Orbital Periodicities Reflected in Ancient Surfaces of our Solar System and the Implications for a Record of Early Life

Dixie Lee Androes

University of Arkansas, Fayetteville

Follow this and additional works at: http://scholarworks.uark.edu/etd

Part of the Geology Commons, Geomorphology Commons, and the The Sun and the Solar System Commons

Recommended Citation

Androes, Dixie Lee, "Orbital Periodicities Reflected in Ancient Surfaces of our Solar System and the Implications for a Record of Early Life" (2012). Theses and Dissertations. 560.

http://scholarworks.uark.edu/etd/560

This Dissertation is brought to you for free and open access by ScholarWorks@UARK. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of ScholarWorks@UARK. For more information, please contact scholar@uark.edu, ccmiddle@uark.edu.
ORBITAL PERIODICITIES REFLECTED IN ANCIENT SURFACES OF OUR SOLAR SYSTEM AND THE IMPLICATIONS FOR A RECORD OF EARLY LIFE
ORBITAL PERIODICITIES REFLECTED IN ANCIENT SURFACES OF OUR SOLAR SYSTEM AND THE IMPLICATIONS FOR A RECORD OF EARLY LIFE

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Space and Planetary Science

By

Dixie Spongberg Androes
University of Arkansas
Bachelor of Science in Earth Science, 2004
University of Arkansas
Master of Science in Geology, 2006

August 2012
University of Arkansas
ABSTRACT

Uniformitarian processes, governed by invariant physical laws, remain the most reliable source for reconstructing the past. Driving many of the repetitive, predictable processes are the orbital dynamics of the Sun-Planet-Moon systems. Astronomical periodicities range from a few hours (tides) to thousands of years (Milankovitch). These periodicities, combined with geomorphic observations of planetary surfaces, constrain the time-dependent processes and allow for reconstruction of events and conditions favorable for sedimentary accumulations. This research suggests that seasonal sedimentary processes are dominant on Titan and Mars, and have played a significant role in the formation of ancient banded-iron formations (BIF’s) on Earth.

Earth, Mars, and Titan, the planetary bodies in our solar system with a history of flowing liquids, are characterized here to preserve seasonal and longer-period orbital signatures in layered strata. Surface features also suggest that volatile transient liquids, subject to solid phase sequestering, are dependent not only on climate forcing, but additionally on unique physiographic features of the planetary body. Climate change is subject to longer period orbital oscillations such as precession, eccentricity, and obliquity, and to the rise in or loss of surface liquids (oceans and seas) and atmospheres.

Thickness and mineralogy time-series profiles from the Dales Gorge Member of the Brockman Iron Formation suggest cycles and periodicities similar to modern current velocity profiles. First-order sinusoidal series patterns are interpreted as seasonal changes in bidirectional movement of ocean floor sediment, displaying second-order tidal influence. Sedimentary accumulations consist of iron-donmate organic sequences linked to slower current movement
alternating with silica-dominate sequences indicative of modestly higher energy currents. Directional current oscillations may also contribute to changing mineralogy.

Titan and Martian’s surfaces also demonstrate active seasonal processes. Rivers within Titan’s northern polar region carry sediments from the more distal highland, through rugged foothills, to the lowland basins. Headward erosion during dynamic hydrocarbon seasonal rains carves the present valley and ridge systems on the flanks of the highlands. This research predicts that layered seasonal sedimentary varves have accumulated in the large endohoreic basin in the northern polar region of Titan.
This dissertation is approved for recommendation to the Graduate Council

Dissertation Director:

____________________________________________

Dr. John Dixon

Dissertation Committee:

____________________________________________

Dr. Timothy Kral

____________________________________________

Dr. Daniel Kennefick

____________________________________________

Dr. Doy Zachry

____________________________________________

Dr. Stephen Pompea (ex officio)
DISSEf\'{\text{E}}TATION DUPLICATION RELEASE

I hereby authorize the University of Arkansas Libraries to duplicate this dissertation when needed for research and/or scholarship.

Agreed

Dixie Spongberg Androes

Refused

Dixie Spongberg Androes
ACKNOWLEDGEMENTS

Special thanks go out to the faculty and staff of the University of Arkansas, the University of Arkansas Graduate School, and the Smithsonian Institute of Natural History, Rock and Ore Collections, Washington, D.C., and Cindy Sigmon, a dear friend and research assistant. Tremendous appreciation is also extended to my advisor, Dr. John Dixon, and each of my committee members for their patience and endurance through the years. Finally, and most importantly, my sincere gratitude to my husband, children, and friends who have abided with me and faithfully supported me through my college experiences.
DEDICATION

This dissertation is the product of years of study and research; however, the years of study and research pale in comparison to the years of devotion extended to me by my parents, Charles and Marilyn Spongberg. I wish to dedicate the hours and years of work to my parents with heartfelt thanks and love.
# TABLE OF CONTENTS

## I. INTRODUCTION

### CHAPTER ONE: Orbital Periodicities Reflected in Ancient Surfaces

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <strong>Background</strong></td>
<td>2</td>
</tr>
<tr>
<td>1.1 Research Objectives</td>
<td>2</td>
</tr>
<tr>
<td>1.2 Problems Addressed in this Research</td>
<td>3</td>
</tr>
<tr>
<td>2. <strong>Radiative Forcing</strong></td>
<td>7</td>
</tr>
<tr>
<td>2.1 Solar Radiation</td>
<td>8</td>
</tr>
<tr>
<td>2.2 The Solar Constant</td>
<td>8</td>
</tr>
<tr>
<td>2.3 Insolation Oscillations</td>
<td>10</td>
</tr>
<tr>
<td>2.4 Climate</td>
<td>13</td>
</tr>
<tr>
<td>2.4.1 Regional Climate Components</td>
<td>13</td>
</tr>
<tr>
<td>2.4.2 Climate Observations for Earth, Mars, and Titan</td>
<td>15</td>
</tr>
<tr>
<td>2.4.3 Earth Climate and Insolation Oscillations</td>
<td>17</td>
</tr>
<tr>
<td>2.4.4 Martian Climate and Insolation Observations</td>
<td>19</td>
</tr>
<tr>
<td>2.4.5 Titan Climate and Insolation Observations</td>
<td>20</td>
</tr>
<tr>
<td>3. <strong>Astronomical Forcing</strong></td>
<td>25</td>
</tr>
<tr>
<td>3.1 Orbital Components</td>
<td>25</td>
</tr>
<tr>
<td>3.2 Obliquity</td>
<td>26</td>
</tr>
<tr>
<td>3.3 Eccentricity</td>
<td>27</td>
</tr>
<tr>
<td>3.4 Precession</td>
<td>28</td>
</tr>
<tr>
<td>4. <strong>Orbital Periodicities</strong></td>
<td>29</td>
</tr>
<tr>
<td>4.1 Earth’s Long-Period Cycles</td>
<td>31</td>
</tr>
<tr>
<td>4.2 Mars’ Orbital Periodicities</td>
<td>34</td>
</tr>
<tr>
<td>4.3 Titan’s Orbital Periodicities</td>
<td>35</td>
</tr>
<tr>
<td>5. <strong>Tidal Forcing</strong></td>
<td>37</td>
</tr>
<tr>
<td>5.1 Tidal Force</td>
<td>37</td>
</tr>
<tr>
<td>5.2 Tidal Friction</td>
<td>38</td>
</tr>
<tr>
<td>5.3 Tidal Bulging</td>
<td>39</td>
</tr>
<tr>
<td>5.4 Earth/Moon Tide System</td>
<td>41</td>
</tr>
<tr>
<td>5.4.1 Tidal Periodicities</td>
<td>41</td>
</tr>
<tr>
<td>5.4.2 Tidal Sequences</td>
<td>42</td>
</tr>
<tr>
<td>6. <strong>Ocean Currents</strong></td>
<td>45</td>
</tr>
<tr>
<td>6.1 Ocean Flow Regimes</td>
<td>46</td>
</tr>
</tbody>
</table>
6.2 Ocean Chemistry and Biology 47
6.3 Origin of Earth’s Ocean and Atmosphere 49
  6.3.1 Rise of Oxygen 50
  6.3.2 Ocean Sediment Oxidation 52

7. Ancient Surfaces and Geomorphology 54
  7.1 Titan’s Surfaces 55
  7.2 Martian Surfaces 56
  7.3 Earth’s Ancient Surfaces 59

II. DOCTORAL DISSERTATION 60

CHAPTER TWO: Periodicities and Profiles of Banded Iron Formations 60
  1. Introduction 61
    1.1 BIF Controversies 61
    1.2 BIF Classifications 63
  2. Depositional Environment of BIF’s 66
    2.1 Source of Sediments 67
    2.2 Microbial Induced Sedimentary Structures 68
  3. Methods 71
  4. Results 74
  5. Discussions 77
    5.1 Source of Iron and Silica 78
    5.2 Silica and Iron Banding 80
  6. Conclusions 84

CHAPTER THREE: Banding Cyclicity for the Dales Gorge Member of the Brockman Iron Formation 85
  1. Introduction 85
  2. Hamersley Group BIF 87
    2.1 The Brockman Iron Formation of the Hamersley Group 88
    2.2 The Dales Gorge Member of the Brockman Formation 90
  3. Methods 92
  4. Results 96
    4.1 Band Identification 97
    4.2 Microbands and Mesobands 99
    4.3 Macrobands 104
  5. Discussions 105
  6. Conclusion 115

CHAPTER FOUR: Climate Forcing and Phase Sequestering for Earth, Mars, and Titan 117
  1. Introduction 118
  2. Methods 122
III. CONCLUSION 168

CHAPTER SEVEN: Ancient Surfaces and the Implications for Preserving a Record of Life 168

1. Requirements for Life 168
   1.1 Finding Life in Ancient Rocks 169
   1.2 Martian Life 172
   1.3 Titan Life 174

2. Astronomical Clocks 176
LIST OF FIGURES

INTRODUCTION FIGURES:

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Solar Angle sine curve of declination (Androes)</td>
<td>10</td>
</tr>
<tr>
<td>1.2</td>
<td>Northern Hemisphere Insolation in Wm$^{-2}$ (Androes)</td>
<td>11</td>
</tr>
<tr>
<td>1.3</td>
<td>Solar Spectral Radiation (NCDC/NOAA US Government Open Files)</td>
<td>12</td>
</tr>
<tr>
<td>1.4 -1.7</td>
<td>Climate Graphs NCDC/NOAA US Government Open Files)</td>
<td>14-15</td>
</tr>
<tr>
<td></td>
<td>Figure 1.4 Omaha, Nebraska</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Figure 1.5 New Orleans, Australia</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Figure 1.6 Berbera, Somalia</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Figure 1.7 Andegoya, Columbia</td>
<td>15</td>
</tr>
<tr>
<td>1.8</td>
<td>Reconstructed Temperatures (R. Rohde 2000)</td>
<td>17</td>
</tr>
<tr>
<td>1.9</td>
<td>Holocene Temperature Variations (R. Rohde 2000)</td>
<td>17</td>
</tr>
<tr>
<td>1.10</td>
<td>Earth’s Insolation Oscillations (Adapted from NCDC/NOAA)</td>
<td>18</td>
</tr>
<tr>
<td>1.11</td>
<td>Martian Insolation Oscillations (Adapted from NASA)</td>
<td>19</td>
</tr>
<tr>
<td>1.12</td>
<td>Saturn &amp; Titan Insolation Oscillations (Adapted from Aharonson 2009)</td>
<td>20</td>
</tr>
<tr>
<td>1.13</td>
<td>Titan’s Mean Daily Insolation (Schaller et al. 2006)</td>
<td>21</td>
</tr>
<tr>
<td>1.14</td>
<td>Obliquity and Nutation at Mid- and High Latitude (Androes)</td>
<td>27</td>
</tr>
<tr>
<td>1.15</td>
<td>Precession of the Equinoxes (Androes)</td>
<td>29</td>
</tr>
<tr>
<td>1.16</td>
<td>Milankovitch Cycles (Adapted from NASA)</td>
<td>32</td>
</tr>
<tr>
<td>1.17</td>
<td>Martian Cycles (Adapted from NASA)</td>
<td>34</td>
</tr>
<tr>
<td>1.18</td>
<td>Viking Lander records atmospheric pressure on Mars (NASA)</td>
<td>35</td>
</tr>
<tr>
<td>1.19</td>
<td>Geostrophic Flow (NASA/GSFC R. Ray)</td>
<td>45</td>
</tr>
<tr>
<td>1.20</td>
<td>Zonal Current Data (TAO Project/NOAA)</td>
<td>46</td>
</tr>
<tr>
<td>1.21</td>
<td>Jack Hills Fluid Inclusions (Cavosie 2004, Valley 2006)</td>
<td>50</td>
</tr>
<tr>
<td>1.22</td>
<td>Victoria Crater layered sediments (NASA/JPL)</td>
<td>54</td>
</tr>
<tr>
<td>1.23</td>
<td>Iron rich Martian spherules (NASA/JPL)</td>
<td>57</td>
</tr>
<tr>
<td>1.24</td>
<td>Martian sedimentary layers (NASA/JPL)</td>
<td>57</td>
</tr>
</tbody>
</table>

DISSESSATION FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Depositional Environment of BIF in Forearc Basin (Androes)</td>
<td>70</td>
</tr>
<tr>
<td>2.2</td>
<td>Microband Thickness Series (Androes)</td>
<td>76</td>
</tr>
<tr>
<td>2.3</td>
<td>Photomicrograph of quartz overgrowths with silica and iron bands (Androes)</td>
<td>80</td>
</tr>
<tr>
<td>2.4a &amp; 2.4b</td>
<td>Plain and cross polar microbands. (Adapted from NASA)</td>
<td>81</td>
</tr>
<tr>
<td>2.5a &amp; 2.5b</td>
<td>Iron microbands in quartz (Androes and Phillips)</td>
<td>82</td>
</tr>
<tr>
<td>2.6</td>
<td>Iron coatings with progressive evolution to laminae (Androes)</td>
<td>83</td>
</tr>
<tr>
<td>2.7</td>
<td>Australia Hamersley Range Map (Androes)</td>
<td>89</td>
</tr>
<tr>
<td>2.8</td>
<td>Hamersley Group composite stratigraphic sequence (Androes)</td>
<td>91</td>
</tr>
</tbody>
</table>
LIST OF TABLES

INTRODUCTION TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1.1</td>
<td>Invariant cycles for Earth/Titan/Mars in Earth time periods</td>
<td>24</td>
</tr>
<tr>
<td>Table 1.2</td>
<td>Variables in the Milankovitch Climate Modulations</td>
<td>30</td>
</tr>
<tr>
<td>Table 1.3</td>
<td>Tidal Constituents – Time Series</td>
<td>42</td>
</tr>
</tbody>
</table>
# DISSERTATION TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.1</td>
<td>Iron Formation Size and Composition</td>
<td>63</td>
</tr>
<tr>
<td>Table 2.2</td>
<td>Location and Age of Banded-Iron Formations</td>
<td>65</td>
</tr>
<tr>
<td>Table 2.3</td>
<td>Earth’s Northern Hemisphere Seasons</td>
<td>119</td>
</tr>
<tr>
<td>Table 2.4</td>
<td>Martian Northern Hemisphere Seasons</td>
<td>120</td>
</tr>
<tr>
<td>Table 2.5</td>
<td>Titan Northern Hemisphere Seasons</td>
<td>121</td>
</tr>
<tr>
<td>Table 2.6</td>
<td>River Valley and Sediment Volumes for Ligeia Mare Drainage Basin</td>
<td>149</td>
</tr>
</tbody>
</table>
INTRODUCTION

CHAPTER ONE: Orbital Periodicities Reflected in Ancient Surfaces

Apart from Earth, planetary hosts with sedimentary records at or near their surface are limited. Without liquid, the prospects of finding extensive layered sequences or extraterrestrial life are minimal; and without layered sedimentary sequences, the potential for finding historic records or fossils of life is almost nonexistent. Several planets or moons in our solar system are believed to have liquid oceans under sheets of ice or other solid surfaces; however, our ability to probe these submarine worlds is a distant reality in light of the high cost of these missions. Therefore, planets with surface liquids are prime candidates for future missions exploring extraterrestrial life or searching for evidence for the origins of life.

In our quest to find extraterrestrial life, exoplanets are sought with surface conditions that are “just right” for habitation; however, finding signs of life outside of our solar system is nearly impossible if we’re unable to recognize life’s signature on our own planet or on planetary surfaces within our solar system. Therefore, it’s essential to analyze the earliest rock records for evidence of life preserved and to develop models for finding potential artifacts of life. The purpose of this research is to: 1) isolate universal driving forces controlling sedimentary processes on Earth and other planets; 2) create a model for deposition, periodicities, and morphologies of Earth’s earliest surfaces; 3) search for depositional potential on other planetary bodies in our solar system using geomorphic interpretations; and 4) analyze the potential for recording early life in our solar system.
1. Background

To reconstruct Earth’s history, two lines of evidence must be invoked: the terrestrial and the extraterrestrial. Terrestrial surfaces, laid down in chronological succession, depict epochs of time that may be exhumed or exposed on Earth; however, erosion and time have erased much of this record. Problems also arise in assigning hierarchical time intervals to sedimentary sequences. For these gaps in our knowledge, understanding Earth’s orbital driving mechanisms has proved invaluable.

Extraterrestrial evidence consists of planetary surfaces and universal or local planetary system driving mechanisms. For example, lunar craters and mares record the late heavy bombardment with much greater detail than Earth, while giant gas planets in our solar system point to the elementary composition of the spinning gas cloud. Geochemical analyses of asteroids, meteors, meteorites, and lunar studies are our primary resource for dating the formation of Earth. Planetary systems, controlled by distinctly different orbital periodicities, should reflect these unique uniformitarian time periods.

Without both terrestrial and extraterrestrial evidence, our historical account is incomplete. Earth’s surfaces alone are insufficient at answering questions such as “how did planet Earth form?” or “when did life begin?” To answer these and many other questions, both lines of evidence are employed.

1.1 Research Objectives

Although random or catastrophic events are evident and were common in our early solar system, these events rarely provide deep insights into how or when? On the contrary, orbital
motion and planetary perturbations are predictable – rendering clockwork-like mechanics to many geologic processes. Irradiation of planetary surfaces by the Sun depends on the position, velocity, and inclination of their orbits. These mechanical processes and gravitational interactions generate the vast majority of Earth’s stratified formations by altering the energy pulses, weather, and climate in the depositional environment. Therefore, the objective of this research is to isolate the predictable uniformitarian processes driving deposition and lithification of planetary surfaces.

The physical laws underlying planetary motion, tides, changes in radiative energy, or the mechanics or hydrodynamics of rivers and ocean define how, when, and where geomorphic features form. These interrelated geologic and astronomic systems follow patterns through time. Research outcomes include finding viable models for how sedimentary sequences were produced during critical periods of Earth’s history, suggesting time parameters for these ancient records, and determining where these sequences may be found in the solar system. In our quest to discover life’s earliest origins, whether on Earth or other planets, our need to explore and understand Earth’s historical record heightens.

1.2 Problems Addressed in this Research

Uniformitarianism suggests that the processes acting on Earth today are similar to those acting in the past (Cannon 1961) This connection also provides interpretive paradigms for other worlds. With extraterrestrial sample or core returns being years in the future, Earth’s ancient sedimentary records are critically needed as interpretive analogs for our distant planetary companions. However, ancient sedimentary surfaces are often considered enigmatic, lacking ties to their origin or periodicities. Although Earth’s modern records form unequivocal tidal (Avsyuk
et al. 2011; Coughenour et al. 2009; Dalrymple et al. 1990; Williams 1997), seasonal (Trendall 1983a; Trendall 1973a), or climate rhythms (Tessier 1993), the origin of Earth’s earliest strata are considered anomalous with a lack of consensus among researchers (Archer 1996; Coughenour et al. 2009; Cuntz et al. 2009; Trendall 2002; Williams 2000; Williams 2005; Wolf and Toon 2010b). Preserved sedimentary sequences that lack extensive deformation from heat are the best candidates to serve as critically needed analogs and historical accounts of early life processes (Trendall 1973a). One of these ancient records is analyzed in this research for patterns and periodicities related to orbital forcing and possible implications for life in a potentially hostile environment.

In addition to Earth, Mars and Titan exhibit eroded terrains and sedimentary sequences causally tied to changing orbital mechanics and solar insolation. For Mars, long-period oscillations in axial tilt and eccentricity appear to be the primary driver of significant exogenic alterations (Armstrong et al. 2004; Head et al. 2006; Jakosky et al. 1993). Layered sedimentary strata have been imaged in Holden Cratera, Meridiani Planum, West Candor Chasma, Vallis Marinaris, Vastitas Borealis, the Columbia Hills of Gusev, and Eberswalde crater on Mars (NASA/JPL Images). Titan’s surface is relatively young and changing due to ongoing sedimentary processes. These planetary strata, visible at the surface and extending into the subsurface, are the product of astronomical forcing, but to what degree? Research linking planetary surface features and processes to orbital mechanics is in its infancy, with wide variations in interpretation. These processes and various geomorphic features of Titan’s polar regions and Ligeia Mare are characterized and interpreted in reference to orbital dynamics by this research.
Titan’s thick atmosphere and surface are subject to tides (Lorenz et al. 2008b; Mitchell 2009; Mitri and Showman 2008) and orbital perturbations from its planetary host (Barr et al. 2010; Bills and Nimmo 2008; Noyelles 2008). Hydrologic processes on Titan are consistent with sedimentary processes that form cyclical layered deposits (Lopes et al. 2010; Talcott 2010; Wall et al. 2010). Although neither Mars nor Titan would be expected to harbor life on their surfaces, both have the potential to render evidence of life in buried sedimentary surfaces.

Earth’s earliest fossilized life forms are found in rock. Rock surfaces preserve, protect, and promote the growth of stromatolites and other non-stromatolitic sedimentary structures. Microbially-induced sedimentary structures (MISS) are commonly found in tidal or subaerial marine settings (Cloud and Licari 1968; Konhauser et al. 2002) where microbial colonies preserve syndepositional sedimentary varves and couplets by the precipitation of cementing agents. The potential for preservation of MISS in shallow to moderately deep marine waters is addressed in the final discussions of this research. Of these MISS formations, banded-iron formations (BIF’s) are the best known and most ancient (Cisne 1984; Dauphas et al. 2004; Fedo and Whitehouse 2002; Weisburd 1986; Westall 2003). BIF’s are also the most controversial with researchers. This stems from the lack of agreement on the degree, type, or role of uniformitarian and anomalous processes. While most researchers agree that banding at some level in BIF’s is a component of sedimentary processes and offers a clue to early Earth conditions (Allen et al. 2004; Cloud 1982; Konhauser et al. 2002; Wang et al. 2009; Weisburd 1986), widespread agreement on the banding periodicity or specific cause is lacking (Morris and Horwitz 1983; Morris and Trendall 1988; Pickard et al. 2004; Weisburd 1986).

Early ocean waters, with oscillations between higher and lower oxygen content, have historically been attributed to cyanobacteria and photosynthesis as the driving mechanism for
banded-iron formation cyclicity (Cloud and Licari 1968). Researchers have proposed alternate pathways to the rise of oxygen during the time period of vast BIF deposition utilizing Cloud’s hypothesis (Goldblatt et al. 2006; Kump 2008; Sessions et al. 2009; Tian et al. 2011), while other recent research suggests that global ocean oxygenation predates the deposition of many BIF’s (Anbar et al. 2007; Cuntz et al. 2009; Farquhar et al. 2011; Ohmoto et al. 2006).

Many BIF researchers consider the bands to be penecontemporaneous with the accumulation of sediment flux from a source other than chemical precipitation (Schneider et al. 2002; Trendall 1983a; Williams 1997). Although modern records form unequivocal tidal or glacial rhythmites, ancient depositional sequences are not readily distinguished as tidal in origin. The problem stems from the inability to link hierarchical ordering to specifically diurnal, semidiurnal, spring, neap, or nodal lunar orbital patterns. Geologic records also suggest that past “events” have obliterated 95% of the diversity of life on Earth; however, the rock record captures only scant detail. The question remains, are these events repeatable cycles or simply a “conspiracy of time and chance” as concluded by well-known author and paleontologist, Stephen J. Gould (1989), in his book Wonderful Life: The Burgess Shale and the Nature of History.

The search to find life is scientifically bound by Earth-like paradigms. Based on planetary evidence and astronomical forcing mechanisms, these inevitable cycles of our solar system could render habitable zones inhabitable, and conversely, inhabitable zones habitable. Whether physical, chemical, or biological, Earth analogs provide the basis for understanding worlds that are only remotely probed by exploration. This quest for the evidence of life’s emergence includes understanding Earth’s earliest sedimentary and fossil record and exploring the planetary bodies with liquid mediums capable of hosting life.
2. Radiative Forcing

The orbital dynamics addressed in this work include, orbits about the Sun and other planets, axial rotation, eccentricity, obliquity, and precession. Changing planetary positions, solar angle, and distance to the Sun drive climate, season, and weather cycles. Radiative forcing and the resulting hydrodynamics are a natural consequence of orbital forcing. At specific surface temperatures, thermodynamically-favored elements are preferentially volatized, condensed, or solidified. These climate-dependent volatiles are the primary agents of geomorphic and dynamic change of planetary surfaces.

Titan, the largest saturnal satellite, is in the “goldilocks zone” for hydrocarbons (methane) with temperatures “just right” for methane cycling. Saturn’s orbital distance from the Sun prevents temperatures from being too hot or too cold for methane phase transitions. In this unique setting, land surfaces are composed of water ice; seas and lakes are filled with liquid methane/ethane; and methane rain or snow falls with potential erosive power. Titan’s physiographic constraints determine the venues for sediment accumulation in basins, flood plains, crater floors, or low lying valleys. Any planetary body with stratigraphic sequences on its surface also has an historical record of importance to science.

2.1 Solar Radiation

Radiation flux alters temperatures, evaporation, transpiration, condensation, wind and weather patterns, pressure systems, atmosphere, and ocean currents. Changes in solar angles or distances from the Sun dampen or enhance the insolation budget to planetary surfaces at any given latitude; which, in turn, alters the sedimentary processes. The degree and extent in time of insolation variability determines which sedimentary process, which sediment delivery method, or which mineral species is dominant. While angular momentum and energy are conserved in a
planetary system, solar radiation is both time and position dependent, conserved only in the context of global or annual averages. Earth’s energy budget and resulting sedimentary cycle is composed of this unique subset of multiple systems. For this research, depositional environments refer to the interplay between the energy of the system and the site of deposition which includes physiographic (geologic/topographic/orographic/hemispheric/regional) variables.

2.2 The Solar Constant

Insolation is the amount of solar radiation received, measured in watts (J/s) per square meter, which varies depending on the incident angle. Incident angle is the angle relative to normal (90°) or vertical to Earth’s surface. The energy of the Sun (Es) is equal to the temperature in Kelvin (T), multiplied by the area of the sphere of the Sun (4πr²), and the Stefan-Boltzmann constant of proportionality (σ) according to the Stefan-Boltzmann Law of Thermal Radiation (Equation 1).

\[ E_S = 4\pi r_S^2 \sigma T_S^4 \]  
Equation 1

Where total solar output is a product of its surface area and temperature (Stefan-Boltzmann’s Law Thermal Radiation – Stefan 1879 and Boltzmann 1884);

As light travels the Earth/Sun distance (Equation 2), only a portion of the total solar output intersects Earth’s radius rₑ and is absorbed (Eabs) or reflected by Earth’s atmosphere as calculated in Equation 3. For planetary bodies, incident angle reflects the observer’s latitude and the altitude or declination of the Sun. Total radiation budget for Earth is represented by the following equations:

\[ E_{a0} = \frac{E_S}{4\pi a_0^2} \]  
Equation 2

Earth receives a portion of the total solar output based on its distance from the Sun equal to 1361 Wm⁻² (Cole and Woolfson 2002).
Radiation received by Earth is the product of the Sun’s output at Earth’s distance and the area of a circle the size of Earth (Cole and Woolfson 2002 and Atmospheric Science Data NASA).

Solar output is relatively constant (solar minima/maxima cycles and the faint Sun problem are not topics of this research); therefore, for this research, Earth’s global solar radiation budget rather than solar output is addressed in detail. The topic of sunspot anomalies and the “Little Ice Ages” is mentioned in climate discussions.

Earth’s solar constant $S_0$ is equal to the amount of solar flux to an imaginary plane intersecting at approximately 100 km above Earth at the top of the atmosphere (TOTAF) at 1 AU distance (generally given in watts per square meter). The Earth/Sun actual distance ($R_E$) relative to the median distance ($R_o$) is a fractional value associated with the standard perihelion and aphelion calculations for the top of the atmosphere flux (TOTAF). Solar flux to Earth at any prescribed distance ($Q$) is quantified by:

$$Q = S_0 \frac{R_o^2}{R_E^2} \cos(\Theta) \text{ when } \cos(\Theta) > 0$$

Equation 4

Values for $\frac{R_o^2}{R_E^2}$ describe the change in the Earth/Sun distance. Changes in radiation flux from the Sun ($S_o$) is a consequence of Earth’s elliptical orbit. Drops or rises in intensity (coefficients < or > 1.0 respectively) relative to the distance ($R_E$) are fractional values of the median solar flux. Total insolation remains relatively constant on bodies with low values (0) for eccentricity. Zero indicates no deviation in radial distances (circular) over 360° of orbit (Cole and Woolfson 2002).
2.3 Insolation Oscillations

Irradiation budgets for specific locations on any planetary body depend on the directness of sunlight calculated from the sine of the incident angle. The axial tilt of planetary bodies to their stellar companion(s) determines the amount of variation for incoming radiation latitudinally, but not in the total global energy budget. Insolation on Earth is most direct between -23.5 S and 23.5 N latitude. Seasonal patterns are attributed to the north/south insolation distribution and are the most pronounced at the longitude of perihelion passage of \( L_p = 90^\circ \) and \( L_p = 270^\circ \) on planetary bodies with higher degree of tilt and greater eccentricity (Figure 1.1).

With solar incident angles or altitudes of 45\(^\circ\), projection results in \( \sim 30\% \) less energy density; at 30\(^\circ\) altitude, 50\% less energy per square meter is distributed to the upper atmosphere (\( \sin 90^\circ = 1; \sin 45^\circ = \sqrt{2}/2; \sin 30^\circ = 1/2 \)). Earth’s insolation budget is based on a subset of latitude-dependent solar angles resulting in \( \sim 956 \) \( \text{Wm}^{-2} \) at 45\(^\circ\) angles and \( \sim 683 \) \( \text{Wm}^{-2} \) at 30\(^\circ\) angles from a potential solar flux of 1361 \( \text{Wm}^{-2} \) at 90\(^\circ\).

Solar spectral irradiance (SSI) is composed of approximately 3\% UV, 44\% visible, and 53\% IR. Only about 4\% of the UV of the S\(_0\) reaches the surface. Planetary insolation is a product of
radiation (Stefan-Boltzmann Laws apply) and the peak stellar wavelength of light (Wien’s Law) for exoplanets orbiting a different star. Atmospheric attenuation determines the final energy flux to the surface.

Total solar irradiance (TSI) to Earth is approximately 1361 Wm\(^{-2}\). Highest solar flux to the surface is \(\sim1100\) Wm\(^{-2}\) at nadir; with an average solar flux to the surface of \(\sim500\) Wm\(^{-2}\) during daylight hours (Figure 1.2) or 250 Wm\(^{-2}\) for a 24-hr period day and night. Latitude positions and the changing solar angle through the year strongly alter the amount of insolation received. Atmospheric attenuation is inversely related to solar altitude/angle resulting from absorption, reflection, and scattering.

Radiation from the Sun peaks in the visible range but spans UV and IR bandwidths. Surface irradiation at \(\sim300\) nm UV-B is only \(\sim0.01\) the total of 340 nm UV-A, meaning that the vast bulk of harmful UV-B is absorbed by the upper atmosphere, primarily by O\(_3\). Without this filter, surface radiation would be deadly to most life forms. In addition, H\(_2\)O results in a number of absorption bands, along with CO\(_2\) and O\(_2\) (Figure 1.3 next page).

