

3 Introduction: Atlas of Deep-Water Outcrops

Roger D. Shew¹, Gary S. Steffens², and Joseph R. J. Studlick³

¹University of North Carolina — Wilmington, North Carolina, USA ²Shell International E&P, Houston, Texas, USA ³Maersk Oil America Inc., Houston, Texas, USA

Executive Summary

The Atlas of Deep-Water Outcrops (AAPG Studies in Geology 56) is a collection of both qualitative and quantitative data on deep-water outcrops from around the world that includes all seven continents and 21 countries (Figure 1; Table 1). These outcrops also span most of the geologic time scale (Table 2). The Atlas includes both a hardcopy version and CD. The hardcopy version presents data on 103 separate outcrops as well as summary overview papers on those outcrop areas with multiple outcrops. Several papers are on selected topics that summarize the types of deep-water deposits, seismic modeling of outcrops, current outcrop study techniques, use of outcrop data in reservoir modeling, and special types of deep-water deposits such as injectites. The companion CD includes 37 journal-style articles on the overview topics and more detailed reviews of selected outcrops.

There are many individual and summary publications on deep-water fields and reservoirs, outcrops, and on modern submarine analogs. The goal of this publication is to not repeat but to build on this previous work by providing new and consistent data that more fully describe the various architectures present in deep-water outcrop deposits. This Atlas provides the first collection of quantitative architectural data on deep-water outcrops that may be used for reservoir modeling. The hardcopy version is designed with a standardized format for the presentation of key outcrop descriptive information (Executive Summary, location maps, geologic setting, photomosaics, etc.) and quantitative data (statistics in a spreadsheet format such as bed thicknesses, bed lengths, net-to-gross ratios (N:G), aspect ratios, facies types, textures, etc.). We acknowledge that the collection of this data was accomplished by multiple authors, which leads to some degree of non-uniformity. However, every effort was made to standardize the material for statistical analyses and for the best comparisons of properties among the outcrops, while still preserving the individuality of the interpretations. These data not only include the types and numbers of the various deep-water deposits but also the locations of the various facies on the submarine fan, bed-length ranges and thicknesses of the various architectures, and vertical and lateral facies relationships. We have begun extracting parts of this data to illustrate the value of these statistics. However, the importance of this data is that it is available for individuals and companies to extract and use in their own modeling and evaluation efforts.

Several outcrops are included in the Atlas that have minimal amounts of statistical data and information; these outcrops are included because either they are relatively new and promising outcrops, or they provide useful qualitative analog information for geologic and reservoir models.

Location	Outcrops
United States	22
Canada	12
Chile	9
South Africa	8
Spain	7
Borneo	6
France	6
New Zealand	5
Ireland	4
Turkey	4
Italy	3

Location	Outcrops
Nicaragua	3
Norway	3
Mexico	2
Pakistan	2
Antarctica	1
Argentina	1
Australia	1
China	1
Greenland	1
Namibia	1
Peru	1

Table 1. Outcrop locations are ranked by country and continent. Although many of these have been described in previous papers, most of those papers did not provide detailed statistical information. There are also new outcrops that have not been previously published or that have been re-interpreted. Several of the outcrops have limited qualitative information only, such as China, Plane Crash Canyon in Texas, and Greenland. The latter area is described only in the Hurst et al. paper on injectites.

