilizing outcrop analogs to improve subsurface mapping of natural gas-bearing strata in the Puchkirchen Formation, Molasse Basin, Upper Austria

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Abstract

Hydrocarbons have been produced from the Oligocene-Miocene Puchkirchen Formation of the Upper Austrian Molasse Basin for decades. A recently acquired 3D seismic volume that covers almost 2000 km² reveals that sediment (and reservoir) distribution in the Puchkirchen Formation was strongly controlled by a large channel complex (3-5 km wide by 10's to > 100 km long) that was active along the axis of the foreland basin. Important reservoir lithofacies are present in channel thalweg (sandstone and conglomerate) and overbank (thin sandstone beds) deposits, as well as in slope fan deposits of the tectonically active southern basin margin. Large-scale depositional elements of the channel system are seismically mappable, however, individual reservoirs are often too small to be observed within the resolution of seismic data. Information from wells provides important information about reservoir properties and vertical facies shifts; however, it typically cannot provide information about the 3D geometry of a reservoir. Tying observations at the bed scale (from core) and depositional setting scale (from seismic) is crucial for optimizing oil and gas exploration in the basin. In order to make this link between scales, as well as improve our understanding of reservoir architecture in the Puchkirchen Formation, outcrops characterized by similar facies that were deposited under the influence of similar sedimentary processes are analyzed.

The Cretaceous Cerro Toro Formation of the Magallanes Basin in southern Chile represents an excellent outcrop analog to the Puchkirchen Formation. In both study areas, sedimentation took place within large channel belts that were present along the axes of foreland basins, channel fills are comparably dominated by conglomerate and sandstone, and sedimentary body geometry is also similar. The outcrop analog provides insight into reservoir architecture and heterogeneity within the Puchkirchen Formation at a scale not imagable in seismic data. Through the incorporation of 3D seismic, well, and outcrop data, a better understanding of sediment distribution in the basin is achieved. The knowledge gained is applicable to future exploration and development of hydrocarbon reservoirs in the Molasse Basin of Upper Austria.

Seit Jahrzehnten wird in der oberösterreichischen Molasse Erdgas aus der Puchkirchen-Formation (Egerium/ Oligozän) und der Hall-Formation (Eggenburgium/Miozän) produziert.

Ein in den vergangenen 12 Jahren sukzessive über eine Fläche von etwa 2000 km² gemessenes 3D-Seismik Datenvolumen macht deutlich, dass die Sedimentverteilung (und damit auch jene von Speichergesteinen für Gas) in der Puchkirchen-Formation von einem großen, 3 bis 5 km breiten und mehr als 100 km langen submarinen Rinnensystem kontrolliert worden ist, welches entlang der Beckenachse der Vorlandmolasse aktiv war. Wesentliche Speichergesteine wie Sandsteine und Konglomerate sind entlang der einzelnen Rinnen („channels") ausgebildet, dünnere Sandsteine als „overbank" Ablagerungen. Hinzu kommen als Hangablagerungen zu bezeichnende Sandpakete am tektonisch aktiven Südrand des Beckens.

Großmaßstäbliche Ablagerungselemente des Rinnensystems sind seismisch kartierbar, individuelle Sandsteinlagen oder Pakete liegen aber durchwegs unter der seismischen Wahrnehmungsgrenze. Bohrungsdaten liefern wichtige Informationen über Reservoir-parameter und vertikale Fazieswechsel; über die 3-dimensionale Geometrie eines Reservoirkörpers sagen sie leider nichts aus. Das Verknüpfen der im Kern messbaren Bankungsdimensionen mit den seismisch erkennbaren Ablagerungsgeometrien ist entscheidend. Um die Verbindung zwischen diesen beiden Maßstäben herzustellen und unser Verstehen der Reservoirarchitektur in der Puchkirchen-Formation zu verbessern, werden Gesteine in Aufschlüssen mit vergleichbarer Faziesausbildung analysiert, welche unter ähnlichen Sedimenationsbedingen abgelagert worden sind.

Die kretazische Cerro Toro Formation des Magallanes Beckens in Südchile stellt ein ausgezeichnetes Aufschluss-Pendant zur Puchkirchen-Formation im Untergrund des Molassebeckens dar. In beiden Studiengebieten erfolgte die Sedimentation in einem groß-flächigen Rinnensystem entlang der Beckenachse eines Vorlandbeckens, die Rinnenfüllungen werden durch vergleichbare Konglomerat- und Sandsteinpakete gekennzeichnet und auch die Geometrie der einzelnen Sedimentkörper ist ähnlich. Die Analogien im Aufschluss erlauben einen Detailblick auf/in die Reservoirarchitektur sowie auf die Heterogenität innerhalb der Puchkirchen-Formation wie dies durch Seismikdaten nicht der Fall ist. Durch die Verbindung von 3D-Seismik, Bohrungsdaten und Aufschlusserkenntnissen wird ein wesentlich besseres Wissen um die Sedimentverteilung innerhalb des Beckens erreicht. Die somit gewonnenen Erkenntnisse unterstützen die künftige Exploration und Entwicklung von Kohlenwasserstoff-Vorkommen im Molassebecken von Oberösterreich, Salzburg und Bayern.

1. Introduction

Over the last two decades, technological advances in acquiring and processing seismic data have allowed the observation of sedimentary bodies in the subsurface with increasing resolution (e.g., Weimer et al., 2000). As a result, our general understanding of deep-water strata, which are often deeply buried, has improved markedly. Three-dimensional (3D) seismic has been particularly important, as detailed architectural analysis of geomorphologic features such as submarine fans, canyons, channels, and intraslope basins is possible (e.g., Weimer et al., 2000; Posamentier and Kolla, 2003; Adeogba et al., 2005). One inherent limitation to seismic studies, however, is the difficulty in resolving deposits at the scale of many hydrocarbon reservoirs (Coleman et al., 2000). As a result, a common approach to better understanding the facies and reservoir-scale architecture of seismically imaged deep-water strata is to assess analogous deposits in outcrop (e.g., Slatt, 2000; Johnson et al., 2001; Gardner et al., 2003; Shultz and Hubbard, 2005). That is, in strata considered to have been deposited in a comparable setting, under the influence of similar sedimentary processes.

In the Upper Austrian Molasse Basin, a significant amount of natural gas has been discovered, and is still sought, in deep-water strata of the Oligocene-Miocene Puchkirchen Formation (Janoschek et al., 1996; Wagner, 1996; 1998). The internal stratigraphic architecture of this formation is extremely complex, therefore the distribution of reservoirs is often difficult to predict. In order to improve prediction of reservoirs in the formation, an extensive 3D seismic data volume (frequency sweep of data: 14-102Hz; nominal fold: 18; bin size: 25 m) was acquired by Rohöl- Aufsuchungs AG over the last decade (Fig. 1a). With these data, a new channel model has been developed that accounts for Oligocene-Miocene sedimentation in the basin (Fig. 1b,c; Linzer, 2001; de Ruig, 2003; de Ruig and Hubbard, in press). Despite the high quality of data, resolving reservoir bodies within the channel complex is difficult. Most reservoir units in the formation are less than a few meters thick, whereas the resolution of the seismic data is on the order of a few tens of meters. Gaining an understanding of sediment distribution at the reservoir scale is an important objective, as it improves the ability to efficiently develop, as well as predict the locations of reservoirs.