![Northern Latitude Insolation](image)

**Figure 1.2** Northern Hemisphere Insolation in Wm\(^{-2}\) at varying latitudes and months of the year. Appendix A. Wm\(^{-2}\) (Androes Appendix B Solar Flux Conversions)
Planets lacking oxygen also lack ozone. The thin CO₂ atmosphere of Mars is relatively transparent to solar radiation (Jakosky et al. 1993; Mckay and Davis 1991); therefore, Martian life would be exposed to high values of UV-A and B. On Titan, an organic haze filters harmful UV rays (Achterberg et al. 2008; Rannou et al. 2010; Teanby et al. 2008). A similar haze is proposed for early Earth by Aharonson et al. (2009) with low oxygen, no ozone layer, and damaging UV radiation (Farquhar et al. 2011; Ohmoto et al. 2006).

Earth’s atmospheric attenuation of UV light is essential to most, but not all life forms. Ocean and subsurface life may thrive beneath planetary surfaces on other bodies in our solar system with minimal atmospheres such as Europa, Enceladus, and Mars. Mars, Europa, Titan, and Enceladus are all candidate planets for submarine or subsurface life exploration.

Atmospheric composition is a function of the distance from the Sun, surface and atmosphere exchange, planetary degassing and, in the case of Earth, the result of living organisms and photosynthesis. Gas retention in the atmosphere is based on planetary mass, and interactions of the magnetosphere, ionosphere, thermosphere, solar energy, and the elemental composition of the atmosphere. Understanding Earth’s atmospheric evolution has been dramatically enhanced by the study of other terrestrial and gas planets in our solar system.

**Figure 1.3** Solar radiation consists of solar flux to the top of the atmosphere (TOTAF), radiation intercepting absorption bands, and the resulting wavelengths of UV, visible, and IR reaching Earth’s surface (NCDC/NOAA US Government Open Files).
2.4 Climate

Climate is a complex system – unique to each planetary body and to each geographic region of that body. Geologic, hydrologic, oceanographic, atmospheric, and astronomic constructs must be combined with insolation values to develop meaningful models. Regional climate variations are large, while global averages maintain a basic continuity. Disruptions or changes in both regional global continuity signal climate change.

2.4.1 Regional Climate Components

Warming or cooling trends over long time periods are a response to the amount of absorbed radiation. Anything that alters the coefficient of absorption (emissivity) alters the climate. The greenhouse effect enhances absorption and has the net effect of warming Earth approximately 33 K, from a calculated 255 K to 288 K. Water vapor, our primary greenhouse gas, provides 72% of the increase; CO₂, methane, and ozone account for most of the remainder. Water vapor induces both positive and negative feedbacks for Earth with the net effect of maintaining relative equilibrium. Water ice, however, reflects solar radiation, increasing Earth’s albedo from its mean (.3) and reducing absorption from its mean (.7). Extensive glaciations can alter the normal equilibrium. The “Snowball Earth” theory examines the tipping points or thresholds for dramatic drops in Earth’s global temperatures. Orbital perturbations, greenhouse gases, and feedback mechanisms are the driving forces behind most climate models.

Climate is also a function of volatile fluid resources and seasonal temperatures (Figures 1.4-1.7). H₂O saturation is temperature dependent varying with latitude, altitude, and air pressure (Figures 1.4-1.5). Regional precipitation is dramatically different for land-locked regions (continentality) or mid-latitude deserts not in close proximity to oceans or reservoirs (Figure 1.6). Figure 1.7 is indicative of tropical ocean effects. High altitudes or mountainous region
create conditions where H$_2$O saturation and condensation is generated by orographic lift and cooling. As a result, rain shadows occur on the lee side of these regions as a result of descending dry air.

**Rainfall and Temperature for 3 Climate Regions**

Weather patterns are latitude and air pressure controlled resulting in prevailing eastward or westward circulation. Orographic obstructions may alter these patterns, creating rain shadows or daily rainout at high altitudes. All Climate graphs NCDC/NOAA US Government Open Files. See Appendix C.

**#1. Available Liquid Resources and Temperature Driven Precipitation**

*Figure 1.4* Omaha, Nebraska, Elev. 298 m  
*Figure 1.5* New Orleans, Australia, 1 m

The apparent correlation between rainfall and temperature indicates that H$_2$O saturation is temperature dependent. Temperatures vary primarily with latitude and altitude, although climate is also physiographic in nature. Proximity to liquid resources, topography, and prevailing winds separate deserts from tropical rainforests.

**#2. Lack of Fluids, Landlocked or Western Continent Boundary**

*Figure 1.6* Berbera, Somalia, Elev. 8 m. Landlocked regions in the interior of continents far from liquid resources, or on western continental boundaries, are commonly low in precipitation with anomalous temperature/precipitation curves. Other planetary bodies with hydrologic cycles are likely to have prevailing climates.
#3. Abundant Availability of Fluid Resources

Figure 1.7 Andegoya, Columbia, Elev. 65 m, High saturation of H$_2$O is linked here to stable temperatures, abundant availability of liquids, and relatively stable insolation in the tropics. Climate graphs NCDC/NOAA US Government Open Files. See Appendix C.

Availability of surface volatiles, kinetically favored for vaporization at surface temperatures, is essential for perpetuation of local or regional hydrology. The thermal inertia of water moderates regions near large bodies of water. Coastal cities, islands, and provinces near the ocean or lakes experience not only abundant rainfall from available H$_2$O, but also dampened temperature swings. Such effects may be vital components in climate models for Titan’s northern polar region (Brown et al. 2009) or for reconstruction of temperature profiles for the Martian Noachian or Amazonian time periods.

2.4.2 Climate Observations for Earth, Mars, and Titan

Geographic regions of planetary bodies receive more or less direct solar radiation dependent on latitude and the amount of radiation retained or reflected. Proximity to oceans/seas/lakes or volatile fluids is an important factor in determining climate. Complex surface and atmospheric systems and variables are difficult to delineate; however, at distinct thresholds, these variables will induce surface modifications, altering the landscape and potentially providing an historical record of the planet’s climate. Ancient surfaces and erosion patterns reflect both long- and short-term extremes affecting surface morphology on planetary bodies, like Earth and Titan with liquid reservoirs, or Mars with a past history of flowing liquids. Erosion, deposition, and stratification
are key processes in the creation of ancient layered surfaces from which climate reconstructions can be derived.

Earth, Mars, and Titan share many long-period climate phenomena and trends. Long-period radiative forcing could shift the location of surface reservoirs, as predicted by Hayes et al. (2011) and Aharonson et al. (2009) for Titan or for Mars as predicted by Murray et al. (1973). Geomorphic features of Mars reveal artifacts of past floods (Jakosky et al. 1993; Mckay and Davis 1991), surficial flows of ice and liquids (Arfstrom and Hartmann 2005; Fastook et al. 2011; Head et al. 2006), and volcanism (Sagan et al. 1973); however, these dynamic surface altering processes have ceased on Mars. Present-day change for Mars is reflected primarily in dust storms (Kieffer et al. 2000; Sagan et al. 1973), mass transfer of CO$_2$ from pole to atmosphere and back (Aharonson et al. 2004; Phillips et al. 2011), and subsurface ice melts resulting in gully formation or dark streaks.

Insolation and fluid regulate not only local climate, but also land surface alteration. The lack of liquid reservoirs on Mars in the present age has halted most erosion processes; although, southern subsurface ice melts appear to flow sporadically (Arfstrom and Hartmann 2005; Kieffer et al. 2000) along crater rims and valley walls. Perpetual shadows isolate dust and rock-covered ice that is resistant to atmospheric sublimation except under climate and seasonal oscillations (Schon and Head 2011). Changes in the Martian ice caps are a function of seasonality, long-period oscillations, and atmospheric H$_2$O and CO$_2$ partial pressure equilibrium (Armstrong et al. 2004; Kieffer et al. 2000; Murray et al. 1973; Phillips et al. 2011).

The abundance of surface fluids in Titan’s northern polar region is consistent with the frequently observed local cloud cover (Griffith et al. 2009; Griffith 2009; Turtle et al. 2009), heavy rainfall (Griffith 2009; Schaller et al. 2006a), deeply incised canyons and broad fluvial
valleys. Liquid methane reservoirs, much like Earth’s oceans, exert strong control over local climate and over the conditions favorable to erosion or depositional processes.

2.4.3 Earth Climate and Insolation Oscillations

Over the past 2000 years, temperature drops of ~1° C on Earth have resulted in the “Little Ice Ages” (Figure 1.8). In the past ~10,000 years, temperature-dependent δ¹⁶O/¹⁸O values suggest that temperature deviations of ~3° C (Figure 1.9) resulted in the end of the Holocene Ice Age (Hansen 1982; Jones et al. 2000). The “Little Ice Ages” have been linked to the sunspot cycles, atmosphere or surface absorption, volcanic gases, and particulate matter in the atmosphere while the Holocene Ice Ages are generally linked to Milankovitch (Milankovitch 1948) orbital cycles.

Earth’s Temperature Anomalies

![Figures 1.8 Reconstructed Temperatures](http://www.globalwarmingart.com/wiki/File:2000_Year_Temperature_Comparison.png)

![Figure 1.9 Holocene Temperature Variations](http://www.globalwarmingart.com/wiki/File:2000_Year_Temperature_Comparison.png)

Data Open Files – images created by Robert A. Rohde

**Figures 1.8 Reconstructed Temperatures**

Temperature variations for the past 2000 years record 1.5° deviation from normal or median temperature over recorded range.

**Figure 1.9 Holocene Temperature Variations.**

Ice core ~10,000 yr reconstruction suggests 3-4° C fluctuations. Anomalies include periods of past glaciations

Figure 1.10 Northern hemisphere solar flux variations. Earth’s estimated total insolation fluctuations from norm of ~250 Wm$^{-2}$ average. Cycles have been converted from orbital changes in degrees or coefficients to solar power. Changes in obliquity, eccentricity, and precession of equinox alter solar radiation and incident angles. (Adapted from NASA and NCDC/NOAA US Government Open Fileshttp://aom.giss.nasa.gov/srorbpar.html -- Androes 2011).

Orbital cycles depicting climate change based entirely on solar flux, however, are not accurate predictions of surface temperature changes (Figure 1.10). To reconstruct historical temperature oscillations, multiple forcing or feedback mechanisms must be evaluated for relevance and impact in light of regional climate. In general, total solar flux remains the same globally with variations in climate dependent on the extent of land, lakes or oceans, surface topography, altitude, and other factors. Physiographic variables are extremely vital to the overall picture.
2.4.4 Martian Climate and Insolation Observations

Changes in insolation over geologic time for both Earth and Mars vary up to ±65 Wm\(^{-2}\) at the surface (Figure 1.11). With little atmosphere, the greenhouse effect on Mars is insignificant in spite of a primarily CO\(_2\) atmosphere. For the present Martian orbital cycles, insolation varies from 200-300 Wm\(^{-2}\) equal to ±50 Wm\(^{-2}\); however, orbital cycles suggest the variations may reach nearly ±100 Wm\(^{-2}\).

The average 12.33 hour day receives 590 Wm\(^{-2}\) TOTAF, or averaged to 245 Wm\(^{-2}\) TOTAF over a ~24.66 hour day. Solar flux (TOTAF) varies from 717 Wm\(^{-2}\) maximum at perihelion and 493 Wm\(^{-2}\) at aphelion. Particulate matter (dust) in the atmosphere reduces solar light penetration significantly during Martian dust storms.

Particulate matter (dust) in the atmosphere reduces solar light penetration significantly during Martian dust storms.

The Martian polar ices, CO\(_2\) and H\(_2\)O, are released into the atmosphere through sublimation during summer seasons (Jakosky et al. 1993; Phillips et al. 2011). The Martian CO\(_2\) atmosphere surface pressure is near equilibrium with the partial pressure of CO\(_2\). Recent research has estimated that approximately equal amounts of CO\(_2\) exist on Mars, half in the atmosphere and half sequestered at the poles (Phillips et al. 2011).
Initially, it was thought that the Martian polar caps were composed entirely of CO₂; however, this is not the case. Frozen CO₂ overlies H₂O accumulations. Much of the water ice is below the surface of Mars. It is estimated that, if all water ice were melted from the Martian polar caps, sufficient volume exists to cover the entire planet with approximately 25 meters of liquid H₂O (Levrard et al. 2007; Phillips et al. 2011). Vaporized, this would account for .6 atm of vapor pressure. Subsurface water ice (as discovered by the Phoenix Lander) may have accumulated at the Martian poles in earlier epochs, much like glacier ices have accumulated near Earth’s poles in Greenland and Antarctica.

2.4.5 Titan Climate and Insolation Observations

Recent Cassini flybys of Titan’s northern polar region (used extensively in this study) have yielded images of seas or mares. Surface methane reservoirs survive in polar regions because of low solar incident angles. Low latitudes yield stronger insolation and evaporation, but unlike Earth, ocean effects are lacking at Titan’s equator. Studies of Titan’s polar latitudes promise to enhance our understanding of Earth, Mars, and Titan’s seasonal insolation swings and erosion processes.

Titan’s surface temperature fluctuations of ~4 K (Figure 1.12) are constrained by Titan’s distance (at 9.6 AU distance with a solar flux of ~12-15 Wm⁻²), by the thermal inertia of Titan’s thick atmosphere, and by an optically-dense stratospheric haze. Median TOTAF ranges,
extrapolated for latitude and annual solar longitude by Schaller et al. (2006), vary from 0 to 7.0 Wm$^{-2}$ (Figure 1.13). Regions of Titan are immersed in darkness for several years during winter (Rannou et al. 2010). Greater incident angles, coupled with atmospheric attenuation, reduces penetration of solar light to higher latitudes of Titan. Models predict only 10-20% of the solar flux at the top of the atmosphere actually passes to the surface of Titan (Friedson et al. 2009; Tokano et al. 2006; Tomasko et al. 2008). Atmospheric attenuation is much greater on Titan than Earth, making the effects of the orbital dynamics potentially less for Titan. In addition, Titan’s thick atmosphere inhibits surface temperature swings due to thermal inertia of $\sim$2000 J m$^{-2}$ s$^{-0.5}$ K$^{-1}$ based on the Rannou et al. (2006) model and by $\sim$335 J m$^{-2}$ s$^{-0.5}$ K$^{-1}$ based on the Tokano (2005) model.

The gas chromatograph mass spectrometer (GCMS) on the Huygens probe detected $\sim$50% humidity at low latitudes on Titan’s surface at 93.7 K (Tomasko et al. 2008). Methane saturation must approach 100% for methane droplets to reach the surface without vaporizing.
of stratospheric circulation over the winter pole (Lorenz 2008; Lorenz et al. 2008b) creates temperature swings on Titan resulting in net fluid transfers between surface and atmosphere.

Titan’s atmospheric circulation patterns have been monitored from satellite and ground-based telescopes. Clouds are observed rising near the latitude of most direct sunlight, generally descending in a poleward direction, with the exception of spring and fall observations of equatorial rainfall. Circulation consists of strong upwelling in stationary systems, Hadley-style cells, and a single large, ascending-descending conveyer belt pattern rather than the latitude-dependent, differential circulation patterns seen on Earth (or Saturn).

Images taken during Titan’s northern polar winter, 2002-2009, appear to contain flooded lakes and valleys. As warmer rainy seasons approach, large volumes of liquid or volatile methane are expected to be transferred from the surface of Titan to the clouds via evaporation and convection. Synthetic-aperture radar (SAR) imagery of the north taken from July 2006 to December 2009 show no discernable change in northern shoreline features, in line with predictions that precipitation and evaporation during winter would be minimal (Mitchell 2009). In contrast, shoreline change has been detected in Ontario Lacus in the south polar region (Wall et al. 2010).

Polar temperature swings yield interesting complications in modeling Titan’s hydrologic cycle (Barth and Rafkin 2007; McKay et al. 2009). Sporadic, methane phase changes between liquid, solid, and gas are possible where Titan’s average surface temperature range is 92-94 K. Methane’s triple point temperature and pressure exists at Titan near surface conditions (90.7 K at 117 millibar – a few km above Titan’s surface). At near surface levels, methane can condense and freeze. Titan’s polar region, unlike Mars or Earth, hosts liquid reservoirs that do not form glaciers or polar ice caps.
In 2009, polar clouds appeared over Titan’s northern lakes where atmospheric saturation levels are high and temperatures reached 93 K with the onset of spring. Clouds have also been noted in the north between 220-260° W longitude between 60-82° N latitude since 2007, a possible lake effect in these regions. Clouds appeared near Titan’s equator at approximately 19°S latitude and 251°W longitude in September of 2010, with dark surface methane accumulations covering 500,000 square kilometers in October 2010 (NASA Press Release). By January 2011, most of the wet methane had disappeared – evaporated, infiltrated, or dried.

Large reservoirs with 100,000’s km² coverage and many smaller ~100 km² lakes appear between 75-90° latitude in the northern polar region of Titan. Large lakes dominate in the north, from 0-140° azimuth. At the opposite pole, only a few modest-sized, mostly empty lakes averaging ~100 km² are apparent. The obvious dichotomy is reinforced by a long-standing asymmetry in insolation oscillations. The northern polar region experiences spring and summer near aphelion, like Earth, giving the northern hemisphere longer direct sunlight, but less intensity, than the southern hemisphere. The southern hemisphere’s spring and summer seasons, near perihelion, are shorter and more intense. This asymmetry has the potential for greater mobility of fluids in the south than in the north, but over a shorter time period.

Changes in long-period orbital cycles for Titan suggest up ~6-17 W m⁻² difference; whereas, Earth varies from 1413-1321 W m⁻² and Mars from 717 to 493 W m⁻² (Table 1.1 on the next page). These cycles are predictable and relatively invariant based on their unique planetary systems, orbital periodicities, incline to the invariant plane, and distance from the Sun. These physical orbital and gravitational parameters provide a foundation for uniformitarian processes such as seasons, tides, and predictable changes in solar radiation.
Table 1.1 Invariant cycles or cycles with little change over time. Earth’s distance 1 AU; Saturn 9.529 AU. Time periods are in Earth days and Earth years.

<table>
<thead>
<tr>
<th>Current Cycles</th>
<th>Rotation Mean &amp; Pres. AU Dists</th>
<th>Incl Invariant Plane</th>
<th>Incl Ecliptic Plane</th>
<th>Solar Flux in W m²</th>
<th>TOTAF Max/ Min W m²</th>
<th>Solar Poles Top/Surface in W m²</th>
<th>Avg Surface in W m²</th>
<th>Days/ Yr. Earth secs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth range</td>
<td>24 hrs 1.57° 1.0 0</td>
<td></td>
<td></td>
<td>1413-1321</td>
<td>345</td>
<td>235</td>
<td>365.3</td>
<td></td>
</tr>
<tr>
<td>Titan range</td>
<td>15.945 days .93° 9.53 2.49 with .0115° proper</td>
<td>11</td>
<td>6.04-16.7</td>
<td>6.06-7.75/.5-1.5</td>
<td>1.5-3</td>
<td>15.95/10,759</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mars range</td>
<td>24.66 1.67° 1.52 1.85 to 2.486°</td>
<td>590</td>
<td>717/493</td>
<td>100</td>
<td>220</td>
<td>686.9 88575</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


3. Astronomical Forcing

Milankovitch cycles, with varying degrees of deviation, are expressed over thousands of years. Gravitational interactions modulate orbital positions, orientations and periodicities. Planetary perturbation theory suggests that the orbital positions of the outer planets exert strong gravitational influence on planets inside their orbit. Neptune and Uranus are vested with proportionally greater angular momentum at distances 4-6 times further than Jupiter and have been proposed as the primary agents of Saturn’s axial precession rate and changing obliquity. Jupiter, however, has the greatest total angular momentum and perturbation potential for all planets within its orbital range, including Earth. Gravitational interactions exerted by the jovian planets in our solar system are predictable and retraceable, an astronomical clock of sorts.

3.1 Orbital Components

Obliquity, eccentricity, and precession represent the primary components of the Milankovitch orbital forcing mechanisms established for Earth. Milankovitch cycles are Earth’s orbital oscillations in insolation with potential for long-term climate alterations. These celestial mechanisms have been modeled to describe changes in the TOTAF (Hinov 2003; Kukla and Gavin 2004). Astronomical forcing cycles are not as well known for Titan (Aharonson et al. 2009) and Mars (Fastook et al. 2011; Rubincam 2004; Segschneider et al. 2005; Wahr et al. 2009).

Obliquity, eccentricity, rotation, inclination to the invariant plane, and tidal forces change through time. For example, Earth’s axial tilt direction precesses a total of 360° from its original polar angle trend over approximately 26,000 years. The conventional polar angle Θ is set at the
vernal equinox $\Theta = 0$, where the longitude of perihelion $\varpi$ is described relative to the vernal equinox ($L_p = 0$). The sine of the declination or insolation angle ($\delta$) is equal to the sine of the obliquity angle ($\varepsilon$) and the separation angle $(\theta - \varpi)$ between the precession position and the position relative to the vernal equinox (Berger 1978).

$$\sin \delta = \sin \varepsilon \sin(\theta - \varpi) \quad \text{Equation 5}$$

Defined for an elliptical orbit of eccentricity $> 0$ (Berger 1978), the change in radial distance through precession cycles can be expressed as:

$$R_E = \frac{R_o}{1 + e \cos(\theta - \varpi)} \quad \text{Equation 6}$$

As a consequence of these changes, and subsequent differences in orbital velocities (Kepler’s Laws), annual orbital progression is nonlinear with shorter or longer periods of time between the northern and southern hemisphere solstices and equinoxes. The sum of these orbital periodicities affects the overall global climate, degree of seasonal change, and extent of hemispheric dichotomies.

### 3.2 Obliquity

The saturnian system is tilted $\sim 26.7^\circ$ producing seasons on Titan similar to Earth ($\sim 23.5^\circ$). Earth’s current obliquity is $23.45^\circ$; Mars is $25.2^\circ$; Titan’s tilt to the ecliptic plane is $\sim 27^\circ$. Titan’s orbit is in close alignment to Saturn’s ringed equatorial plane which is tilted $\sim 26.7^\circ$. Downward trends in obliquity (less tilt) lead to warmer winters and cooler summers (Fig. 1.14) or overall, less extreme summers and winters on most planets and planetary satellites.

Obliquity instabilities result from gravitational perturbations by other planets, primarily Jupiter, and by precession of the spin axis. Earth’s obliquity varies from $22.1 - 24.5^\circ$ over a 41,000
year cycle. Average obliquity approximations for Mars, currently 25.2°, vary from approximately 15 to 45° on time scales of ~120,000 years and 2,000,000 years (Armstrong et al. 2004; Francois et al. 1990; Segschneider et al. 2005). Head et al. (2006) infer obliquity of 45° or larger for a sustained period of time. Laskar et al. (1993) and others suggest that the extreme obliquity swings on Mars are due to the lack of a stabilizing moon. A maximum axial tilt near 38° (Armstrong et al. 2004; Francois et al. 1990; Segschneider et al. 2005) has been proposed.

**Obliquity and Nutation at mid- and high-Latitudes**

| Lesser tilt (21.1°E) Earth | Greater tilt (24.5°E) |
| Lesser tilt (26.0°S) Saturn | Greater tilt (28.0°S) |
| Lesser tilt (10.0°M) Mars | Greater tilt (45.0°M) |
| Warmer winters | Colder winters |
| Cooler summers | Hotter summers |

**Figure 1.14** Axial wobble or nutation cause modest change in obliquity. Obliquity variations are a consequence of tidal forces and slight differences in sphericity that result in a tidal bulge. Higher latitudes are impacted most by the changes (Androes 2012).

Insolation cycles are amplified as obliquity increases. High axial instability is evidenced on the Martian surface by time-transgressive sediment and ice overlays, apparent migration or flow of subsurface ice, changes in polar ices, glacial features, and cross-cutting relationships of water-dependent features. Polar ice caps melt or sublimate as the axial tilt migrates.

### 3.3 Eccentricity

Eccentricity (e) is a measure of the deviation from a perfect circle (circle is e = 0). Solar insolation varies by a factor of approximately 4 times the eccentricity and follows Newton’s
inverse square law. Radial distances are inversely proportional to changes in the semi-minor axis:

\[
e = \frac{(r_a - r_p)}{(r_a + r_p)} \quad \text{Equation 7}
\]

Where, \( r_a \) is the radius at apoapsis and \( r_p \) is the radius at periapsis (Berger 1978, Arnold 1989).

Due to the non-spherical nature of planetary bodies, perturbations by other planetary orbits, and transfers of angular momentum, eccentricity varies through time. Cyclic gravitational interactions create an eccentricity range from a low of 0.0034 to a high of 0.058 for Earth (0.0167 at present). In general, a decline in eccentricity results in warming or moderation of the climate. Earth’s eccentricity and obliquity are both in decline; however, orbital-forced climate warming is not anticipated due to an offset by precession and to a general loss of extremes in temperatures rather than an overall gain in temperature.

Saturn’s elliptical orbit has a present deviation of 0.054 (\( e \)) from a perfect circle. Velocities increase near perihelion resulting in slightly shorter seasons, and decrease near aphelion, leading to longer seasons. With a relatively high value for eccentricity, currently at \( \sim 0.0934^\circ \), the Mars/Sun distance at perihelion is 206.7 mil km and 249.2 mil km at aphelion. Eccentricity for Mars varies from 0.01-0.12° and is currently near its higher value of .0934. Mars exhibits greater hemispheric dichotomies in insolation than Titan or Earth at its present eccentricity.

### 3.4 Precession

Eccentricity variations are most profound when coupled with precession (Wigley 1976, Berger 1978). Precession is the general trend in the axis of rotation which results from complex tidal forces and other gravitational perturbations. Precession affects the position where the
solstice and equinox occur on the orbital ellipse. As the axial trend precesses a full 180°, planetary bodies swap hemispheric-dependent seasons from perihelion to aphelion (Figure 1.15). Summers at perihelion are hotter, but shorter, and winters near aphelion are colder and longer. Climate moderation trends follow summers at aphelion and winters at perihelion for most planets although these are hemisphere specific.

**Precession of the Equinoxes**

<table>
<thead>
<tr>
<th></th>
<th>Average Tilt</th>
<th>Approximate Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>~23.5°</td>
<td>~21,000 yr. cycle</td>
</tr>
<tr>
<td>Saturn</td>
<td>~26.5°</td>
<td>~1,800,000 yr. cycle</td>
</tr>
<tr>
<td>Mars</td>
<td>~25.2°</td>
<td>~175,000 yr. cycle</td>
</tr>
</tbody>
</table>

**Figure 1.15** Precession of the spin axis over time results in a directional change in the axial trend. Example: Earth’s rotational axis trends towards Polaris in our current cycle, but 10,000 years ago, the trend was closer in line with Vega. Nutation or obliquity-wobble is noted within the spin axis resulting in epicycles. Axial wobble, illustrated by the Max/Min, is a function of obliquity (Androes 2012).

Earth’s current precession position, \( \mathbf{L}_{c,p} \approx 283.7° \), is reflected in Earth experiencing winter (northern hemisphere) during perihelion (Aharonson et al. 2009). Through the next ~5,000 years, Earth, Mars, and Titan are all moving closer to \( \mathbf{L}_{p} = 0° \) when perihelion occurs at the vernal equinox. Titan and Mars, however, will take much longer. Earth completes 70+ precession cycles in the time it will take the saturnian system to precess once and 8 ½ cycles for a single precession cycle of Mars.

4. **Orbital Periodicities**

Forcing frequencies are superimposed over the continuous background. Cycles vary from ten’s of thousands of years to millions of years with each planetary body having a unique cycle
Although the magnitude of these orbital insolation oscillations are $10^{-2}$-$10^{-3}$ less than daily or annual insolation variations, the potential for global climate change is greater with the long-term than with annual or daily insolation cycles.

Solar flux to any solar system body is primarily a function of the distance from the Sun. Using Newton’s law (inverse square of the distance), the irradiation received at Saturn’s distance is $\sim 1/9.529^2$, and at Mar’s distance, $1/1.52^2$ of Earth’s irradiation. For Saturn, this is equal to nearly $10^{-2}$ magnitude between Earth and Saturn’s radiation budget. For Mars, the differential is $2.3 \times 10^{-1}$.

**Table 1.2** Variables in the Milankovitch Climate Modulations for Earth, Mars, Saturn, and Titan

<table>
<thead>
<tr>
<th>Cycle Mech</th>
<th>Obliquity Current Range</th>
<th>Cycles in 1000 yrs</th>
<th>Eccentricity Current/Med. Range (trend)</th>
<th>Cycles in 1000 yrs</th>
<th>Perihelion Current N. Season</th>
<th>Precession Change in arcsec yr$^{-1}$</th>
<th>Cycles in 1000 yrs</th>
<th>AU/Radius Range in 150 mil. kms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth range</td>
<td>23.44°↓ 22.1-24.5°↑</td>
<td>41</td>
<td>0.0167/.028↓ 0.0034-0.058↑ 100*</td>
<td>400</td>
<td>Winter</td>
<td>~50</td>
<td>19-26</td>
<td>.98</td>
</tr>
<tr>
<td>Titan range</td>
<td>.28°-32°↑ .045°±.053°</td>
<td>45-50</td>
<td>.0289↓ .028↑/.053↓ ~50</td>
<td>~50</td>
<td>Follows Saturn</td>
<td>~59</td>
<td>.7</td>
<td>9.59</td>
</tr>
<tr>
<td>Saturn range</td>
<td>26.73°↑ (unk./±.5°)</td>
<td>45-50</td>
<td>0.054</td>
<td>~50</td>
<td>Winter</td>
<td>~9.72 (±.21°)</td>
<td>1800</td>
<td>9.03</td>
</tr>
<tr>
<td>Mars range</td>
<td>25.1894° ~13°-40°↑</td>
<td>120</td>
<td>0.0934° 0.01-0.12°</td>
<td>95-100</td>
<td>Winter</td>
<td>~19.5°</td>
<td>1728-2540</td>
<td>10.04</td>
</tr>
</tbody>
</table>

*Negative values imply Titan values are opposite Saturn’s invariant pole or in retrograde.


Climate change potentials are unique to each planetary body. Earth, Titan, Saturn, and Mars have separate climate or albedo mechanisms. Non-linear amplification implicated for Earth includes: glaciation (Birchfield and Weertman 1978, Imbrie and Imbrie 1980), continental weathering and sequestering of CO$_2$, bioturbation of deep sea sediments Goreau (1980), water-
vapor temperature feedbacks (Berger et al. 1993), CO$_2$ (Pisias and Shackleton 1984, Shackleton 2000), and uplift of continents and mountains (Berger and Jansen 1994, Mudelsee and Schulz 1997, Raymo et al. 1997, Clark and Pollard, 1998). Mars is also subject to glaciation with polar caps, but at present, dust storms and CO$_2$ solid to gas phase transitions have greater climate implications than H$_2$O. Saturn and Titan’s long-term orbital cycles are similar as orbital pairs; but, a tidally-locked Titan has a distinct daily solar cycle with an axial rotation of ~15.95 days as opposed to Saturn’s ~10 hours. In addition, Titan has a solid surface, liquid seas, and a hydrologic cycle based on methane volatility. Table 1.2 provides spatial and temporal orbital details for Earth, Mars, Saturn, and Titan.

4.1 Earth’s Long-Period Cycles

The present downward trends and lower values for Earth’s eccentricity and obliquity, and current longitude of perihelion during the northern hemisphere’s winter minimizes the impact of Earth’s long-period orbital forcing mechanisms; therefore, current climate concerns are primarily focused on the awareness that greenhouse gases are on the rise. If climate thresholds are exceeded (Shackleton 2000), or the areal extent of glaciers dramatically changed (Imbrie and Imbrie 1980), or ocean circulation disrupted (Imbrie et al. 1984), positive feedback mechanisms are initiated that amplify or depress Earth’s seasonal patterns.

Maximum eccentricity for Earth (.058) yields ~23-25% more insolation at perihelion than aphelion. At present, Earth’s eccentricity is only 0.0167 for a possible 6.25% insolation variability. With the current downward trend in eccentricity, oscillations in obliquity are more dominant than eccentricity. If eccentricity is set to zero, insolation at the TOTAF varies by approximately 25 W/m$^2$ on the summer solstice due to obliquity and precession. Total global insolation remains unchanged.
Figure 1.16 Earth Milankovitch cycles for the primary orbital change mechanisms. Oscillations are extrapolated from Earth’s known orbital forcing mechanisms. In comparison to Earth, Mars receives approximately 45% the solar flux of Earth and has almost no greenhouse effect. Adapted from NASA; http://aom.giss.nasa.gov/sorbpar.html.