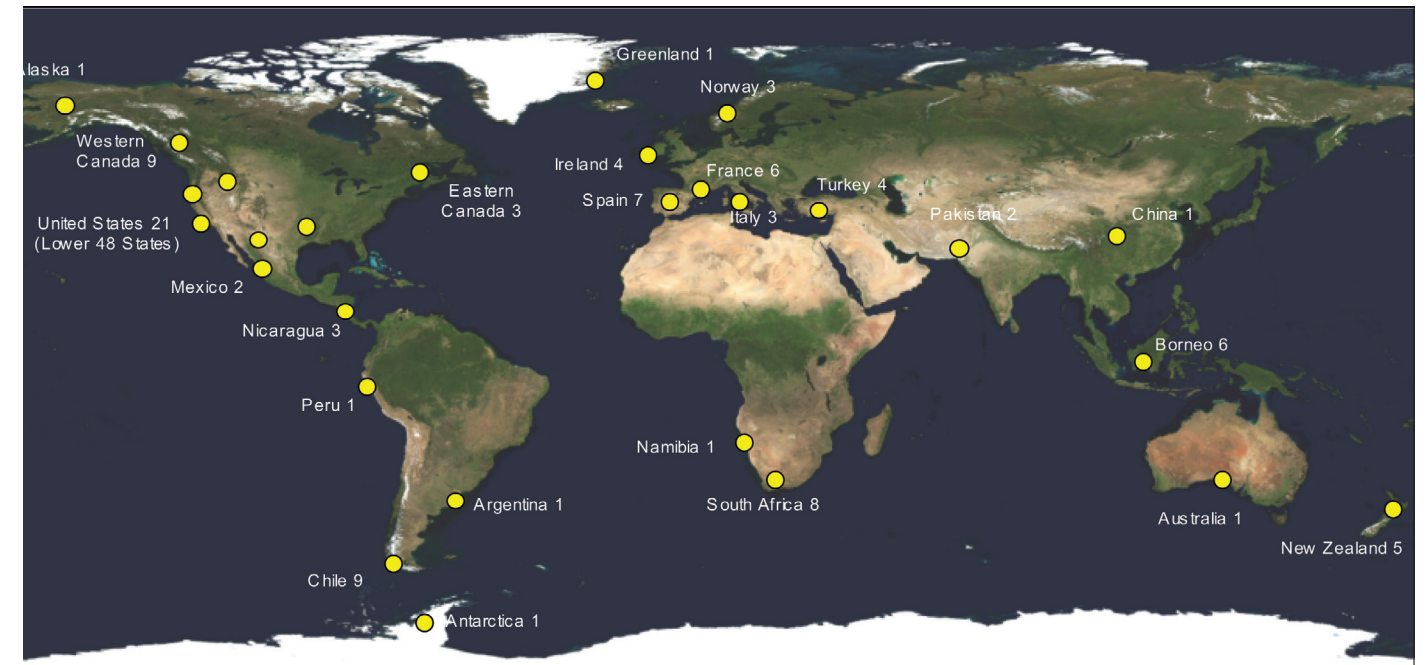


Figure 1. Location map of the outcrops described in the Atlas of Deep-Water Outcrops. Although the United States has the most outcrop summaries (21%), there are a variety of geographic locations (21 countries and seven continents), age ranges (Miocene to Neoproterozoic), and types of deposits (sheets, channels, thin beds, mass-transport deposits, and injectites) in various deep-water fan settings (submarine canyon to distal/outer fan).

Eon	Era	Period	Epoch	Number of Outcrops		
Phanerozoic	Cenozoic	Quaternary		Holocene	None	
				Pleistocene	None	
		Tertiary	Neogene	Pliocene	None	
				Miocene	20: Borneo, Italy, New Zealand, Spain, Turkey, USA	
			Paleogene	Oligocene	12: Borneo, France, Nicaragua, Norway, Peru, Turkey, USA	
				Eocene	20: France, Nicaragua, Spain, USA	
				Paleocene	4: Mexico, Spain, USA	
		Mesozoic	Cretaceous		17: Antarctica, Chile, Mexico, Pakistan, USA	
	Jurassic		2: Antarctica, Greenland (injectite example)			
	Triassic		1: China			
	Paleozoic		Permian		18: South Africa, USA	
			Carboniferous	Pennsylvanian	4: Ireland - Carboniferous; 3: USA	
				Mississippian	1: USA	
			Debonian	None		
		Silurian	None			
		Ordovician	2: Canada			
		Cambrian	2: Australia, Canada			
Proterozoic	Neoproterozoic			10: Canada, Namibia, Norway		
	Mesoproterozoic			None		
	Paleoproterozoic			None		
Archean			None			
Hadean			None			

Table 2. Outcrops are sorted by geologic age. Although a majority of the outcrops are Cenozoic, the outcrops span the time range from the Neoproterozoic to the Miocene.

Introduction

The study of deep-water outcrops has long preceded the exploration for and exploitation of deep-water reservoirs that emerged on a global scale in the 1980s. However, there are examples of deep-water fields that have been producing for many years (e.g., California) and where outcrop studies were important in the understanding of reservoir architectures and continuity issues. Exciting exploration discoveries and development of more detailed geologic models in the past few decades suggested the likely occurrence of thick, high-quality deep-water sands in deep-water settings. This, coupled with new technology, provided the impetus for more studies and research to help minimize reservoir-development uncertainties. Many of these new discoveries were quite significant and found to have world-class production rates and per-well ultimate recoveries. Significant improvements in seismic, evaluation, drilling, completion, and production technologies have allowed the routine exploration and development of such deposits in water depths >1524 m (5000 ft). Deep-water is now a core area for the exploration and production (E&P) industry and is becoming a significant producer and reserve base. With this industry effort and commitment, a corollary effort began to better understand analogs. How are these reservoirs constructed? Are there baffles and/or barriers? Do they have aquifer support? What is beyond the well and seismic coverage? Thus, there was an explosion of outcrops field work, which is ongoing around the world to describe and characterize deep-water outcrops.