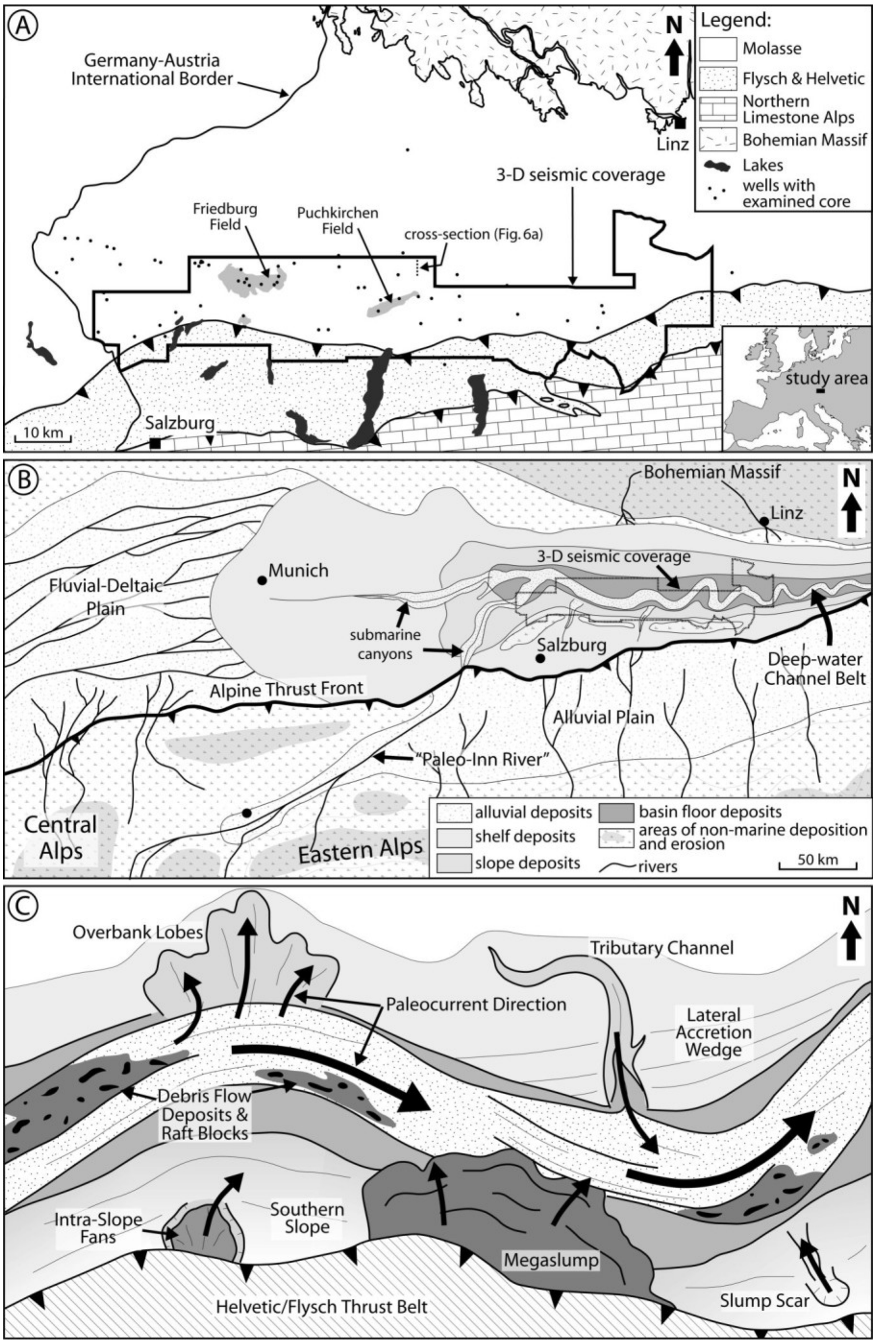

Figure 1: a) Upper Austria study area showing distribution of wells with deep-water cores analyzed, as well as the area covered by 3D seismic data. b) Interpreted Oligocene-Miocene paleogeography of the Central and Eastern Alps, and the Molasse Basin. Note the location of the extensive, east-west trending channel belt present along the Molasse Basin axis (modified from de Ruig and Hubbard (in press), with data from Frisch et al. (1998) and Ortner and Stingl (2001)). c) Interpreted depositional model for deep-water channel deposition in the Molasse Basin (modified from de Ruig and Hubbard, in press). The channel belt ranges in width from 3 to 5 km.

Utilizing outcrop information to bridge the gap between bed-scale observations in core, and architectural observations made in seismic data is readily accomplished in some basins, where subsurface beds have direct equivalents preserved in a nearby outcrop belt (e.g., Williams et al., 1998; Browne and Slatt, 2002). This is not the case for the deep-water Molasse, as Puchkirchen Formation outcrops are few, poorly exposed and of limited extent, consisting largely of lithofacies that are not productive in the Molasse Basin. Following the methodology of other workers, outcrops of deposits from a similar depositional setting are utilized as analogs (cf., Slatt, 2000). The utility of an analog is assessed based on numerous factors, such as whether the two formations are associated with similar grain-sizes, gravity flow deposits, sediment-body geometries, depositional settings, and basin settings. For all of these reasons, the Cretaceous Cerro Toro Formation of the Magallanes Basin in southern Chile is considered to be an appropriate analog to deepwater Molasse Basin strata. In this paper, we examine the utility of this outcropping formation for the purposes of gaining a better appreciation of reservoir characteristics in the Puchkirchen Formation.

2. Upper Austria study area overview

2.1 Dataset and methodology

Greater than forty gas fields have been found to date in the Upper Austrian Molasse Basin between Linz and Salzburg (Fig. 1a). The extensive volume of 3D seismic data (almost 2000 km^2) and well data (approximately 700 wells drilled to date) collected over the last few decades is the focus of our work in Austria (Fig. 1a). Gas production in the basin is from Oligocene-Miocene deep-water sediments of the Puchkirchen and basal Hall formations (Fig. 2).

Within the 3D seismic dataset, only two regionally mappable seismic marker horizons are present, including the top of the Eocene Lithothamnium Limestone and an unconformable surface that defines the boundary between the Upper Puchkirchen and basal Hall formations (Fig. 2). Therefore, seismic mapping in the basin was guided by a series of structurally conformable horizons defined across the study area. Maps were constructed capturing seismic attributes (amplitude and frequency) over 40 ms time intervals above and below each of the structurally mapped horizons. The seismic stratigraphic analysis was calibrated with data from wells, including wireline logs and drill cores. Over 1600 m of core was analyzed in cm-scale detail to gain an understanding of the sedimentological processes associated with the gravity flow deposits that comprise the seismically imaged channel belt (see Figure 1a for drillcore locations). An important objective was to gain an appreciation of the distribution of lithofacies on a basin-wide scale within the Puchkirchen and basal Hall formations. Results of this regional scale study have recently been summarized by de Ruig and Hubbard (in press). This paper builds on their work, which provides the framework for the comparative analysis that is the objective of this paper.

2.2 Background geology

Upper Eocene through to Miocene strata of the Molasse Basin in Upper Austria constitute the fill of the Alpine foredeep, which formed in response to the collision of the North European Craton and the Apulian continental microplate (Ziegler, 1982). In the study area, between Salzburg and Linz, the basin is bounded to the north by the Bohemian Massif (Fig. 1), a crystalline basement high comprised of Paleozoic and older granites and metamorphic rocks. To the south, the Alpine foldthrust belt represents the basin margin, now shortened, although autochthonous molasse is known to exist beneath the thrust sheets (Fig. 1; see reviews in Steininger et al., 1987; Wagner, 1998). Throughout most of the Oligocene-Miocene time period, freshwater to marginal-marine/deltaic sedimentation persisted to the west, as interpreted from German and Swiss Molasse basin strata (Bachman and Müller, 1991; Fertig et al., 1991; Jin et al., 1995). East of the study area, almost all of the molasse strata is overthrust, or itself incorporated into the fold-thrust belt. Locally, Tertiary foreland sediments unconformably overlie Cretaceous and Jurassic deposits (Fig. 2), as well as crystalline of the Bohemian Massif to the north (Wagner, 1996).

The general depositional history of the Tertiary Molasse Basin in Upper Austria (Rögl et al., 1979; Steininger et al., 1987; Wagner,

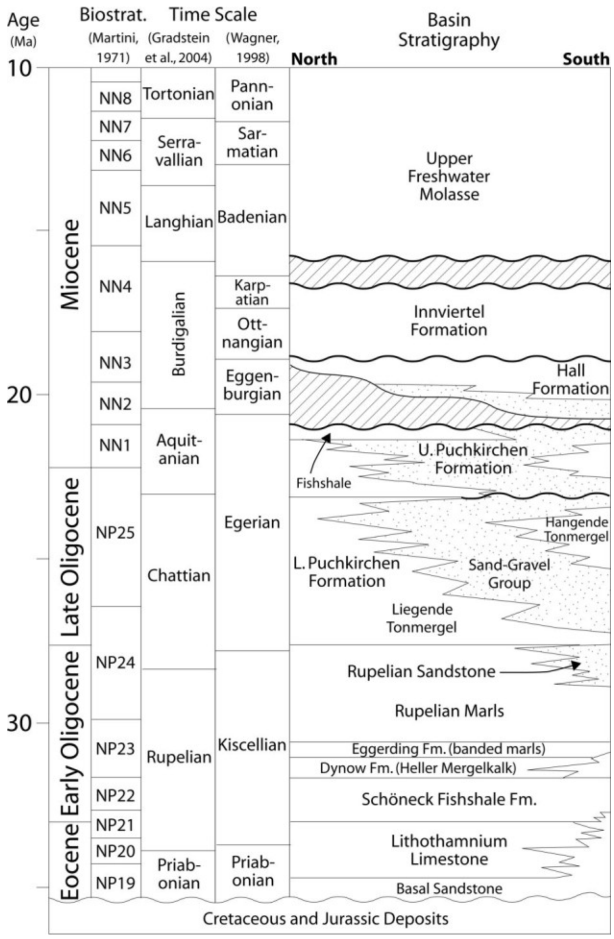

Figure 2: Generalized stratigraphy of Tertiary foreland basin units in the Upper Austrian Molasse Basin (modified from de Ruig and Hubbard, in press, and Zweigel et al., 1998).

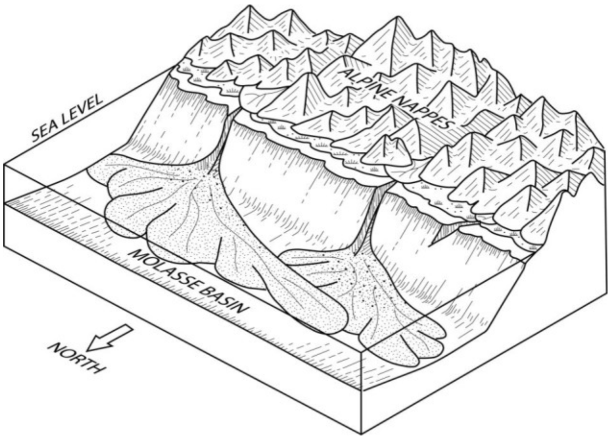

Figure 3: Early depositional model developed to explain deep-water deposition in the Puchkirchen Formation (modified from Kollman and Malzer, 1980). North-south oriented deep-water fans were thought to have coalesced along the foredeep of the Molasse Basin.

