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The SEDIMENTARY Record

A publication of SEPM Society for Sedimentary Geology
with the Sedimentary Geology Division of GSA

INSIDE: THE SEDIMENTARY RECORD OF MARS

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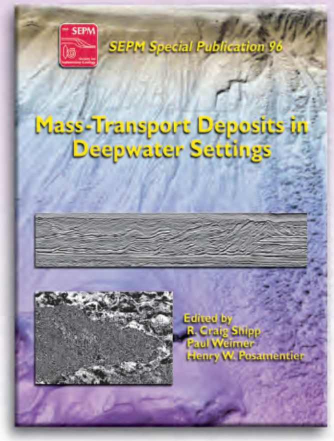
Special Publication #96

Mass-Transport Deposits in Deepwater Settings



Edited by: R. Craig Shipp, Paul Weimer, and Henry W. Posamentier

Historically, submarine-mass failures or mass-transport deposits have been a focus of increasingly intense investigation by academic institutions particularly during the last decade, though they received much less attention by geoscientists in the energy industry. With recent interest in expanding petroleum exploration and production into deeper water depths globally and more widespread availability of high-quality data sets, mass-transport deposits are now recognized as a major component of most deep-water settings. This recognition has lead to the realization that many aspects of these deposits are still unknown or poorly understood. This volume contains twenty-three papers that address a number of topics critical to further understanding mass-transport deposits. These topics include general overviews of these deposits, depositional settings on the seafloor and in the near-subsurface interval, geohazard concerns, descriptive outcrops, integrated outcrop and seismic data/seismic forward modeling, petro¬leum reservoirs, and case studies on several associated topics. This volume will appeal to a broad cross section of geoscientists and geotechnical engineers, who are interested in this rapidly expanding field. The selection of papers in this volume reflects a growing trend towards a more diverse blend of disciplines and topics, covered in the study of mass-transport deposits.

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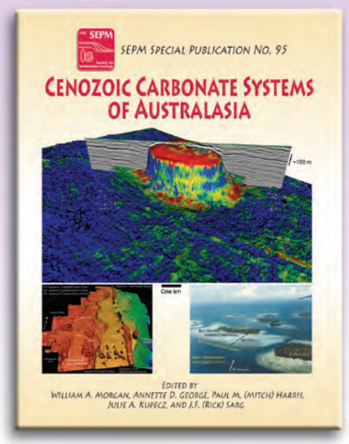

Special Publication #95

Cenozoic Carbonate Systems of Australasia

Edited by: William A. Morgan, Annette D. George, Paul M. (Mitch) Harris, Julie A. Kupecz, and J.F. (Rick) Sarg

The Cenozoic carbonate systems of Australasia are the product of a diverse assortment of depositional and post-depositional processes, reflecting the interplay of eustasy, tectonics (both plate and local scale), climate, and evolutionary trends that influenced their initiation and development. These systems, which comprise both land-attached and isolated platforms, were initiated in a wide variety of tectonic settings (including rift, passive margin, and arc-related) and under warm and cool-water conditions where, locally, siliciclastic input affected their development. The lithofacies, biofacies, growth morphology, diagenesis, and hydrocarbon reservoir potential of these systems are products of these varying influences.

The studies reported in this volume range from syntheses of tectonic and depositional factors influencing carbonate deposition and controls on reservoir formation and petroleum system development, to local studies from the South China Sea, Indonesia, Kalimantan, Malaysia, the Marion Plateau, the Philippines, Western Australia, and New Caledonia that incorporate outcrop and subsurface data, including 3-D seismic imaging of carbonate platforms and facies, to understand the interplay of factors affecting the development of these systems under widely differing circumstances.

This volume will be of importance to geoscientists interested in the variability of Cenozoic carbonate systems and the factors that controlled their formation, and to those wanting to understand the range of potential hydrocarbon reservoirs discovered in these carbonates and the events that led to favorable reservoir and trap development.

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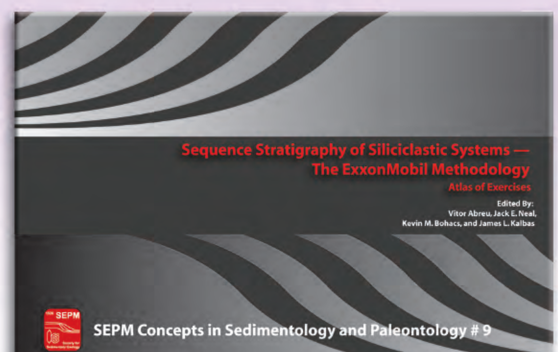
Concepts in Sedimentology and Paleontology #9