There are many significant individual papers, books, and conference proceedings that pioneered the development of deep-water models that are derived entirely or in part from outcrop studies (e.g., Mutti and Ricci Lucchi, 1974; Bouma et al., 1985; Pickering et al., 1986, Mutti and Normark, 1987; Weimer et al., 1994; Pickering et al., 1995, to name only a few). The Pickering et al. (1995) volume is notable for its large photomosaics that allowed for the easy visualization of many outcrops. The idea of large photomosaics is most instructive, and is a central component of this Atlas. Additionally, in this publication, the authors were asked to provide detailed outcrop statistics and illustrations in a consistent format that would allow for easy comparisons to be made and for data entry into reservoir models. The format and types of data are summarized in subsequent pages in this introductory section.

The Project

Having worked on numerous deep-water fields and from studying numerous outcrops, the editors felt that the many excellent outcrop examples from around the world and the numerous papers that describe those outcrops would be much more helpful as analogs if they were summarized and presented in a consistent format. Two important requirements were established early on in the project: 1) A standard presentation format for the geologic setting and outcrop photomosaics, and 2) Statistical data for each architectural element that occurred in the outcrop for direct comparison to other outcrops, as well as for seismic and reservoir modeling.

Although some of the measures are only semiquantitative, we believe this information is still valuable data and should be included with the other quantitative statistics.

The project was initiated in 2004 with a proposal to AAPG for a book that would include 25 to 50 detailed outcrop papers. A letter was sent to prospective authors from the deep-water community soliciting interest in participation. Papers began to be submitted and the number quickly grew to more than 100 outcrops, including summary papers in the 11 x 17 hardcopy format and full paper versions, for a total of 152 contributions. Although it has been a relatively long process, it has flowed relatively smoothly and quickly, considering the number of papers (152), authors (171), and the many affiliations (18 E&P companies, 8 E&P service companies, 42 universities, and 4 other governmental or consulting groups; Table 3) involved. Final galley proofs started being issued in early 2006 for final authors' and editors' reviews and by January, 2007 all of the papers were completed.

Atlas Content

The Atlas has two formats: 1) An oversized hardcopy of 115 papers and 2) a CD-ROM in the Atlas pocket containing 35 extended papers. The geographic coverage is extensive, including 21 countries and all seven continents. The geologic coverage spans the Neoproterozoic to the Miocene. And most importantly, it includes all types of depositional settings, from submarine canyons to the distal basin plain, as well as unusual deep-water settings (e.g., fjord) and all types of deep-water deposits, from the commonly described sheets, channels, and thin beds, to mass-transport deposits and injectites. Examples of these types of deposits are shown on the following pages, including photos and descriptions. In addition, an example of the types of statistics and spreadsheet are also shown.

References:

- Bouma, A. H., W. R. Normark, and N. E. Barnes, eds., 1985, Submarine fans and related turbidite systems, Springer Verlag, New York, 351 p.
- Mutti, E., and W. R. Normark, 1987, Comparing examples of modern and ancient turbidite systems: Problems and concepts, *in* J. K. Leggett and G. G. Zuff, eds., *Marine Clastic Sedimentology*, London, p. 1–38.
- Mutti, E., and F. Ricci Lucchi, 1974, La signification de certaines unites sequentielles dans les séries à turbidites, *Bulletin de la Société géologique de France* 16, p. 577–582.
- Pickering, K. T., D. A. V. Stow, M. Watson, and R. N. Hiscott, 1986, Deep-water facies, processes and models: a review and classification scheme for modern and ancient sediments: *Earth Science Review* No. 22, p. 75–174.
- Pickering, K. T., R. N. Hiscott, N. H. Kenyon, F. Ricci Lucchi, and R. D. A. Smith, eds., 1995, *Atlas of deep water environments: Architectural style in turbidite systems*, Chapman and Hall, London, 175 p.
- Weimer, P., A. H. Bouma, and R. R. Perkins, eds., 1994, *Submarine fans and turbidite systems: Gulf Coast Section, SEPM Foundation, 15th Annual Research Conference*, 440 p.