1998), and its tectonic evolution (Schmidt and Erdogan, 1993; Wagner, 1996), are well documented. Foreland basin initiation from the Late Eocene to Early Oligocene is recorded by a series of shallow water facies including marginal marine clastics, shallow-water limestones, and deep-water (150-500 m) marls (Fig. 2; Steininger et al., 1987; Sissingh, 1997).

Rapid subsidence and an associated increase in water depth commenced in the Early Oligocene (condensed section of the Schöneck fish shale) as a consequence of Alpine thrust loading (Lemcke, 1974; Schmidt and Erdogan, 1993). Deep-water conditions persisted until the Early Miocene and during this time, the thick succession of gravity flow deposits that comprise the Rupelian Sandstone, as well as the Puchkirchen and basal Hall formations, accumulated in the elongate basin (Fig. 2; Wagner, 1998). The total thickness of the turbiditic Puchkirchen Formation is up to 2000 m locally (Wagner, 1996). During deposition of deep-water strata, basin geometry was dominated by a steep southern slope and a gentle northern slope that bounded the deep basin axis, located proximal to the Alpine thrust front. As the basin was progressively overridden from the south by thrust sheets, sediment supply into the basin increased and accommodation space decreased, resulting in deposition of a shallowing-upwards, deep- to shallow- to non-marine clastic wedge.

2.3 Puchkirchen Formation sedimentology: previous work

Interpretation of the depositional history of deep-water strata in the Austrian Molasse basin has evolved over the last few decades, as new data has been collected and different approaches to its study have been undertaken. Deposits of the Puchkirchen Formation were first recognized as deep-water facies from analysis of drill cores in the mid to late 1970s (Richard Moiola, consulting report to RAG, 1976; Kollmann and Malzer, 1980). Paleobathymetry of the basin is considered to have been on the order of 1000-1500 m based on foraminiferal assemblages (Rögl et al., 1979; Robinson and Zimmer, 1989).

The original deep-water model for the Puchkirchen Formation suggested that coarse material derived from the Eastern and Central Alps was brought to a narrow southern shelf of the basin by fluvial processes (Kollmann and Malzer, 1980; Fig. 3). Subsequently, sediment was destabilized by earthquakes associated with advancement of the Alpine nappes and by fluctuations in sea-level, and re-sedimented onto submarine fans on the basin floor (Kollman and Malzer, 1980; Robinson and Zimmer, 1989; Fertig et al., 1991). In this early model, coarse-grained basinal sediments were considered to have been derived predominantly from the south. Lemcke (1984) proposed that a “Paleo-Inn River” was an important conduit that provided abundant coarse-grained material to the Molasse Basin, derived from the Central Alps and

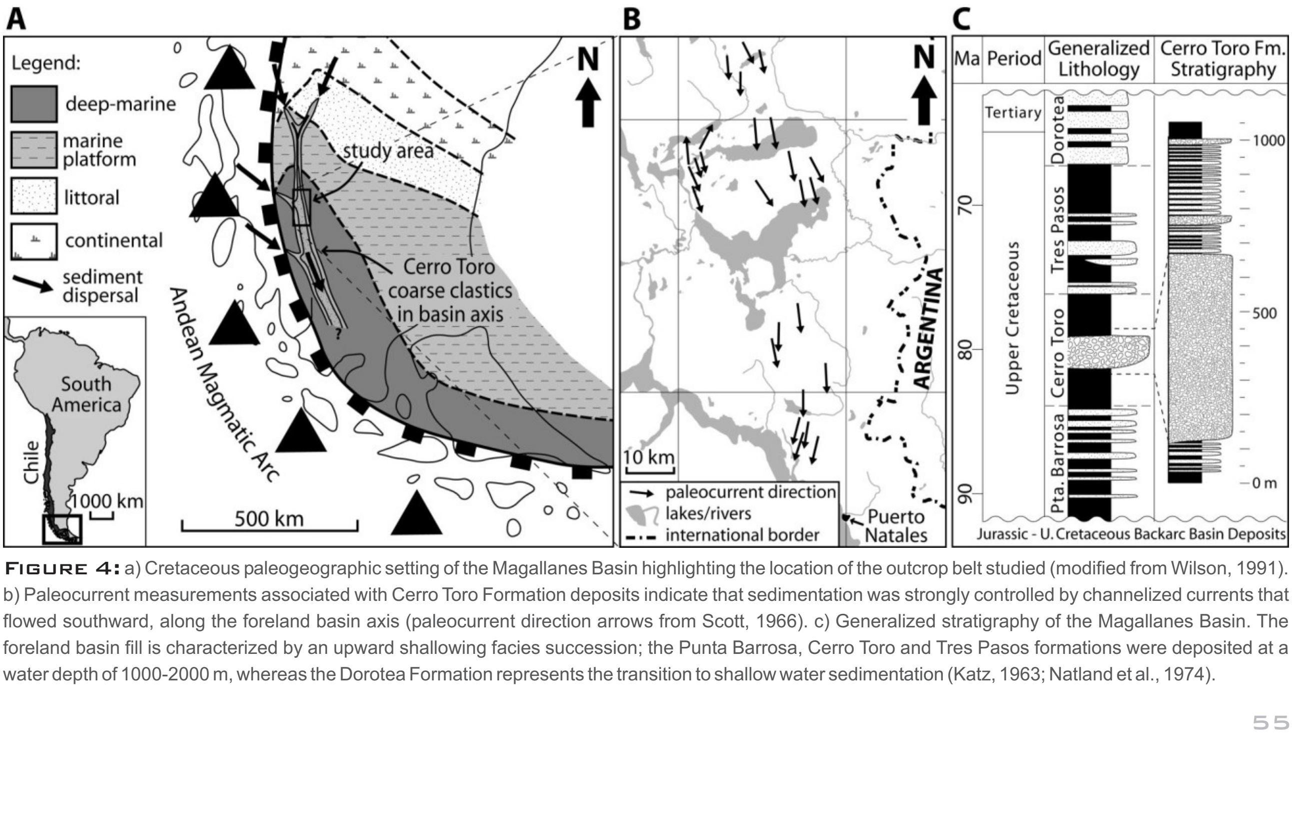

Figure 4: a) Cretaceous paleogeographic setting of the Magallanes Basin highlighting the location of the outcrop belt studied (modified from Wilson, 1991). b) Paleocurrent measurements associated with Cerro Toro Formation deposits indicate that sedimentation was strongly controlled by channelized currents that flowed southward, along the foreland basin axis (paleocurrent direction arrows from Scott, 1966). c) Generalized stratigraphy of the Magallanes Basin. The foreland basin fill is characterized by an upward shallowing facies succession; the Punta Barrosa, Cerro Toro and Tres Pasos formations were deposited at a water depth of 1000-2000 m, whereas the Dorotea Formation represents the transition to shallow water sedimentation (Katz, 1963; Natland et al., 1974).

Northern Calcareous Alps to the south-southwest (Fig. 1b for location). "Paleo-Inn River" sediment fed into one of the north-to-south oriented alluvial fans/fan deltas located in southeastern Germany, just to the southwest of Salzburg (Fig. 1; Lemcke, 1988; Brügel, 1998; Frisch et al., 1998; Ortner and Stingl, 2001).

In a modification of earlier models, it was proposed that a broad, subaqueous shelf existed along the southern basin margin (Steininger et al, 1987; Wagner, 1996). This model held that Puchkirchen sediments consist of >80% slide and slump material, derived from both the southern and northern sides of the basin. Wagner (1998) proposed that east-to-west flowing bottom currents played an important role in re-mobilizing fine sands along the elongate basin axis. This was a significant development, as it was the first time that an east-west trending, basin axial current was interpreted. This model however suggested that sediment dispersal was westward, rather than to the east.

To the west of the study area, the Oligocene-Miocene Freshwater Molasse of south-southeastern Germany consists of extensive alluvial deposits (Fig. 1b; Brügel, 1998). These sediments were sourced from the Alpine front to the south and reworked by an easterly flowing fluvial, axial channel belt (Jin et al., 1995). A large delta formed in southeastern Germany, feeding sediment into the deeper marine Molasse Basin to the east (Fig. 1b). Through a series of sea-level fluctuations, a submarine canyon formed, through which additional clastic input into the deep Molasse basin of Upper Austria passed (Sissingh, 1997; Zweigel et al., 1998).

Utilizing the recently acquired 3D seismic data and borehole information from Upper Austria (Fig. 1a), Linzer (2001), de Ruig (2003), and de Ruig and Hubbard (in press) have derived a new model to account for sediment gravity-flow deposition in the Austrian Molasse basin. They recognized that a large (3-5 km wide and 10s of km long), meandering, deep-water channel belt was present along the basin axis, which largely controlled gravity flow transport and deposition across Upper Austria (Fig. 1b,c). In this model, significant sediment was fed into the basin via the "Paleo-Inn River" drainage, as well as directly off the southern basin margin. The "Paleo-Inn River" supplied the bulk of the coarse, conglomeratic material to the channel system from the west-southwest; cores from submarine fan deposits on the southern slope are characterized by a clast lithology distinctly different than that which dominates the axial channel system (de Ruig and Hubbard, in press).