Sequence Stratigraphy of Siliciclastic Systems – The ExxonMobil Methodology

Edited by: Vitor Abreu, Jack E. Neal, Kevin M. Bohacs and James L. Kalbas

The stratigraphic concept of a depositional sequence was introduced to the scientific literature by Exxon Production Research Company (EPRco) in the late 70s, building on the shoulders of giants like Chamberlain, Sloss and Wheeler. Since then, several papers compared and contrasted the original Exxon (and later, ExxonMobil) sequence-stratigraphic school with other approaches to subdivide the geologic record, as well as, debating the ExxonMobil model validity and impact on the community. At its core, the ExxonMobil "model" is really a stratigraphic interpretation method, which was never explicitly documented in the literature. The objective of this book is to present the ExxonMobil sequence stratigraphic method in its current form in an attempt to clarify its usage and application in diverse geologic data and depositional environments. This publication is the result of more than 3 decades of sequence stratigraphy research and application at EPRco and at the ExxonMobil Upstream Research Company (URC). The objective is to emphasize the most important aspects of Sequence Stratigraphy – a method to guide geologic interpretation of stratigraphic data (seismic profiles, well-logs, cores and outcrops) across scales (from local to regional and global) and depositional environments (from continental to deep marine).



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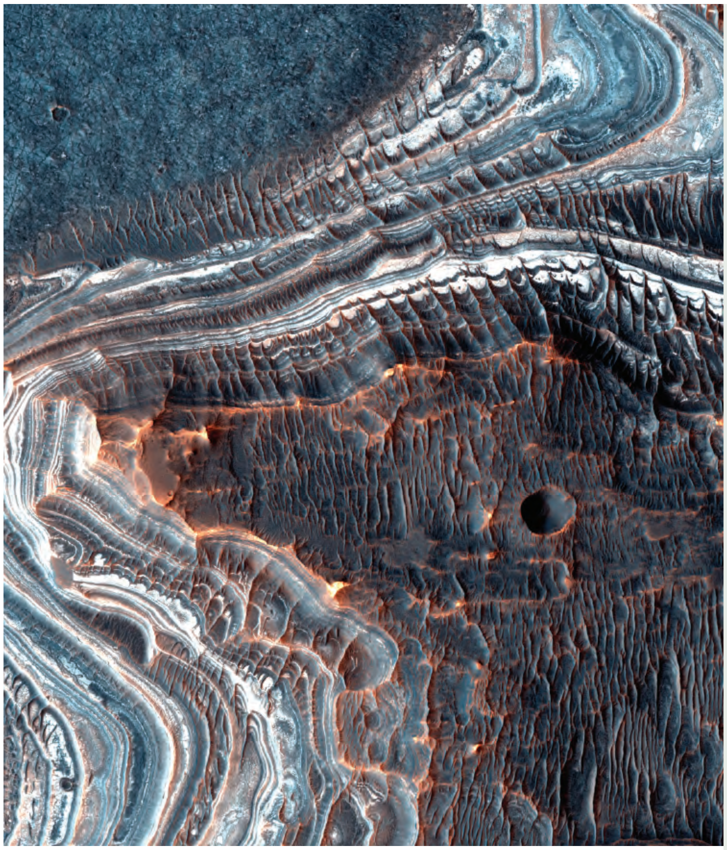

Cover art: Portion of HiRISE image PSP_003434_1755 showing the plains west of Juventae Chasma. In this region, finely stratified layers form narrow, sinuous laminations that are continuous for up to tens of kilometers. These layers are thought to be in part composed of opaline silica among other minerals. Image is 1.2 km across.

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The Sedimentary Record of Mars

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INTRODUCTION

Mars presents a remarkable opportunity for geologists interested in early evolution of terrestrial planets. Although similar to the Earth in several respects, there are a number of differences that make comparative analysis of the two planets a rewarding study in divergence and evolution of surface environments on terrestrial planets. Perhaps the most intriguing is the geologic evidence for a wet ancient climate despite the unlikelihood that Mars' current climate could support extensive liquid water. Incision of bedrock by fluvial channels provides the cannonical line of evidence used to support this nonuniformitarian interpretation of climate history. However, carved channels provide evidence only for the integrated effects of the event and not so much a sense for how conditions may have evolved between Mars' early wet phase and its current dry phase. It is significant therefore, that the growing evidence for a sedimentary record on Mars creates the possibility to observe a time series of environmental evolution – a record that can be compared to that of Earth across the same time interval.