Exploration and Production Companies		Service Companies	Other (Government and Consultants)	Academia			
Anteon Corporation	Imperial Oil Resources Ltd.	Baker Hughes Inc.	Independent Consultants	Bristol University	Louisiana State University	University of Barcelona	University of Manchester
British Petroleum	Maersk Oil America Inc.	DeepMarine	Bureau of Economic Geol.	Cardiff University	Massachusetts Institute of Technology	University of Bergen	University of Naples Federico II
Chevron Corporation	National Petroleum Corp. Namibia	Géosciences — Rennes	Geol. Survey of Emilia-Romagna	Colorado School of Mines	Mersin University	University of Brest	Univ. of North Carolina —Wilmington
Devon Energy Corporation	Noble Energy Inc.	Midland Valley Exploration Ltd.	U.S. Geological Survey	Cukurova University	Stanford University	University of Bristol	University of Oklahoma
EOG Resources Inc.	Petroliaam Nasional Bhd. (Petronas)	Nautilus		Delft University	Stellenbosch University	Univ. of California — Santa Barbara	University of Ottawa
ExxonMobil Corporation	Royal Dutch Shell PLC	Roxar AS		Depauw University	Texas A&M University	University of Colorado	University of Potsdam
Hess Corporation	Statoil ASA	Schlumberger Ltd.		Firat University	University de la Serena	University of Gothenburg	University of Sannio
Hydro	Total	Task Geoscience Ltd.		Goteborg University	University of Aberdeen	University of Hanover	University of Texas
IFP	Vanco Energy Company			Heriot-Watt University	University of Adelaide	University of Leeds	University of Texas — Dallas
				Imperial College (Univ. London)	University of Alberta	University of Liverpool	
				Keele University	University of Arizona	University of Malaysia Sabah	

Table 3. Affiliations (Exploration and production companies, oil service companies, governmental and consulting, and academia) of authors

Architectural Classification System

The classification used in the Atlas of Deep-Water Outcrops is the widely accepted, three-end-member, reservoir-architectural system of sheets, channels, and thin beds. Some workers have used levees instead of thin beds as the third end-member, but this is only one site of thin-bed deposition, which is obvious from the varied and numerous types shown in this Atlas. A fourth type of deposit that is primarily non-reservoir, but that was found to be a major component of many of these outcrops, is mass-transport deposits. These were most often found as components of the outcrops (between and within the reservoir bodies), but in some outcrops they were the dominant type of deposit. In the descriptive and data spreadsheets, the subject deposits are labeled as S (Sheets), C (Channels), TB or T (Thin Beds), and MTD or MTC (Mass-Transport Deposits, Mass-Transport Complexes). Injectites are present in several outcrops but they are not treated separately; they are described in detail in Hurst et al. (this volume).

Channels, followed by sheet sands, are the dominant single architectural elements (Figure 2A). And even though one architectural element is most prevalent in an outcrop (e.g., channels cutting smaller sheets in Figure 2B), most of the outcrops contain multiple reservoir and/or non-reservoir elements (Figure 2C).

Most of the papers refer to reservoir (sandstone or siltstone) bodies when describing the different types of deposits or architectures; however, it is important to note that in some cases, the terms are used to describe the geometry only. For instance, there are several examples of sheets that are used strictly as a geometric term that may include many different kinds of deposits, including mudrocks and/or debris flows (Figure 2D). Channel fills may also be mudrocks or shales of varying origins. Most importantly, the properties of the architectures in each outcrop are fully described so that comparisons with other outcrops and with subsurface data can be easily made. The descriptions and representative photos/outcrops of the three main architectural elements are shown in Figures 3.