The 3D seismic-based model for deep-water deposition in the Molasse Basin is substantially different than previous models. Through the use of an outcrop analog from the Magallanes Basin in southern Chile, we may consider the validity of this seismically-generated model. Some of the research questions to be addressed through comparison of Molasse sediments with the outcrop analog include: (1) Is the presence of a basin axial channel unique to the Austrian Molasse Basin? (2) Is it possible that conglomeratic sediment derived from the Central Alps could travel 10s to 100s of kilometers in the deep sea? (3) Are litho-facies distributed in a predictable fashion within the system? We also consider potential reservoir implications from the comparison of outcrop and subsurface data, including reservoir lithofacies properties, reservoir geometries, potential sealing facies, and stratigraphic trapping mechanisms.

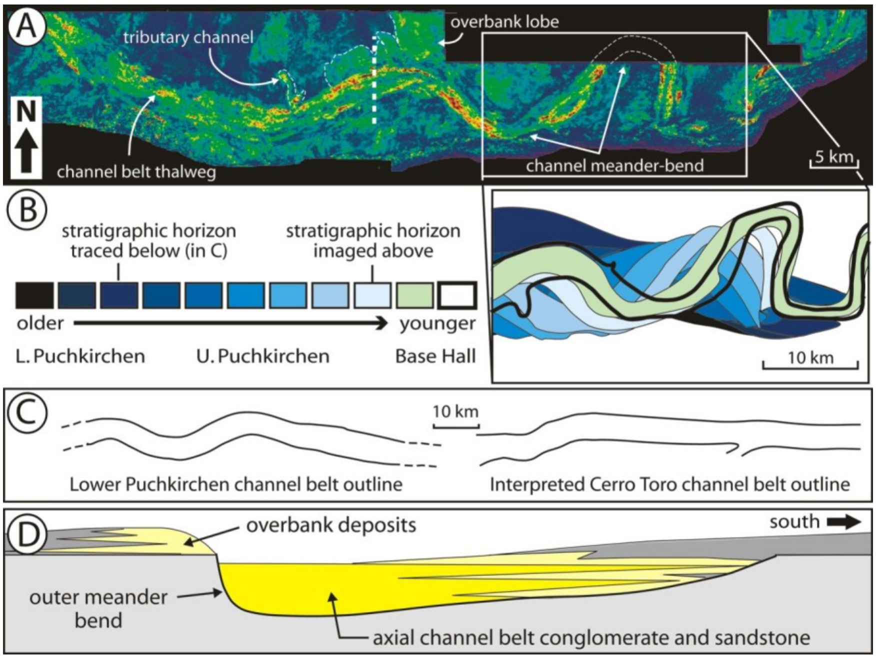

Figure 5: a) 3D seismic image highlighting channel features through ~ 40 m of strata in the upper part of the Puchkirchen Formation. Bright areas correspond to conglomeratic deposits in the channel thalweg, whereas darker areas are associated with finer out-of-channel deposits (overbank, slope). Images like this were made for eleven successive stratigraphic layers, from the upper part of the Lower Puchkirchen Formation into the overlying Basal Hall Formation. The outline of the channel belt thalweg from each interval, stacked on top of one another is present in part (b) (modified from de Ruig and Hubbard, in press). Note the shifts in channel meander loops from west to east, indicating that paleoflow was eastward during deposition of the formation. c) Outline of basin axial channel belts in the Lower Puchkirchen and Cerro Toro formations showing the similarity in scale of the two systems. The outline of the channel in the Cerro Toro Formation is based on mapping of field exposures of coarse-grained deposits in the Chilean outcrop belt (from Hubbard et al., in press a). d) Schematic cross-sectional model for channel deposition in the Puchkirchen Formation (modified from de Ruig, 2003). Paleoflow direction was into the plane. The channel belt is asymmetric, associated with significant erosion on the outer edge of meander bends and lesser erosion and more aggradation on the inner edge of meander bends. See vertical dashed line in part (a) for approximate location (channel is 3-5 km wide).

3. Chile study area overview

3.1 Dataset and methodology

Deposits of the Cretaceous Cerro Toro Formation are present capping a series of mesa-like mountains over an outcrop belt >100 km long in southern South America (Fig. 4a). The outcrop belt has a north-south orientation, as it is located adjacent and parallel to the Andean fold-thrust belt (Fig. 4a). The Cerro Toro Formation is >2000 m thick in the area studied, consisting predominantly of thin-bedded turbiditic mudstone and sandstone, punctuated by a middle, coarse-grained (conglomeratic) member 400-600 m thick (Fig. 4c).

Thousands of meters of section were measured in detail from the outcrop belt in order to capture the sedimentological characteristics of the formation. The orientation of features indicating paleoflow direction in the ancient setting, such as sole marks, ripples and imbricated clasts were measured. The coarse-grained member and laterally equivalent fine-grained beds have been the focus of our research in the area. Exceptionally large exposures (up to 400 m high and several km wide) allow for the geometrical analysis of sedimentary bodies within the formation. Mapping on photomosaics taken of various outcrop faces represent an important methodology in characterizing submarine channel deposits in the region.

Work on the Cerro Toro Formation by Stanford University geologists over the last 5 years (e.g., Crane and Lowe, 2001; Hubbard et al. 2004; in press a, b, c). permits the comparison between the Cerro Toro and Puchirchen formations presented here.

3.2 Background geology

During the Late Cretaceous (Campanian), clastics of the Cerro Toro Formation accumulated along the axis of the Magallanes Basin in southern Chile, a foreland basin formed as a consequence of the rise of the Patagonian Andes and associated load-induced subsidence. Andean-derived conglomeratic deposits of the formation were exhumed during Tertiary uplift and now crop out in a north-south oriented outcrop belt (Fig. 4; Winn and Dott, 1979). The outcrops have proven to be particularly interesting to both sedimentologists and petroleum geologists, due to their large scale (often scaled similarly to seismically imaged sedimentary bodies), and the three-dimensionality of some exposures (e.g., DeVries and Lindholm, 1994; Crane and Lowe, 2001; Beaubeouf, 2004; Hubbard et al., in press b).

Based on extensive paleocurrent data indicating north-to-south transport, Winn and Dott (1979) envisioned a southward propagating, canyon-fed submarine fan characterized by a basin-axial channel belt (Fig. 4a). Crane and Lowe (2001) first proposed that some of the outcrops present in the Magallanes basin might represent the fill of large-scale tributaries that fed coarse material into the basin axial channel complex. Important architectural elements recognized in the outcrop belt include channel thalweg, overbank channel, and levee deposits (Beaubouef, 2004; Hubbard et al., 2004; in press c).

4. Comparing the Puchkirchen and Cerro Toro formations

4.1 Basin scale

Both the Magallanes and Molasse basins are foreland basins characterized by a significant thickness of deep-water strata (Winn and Dott, 1979; Wagner, 1996). As a result of mountain-building events (Andean and Alpine, respectively), a long (150 km+), narrow (<10-15 km), and deep (1000-2000 m) trough developed along the basin axis in each region (Figs. 1b, 4). In both settings, axial currents were dominant, fed from major fluvial systems at one end of the basin (Figs. 1b, 4). Lateral conduits originating from active thrust fronts were also an important source of coarse-grained sediment in each setting (Crane and Lowe, 2001; de Ruig and Hubbard, in press).

Basin configuration imparted a strong control on sediment

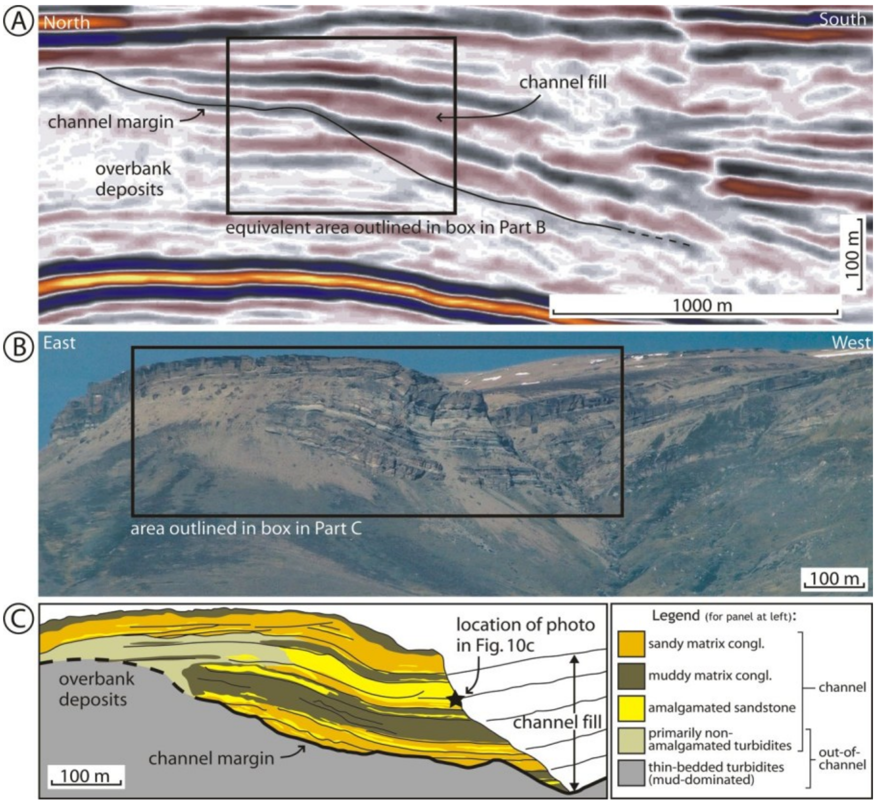

Figure 6: a) Seismic cross-section through the Puchkirchen Formation channel belt, with the major seismostratigraphic features identified (see Fig. 1a for location). Paleoflow direction was into the plane. Bright reflectors correspond to strata characterized by coarse-grained deposits (channel) whereas lighter areas are associated with finer, less porous strata (overbank). b) Outcrop of the Cerro Toro Formation, showing a channel sequence of comparable size and lithology to that imaged in the seismic line in part (a). Paleoflow direction was into the plane. c) Line drawing trace of the outcrop showing the distribution of sediment within the channelform body (b and c modified from Hubbard et al., in press a).