Sedimentary rocks on Mars have been known for only the past decade (Malin and Edgett, 2000). Data collected over the past five years by the Mars Express and Mars Reconnaissance Orbiter (MRO) spacecraft have shown the widespread distribution of these sedimentary rocks. It is remarkable how similar some of these of these rocks are to those formed on Earth, including evidence of transport, deposition, and diagenesis in water. Phyllosilicate-rich strata form terminal deposits of source-to-sink systems with well-developed fluvial networks (Metz et al. 2009; Ehlmann et al., 2008) whereas in other cases sulfate-rich deposits form thick successions analogous to terrestrial evaporites (Grotzinger et al., 2005). On the other hand, there are deposits whose origin may differ significantly from terrestrial processes, including thick veneers of strata that may have formed entirely from settling of wind-transported dust (Bridges et al., 2010). Mars science is in its golden era of exploration and the past decade of orbiter and landed missions has produced an extraordinary amount of new data relevant to the analysis of sediments and sedimentary rocks. These new data provide an excellent opportunity for the terrestrial Sedimentary Geology community to become involved in frontier research on Mars.

In April of 2010, the First International Conference on Mars Sedimentology and Stratigraphy was convened in El Paso, Texas for the purpose of reviewing the status of the field and what its major discoveries have been. Following two days of talks a field trip was led to the Guadalupe Mts., with emphasis on rocks that might be suitable analogs, particularly sulfate evaporites. This report summarizes some of the key conference conclusions, and the general state of understanding of Mars sedimentary geology (see also Grotzinger et al. 2011).

HISTORY AND THE STRATIGRAPHIC RECORD OF MARS

The formation of sedimentary minerals on Mars shows evidence of time-dependent transitions in the history of sedimentary mineral formation. These transitions may define global environmental breakpoints (Figure 1), just as the Earth's sedimentary rock record (e.g. banded iron formation) has been used as a proxy for understanding its evolution. Global mineralogical mapping of Mars shows an evolution from a Noachian (4.5 - ~3.7 Ga) era that generated clay minerals (wet, neutral pH Mars), to a Hesperian (~3.7 - ~3.2Ga) era marked by sulfate generation (wet, acidic pH Mars), to an Amazonian (~3.2 – 0.0 Ga) era dominated by formation of anhydrous ferric oxides (dry Mars; Bibring et al., 2006; McLennan and Grotzinger, 2008; Murchie et al., 2009; Milliken and Bish, 2010). These inferences based on global mapping are now being tested by mapping vertical stratigraphic sections that show upward changes in mineral composition.

The succession of sedimentary rocks at key reference sections (e.g. Gale crater; Milliken et al., 2010) appears to support the hypothesis that sulfate-rich strata succeeded clay-rich strata in time. In detail, there is evidence that this transition may also be gradational due to interbedding of the two mineralogically-defined facies (see Figure 2). In contrast, there are some places where the stratigraphic order of minerals may be reversed (e.g. Wray et al., 2010). It is clear that more work is required to establish the global nature and timing of sedimentary mineral deposition.

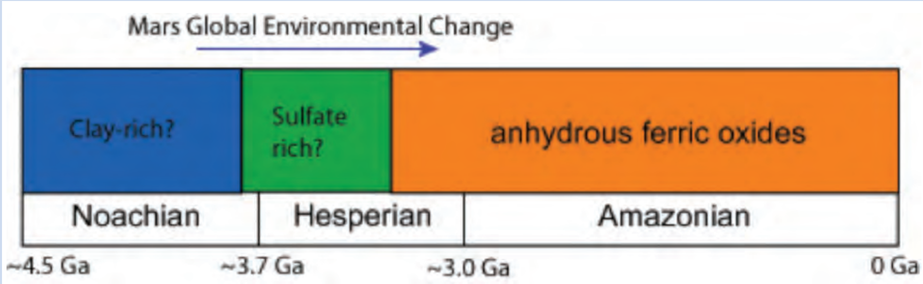

Figure 1. Model for the mineralogic evolution of Mars surface environments through time (after Bibring et al., 2006).

MECHANISMS FOR SEDIMENT PRODUCTION ON MARS

Sediment production on Mars occurs through physical and chemical weathering, but physical weathering likely dominates over chemical weathering, as compared to Earth. Significant volumes of sediment have been generated on Mars as inferred by the presence of sedimentary strata, eolian bedforms, fluvial networks, glacial ice caps, and blankets of impact ejecta. Physical weathering is known to be promoted by eolian abrasion, thermal stress, permafrost processes, and gravity-driven mass-wasting (Bell et al., 2004; Squyres et al., 2004). Bedrock erosion by eolian saltation-induced impact abrasion appears to have been an important ongoing process at the Martian surface. In the geologic past, fluvial incision of bedrock would have likely been driven by saltation abrasion and rock plucking.

Chemical weathering appears to have substantially differed from the behavior of Earth's carbon cycle for significant portions of Martian geologic history. Instead, chemical weathering likely occurred within a sulfur cycle dominated by low pH, water limitation, and cold environments (Hurowitz & McLennan, 2007; McLennan & Grotzinger, 2008), where chemical reactions did not proceed to completion (Madden et al., 2004; Tosca & Knoll, 2009) and were instead terminated by freezing and evaporation (Zolotov & Mironenko, 2007).