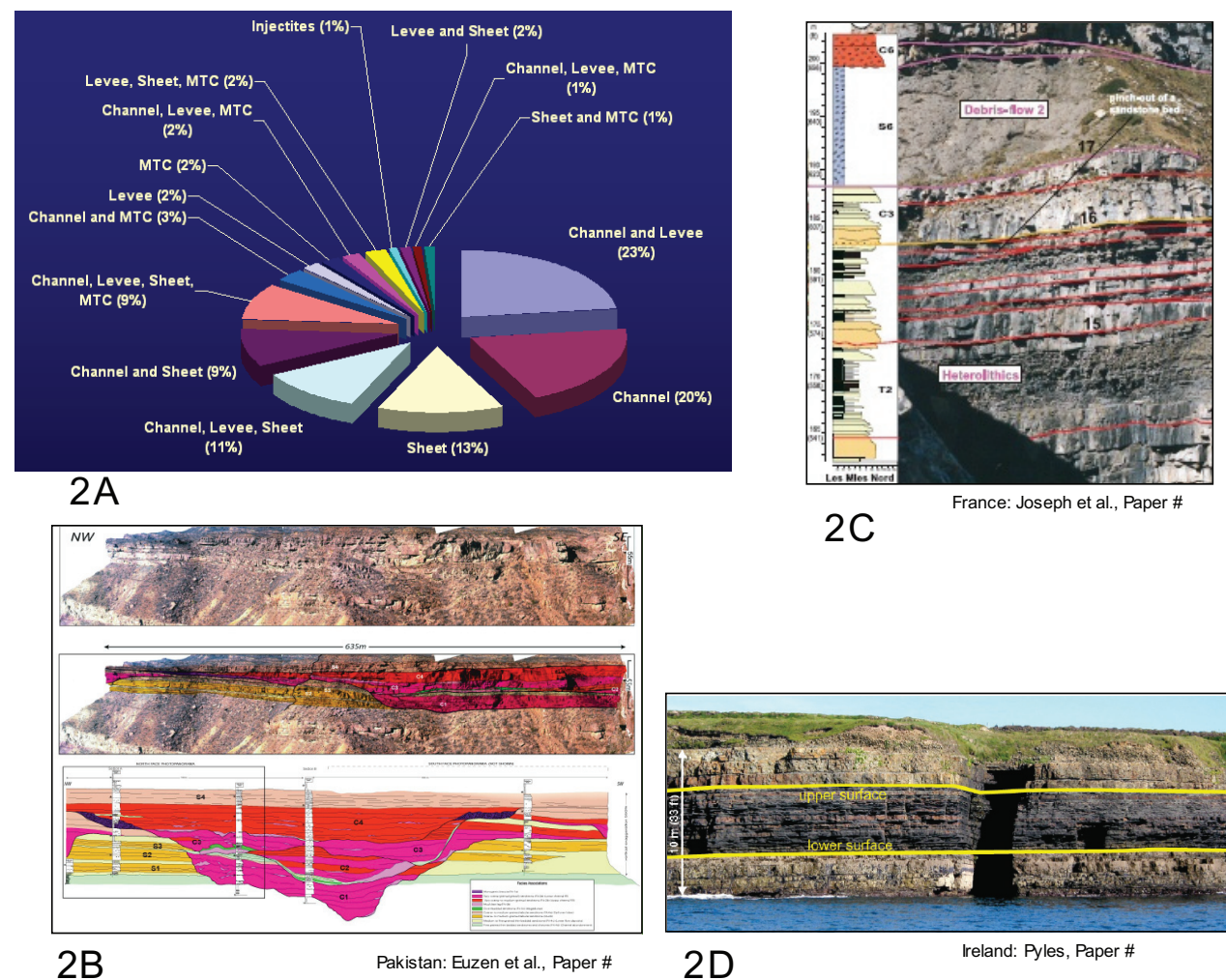
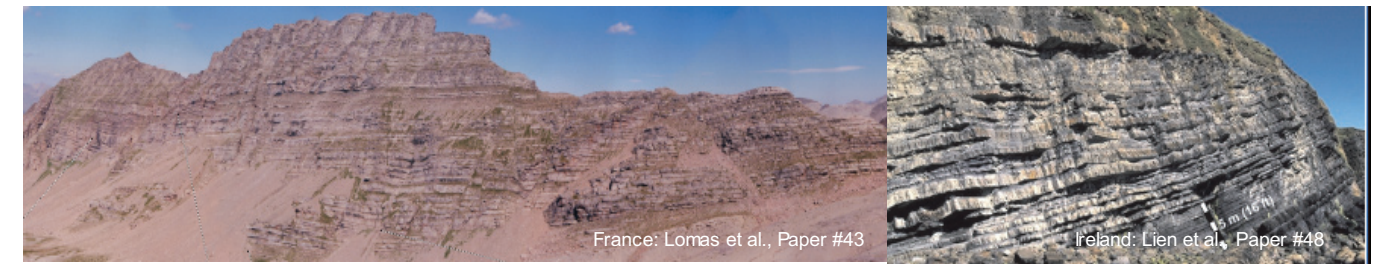
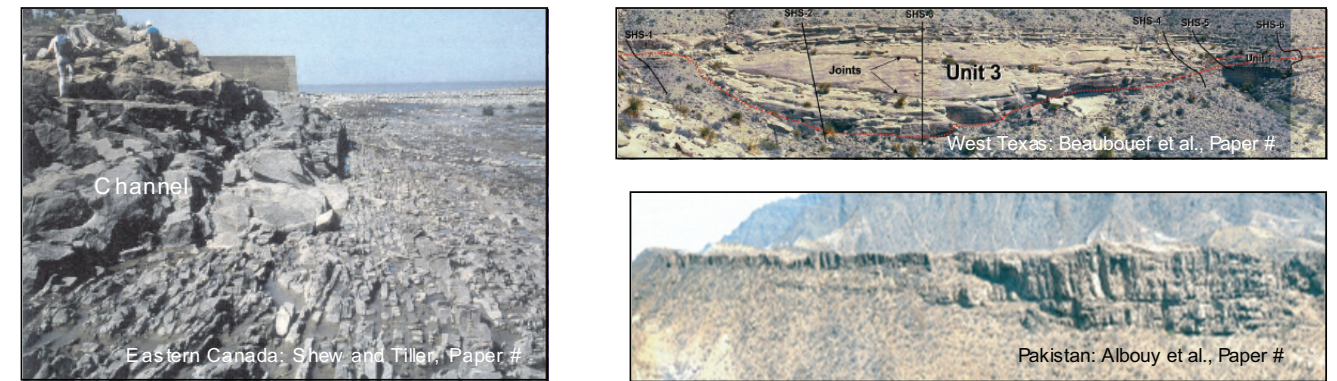