Earth’s forcing mechanisms are minimized in absolute terms over the next 10,000-year period indicating climate moderation, excluding any anthropogenic influence. Time-series transforms extract periodicities with minima and maxima commonly at 20,000, 100,000, and 400,000 years for Earth.
Warming or cooling trends over long time periods on Earth are highly dependent on Earth’s positive or negative feedback mechanisms, extent of glaciation, volcanism, and complex circulation patterns. Solar radiation reflected from the surface of glaciers and glacier thaw/melt cycles greatly affect Earth’s albedo, feedback mechanisms, sea levels, and ocean/atmosphere circulation patterns; therefore, glaciation is a powerful climate mechanism. The “Snowball Earth” theory examines the tipping points or thresholds for dramatic drops in Earth’s global temperatures. Orbital perturbations, greenhouse gases, and feedback mechanisms are the driving forces behind most climate models. Greenhouse gases have a net effect of warming Earth by approximately 33° C. Water, our primary greenhouse gas, provides 72% of the increase; CO₂, methane, and ozone account for most of the remainder. Gas retention in the atmosphere is based on planetary mass, the magnetosphere, and interactions of the ionosphere, thermosphere, solar energy, and the elemental composition of the atmosphere.

Water vapor induces both positive and negative feedbacks for Earth insolation. Combined effects, however, produce a net equilibrium with little increase or decrease in global temperatures, except during periods of glaciations when positive feedbacks outweigh negative. H₂O saturation is temperature dependent varying with latitude, altitude, and air pressure.

Glacier melt, thaw, and flow cycles produce seasonally-driven sedimentary varves on Earth. Melt/thaw cycles are visible in polar ice cores, such as the Vostok cores from Antarctica, which are used to provide climate and temperature data. Paleoclimate reconstructions of ice cores predict approximately ±3° C past climate fluctuations with approximately ±1° C CO₂ forcing component (Hansen et al. 2006). Earth’s southern ocean moderates temperatures for the southern hemisphere where Vostok cores reveal age and composition of trapped gases. Problems arise in
interpretation of ages for southern ice cores. Isotopes values extracted from ice cores vary as much as 2500 - 6000 years (Barnola et al. 1991) in the same annual layer.
4.2 Mars’ Orbital Periodicities

Earth’s obliquity swings are maintained within a few degrees but they can have a dramatic impact on regional climate or habitats for living organisms. Mars lacks this stabilizing force with slower nutation velocities (Figure 1.17 & 1.18), but with the potential for greater obliquity magnitudes over time (possible angular separations of $30^\circ$ or more). Earth’s lunar influence helps stabilize axial orientation and support living habitats. Mars, on the contrary with two captured asteroids exerting little gravitational influence, lost most of its potentially habitable surface climate or ability to support life as a consequence of its lack of orbital stability, in addition to its low mass, weaker magnetic field, and orbital distance from the Sun – although with greenhouse atmospheric warming, Mars is within the habitability zone.

![Figure 1.17](http://spacescience.arc.nasa.gov/mars-climate-modeling-group/past.html)
Atmospheric pressure recorded by the Viking Lander through a full Martian year (Figure 1.18) reflects mass transfer from the surface to the atmosphere seasonally. Neutron flux variations, determined from H or OH mapping of the Martian soil-water content, tend to be small in regions that lack subsurface moisture/ice and greater where subsurface ice is close to the surface. Martian hemispheric dichotomies also suggest a mass transfer of subsurface moisture from slow seasonal dehydration. A similar mass transfer process is suggested for Titan’s surface liquid inventories by Aharonson et al. (2009) and Hayes et al. (2011).

**4.3 Titan's Orbital Periodicities**

Titan’s longer days (15.95 Earth-days) allow surface temperatures to rise diurnally in spite of extensive atmospheric haze. Solar-intensities support evaporation temperatures during much of the summer for both hemispheres. Longer term hemispheric insolation effects are difficult to assess for Titan with complex surface interactions and strong attenuation between the atmosphere, surface liquids and volatiles, and circulation patterns. Aharonson *et al.* (2009) and Hayes *et al.* (2011) suggest that Titan’s volatiles have migrated to the northern hemisphere as a
consequence of orbital cycles. Large-scale patterns support Aharonson’s et al. prediction of mass transfer of liquids from one hemisphere to another; however, condensation occurs in the troposphere’s inversion layer or below, whereas it is stratospheric winds that are capable of global transport (Aharonson et al. 2009).

Orbital comparisons for Earth, Saturn, and Titan reveal major differences: 1) in AU distances and solar constants (Sₒ); and 2) in eccentricity between Earth and Mars or Saturn/Titan and Mars. Similarities are apparent in: 1) the obliquity and perihelion precession for Mars, Saturn/Titan, and Earth; and 2) the impact of orbital cycles over long-periods. Further research is needed for more precise comparative planetary studies. Various sources (though not in complete agreement) have delineated these time-frequency analyses.
5. Tidal Forcing

Tidal forces exerted by the Sun, moons, and planets create friction and bulging of planetary materials. In a two-body orbiting system, forcing mechanisms are sinusoidal if unperturbed, but two body systems are rare. Phase interference from a third or fourth body alters harmonic amplitudes and frequencies. This interference is useful for interpreting sedimentary sequences such as lunar tidalites or rhythmites. Orbital parameters for all planets were derived from Keplerian and Newtonian orbital mechanics using a Cartesian coordinate system with 6 degrees of freedom. Modulations are based on an arbitrary epoch in time and inertial frame of reference. Unperturbed 2 body orbital systems are normally conic sections; however, the gravitational pull of additional bodies, the nonsphericity of planetary bodies, and relativistic effects cause orbits to evolve and change through over time may be important.

5.1 Tidal Force

The universal law of gravitation describes the forces acting on planetary orbits. This force (F) is proportional to the 2 masses (m₁ and m₂) and is inversely proportional to the square of the distance (r²) between them (Arnold 1989). The value of constant G is 6.674 x 10⁻¹¹ N m²kg⁻².

\[ F = G \frac{m_1 m_2}{r^2} \quad \text{Equation 8} \]

For our solar system, angular measures are given relative to the ecliptic plane which is defined by the orbit of the Earth and Sun. However, the invariant plane, rather than the ecliptic plane, is most significant in determining the magnitude of axial wobble and precession. The invariant plane is defined as a plane perpendicular to the orbital angular momentum vector. In our solar system, the jovian planets are vested with 98% of the total angular momentum.
As gravity acts upon the constant motion of orbiting bodies, tidal friction slows the rotation or orbit and generates heat within the bodies. The gravitational attraction of 2 or more bodies can be measured and used to extrapolate past and future changes in planetary motion. Tidal distortions known as bulges on spherical bodies result in an oblate spheroid elongated in the direction of the attraction. Tidal bulges on Earth are most discernible in the ocean as the high tide propagates across the surface, creating a temporal and spatial rise in sea level, mobilizing and depositing sediments. Changes in orbital periods through time have been extracted from ancient rhythmtes – tidally derived sediments – to provide a partial record of Earth-Moon orbital cycles.

5.2 Tidal Friction

Titan, like our moon, lost most of its axial spin in a geologically short period of time. Tidal forces create an exchange of angular momentum that can result in the loss rotation speed known as tidal breaking. Loss of spin is inferred from the general calculation for tidal locking ($t_{\text{lock}}$).

$$t_{\text{lock}} = 6 \frac{a \delta R \times 10^{10}}{(m_s m_p)^2} \text{ years} \quad \text{Equation 9}$$

*[The semi-major axis (a) is the average radial distance and $m_p$ is the mass of planet.] It should be noted that for most planetary bodies, the larger the mass ($m_s$) of the satellite, the quicker it loses rotation since mass $m_s$ grows faster than the satellite distance radius ($R$), which is not squared (Arnold 1989).

Tidal friction is slowing the rotation of the Earth about its axis. Angular momentum is conserved in the Earth-Moon system. Loss of the Earth’s rotational velocity translates to changes in the Moon’s recessional radial distance from Earth. Based on present rates of recession, a close approach of the Moon would have occurred in the late Proterozoic. Anticipated axial rotation rates (extrapolated from predicted past recession distances) have been compared with sedimentalogical data with varied results (Bills and Ray 1999; Gao and Xiao 2008; Olson and
Cloud 1968; Sonett et al. 1996; Williams 1997). Ancient rhythmite sedimentological data, interpreted for recession velocities, suggest rates of recession were equal to or lower in the past than in the present (Bills and Ray 1999; Gao and Xiao 2008; Olson and Cloud 1968; Sonett et al. 1996; Williams 1997).

Earth’s spin, coupled with tidal forces from the Moon and Sun, produce variable ocean tides. These variable tides initiate sedimentary sequences, such as tidalites or rhythmites, which have been used to extract orbital signatures. Although the tidal forces exerted on Titan are much larger than Earth (Hussmann et al. 2010; Strobel 2006), Titan’s rotation is too slow to initiate resonate tides like Earth (Bills and Nimmo 2008; Karatekin et al. 2008; Noyelles 2008). Titan’s prime meridian (0 degrees) is directly overhead Saturn, with longitudes 90°W-270°W always facing away from Saturn (Lorenz et al. 2008b; Noyelles 2008). It takes approximately 15.95 days for Titan to complete its orbit around Saturn and to make one complete rotation.

5.3 Tidal Bulging

Stiles et al. (2010) calculate Titan’s axial spin rate is on the order of .36 degrees faster than synchronous rotation in its orbit with Saturn. Titan’s unknown interior composition/layers and thick atmosphere restrict efforts to definitively identify the cause; however, a number of studies (Barr et al. 2010; Bills and Nimmo 2008; Karatekin et al. 2008; Lorenz et al. 2008b; Stiles et al. 2010) have postulated that Titan’s outer layer partially decouples from its core. Lorenz et al. (2008) suggest that the acceleration of the outer crust may be associated with Titan’s elongate, nonspherical tidal bulge and with a possible deep subsurface, less viscous ice. Models by Noyelles et al. (2008) predict the spin rate and axial wobble of Titan may be sufficient to explain the apparent faster rotation of its surface (Noyelles 2008).
Saturn’s gravitational interaction with Titan’s thick atmosphere creates tide-like currents interacting with (Sotin and Tobie 2008; Tokano and Neubauer 2005; Tokano 2010b) convection cells and fixed thermal conveyances (Strobel 2006; Tokano 2010b; Van Hoolst et al. 2009). Wind shears in Titan’s massive atmosphere are far greater than those on Earth. Tokano and Neubauer (2005) link spin-rate variations to Titan’s thick atmosphere, Sotin and Tobie (2008) to surface interactions, and Tokano (2010) to seasonal change in the atmosphere. Continued research is warranted in this area (Sotin and Tobie 2008; Tokano 2010b).

Results from this study are likely to be affected by a more thorough understanding of dynamic tidal links to Titan’s climate, weather, atmospheric change, and surface morphologies. The Cassini Solstice Mission and ongoing ground-based telescope observations are needed to assess the diverse effects of tidal forcing on Titan and the possible geomorphic consequences; therefore, these tidal variables and their consequences are not included in the scope of this research.

However, tidal forces do have two primary manifestations of interest in this study: 1) perturbation of planetary orbits or rotation – tidal breaking and bulging or alterations to obliquity, eccentricity, and axial wobble; and 2) creation of sedimentary varves or bands, laminae, depositional couplets, rhythmites, and tidalites.

Examination of tidal influence on Earth and Titan demonstrates that tidal mechanisms are powerful and significant to the characterization of sedimentary sequences in systems with large moons. Orbital parameters in 3-body systems, although more complex, are more accurate for packaging intervals of time. Marking time daily, monthly, or seasonally requires these distinct gravitational perturbations. Orbital parameters are universal timekeepers set in motion. These forcing mechanisms and uniformitarian processes, governed by invariant physical laws, refine our interpretation of geological history.
5.4 Earth/Moon Tide System

If the Earth/Moon system evolved from a collision of a Mars-sized planet with Earth, or from the separation of a molten outer layer of Earth, the Moon is theorized as having been much closer to Earth in the past. The current recession rate of the Moon is approximately 3.8 cm annually. At a closer approach, the Moon’s orbital time periods are shorter and Earth’s axial rotation is faster. The position of the Moon relative to the Earth and Sun significantly alters tidal dissipation and tidal energy. Tidal signatures extracted from marine sequences have a unique potential to record Earth’s early history.

5.4.1 Tidal Periodicities

Neap-tides occur when the Moon is in the position of quadrature and spring-tides occur when the Moon is in the position of syzygy. Daily tidal ranges are characterized by their location on Earth, shoreline contour, resonance, and timing. Shoreline shape and basin size dictate the magnification or reduction in the intensity of tidal ebb and flow. Amplitude, frequency, and variability are keys to distinguishing characteristic laminae signatures in sedimentary sequences (Archer 1996; Avsyuk et al. 2011). Tidal phases may be mixed, diurnal, or semi-diurnal.

Sea level rise in response to the Earth-Moon-Sun orbital dynamics varies with a hierarchy of cyclicities beginning with daily phases, followed by fortnightly spring and neap tides. The Moon’s orbital position relative to the Earth-Sun ecliptic plane (declination) modifies the tidal energy distribution. With stronger tides, shorter lunar months, more days and months per Earth year, enhanced depositional cycles are anticipated. Gravitational perturbations, reflected in tidal rhythmites, reveal close encounters of the Earth/Moon at perigee or nodal crossings and solar/lunar alignment (Table I.3: diurnal: K₁, O₁, P₁; semidiurnal: M₂, S₂, N₂).
Table 1.3: Tidal Constituents – Time Series

<table>
<thead>
<tr>
<th>Tides</th>
<th>Symbol</th>
<th>Period</th>
<th>Amp#</th>
<th>Type</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi</td>
<td>M₂</td>
<td>12.42 hrs</td>
<td>100</td>
<td>Lunar</td>
<td>28.984 degrees per mean solar hr</td>
</tr>
<tr>
<td></td>
<td>S₂</td>
<td>12.00 hrs</td>
<td>46.6</td>
<td>Solar</td>
<td>30.000 degrees per mean solar hr</td>
</tr>
<tr>
<td></td>
<td>N₂</td>
<td>2 wks</td>
<td>19.1</td>
<td>Dist</td>
<td>28.440 degrees per mean solar hr</td>
</tr>
<tr>
<td></td>
<td>K₂</td>
<td>4 wks</td>
<td>12.7</td>
<td>Decl</td>
<td></td>
</tr>
<tr>
<td>Diurnal</td>
<td>K₁</td>
<td>23.93 hrs</td>
<td>58.4</td>
<td>S/M</td>
<td>15.041 degrees per mean solar hr</td>
</tr>
<tr>
<td></td>
<td>O₁</td>
<td>25.82 hrs</td>
<td>41.5</td>
<td>Lunar</td>
<td>13.943 degrees per mean solar hr</td>
</tr>
<tr>
<td></td>
<td>P₁</td>
<td>24.07 hrs</td>
<td>19.3</td>
<td>Solar</td>
<td></td>
</tr>
<tr>
<td>Long</td>
<td>Mₖ</td>
<td>327.86</td>
<td>17.2</td>
<td>Lunar</td>
<td></td>
</tr>
</tbody>
</table>

Amp# = number of oscillations in series peaks
S - Sun or solar; M = Moon; N = Lunar elliptic semidiurnal constituent
K - Luni-solar declination, diurnal constituent
O₁ - Lunar declinational diurnal constituent (speed: 13.943 degrees per mean solar hour)
M₄ - First overtide of M₂ constituent (speed: 2 x M₂ speed)
M₆ - Second overtide of M₂ constituent (speed: 3 x M₂ speed)
S₄ - First overtide of S₂ constituent (speed: 2 x S₂ speed)

5.4.2 Tidal Sequences

Depositional regimes citing tidal mechanisms for ancient sedimentary surfaces are generally disputed (Williams 2005). To establish an agent of cyclicity, clear tidal signatures reflecting tidal constituents (Table 1.3) are required (Trendall 1973b) agreement for rhythmic sequences rests with orbital mechanism, specific forcing mechanisms are usually not clearly defined. Modern tidalites suffer from bioturbation, mixing at or above storm base, and coastal erosion. In addition, ocean gyres, currents, and seasonal inequalities modulate tidal energy. Establishing a time-series is difficult due to problems in isolating uninterrupted, long-term patterns; however, unequivocal tidal rhythmites have been demonstratively identified in recent research. Correct interpretation of ancient rhythmites promise historical insights for: a) Milankovitch long-term periodicity; b)
lunar recession rates; c) lunar origin and stability; d) and Earth’s rotational deceleration (Bills and Ray 1999; Kvale et al. 1999; Olson and Cloud 1968; Walker and Zahnle 1986a).

A number of studies also suggest cyclic/rhythmite foreset or laminae couplets preserved in Paleoproterozoic formations reveal tidal cycles (Archer 1996; Kvale et al. 1999; Oost et al. 1993; Sonett et al. 1988; Sonett and Chan 1998). Depositional couplets from the Elatina (Avsyuk et al. 2011; Sonett et al. 1988), the Reynella Siltstone (Tessier 1993), Big Cottonwood (Chan et al. 1994; Ehlers and Chan 1999; Sonett and Chan 1998), and Weeli Wolli Formations (Trendall 1973b) display rhythmic sequences interpreted as 10-20 diurnal or 20-30 semidiurnal tidal deposits. The suggested “time intervals” represented by these sediment accumulations are days, weeks, months, and years. Strong asymmetry between high and low, spring and neap tides, along with modest asymmetry relative the perigee and apogee positions, lunar inclination to the ecliptic plane provide needed tidal markers (diurnal: K₁, O₁, P₁; semidiurnal: M₂, S₂, N₂).

Modern tidal rhythmites preserved in modern estuarine and bay environments are found. Ancient tidal rhythmites of the Elatina Formation of Western Australia (Williams 2000) and the Big Cottonwood Canyon of Utah (Archer 1996; Chan et al. 1994) are interpreted as shallow-marine, continental-shelf tidal deposits with broad areal extent, not limited to estuarine or inland bay areas.

Estimates for the length of a day at 2.45 Ga, based on the iron-rich Weeli Wolli Formation, are between 17 and 19 hours (Williams 2000). Extrapolation of appropriate phase-lag angles provides insight into past rates (Hansen 1982). Reconstruction of recorded historical astronomical data and eclipse records support a shorter Earth day. In addition, well-preserved, Neoproterozoic rhythmites in the Reynella and Elatina Formations (Williams 1997; Williams 1998) and in the Big Cottonwood Canyon (Chan et al. 1994) at ~620 Ma contains well preserved
tidal signatures that record 13.1 ± 0.1 synodic months/year, 21.9 ± 0.4 hours/day, and a mean lunar recession rate of 2.17 ±0.3 cm/year (Chan et al. 1994) over the time period of deposition, a little more than half the present rate. The present (3.82 cm/yr) rate and the Big Cottonwood Canyon extrapolated lunar recession rate [2.17 cm/yr to ~620 Ma, (Williams 2000)] suggest that faster, more pronounced tides would have existed in the Proterozoic.

Settings such as inlets, bays, and estuaries have provided much of the modern valuable rhythmite data by constraining the number of variables and by amplifying tidal constituents. Laminae couplets, attributed to lunar periodicities such as daily or neap/spring tides, must remain undisturbed by storm surges to preserve harmonic or rhythmic oscillations. Trendall (1973b) and Williams (2000) isolated possible diurnal or semidiurnal and neap/spring inequalities from the Weeli Wolli Formation of the Hamersley Basin, Pilbara Craton. Though uncertain of their findings, the fine laminae couplets of the Weeli Wolli are at this time the oldest and best candidates for ancient BIF rhythmites.
6. Ocean Currents

In addition to tides, currents affect the energy and sediment delivery within marine environments. Currents, like climate, originate from Earth’s latitude-specific insolation patterns, and from Earth’s rotation and Coriolis Effect resulting in wind shear, tidal friction, and geostrophic flow. In addition, bathymetry, gravity, and water density drive circulation patterns. Surface currents on the ocean are generated by wind shear pushing or “piling” ocean waters resulting in amphidromic points of circulation (Figure 1.19). Gyres result from ocean surface height variations of ~140 cm, and from the Coriolis effect, pressure gradients, and prevailing tides. Flow along the western boundary of continents (Wirth 2009) accompanies upwelling of nutrient rich waters.
Figure 1.19  Ocean surface currents are wind and gravity driven in response to pressure gradients. Geostrophic flow is moves from high (red/yellow/green) to low (blue). Flow directions are driven by gravity, interactions with Coriolis forces, thermohaline circulation patterns, and shoreline or bathymetric morphologies. R.Ray NASA/GSFC, Space Geodesy, June 1999. http://sealevel.jpl.nasa.gov/science/invest-ray.html

6.1 Ocean Flow Regimes

In the Northern Hemisphere, at ocean depths 10-100 meters, a constant deflection to the right of the wind direction develops. The frictional interaction between the atmosphere and the surface

Figure 1.20  Unidirectional current, with mixed tidal and seasonal variations, dominates large portions of the ocean. Winter current velocities are highest up to 100 meter depth. Ekman spiral results in changing flow directions between surface and depth (200 meter). Data requested from the TAO Project/NOAA, Androes, Nov 2011. http://www.pmel.noaa.gov/tao/data_deliv/deliv.html
of the ocean transfers energy to the ocean surface and depths. This deflection, at approximately 45° angles, is known as the Ekman Spiral resulting from Earth’s rotation. As the spiral propagates downward, current flow directions are at approximately 90° angles to the wind direction. Submarine sediment accumulation is driven by these energy and flow velocity regimes.

Waves, tides, gyres, and currents circulate and suspend sediment in the water column. Deposition and erosion are a response to bathymetry and energy pulses. Storm events, volcanism, and hydrothermal activity disrupt uniform cyclic tidal or seasonal patterns; therefore, proximity to these events or position relative to storm wave base must be taken into account.

Prevailing currents change seasonally (Figure 1.20) in response to solar radiation, pressure and temperature change, the ocean’s thermohaline circulation (Dong et al. 2007; Qu and Meyers 2005; Rodrigues et al. 2007; Yuan and Han 2006), and major oscillations such as El Nino and La Nina (Morris 1993; Wen et al. 2010). Greater resolution of these dynamic forces at work in the global ocean has been achieved as a result of NASA and Goddard Space Flight Center monitoring.

6.2. Ocean Chemistry and Biology

Ocean chemistry dictates marine biological and mineral precipitates. In modern oceans, silicon, iron, nitrogen and phosphorus (Si, Fe, N, and P) are limiting factors in biological productivity and are depleted relative to saturation levels. Continental sources renew ocean nutrients and ions through weathering and erosion cycles. Iron flux increases during glacial maximums resulting in enhanced diatom production relative to other biota. Iron also stimulates the growth of diazotrophs, altering the N/P balance, releasing more phosphorus. Microbes
forming MISS (microbially-induced sedimentary structures) include bacteria, fungi, algae, archaea, and protozoans. Stromatolites are a specific type of microbial mat.

*In situ* precipitation of minerals is a function of ocean chemistry and the energy of the environment. Silica is the most abundant precipitate or ooze component of the ocean floor. Episodic precipitation of amorphous silica or microcrystalline quartz in the ocean can be linked to saturated freshwater mixing, lower pH values, changing depths, or influx of suspended or dissolved silica-rich sediment, volcanic ash, or biogenic tests. Freshwater contains higher silica concentrations, but is rapidly depleted by biotic uptake upon mixing with the ocean. A soda ocean model has been proposed for the Archea (Kempe and Degens 1985) with high alkalinity and high pH permitting supersaturation of silica with respect to the present ocean; however, this is not required to produce precipitates in the presence of iron. Iron shuttles (Fischer and Knoll 2009; Kempe and Degens 1985) provide an alternate method of silica formation as proposed also by early research (Krauskopf 1959). Primary silica precipitation is evidenced in Archean formations of Western Australia (Barley et al. 1997; Fischer and Knoll 2009; Pickard et al. 2004; Schneider et al. 2002; Sugitani et al. 1998) in banded iron formations (BIF’s) of Hamersley Basin, quartz arenites of Jack Hills, and in the Apex cherts of Pilbara Craton.

Early oceans are thought to have been depleted in oxygen (Blank and Sanchez-Baracaldo 2010; Cloud 1973; Cloud 1968; Farquhar et al. 2007a). Most of the available oxygen oxidized iron and carbon, the primary continental elements weathered and dissolved in the early ocean. Calcium, magnesium, potassium, aluminum, and sodium were also released into the ocean. Atmosphere, water (rainfall, river, or ocean) and surface interactions produce sediment suggesting sedimentary layers from early Earth contain multiple lines of evidence. Example: Epeiric seas produced massive carbonate deposition in shallow seaways. Carbonates are warm
water mineral precipitants and are most commonly formed in shallow ocean, tidal, and supratidal settings. Carbonate is unstable at depths greater than 4500 m or in cold ocean waters.

Recent research suggests that in the past, sulfides were preferentially precipitated in marine sediments dated prior to 2.45 Ga (Farquhar et al. 2007b; Masterson et al. 2011; Zahnle et al. 2006). Sulfate deposition is possible in the modern, oxygenated ocean setting; but in the past, primarily sulfides were stable (Zahnle et al. 2006). Mass-independent fractionation (MIF) during sulfide formation is possible under conditions of higher UV light (high energy photons) flux. Ultraviolet radiation facilitates $\delta^{33}$S and Fe$^{2+}$ oxidation. An atmosphere without oxygen is also lacking ozone – the primary filter of UV light. With a low ozone abundance, far higher levels of UV radiation participate in chemical bonding and fractionation. Shortwave UV (200-280 nm) and UV-B (280-320 nm) attenuation accompanying the rise of oxygen may exert a temporal limitation on the formation of BIF’s (Farquhar et al. 2011). The origin of mass-independent fractionation (MIF-S) of sulfur isotopes ($\delta^{33}$S) in sediments older than 2.45 Ga is widely interpreted in terms of UV-triggered reactions under oxygen-poor ozone-depleted atmosphere conditions (Bau and Moller 1993; Farquhar et al. 2007b).

Discoveries of sulfate in shallow Archean sea sediments (Ohmoto et al. 2006) lend support to a stratified early ocean, rather than wholesale global anoxia, where oxidizing conditions were present near the surface but not in the deep ocean (Cuntz et al. 2009; Reinhard et al. 2009). Changing Eh-pH potential in stratified ocean basins has been noted in the Mediterranean waters in recent work (Einsele 2000). Transient oxidants, primarily O$_2$, permeate the photic zone and deeper leading to iron precipitation at the oxic/anoxic boundary.

6.3 Origin of Earth’s Ocean and Atmosphere
The young Earth consisted of degassing hot rock, water vapor, and a nitrogen rich atmosphere. Volcanism and degassing releases methane and sulfur injecting the atmosphere with haze molecules (Domagal-Goldman et al. 2008; Kump and Barley 2007) having strong similarities to Titan’s haze layer (de Kok et al. 2010). Ocean development coevolved with the cratons (Bekker et al. 2010; Lunine 2006; Schopf 1993). The earliest evidence for the existence of ocean and water in the atmosphere is based on δ\textsuperscript{18}O isotopic fractionation suggesting an age of 4.3-4.4 Ga for fluid inclusions (Figure 1.21) in the Jack Hill’s zircons (Cavosie et al. 2004; Valley et al. 2006).

6.3.1 Rise of Oxygen

A recent hypothesis (Goldblatt et al. 2006) suggests that “bistability” of oxygen levels mediated first by UV and alternately by ozone may account for the chemical evolution of the ocean and atmosphere. Two distinct oxygen stability ranges exist, one at 21% and the other at less than 1% (Goldblatt et al. 2006). The rise in oxygen, as suggested by Cloud (1968), from photosynthesis or photolysis of water is a slow process; however, a slow rise in oxygen is unstable due to high UV light in absence of ozone. Ultraviolet light is harmful to surface life, the primary source for the rising oxygen. As a shield for life, a haze layer has been proposed by researchers (Domagal-Goldman et al. 2008; Kump...
to overcome the obstacle of destructive UV radiation without a layer of ozone. Sustainability of a slow rising oxygen level may lie in the presence of a haze, similar to Titan’s organic stratospheric layer. The proposed atmospheric haze layer (Wolf and Toon 2010a), with HCN organic molecules, may have provided both the necessary ingredients and protection for early life (Hasenkopf et al. 2011; Kump and Barley 2007).

Ocean oxygenation is a byproduct of pressure, temperature, depth, and oxygen concentration in the atmosphere. Modern ocean anoxia is primarily at depth and in limited coastal regions covering more than 95,000 square miles (Blank and Sanchez-Baracaldo 2010; Machín et al. 2010) where it is strongly seasonal, except in the Baltic and Black Seas where anoxic conditions persist year-round (Johnson et al. 1999). Hypoxia accounts for red tides, mass fish kills, and loss of dissolved oxygen content in the water column. Hypoxia may also be locally stratified confined to smaller regions or deeper ocean (Heising and Schink 1998). Deep ocean anoxia is strongly linked to the thermohaline circulation patterns (Jeppsson 1990). Recent studies have found that a few larger scale ocean anoxic events are sporadically distributed in deep ocean drill core (DSDP or ODP) and have been named the Aptian or Selli Event (120 Ma), Bonarelli Events (93 Ma).

Apart from their value as iron ore, interest in BIF formations stems from their anomalous widespread thickness in ancient sequences and their relative absence in the modern rock record. Banded-iron formations are also noted for their historical record of ocean chemistry, their potential record of biochemical evolution of life, and for the proposed global ocean anoxic hypothesis (Cloud 1968). Graphite δ^{13}C isotopes >25‰ from the greenstone belts of the Isua Akilia BIF’s, dated at 3.83 Ga, are considered to be possible signatures of earliest life on Earth (Dauphas et al. 2004; Fedo and Whitehouse 2002; Konhauser et al. 2002; Mojzsis and Harrison 2008; Tian et al. 2011; Wolf and Toon 2010a).
2002; Westall 2003). Although Cloud’s model for a biogenic origin of BIF’s remains valid, linking solely steps in biochemical evolution with increasing oxygen content of the atmosphere is only narrowly accepted (Anbar et al. 2007). The oxidation of Earth described as the “Great Oxidation Event” (Anbar et al. 2007; Cuntz et al. 2009; Goldblatt et al. 2006; Heising and Schink 1998; Sessions et al. 2009) is commonly given an average age of ~2.5 Ga (Eriksson et al. 2011).

Recent analyses of a number of BIF sequences report that glass spherules or impact-generated granules have been found in underlying or stratified layers (Glikson 2010; Ohmoto et al. 2006). Asteroid collisions have the capacity for dramatic changes in ocean and atmosphere creating an environment favorable for ferrous iron and sulfides (Glikson 2010; Ohmoto et al. 2006). This evidence has been used to form a new theory for ocean and atmosphere evolution linked to astronomical events and to chemical oscillations between sulfur/sulfate and ferrous/ferric iron.

6.3.2 Ocean Sediment Oxidation

Ocean floor sediments accumulate principally as precipitants such as sea floor ooze and unsorted particulate matter, or as sorted horizontal laminations. Stability for mineral precipitation require specific temperature, pressure, Eh-pH, and salinities conditions. Most mineral precipitation is facilitated in quiet waters or during metabolic respiration. Deep ocean deposition and organic dissolution is commonly associated with anoxic conditions (Fischer and Knoll 2009; Widdel et al. 1993). The Lower Cretaceous ocean sediments indicate wide-spread strongly anoxic conditions related to changes in plankton and organic matter circulation patterns.

Alternating stagnant and oxic conditions are also common in recent geologic time. The Mediterranean basin sediments record Quaternary and Holocene fluctuations in dissolved oxygen documented by thin sapropel (>2% organic) or thick sapropel layers (.05-2% organic) within hemipelagic and pelagic sediments (Einsele 1996) along the shelf margins and also periodically in the deep sea sediments (DSDP 125). Low surface salinities led to high surface productivity and subsequent eutrophic stagnation in deeper, stratified layers of the ocean. Processes implicated include high seasonal monsoonal precipitation (Murat and Got 1987; Rossignolstrick 1985), fresh water flooding from the Nile resulting in stratification, convection overturning, and ventilation of ocean floor (Einsele 1996).
7. Ancient Surfaces and Geomorphology

Sediment-derived strata (as opposed to lava flows, ash falls, impact debris aprons, or volcanic sediments) are limited to planets with 1) terrestrial surfaces (as opposed to gaseous or icy surfaces), 2) surface and atmosphere interactions via volatile liquids, and/or 3) flowing liquids or solids (such as glaciers). Only two known planetary bodies in our solar system, other than Earth, are capable of fluid derived sedimentary layers, Mars and Titan. The Martian surface is transected by sinuous flow features. Layered deposits have been imaged at the surface by Spirit and Opportunity (Figure 1.22), MOC, and MRO. Recent discoveries by the Cassini orbiter reveal lake basins, river drainage systems, and methane rains on Titan. This research predicts that layered deposits will be found on Titan. In short, sufficient evidence exists to suggest that sedimentary processes are at work or have been active in the past on planetary bodies other than Earth.