Lastly, a very insignificant earth process, albeit with great Martian significance would have been impact shattering of bedrock. This was also a key process for regolith generation on the moon (Haskin et al., 2003; Petro and Pieters, 2008), and would likely have been the case for Mars, particularly early on in its history when the flux of impacts was highest. However, in contrast to the Moon, the presence of a significant atmosphere and high *g* (~0.4 Earth) led to lateral transport of impact regolith by wind, water, and gravity. This may have created a rock record consisting of impact-derived debris, reworked by surface processes, to form significant sedimentary deposits ultimately derived from impact generated regolith (Figure 3).

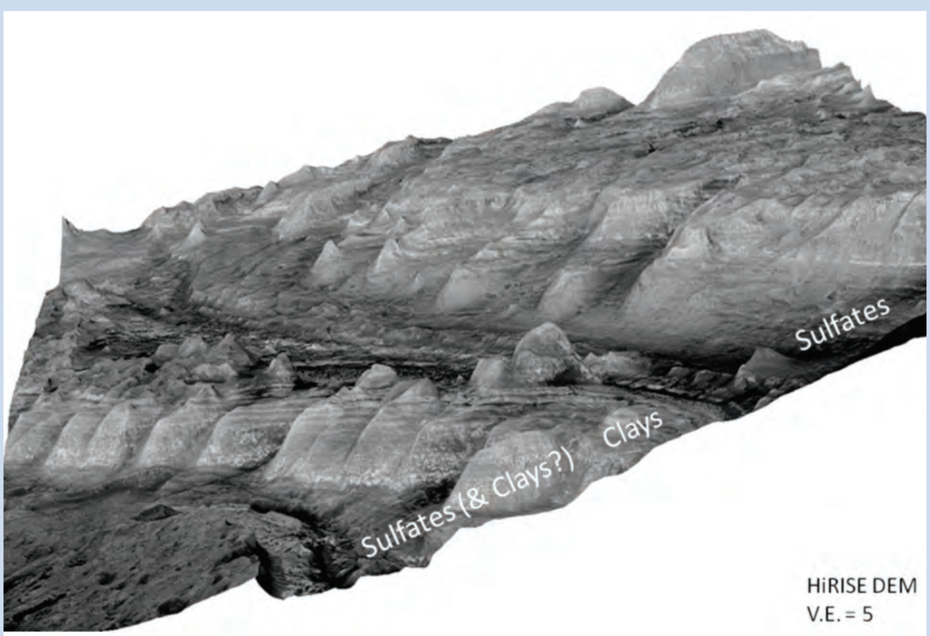

Figure 2. Perspective view of lower Gale mound deposits showing stratigraphic change from clay-rich strata to overlying sulfate-rich strata (Milliken et al., 2010). The mineralogy of beds correlates with changes in stacking patterns such that clay-rich strata tend to be thin-bedded whereas sulfate-rich units show thicker, possibly amalgamated, bedding. This image shows exposures through a section about 300 m high, as viewed to the south; the complete stratigraphic section at Gale exceeds 5000 m.

CHANNELS AND DISTRIBUTARY NETWORKS

Fluvial valley networks, exhumed meandering and branched distributary channels, deltaic sediment bodies formed in ancient crater lakes, and channel-linked crater-lake chains are all characteristic of the Noachian to early Hesperian surface of Mars (Figure 1) (Grant and Parker, 2002; Fassett and Head, 2008; Pondrelli et al., 2008). The end of Noachian time records a dramatic change in martian fluvial systems; huge equatorial outflow channels from pressurized groundwater sources episodically debouched into the Northern Lowlands (Warner et al., 2009), perhaps forming transient seas. The regions from which these outflows emerge locally contain layered sedimentary strata that host sulfate minerals. Sometimes they are brecciated at a scale of tens to hundreds of km, forming "chaos" terrain. Other strata within depressions of the great Vallis Marineris system have been interpreted as sub-lacustrine fan deposits (Metz et al., 2009), representing terminal sediment sinks (e.g. Figure 4).

In addition, there appear to be vast deposits (km-scale thick, hundred-to-thousand km-scale lateral extent) of wind-blown dust, analogous perhaps to terrestrial loess deposits, but deposited on a scale unlike anything that ever occurred on Earth (see Figure 5; Bridges et al., 2010; Lewis et al., 2008). In the absence of rainfall over hundreds of millions to billions of years it is conceivable that dust could have accumulated to form enormous deposits.