Figure 3. Summary descriptions and representative outcrop examples of the primary architectural elements.



A. SHEETS: Composed of layered and/or amalgamated sheets

1. Layered: laterally continuous, moderate N:G, low to moderate vertical connectivity, base- missing Bouma sequences.
2. Amalgamated: laterally continuous, high N:G, high vertical connectivity, top-missing Bouma sequences.
3. Wireline log response is blocky in amalgamated sheets vs. variable (serrate to thinning or thickening, depending upon location) in layered sheets.
4. External geometry resolvable on seismic; seismic loops may be symmetric or skewed.
5. Occurrence: Basin plain and inner to outer fan, but the mid fan lobe is most common for amalgamated sheets.
Layered sheets are often lateral to or downdip of these deposits.



B. CHANNELS: Multiple types — Single, composite, and channel complexes (single- to multi-story)

1. Moderate to high N:G; higher N:G = amalgamation of internal channel fill.
2. Bed lengths and connectivity are related to channel geometry, N:G, and percent shale drapes.
3. Channel margins are often poorer quality sands relative to the channel axes; amalgamation is greater in the channel axes.
4. Grain size is variable; often top-missing Bouma sequences.
5. Wireline log curve shape is blocky to bell-shaped.
6. External geometry is often resolvable on seismic.
7. Occurrence: Slope to inner fan and mid fan.



C. THIN BEDS: Average bed thickness ≤10 cm (4 in.)

1. Low energy deposits; low to moderate N:G.
2. Laterally continuous (tabular to wedge shape); high lateral and low vertical connectivity.
3. Generally fine-grained, base-missing Bouma sequences.
4. Low (usually)-resistivity pays; poor log resolution.
5. Seismic resolution not possible for any internal architecture; external geometry may be seen if hydrocarbon-bearing.
6. Occur in all settings (levee, slope, interchannel, interbedded with sheets and channels, and outer fan). Mudrock properties, sedimentary structures, depositional sequences, and lateral and vertical facies relationships to other types of deposits are helpful for the interpretation of the setting.

Format and Statistics

A full description of the deep-water package is essential for the most accurate and useful seismic and reservoir models (Chapin and Tiller, Slatt et al., and Joseph et al., this volume). The description of all of the units was encouraged for each of the outcrop examples, with most of the data centering on the reservoir bodies. An illustration of the types of data in the Atlas is shown below (Figure 4) that contains three different architectural elements in a vertical sequence. From base to top there is a layered sheet sand, a thin-bed package, and a laterally migrating channel that cuts the thin bed interval. The photos (Figures 4B and 4C) show parts of these three elements. The statistics for the elements are presented in the spreadsheet (Figure 4D). These include gross outcrop data such as total length and thickness, net-to-gross, outcrop orientation, paleocurrents, and facies succession and description. For the channel forms, it also includes aspect ratios and infill-bedding descriptions. Detailed reservoir and non-reservoir statistics are also given including bed lengths, thicknesses, and textural data. These statistics may then be used to establish dimensional and property data that may be used for input into reservoir models. It should be noted that depositional settings are also provided in a separate outcrop summary spreadsheet for each outcrop.