distribution in each study area. In particular, the slopes that bounded the foredeep in both the Molasse and Magallanes basins confined the large-scale axial channel systems that developed in each area. These channels were not free to migrate laterally over a very large distance and as a result, the stratigraphic architecture of fill in both basins is dominated by thick successions of vertically aggraded channel deposits. The thick successions (hundreds of meters) of laterally restricted conglomeratic deposits are differentiable from the deposits of many other deep-water fan-channel systems (e.g., Mutti and Ricci Lucchi, 1972; Walker, 1978). Massive amounts of gravel-sized sediment was fed into both basins, associated with the denudation of syn-depositionally uplifting mountain belts. In both areas it is interpreted that sediment was fed to the respective basins through intermontane rivers laden with sediment from mountainous catchment areas.

4.2 Depositional system scale

Sedimentation in the two basins was dominated by immense channel belts, 3-5 km wide by 10's to >100 km long (Fig. 5a,c; Hubbard and de Ruig, 2005). Conglomeratic channel fill is pervasive, and thick successions of fine-grained deposits accumulated away from channel axes, associated with overbank processes (Figs. 6 and 7). The typical channel in the Puchkirchen Formation is notably asymmetric, characterized by erosive outer meander bend channel margins, and inner meander bend channel margins that were sites of sediment accumulation (Fig. 5d). A similar relationship appears to exist in the Cerro Toro Formation (Hubbard et al., 2004).

Within the seismic data analyzed from the Molasse Basin, large-scale architectural elements of the Puchkirchen channel system identified include channel belt thalweg deposits, overbank lobes and tributary channels (Figs. 1c, 5a). From these observations, gross sediment distribution can be predicted. For example, coarse, conglomeratic deposits are restricted to the

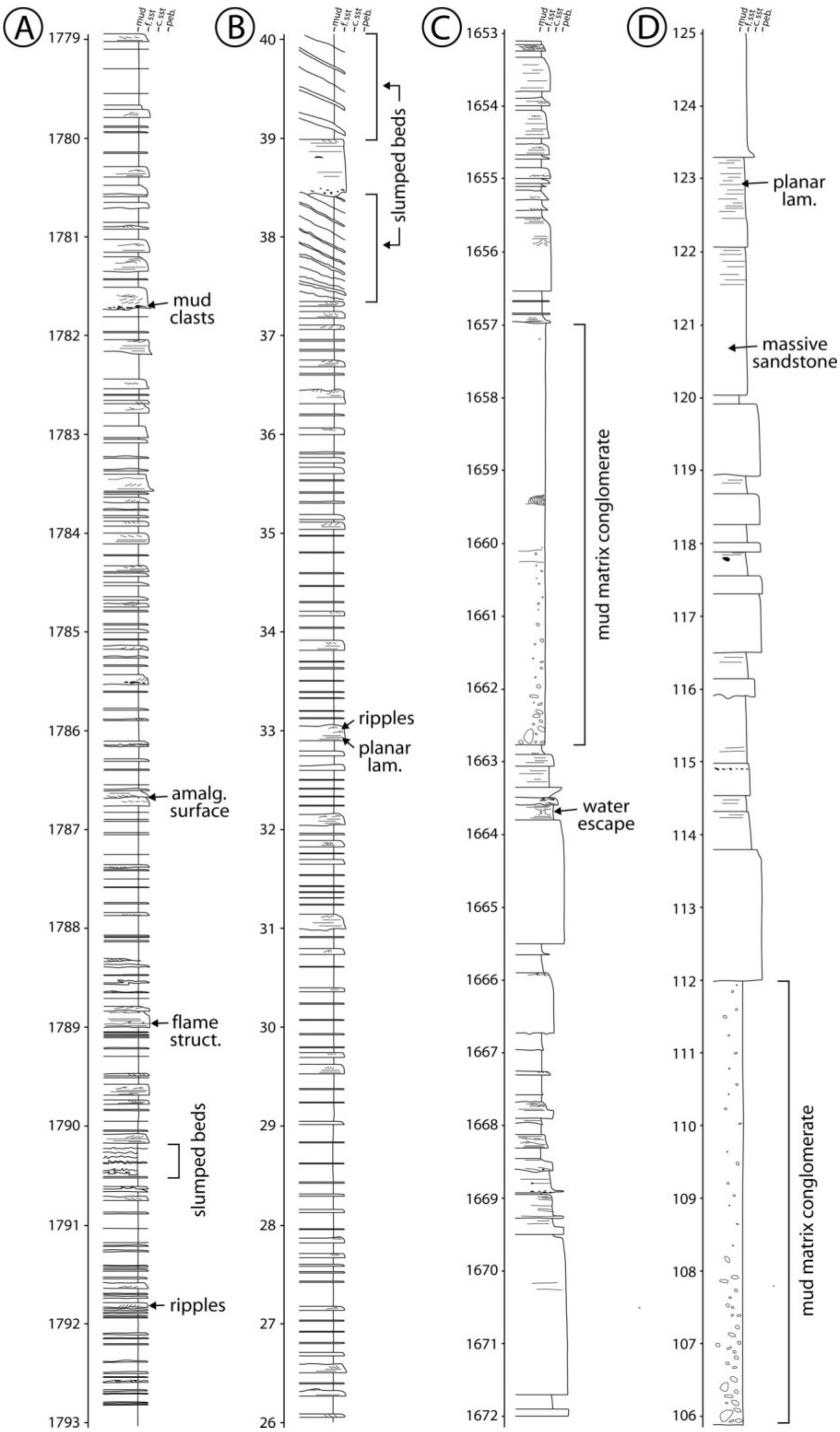

Figure 7: Measured stratigraphic sections from the Puchkirchen and Cerro Toro formations. Overbank deposits are characterized by a dominance of thin-bedded turbidites with abundant traction structures (Bouma sequences) in both the Puchkirchen Formation (a) and the Cerro Toro Formation (b). The slumped deposits in both sections (a and b) resulted from mass failure on shallowly dipping slopes, likely associated with topography on levees or overbank lobes. Channel fill in the Puchkirchen (c) and Cerro Toro (d) formations is dominated by thick, coarse-grained units. These include mud-matrix conglomerate beds > 5 m thick, sandy matrix conglomerate beds 1-3 m in thickness, and 0.5-2 m thick predominantly structureless sandstones. Thin-bedded turbidites are more prevalent in channel fill of the Puchkirchen Formation.

thalweg of the channel, whereas overbank lobes are known to be largely associated with interbedded sandstone and mudstone. Similar relations typify the Cerro Toro Formation; Figure 7 highlights the comparison of stratigraphic sections from channel thalweg and overbank areas in each basin.

Changes in sediment distribution are observed through the stratigraphic succession in the Molasse Basin, allowing an interpretation of the evolution of the depositional system. As such, de Ruig and Hubbard (in press) have shown that meanders in the Puchkirchen channel belt migrated from west to east over time, leading to the conclusion that the channel flowed eastward along the basin axis (based on similar observations in fluvial channels) (Fig. 5a). Paleocurrent measurements from the Chilean outcrop belt demonstrate that the channel in the Cerro Toro Formation behaved similarly (Fig. 4b; Scott, 1964; Winn and Dott, 1979; Hubbard et al., in press a; c). In both the Cerro Toro and Puchkirchen-basal Hall formations, an overall fining upwards is observed through the entire succession of channel deposits. In the Molasse Basin, deposits are: (a) largely conglomeratic in the Lower Puchkirchen Formation, (b) sand-dominated within the uppermost beds of the Upper Puchkirchen Formation, and (c) characterized by a dominance of silt and fine-grained sandstone in the basal Hall Formation (de Ruig, 2003). A stratigraphic section through the coarse-grained member of the Cerro Toro Formation also indicates an overall upward fining trend (Fig. 4c). These grain size trends are related to the transition to less competent, and perhaps volumetrically smaller, flows as the channel systems evolved (cf. Kastens and Shor, 1985).