DISTRIBUTION AND ACCUMULATION OF SEDIMENTS

Sedimentary deposits have been identified across the southern hemisphere and near the equator of Mars, and in a fewer number of locations in the northern hemisphere (Figure 5). A variety of eolian facies tracts (Grotzinger et al., 2005), alluvial geomorphological

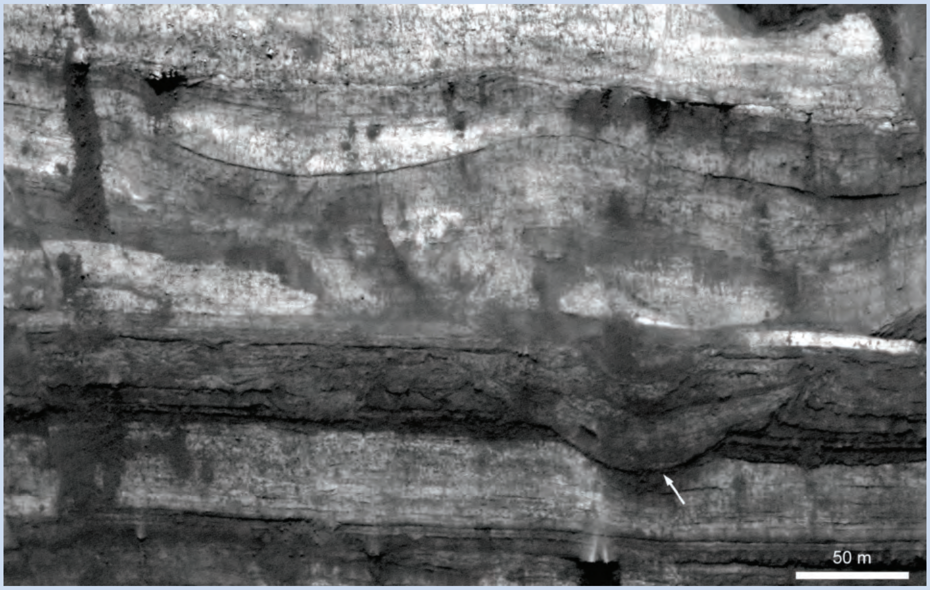

Figure 3. Strata exposed on the gently-sloping wall of a crater in the Mawrth Vallis region. An important feature of the strata is an inferred buried impact crater (arrow). Note dark stratigraphic unit pierced by impact depression that is also marked by overturned strata along right margin. Younger strata onlap margins of paleo-crater and bounding strata may represent reworking of impact-derived detritus.

elements (Pondrelli et al., 2008), and sub-lacustrine sediment fan deposits (Metz et al., 2009) have been documented. Most of these occurrences are preserved as erosional remnants and so it is suspected that the sedimentary record was previously much more continuous than it is today.

Lithospheric subsidence is not the primary mechanism for creating accommodation space on Mars. The Valles Marineris rift valley system is a spectacular but unique case of anomalous sediment accumulation up to several km-thick. It is a site of a significant (almost continuous from end to end) sedimentary accumulation (Figure 5). Generally, regional topographic lows evidently resulted from the removal of uppermost crust during impacts that created multi-ring crater basins. At a much smaller scale, single impact craters represent sites (Figure 5) very prone to sediment accumulation and preservation (i.e. the cores of remnant buttes are often preserved in crate interiors; Loizeau et al., 2008).

Subsurface ice and liquid water of capillary fringes above underground water tables were certainly essential to the cementation of unconsolidated sedimentary deposits (McLennan et al., 2005). Oscillations in the water level of lakes formed in Early Mars topographic enclosures may have organized sedimentary accumulations into distinct depositional units that define patterns of baselevel change. Typical stratal geometries associated with prograding clinoforms (i.e. truncations, onlap and downlap features) have been observed (Dromart et al., 2007).

DIAGENESIS

Alteration minerals such as clays and chemical precipitates (sulfates, chlorides, sedimentary silica, etc.) contain information useful in deciphering the evolution of Mars' surficial environment. Existing image data provides clear evidence for a range of diagenetic textures, that should be familiar to Earth scientists (e.g. Figure 6). On the downside it can be difficult to reconstruct primary processes given the overprint of diagenetic textures in ancient rocks (e.g., McLennan et al. 2003), and Mars is no exception.

Sulfate-rich sandstone outcrops examined by the *Opportunity* rover (Figure 6) show evidence of spatially variable recrystallization (McLennan et al., 2005; Tosca et al., 2005). This is expressed through disruption of primary rock textures in addition to mineral phase changes. The apparent persistence of amorphous silica in ancient sedimentary deposits helps constrain the thermal and fluid/rock regime of at least some specific Martian diagenetic environments (Tosca and Knoll, 2009). This observation suggests that silica-bearing deposits did not experience sustained interaction with fluids after their initial formation and thereafter remained stable for billions of years. In a similar way, the composition of martian clays (e.g., mixed-layered or illitic) indicates the extent to which they have experienced post-depositional heating or interaction with fluids. Understanding the effects of burial diagenesis and impact processes on martian sediments remains an important area of study because of its implications for preservation of organic carbon. In general, cementation and lithification processes on Mars remain poorly understood due to the absence of all but a handful of well-studied *in situ* surface locations.