Figure 1.22 The Martian surface exhibits layered sedimentary formations of iron oxides and clay minerals. Victoria crater image by Mars Exploration Rover Opportunity (Nov. 2006) suggests that a sediment sorting and cementation mechanisms once existed on Mars (Bell et al. 2004) NASA/JPL Pancam 753 nm, 535 nm, and 432 nm.
Earth’s earliest sedimentary sequences are found in close proximity to craton exposures and are artifacts of continental weathering. Greenstone belts, banded iron formations, and accretion wedges or allochthons comprise much of the terrain. The potential discoveries from ancient Earth terrain include 1) crust, ocean, and mantle characteristics (a possible record of differentiation processes), 2) early Earth conditions, 3) Earth and Moon astronomical rhythms (and the timing of the Moon’s formation), 4) the rise of oxygen on Earth, and 5) the earliest life on Earth.

7.1 Titan’s Surfaces

Fluid carved valleys, vast areal extensions of equatorial dunes, and ethane/methane lakes on Titan appear to be the product of latitudinal and seasonal insolation patterns coupled with topographic, orographic, and orbital forcing mechanisms. Like Earth, the orbital dynamics of the Titan/Saturn system modulate radiation flux to the atmosphere and surface, preferentially distributing volatiles (in gas, liquid, and solid forms) along stability pathways.

Aharonson et al. (2009) point to the present asymmetric lake distributions on Titan as a consequence of orbital forcing, more specifically, to Titan’s eccentricity and precession cycles (Aharonson et al. 2009). The total area of known dry and filled lakes stands at ~7.5% identified in the south and ~92.5% in the north (Hayes et al. 2011). Based on the magnitude of the present dichotomy in fluid volumes and observed volatile mobility, long-standing asymmetry is apparent. Links to longer period astronomical forcing, such as changes in obliquity or eccentricity as a cause for this asymmetry, are more difficult to ascertain.
7.2 Martian Surfaces

Erosion processes on Mars are presently limited to dust storms, occasional ice melts or ground water or debris flows, mass wasting, impact cratering, and space weathering. The discovery of horizontal-layered sedimentary rock on the Martian surface by Opportunity suggests that a sediment sorting and cementation mechanisms once existed on Mars (Bell et al. 2004). This hydraulic sorting mechanism no longer exists on a large scale, but may be good evidence of the past energy presence and upward-finining gradation that occurs in water-lain sediments. Today, the Martian terrain is littered with boulders, rocks, sand, silt, and dust – the antithesis of sorting.

The majority of the Martian surface correlates to the Archean on Earth. Early Mars was a wetter and more geologically active planet. During the Archean on Earth, volcanoclastic and igneous derived sediments, including banded-iron formations, were formed and may serve as analogues for Noachian-age and Siderikan epoch Martian sedimentary deposits (Westall 2003). Formation of hematite and sulfate minerals during this interval has been interpreted from spectrometry of TES (MGS), Mössbauer Spectrometer, aboard the Mars Exploration Rover Opportunity, and the Alpha Proton X-ray Spectrometers. Both CRISM and Opportunity have detected sulfate salts with magnesium, calcium, and iron – strong indication of igneous dissolution in water.
Hematite was observed from thermal infrared on Mars. Christensen (*et al.* 2000) and others interpreted hematite as evidence of liquid water (Allen *et al.* 2004; Christensen *et al.* 2000), either from basinal or ground water precipitation. Additional evidence of iron mobility and water alteration, most likely ground water, comes from the discovery of hematite blueberries (Figure 1.23). Spectral analyses of layered surfaces have identified high iron concentration.

Hematite blueberries from the Opportunity Ledge provide a critical historic link to the outcrop and to the surrounding Meridiani Planum region. Hematite, detected by TES (Thermal Emission Spectrometer) aboard the Mars Global Surveyor (MGS) spacecraft, piqued the interest of scientists in Meridiani as a landing site. Hematite occurs as rhombohedral crystals, as reniform (kidney-shaped) crystals, or as fibrous aggregates in igneous, metamorphic, and sedimentary rocks. Blueberries are hematite
concretions formed from sedimentary processes, potentially from jarosite \((\text{H}_2\text{O}, \text{K})(\text{Fe}^{3+},3\text{(OH)}_6\text{(SO}_4)_2)\) and minor ferric sulfates. If their origin were related to volcanic or meteoric episodes, layers of spherules would be expected rather than random occurrences. Ferrous iron released from oxidized minerals is another possible source.

Iron oxides or iron carbonates derived from weathering high iron-magnesium silicate minerals (basaltic rock) are commonly associated with banded-iron formations. Duricrusts have been observed at every landing site indicating cementation has occurred (Pirajno and Van Kranendonk 2005; Stillman and Grimm 2011). Iron and silica layers may be common on the Martian surface, much like early Earth, as a result of the presence of liquids, abundance of igneous minerals, high surface energy on windblown silt and clay particles, and from possible pressure solutioning after burial. Cementation, duricrust formation, and sorting imply a wetter past and a possible iron formation pathway for Mars.

Fine-layered lithologies in Holden Crater, West Candor Chasma, Vallis Marinaris, and many other locations attest to the abundance and availability of fine fragments (Buhler et al. 2011; Mckay and Davis 1991). Eolian processes produce abundant sources of very fine silicate dust, readily hydrated to form silica in solution during wet periods. Clay-size particles are common on the Martian surface due to wholesale dissolution or sorting in the environment by either water in the past or by wind (Fastook et al. 2011; Schon and Head 2011). Sedimentary rocks from Meridiani Planum record aqueous and eolian conditions of ancient dune and interdune environments (Buhler et al. 2011).
7.3 Earth’s Ancient Surfaces

The oldest sedimentary rocks are found in the greenstone belts of Isua, Greenland (Appel 1980; Dymek and Klein 1988a), and the oldest fossils in the Jack Hills zircons of the Pilbara Craton (Cavosie 2006, Valley 2006). These formations and those of the Kaapvaal Craton, Guyana Shield, and Liberian Shield of Sierra Leone, Guinea, Liberia, and Ivory Coast are some of the earliest sedimentary rocks and are associated with weathered volcanic ultramafic sequences (Barley et al. 1997; Bekker et al. 2010; Nisbet et al. 1993; Schneider et al. 2002).

Differentiation of Earth’s upper mantle and crust initiated the growth of continents and the first constituents of sedimentary strata (Bekker et al. 2010). Of these strata, iron-rich formations have been proposed as candidates for preserving fossilized life (Dauphas et al. 2004; Konhauser et al. 2002; Schopf 1993; Sugitani et al. 1998), for recording past conditions or events on Earth (Cannon 1961; Eriksson et al. 2011; Mojzsis and Harrison 2002), and for providing a possible analog for other planets. This research explores climate-driven depositional models for sedimentary sequences, for interpretation of geomorphic features on planetary surfaces in our solar system, and for their potential to record ancient life.
CHAPTER TWO: Mineralogy and Micro-Banding Profiles of Banded Iron Formations

Tidal rhythms, mimicking those in modern estuarine settings, have been suggested as the origin iron-rich ancient formations, affording the possibility that uniformitarian processes of orbitally-induced deposition may preserve daily, fortnightly, seasonal, and annual rhythms. Banding profiles examined at the $10^{-2}$ m, $10^{-1}$m, and 1-10 m scale exhibit periodic functions in time series analyses relative to cyclical processes. Each series is distinct, derived from a 3-dimensional energy transport model, with a minimum of 4 frequencies. The dominant sinusoidal series at $10^{-1}$ m correlates to ocean energy pulses with a harmonic vibrational interference at a 1.3-1.4 x $10^{-2}$ scale. At the lowest frequency and periodicity (1-10 m), a non-uniform alternate process is evident. Potential driving mechanisms for macroband time-series include periodic volcanism, downwarping or uplift, or other tectonic pulses – predictably slow processes. Orbital forcing, and the resulting eustatic sea level oscillations, is an alternate explanation. Harmonic vibrational phase interference is interpreted as deposition of fine, relatively unsorted, mixed mineral grains, primarily silica and iron. Over time, sorting and mineral migration create laminar structure through dissolution and crystal migration. Fine laminae develop, which is thermodynamically favored and common to many chalcedonic and banded silica and iron strata.
1. Introduction

Banded-iron formations (BIF) of late-Archean age found in the Yilgarn Block of Western Australia (Klein 2005), the Zimbabwe craton of Africa (Eriksøn et al. 2011), and northern Minnesota and the Michipicoten district of north-central Ontario (Barley et al. 1997; Schneider et al. 2002), contain magnetite, a reduced form of iron, chert, and assorted other mineralogies. Enigmatic problems with BIF’s in general tend to focus on: 1) the oxidation state and triggering mechanisms for large accumulations of cyclic iron precipitation; 2) the extent of involvement from biological mediators; 3) the oxygen content of the global ocean and atmosphere; and 4) the preservation or existence of a stable depositional environment over vast periods of geologic time. Similarities and differences between regional BIF formations provide constraints on the triggering mechanisms and variables.

1.1 BIF Controversies

Controversies surrounding banded-iron formations (Emerson 2009; Fedo and Whitehouse 2002; Johnson et al. 2003; Johnson et al. 2008; Mojzsis and Harrison 2002) stem from departures from present-day processes. Despite the research attention iron formations (IF) have received during the past century, a conclusive depositional mechanism remains elusive (Eriksson et al. 2005; Weisburd 1986). Any geologic model put forth for iron formations must explain the vast regional coverage, horizontally continuous scale, the vertically cyclic nature of the banding, and the uniform precipitation of oxidized minerals.

The oxidation state of iron in BIF’s is historically linked to the Cloud (1968) hypothesis that postulated an early anoxic global ocean. Recent studies suggest that ferric iron, rather than ferrous iron, is authegenic in iron formations (Konhauser et al. 2007) and magnetite is a product
of digenesis rather than primary deposition (Hyslop et al. 2008; Hyslop et al. 2008; Johnson et al. 2003). Numerous other studies of BIF’s find that iron species are the product of metamorphism (Johnson et al. 2003; Klein 2005; Shibuya et al. 2007) leading to reclassification of iron original valance states from divalent to the higher trivalent oxidation state. In the Zimbabwe craton, the greenstone BIF’s was reclassified as a silicified shear zone (Nisbet et al. 1993). Questions also arise from isotopic analysis of UV light-driven sulfur δ³⁴S mass-independent fractionation sulfide precipitants (Glikson 2010) as hydrothermal rather than primary δ³⁴S signatures in sulfides and heavy δ¹⁸O signatures in chert (DeWitt et al. 2010; Masterson et al. 2011) as indication of metasomatism. Light isotopic fractionation signatures mimic biological fractionation effects whereas heavy fractionation signatures are consistent with mass independent, high energy environments such as an early Earth without an ozone filter (Goldblatt et al. 2006; Hasenkopf et al. 2011), or hydrothermal activity within the system.

Free oxygen on Earth is unstable in modest fractions (Goldblatt et al. 2006) and must be constantly replenished by photosynthetic organisms. An ozone shield for Earth’s biota is not possible without life. The widespread formation of banded-iron formations and MIF sulfides in the ancient ocean is consistent with anoxia in the global ocean, but is not consistent with the sporadic occurrence of sulfates in Archean marine sediments, or oxygen rich oxides. Sulfides associated with volcanism and hydrothermal vents (Poulton et al. 2004; Reinhard et al. 2009) give pause to the wholesale interpretation of mass-independent fractionation (MIF) of sulfur isotopes at 2.45 Ga as evidence of global ocean chemistry (Halevy et al. 2010; Masterson et al. 2011). In summary, research continues both to challenge and to support the Cloud hypothesis, lacking a better model to replace it.

1.2 BIF Classifications
Multiple classification schemes exist for iron formations also reflecting a lack of unified interpretations. Dominant mineralogies include oxides, silicates (chert), and carbonates with minor, digenetic alterations by sulfide mineralization. More recent formations contain higher aluminum concentrations and are known as ironstones. Chert dominates the Archean. James (1954, 1982) defined IF as “chemical sediment, typically thin-bedded or laminated, containing 15 percent or more iron of sedimentary origin commonly, but not necessarily, containing layers of chert (James and Trendall 1982; James 1954).” Trendall classified IF’s as banded-iron formations (BIF) generally older than c.2.0 Ga with distinct microbanding, and granular-iron formations (GIF) for formations generally younger than c2.0 Ga. with larger grain size (Trendall 1973a). Table 2.1 characterizes the dominant components found in BIF’s.

**Table 2.1 Iron Formations Size and Composition**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Less than 2.0 Ga</th>
<th>More than 2.0Ga</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Thickness</td>
<td>&lt; 50 meters</td>
<td>50-500 meters</td>
</tr>
<tr>
<td>Areal Coverage</td>
<td>&lt; 150 kilometers</td>
<td>&gt;100 kilometers</td>
</tr>
<tr>
<td>Banding Profiles</td>
<td>Massive to alternating silica and oxide facies</td>
<td>Thin banding, with chert, and iron oxides</td>
</tr>
<tr>
<td>Dominate Oxide</td>
<td>Goethite with common contributions from hematite,</td>
<td>Hematite, magnetite,</td>
</tr>
<tr>
<td>Dominate Silicate</td>
<td>Chamosite and cellophane</td>
<td>Quartz/chert greenalite</td>
</tr>
<tr>
<td>Sulfide</td>
<td>Pyrite</td>
<td>Pyrite</td>
</tr>
<tr>
<td>Carbonates</td>
<td>Siderite, calcite, dolomite</td>
<td>Ankerite, siderite, and dolomite</td>
</tr>
<tr>
<td>Common identification</td>
<td>Ironstones</td>
<td>BIF’s</td>
</tr>
</tbody>
</table>

Gross (1983) uses a classification scheme, based in part on size, tectonic setting, and lithological associations, separating iron formations (IF) into the Superior-type and Algoma-type (Gross et al. 1983). Superior-type IF’s are thought to be shallow marine, submerged platform deposits under transgressive seas. Algoma-type IF’s are deposited in tectonic or volcano-
sedimentary basins. Algoma-type are common in Kaapvaal, Minnesota and Ontario. Superior-type are common in parts of Canada, Australia, and South Africa.

Thickness is a function of sediment supply. In general, BIF’s are thicker and more laterally extensive in the Late Archaean to early Proterozoic than in the older greenstone belts. Volcanically derived BIF’s commonly exceed thicknesses of ten’s of meters and can be laterally continuous over ten’s of kilometers (Barley et al. 1997; Morris and Trendall 1988). The laterally extensive Isua, Marquette, Hamersley, and Kraaipan Greenstone Belts and the smaller Dubois and Belingwe Greenstone Belt are all examples of volcanically influenced belts (Condie and Nuter 1981; Friend et al. 2002; Nisbet et al. 1987).

Algoma-type BIF’s are smaller in extent than Superior-type rarely exceeding 10 km areal distribution, with 10-100 m thickness and less than $10^{10}$ tons of iron (Appel 1980; Condie and Nuter 1981). Island arc/back basin depositional environments and intracratonic rifts are preferred for this type of BIF. Tectonic settings are common for early to mid-Archaean greenstone-belt BIF’s (Bekker et al. 2010; Cisne 1984; Krapez et al. 2003) with a transition to shallow marine basins for Superior-type BIF deposition.

Isolating the environment, depth, or circumstances (syngensis or diagenic processes) creating submillimeter-scale varve-like laminae with alternating meter-scale macrobands complicates classification systems. James, Trendall, and Morris used mineralogy or grain-size (James 1954; Morris and Trendall 1988; Trendall 1973a); Gross (1983) used tectonic classifications (Gross et al. 1983). Table 2.2 provides the location and age of some of the larger iron formations.
<table>
<thead>
<tr>
<th>Craton</th>
<th>Location</th>
<th>Formation</th>
<th>Age in Ga</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenland</td>
<td>West</td>
<td>Isua (and Akilia)</td>
<td>3.8</td>
<td>BIF</td>
</tr>
<tr>
<td>Australia</td>
<td>West Central</td>
<td>Frere Formation</td>
<td>2.2</td>
<td>GIF</td>
</tr>
<tr>
<td>Pilbara</td>
<td>Western Australia 2.5 km thick</td>
<td>Pilbara Hamersley Group</td>
<td>2.8-2.4</td>
<td>BIF</td>
</tr>
<tr>
<td>Yilgarn</td>
<td>Australia 650K km</td>
<td>Yilgarn Middlebacks</td>
<td>2.6-2.0</td>
<td>BIF</td>
</tr>
<tr>
<td>Africa</td>
<td>South Africa Transvaal Basin</td>
<td>Kuruman Iron Formation of the Transvaal Supergroup</td>
<td>2.5-1.6</td>
<td>BIF</td>
</tr>
<tr>
<td>Africa</td>
<td>South Africa Northern Province Transvaal Basin</td>
<td>Kraaian Greenstone Belt Pege Iron Formation</td>
<td>2.5-1.6</td>
<td>BIF</td>
</tr>
<tr>
<td>Africa Kaapvaal</td>
<td>South Africa Griqualand West Basin</td>
<td>Griqualand West Kaapvaal</td>
<td>2.5-1.6</td>
<td>BIF</td>
</tr>
<tr>
<td>Western Africa</td>
<td>West Africa</td>
<td>Nimba</td>
<td>2.5-1.6</td>
<td>BIF</td>
</tr>
<tr>
<td>Superior Circum-Ungava</td>
<td>Canada</td>
<td>Labrador Lake Superior Gunflint (biota) Mesabi Cuyuna Marquette</td>
<td>2.2-1.5 2.5-1.6</td>
<td>GIF</td>
</tr>
<tr>
<td>Superior</td>
<td>Northern Canada</td>
<td>Biwabik Formation of the Mesabi Range Abitibi</td>
<td>&lt;2.0 1.6-.9</td>
<td>BIF Superior</td>
</tr>
<tr>
<td>Baltic Shield</td>
<td>Finland</td>
<td>Kostomushka</td>
<td>&lt;2.0</td>
<td>BIF</td>
</tr>
<tr>
<td>Amazon</td>
<td>Brazil</td>
<td>Carajas Formation of the Grao Para Group Minas Gerais</td>
<td>2.5-1.6</td>
<td>BIF</td>
</tr>
<tr>
<td>Brazil</td>
<td>South America</td>
<td>Mimas Supergroup</td>
<td></td>
<td>BIF</td>
</tr>
<tr>
<td>Amazon</td>
<td>Venezuela</td>
<td></td>
<td>2.5-1.6</td>
<td>BIF</td>
</tr>
<tr>
<td>Sao Francisco</td>
<td>South America</td>
<td>Caue Itabirite Itabira Group</td>
<td>1.6-.9</td>
<td>BIF</td>
</tr>
<tr>
<td>China</td>
<td>China</td>
<td>An Shan</td>
<td></td>
<td>BIF</td>
</tr>
<tr>
<td>Ukraine</td>
<td>Ukraine</td>
<td>Krivoi Rog and Kursk</td>
<td>1.6-.9</td>
<td>BIF</td>
</tr>
<tr>
<td>Karnatka</td>
<td>India Bababudan Basin</td>
<td>Orissa Mulaingiri Formation</td>
<td>1.6-.9</td>
<td>BIF</td>
</tr>
<tr>
<td>Other:</td>
<td>Rapitan Alaska Urucum Brazil</td>
<td></td>
<td>&lt;.9</td>
<td>IF</td>
</tr>
</tbody>
</table>
General agreement among BIF researchers includes: 1) BIF’s form primarily by sedimentary processes, including clastic deposition and diagenic recrystallization; 2) banding patterns, at some level, are indicative of cyclic or periodic events; and 3) formation occurs under non-uniformitarian Earth conditions, processes, or in settings that do not exist today. Recent research results are consistent with the following understandings: 1) deposition is aqueous, basinal, and in regions with active tectonic evolution; 2) in addition to terrestrial weathering, the origin of large volumes of iron and silica is associated with volcanoclastic, hydrothermal, or mobilizing resources such as changing Eh/pH, oxic/anoxic, or temperature conditions; and 3) the extent of metamorphism, diagenesis, and metasomatism is variable, but is not the primary or sole source of banding. This study assumes these premises and the foregoing conclusions stated above are valid.

2. Depositional Environment of BIF’s

Depositional environments range from shallow marine conditions under transgressing seas on the continental shelf to abyssal off-shelf environments. The list of depositional environments includes, but is not limited to: a) a restricted or barred basin, below-wave base, b) an extended shelf, c) off-the-shelf, d) deep ocean, e) abyssal ocean; f) forearc or backarc basin, g) spreading zone, h) proximal location to ocean ridge, hydrothermal or smoker vents, and i) shallow marine. Tying the depositional environment to global or uniformitarian processes supplying adequate iron and silica, operating in cycles under relatively stable conditions, has lead many BIF workers to prefer the deep or abyssal ocean model and millions of years of slow accumulation. Silica-rich, saturated waters are commonly found in the deep ocean ooze. However, terrestrial influence is
evidenced in some BIF’s by sedimentary structures such as ripples or mud drapes, clasts, stromatolites, and isotopic values characteristic of terrestrial, not marine fractionation.

BIF sequences are commonly linked to Milankovitch orbital/climate cycles (Milankovitch 1948), but rarely to daily, seasonal, or shorter term cycles. While rising and falling sea levels are important for near shore depositional cycles, deeper ocean settings would be less affected by climate-driven rising and falling sea levels, by bioturbation, or by storm events. For this research, both a shallow marine environment and a deeper, more distal ocean environment are candidates.

2.1 Source of Sediments

Detrital clasts and strong terrestrial signatures are limited, but not completely absent in BIF’s (Bau et al. 1997; Dauphas et al. 2004; Frost et al. 2007; Krapez et al. 2003; Laberge 1966; Pickard et al. 2004; Shibuya et al. 2007). Alternating macrobands of shale and an abundant source of silica and iron are consistent with a nearby continental influence and shorter geologic time. Isotopic analyses suggest a mixing of terrestrial and hydrothermal sources, in addition to possible volcanism (Frost et al. 2007; Isley 1995; Raiswell et al. 2011; Steinhoefel et al. 2009; Trendall et al. 2004; Tsikos et al. 2010).

Volcanic sediments, such as ash fall, tephra, and glass shards, are associated with many BIF’s, but not GIF’s (Morris and Trendall 1988; Morris 1993), granular-textured iron formation. Crocidolite and riebeckite minerals, used to produce asbestos, are identified with metamorphosed igneous minerals in banded iron formations (Morris 1993; Raiswell et al. 2011; Trendall and Blockley 1970). Igneous sediment contributions signal volcanic activity from continental, island arc, or submarine volcanism (Barley et al. 1997; Laberge 1966; Pickard et al. 2004; Schneider et al. 2002).
Sediment source and delivery include: 1) craton weathering, erosion, and transport from rivers and seasonal rains, potentially transecting volcanic ash fields; or 2) tides or currents delivering sediments to a basin, ridge, shoal, or shoreline; or 3) slow deep water accumulation of clastic sediments over vast time periods. If volcanism is submarine, convective currents could be invoked as both the delivery and depositing agent.

2.2 Microbial Induced Sedimentary Structures

Ancient sedimentary layers contain the signature of life and oxygenation early in Earth’s history. Isotopic fractionation values for carbon isotopes were gleaned from graphite inclusions in apatite providing a 3.8 to 3.85 Ga date – the oldest evidence of life (Dymek and Klein 1988a; Fedo and Whitehouse 2002; Mojzsis and Harrison 2002). Apatite crystals were found in BIF sequences of the Isua Greenstone Belt, near Akalia West Greenland dated from 3.65-3.85 Ga (Appel 1980) based on U-Th-Pb radioisotopes (Cavosie et al. 2004: Appel 1980). Fluid inclusions from Isua zircons contain oxygen isotopes suggesting the early presence of an ocean (Valley et al. 2006; Appel 1980; Cavosie et al. 2004). Cyanobacteria microfossils from the 3.465 Ga Apex chert (Friend et al. 2002; Schopf 1993) are often recognized as the earliest, but not unequivocal, evidence for fossilized life structures. Microfossils continue to be a source of controversy in the quest to uncover relics of life, with the most notable case the ALH84001 Martian meteorite (McKay et al. 1996b). Whether on Earth, Mars, or the next “Earth-like” planet, discoveries of the earliest life or extraterrestrial life will be hotly debated in the arena of peer reviews.

Many banded iron formations (BIF’s) are microbial mats or microbially induced sedimentary structures (Johnson et al. 2008; Konhauser et al. 2002). Anaerobic phototrophs populate a
stratified ocean water column (Kappler et al. 2005) in deeper ocean water. Low abundance of Precambrian iron is evident in shallower water chert formations (carbon-rich zebra chert of Western Australia), as a possible consequence of rapid aerobic precipitation of iron (Dymek and Klein 1988a; Macphail and Stone 2004; Raiswell et al. 2011) by photosynthetic microbially induced sedimentary structures (MISS). Higher values for light isotopes, consistent with biotic mediation (Becker and Clayton 1976; Frost et al. 2007; Tsikos et al. 2010), commonly form in conjunction with cyanobacteria, stromatolites, and microbial mats (Appel 1980; Becker and Clayton 1976; Johnson et al. 2003; Johnson et al. 2008). Microbially induced sedimentary structures utilize biostabilization to baffle or trap sediments, enhancing preservation of laminae, including daily, fortnightly, seasonal, or other sedimentary cycles. Cloud’s (1968) long-standing theory for the initial rise of oxygen requires microbial mediation in the formation of BIF’s and the rise in oxygen or Great Ocean Oxidation Event (Anbar et al. 2007; Cuntz et al. 2009; Eriksson et al. 2011; Konhauser et al. 2011; Sessions et al. 2009).

Biotic precipitation rates can be up to 60 times faster (Paterson et al. 1997). Mechanisms for ferrous (Fe$^{2+}$) oxidation include diffusion, photochemical, sedimentalogical, and biological. Numerous microorganisms use iron as a metabolic agent, thus the hypothesis that the banding in BIF may be microbially mediated is attractive. The earliest fossil evidence for life has been linked to banded-chert formations (Schopf 1993).

Biological mechanisms for photic or subphotic BIF formation in either anoxic or oxygenated zones are abundant; however, aphotic biological mechanisms are rare for known BIF mechanisms. Iron-oxidizing anoxygenic phototrophs (Kappler et al. 2005), in addition to aerobic photoautotrophs and chemolithoautotrophs, provide pathways for microbially-mediated IF’s in
near-shore or continental shelf environments (Emerson 2009; Konhauser et al. 2005; Konhauser et al. 2002).

Modern ocean waters are depleted/undersaturated in both iron and silica. Only trace amounts of iron and silica are available for abiotic production (Konhauser et al. 2002). Modern biota sequester large quantities of silica, outproducing abiotic precipitation (Sugitani et al. 1998). Near-shore waters are undersaturated (6 ppm) in silica due to uptake by diatoms and radiolarians in shallow marine settings where terrestrial weathering delivers vital nutrients (Ross and Fisher 1986; Sugitani et al. 1998). Dissolved silica at 20 times modern levels would have been possible in the Archean ocean (Lunine 2006; Sugitani et al. 1998).

The preferred depositional model and the forcing mechanism for this study and for

**Depositional Environment of BIF in Forearc or Backarc Basin**

![Depositional Environment of BIF in Forearc or Backarc Basin](image)

**Figure 2.1** The depositional environment interpretation for the Hamersley Group, more specifically for the Brockman Formation. The Hamersley Basin Profile is a pre-accretion time, prior to the closing of the oceanic arc basin, on ramped to the western shore of the Pilbara craton. Ocean currents or tidal influence were present. The Hamersley Group Brockman Formation BIF’s are likely a basinal, off-slope, current-dominated setting (Androes 2012).
anomalously large accumulations of alternating shale and iron/silica-rich layers is a tectonically active island arc setting with active volcanism. These conditions are consistent with an early Earth.

Depositional regimes are rarely stable for long geological periods of time. Therefore, time-series for Milankovitch-cycle BIF’s in deep or abyssal marine environments present problems for researchers. Macro and meso band rhythms for extended geologic periods suggest a relatively quiet, rather than a tectonically active environment; however, most BIF’s have volcanic or hydrothermal source sediment interbedded with terrestrial or ocean sediments. Annual microband varves are suggested for BIF’s in stable deep-water environments. Sediment mineralogy oscillates with changes in depth, velocity, delivery mechanisms, and with saturation equilibrium kinetics. Depth may be a function of glacio-climate cycles, tectonic pulses, or isostasy. With dense iron minerals, such as magnetite, subsidence or isostatic accommodation could be a factor in depth.

3. Methods

A complete macroband and mesoband thickness profile was produced for approximately 400 meters of drill core from the Dales Gorge Member of the Brockman Formation, Hamersley Group, Wittenoom Gorge and Tom Price locations. In addition, three extended microband time-series were produced from the measured depositional couplets. Each band width was measured using a sub-meter to meter scale. For the purpose of this research, mesobands were isolated by 1) iron concentration and oxidation state, 2) width, and 3) position in series. The frequency resolution was obtained by taking the median of the individual estimates from an interpolated periodogram and confidence intervals constructed on frequency estimates by methods discussed.
in Coughenour (2009). A small number of outliers were removed from long series transformations. These procedures are useful for shorter sequences of data if there are enough sequences of sufficient length. The median frequency estimate generally begins to converge on the “true” frequency for $N \geq 50$ with 100 sequences (Archer 1996; Coughenour et al. 2009).

**Data Collection and Delineation of Intervals:**

1. **Frequency:** Frequency intervals were established by a combination of the sedimentary bedding plane thickness or band (amplitude) consisting of a specific mineralogy.

2. **Series:** A series number is represented by $\frac{1}{2}$ a complete cycle exhibiting a maxima and minima within 1 cycle.

3. **Measures:** Bedding planes thicknesses were obtained from the entire length of the Dales Gorge core using precision 6” and 12” Starrett dial caliper for microbands and mesobands. Data were recorded in Excel. Macrobands were measured with less accuracy using a standard tape measure. Breaks in the core were numbered, but also prevented actual macroband thickness accuracy.

4. **Depth:** Periodic drill core depths were documented to assure corresponding thickness with depth. These records were compared with the Australian Blue Asbestos Company drilling company records from a Wittenoom Gorge, Hole EC10, location in the Hamersley Range.

5. **Macrobands:** Established by A. F. Trendall and J. G. Blockey in the Geological Survey of Western Australia Annual Report 1967, pg. 48-53 (also corresponding to widely accepted divisions seen in the field) and Trendall (1970), 33 macrobands refer to rigid BIF alternating with less rigid shale thicknesses. The composite type section referenced has a thickness of 466.25’ (not found at any one location) with macobands BIF0-BIF16 and S1-S16. Macrobands can be traced over 185 miles in natural exposures. A total of 301.5 feet of core
was obtained at the EC10 location; therefore the total thickness of core is approximately 165 feet less than the type section. Thicker to thinner sequences (where sediment influx is less or pinching out) bands commonly have similar and correlating mesobands and microbands, but are thinner.

6. **Mesobands:** Mesobands established by this research differ from those loosely referred to in the survey publication as an “average thickness of less than an inch.” The earlier analysis identified mesobands as wider banding and microbands as thinner banding without segregation by mineralogy or magnetism. Mesobands in this research vary from approximately 50-200 mm and are identified by a change in hematite and magnetite concentrations. A mesoband number corresponds to a couplet of one primarily non-magnetic thicknesses and one strongly magnetic thickness. Periodic influx of non-ferrigenous material such as organic shales, volcanic glass or microcrystalline quartz (chert), riebeckite, crocidolite, or asbestos were designated as an anomaly, event, or change to a macroband as designated in #3. These anomalies are noted.

7. **Microbands:** Established by Trendall (1970), microbanding on the scale of .5-2.0 mm is evident within the mesobands. Microband couplets were identified as a set of bands; one with a strong magnetic signature and one with a non-magnetic signature. While mesobands contain more or less dominate magnetic signatures, microbands had predominately dark grey magnetite or red/brown hematite alternating with predominately chert/quartz. Chert is denoted as quartz in this documentation.