Despite the insight gained from the 3D seismic data that can be applied to hydrocarbon exploration in the Molasse basin, the vertical resolution of the seismic data is generally not more than 40 m, and therefore it has inherent limitations to its utility. Unequivocally identifying sedimentary bodies less than 20-30 m thick is typically not possible. As numerous reservoirs in the Puchkirchen Formation are less than a few meters thick, seismic data provides a depositional framework, but alone, it is obviously insufficient for successful mapping of all reservoir-scale units. Bed-scale observations from both the Puchkirchen Formation

Facies	Description	Depositional Processes and Setting
thin-bedded fine-grained sandstone and shale	- normally graded sandstone - partial Bouma sequences (Tb-e) - beds < 20 cm thick - sharp bases and sharp or graded tops	- low density turbidity currents - out-of-channel/ overbank
thick- to thin-bedded fine-/ medium-grained sandstone	- normally graded sandstone - partial to complete Bouma sequences (Ta-e) - beds < 1 m thick - sharp bases and sharp or graded tops	- low to high density turbidity currents - channel/proximal overbank
thick-bedded medium-/ coarse-grained sandstone	- normally graded - massive with plane to ripple-laminated tops - beds 1-4 m thick - sharp/erosive bases and sharp tops	- high density turbidity currents - channel
sand matrix conglomerate (clasts granular to 10 cm in diameter)	- ungraded or graded - massive or stratified - rounded metamorphic and igneous clasts - beds 0.5 - 2 m thick - sharp bases and tops	- traction - channel
mud matrix conglomerate (clasts granular to 10 cm in diameter)	- clast size and % decreases upwards locally - rounded metamorphic and igneous clasts - associated with muddy, chaotic blocks - beds 0.5 - 24 m thick - sharp bases and tops	- debris flow through to slurry flow - channel

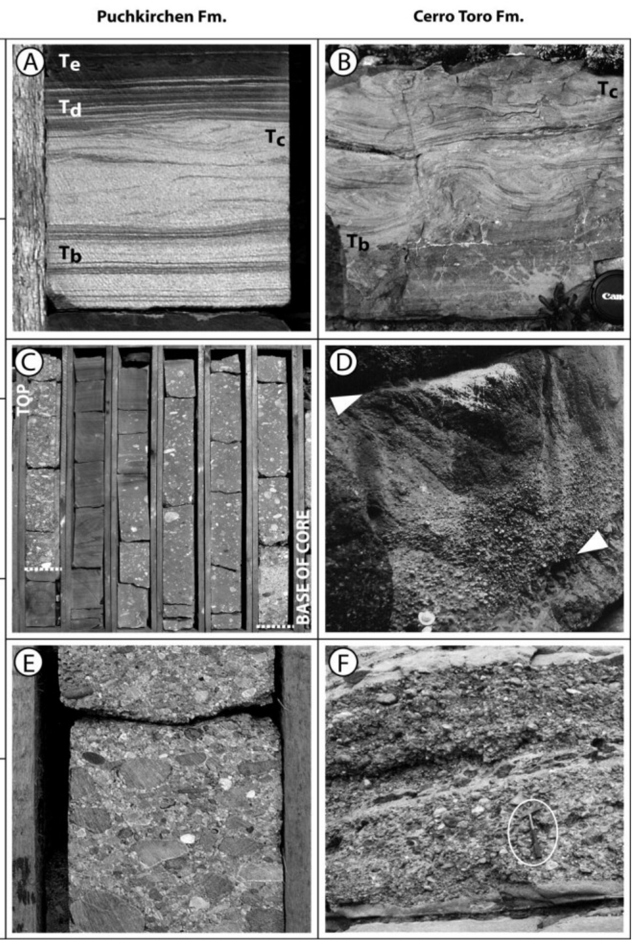

Figure 8: Dominant lithofacies of both the Puchkirchen and Cerro Toro formation channel belts, and their interpreted depositional processes and settings. Photographs highlight numerous, comparable facies types of the two formations. a) Thin-bedded turbidite characterized by a partial Bouma sequence (T_{b-e}) from the Puchkirchen Formation (core is 10 cm in diameter). b) Thick sandstone bed characterized by T_{b-c} divisions in the Cerro Toro Formation (camera lens cap is 6 cm in diameter). c) Mudmatrix conglomerate characterized by an overall upwards decrease in clast percentage in the Puchkirchen Formation (core boxes are each 1 m long). The base and top of one gravity-flow bed (>5 m thick) are indicated by dashed lines. d) Mud-matrix conglomerate characterized by an overall upwards decrease in clast percentage and size in the Cerro Toro Formation (hat at base of photo is ~30 cm in diameter). The base and top of one gravity-flow bed (> 5 m thick) are indicated by arrows. e) Closeup of sandy matrix conglomerate in the Puchkirchen Formation (core is 10 cm in diameter). f) Sandy matrix conglomerate beds in the Cerro Toro Formation (rock hammer is 30 cm long).

and the analogous Cerro Toro Formation are necessary to more comprehensively understand and successfully predict reservoir distribution in the Molasse Basin.

4.3 Bed scale

Sedimentological analysis of cores and outcrops has allowed for classification of the various gravity-flow deposits present in the Puchkirchen and Cerro Toro formations into lithofacies (Fig. 8). Each lithofacies is characterized by a unique set of characteristics and reservoir properties. Structureless, normally-graded sandstone beds deposited from high-density turbidity currents (Lowe, 1982), and thinner-bedded turbidites characterized by partial Bouma sequences represent two of the most important reservoir facies within the Puchkirchen channel complex (Fig. 8). Thick successions of conglomerate (mud- or sand-dominated matrix) are the most prevalent component of the channel fills in both basins (Fig. 8). Systematically upward fining successions (20-60 m thick) of conglomerate through to thin-bedded sandstone and mudstone are notable in the Puchkirchen channel complex, and reflect processes associated with the lateral migration of channel elements in the basin (de Ruig and Hubbard, in press). Off the axis of the channel system in areas where overbank deposition was dominant, thinly interbedded sandstone and mudstone beds are common locally, and represent important reservoirs (Figs. 7 and 8).

Core and log data have limitations with regards to comprehensively characterizing reservoirs in the Molasse basin. Important factors that typically cannot be determined solely from a vertical well/core profile through a reservoir include the lateral extent and variability of beds (for example, are they tabular or lenticular?), and the depositional nature of a unit (for example, was it deposited as part of a fan-shaped lobe, an elongate channel bar, or on a channel levee?). As individual beds identified from core and wireline log analysis are generally less than a few meters thick, they usually cannot be tied to a single seismic reflection (which typically represents tens of meters of stratigraphy). There is therefore an information gap between bed-scale geological observations from logs and core, and large-scale sedimentary body geometries characterized in seismic data that can only be bridged by interpretation. In this context, we look to the outcrop data from the Cerro Toro Formation to provide a natural database of possible bed-scale (to reservoirscale) geometries.

Packages of conglomeratic beds in channel thalweg deposits of the Cerro Toro Formation can often be traced laterally over hundreds to thousands of meters (Figs. 6b, c and 9). Within these conglomeratic packages however, erosional surfaces with up to 5-10 m of relief are common (Fig. 9). They are associated with the complicated cut-and-fill histories common to channel environments in the deep sea (e.g., Deptuck et al., 2003; Posamentier and Kolla, 2003). Thick turbiditic sandstone beds are highly lenticular, related to the variation in erosional incision of the original gravity flow as it passed along the channel floor. Sandstone-dominated sedimentary