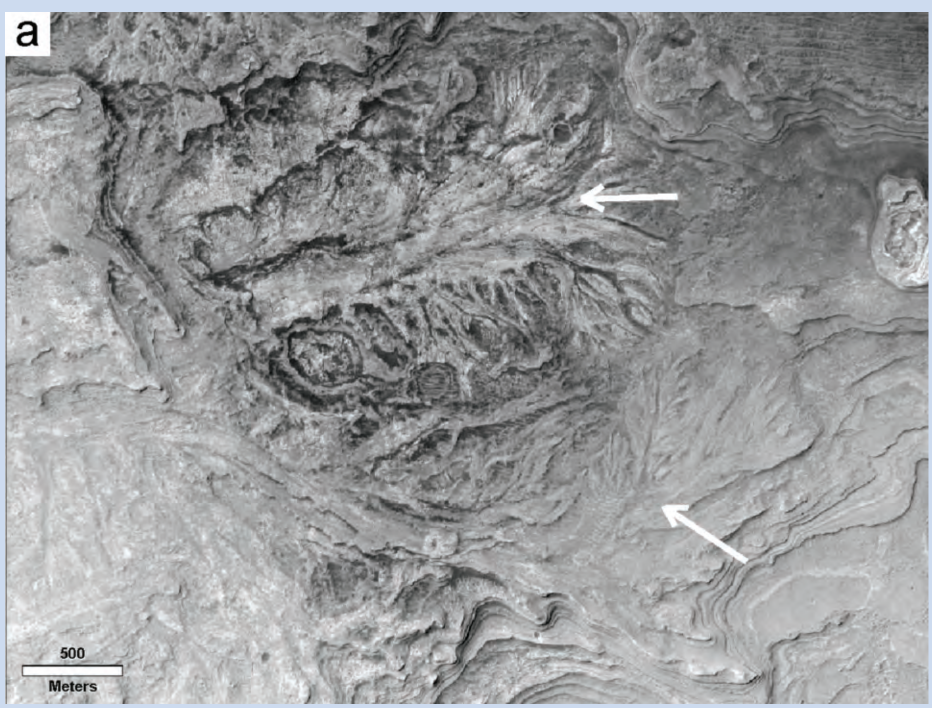

Figure 4. Interpreted sub-lacustrine fan systems in Southern Melas Basin, Valles Marineris (Metz et al., 2009).

CONCLUSIONS

The dynamics and evolution of Martian surface environments is preserved within a well-defined record of sedimentary rocks. The preserved record overlaps in age with the earliest record on Earth, even predating the oldest terrestrial rocks; the oldest Martian sedimentary rocks likely exceed 4 billion years. Younger Martian strata are comparable in age to Archean rocks on Earth but these Martian strata bear evidence for a dramatic divergence in the evolution of Mars' surface environments relative to Earth. As a result of the absence of plate tectonics and crustal recycling on Mars, the stratigraphic record on Mars is not just older but sedimentary textures may be better preserved, given the absence of overprinting thermal/metamorphic effects or penetrative deformation. Lower thermal overprints and water/rock ratios during diagenesis are suggested by the presence of unexpected minerals such as amorphous silica and smectites in rocks that are billions of years old. Consequently, the record of Martian strata may permit analysis of a dramatically different environmental course featuring global change from a wet, pH-neutral planet to a drier, more acidic environment. Comparative analysis with Earth's stratigraphic record yields the extraordinary opportunity to evaluate two terrestrial planets whose surface processes were subject to different initial and boundary conditions, including gravitational constant, degree of crustal differentiation, atmospheric properties, and liquid water composition.