8. **Thicknesses:** With exception of macrobands, thicknesses are provided in millimeters. Series thickness were generally treated as a set or couplet including 2 bands (1 chert rich and 1 iron rich), or specifically as a band or laminae thickness.
Cyclic patterns in the mesobands included alternating packages of condensed couplet sets and wider couplet sets. Common patterns of 12-15 couplets per mesoband were seen; however, numbers ranged from 3-21. A condensed mesoband section generally contained more magnetite and thicker mesoband section contained more quartz, chert, or hematite. Mineralogy alternations, variations from chert to magnetite or hematite, were consistent at both microband and mesoband interval. Thin microband laminae contain high concentrations of magnetite throughout, whereas the thicker couplet set member was primarily silica-based.

4. Results

Core samples from the Dales Gorge Member of the Brockman Iron Formation contain approximately 30% iron in the BIF macrobands (Raiswell et al. 2011). Only minor amounts of iron are present in the shale macrobands (Morris and Cowan 2002). Dales Gorge BIF composition is primarily SiO$_2$, (K, Mg, Fe)AlSi$_3$(O,OH)$_8$, Fe$_2$O$_3$, and Fe$_3$O$_4$ (or other forms of iron oxide/hydroxide and siderite FeCO$_3$). Chert, silt-size SiO$_2$, aluminum silicate clay, magnetite and hematite may be formed from chemical precipitants or from dissolved clastic sediment – both are likely in the Dales Gorge core sample.

The spectrally interpolated microband thicknesses contain an average of undifferentiated 23.267 ± 2.327 intervals for the complete mesoband time series of the Dales Gorge drill core. This number is low for the “expected” value for semidiurnal tidal cycles (Coughenour) in modern rhythmites (Coughenour et al. 2009). Frequency peaks and distribution produced by the mineralogy thickness time series transforms reveal no discernible spring/neap trends in the mesobands. Tidal rhythmites display daily diurnal or semidiurnal tidal signatures in the number and thickness of laminae couplets. This does not appear to be the case for the Dales Gorge
microband lamellae, which are thicker than the overlying Weeli Wolli Formation, with a similar 24-30 microband semidiurnal cycles.

The inequality between the deposit thickness of a spring cycle and the deposit thickness of a neap cycle (as well as the diurnal inequality) is more pronounced in deposits than in tidal height records. This can be helpful when dealing with individual tidal event deposits. In semidiurnal and mixed systems, if one takes the maximum tidal height during a spring cycle and compares it to the maximum heights of other spring cycles, a saw-tooth like pattern from one spring cycle to the next is generally seen. This is primarily due to the ellipse of the lunar orbit and the Earth's orbit around the Sun. Tidal height is not linearly correlated to deposit thickness. Numerical deposition models, however, do indicate that maximum deposit thickness will also vary from the spring cycle to the next spring cycle in a repeating thick-thin pattern.

Figure 2.2 (next page) provides a pattern characteristic of the Dales Gorge banded iron mineralogy thickness profiles. Although a sawtooth pattern is present, the pattern is bimodal with 2 peaks and 2 troughs per mesoband cycle. Maxima and minima peaks represent iron-rich and iron-poor mesobands consisting of approximately 25-30 bands. Strongly diurnal systems behave differently and instead of a sawtooth pattern display a progressive thickening and then thinning variation in a single cycle.
Figure 2.2 Series breaks signify lapse in deposition or periods of erosion between cycle initiations with alternating peaks in depositional regimes. Microband cycles are bimodal, with alternating max and min periods. Cycles include 25-30 spring/neap oscillations subordinate oscillations in a complete max/min cycle. A total of 12.5-15 cycles are present within mesobands with subordinate exhibiting a bimodal pattern (Androes 2012).

The maximum and minimum oscillators of the Dales Gorge periodogram are dissimilar to tidal rhythmites. Summed thicknesses were also shown by the models to display a similar overall effect, even in fairly irregular semidiurnal tidal origins with bimodal peaks within a complete cycle. However, at higher resolution of $10^{-2}$ m, the max/min oscillations are not strongly bimodal. The subordinate phase interference amplifies and dampens the sinusoidal background cycle. Microbands, in this scenario, represent the fortnightly inequalities as spring/neap cycles with annual cycles of ~26 cycles – a close match to cycles today. Energy pulses for mesoband
cyclicity would be annual solar cycles or seasonal patterns (greater and lesser depositional thicknesses). Possible explanations for annual or season patterns include wind, rainfall/monsoons, weathering patterns, and ocean currents.

Cyclic microbanding in early Proterozoic iron-rich formations have commonly been interpreted to represent annual seasonal varves (Trendall 1973b; Walker and Zahnle 1986b) corresponding to melt/thaw cycles, and recurring mesobands or macrobands have been linked to Earth-Sun periodicities described by Milutin Milanković (Hinnov 2003; Milankovitch 1948). However, a summer/winter microband fails to explain the max/min cycles packaging average of 13.85 couplet sets. A framework for interpretation is essential. The initial test or model used was diurnal or semidiurnal tidal cycles. This did not fit the data and would have broad implications for rapid sedimentation of the Dales Gorge Member. Microband interpretation as fortnightly inequalities is the only interpretation consistent with the majority of Hamersley Basin interpretations or other BIF workers. This research suggests that fortnightly microbands, deposited on the deep continental shelf, most closely fit the banding regime, with potential seasonal mesobands.

5. Discussion

Banded-iron genesis commonly links band rhythms with longer-period astronomical variations (glacial and eustatic fluctuations) or fluctuations in ocean oxygen content. Cloud’s comprehensive hypothesis (1968) asserts cyclical oxic/anoxic global oceans were the primary agent of the rhythms. However, preservation of significant climate oscillations through time with bimodal periodicity is highly unlikely. Insolation forcing periodicities span ten’s to hundred’s of kyr and are of such low resolution on short time scales that these annual or seasonal increases in
solar flux would not be rhythmic and bimodal. Other possible mechanisms, however, are discussed here.

5.1 Source of Iron and Silica

Changes in sea levels related to longer-period astronomical forcing mechanisms -- eccentricity, obliquity, and precession -- are commonly invoked for macroband variations in these sedimentary sequences. A total of 19 macroband cycles were examined. Macroband cycles alternate between BIF and shale or volcanic sequences. Contrary to early beliefs, the availability of iron and silica of sufficient quantity to deposit huge iron formations is not anomalous with mafic exposures of early cratons and proposed weathering regimes. Using the extensive Hamersley Basin as a model, at only 10 ppm Fe saturation (from 100-400 ppm are possible) with a 7 ppm outflow and approximately 15% of the basin water volume, the potential for large iron reservoirs is easily derived (Trendall 2002). The corresponding drop in the global-ocean dissolved iron content would only be .00002 ppm (Trendall 2002).

Continental weathering supplies 960 Tg of iron annually through riverine transport to the ocean (2008); however, only about .2% of this flux is dissolved. An estimated 2% of the particulate iron later dissolves into the water column on the continental shelf (Johnson et al. 2003). Dust particles supply 16 Tg of iron annually to the ocean. Dissolution in the ocean of wind driven particles is strongly dependent on light-driven reduction resulting in diurnal variations in the solubility of particulate Fe. Coastal upwelling can supply Fe by re-suspending fine particles that dissolve in the water column providing much of the needed iron for production of phytoplankton (Beard et al. 1999; Johnson et al. 1999). High productivity of the coastal waters traps Fe on the continental shelf (Emerson 2009; Fischer and Knoll 2009; Thierry et al. 2006).
Alternating iron mobilization and oxidation events appear to accompany successive recrystallization events resulting in fine lamellae of iron oxide coatings and cements. Silt and clay particles, including volcanic shards, combined with dissolved silica from continental-scale weathering, would have supplied an abundant source of $H_4SiO_4$ during the formation of the Hamersley Basin.

Recent research analyses using rare earth elements (REE) and Nd isotope data point to iron sources from both terrestrial and hydrothermal fluxes (Bau and Moller 1993; Fryer 1983; Graf 1978; Isley 1995). Bulk volume requirements suggest terrestrial resources are required. Isotopic analyses point to mixing with Fe input from oceanic vent and hydrothermal activity (Bau and Moller 1993; Dymek and Klein 1988b; Frost et al. 2007; Fryer 1977; Graf 1978; Johnson et al. 2008) in addition to continental weathering. Hamade et al. (2003) analyze the Ge/Si ratios in BIFs, decoupling of the iron and silica fluxes into changes in sources from the weathering of continental landmass to hydrothermal origin (Hamade et al. 2003). In this scenario, chert- and iron- rich layers reflect the dominance of both continental and hydrothermal sources.

Banded-iron formations resisted extensive overprinting in stable cratonic settings. Experiments have shown that ferric hydroxide rapidly accelerates coagulation and polymerization of silica gel (Krauskopf 1959). Thus, dissolved iron may have acted as a catalyst to promote the precipitation of amorphous silica, chalcedony. Microband couplets (aka aftbands) represent mineralogy variations linked to depositional regimes and diagenic processes. The presence of dissolved iron enhances the precipitation or polymerization of silica from solution $H_4SiO_4$. Thus a chemical, thermodynamic mechanism for early preservation of iron- and chert-dominated rhythmites may exist in addition to the influence of external supply and energy sources.
Silicate verses carbonate, oxide verses sulfide, and hematite verses magnetite oxidation states are commonly linked to water depth or stratified oxic and anoxic facies. Sulfide rich, pyrite [FeS₂] and/or pyrrhotite [FeₓS] iron formations and magnetite rich formations, in contrast to sulfate, carbonate [ankerite Ca Fe²⁺ (CO₃)₂], hematite (Fe₂O₃) or goethite rich formations were previously thought to demonstrate low oxygen content of ocean waters (Fripp 1976; Hyslop et al. 2008; Raiswell et al. 2011; Widdel et al. 1993). However, research suggests these minerals are replacement, not primary minerals (Groves et al. 1987; Hyslop et al. 2008; Krapez et al. 2003; Lascelles 2006; Phillips et al. 1984; Tompkins and Cowan 2001).

5.2 Silica and Iron Banding

The small scale structure of iron and silica banding is energetically favorable and able to be preserved relatively early in deposition. Microbands at some level are authogenic; however, pressure from overburden, geothermal gradients, or the drive to lower free energy state leads to mineral migration and recrystalization (Alpermann et al. 2011; Becker and Clayton 1976; Hazen et al. 2008; Tyler and Thorne 1990). Isotopic signatures (¹⁸O/¹⁶O) in chert and magnetite BIF’s indicate progressive or diagenetic fractionation over time (Fedo and Whitehouse 2002; Hyslop et al. 2008; Johnson et al. 2003; Johnson et al. 2008).

It should be noted that under higher temperature or pressure conditions, the opposite is true. Greater migration of iron and quartz is thermodynamically favored. Thus, thick massive iron
formations under lithostatic pressure experience dissolution and migration of grains. Vastly different conditions, as suggested by Cloud (1968), exist today than in the past (Cloud 1973; Cloud 1982; Cloud 1983; Cloud and Licari 1968). A stable environment capable of preserving authigenic depositional laminae is inferred from the lateral continuity of micro, meso, and macrobands. Thermodynamic stability is another component of the banding process. At the microcrystalline scale, preservation of crystallinity is a function of surface area (surface area to mass ratio), crystal density and water content, and crystal structure or mineralogy. Stability is attained by lowering the area-to-mass ratio (moving from cryptocrystals to megacrystals), reducing structural water content. Archean waters were likely to be well over 100 ppm (110-140 ppm at 25° C; 360-420 ppm at 100° C -- saturation concentration for amorphous silica from Krauskopf (1959) in acidic or lower pH environments.

Metamorphic processes are not suggested for bands seen in the Dakota Formation of Iowa or the Wilcox sandstones of Arkansas (Figures 2.4 & 2.5), but bands are present. Oxide coatings are red-to-opaque on overgrowth substratum in Figures 2.4a & b. Mineralogic affinities and geochemical constraints at the time of precipitation result in alternating banding in SiO₂ and Fe with crystal structures providing substrate templates.

Figure 2.4a & b Side RQV A-5 plain polarized light 200 X; 43b Side RQV A-5 crossed polars. A1 colloidal silica. Ferric hydroxides can cause rapid coagulation (Krauskopf 1959).
Well-developed nearly identical patterns of iron oxide stains are present on multiple grains. Q1 quartz, overgrowth cements (no meniscus or stalactitic cements); Q2 detrital quartz; 3) iron lamellae are stable or ordered configuration (Androes et al. in process).

**Figures 2.5a & b** Banding in the Nishnabotna Member, Outer bands of microcrystalline quartz or chalcedony have not yet “ripened” or aligned. Calcite grains are coated with iron, then silicified. Bands of oxides and other minerals are more stable configurations, less surface area. These photomicrographs are from the Dakota Formation of the Hawarden core in northwest Iowa. (Figures 2.5a & b photos by Lee Phillips, University of Iowa).

Figures 2.4a and 2.4b demonstrate the affinity of iron and silica cements to precipitate together. Note precipitated chalcedonic quartz is first fibrous and elongated perpendicular to previous cements. Crystal evolution to a more stable, parallel crystal structure is the preferred alignment for quartz or micro. Thermodynamically-favored states include mineral speciation – separating like mineralogies into bands with the least amount of surface area. Epitaxial templates and crystal maturation resulted in the realignment of the crystals with both horizontal and vertical migration. Parallel banding at microscopic levels mimics banding BIF laminae.
Figure 2.6 Slide RQV A-4 crossed polars 200X with inset (46b) plain polarized light, 200X slightly different stage orientation. Distinct growth zones marked with iron stains indicate oxidation episodes intervening between precipitation of SiO$_2$. Outer fringe of cement remains chalcedonic microquartz (mQ4). Gray regions (A1) appear to be crystallizing silica species from earlier precipitants. Definitive boundaries are not apparent in these masses suggesting a progressive process was occurring. Movement towards linear laminae or microbands is apparent (Androes et al. in process).

Iron coatings on minerals, sediments, or dissolved ocean iron correlates well with the experimental results of Krauskopf (1959). Accumulation of SiO$_2$ and Fe oxides occurs during periods of high saturation. Volcanic ash, hydrothermal or ocean floor spreading regions, and intense continental weathering are all candidates for enhanced iron and silica saturation necessary to produce abundant iron formation.
6. Conclusions

Thickness profiles in the Dales Gorge strata lacked strong correlation to tidal constituents indicating deposition was not solely tidal in origin. Although microband couplets within mesoband intervals resemble a modified fortnightly or spring/neap inequality, tidal periods could not be firmly established. The primary concern for the Dales Gorge meso thickness series was the lack of fortnightly inequalities typical with tidal rhythmites. Cyclic formation of micro and mesobands in the late Archean do not represent exclusively tidal deposits, but some alternate time-series interval. Further work is needed to provide a closer correlation to the banding cycles of Dales Gorge BIF. The preferred depositional environment for this study and for application to BIF’s in general, is an active volcanic and tectonic basin common on early Earth, in an island arc setting. The forearc basin is characterized by 1) below wave base, deep ocean on the continental shelf; 2) broad ocean access; 3) volcanism; and 4) episodic compressional stress.

A stratified ocean with varied degrees of oxygenation is proposed. Iron is a metabolic agent used by numerous microbes, both aerobes and anaerobes. Iron fluxes may have led to biotic eutrophication (microbial growth spurts) under oxic conditions resulting in algae blooms and subsequent loss of dissolved oxygen in ocean waters or stagnant bottom conditions. These processes are common near the bottom of reservoirs, rivers, and oceans. Bacteria, archea, and protozoa’s are found in conjunction with most sedimentary films, MISS, and biomats. These include Archea and extremophiles with primitive metabolisms capable of operating at multiple redox and photic levels at various depths.
CHAPTER THREE: Banding Cyclicity for the Dales Gorge Member of the Brockman Iron Formation

Hamersley Basin, the most studied of all provinces containing banded-iron formations (BIF’s), provides a near continuous record of sedimentary deposition during the late Archean. Successive BIF’s in the Hamersley Group account for nearly 900 meters of vertical accumulations covering more than 100,000 km² (Trendall 1983a). Horizontal macro and mesobands of the Hamersley’s Dales Gorge Member of the Brockman Formation display lateral continuity of deposition over approximately 60,000 km² (Morris and Trendall 1988). The bulk of past research on Paleoproterozoic or Archean intervals assumes Milankovitch, glacioeustatic, or climatic events influenced deposition of BIF’s. In addition, burial and regional metamorphism adds uncertainty to determination of small-scale ubiquitous laminations.

1. Introduction

Banded-iron cyclicity and early stratified or global ocean changes have been linked to Milankovitch-scale Earth orbital parameters (Morris 1993; Trendall 1973b) rising atmospheric oxygen alternating between oxic and anoxic conditions (Cloud 1968; Farquhar et al. 2007b; Farquhar et al. 2011), fluctuating UV irradiation with MIF-S (Farquhar et al. 2007a; Zahnle et al. 2006) igneous emplacement and hydrothermal vent activity (Barley et al. 1997; Laberge 1966), lunar orbital periodicities (Chan et al. 1994; Kvale et al. 1999; Williams 2000), and tectonic/volcanic activity (Krapez 1999; Kump 2008; Lascelles 2007; Tyler and Thorne 1990). Complex interactions are required to explain the accumulation of massive, thick banded-iron formation (BIF’s).
Modern rhythmite research (Archer et al. 1995; Coughenour et al. 2009; Dalrymple et al. 1990; Dalrymple et al. 1992; Tessier 1993), confined primarily to tidal inlets, bays, or restricted basins, clearly demonstrates that preservation of small-scale tidal patterns is possible. Orbitally-induced rhythmites are known in the Bay of Fundy in eastern Canada (Avsyuk et al. 2011; Dalrymple et al. 1990), the Bay of Mont-Saint-Michel in France (Coughenour et al. 2009; Tessier 1993), and Cook Inlet in south-central Alaska (Archer 2004) among many others. Laminar patterns reveal diurnal, semidiurnal, fortnightly, monthly, and other annual periodicities. Foreset thickness and grain size are amplified during high tide and minimized during low tide providing harmonic time-series signatures for researchers.

The Neoproterozoic Reynella siltstones contain 3-8 mm thick, diurnal laminae marked by alternate darker or opaque bands and lighter bands (Tessier 1993) similar to the Dales Gorge darker magnetite bands and lighter chert bands. The Reynella contain ~10-14 recognized bundled diurnal increments (Tessier 1993). Fourier spectral analysis of the Elatina neap-spring cycles provide paleotidal cycles consisting of up to 16 (8-16 laminae) sandy or silty thin graded laminae (0.5-3.0 mm) that are interpreted as >60 years of continuous tidal deposition (Williams 1998; Williams 1990) accounting for 10 meters thickness. The rate of deposition implied is ~15-20 cm per annual cycle. This high rate of deposition, and even higher Reynella rhythmites depositional thickness of nearly 50 cm annually is commonly disputed by Precambrian researchers (Tessier 1993; Kvale et al. 1999; Varga et al. 2006; Williams 2005).

Laterally continuous, shale and banded-iron macroband sequences are identified and described by MacLeod (1966), Trendall and Blockley (1970), and Harmsworth et al. (1990) in the Dales Gorge Member of the Brockman Formation (Harmsworth et al. 1990; MacLeod 1966; Trendall and Blockley 1970). Preserved within the macrobands are mineralogically variable
mesobands and smaller scale laminae couplets referred to as microbands or aftbands. Rhythmic depositional patterns suggest cyclicity at an undefined depositional interval traditionally considered episodic precipitation of chemical sediments defined by ambient ocean iron, silica, and oxygen levels.

Within the mesobands, subbands referred to as microbands or aftbands ranging from .5 to 13 millimeters reflect primary bedding (Morris et al. 1980; Morris and Horwitz 1983; Trendall 1983a; Trendall et al. 2004) or possible diagenetic or metamorphic overprints. Microbands consistently exhibit fine magnetite iron bands interbedded with thicker chert/quartz/hematite microbands. In light of the large volume of volcanic clastic material, containing Mg, Fe, Si, and O elements within the Hamersley Basin, it’s likely that clay and silt size particles were abundant at the time of deposition. Downwarping and uplift of the Hamersley Basin, recognized as tectonically active, is anticipated in forearc or backarc setting.

2. Hamersley Group BIF

The broad global distribution of banded-iron formations provides evidence that iron, silicon, and oxygen are not only abundant elements in the earth’s crust, but they are also mineralogically compatible under certain situations. Oxide-facies bands become particularly common during this time, as evidenced by their dominance in some of the largest BIF sites in Western Australia and Canada at ~2.9–3.0 Ga. The deposition of the Hamersley Group and Superior region iron-formations corresponds to a prominent peak in the geological BIF record. Superior-type BIF’s extend over $10^5$ km$^2$ and to be associated with other sedimentary units and iron content generally exceeds $10^{13}$ tons (James and Trendall 1982; Trendall 1983a; Trendall 1983b).
Hamersley Basin is widely recognized as a tectonically active, platform or broad continental shelf setting. The Hamersley Group BIF’s contain both Algoma-type volcanic laminations in a greenstone belt and Superior-type clastic facies (Gross et al. 1983; Klein and Beukes 1989) making distinct classification difficult. Frequent alternation between fine and coarse grains, silica, iron, and clay suggest a location influenced by changing depositional patterns, near terrestrial and volcanic sources.

2.1 The Brockman Iron Formation of the Hamersley Group

The Hamersley Group is bounded by the Fortescue Group and the Turee Creek Group. The Brockman Iron Formation within the Hamersley Group is comprised of four iron formations including the Marra Mamba, the Dales Gorge, Weeli Wolli, and Boolgeeda. Volcanic, carbonate, and various silica-rich mud units separate the BIF sequences. The Dales Gorge Member conformably overlies the Colonial Chert Member and underlies the Whaleback Shale Member of the Brockman Iron Formation. Shale and chert sequences are interspersed within the Dales Gorge strata.
Figure 2.7 Mapped region of the Hamersley Range and the Dales Gorge. The Dales Gorge Member Drill Core from the Smithsonian Collection came from the Wittenoom Gorge location and correlates with the Dales Gorge and Tom Price composite section on deposit with the Geologic Survey of Western Australia (Androes 2012).
2.2 The Dales Gorge Member of the Brockman Formation

Metamorphosed igneous and sedimentary strata, punctuated by erosional unconformities, are found in the units directly underlying the Dales Gorge Member. These strata suggest that prior to deposition of the Dales Gorge Member, the underlying surfaces were exposed, deformed, and subsequently underwent subsidence or downwarping. Transgressive-regressive or tectonic pulses flooded and exposed portions of the Pilbara Craton during the Hamersley deposition. Horwitz and Smith (1978), Gee (1979), Tyler and Thorne (1990), Powell and Horwitz (1994), and Krapez (1999) have described the tectonic evolution of the Hamersley basin (Gee 1979; Horwitz and Smith 1978; Krapez 1999; Powell and Horwitz 1994; Tyler and Thorne 1990).

The younger Weeli Wolli Formation (BIF) directly overlying the Brockman Formation contains rhythmic deposits at the microband level with repeating laminar sets of 23-30. Trendall (1973) suggested 23-year annual solar cycles (Trendall 1983a; Trendall 1973b; Williams 1997, 2000) revised the numbers from 23 to 28-30, linking diurnal lunar cycles to the deposits (Williams 1997; Williams 2000). Trendall suggested the Dales Gorge Member contained an amplified cycle similar to the Weeli Wolli Formation (Trendall 1983a; Williams 1997), or a revised 25 aftbands in a possible 25 year cycle (Trendall, Presidential Address, Brisbane, May 25, 1971).

Cores samples for this study were obtained from a location in Wittenoom Gorge (EG-10), Australia, and are housed in the Smithsonian Ore and Mineral Collections, Washington, D.C. The Dales Gorge Member composite type section is in collections at the Geological Survey of Western Australia. Drill cores from Dales Gorge, Wittenoom Gorge, and Tom Price locations were all used to complete the type section (Figure 2.8).
## Hamersley Group

<table>
<thead>
<tr>
<th>Turee Creek Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boolgeeda Iron Formation</td>
</tr>
<tr>
<td>Woongarra Volcanics</td>
</tr>
<tr>
<td>Brochman Iron Formation</td>
</tr>
<tr>
<td>Mt Sylvia Formation</td>
</tr>
<tr>
<td>Wittenoom Dolomite</td>
</tr>
<tr>
<td>Marra Mamba Iron Formation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fortescue Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeli Wolli Formation</td>
</tr>
<tr>
<td>Dales Gorge Member</td>
</tr>
<tr>
<td>Mt McRae Shale</td>
</tr>
<tr>
<td>Bee Gorge Member</td>
</tr>
<tr>
<td>Paraburdoo Member</td>
</tr>
</tbody>
</table>

### Brockman Iron Formation

- Weeli Wolli Formation
- Yandicoogina Shale Member
- Joffre Member
- Whaleback Shale Member
- Dales Gorge Member
- Colonial Chert Member

#### Composite BIF sequence

- Bedded chert
- Plane-laminated nodules
- Mudrock
- Plane-laminated Carbonates
- Dolostone
- Limestone

#### Composite Shale sequence
Figure 2.8  Compositional stratigraphic sequence of the Dales Gorge Member of the Brockman Iron Formation, Hamersley Group. Microbands consistently exhibit fine magnetite bands interbedded with thicker chert/quartz/hematite microbands (Androes 2012).

3. Methods

The cyclicity of the Dales Gorge banding was probed via spectral and mineral analysis. To analyze the drill core for tidal signatures a complete macroband and mesoband thickness profile was produced for approximately 400 meters of drill core. Each band width was measured using a sub-meter to meter scale. In addition, a complete microband series (number of microbands ~40-50,000) was obtained. Thickness profiles were recorded for approximately 10% or 5000 bands. A complete photolog of supporting data was produced and placed on deposit with the Smithsonian.

Each data set was cataloged by drawer, row, and section numbers. Sections were individual numbered in the Smithsonian collections and can now be compared to the complete photolog DVD (Appendix E). The following specific numbering system was used with the time-series frequencies:

1. **Drawer numbers**: Numbers 1-19 correspond to the Smithsonian Natural History Museum Collections (DC Rock and Ore Collections) storage and catalog registers for the Dales Gorge Drill Core – 111062-1 thru 648.
2. **Row numbers**: These numbers correspond to drawer rows in individual drawers from 1-19. These may also be useful in making comparisons to the photolog (Androes 2012) housed at the Smithsonian.
3. **Core Sample numbers**: correspond to Smithsonian catalog registers for each section of drill core numbered and cataloged – samples from 1-648.

Cyclic patterns in the mesobands included alternating packages of condensed couplet sets and wider couplet sets. Common patterns of 12-15 couplets per mesoband were seen; however, numbers ranged from 3-21. A condensed mesoband section generally contained more magnetite and a thicker mesoband section contained more quartz, chert, or hematite. Mineral alternations
were consistent at the microband and mesoband intervals. Thin microband laminae contain high concentrations of magnetite, whereas the thicker couplet member was primarily silica-based.

**Procedure for Data Collection and Identification:**

1. **Measuring:** Thickness measures of bedding planes were obtained from the entire length of the Dales Gorge core using precision 6” and 12” Starrett dial caliper for microbands and mesobands. Data were recorded in Excel. Macrobands were measured with less accuracy using a standard tape measure. Breaks in the core were numbered, but also prevented actual macroband thickness accuracy.

2. **Depth:** Periodic drill core depths were documented to assure corresponding thickness with depth. These records were compared with the Australian Blue Asbestos Company drilling company records from a Wittenoom Gorge, Hole EC10, location in the Hamersley Range.

3. **Macrobands:** Established by A. F. Trendall and J. G. Blockey in the Geological Survey of Western Australia Annual Report 1967, pg. 48-53 (also corresponding to widely accepted divisions seen in the field), 33 macrobands refer to rigid BIF alternating with less rigid shale thicknesses. The composite type section referenced has a thickness of 466.25’ (not found at any one location) with macobands BIF0-BIF16 and S1-S16. Macrobands can be traced over 185 miles in natural exposures. A total of 301.5 feet of core was obtained at the EC10 location; therefore the total thickness of core is approximately 165 feet less than the type section. Thicker to thinner sequences (where sediment influx is less or pinching out) bands commonly have similar and correlating mesobands and microbands, but are thinner.

4. **Mesobands:** Mesobands established by this research differ from those loosely referred to in the survey publication (Trendall and Blockey) as an “average thickness of less than an inch.” The earlier analysis identified mesobands as wider banding and microbands as thinner.
banding without segregation by mineralogy or magnetism. Mesobands in this research vary from approximately 50-200 mm and are identified by a change in hematite and magnetite concentrations. A mesoband number corresponds to a couplet of one primarily non-magnetic thicknesses and one strongly magnetic thickness. Periodic influx of non-ferrigenous material such as organic shales, volcanic glass or microcrystalline quartz (chert), riebeckite, crocidolite, or asbestos were designated as an anomaly, event, or change to a macroband as designated in #3. These anomalies are noted.

5. **Microbands:** Established by Trendall (1965), microbanding on the scale of .5-2.0 mm is evident within the mesobands. Microband couplets were identified as a set of bands; one with a strong magnetic signature and one with a non-magnetic signature. While mesobands contain more or less dominate magnetic signatures, microbands had predominately dark grey magnetite or red/brown hematite alternating with predominately chert/quartz. Chert is denoted as quartz in this documentation.

6. **Thicknesses:** With exception of macrobands, thicknesses are provided in millimeters. Series thickness were generally treated as a set or couplet including 2 bands (1 chert rich and 1 iron rich), or specifically as a band or laminae thickness.

7. **Series Numbers:** Mesoband series are divided into Drawers, Sections, and Cores.

8. **Sorting column:** Data may be sorted in ascending or descending order to provide a better view of the depositional history. From top down (290’to 591’ depth) it is a backwards look through time. More appropriate, the bottom up (591’ to 290’) sorts from oldest to youngest deposits.

9. **Data log page:** Page numbers correspond to a 90-page documentation of the drill core conducted by D. Androes and C. Sigmon, Smithsonian geologists S. Sorrenson and D.
Gerlach for on 1-29-86, and contained in the Smithsonian catalog data. Notations of magnetic signatures, mineral types or colors, mesoband thicknesses, and band numbers are recorded.

10. **Mineralogy:** Magnetic mineralogies were detected using and noted for each mesoband. Observable mineralogic composition of the sediments are noted, but not definitive. Records provided by previous work included mineralogic analyses.

11. **Photolog:** This extensive log provides a photographic data reference corresponding to each meso and microband. Documentation follows a Drawer/Row/Section (not core sample number) series. Adobe software may be required to view the photolog in Appendix E.

12. **Description:** Additional notes were provided by Androes, Gerlach, Sorrenson, and Trendall.

<table>
<thead>
<tr>
<th>Drill core Sections – Mineralogy and Thickness Profile Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A Composition: Hematite, magnetite, chert, shale, and riebeckite. Modest magnetism, pronounced banding, enhanced volcanic sediment composition. Mesobands typically are thicker and with more color contrasts.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type A Mineralogy</th>
<th>Type B Mineralogy</th>
<th>Type C Mineralogy</th>
</tr>
</thead>
<tbody>
<tr>
<td>W:Mesoband broader/thick depositional couplets containing more chert and hematite.</td>
<td>S:Mesoband condensed deposition, with thin couplets, consisting of Fe II valence iron, shale, volcanic chards, sediments and in a few sequences, riebeckite.</td>
<td>Change from Type B magnetic dominant bands to Type C hematite/chert dominant bands for S and W mesobands. Note the increase in thickness.</td>
</tr>
</tbody>
</table>

![Diagram of drill core sections showing mineralogy and thickness profile correlations.](image)
Figure 2.9 Drill core sections and variability in bands (mesobands magnetic thickness demonstrated – comprised of individual microbands. (Androes 2012).
For the purpose of this research, mesobands were identified based on their 1) iron concentration, 2) width, and 3) numbers/series. The frequency resolution was obtained by taking the median of the individual estimates from an interpolated periodogram and confidence intervals constructed on frequency estimates by methods discussed in Coughenour (2009). These procedures are useful for shorter sequences of data if there are enough sequences of sufficient length. The median frequency estimate generally begins to converge on the “true” frequency for \( N \geq 50 \) [with 100 sequences (Archer 1996; Coughenour et al. 2009)].

Most of the Dales Gorge sequences (12 of 13) possessed original sample sizes between 25 and 52 mesobands per macroband. Only one sequence exceeded this. Eight had sample sizes exceeding 30 mesobands. This is potentially significant, as one expected periodicity in the tidal interpretation would be around 13 fortnights per cycle (26 mesobands per cycle) corresponding to a semiannual period in spring tidal heights (Williams 2000). Clearly, only records in excess of 26 mesobands would capture this periodicity in modern records.