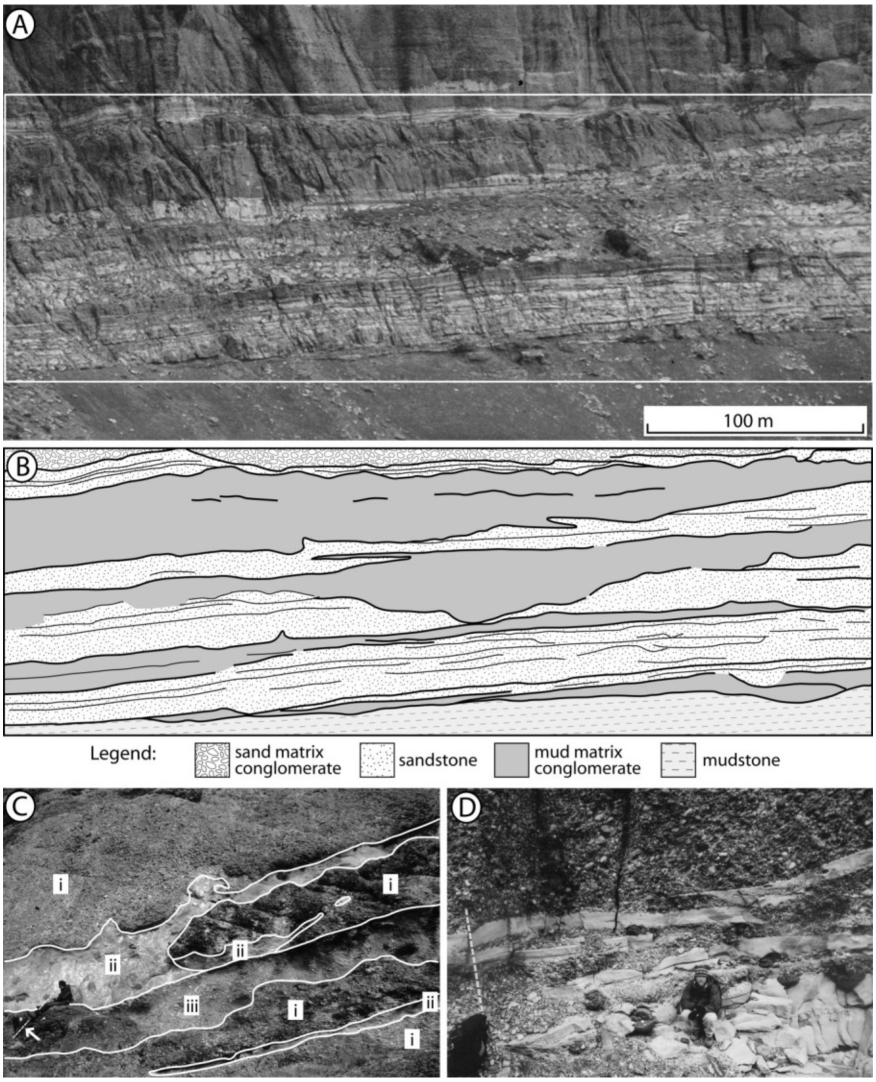

Figure 9: Cerro Toro Formation outcrops highlighting the heterogeneity associated with channel deposits. a) Large outcrop face showing alternating layers of reservoirquality (sand matrix conglomerate and sandstone) and non-reservoir-quality (mud matrix conglomerate and mudstone) lithofacies. Paleoflow direction was approximately into the plane. b) Line drawing trace of the outcrop in (a). Packages of sediment are highly lenticular, associated with deeply eroded surfaces and gradational lateral facies changes. c) Reservoir-scale architectural complexity associated with the variable arrangement of (i) sand matrix conglomerate, (ii) sandstone, and (iii) mud matrix conglomerate. Arrow points to 1.5 m long staff. d) Interbedded sandstone and sand matrix conglomerate.

bodies are <1 - 20 m thick on average, and are defined by channelform geometries. These composite sedimentary bodies range from a few meters to greater than 1000 m wide (Figs. 6 and 9). As a result of the lenticular nature of depositional units, as well as erosional incision locally, the internal architecture of channel fill is highly complex.

Sandstone beds present lateral to coarse-grained channel thalweg sediments represent the deposits of gravity flows that spilled over the bank of the basin axial channel (Fig. 7a,b); measured sections of these strata from both the Magallanes and Molasse basins are characterized by numerous similarities. Shared characteristics include normal grading of beds (maximum grain size fine to lower medium sandstone), preservation of partial Bouma sequences (plane laminations and ripples common), sharp basal bed surfaces (rare amalgamation surfaces between beds), and bed thicknesses of typically < 20 cm (although beds up to 1 m thick are present in rare instances) (Figs. 7 and 8). In the Cerro Toro outcrop belt, some additional observations can be made due to the two- and sometimes three-dimensionality of exposures. In particular, individual beds change in character from proximal positions (i.e., close to the channel margin) to sites located more distally, or further away from the channel margin. Beds typically get thinner, finer-grained and show less evidence of erosion (less amalgamation surfaces) in more distal localities. Additionally, more complete Bouma sequences (T_{b-e} with T_a present locally) are characteristic of beds adjacent to the channel margin, whereas only the uppermost Bouma divisions (T_{c-e}) are identified in beds distally. As a whole, beds are typically tabular over large distances, but thin scours (<3 m deep) filled with lenti-cular sandstone beds are present locally.

5. Discussion: applications of study

5.1 Evaluation of depositional model

The original deep-water depositional model for the Puchkirchen Formation, dominated by south-to-north oriented fans fed directly into the Molasse foredeep from the northward propagating thrust sheets (Fig. 3; Kollmann and Malzer, 1980), was based largely on classical submarine fan models developed in the 1970s (e.g., Mutti and Ricci Lucchi, 1972; Walker, 1978). Application of these models to deposits of the Puchkirchen Formation is problematic in many instances, because in these models, an overall decrease of grain size is generally notable from the proximal to distal positions on the fan (Mutti and Ricci Lucchi, 1972). In the Molasse basin, this proximal to distal fining is notable from the axis of the basin, where the coarsest sediment is located, to both the north and south (Fig. 5). Instead of distally fining submarine fan lobes originating from the southern basin margin, northward and southward progradation of sedimentary bodies record the transition from coarse, channel deposits through to finer, channel overbank sediments (Fig. 1c). Consistent with the early depositional models for the basin, small fans have been identified prograding northward on the southern Molasse basin margin that were presumably fed directly off the active thrust front (Fig. 1c). These fans, though representing important reservoirs, record only relatively minor sedimentary input into the basin (de Ruig and Hubbard, in press).

The origin of gravel-size particles in the Puchkirchen Formation has been cited as support for the classic submarine fan model for the Molasse basin (Kollmann and Malzer, 1980). Coarse material would have had a relatively short distance to travel subaqueously if it was brought to the basin via a series of rivers that directly fed submarine fans along the southern basin margin (Fig 3). In the recently developed model for the

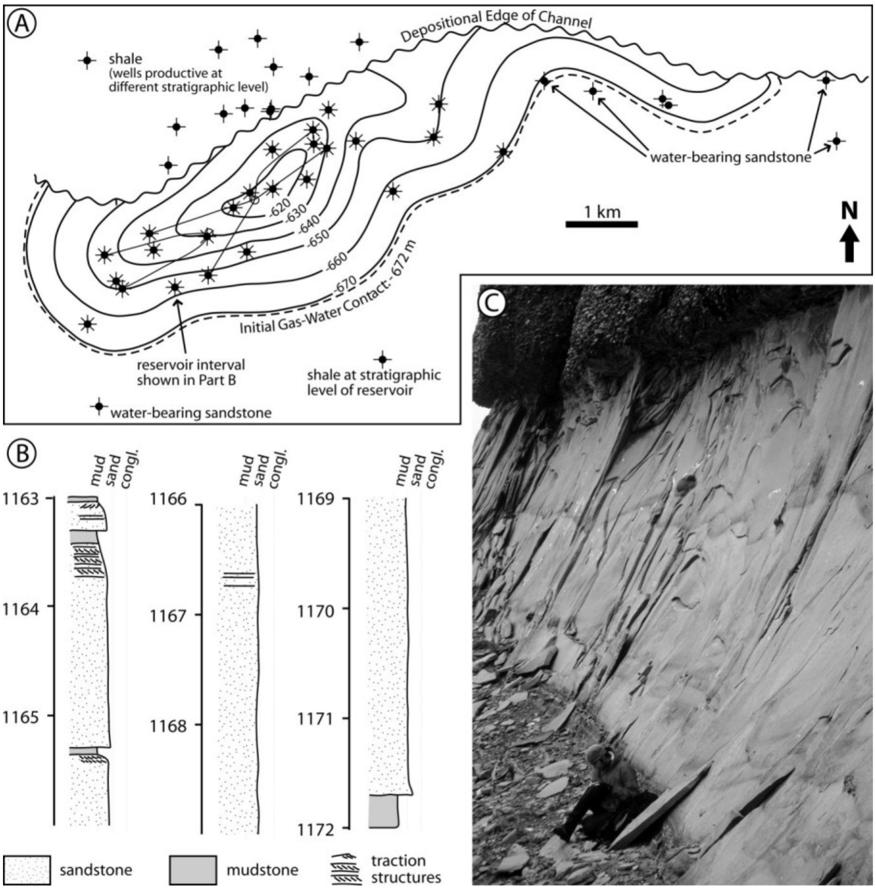

Figure 10: a) Structural map of the Puchkirchen Field (see Fig. 1a for location); gas is trapped in a structural high, stratigraphically sealed in part by juxtaposition of channel sandstone with impermeable facies to the north. b) Stratigraphic section in the Puchkirchen Field area showing the thick, structureless sandstone beds associated with the reservoir (see part (a) for well location). c) Similar, thick, structureless sandstone beds in the Cerro Toro Formation. The location of this photo is shown in Figure 6b.

Puchkirchen Formation, gravel-sized particles would have had to travel over much greater distances along the basin foredeep to the positions where they eventually came to rest (Fig. 1b). Long-distance transport of gravel on the order of 10s to 100s of kilometers seems certain during deposition of the Cerro Toro Formation (Winn and Dott, 1979; Hubbard et al., in press a, c). This interpretation is based on hundreds of paleocurrent measurements from sole marks, imbricated clasts, and bedforms, which all indicate that the flow associated with gravel was southward, along the axis of the Magallanes basin (Fig. 3a, b). Studies of Quaternary gravel-rich deep-water deposits off of the western and Gulf of Mexico coasts of North America have interpreted the subaqueous transport of coarse material in channels over distances of up to 600 km (Griggs et al., 1970; Stelting et al., 1985). These observations from the Cerro Toro Formation and offshore Quaternary deposits support the plausibility of long distance gravel transport in the Puchkirchen channel belt.