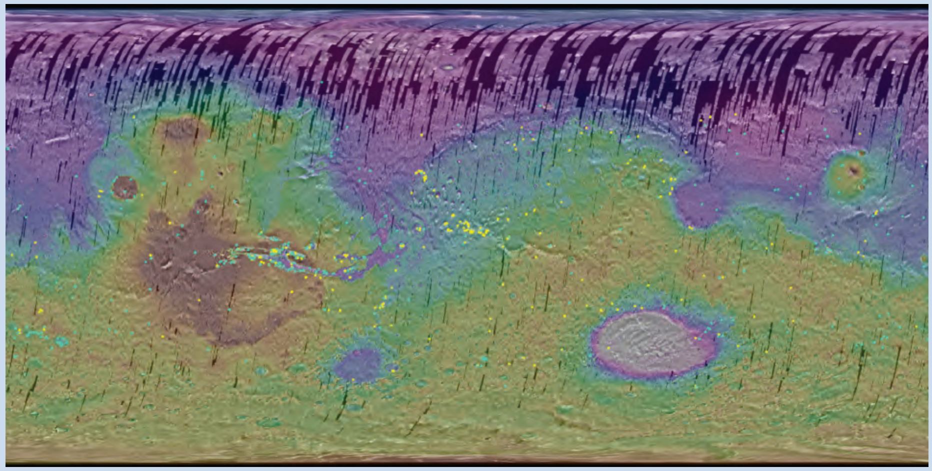

Figure 5. Distribution of sedimentary rocks on Mars plotted on map showing topography of Mars. Blue dots correspond to strata exposed inside of craters or wallrock of major canyon systems such as Vallis Marineris (high concentration of blue dots in center left part of image). Yellow dots correspond to strata preserved on plains away from obvious topographic depressions.

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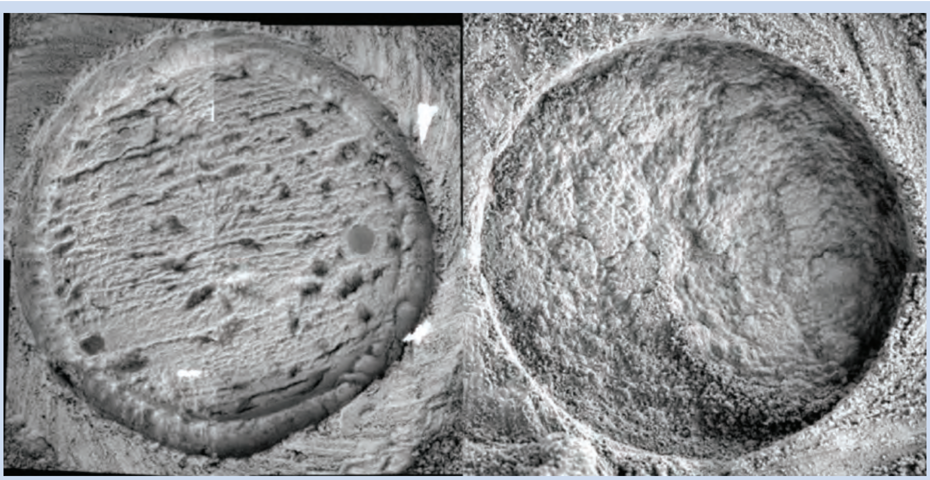

Figure 6. Textures consistent with recrystallization of sulfate-rich sediments. Left; well-stratified sulfate-rich sandstone showing crystal molds after unknown (possibly sulfate) mineral, and hematitic concretions, some of which are rimmed by later cement. Right; recrystallization results in homogenization and more coarsely crystalline texture. See McLennan et al. (2005). Each grind hole is ~4.5 cm in diameter.

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SEDIMENTARY RECORD ONLINE BOOK REVIEW

The revolution in geology from the Renaissance to the Enlightenment

edited by Gary D. Rosenberg, 2009. GSA Memoir Series # 203

PRESIDENT'S COMMENTS

It is my pleasure to write these remarks as the incoming President of SEPM. Thanks are due to Mitch Harris for his recently-completed year of leadership. Many of us recently enjoyed a variety of excellent activities at the last Annual Conference and Exhibition (ACE) in Houston, TX, and as always it was a great occasion. It was an honor to be in attendance at the Annual SEPM Awards Ceremony and to see some of our most esteemed colleagues receive awards in recognition of their contributions to science. Our business luncheon was again well-attended, and we were entertained and informed by a superb talk by John Grotzinger on the plans for Martian geological exploration. As always, SEPM played a major role in shaping the scientific program of the ACE, and I wish to convey our thanks to the many individuals who helped to bring that about. The SEPM booth in the Exhibition Hall was well-frequented, and the focal point for many fruitful conversations.

Behind the scenes, the SEPM HQ staff continues to work towards the updating of society facilities. You may have noticed their efforts to modernize the Society webpages, and that effort continues. We apologize for any temporary frustrations experienced by members during this period of transition. We live in a time of rapid change, many aspects of which affect the Society. Council, in collaboration with HQ staff and our editorial personnel, are striving to maintain SEPM at the forefront of Sedimentary Geology, and you will see some substantial changes to the way we operate in the foreseeable future. This is nowhere more important than in the evolving nature of scientific publications, a major part of our core business.