4. Results

Evidence for primary deposition included granular features, clasts, ooliths, and a limited number of sedimentary structures. Microcrystallinity in much of the core sample is consistent with dissolution and reprecipitation of silica species. Volcanic ash, hydrothermal silica and iron supersaturation, and weathered mafic sediments are suspected for much of the iron and silica sediment source. Silt-sized silicate particles, typical of volcanic ash, are readily dissolved in undersaturated sea water. Stilpnomelane, a hydrated aluminum sheet silicate \([\text{Ka} (\text{Mg, Fe}^{2+}, \text{Fe}^{3+})_6\text{Si}_8\text{Al(O, OH)}_{27}^+ 4\text{H}_2\text{O})]\) closely associated with riebeckite and crocidolite, is interspersed
within both the mesobands of BIF and shale and is commonly a byproduct of metasomatism or hydrothermal activity.

4.1 Band Identification

Fine-scale bands alternate between primarily microcrystalline quartz and silicious clays mixed with hematite (Fe₂O₃) to distinctive magnetite (Fe₃O₄) rich microband laminae. Couplets average ~1.105 mm with magnetite commonly only 2.5 mm. Mesoband sets averaged 15.3 cm with max/min oscillations between magnetite-rich mineralogy and clay, chert, and/or hematite rich wider bands. Microband laminae were of the purest magnetite concentrations throughout; however, thicker mesoband magnetic sequences were also common.

Neither microbands or mesobands present purely as tidal origin. Microband couplets, initially examined for diurnal and semidiurnal depositional sequences, did not fit the expected diurnal: K₁, O₁, P₁ or semidiurnal: N₂ inequality patterns. During the Proterozoic, more fortnights per year are predicted exceeding 26 cycles per year. With only 8 mesoband records over 30 bands, it’s not possible to construct meaningful confidence limits on calculated frequency estimates. Mesoband mineral/spectral series commonly consisted of chert/hematite averaging 80% and magnetite at 20% (Figures 2.9). Mineralogy oscillations appear to be the product of two distinct supply sources.
Time series transformations provide constraints for possible seasonal ties in the Dales Gorge BIF. Thickness series suggest potential accumulations of 100-150 mm per season. These values are not unlike modern settings, near shore or continental shelf accumulations. Cyclicity is evident in the sawtooth pattern of thickness developed in the Dales Gorge BIF. Note peaks averaging 100 mm and troughs near 20. Strong similarities are seen in both the directional

**Figure 2.10** Time series transformations provide constraints for possible seasonal ties in the Dales Gorge BIF. Thickness series suggest potential accumulations of 100-150 mm per season. These values are not unlike modern settings, near shore or continental shelf accumulations. Cyclicity is evident in the sawtooth pattern of thickness developed in the Dales Gorge BIF. Note peaks averaging 100 mm and troughs near 20. Strong similarities are seen in both the directional
vectors and velocity of submarine currents.
The spectrally interpolated estimate is $23.267 \pm 2.327$ for the complete time series mesobands/cycle of the Dales Gorge drill core. This does not approach the “expected” value if mesoband cyclicity were spring/neap cycles. Other frequency peaks and distribution produced by the periodogram reveals no discernible spring/neap trends.

4.2 Microbands and Mesobands

Microband structures seen in the Dales Gorge are thicker than those of the Weeli Wolli Formation, the overlying banded-iron formation in the Hamersley Group analyzed for tidal origins by Williams (2000) and Cisne (1984) suggested two broad interpretations of the Weeli Wolli microbands: 1) Lamina couplets as diurnal increments arranged in monthly cycles (Cisne 1984) or semidiurnal grouped in fortnightly cycles (Williams 1997; Williams 2000); 2) Lamina couplets of ~28-30 fortnightly increments arranged in annual cycles (Williams 1997) represent 14.5 synodic months per year. This second interpretation by Williams is consistent with complex microbands in other BIF’s interpreted as annual increments containing as many as 27 laminae indicative of seasonal variations (Ewers and Morris 1981) or, as suggested by this study, 27-28 laminae representing a
Figure 2.11 Bottom or A) Modern current flow is given in directional vectors indicating opposite flow directions. Mirror Inset inverts all negative current flow to the positive axis 0-100 cm\textsuperscript{-1}. The mirror inset (A) removes the velocity vector to model only speed not direction. The potential accumulation of sediment as a function of flow speed represents a better correlation to a thickness profile than a combination of positive/negative vectors representing both speed and direction (A). C) Lower resolution of microbanding in the drill core suggests 25-30 microbands per mesoband (C), 12.5-15 cycles are present within each series. Grouped peaks and troughs represent mesoband accumulations or thickness (top). Thickness peaks mimic current velocities more closely than spring/neap rhythms. Current cycles at mesoband resolution show seasonal periodicities with directional reversals equivalent to bimodal peaks in intensity. Dales Gorge Member microband resolution demonstrates bimodal intensity.
modified spring-neap cycles packaged seasonally as mesobands, equal to ~13-14 lunar or synodic months for the Dales Gorge Member. Similar interpretations may extend to the Weeli Wolli.

Deeper-water more distal accumulations are consistent with thinner microbands, rather than thicker. The Weeli Wolli preserved thin daily tidal laminae; the Dales Gorge did not; therefore, the thicker laminae for the Dales Gorge are interpreted as deeper shelf. One depositional couplet is equal to ~14 of the Weeli Wolli. The greater thickness, however, is not unusual in modern tidal settings. Microband interpretation as possible fortnightly inequalities or annual varves is the only interpretation consistent with the majority of Hamersley Basin interpretations or other BIF workers. At microband resolution, fortnightly inequalities, deposited on the deep shelf ocean most closely fit the banding regime, with seasonal mesobands linked to bidirectional current sediment delivery.

Figure 2.12  Isostatic tectonic trends from shallow to deeper water regimes. Dales Gorge, Hamersley Basin, macrobands consist of shale alternating with BIF’s (Adapted from Pickard 2004/Androes 2012).
Figure 2.13 Drawer 7 Row 7 Sec 3 Core 204 Drawer 7 Row 8 Sec 4 Core 208 Smithsonian Collections, Dales Gorge Member, Brockman Formation. Mineralogy transition from magnetite signature in Section 3 (2 upper cores segments) to higher hematite concentration in Section 4 (3 lower cores). Fine microbands in all 5 segments are strongly magnetic. Spectral distinctions are more clearly defined in the hematite rich mesobands (lower 3); whereas, increases and decreases in magnetism are more clearly defined in magnetite rich mesobands (upper 2).
Figure 2.14  Higher resolution of microbanding in the drill core suggests ~25-30 microbands, 12.5-15 cycles are present within each series. Grouped peaks and troughs represent mesobands. Peaks in thickness mimic current velocities more closely than spring/neap rhythms. Microband peaks in both the maximum and minimum mesoband cycles suggest potential change in direction (bidirectional cycles) with harmonic dampening during directional change and amplification during cycle peaks.

Figure 2.15  Tropically driven, neap-spring tidal rhythmites from the Upper Carboniferous, Brazil Formation, in Indiana, USA, modified from Kvale (2003). Series laminae in the Dales Gorge Member (Figure 2.14) display peaks in both maximum and minimum cycles. Compare to the simple sinusoidal harmonics demonstrated by graph B and D.
Compact microbands, in the Weeli Wolli, contain chert nodules (up to 0.4 mm) exemplify the thickest and most readily identified cyclic deposits, interpreted by Williams as neap-spring cyclicity. Weeli Wolli microband sets display a total thickness of less than 1 cm for a complete “neap-spring” cycle. For the Dales Gorge, a single microband couplet is consistent with a complete “neap-spring” cycle and is ~1.105 cm. Daily tidal rhythms are not discernable. This finding is consistent with Trendall (1970) and Williams (1997) (Trendall and Blockley 1970; Williams 1997).

Rate of deposition is estimated at ~15.3 cm/yr with seasonally derived mesobands and falls within a normal range for an active tectonic basin. The suggested annual thickness of the Dales Gorge and Weeli Wolli is an order of magnitude higher than suggested by Trendall’s preferred interpretation and implies much faster rates of deposition for the Dales Gorge BIF and for the Weeli Wooli than anticipated by most BIF workers.

Although rates of deposition equal to ~15-20 cm per year are not commonly accepted for ancient BIF sequences, these rates are consistent with modern rhythmites or tidalites. This study also suggests that similar processes (depositional and/or post-depositional) may be applicable to other banded iron formations.

4.3 Macrobands

Transgressive/regressive cycles are a consequence of glacier melt or tectonic pulses. Isostacy, including downwarping, subsidence, and rebound, is suggested. Figure 2.12 provides an interpretation based on uplift/subsidence with a general trend of downwarping. The Ophthalmia Thrust Belt is indicative of major change in the region including cycles of uplift, compression, and downwarping. A different interpretation, and more widely accepted, is
transgressive/regressive 2\textsuperscript{nd} and 3\textsuperscript{rd} order glacio- or Milankovitch cycles moving from low to high stand. Macrobands reflect changes in the volcanic and tectonic activity of the basin, including periods of high volcanic sediment flux, subsidence, downwarping, and rebound or uplift from compressional stresses, and changes in depth through time.

The depositional environments and sediment supply were different, but the mechanisms were similar. Results discourage interpreting the magnetite and hematite/quartz microbands as either diurnal cycles or as purely deep water ooze accumulation. Microbands are, as stated previously, likely the product of combined deposition of mixed mineral species through 1 spring-neap cycle and pressure solutioning, mineral migration towards lowest-state free energy stability – maturation of microbands. Bands appear to align perpendicular to normal stress. Daily deposition from mixed current and tidal processes formed a single fortnightly band of magnetite and alternately a single band of silica rich minerals.

5. Discussions

Current velocities at deeper ocean depths follow seasonal and geostrophic patterns displaying moderate to strong influence from tides. Sub-seasonal cyclic current patterns exhibit bidirectional flow and sufficient velocity to 2 or more distinct sources. Mineral composition is likely to vary with alternating sediment sources. Thickness and mineralogy frequencies displayed weekly and annual winter/summer seasonal cycles. Thickness ratios are consistent with nearby terrestrial sources in a transgressive-regressive sequence, a tectonic/compressional setting, or an isostatic downwarping and uplifting basin.

If microbands prove to be consistent with spring/neap cycles and mesobands were seasonal, then higher cyclicities would relate to 1000’s or 10,000’s years, but not 100,000 years. At the
$10^3$-$10^4$ year level, Milankovitch orbital periodicities are relatively unchanged, with the exception of precession. Documented higher-order thickness-frequency series would require 1000’s of meters of thickness to reliably link to Milankovitch cycles.

![Graph showing oxidation rates vs. light intensity](image)

**Figure 2.16** Light driven oxidation rates of Fe (II) in laboratory experiment by Kappler *et al.* (2005). Relationship of Fe (II) oxidation by anoxygenic photoautotrophs (Rhodobacter ferroxidan strain SW2 (square) and Thiodictyon sp. Strain F4 (triangle) and light intensity is linear indicating the direct correlation between the angle of sunlight and precipitation of oxides in the water column (Kappler *et al.* 2005).

A distinctive feature of the tidal regime is the distinct change in trends of tidal range, height and current velocity that occur during a fortnight. The resulting neap to spring pattern of relatively low high tides to relatively high, high-tides repeats quite dependably and is readily observed in tide height records. Current velocities and direction exhibit seasonal cycles with 1-2 month lag, similar to insolation/temperature lag cycles. The thermal inertia of the ocean and H$_2$O slow the turnaround of seasonal cycles. Gravity waves frequencies and dispersions are implicated with the spring/neap tidal influence.
When moving beyond tidal height records and analyzing depositional records for neap to spring inequality patterns, the picture is complicated by several factors. Some factors that could alter the neap to spring pattern are erosion, depositional hiatus, and differential post-depositional diagenetic processes. These can be very difficult to quantify, even with very careful petrologic study. Additionally, deposition is not a simple linear proxy for tidal range or current velocity and tide height is a variable that can often serve more as a threshold for deposition (Archer and Johnson 1997; Coughenour et al. 2009). For a tidal origin hypothesis for the Dales Gorge deposits, the hematite/quartz mesoband thickness would correspond to the sum thickness of spring cycle deposits and the magnetite mesoband thickness would correspond to the sum of neap cycle deposits. Individual neap deposits are relatively truncated in comparison to their spring cycle counterparts, but it is possible to have the sum of neap cycle deposit thicknesses exceed the spring cycle sum. This scenario is most apt to occur in mixed semidiurnal and diurnal systems where there is tremendous diurnal inequality during spring tides producing very low lower high tides and a neap cycle that exhibits high tides that are significantly higher than the spring lower high tides. The tidal regime described by Kvale (2006) for Booby Island, Australia is a good example of such a system. The condition described above does not occur, however, during most neap-spring cycles; for modeled deposits from simple modeled tides using only 7 primary constituents, it took a simulation run of nearly 625 days to find a clear example of this.

The Dales Gorge deposits, in 9 sections of 25 or more mesobands, display a regular thick-thin alternation, similar to that expected in spring-neap cycles. There are 3 sections that have 1 or 2 discontinuities. We cannot reject the tidal origin hypothesis solely on the mineralogic thickness observed. Discernible neap-spring patterns are generally not displayed in deeper water deposits.
A synthesis of the depositional setting, the variability in mineral supply, and the degree of deformation or diagenesis provides a framework for reconstruction. The depositional setting, as suggested by the bulk of research, is a deep continental shelf or inlet, within a tectonically active basin.

**Figure 2.17:** Fine dark lines represent iron rich organic material; white are silica rich sequences including ooze, muds, silt, and sand. Volcanic shards and ash may account for large sediment flux. Current velocities show directional change resulting, for example, in azimuth swings from 45° to 135° or 225° to 315°. As changes in velocity and direction occur, turbidity maybe reduced or increased, and sediment composition may vary with each change resulting in not only changing grain size but additionally in changing mineralogy. The major axis of flow remains predominately unidirectional in some regimes and alternately bidirection in other regimes (Androes 2012).

**Figure 2.18** Seasonal current depth velocity profile display changing velocities including vertical exchange (turnover) in the bottom and surface currents result in rise or drops in oxygenation, oscillations in mineral and organic concentrations, and variation in sediment grain-size transport or deposition. http://www.pmel.noaa.gov/tao/data_deliv/deliv.html

Current velocities are strongly seasonal, showing velocity fluctuations and alternating directional flows. Deep bottom currents are modulated strongly by bidirectional flow of differing velocities.
Velocity fluctuations recorded by TRITON/TAO correlate well to thickness or grain-size characteristics for the Dales Gorge histogram. Directional flows correspond to supply sources and mineralogic change. Modified neap/spring sequences, appear at multiple depths up to and exceeding 200 m depth (Figure 2.18-2.19). The weekly rise and fall in current velocities (Depth – ADCP Meridional Current) appear to cycle with the fortnightly inequality in tides, although in many instances a fortnight blends into one rather than two cycles. Stronger velocities are apparent in the winter than summer. Sediment thickness oscillations and mineralogy profiles in the Dales Gorge are consistent with these velocity and directional alternations, including annual periodicities containing 13-15 cycles, with a summer and winter seasonal inequality.

**Figure 2.19.** Current velocity profiles for various ocean depths. Note strong bidirectional currents with pronounced seasonal (winter/summer) flow variability. (TAO Project/NOAA 1992)
Microband time-series are consistent with weekly tidal inequalities. Rates of deposition suggested for the Dales Gorge BIF, based on spring-neap inequalities, mimic energy profiles in the environment and current velocities. Cyclical tidal pulses in the environment produce rhythmites; however, the influence of ocean circulation, seasonal inequalities, and geostrophic flow modify the tidal rhythms. Deep shelf ocean current rhythms rarely display tidal constituents or frequencies at diurnal or semidiurnal + N₂ or K₂ amplitudes alone. TOA/TRITAN data records average daily or 5-day velocities, eliminating any diurnal/semidiurnal resolution. The translation of time-series current profiles to TOA/TRITON current profiles indicate that current flows appear to slow and change direction. Rhythms appear to follow fortnightly pulses (Figure 2.18) with strong seasonal phases. Future work is needed to model or extract and quantify orbital components (diurnal: K₁, O₁, P₁; semidiurnal: M₂, S₂, N₂) to determine if indeed spring and neap rhythms or diurnal/semidiurnal inequalities, mixed tidal and seasonal exist, or if the complexity of deep ocean currents require new models for periodicities.
Strong upwelling of nutrient rich waters occurs in spring and summer, with weak to no upwelling in winter. Dense nutrient rich water rising to the surface is transported via Ekman transport, perpendicular to easterly or westerly winds, resulting in longshore currents propagating north/south near continental shelves and shores. High phytoplankton concentrations are found today near the equator relative to the ITCZ along with Easterly winds from Earth’s rotation. In the north, waves are deflected to the right of the prevailing wind (due to the Coriolis effect) and in the southern hemisphere, waves and winds are driven south, to the left of the prevailing wind. Shallower, wind-driven upwelling occurs.

Figures 2.20 Vector velocities for low latitude currents at 200 meter depths. Current trend for 0N 165E is essentially unidirectional seasonally, but variable in velocity and bidirectional fortnight NE and SE dominant flow alternating between 35 cm/s and -25 cm/s (southerly component is negative). Data demonstrate seasonal change with strongest velocity between Feb-May at 200 m depths. Depositional regimes require periods of lower velocity note the fortnightly peak and troughs (~1-2 cycles per month) in the top periodogram. Transport or erosional regimes require periods of stronger or maximum velocities. Directional change is indicative of changes in sediment supply. Longer, 9-10 year periods at various locations globally, including 110W, 140W and 155E Longitude TOA Project data files Appendix D.
Along the continental shelf of southwestern Australia.

Along-the-shelf current upwellings brings nutrients to the shelf environment by suspending fine particles that have settled out of the water column or are entrained in bottom currents (Figure 2.20). Current monitors, at depths of 200 meters, record bidirectional velocities and indicate that sufficient sediment supply is present from varied sources. Thermohaline circulation is also temperature and density sensitive, a response to seasonal insolation absorption. Change in local, seasonal, and global thermal insolation or salinity results in change in local flow regimes.

**TAO/TRITAN:**

In addition, data from the TAO/TRITON global array consisting of approximately 70 oceanographic and meteorological moorings (Figures 2.21 and 2.22) via the Argos satellite system were used. The array is a major component of the El Niño/Southern Oscillation (ENSO) Observing System.

**Figures 2.21** Ten year data structure for ocean currents. Note distinct oscillations seasonally. Velocities (±) are consistent with changes in wind shear, temperature, and current profiles (Figure 1.25) indicative of deeper bidirectional seasonal flow at ~200 meters. Data requested from the TAO Project/NOAA, Androes, Jun 2011.
the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS). Data resources from NOAA/TAO include temperature, salinity, wind, humidity, and daily or five-day velocities are reported for shallow to 300 meters depth.

Dominant daily tidal constituents are eliminated by averaging. Five-day data demonstrate clear seasonal oscillations (Figure 2.21 on previous page) in direction and magnitude; daily data suggest possible influence from spring-neap tidal cycles and from seasonal differences in direction and magnitude (Figure 2.22).

Although velocity profiles averaged for five-day and 24-hour periods lose diurnal and semidiurnal resolution, they retain longer-period harmonic in-phase convergence of the $M_2$ component.

**Figure 2.22:** Daily current velocity data. Note distinct oscillations associated with spring/neap tides. Apparent spring/neap inequalities are visible. Velocities (±) denote directional swings suggesting sediment transport is bidirectional rather than unidirectional. Data requested from the TAO Project/NOAA, http://www.pmel.noaa.gov/tao/data_deliv/deliv.html Androes, Nov 2011.
and $S_2$ for synodic neap-spring cycles of 14.77 days and $K_1$ and $O_1$ tropical neap-spring of 13.66 days. Prevailing currents, winds, and surface heights show prominent seasonal (Figure 2.21) oscillations (Machín et al. 2010; Qu and Meyers 2005; Ramp and Bahr 2008; Thierry et al. 2006) and potential tidal (Figure 2.22) oscillations. Velocities ±85 cm/s, at depths up to 200 m, display prominent 13/14-day cyclicities (see vertical stripes in Figure 2.22). These bidirectional patterns demonstrate that tidal force, at some level, interacts with ocean current velocities (Figure 2.22).

Drops in velocity deposit sediments, while higher velocity currents transport, truncate, or suspend greater volumes of sediments in the water column. Thickness series depend also on the supply of sediment or the precipitation of minerals, and the bathymetry, basin geometry, or topographic setting. Sediment transport is observed at 10 and 80 meter depth. Volume of transport varies from 0-45 m$^2$/sec at 80 meters depth.

Deeper ocean current data yield modified patterns with strong seasonal inequalities and 7-14-day frequency cycles. Bidirectional movement of dissolved, suspended, and potential bedload sediments is indicated for both shallow shelf facies and deep shelf environments (Liu and Weisberg 2007; Rodrigues et al. 2007; Van Haren and Proctor 2004). Velocities at depths of 10 meters are consistent with wind and shallow wave structure. For depths greater than 200 meters, 14 day cycles and seasonal amplitudes are most prominent. Thickness profiles are reasonable if one assumes that the mesobands represent seasonal change from winter to summer. Change includes periods of greater and lesser rainfall, current velocity variations, and sediment sources. Note the general trend in lower velocity currents from
6. Conclusion

Thickness and mineralogy time-series profiles from the Dales Gorge Member of the Brockman Iron Formation suggest cycles and periodicities similar to modern current velocity profiles. First-order sinusoidal series patterns are interpreted as seasonal changes in bidirectional movement of ocean floor sediment, displaying second-order tidal influence. Sedimentary accumulations consist of iron-dominate organic sequences linked to slower current movement alternating with silica-dominate sequences indicative of modestly higher energy currents. Directional current oscillations may also contribute to changing mineralogy.

Obvious oscillations are recorded in 3 levels of cyclicity: macro, meso, and microbands. Based on interpretations by this study, large volumes of iron and silica are the result of a tectonically active Earth, more specifically, a tectonically active basin during the time of deposition of the Dales Gorge BIF. Banding reflects combined depositional and diagenetic processes, including microband mineral migration under pressure from overburden. Microbands, as depositional couplets, correlate well with the spring/neap inequalities of current flow velocities; mesobands package seasonal varves into max/min rates of deposition, while macrobands represent higher order processes such as isostasy, tectonic pulses, or orbital changes.

Meter-scale BIF macrobands grade into shale macrobands which are generally thinner than the BIF sequences. Macrobands clearly display major depositional change, either in the environment or in the supply of detrital material. The Hamersley Basin represents 50,000 km$^2$ of high density (>30% iron) IF’s with an estimated $\sim 6 \times 10^{12}$ tons of iron (Lord and Trendall 1976). Mantle loading of high density materials induces subsidence or downwarping. Shale macrobands indicate strong increases in volcanic, organic, or clay-sized particles.
Depositional rates assuming a spring-neap microband accumulation of 0.5-1.5 cm are reasonable. Mesobands suggest annual winter/summer inequalities, including alternation between volumes of terrestrial and submarine sediments. Examinations of magnetic, mineralogic, and time-series profiles indicate there is a strong correlation between mesobanding and Fe valence alternation. These variations are likely diagenic in origin, with strong depositional influence in the concentration of iron rather than on the iron species such as hematite verses magnetite.

Microband frequency profiles obtained from the Dales Gorge Member of the Brockman Formation lacked strong correlation to daily tidal constituents (diurnal: K₁, O₁, P₁; semidiurnal: N₂) indicating deposition was not primarily of tidal origin. Laminae or microband couplets converged on a median frequency of ~13.85 microbands confined to a subset of a more dominant max/min series profile. TRITON/TAO zonal current profiles demonstrate similar max/min seasonal inequalities with 7-14 day and 28 day cycles equal to approximately 14 periods per year. Drops in current velocity between seasonal cycles show 1-2 month lag, similar to insolation/temperature lag cycles, amplified by the thermal inertia of H₂O. Frequency dispersions of gravity waves and spring/neap tidal influence are implicated in distal shelf, below wave base, depositional cycles. Sediment thicknesses equal to ~1.105 cm per cycle reflect an annual rate of deposition of ~15.30 cm/yr. These rates are high for deep ocean, but are consistent with the analyses of the overlying Weeli Wolli Formation and with modern rhythmite. Mineralogy-thickness frequencies contained cyclic oscillations at the micro- and mesoband levels suggesting the Dales Gorge BIF contained fortnightly varves modified by seasonal amplification. Formation of tidalites, rhythmites, or subaerial marine sequences is a response to the energy in the system normally in a near-shore environment.
CHAPTER FOUR: Climate Forcing and Phase Sequestering for Earth, Mars, and Titan

Orbital mechanics strongly influence the geomorphology of planetary surfaces. Seasonal cycles are on the order of $10^2$ greater than Milankovitch climate cycles; however, amplification or dampening of seasonal cycles can lead to dramatic hemisphere-specific alterations of surface features. Hemispheric dichotomies are a function of both physiographic and astronomic forcing mechanisms. For Earth, the southern hemisphere experiences less dramatic seasonal temperature change due to the ocean’s thermal inertia. Land verses ocean distribution (continentality) is denser in the north than the south. As a result, Earth’s seasonal temperature oscillations are anomalous and unique to our planet. Earth is closest to the Sun in January, during the northern hemisphere winter, and furthest from the Sun in July, during the northern hemisphere summer. Under normal planetary surface conditions, temperatures and seasons should be less pronounced in the northern hemisphere and more pronounced in the southern hemisphere. This is not the case for Earth.

On Titan, glaciers and global-scale oceans are absent and climate cycles are interpreted from the hemispheric distribution of empty and filled lakes, equatorial hydrocarbon sinks, and potential variations in erosion surfaces, drainage systems, or sedimentary sequences. The Martian climate cycles are strongly linked to changing eccentricity and obliquity resulting in vaporizing polar ice caps. Positive feedback mechanisms during glaciation on Earth can dramatically alter Earth’s albedo and landscape evolution.
1. Introduction

For most planetary bodies in the solar system, season-resolved energy fluxes are the primary control of atmospheric change. Seasons are the product of the tilt of a planetary body and its orbit about the Sun or planet. Axial tilt refers to the angle formed between the rotation axis of the planetary body and an axis perpendicular to the ecliptic plane of the solar system. This angle varies in response to gravitational interactions with other bodies.

Figure 2.23 combines the precession of equinoxes with eccentricity change for both the Earth/Sun. Note the trend to lesser eccentricity and to lower overall seasonal extremes. During the current precession cycle, Earth’s eccentricity is lowest (least impacting) as it approaches the summer solstice perihelion passage near 10,000 BCE.

Figure 2.23 Four astronomical positions are depicted: a) autumnal equinox - alignment of the equator and ecliptic plane in the fall; b) winter solstice - maximum southern exposure of the Sun; c) vernal equinox - alignment of the equator and ecliptic plane in the spring; d) summer solstice - maximum northern exposure of Sun. Effects of eccentricity (exaggerated for illustration purposes) are most prominent on Earth when a summer solstice occurs at perihelion and the winter solstice occurs at aphelion which is opposite of its present state. With velocities increasing during perihelion approach and decreasing during aphelion approach, hemispheric dichotomies in the length and temperature
variations between seasons are enhanced. Planets with higher eccentricity, like Mars and Titan/Saturn, experience more variability (Androes 2012).
Table 2.3

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Beginning</th>
<th>End</th>
<th>Length (Earth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>June 21, 2012</td>
<td>September 23, 2012</td>
<td>93.65 days</td>
</tr>
<tr>
<td>Fall</td>
<td>September 23, 2012</td>
<td>December 22, 2012</td>
<td>89.85 days</td>
</tr>
<tr>
<td>Winter</td>
<td>December 22, 2011</td>
<td>March 20, 2011</td>
<td>88.99 days</td>
</tr>
<tr>
<td>Spring</td>
<td>March 20, 2011</td>
<td>June 21, 2012</td>
<td>92.75 days</td>
</tr>
</tbody>
</table>

The lengths of seasonal periods are not fixed, but vary with axial wobble and precession (Table 2.24). The northern hemisphere on Earth experiences 88.99 days in winter and 93.65 days in summer. Martian seasons reflect this inequality more strongly than Earth. With Earth, seasons vary by approximately 4 days. Martian seasons vary by 52 days. Greatest variability occurs during a summer or winter perihelion or aphelion approach. All three planetary bodies are presently experiencing perihelion near the northern hemisphere winter solstice producing summer and winter seasonal extremes in their southern hemispheres.

Figure 2.24 Fall is the shortest northern hemisphere season for Mars under its present-day precession position. The length of the Martian season varies from 142 to 194 days. With an eccentricity of .094, the difference in solar flux is approximately 35% between periapsis and apoapsis. The combination of shorter seasons near perihelion and longer seasons near aphelion changes in the amount of annual solar radiation hemispherically. Seasonal effects for Mars are greatest in polar ice cap changes (Androes 2012).
Table 2.4 Martian Northern Hemisphere Seasons (Including Recent Dates)

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Beginning</th>
<th>End</th>
<th>Length (Mars Sol)</th>
<th>Length (Earth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>March 30, 2013</td>
<td>Sept. 30, 2012</td>
<td>178 sols</td>
<td>93 days</td>
</tr>
<tr>
<td>Fall</td>
<td>Sept. 30, 2012</td>
<td>Feb. 24, 2012</td>
<td>142 sols</td>
<td>90 days</td>
</tr>
<tr>
<td>Winter</td>
<td>Feb. 24, 2012</td>
<td>March 13, 2013</td>
<td>154 sols</td>
<td>89 days</td>
</tr>
<tr>
<td>Spring</td>
<td>Sept. 14, 2011</td>
<td>March 30, 2012</td>
<td>194 sols</td>
<td>93 days</td>
</tr>
</tbody>
</table>

Precession for Mars is predicted to be on the order of 175,000 years (Armstrong et al. 2004; Sagan et al. 1973) with a present longitude of perihelion for Mars near the winter solstice \( L_{m,p} = \sim 270^\circ \). At \( L_{m,p} = \sim 270^\circ \), the Martian southern summer is hotter and winter is colder. Perihelion occurs during the height of the southern hemisphere’s summer (251° = \( L_{m,p} \)), noted at approximately -25° (S) latitude. Solar intensity is approximately 35% stronger at this latitude/declination than it is at 25° N on the northern summer solstice. Seasonal processes magnified by orbital changes in eccentricity and perihelion passage have resulted in the transfer or net loss of south polar ices.

**Figure 2.25** Orbital patterns for Titan are represented by Saturn’s precession and eccentricity, as well as Saturn’s axial tilt or solar angle. A complete cycle of precession is much longer for Saturn than Earth or Mars at approximately 1,800 kyr. With eccentricity values of .054, the Saturn/Titan system experiences greater TOTAF differences hemispherically than does Earth, but much less difference than Mars (Androes 2012).
For the saturian system, which includes Titan and all of the saturnian satellites, a precession cycle is anticipated at approximately 1.8 million years (Hamilton 1994; Ward and Rudy 1991). (Titan’s orbital cycle about Saturn is of little consequence in total solar flux or aphelion and perihelion distances.) Titan and the other saturian satellites follow Saturn’s ~29.5 yr. orbit with 7-8 year long seasons. This period is equal to 10,759 Earth days. Seasons on Titan vary by as much as an Earth year as result of slower orbital velocity at further distances (Kepler’s 2\textsuperscript{nd} Law of Planetary Motion). Saturn experiences perihelion at $L_{s,p} \approx 277.7^\circ$. Models are currently being refined to provide better predictions for the Titan/Saturn system orbital change.