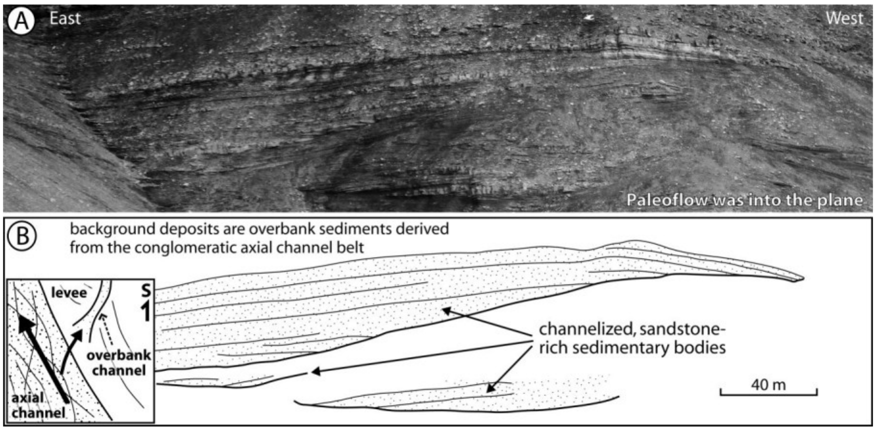

Figure 11: a) Overbank channel deposits in the Cerro Toro Formation. b) Annotated line-drawing trace of features in part (a). Inset map shows the relationship of overbank channels with the main axial channel (bold arrows indicate paleocurrent directions).

The large "Paleo-Inn River", sourced in the mountainous Central Alpine catchment area to the southwest of the Austrian study area (Fig. 1b), is thought to have fed coarse sediment into the Molasse Basin via a relatively narrow fluvial valley (Frisch et al., 1998; Ortner and Stingl, 2001). Along the depositional profile, the steep inner walls of the Puchkirchen channel belt confined gravelly gravity flows in the deep axis of the basin, maintaining the flow strength and competence necessary to carry the gravels 10's to >100 kilometers along the foredeep (de Ruig and Hubbard, in press).

Recent interpretation of high-quality seismic data imaging the channel belt in the Puchkirchen Formation leaves little doubt that axial transport was the dominant factor controlling sediment distribution in the Molasse Basin (Fig. 5). Deposits of the Cerro Toro Formation indicate that this depositional model is not unique to the Molasse foreland. Sinuous channel morphology, associated with the downstream and lateral migration of channel meander bends (Fig. 5a), is in fact consistent with deepwater depositional models proposed in many recent studies (e.g., Abreu et al., 2003; Deptuck et al., 2003; Posamentier and Kolla, 2003).

5.2 Explaining the distribution of reservoirs

Most of the largest gas reservoirs in the Puchkirchen Formation were discovered through the drilling of subtle structural highs in the Upper Austrian Molasse basin (Fig. 10a). Sedimentologically, however, their distribution was difficult to predict using the original submarine fan model (Fig. 3; Richard Moiola, personal communication, 2004). For example, the presence and distribution of reservoir quality sandstone at the Puchkirchen Field, one of the larger gas fields found to date in the Upper Austrian Molasse Basin, was not easily explained (see Fig. 1a for location). The elongate, east-west trending reservoir is characterized by thick, massive sandstone beds (Fig. 10). Similar beds (sedimentologically and dimensionally) that crop out in the Cerro Toro Formation are a useful analog for the Puchkirchen Field, where they are interpreted to have accumulated in an erosive, topographic low on the channel floor. The thick sections of reservoir-quality, massive sandstone present in both areas, originated from the collapse of high density turbidity currents within the axial channel belts.

Most of the potential structural traps in the Austrian molasse have been drilled, and future drilling will focus on subtler, and perhaps smaller stratigraphically trapped gas accumulations. To gain a better understanding of potential stratigraphic trap types, study of (1) older, extensively drilled gas fields, and (2) stratigraphic relationships observed in outcrop are both important. Knowledge from producing fields yields information about stratigraphic architectures and trap potential that is already proven in the basin. Through the analysis of outcrops, new play concepts, not yet deduced from the Puchkirchen Formation can be developed.

An example of a potential hydrocarbon play not yet documented from the subsurface of Upper Austria but identified in the Cerro Toro outcrop belt, is thick successions of channelized sandstone present within overbank deposits (Fig. 11). In outcrop, these features are 30-40 m in thickness, comprised of thick, reservoir-quality sandstone beds. Based on paleocurrent measurements, these channels originated from the main basin axial channel belt and likely formed through the focusing of overbank flow (Fig. 11). The composite sedimentary bodies are completely encased in fine-grained overbank deposits, which in the subsurface would potentially act as a hydrocarbon seal. Even the largest of these features might not be imageable in the 3D seismic dataset of the Molasse Basin so exploration for these channels in the subsurface entails significant risk. Nevertheless, the Cerro Toro outcrop analog predicts this should be a viable play in the Puchkirchen Formation.

5.3 Visualizing reservoir architecture

Due to the fact that hydrocarbon reservoirs are often associated with sedimentary bodies that are too small to be recognized with seismic data, outcrops of analogous deposits sometimes represent the only way to visualize their internal architecture (Coleman et al., 2000; Slatt, 2000). In the expansive exposures of the Cerro Toro Formation, entire seismic-scale channelform sedimentary bodies are present that can be compared with similar features in the Puchkirchen Formation (Fig. 6). Whereas details of the internal architecture of the channels in the subsurface cannot be determined without drilling numerous wells, individual gravity-flow beds can be traced across the outcrop through careful analysis (Fig. 6b, c). From this detailed analysis, hydrocarbon trap styles and sealing lithologies, as well as potential reservoir quality of units, can be inferred. As a result, predictive reservoir models can be made at the sub-seismic scale.

In the Cerro Toro Formation, sandstone bodies associated with erosive bases are observed abutting against fine-grained overbank deposits at the margin of the channel belt locally (Fig. 12a). In many instances, these sandstone packages are covered by widespread mudstone beds, or mudstone-matrix conglomeratic units emplaced as a result of debris flow processes. This architecture represents the ideal configuration for a hydrocarbon reservoir, as it consists of porous sandstone overlain by, and laterally juxtaposed with, fine-grained, potentially impermeable lithofacies that would act as a hydrocarbon seal. Not surprisingly, these stratigraphic relationships in outcrop are analogous in some respects to numerous fields in the Puchkirchen Formation (e.g., Friedburg Field; Fig. 12b).

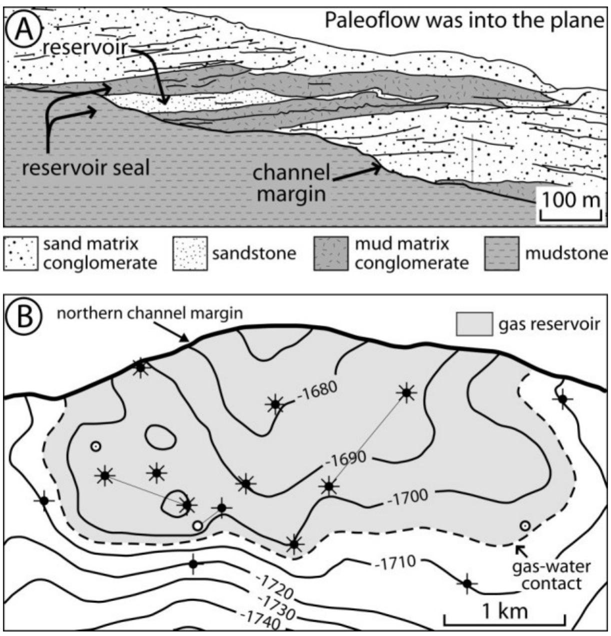

Figure 12: a) Stratigraphic relationships at the margin of the channel belt in the Cerro Toro Formation. Channel sandstone sealed laterally and above by fine-grained facies would comprise an ideal reservoir scenario. b) Example of a reservoir in the Friedburg Field consisting of porous channel sandstone in lateral contact with low permeability overbank units at the northern margin of the channel belt (see Fig. 1a for location of the Friedburg Field).

As discussed, the internal architecture of the channel belts is very complex. Intra-channel hydrocarbon traps rely on the presence of widespread packages of impermeable, muddy-matrix conglomerate and slumped material, or concordant shale beds. Outcrops of the Cerro Toro Formation (Figs. 6b and 9) reveal the internal heterogeneity likely to effect the movement of fluids within analogous deposits in the subsurface Puchkirchen Formation. Alternating stratigraphic packages of sandy (high permeability) and muddy (low permeability) deposits would give rise to highly compartmentalized reservoirs (Fig. 9a, b). At a finer scale, within sedimentary bodies, intra-reservoir features capable of effecting reservoir performance are common. Gravity-flow bed boundaries, lateral variability within units, incision surfaces, and even physical and biogenic structures defined by significant changes in grain size or sorting, can all act as barriers, baffles, or conduits to the flow of hydrocarbons (Fig. 9c, d; Weber, 1982; 1986; Pemberton and Gingras, 2005). In Figure 9, numerous sedimentologic and stratigraphic features from the Cerro Toro Formation highlight the heterogeneity associated with potential reservoir units.

6. Implications and conclusions

Through the analysis of 3D seismic data, wells, and an outcrop analog in southern Chile, a model for deposition in the Puchkirchen Formation has been devised. Seismic analysis allows the construction of a depositional framework for the formation; an understanding of reservoir properties is achieved through the study of drill cores. Examination of the Cerro Toro Formation outcrop belt in South America provides needed information on reservoir-scale architecture in the subsurface of Upper Austria. Interpretation of all these observations yields a robust depositional model for the Puchkirchen Formation that can help guide future exploration for gas in the Molasse Basin. This is especially important, as future exploration success will rely on the discovery of subtle, more elusive reservoirs.

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