Applications

The qualitative data presented in this Atlas is important for developing models and for comparing various depositional settings and architectures. However, it is the quantitative data that allows us to create multiple realizations and possibilities for the seismic modeling and for reservoir performance predictions. The primary goal for this Atlas has been to at least begin that acquisition of quantitative data with direct ties to the outcrop photomosaics that we typically use. We have tried to adhere to a uniform format, although some outcrops were difficult to fit to that format, and there were instances where complete statistics were not available for an individual outcrop. Regardless of the circumstances, the authors have done a good job of supplying the architectural element data in as consistent a format as possible.

There are multiple applications for this quantitative data. From a reservoir-development standpoint, bed-length and thickness statistics can be individually and collectively compared for each architecture type. Additionally, N:G, channel dimensional data (e.g., width: depth aspect ratio), and facies associations (e.g., where do the individual elements occur and how do they stack?) are also useful to the reservoir modeler in building multiple reservoir scenarios. Another important type of information in the Atlas, which is rarely included in most publications, is shale-bed statistics. Although these are not included for every outcrop, there are sufficient examples given where shale-bed thickness and extents can be used to build models of baffles and barriers in the various reservoir architectural elements.

These data can also be valuable to the explorationist. The seismic data may only provide indications of potential reservoir architectures, as the internal geometries and even multiple architectural elements are below seismic resolution. Such a large database of outcrops and statistics provides an initial estimate of the distribution and thickness, as well as internal geometries, of these potential reservoirs for volumetric analyses. Another use in early prospect-appraisal is aiding the interpreter with integrating well and seismic data to construct a reasonable geological model for well placement.

It is hoped that through combining the outcrop data presented in this Atlas with other analog data (shallow near-seafloor analogs, new advances in numerical and physical (flumes) modeling, and well-constrained subsurface examples) that the geological community will have an arsenal of tools with which to gain greater insight into the transport and depositional processes that govern sand geometries, overall facies distribution, and reservoir properties within the deep-water environment. Only then, through this integrated approach, will the uncertainty in deep-water reservoir prediction be greatly reduced in the subsurface.

Acknowledgments

The 171 authors who contributed to this Atlas have invested many tens of thousands of hours in studying and documenting these outcrops. They represent many sources of deep-water knowledge (Tables 2 and 3). We thank them for their writing efforts and coping with our many editorial comments and demands. Sincere thanks must go to Ms. Beverly Molyneux of the AAPG staff, who has been our guiding light and true editor throughout this last year. The consistent and attractive look and feel of the Atlas is a testament to Beverly's efforts. John Lorenz, AAPG's Editor when we submitted our proposal, and Ernie Mancini, AAPG's Editor during the Atlas compilation, deserve our thanks for their support and encouragement. Many others on the AAPG staff provided needed support, advice, and resources. Finally, and as folks say, not least, a thanks to our families for allowing us the immense time commitment required to edit the 152 contributions and correspond via many thousands of e-mail notes to the authors, AAPG, and each other. We survived.

Roger Shew, Gary Steffens, and Joe Studlick
Wilmington, North Carolina and Houston, Texas, USA
and Tor Nilsen, in spirit
February, 2007