<p>| Table 2.5 Saturn/Titan Recent Northern Hemisphere Seasons |  |</p>
<table>
<thead>
<tr>
<th>Seasons</th>
<th>Begin</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>December 1987</td>
<td>November 1995</td>
</tr>
<tr>
<td>Fall</td>
<td>November 1995</td>
<td>October 2002</td>
</tr>
<tr>
<td>Winter</td>
<td>October 2002</td>
<td>August 2009</td>
</tr>
<tr>
<td>Spring</td>
<td>August 2009</td>
<td>May 2017</td>
</tr>
</tbody>
</table>

Astronomical forcing is of minimal consequence for Titan and Earth, as compared to Mars, in the present cycle. Although all three planetary bodies experience perihelion during the southern summer, however, the lack of fluid reservoirs on Mars suggests that the effect of astronomical forcing on the Martian surface may be much less. As models for astronomical forcing mechanisms are refined, numbers will become more precise.
2. Methods

Temperature records are available for most major metropolitan areas around the world. Global climate change cooperative partnerships provide a platform for the dissemination of information to the science community via database resources. For this study, 30 years of surface temperature records were requested for varying latitudes and climate zones (Appendices B & C and http://www.ncdc.noaa.gov/climate-monitoring/index.php) from the NOAA National Climate Data Center and NOAA National Environmental, Satellite Data, and Information Services. Comparisons include top of the atmosphere flux (TOTAF) and radiative temperature absorbed or reflected by Earth at the surface. Temperature records were compiled as:

1) Annual year averages 24-hr period for 10 distinct latitudes;
2) 30 year averages 24-hr period for 10 distinct latitudes
3) 30 year averages 24-hr period for 4 dates: Vernal and autumnal equinoxes; summer and winter solstices for 10 distinct latitudes

3. Results

Temperature differences across the globe recorded over a 30-year period include annual temperature change of \(\sim 60^\circ C\)
(Appendix C). The global average temperature ~14-15°C, includes 29-30° C at the equators and average seasonal variations outside the tropics of ±30° C (-17 to 42° C). Historical temperature reconstructions record ±3° annual global variations (Figure 2.26), or approximately one magnitude less difference in temperature (~3° C verses ~30° C) than orbital or seasonal variations.

Solar angle and distance from the Sun determine latitude-specific radiative flux to the top of the atmosphere of any planet in our solar system. Seasonal oscillations are an order of magnitude higher than long-period forcing mechanisms and are inextricably tied to geologic and hydrogeologic features on the planetary surface. The Solar Radiation Budget average of 341 Wm⁻² provides the daytime solar flux, diminished by Earth’s albedo equal to ~.3 or 30% reflection of solar insolation. Approximately 70% is absorbed – 51% by Earth’s surface (land/water) and 19% by the atmosphere itself. The median value of ~250 Wm⁻² is averaged for all latitudes. Temperatures are a product of the average insolation reaching Earth, the value of all reflected, absorbed and reradiated radiation, and the local geography which results in temperature ranging from 57.8° C to -89.2° C.
Climate models, based on insolation values as a function of time, suggest that the hemisphere experiencing summer at perihelion and winter at aphelion should have hotter summers and colder winters. Temperature records for Earth (Jones et al. 2000) demonstrate that the opposite is true (Figure 2.27). The southern hemisphere is currently at perihelion during summer and aphelion during winter. Average temperature variations for the southern hemisphere are only about ~8° difference whereas average temperature extremes are ~15° C for the northern hemisphere. The thermal inertia of the ocean dampens temperature oscillations driven by insolation flux. Earth’s southern hemisphere with disproportionately more ocean than land, moderates changes; whereas the northern hemisphere, with disproportionately more land than ocean, amplifies temperature swings. The difference in heat retention capacity between land and
water suggests that insolation alone cannot predict climate change. Based solely on insolation values, the southern hemisphere TOTAF receives approximately 6.25% more solar radiation energy as a consequence of orbital forcing mechanisms. The high specific heat capacity of Earth’s ocean, ocean circulation, and proximity to large reservoirs of water are essential components in any climate model.

Light density from solar radiation is a function of the projection angle. Direct radiation at 90° results in the greatest solar flux density and the least amount of areal coverage (no projection effect). Any incline to normal (90°) spreads light over greater surface area (solar footprint) decreasing the energy received (TOTAF) and scattering more light as it transits the atmosphere. The most direct sunlight occurs May – July; however, seasonal lag results in warmer temperatures June – August (seasons follow the warming pattern of the Earth’s surface rather than insolation patterns). Solar radiation is maximized at the equator on the equinoxes and at the Tropics of Cancer and Capricorn during the solstices (Figures 2.26-27).

At present, perihelion and aphelion distances vary by only a few percent for Earth and Saturn to 12% for Mars. However, solar flux varies up to ~25% for Earth and Saturn/Titan and ~50% for Mars which oscillations in eccentricity. Smaller differences are manifested between the northern and southern hemispheres when precession cycles are coupled with low eccentricity or with perihelion passages near the equinoxes.

Cycles on the order of 95,000 – 100,000 years relate to Mars’ perihelion precession and eccentricity (Segschneider et al. 2005; Stillman and Grimm 2011). Observations and images from ground-based telescopes, Cassini, and the Mars Orbiter NASA/JPL provided surface and atmosphere time-period analyses for this study. Direct detection of clouds from the Gemini 8-m telescope and the Keck 10-m monitoring program achieved by Brown et al. (2002) and Roe et al.
(2005) were examined for Titan’s summer solstice cloud observations of October 2002. Further confirmation by Schaller et al. (2006) on the Palomar 200-inch on October 2004 provide seasonal weather confirmation. Additional observations of global brightening of 7-9% with portions of the whole disk spectroscopic monitoring Griffith et al. (1998) showing a 200% increase in brightening near the spring equinox were examined.

4. Discussion

Climate variations on Mars are evident in recorded fluvial, pluvial or glacier features, and destroyed crater basins. Martian geomorphic features reveal artifacts of glaciation and flowing liquid. Heavy bombardment scarred the Martian surface; but, unlike Earth, many craters are preserved. This was also the time of the Tharsus Bulge formation. Flood features appear after most impacts from either surface flowing liquids or melted subsurface ices.

4.1 Mass Transfer

Any process driven by temperature or radiative energy, such as rainfall, weather, currents, weathering, erosion, and deposition, is highly sensitive to changes in insolation seasonally or independently by latitude. Volatile mass transfer results in solid H₂O sinks in the polar region of Earth. Observations for Titan indicate sinks may be in the form of liquid in methane/ethane lakes at the polar region or solid methane or complex hydrocarbon sinks in equatorial dunes. Mars supports CO₂ transfers from gas to solid and solid to gas seasonally.

Martian surfaces are used to recreate periods of time, climate, and events. The Noachian is the oldest (considered to include 4.6-3.5 Ga) and is associated with extensive flooding and impact crater features. The Hesperian epoch includes 3.5 to 1.8 Ga and is a time of volcanism and the formation of lava plains. The most recent epoch, Amazonian, includes possible river or glacier
features, and more recent volcanism such as Olympus Mons. Evidence from Becquerel crater (Figure 2.25) depicts ancient layered surfaces suggesting glaciers may have flowed on valley floors at mid-latitudes (Head et al. 2006). A significant transfer of ice from the poles to the valleys would be required for the Late Amazonian glaciations (Francois et al. 1990; Head et al. 2006) of Mars.

MARS – GLACIER SINK

Figure 2.28 NASA/JPL HiRISE University of Arizona, 8 North 343 East in Arabia Terra PSP_002733_1880 Vertical Exaggeration X 2. Based on patterns in Becquerel crater on Mars, In Quasi-Periodic Bedding in the Sedimentary Rock Record of Mars. Head et al. 2006. http://www.msss.com/mars_images/moc/2003/04/26/

4.2 Titan Seasonal Oscillations

Seasonal temperature changes on Titan appear to drive the haze layer and polar hood. Between 2007 and 2010, Titan’s upper atmosphere/haze layer experienced a 120 km drop in height (de Kok et al. 2010; Griffith et al. 2009). On the equinox date, the equatorial haze was 30 km higher than the polar haze (West et al. 2011). Convective methane volatiles in the atmosphere form strongly high-latitude dependent, hemisphere-specific clouds during summer.

Figure 2.29 Polar haze altitude experienced a seasonal drop of 120 km in Titan’s upper atmosphere. On equinox the equator was 30 km higher than the polar haze NASA/JPL.
seasons (Friedson et al. 2009).

Seasonal cycles potentially translate to insolation changes by a factor of ~3. Combined effects of seasonal and long-term cycles inevitably augment amplitudes leading to more dramatic dichotomies by a factor of ~.5 to 1.0 or a total of ~3.5 to 4.0. Aharonson et al. (2009) correctly assert that orbital cycles induce smaller energy differences than seasonal ones, but span timescales three orders of magnitude longer.

In 2004 high latitude clouds were commonly seen in the southern hemisphere with wind speeds of 10 m/s. Eastward moving clouds at the mid-high southern latitude (53°S) were captured in December 2009. Clouds have also been noted in the north between 220-260°W longitude between 60-82° N latitude since 2007, a possible lake effect in these regions. Clouds appeared near Titan’s equator at approximately 19°S latitude and 251°W longitude in September of 2010, with dark surface methane accumulations covering 500,000 square kilometers in October 2010, and by January 2011, most of the wet methane had disappeared – evaporated, infiltrated, or dried.

Observed patterns indicate that seasonal cycles effectively transfer fluid from higher latitudes to equatorial regions or from one regional location to another. Future studies are needed to more accurately model Titan’s atmospheric circulation patterns and to recognize potential thresholds or tipping points of global verses hemispherical magnitudes.

Figure 2.30
Longitudinal dune fields at low latitudes serve as a sink for methane, hydrocarbon derivatives or tholins.
Average solar flux of 6-8 W/m² to Titan’s upper level atmosphere is ~20 times less than Earth’s, but is significant enough to drive the methane cycle and to initiate UV photolysis for hydrogen escape from Titan’s upper atmosphere (Achterberg et al. 2008; de Kok et al. 2010).
4.3 Greenhouse Effects

Atmospheric transmissivity, albedo, emissivity, greenhouse gas concentrations, and surface interactions determine how much insolation is trapped and subsequently reradiated. Temperature oscillations are more complex than insolation. Mean temperatures spanning 30 years demonstrate the inequality of thermal energy retention and distribution (Jones et al. 2000) between the northern and southern hemisphere. The time/temperature lag between peak solar radiation and peak temperature is an artifact of Earth’s absorption and infrared reradiation.

Planetary constructs must be analyzed and combined with insolation values to develop meaningful extraterrestrial models. Regional climate variations are large and physiographically defined, while global averages maintain a basic continuity. Disruptions or changes in global continuity signal climate change. Availability of surface volatiles, kinetically favored for vaporization at surface temperatures, is essential for perpetuation of local or regional hydrology. Regions near a large body of water on Earth experience ocean or lake effects including temperature moderations and formation of rain clouds. Such effects may be vital components in climate models for Titan’s northern polar region (Brown et al. 2009) or for reconstruction of temperature profiles for the Martian Noachian or Amazonian time periods.

4.4 Hemispheric Dichotomies

Saturn is 12% closer at perihelion than aphelion, with an eccentricity of .054, equivalent to ~24% difference in radiant flux between perihelion and aphelion. At longitude of perihelion of $L_{s,p} \approx 270^\circ$ Titan’s northern winter occurs at Saturn’s nearest approach to the Sun. Under current astronomical positions, lower temperatures and less evaporation are expected for the northern hemisphere than were possible in the past. When Saturn approaches $L_{s,p} \approx 90^\circ$, a summer solstice
perihelion, the potential for greater evaporation, precipitation, and transport of methane liquids exists due to the abundance of liquid volatiles in the northern polar region. Hemispheric insolation patterns would be reversed (6.47 W m\(^{-2}\) in the southern summer and 7.75 W m\(^{-2}\) in the northern summer) at the top of the atmosphere flux (TOTAF). In this setting, a maximum asymmetry of 1.5 W m\(^{-2}\) TOTAF for a total difference of no more than .3 W m\(^{-2}\) at Titan’s surface (Aharonson et al. 2009).

Even with this low insolation, dramatic changes follow Titan’s seasons with 2.5 times more radiant heat to the equatorial verses the polar region. Mass transfer processes are active on Titan and have resulted in large accumulations of solid hydrocarbon dunes near the equator (Barnes et al. 2008; Reffet et al. 2010). Active photolysis of hydrocarbons in the upper atmosphere results in permanent loss of liquid methane to equatorial dunes and potentially to the atmosphere and the northern hemisphere (Lorenz et al. 2008).

Seasonal cycles potentially translate to insolation changes by a factor of ~3. Effects of long-term cycles, however, augment amplitudes by a factor of ~.5 to 1.0 or a total combined effect of ~3.5 to 4.0. Aharonson et al. (2009) correctly assert that orbital cycles induce smaller energy differences than seasonal ones, but span timescales three orders of magnitude longer. Under the current higher eccentricity for Titan/Saturn, and a longitude of precession near the winter solstice (northern), Titan’s northern hemisphere seasons are moderated whereas Titan’s southern hemisphere has longer, colder winters and shorter more intense summers. Southern summers would result in more evaporation from the southern lakes.

During winter, frozen ethane and methane may be present in the shallow subsurface or in porous ice shorelines where it may be undercut by river flows. Subsequent melting of ethane and methane in the subsurface would result in mass wasting of water ice and loss of shallow
subsurface solids. Steep-sided lake bed morphologies may be evidence of this loss of solid ethane/methane, karst-like dissolution, or subsurface connectivity with deeper reservoirs. Subsurface reservoirs may also serve as recharge liquids for lake levels. The morphology of lake beds is worthy of further investigation. Most lake shorelines on Titan are steep-sided, especially the small or empty lake beds. Water ice can be brittle and subject to fracturing, mass wasting, and on Titan, saturation with ethane or methane.

Extensive equatorial hydrocarbon dunes indicate that a likely sink for liquid methane includes conversion of liquid methane to mixed solid hydrocarbons. Over time, both the southern and northern polar regions have lost methane reserves and along with the permanent phase-change loss, an extensive relocation of the reserves to the equator. Rather than a solid sink at the poles, Titan exhibits a solid phase sequestering of methane near the equator. For Titan, the sink is permanent, slowly removing the active atmospheric volatile.

Unlike Earth, and possibly Mars, where orbital oscillations can dramatically alter the ice/water/albedo of the planet, ice/water/albedo feedback mechanisms are absent on Titan. Evidence of climate change on Earth is extracted from ice cores, sedimentary sequences, mineralogy, and isotopic analyses. Glaciations on Earth results in pluvial cycles, sea level rise and fall, and distinct erosion patterns. Physical evidence from ice/water/albedo mechanisms is lacking for Titan. In absence of cores or exposed sedimentary layers on Titan, we must rely only on surface features to provide insights into Titan’s past.

A clearly identified, perpetual source of methane to recharge Titan’s surface liquid inventory is presently unknown, but may be derived from subsurface reservoirs, clathrates, or serpentization processes in the silicon rock. Hydrocarbons are recycled in the hydrologic cycle which is active and dynamic with the saturation of Titan’s atmosphere. Porous ice surfaces are
also likely to be saturated with methane/ethane liquids; however, based on images observed to date and current research, recharge through time has not kept pace with total liquid inventories except in the northern polar basin region. Equatorial dunes are likely long-period sinks for hydrocarbons, once filling lake basins on Titan that are now empty. The southern polar region has undergone recent loss of fluids, but long-term hemispheric dichotomies in fluid resources do not appear to be solely linked to climate.

5. Conclusions

Earth, Mars, and Titan, the planetary bodies in our solar system with a history of flowing liquids, preserve seasonal and longer-period orbital signatures in layered strata. Surface features also suggest that volatile transient liquids, subject to solid phase sequestering, are dependent not only on climate forcing, but additionally on unique physiographic features of the planetary body. Climate change is subject to longer period orbital oscillations such as precession, eccentricity, and obliquity, and to the rise in or loss of surface liquids (oceans and seas) and atmospheres. Climate variations on Earth and Mars have produced dramatic geomorphic evidence of change, primarily related to glaciers. Orbital periodicities are likely to play an important role in fluid mobility on Titan over short term periods working in conjunction with seasonal insolation changes. Seasonal cycles appear to be the most prominent force on Earth, Mars, and Titan altering surface morphology.

Regional and hemispheric climate variations are large and highly dependent on the ratio of land verses ocean. The northern hemisphere’s land density difference and reradiation is vastly stronger than the southern hemisphere’s response to insolation change due to the thermal inertia of the ocean. When the northern hemisphere experiences summer at the longitude of perihelion of 90°, a global climate change may be induced by positive feedback mechanisms driven by
Earth’s changing albedo. Based on theories by Serbian mathematician and engineer, Milutin Milankovitch, these nonlinear oscillations in insolation are linked to long-standing climate patterns with varying degrees of deviation.

Long-term orbital cycles, on the order of $10^3$-10$^5$ times longer than annual cycles, have been theorized to cause extreme changes in climate for Earth, including “Snowball Earth” (Eriksson 2011), at threshold points of extreme changes in radiative forcing coupled with positive feedback mechanisms. Climate is a function of the interplay between 1) physiographic location and geologic setting; 2) temperature, composition, and structure of the planet’s atmosphere; 3) and orbital forcing mechanisms affecting insolation on diurnal, seasonal, and long-period time scales. Zonally-averaged models detail radiative transfer, surface energy balances, snow and sea-ice budgets (Gallee et al. 1991).
CHAPTER FIVE: Characterization of Ligeia Mare and Titan’s Northern Polar Region
(Wasaik and Androes collaboration)

Ligeia Mare, the second largest sea on Titan, resides in an endorheic basin dominated by seas in the northeastern polar region. Ligeia’s shoreline morphology resembles terrestrial man-made reservoirs where water is dammed and valleys are flooded. Here we describe the mare and surrounding geologically diverse terrain including rugged high and lowlands, incised valleys, and smooth plains. Observations include active processes evidenced by drainage flow directions, areal extent of rivers and river valleys, sediment volume estimates, and varied drainage patterns. Headward erosion has carved valley and ridge systems in the flanks of the highlands, while the more distal highland plateau is mostly uncut by rivers or extensive erosion and contains smaller lakes, lakebeds, and mottled terrain.

1. Description

Ligeia Mare (250 W, 80 N) occupies ~10⁵ km² of a nearly 10⁶ km² basin region in Titan’s northern latitudes from 220-360° W (Lorenz et al. 2008; Lorenz 2008) where the large seas Ligeia, Punga, and Kraken Mares are found. Smaller lakes are scattered throughout the remaining northern region; deep lakes are seen above 65°N, while below 77°N shallow lakes and empty basins appear (Hayes et al. 2008). Of the approximately 54% of the north polar region surveyed by radar, ~10% is currently covered by lakes (Lorenz et al. 2008b). Cassini Synthetic Aperture Radar (SAR) swaths T25, T28, and T29, obtained 22 Feb 2007, 10 April 2007, and 26 April 2007, are mosaicked in Figure 2.32, showing Ligeia Mare in its entirety.
Deeper lakes appear dark in SAR images (Paillou et al. 2008), suggesting a complete absorption and reflection of microwave energy (Hayes et al. 2008; Paillou et al. 2008). SAR analysis by Hayes et al. (2008) indicates that granular (shallow) lakes are consistent with radiation penetrating a liquid layer and interacting with the bottom, though varying liquid saturation levels also cause radar darkening (Hayes et al. 2008). Radar bright depressions, morphologically similar to small lakes, are interpreted as dry lakebeds 200-300 m deep (Hayes et
The radar bright reflections from empty lakes show volume scattering effects, implying penetration and/or multiple scattering of incident microwave energy. Geologic interpretations include the presence of porous surfaces, perhaps through karstic dissolution, lakebeds with indurated surfaces, cracked evaporative deposits (Hayes et al. 2011), or material with differing properties than the surroundings (Hayes et al. 2008).

Titan’s atmospheric pressure is ~1.5 bars at the surface, where it consists of almost 95% nitrogen, 4.9% methane, and a myriad of other species. The temperature in the northern polar regions is ~91 K (Jennings et al. 2009) and was measured to be ~94 K near the equator by the Huygens probe (Fulchignoni et al. 2005).

Although estimates of lake composition include ethane, methane, propane, and other constituents (Brown et al. 2008; Cordier et al. 2009), methane is thought to dominate the hydrological cycle due to its rapid evaporation and low density (Hayes et al. 2011; Mitri et al. 2007). Ethane, being relatively stable under Titan conditions, may dominate in subsurface aquifers. SAR imagery of the north taken from July 2006 to December 2009 shows no discernible change in northern shoreline features, in line with predictions that precipitation and evaporation during winter would be minimal (Mitchell 2009). In contrast, shoreline change has been detected in Ontario Lacus in the south polar region (Wall et al. 2010). As on Earth, many factors likely contribute to lake levels, including topography, ground flow from local aquifers, crustal permeability, substrate morphology, and infiltration rates. The Huygens probe detected an increase in methane abundance following impact, suggesting the warm probe caused methane to evaporate from a surface moist with hydrocarbons. Laboratory experiments indicate liquid methane readily soaks into water ice, which is consistent with an unconfined aquifer or "water table" and ground saturation of the solid ice (Sotin and Tobie 2008). Analysis by Lorenz and
Lunine (1996) predicts that chemical weathering of water ice on Titan’s surface by liquid methane is insignificant (Lorenz and Lunine 1996). However, complex hydrocarbons originating from atmospheric photochemical processes, and delivered via precipitation, could potentially form karst terrain (Mitchell 2009).

Precipitation levels on Titan are thought to be seasonally dependent on Saturn’s 29.5 year orbit around the Sun (Stofan et al. 2006; Stofan et al. 2007). Titan’s north is currently in the spring season. Insolation, and consequently precipitation, is impacted by the perihelion/aphelion seasonal positions of the Saturnian system. Precession and the changing eccentricity of Saturn’s orbit, much like glacial cycles on Earth, would have periods of tens to hundreds of thousands of years. Such cycles could account for the hemispheric distribution of lakes, which are sparse in the south polar region (Aharonson et al. 2009). Although relatively weak insolation is thought to allow only ~1 cm of average rainfall per Earth year across Titan (Lunine and Lorenz 2009), increased precipitation at the poles and episodic storms, similar to events on Earth’s deserts, could carve the geomorphic features observed.

Fluvial incision into bedrock (water ice) is likely to be similar to that on Earth for similar conditions of slope, discharge, and sediment supply (Collins 2005). Although sediments are accelerated more slowly due to Titan’s lower surface gravity, this is offset in part by liquid methane’s lower viscosity to that of liquid water, and, for a given shear velocity, larger sediments can be transported on Titan due to sediments being more buoyant (Burr et al. 2006). While the kinetic energy of particle impacts through liquid may be lower on Titan, the abrasion resistance of water ice to that of terrestrial sandstone, for example, is also lower (Collins 2005). Work by Burr et al. (2006) on organic and water ice sediment movement by liquid methane flow under Titan gravity indicates that non-cohesive material would move more easily on Titan than
Earth. Additionally, hyperconcentration of fine grain organic sediment precipitated from the atmosphere would enhance coarse grain transport, with the possibility of convection driven rainstorms leading to hyperconcentrated flows, and surficial liquid flow events incurring significant sediment transport (Burr et al. 2009; Burr et al. 2006).

2. Methods

For this study, Cassini SAR swaths T25, T28, and T29, which encompass Ligeia Mare, were projected to a polar stereographic north coordinate system utilizing Integrated Software for Imagers and Spectrometers (ISIS-3), then imported to the Environmental Systems Research Institute (ESRI) ArcGIS 10 environment. To facilitate data management and overlays, files were further processed within the ERDAS Imagine format to allow for size reduction while maintaining data integrity, which included removal of the ample “NoData” within the files.

Distance measurements of features within the Ligeia Mare region were carried out utilizing a combination of ISIS-3 and ArcMap 10, while area measurements were performed utilizing ArcMap 10, with the advantages of layers.

Flow directions into Ligeia are predominately northwesterly originating in the highlands to the south. Lesser flow
contributions are afforded from the north in the high latitude lake region. Figure 2.33 illustrates key river drainage into Ligeia Mare based on main channel areal extent (km²) and flow direction. Channel lineations are dark, suggesting smooth surface characteristics or liquid; however, shadowing effects may occur in valleys due to radar incident angle. All rivers surrounding Ligeia flow into the basin with no apparent outflow. Together with Punga and Kraken Mares, the entire watershed is a closed basin hosting the largest surface ethane/methane reservoirs on Titan.

3. Characterization of Ligeia Mare and the Northern Polar Region

3.1 Location A: Crater

At the top of Figure 2.32, a wide channel is seen to empty into the northern most reaches of Ligeia Mare, near an apparent impact crater (Figure 2.34). Channels emptying into the sea appear submerged within a shallow floodplain or delta before disappearing into the depths, which is typical for Ligeia Mare. Although radar can penetrate for meters through liquid methane and interact with the bottom, a saturated regolith, exposed smooth lake sediment, or combination thereof could produce these effects as well, blurring a transition from shore to sea (Hayes et al. 2008; Lorenz 2008; Lorenz et al. 2008a; Paillou et al. 2008). Submerged channels suggest lower sea levels in the past, hydrodynamic submarine channel flow, or cohesive sediment fill restricting flow within narrow channel walls.
A structure, indicative of an impact crater, features a circular bright rim rising out of the dark liquid with an apparent central peak. Ejecta and crater fill are not detectable; these impact characteristics are seen for recognized crater structures on Titan (Wood et al. 2010) but would not be visible in or around the flooded crater. Alternative formation processes include cryovolcanism or fluvial deposition, the later the result of proximity to a channel and shoreline, coupled with unknown liquid dynamics, morphologically similar to a terrestrial spit. What is certain is that flow regimes in this shallow arm of Ligeia have been insufficient in either time or energy to erode the craterform. Although the well-preserved portion of the crater is in close proximity to the mouth of a major river, little alteration has resulted. The crater rim is intact with the exception of the eastern edge having suffered from erosion, flow melt, or other degradations.

Continuing along the shoreline in a clockwise direction is a series of broad incised bays that appear flooded, typical of Ligeia's littoral zones. The terrain appears mottled for ~50 km up to the shorelines of a large bay containing several islands. Beyond this bay the terrain becomes more radar bright and hummocky with increased variability in brightness and apparent chains or ridges further south (Lopes et al. 2010).

3.2 Location B: Hummocky Region

The easternmost region of Ligeia Mare appears granular (Hayes et al. 2008) or shallow, gradually deepening seaward. The inland region is hummocky and mountainous terrain, rising to ~1500 m just 75 - 100 km from the sea. Such radar bright textured terrains have been interpreted to be of tectonic origin (Lopes et al. 2010; Lorenz et al. 2011; Radebaugh et al. 2007; Stiles et al. 2010); however, exogenic processes are clearly active in the drainage basin. Offshore islands and a more rugged shoreline emerge from the broad, gradual sloping eastern bay. Tributaries with
high angle, steep-sided valleys are similar to terrestrial fjords or regions subject to mass wasting processes. Rock falls, debris flows, and slides are all gravity driven processes common to steep-walled valleys and are a likely source of sediment generation in this region, and in the rugged hills and mountain regions. Talus accumulation likely mantle the valley terrains and may consist of talus cones, aprons, alluvial fans, float boulders, unsorted regolith, and deltas in flooded valleys - all erosional remnants of highlands.

About 50 km further, the confluence of four primary drainage systems empty into Ligeia where extensive fluvial deposits are anticipated. Dendritic drainage originates near highland escarpments, dissecting rims through headward erosion and continuing on through rugged terrain where tributaries feed into downriver channels.

3.3 Location C: Peninsula

A large peninsula located at 245 W, 75 N, with islands 5-35 km off shore, is flanked on the east and west by river valleys and highlands to the south. Altimetry estimates on the east and west flanks, along with an offshore island, indicate lower elevations, with hummocky and diverse terrains near the shore (Lopes et al. 2010). Morphologies of the drainage patterns and shorelines suggest erosion, rather than deformation, formed the valley and ridge systems. Extensive shorelines can be traced throughout this region, lined with finger coves and alcoves, islands, and peninsulas, indicative of branching drainage patterns and erosional features rather than tectonic. Morphologies are similar to flooded valleys, destructive coastlines, and endorheic drainage basins with modest to high-angle slopes. For Earth, these features and are strikingly similar to man-made reservoirs where water is dammed and lowlands flooded.
3.4 Location D: River System

The river system to the west is approximately 260 km long and originates in the highlands near an area ~900 m in altitude from sea level (Lorenz et al. 2011). The flow is northwesterly with branching gully and ridge tributaries initiated on the down slope rim of the highlands (Figure 2.35). Incised channels span the entire distance from highlands to basin (Figure 2.36). Although primarily dendritic, trellis drainage patterns appear near the southern plateau, gradually descending into anastomosing systems. The channel feeds into what appears to be an extended cove of Ligeia's southern shore. The local watershed, the area half-way between adjacent rivers, is some 10,000 km$^2$.

3.5 Location E Highlands

The inland highlands south of Ligeia are a mottled terrain superimposed with dark and granular lakes, and dry lake beds, varying in size from 25 - 1000 km$^2$. The dark and granular

---

Figure 2.35 A 260 km river channel originates in the highlands and terminates in Ligeia Mare. Trellis and dendritic drainage patterns can be seen.

Figure 2.36 Confluence of drainage channels into a single channel. The channel appears darker than its granular surroundings.
lakes are predominately clustered in what appears to be a modest depression in the south-eastern region, while bright lakes dominate to the west. Radar analyses from Hayes et al. (2008) indicate radar bright lake beds have similar roughness to their surroundings with differing material properties. This may result from the accumulation of fine sediments, precipitation of minerals, evaporites, or sub-surface porosity structures. Liquid methane readily absorbs into water ice, the prime component of Titan’s bedrock; therefore, the appearance of filled lakes could depend on saturation levels as well as the methane/ethane table. This, of course, does not exclude the existence of some type of impermeable surface creating a perched methane/ethane table. Though many of the lacustrine features are circular in shape, there is a lack of supporting evidence for impact origins; i.e. central peaks, dark floors, and ejecta. The clustering of these features, as well as a lack of more definitive impact craters in the north compared to the rest of Titan, also does not offer support for impact origins (Wood et al. 2010). Cryovolcanically produced calderas is another possible formation mechanism, although no evidence of lava flow can be seen. Karstic processes may be at play. Steep-rimmed depressions

Figure 2.37 Highlands south of Ligeia Mare. In the lower right, the highlands contain a cluster of dark or deep lakes, while a cluster of bright, or empty lakes, can be seen in the lower left (Hayes et al., 2008). Hummocky region of Figure 1 B. can be seen in the top right (Lopes et al. 2010). Drainage channels terminate in the shallow littoral zone of Ligeia Mare.
and clustering of lacustrine features in the highlands are consistent with terrestrial analogs. This region lacks visible drainage systems or incised channels. Drainage systems, radial and dendritic patterns, appear only on the basinward slope. This does not preclude the possibility of subresolvable features or indurated surfaces. Sheet flow during rain events across the highlands evolves into the gullies and rills in the north, terminating in canyons and river valleys. Earth analogs for the highlands include the Great High Plains tableland and/or the Colorado Plateau and monocline of North America, or the retreating escarpments of the Yilgarn Craton, Australia. Rugged terrains, separating the highlands and Ligeia Mare, are similar in their erosional origin and form to deeply incised canyonlands, badlands, and benchlands, with terraced plateaus, foothills, and piedmonts. Ancient terrains in the highlands are likely to be partially buried by mineralized deposits, tholins, and sheet or mud flow sediments.

3.6 Location F: Parallel Channels

Northwest flowing parallel drainage channels, one trellis, the other dendritic, flanked by elevated terrain to the east and low-lying terrain to the west, empty into the southern-most region of Ligeia (Figure 2.39). The eastern 325 km dendritic system originates near the highlands, and the western 105 km trellis system originates in lower terrain. These extensive systems drain into a catchment area either embayed by “flood waters” or filled with saturated regolith along Ligeia's low-angle shoreline. Within this floodplain, submerged sinuous channels are observed. Channels in this area are typical of terrestrial base level flow with small gradients, including meander, braided, and anastomosing. Such systems expend energy horizontally, rather than vertically, with a net sediment transport equilibrium between erosion and deposition. This process often creates cut banks and point bars. Deposition occurs on point bars or in overbank deposits. Trellis
drainage is indicative of ridge controlled flow patterns or steep-sided valleys. These systems are also common in rigid or indurated surfaces, fractures, or regions where extension or compression have resulted in fault blocks or fold belts. Wrinkle ridges on Titan may have formed in response to a shrinking crust or to tectonic stress perpendicular to fold direction. The pattern is also consistent with fault-bound ridges, with extensional deformation as opposed to compressional. Parallel ridge and valley systems on Earth exhibiting trellis drainage systems are commonly the product of tectonics and stratified in rock layers with varied degrees of resistant rock, rather than simple gravity-driven stream erosion. If extensional, the valley may have resulted from a downthrown, fault-block graben. The graben would be flanked to the north by scarps caused by tilting, uplift, or alternately by downwarping to the north into Ligeia. In the low-lying area, rivers drain into orthogonal channels, indicating bedrock rigidity or fracture morphology. On Earth, drainage such as this is typically associated with stress fractures, faults, or cracks. Much of the drainage into the orthogonal main channel appears to be annular or fracture-controlled. The westernmost portion of the low-lying region is within several kilometers of tributaries emptying into an estuary of Kraken Mare.