One project that we are engaging in this year is to help increase the profile and presence of Sedimentary Geology at the Geological Society of America Annual Meeting. This will be achieved in part through a greater level of collaboration with the Sedimentary Geology Division of GSA. Our efforts have already resulted in the availability of a much broader and larger array of technical sessions for the coming meeting in Minneapolis, MN, than has been seen in the past couple of years. SEPM will be seeking to have a stronger role in setting the scientific program for future GSA meetings. This is particularly important to our members as for many it is the meeting of choice for presenting scientific results, and it serves a somewhat different constituency than the AAPG/SEPM ACE.

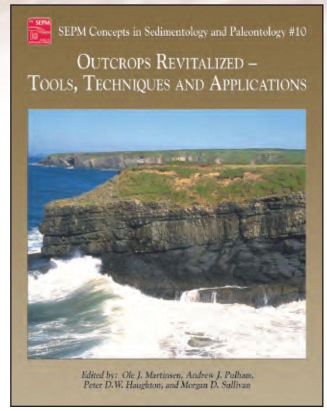
For those of you who, like me, are heading into the field, happy hunting!

Chris Fielding

COMING SOON

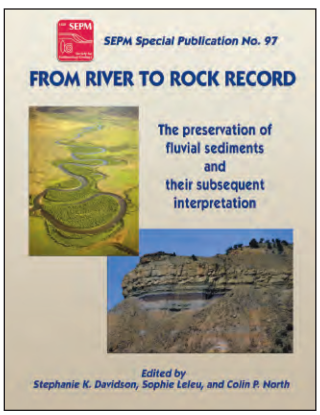
SEPM Books in the publication pipeline

Outcrops Revitalized-Tools, Techniques and Applications



Edited by: Ole J. Martinsen, Andrew J. Pulham, Peter D.W. Haughton, and Morgan D. Sullivan

This printed volume based on the 2008 SEPM Research Conference of the same name held in Kilkee, Ireland is planned as Concepts in Sedimentology and Paleontology #10. It contains chapters about the latest ways to study outcrops and to use the results across a wide range of geological applications. The book is laid out for use as an upper level text book or reference for outcrop studies. Volume sponsorship is from Statoil and SEPM Foundation. This book is in press and will be available very soon - look for the email announcement.



From River to Rock Record: The Preservation of Fluvial Sediments and Their Subsequent Interpretation

Edited by: Stephanie K. Davidson, Sophie Leleu, and Colin P. North

This Special Publication Series volume is based on the 2009 River to Rock Conference held in Aberdeen, Scotland. This will be a printed volume with an included CD which holds a full color digital copy of the book and supplementary data. this book is in the final production phases and should be out this summer - look for the email announcement.

Permian Rotliegend of the Netherlands

Edited by: Jürgen Grötsch and Reinhard Gaupp

This Special Publication volume will be full color printed book in A4 size. The contents are based on a core workshop commemorating the 50th anniversary of Rotliegend production. There will be an extensive selection of core photos accompanying the chapters describing all aspects of this important reservoir. This book has special sponsorship from Shell. This book is in the final editing stages and should be out by Fall, 2011.

Application of Seismic Geomorphology Principles to Continental Slope and Base-of-Slope Systems: Case Studies from Seafloor and Near-Seafloor Analogues

Edited by: Bradford E. Prather, Mark E. Deptuck, David Mohrig, Berend van Hoorn, and Russell B. Wynn

This Special Publication volume is based on the 2009 SEPM Research Conference of the same title held in Houston, TX. This volume is planned as digital online and CD version. Shell sponsorship will make the online version free access at www.sepmonline.org. The CD version will contain the full resolution version of all images. This book is in the final editing stages and should be out by Fall, 2011.

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SEPM Research Conference Deciphering Paleoclimatic Signals from Continental Successions

Truro, Nova Scotia • August 2 - 6, 2011

There is now an increased awareness of the potential of continental stratigraphic archives (fluvial, lacustrine, eolian, glacial, paleosol, etc.) for providing highly resolved records of environmental change over geological timescales. This meeting brings together researchers from the various cognate disciplines to review the state of the art, consider the potential for future advances and discuss potential applications of this area of research to resource exploration. We anticipate that papers presented at the meeting will form the basis for an SEPM Special Publication.

The conference will combine oral and poster presentation sessions with field excursions to facilitate discusssion on a wide range of topics. The meeting's field trips with focus on the Carboniferous Maritime Basin and Mesozoic Fundy Basin in mainland Nova Scotia, where there are spectacular exposures of successions germane to the conference theme. These include the World Heritage listed Joggins Cliffs. Truro is centrally located ot the outcrops of interest and is within 60 minutes drive from Halifax International Airport.

For further information contact:

Chris Fielding (cfielding2@unl.edu) or Jon Allen (jonathan.allen@chevron.com).

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