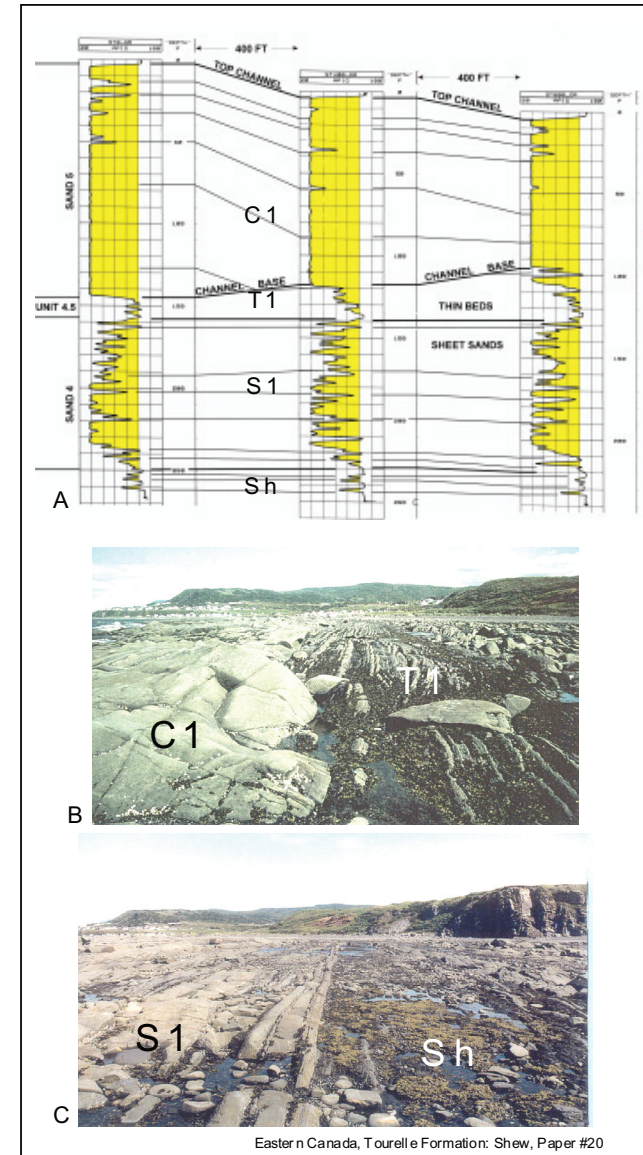


Figure 4. A) Cross section constructed from measured sections. B and C) From base to top are shales (Sh), sheets (S1 — mostly layered), thin beds (T1), and a channel (C1) cutting the thin beds. D) Statistics for each architectural element with both sandstone and shale statistical data.

Architectural Elements	
Sheetform Architectural Element	S1
Length	245 m (800 ft)
Thickness	27 m (90 ft)
Net-to-gross	85%
Outcrop orientation for this element	95°, beds near vertical
Average paleocurrent	280°
Typical facies succession	Top-missing Boumas, locally erosive bases. Mudrocks separate the sandstone beds.
Sand/Conglomerate-bed Architecture	
Bed-length range	170–>240 m (550–>800 ft)
Bed-length average	>240 m (>800 ft)
Bed-thickness range	0.1–1.2 m (0.3–3.3 ft)
Bed-thickness average	0.4 m (1.3 ft)
Texture — grain-size range; average; sorting	Fine- to coarse-grained sandstone; average medium-grained; poor sorting
Shale-bed Architecture	
Bed-length range	98–244 m (320–800 ft)
Bed-length average	>244 m (>800 ft)
Bed-thickness range	0.02–0.3 m (0.08–1.0 ft)
Bed-thickness average	0.15 m (0.5 ft)
Channelform Architectural Element	C1
Channel form	Partial: Erosive base and sharp-top, no margins exposed except the edge of erosive base
Width	>305 m (>1000 ft)
Thickness	41 m (135 ft)
Aspect ratio: Width/thickness	No margins (estimate 11:1)
Net-to-gross	95%
Outcrop orientation for this element	95°, near vertical beds
Average paleocurrent	280°
Typical facies succession	Channel base erosive. Individual beds have erosive bases, usually top-missing Boumas, local scour with clasts, and some slurry beds.
Channel infill bedding architecture	Base erosive with the lower half of the channel fill with some lateral accretion. Beds become thinner toward the top with a relatively rapid abandonment of the channel to mudrocks and minor thin beds.
Sand/Conglomerate-bed Architecture	
Bed length range	>90–>305 m (300–>1000 ft)
Bed length average	>245 m (800 ft) (margins missing)
Bed thickness range	0.3–3 m (1–10 ft)
Bed thickness average	1.3 m (4 ft) (some beds amalgamated)
Texture — grain-size range; average; sorting	Upper fine-grained to granule size; average lower coarse-grained sandstone; poorly sorted
Channel-base shale-drape coverage	None
Channel-base shale-drape thickness	None
Shale-bed Architecture	
Bed-length range	122–>305 m (400–>1000 ft)
Bed-length average	>305 m (1000 ft)
Bed-thickness range	0.02–0.30 m (0.08–1 ft)
Bed-thickness average	0.1 m (0.3 ft)
Thin-bed Architectural Element	T1
Length	>305 m (1000 ft)
Thickness	Packages are variable: 2–5 m (6.5–16 ft)
Net-to-gross	55%
Texture — grain-size range; average; sorting	Siltstone to fine-grained sandstone, average very fine-grained sandstone, poorly sorted
Outcrop orientation for this element	95°, near vertical beds
Average paleocurrent	270 to 290°
Typical facies succession	Base-missing Boumas, graded tops
Sand-bed Architecture	
Bed-length range	213–>305 m (700–>1000 ft)
Bed-length average	>305 m (>1000 ft)
Bed-thickness range	0.01–0.3 m (0.04–1.0 ft)
Bed-thickness average	0.07 m (0.25 ft)
Shale-bed Architecture	
Bed-length range	245–>305 m (800–>1000 ft)
Bed-length average	>305 m (>1000 ft)
Bed-thickness range	0.005–0.38 m (0.02–1.25 ft)
Bed-thickness average	0.1 m (0.3 ft)