Figure 2.38 Parallel channels, one trellis, the other dendritic, terminate into southwestern Ligeia Mare. Drainage appears to follow fractures in lake area surface material. Parallel ridge and valley systems on Earth...
3.7 Location G: Two Dome

Continuing northwest, two large apparent domes separate Ligeia from Kraken. The domes, located at 270 W, 77 N, and 290 W, 81 N, are on the order of 150 km in diameter and appear to reach heights of 1500 m above sea level (Stiles et al. 2009). Between the domes, the Kraken estuary discussed in section F is only ~37 km from Ligeia. Terrestrial domes are commonly formed from compression, subterranean expansion or diaperic anomalies, folding, tectonic uplift, rebound or from surface expansion and exfoliation. Brittle deformation and exfoliation result in dissection and annular drainage. The first dome, with an average eastward slope of approximately 22 m/km to the shoreline of Ligeia, exhibits annular drainage, becoming more dendritic downwards towards Ligeia (Figure 2.38). Should surface features on Titan result solely from exogenic processes

Figure 2.39 Dome with annular (dashed arrow) and dendritic (solid arrow) drainage patterns. Indurated, brittle crustal material are commonly dissected by annular or rectangular drainage.
(Moore and Pappalardo 2011), the domes may be capped with materials or duricrusts much more resistance to erosion than the surroundings.

The second dome has a lower gradient of 15 m/km on its Ligeia facing slope. Features of this slope are difficult to identify due to the lower resolution of the T25 swath. This second dome borders the westernmost portion of Ligeia, with the above mentioned estuary to its southeast, and establishes a watershed between Kraken, Punga, and Ligeia. Punga Mare lies across undifferentiated plains to the northwest. To the south, lower lying rough terrain, leads to an east-west ridge.

3.8 Location H: Low Lying Region

Continuing clockwise, a region of smoother terrain and lower elevation separates Ligeia from Punga Mare to the northwest. Two channels empty into Ligeia and continue a southerly flow appearing as submarine or submerged channels within a granular offshore region. Continuing east, the terrain again becomes rugged and elevated, approaching 1000 m in elevation (Lorenz et al. 2011). To the north is a small lacustrine feature with an area of ~100 km².

4. Discussion

Ligeia Mare is similar in form to the Caspian or Dead Seas, with no evidence of outflow, and is morphologically similar to a flooded valley, with a young intricate shoreline such as Lake Mead in the USA. Extensive dissection along the flanks of the highlands has resulted in steep-sided valleys, long narrow ridge formation, and vast networks of dendritic drainage systems. Brittle deformation of surface rock often leads to mass wasting or gravity-driven mass movement, exfoliation, and other mechanical weathering and erosion processes. Regolith and
talus accumulation on slopes and in alluvial cones, aprons, or fans provide detritus to be moved during rain or flood events. These transported sediments serve as pummeling agents to enhance downstream erosion. The combined erosive and transport capacities of rivers, along with the topographic relief of hundreds of meters, suggests that large quantities of sediment have been exhumed and deposited into Ligeia. For instance, by estimating resolvable river valley areas utilizing geographic information systems (GIS) software, assuming an average depth of 50 m for main channels, and 20 m for tributaries, sediment accumulation volumes through time have been estimated (Table 2.6). It is curious to contemplate the abundance of fluvial features that are beyond Cassini’s SAR resolution of ~350 m to ~2 km. Note that the Huygens probe detected fluvial features during its decent that are not detectable via Cassini’s SAR.

### Table 2.6

<table>
<thead>
<tr>
<th>Direction of Flow</th>
<th>Sediment Volume ($10^9$ m$^3$)</th>
<th>Valley Area (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE: 0-90</td>
<td>8.2</td>
<td>175</td>
</tr>
<tr>
<td>SE: 90-180</td>
<td>6.2</td>
<td>124</td>
</tr>
<tr>
<td>SW: 180-170</td>
<td>13.3</td>
<td>268</td>
</tr>
<tr>
<td>NW: 270-360</td>
<td>49.7</td>
<td>1255</td>
</tr>
</tbody>
</table>

Stiles et al. (2009) and Lorenz et al. (2011) estimated surface topography from Cassini SAR data based on the apparent backscatter differences from the overlap of antenna footprints between two of the five Radar antenna feeds, and knowledge of spacecraft pointing, ephemeris, antenna beam patterns, and the nominal 2575.0 Titan reference sphere. Utilizing these altimetry maps and drawing curved lines between measurements, Figure 2.40 was generated to provide a sense of the topography in this region.
Figure 2.40 Estimated altimetry along the horizontal line shown in Figure 1, showing the Ligeia basin, rugged valleys, and highlands. Liquid depths in are inferred (Lorenz et al. 2011; Stiles et al. 2009).

Ligeia Mare has many high-gradient downcutting river systems, the lower stretches of which appear flooded. These rivers are capable of transporting assorted alluvium, similar in size range to those seen by the *Huygens* probe; however, as the slope profiles flatten into flood plain valleys, sediments are likely to drop out near the base of the mountains where sorting may begin. Sediment eroded from upland sources would likely consist of various sizes due to the diversity of river gradients, mass wasting, and gravity flows. Sediment sorting occurs during transport as a result of flow velocity, distance traveled, changes in gradients, or as suspended sediments settle out in a basin or low-energy environment. Longer transport suggests greater mechanical breakdown and sorting; shorter transport implies less mechanical breakdown and sorting. Deposits from rain and flood events would form layers or varves in the endorheic basin. Depositional couplets, laminations, and graded strata are possible in regions where flow regimes...
vary, become quiescent, or where ephemeral streams empty into basins, or high-energy flows meet lower gradients such as flood plains, deltas, and mares. Progressive sediment fill over time makes the prospect of stratified sediment accumulations in Ligeia not only intriguing, but probable, and would contain elusive records of the region's geologic and climatologic past.

**Characterization of Ligeia Mare in the Northern Polar Region**

*Figure 2.4* Geology surrounding Ligeia Mare include: 1) A deep channel visible in the broader shallow, fluid-filled valley; b) a modified, flooded crater with a central peak visible; c) steep-sided tributaries; d) confluence of several high-angle drainage valleys merging into Ligeia; e) highland region containing both filled and empty small lake basins; f) fault or fracture controlled river channels; g) lobate filled meander channel intersecting with fracture/fault channels; h) rectangular drainage patterns in steep topographically-high, rugged mountains separating Kraken and Ligeia Mares; i) low-angle shoreline with shallow-valley features, lacking deep incised, fluid-filled valleys. Ligeia composite is from Cassini SAR swaths T25, T28, and T29.
CHAPTER SIX: Consequences of Astronomical Forcing for Titan

Polar regions on Titan have also been described by their strong volumetric asymmetry (Aharonson et al. 2009; Hayes et al. 2011; Wall et al. 2010) between the southern and northern high latitudes. The 3 largest reservoirs, Kraken, Ligeia, and Punga Mare, are all in the north with Ontario Lacus the only modestly large fluid body in the south. Interpreting geologic sequences as a consequence of nonlinear climate mechanisms is wrought with pitfalls. Careful analyses through time, however, may allow regional, seasonal, and longer-term orbital cycles on Titan to be differentiated, building our knowledge not only of Titan, but also of climate processes that have shaped planetary surfaces in our solar system and possible exosolar planetary surfaces. Titan, like Earth, appears to be geologically and hydrologically diverse and uniquely complex.

1. Introduction

Although estimates of lake composition include ethane, methane, propane, and other constituents (Mousis et al. 2009; Brown et al. 2011) methane is thought to dominate the hydrological cycle due to its rapid evaporation and low density (Hayes et al. 2011; Mitri et al. 2007). Ethane, being relatively stable under Titan conditions, may dominate in subsurface aquifers. SAR imagery of the north taken from July 2006 to December 2009 show no discernible change in northern shoreline features, in line with predictions that precipitation and evaporation during winter would be minimal (Mitchell 2009). In contrast, shoreline change has been detected in Ontario Lacus in the south polar region (Wall et al. 2010).

Methane liquid in lakes and rivers is subject to evaporation, precipitation, surface flows, flooding, and migration much like water on Earth. Condensed methane vapor falls to Titan’s
surface as either liquid or solid. Liquid methane possesses the greatest erosion capacity on Titan. Solid methane or ethane ices may accumulate in valleys and craters, melt and flow to rivers, or collect at the base of reservoirs where melting would be difficult and thus would have little impact on geomorphology in comparison to the water/ice processes on Earth.(Mitri et al. 2007; Notarnicola et al. 2010; Lunine and Lorenz 2009).

Atmospheric pressure is ~1.5 bars at 93° K on Titan’s surface, consisting of ~95% nitrogen and 4.9% methane, with other species accounting for ~0.1%. At higher latitudes, ~90 K (Jennings et al. 2009), at low latitudes 92 K, and 94 K was measured by the Huygens probe near the equator (Fulchignoni et al. 2005). Methane is stable as liquid for most of Titan’s higher latitude provinces during winter and as liquid or vapor during the remaining portion of a Titan year. At high methane saturation levels in the atmosphere, large raindrops condense in Titan’s inversion layer of the troposphere. With saturation levels less than 100% humidity, droplets evaporate before reaching the surface. Only large droplets of methane, approximately 1 cm, successfully reach the surface. Titan’s troposphere is capable of holding approximately 10 times more liquid water vapor than Earth.

Ethane is the dominant product in photolysis in Titan’s atmosphere and is likely the dominant constituent of Titan’s lakes. These lakes are likely stratified with methane near the surface. Unlike Earth, however, frozen liquids, ices or solids sink where subsurface melting is not likely to occur. Ethane, and possibly methane, may be preserved in solid-state in reservoirs at depth (freezing temperatures 89.3 K and 90.7 K respectively). As lake levels diminish during peak insolation, exposed or shallow subsurface solids may melt. Therefore, seasonal change may liberate additional fluids; however, without glacier movement, phase transitions from liquid to solid or solid to liquid would have little effect on Titan’s surface geology except in lake bed
morphology or in the availability of fluids. Flowing solids (such as glaciers) or liquids on inclined surfaces are intrinsic to exogenic landscape evolution; therefore, it is essential to examine the possible influence of these physiographic features.

Precipitation rates are estimated at 1 cm yr\(^{-1}\) (Earth) and are highly variable with latitude and seasonally dependent on Saturn’s 29.5 year orbit (Stofan et al. 2007) and somewhat variable in longitude. Lunine and Lorenz estimated 16 cm yr\(^{-1}\) global average over a period of one Titan year, or \(\sim 1\) cm per Earth year across Titan (Lorenz et al. 2008; Lorenz 2008). Increased precipitation at the poles and episodic storms are common seasonally. Observations, which began in September 1995, revealed enormous tropospheric storms (Griffith 2009) and ongoing cloud activity linked to the south polar spring (Brown et al. 2009; Roe 2008; Roe et al. 2005). Storms in summer 2004 (Schaller et al. 2006a; Schaller et al. 2006b) were evidenced by changes in volatile inventories.

In addition to the weather or climate seasonally on Titan, as observed from ground based telescopes and in SAR images, the physiographic features are widely varied between the poles. The comparison of liquid methane reserves provide evidence of distinct differences. Polar dichotomies are apparent in NASA/JPL maps (Figure 2.42 next page). The obvious difference in the inventory of methane between the north and south includes loss of liquid methane to solid sinks at the equator in the form of equatorial dunes composed of mixed solid hydrocarbons or tholins.
Laboratory experiments indicate liquid methane readily soaks into water ice, possibly implying the lakes region represents an over-saturation of the solid ice (Sotin and Tobie 2008). However, complex hydrocarbons originating from atmospheric photochemical processes, and delivered via precipitation, could potentially form karst lakes and terrain (Mitchell 2009; Tomasko et al. 2008).

The earliest description of Titan’s equatorial region included references to long, wrinkle structures which were eventually determined to be dunes (Lorenz et al. 2008; Lunine et al. 2008; Reffet et al. 2010; Rubin and Hesp 2010). Lorenz and Tokano describe equatorial winds directly linked to seasonal variations (Lorenz et al. 2010; Radebaugh et al. 2010; Tokano 2010a). Equatorial winds vary from east to west, with prevailing Westerlies on the order of .5 to 1 m/s with only very modest Easterlies of ~.1-.3 m/s through the year with the exception of the seasonal autumnal and vernal equinox cycles when the Easterlies strongly overshadow

**Fig. 2.42** North and south polar regions on Titan (>60° latitude). Liquid distribution is strongly asymmetrical. Southern region map. Ontario Lacus and other dark regions potentially lake beds or empty mares. Evidence for southern lakes or mares is lacking with the exception of Ontario Lacus (NASA image).
Westerlies at speeds of 1-1.5 m/s. Windspeeds on Titan, based on energy-flux models, predict 1 cm s\(^{-1}\). However, the Huygens probe measured 0.5-1 m s\(^{-1}\) with the prevailing Westerlies, much like Earth. Near-surface winds on Titan have also been linked to Saturn’s gravitational tides (Tokano and Neubauer 2002) unique to our solar system.

Dune formation is clearly driven by this infrequent, westward (east to west or Easterly) wind with sufficient wind speed and direction necessary to mobilize sticky hydrocarbon particles (Radebaugh 2009; Radebaugh et al. 2010; Reffet et al. 2010; Tokano 2010a). Dune systems account for 250,000 km\(^3\) (Lorenz et al. 2008) of solid hydrocarbons and represent a substantial sink for methane or other hydrocarbon molecules. In October of 2010, approximately 500,000 square kilometers of wet methane rained out at low latitudes, had disappeared, evaporated, infiltrated, or dried. The transient nature of methane is clearly visible in observations such as these.

The primary climate link for Titan is methane mobility. Methane movement increases or decreases in intensity with orbital cycles. Hydrodynamic forces change with climate and seasons, proportionally altering the landscape. Consequently, evidence of higher-order forcing effects on Titan is limited to these liquid geomorphic alterations. Erosion potential is a function of the availability, volatility, and condensability of methane. This study surveys the geomorphic evidence for climate change on Titan’s surface as it relates to liquid methane mobility and evaluates the seasonal effects verses the potential longer term effects of changing insolation.

The geologic distinction between nonlinear climate periods and seasonal change is limited to the degree of change in surface features such as, the total volumetric distribution of methane and ethane liquid surface reservoirs past and present, the number, degree, or width of incisions into the landscape, the type of drainage or erosion present (flood driven or slow progressive erosion),
or the percentage of empty lake basins in one region verses another. These factors contribute to the present-day surface geomorphology and to an understanding of past conditions that have had an impact on Titan’s surface.

This research focuses on the 1) required temperatures and pressures of methane evaporation; 2) the past and present surface methane reservoirs; and 3) the geomorphology of the three primary latitude-specific regions: the northern, southern, and equatorial. The northern polar region is the best imaged portion of Titan’s surface and will be used extensively to formulate comparative analyses. Surface features were examined in the north and south polar regions. Contributing data include number and size of lake basins, length, depth, and width of river channels and valleys, vertical relief caused by erosion, destroyed craters or basins, signs of changing topography. Emphasis is placed on possible surface features linked to climate variables examined in the previous sections. Although glacial features are absent on Titan, other climate change variables enhance or diminish the potential for erosion.

2. Methods

To date, only ~1/3 of Titan has been imaged with sufficient resolution to identify distinct geomorphic features. These higher resolution images are utilized for this study. Previous studies using Cassini SAR, RADAR and VIMS data and Huygens have provided extensive analyses of Titan’s surface. We extend these interpretations to local and global, seasonal and long-term climate processes shaping Titan’s geomorphology. Contributions from the ground based telescopes provided spatial and temporal coverage. Synthetic Aperture Radar (SAR) swaths T25, T28, and T29, obtained 22 Feb 2007, 10 April 2007, and 26 April 2007 were used for the northern polar region, and swaths T39, T55, T56, T57, and T59 obtained 20 Dec 2007, 21 May
2009, and 25 June 2009 for the southern polar region. Equatorial images provided by SAR include T39, T55, and T56, which include polar regions as well, and swath T07.

For this study, Cassini SAR swaths T25, T28, and T29, which encompass Ligeia Mare, were projected to a polar stereographic north coordinate system utilizing Integrated Software for Imagers and Spectrometers (ISIS-3), then imported to the Environmental Systems Research Institute (ESRI) ArcGIS 10 environment. To facilitate data management and overlays, files were further processed within the ERDAS Imagine format to allow for size reduction while maintaining data integrity, which included removal of the ample “No Data” within the files.

Titan surface vapor pressure and temperatures were achieved in a Titan simulation chamber created at University of Arkansas (Wasaik, Chevier, and others in 2011). Vapor pressure of methane dictates whether liquid methane will survive to reach the surface of Titan as rain or be revaporized. These results were incorporated into this study.

3. Discussions

The southern hemisphere empty and filled lake basins account for only 7.5% of the presently imaged surface with 92.5% for the northern hemisphere. Our interpretation of the region is based on the geomorphic evidence currently available for the north and south polar regions and characterization of the equatorial dune systems. Empty basin abundance extrapolated for the two polar regions and the existing disparity is discussed in the remaining sections.

Decreases in lake levels are assumed to be approximately 1 m/yr (15 m/season maximum). Northern lakes outnumber southern lakes by 3 to 1 dry lakes; 7 to 1 partially-filled lakes in presently known higher resolution images. Small lakes, trending 180-340° azimuth from Ligeia in Titan’s north polar region, are abundant during Titan’s northern winter. Small dry lakes beds
were present in the northern polar region even during winter indicating a different configuration or abundance of surface liquids in the past.

Rapid methane evaporation is expected at temperatures above 92 K which are most common during Titan’s summer. At the 90-92 K range for the northern pole, evaporation rates were sufficiently slow (assuming ~1.5 bars pressure). Tests conducted using the Titan experimental chamber (Figure 2.43) demonstrated the evaporation of 6 grams of methane at 1.5 bar and 93 K over a time period of 1500 secs (Wasaik and Chevier 2012 in process) – a higher rate of evaporation than anticipated at 92-92.5K.
Observed polar geomorphologies during northern polar winter, prior to the vernal equinox August 2009. Figures 1-7 are from the northern polar region; figures 8-9 from southern polar. Empty and filled basins, shorelines, channels, and river terminations to be observed for change. Geomorphic features were observed and along with evidence for transient fluids:

1. Punga Mare, the third largest known fluid-filled reservoir, is seen with rounded lobate shorelines in valley regions. Lakes formed from dendritic drainage systems on Earth terminate in narrow branching stream valleys. On Titan, however, many of the stream valleys emptying into the northern lakes appear to be higher than base-level. Punga Mare base level is high in lobate channels. Erosion processes are minimal with high sea levels.

2. Numerous filled and partially filled small lakes are common in the northern polar region, with both lake types in close proximity. The majority are filled. Average basin depths have been estimated at 500 meters. Such deep basins are likely to intersect ethane/methane saturated zones. Shallow basins may be seasonally empty, may be too shallow to intersect subsurface fluids, or may represent a loss of liquid methane either hemispheric or permanent. Other possible interpretations of Titan’s basins or surface floors are mixed and include: basins form by karstic dissolution of Titan’s surface water ice, lake beds are indurated and possible sites of sediment precipitates (fine-grained playa-type settings) or sediment-filled (empty) with fluids buried in fine-grained regolith, basins are ancient crateriforms or collapsed calderas, or Titan’s surface is porous with higher connectivity or permeability in filled basins.

3. Multiple steep-sided basins – most are empty. Basin floors are bright in SAR images. Bright radar reflections support the hypothesis that porous undifferentiated sediments cover the floor.
Elevations are higher than the images in picture 2, with the possible implications that depths to the water table may be greater. Other possible interpretation include
4. Ligeia Mare, endorheic basin capturing watershed flow covering more than 100,000 square kilometers.
5. High fluid levels are apparent in rivers feeding Ligeia Mare. Saturated fracture zones near base level.
6. Kraken Mare flooded valleys, wrinkle ridges in icy terrains.
7. Deep trellis and dendritic drainage channels apparent in the drowned valleys.
8. Ontario Lacus, the largest known lake in the southern region. Proposed sediment accumulations, identified as shallow deltaic lobes, were described as low velocity flows with low sediment supply (Wall et al. 2010). Clouds produced sporadic methane filled depressions.
9. Potential flowing rivers near empty or partially filled lake basins. Transient fluids documented during the southern polar summer.
10. Global map of Titan’s imaged surface. A large portion of Titan remains unphotographed at higher resolution; however, a significant portion of the north and south have sufficient detail to document the location of large reservoirs of methane.

Sustained methane loss from Titan has long been predicted. The production of Titan’s haze from volatized surface liquids suggests a particulate or solid sink in Titan’s atmosphere. This liquid-to-solid or vapor-to-solid phase change is recognized in the photochemical production of tholins in Titan’s atmosphere. The solid particulate matter eventually falls to Titan’s surface and has sufficient sediment integrity to be mobilized and self-organized into readily recognizable depositional patterns.

The total volume of liquid methane is about 1/10th of the amount estimated for these sand-size particles (Lorenz et al. 2008) sequestered from Titan’s atmosphere or photolysis processes. The loss of methane reserves from higher latitudes to the equator is supported by geomorphic interpretations of the volumes of fluids mobilized from empty lake basins in the northern polar region. During evaporation, methane may be converted to ethane or more complex hydrocarbons in photochemical reactions. Haze production and hydrogen escape result in permanent methane loss or solid methane sinks. These transformations in the upper atmosphere could lead to the present asymmetry in fluid reservoirs and to the wholesale sequestering of methane at the equator.
During evaporative seasons, the mass balance between available methane in small lakes and the atmosphere may be altered significantly. Models (Burr 2010; Lunine and Lorenz 2009; Perron et al. 2006; Stofan et al. 2007) predict rain events would be large and sporadic. The equatorial region receives methane rains, subject to ephemeral flows that quickly evaporate yielding to prevailing arid dry conditions through much of the Saturn year. The equatorial region is also the most likely area on Titan to serve as a sink for deposits of solid methane/ethane or other hydrocarbon compounds;

At 100% saturation, precipitation events can release large volumes of methane leading to surface sheet flow, mass wasting, and erosion of gullies, stream, and v-shaped valleys in areally confined regions. Lake level seasonal change is estimated at approximately 1 m yr\(^{-1}\) (Hayes et al. 2011). The close proximity and interspersed nature of numerous dry and flooded lakebeds in Titan’s northern latitudes argues for locally or regionally transient methane with the potential of modest spatial change on short term or seasonal cycles. These sporadic, spatially dependent interactions between the atmosphere and surface, between the liquid and gas phases, may be confined on a temporal scale by the short lived seasonal insolation increase and atmospheric saturation episodes.

The southern latitudes, however, also demonstrate the wholesale loss of fluids from river systems and lake basins. Figure 2.45 contains evidence of much greater volumes of fluid than now present in the southern
hemisphere on Titan.

High plateaus on the right show development of river systems into a canyon below. A river channel snakes through what appears to be dark accumulations of material (Figure 2.44) provides evidence of a river in the southern polar region, in this case an incised feature. The southern portion includes several basins and ridge systems, with possible sediment fill, surrounded by eroded terrains or regions of high relief, and channels of ancestral rivers or tributaries.

General transient movement of methane liquids appears to be confined locally, i.e. from lake to lake or lake to sea in the same region. This observation is supported by the more frequent sporadic upwelling, condensation, and precipitation of liquid methane regionally rather than globally. Although stratospheric circulation is observed globally, tropospheric circulation is primarily hemisphere-specific. On longer time scales, methane reservoirs appear to be depleted where global-scale atmospheric circulation patterns may preferentially deposit solid methane/ethane tholins at lower latitudes. This stratospheric circulation pattern has been observed by West et al. (2011).

Physiographic variables such as altitude, continentality, and orographic or lake effects are intimately linked to the landscape evolution, in spite of dramatic seasonal or higher-order insolation oscillations. Permanent sinks for volatiles on Titan, such as hydrocarbon dunes or submarine sediments, alter the areal distribution and available volume of surface fluids. These include, but are not limited to a) hemispherical differences in present verses past fluid levels, i.e. numerous empty or flooded lacustrine and marine features, or changing shorelines; b) erosion or mass wasting from past pluvial, fluvial, or ephemeral-fluid cycles that do not correlate to present weather patterns or fluid volumes; c) superimposed river systems on old systems, such as braided streams or small channels inside large channels or lakebeds, spatially distinct ancestral streams,
rivers, cross-cutting or superposition evidence such as extensive dissection of Titan’s surface of drainage systems, or a variety of other geomorphic features indicative of changes in hydrologic patterns.

Titan’s anticipated seasonal changes include: a) observable shoreline alterations in ephemeral rivers, lakes, and valleys or change in sea levels, i.e. increases or decreases primarily in methane; b) temporal change in weathering and erosion; and c) spatial change in the distribution of small filled lakes; d) loss of methane volatiles in the southern hemisphere (and potentially northern hemisphere) and probable growth of dune fields. The southern hemisphere depletion in liquid methane shows only modest evidence of methane surface reservoirs, past or present. This suggests that the dichotomy of liquid methane/ethane reserves is long standing and more closely aligned with solid hydrocarbon sinks than with wholesale climate-driven, transfer of transient fluids to the north. Titan’s surface features offer geologic evidence of change, essential in establishing baselines for spatial and temporal clarity.

4. Conclusion

Interpretations of climate cycles for this study were based primarily on erosion processes and features, fluid levels past and present, and topography. Changes in the mass distribution of methane liquids through time should be evident from geomorphic features on Titan; however, strong evidence is lacking for a hemispheric reversal in the location of surface methane reservoirs. The northern polar region appears to have a long history of surface fluids based on the extensive drainage systems, erosion features, and presence of many dry lake beds. Flooded valleys appear to be offset by regional empty basins indicating regional or modest fluid migration. The southern polar region possessed greater volumes of fluids in the past; however,
based on the lack of known large empty basins in the southern polar region, a Milankovitch climate/orbital forcing mechanism is not proposed as the primary driving force. Rather, a physiographic feature is proposed, such as a subsurface reservoir replenishing methane to the surface or an original artifact of planetary formation. A dramatic hemispheric change in fluid volumes via transient liquids from southern to northern hemisphere in recent orbital cycles lacks strong evidence.

Equatorial dunes and high latitude northern seas are the primary surface reservoirs for hydrocarbons. Present spatial distributions point to gradual loss of liquid reserves and an apparent accumulation of solids at equatorial latitudes, with only modest evidence of change from Milankovitch cycles. Lack of geomorphic evidence is insufficient to suggest that longer-period orbital dynamics are inconsequential, or that a long-standing hemispheric dichotomy in surface liquids is. Just as Earth has more ocean in the southern hemisphere than the northern, planetary formation and topography may be better at explaining the dichotomy than climate.

Although pole-to-pole migration of methane is possible, as stated by Aharonson et al. (2009) and demonstrated by observed circulation patterns, climate-driven wholesale reversals of fluid inventories cannot be inferred from the vast numbers of dry lakes in both the north and the south (Aharonson et al. 2009). Unequivocal geologic evidence points to greater numbers and volumes of southern seas in the past, greater flows into deep incised valley systems and other erosional remnants consistent with more fluids in the southern region than are present today; however, the same is true for portions of the northern polar region.

Based on surface morphologies, transient fluids are part of the seasonal, short-term cycles, accompanied with a gradual global depletion of methane. Long-period climate cycles may be sufficient, however, to reach potential thresholds or tipping points of global verses hemispherical
magnitudes. The wholesale reversal of fluids from south to north is not likely, based on the geomorphic evidence; however, the southern region appears to be more strongly depleted during the present cycle. This conclusion agrees with (Aharonson et al. 2009).

Observed patterns do indicate that seasonal cycles effectively transfer fluid from higher latitudes to equatorial regions or from one regional location to another. Fluid losses are also apparent during the southern summer season. However, future studies are needed to more accurately model Titan’s atmospheric circulation patterns and to recognize the extent and behavior of short-term mobility of methane. A complete year of observation is the minimum necessary – 29.5 Earth years. At that time, further advances will be possible.

Remote imaging of Titan’s surface has yielded evidence of seasonal change and possible climate cycles. Climate fluctuations resulting from Milankovitch or longer period cycles may be inferred from significant differences in fluid levels and erosion patterns than suggested by the present observed weather, fluids, and seasonal cycles. The erosion capacity of methane on Titan is a function of rainfall volumes (per event, annually, and longer), atmospheric pressure, substrate integrity, slope and flow velocities. Each of these components varies spatially and temporally across Titan. Using the predicted insolation variations for Titan’s orbital perturbations, geomorphic evidence suggests surface alterations have been greater in the past.

Geologic features of Titan’s north and south polar regions exhibit strong contrasts and similarities. Highly depleted methane reserves in the southern hemisphere are a limiting factor on the geomorphic evolution and erosion of this region. Drainage systems carve out vast ridge and valley systems in the northern sea region, whereas, extensive systems are absent near the southern lake basins though present in multiple southern locations. Elevation, lake effects,
continentality, and topography are key factors in the notable differences. Equatorial dunes appear to serve as a sink for transient methane condensates.

The most prominent feature of Titan’s methane distribution is the equatorial dune system. The presence of extensive hydrocarbon dunes indicate that much like glaciers on Earth or Mars serve as climate variables, these equatorial dune systems serve as a climate variable for Titan. However, the conversion of liquid methane to mixed solid hydrocarbons is a permanent and irreversible climate change mechanism. Over time, both the southern and northern polar regions have lost liquid methane reserves in this phase-change, along with extensive relocation of the reserves to the equator.

Although models for Saturn and Titan’s cyclical orbital patterns are emerging; further studies are needed to accurately quantify the saturnian system and to better estimate changes in insolation patterns. Based on the magnitude of the present dichotomy in fluid volumes, the apparent geomorphic features, and the observed volatile mobility, long-standing asymmetry is apparent. Climate driven, hemispheric asymmetry as interpreted for Titan by Aharonson et al. (2009) is likely to be partially in response to Titan’s current longitude of perihelion and eccentricity. However, fluid volumes are clearly transient and lost through time to the equatorial sink. This depletion of evaporative fluids from the southern hemisphere also suggests that any net advantage provided by seasonal and Milankovitch cycles, such as increased insolation, evaporation, precipitation, and subsequent erosion will be countered by the scarcity of methane liquids in the south. Therefore, a dichotomy between hemispheres alone cannot be interpreted as the primary evidence for climate change as inferred by this or any other research.
CONCLUSION

CHAPTER SEVEN: Ancient Surfaces and the Implication for Preserving a Record of Life

Organized, self-sustaining processes fostering life are theorized to arise from natural physical laws acting upon the available raw materials and energies of their environment. Whether living or non-living, organic matter must be sufficiently concentrated, spatially and temporally, to promote complexity and organization. A functioning system will need to effectively establish a chemical/energy gradient and a mediator or metabolism between it and the environment. Sustainability requires a method for maintaining, transferring, and replicating a sequence. As our quest continues to focus on finding and recognizing pathways to abiotic evolution, our confirmation will only be derived from finding life in ancient surfaces. Whether Earth, Mars, or Titan have relics of biogenesis is very much in question; but the presence of the necessary ingredients for life is not in question. Therefore, the discovery of actual preserved life forms in early sedimentary rock or icy surfaces is the ongoing quest of science. Probes that remotely extract rock from planetary surfaces are the first step in surveillance for extraterrestrial life artifacts; however, as stated in the introduction, if science is unable to unequivocally identify life forms in Earth’s earliest sedimentary sequences, then recognition of extraterrestrial life is highly unlikely as well.

1. Requirements for Life

“Follow the water” is an iconic NASA theme for astrobiology. Subsurface environments on Earth and Mars are only broadly similar with the potential for liquid water on Mars a few meters deep, based on spectral analyses by the Phoenix lander. On our own planet, microbial chemoliths
survive at great depths. Discovery of microbial life within the Martian subsurface would mark the first actual data set for astrobiology and spark renewed interest in discovering pathways for abiotic evolution or pangenesis. From this vantage point, planetary or extraterrestrial science may become the Rosetta Stone for Earth by deciphering life’s pathways.

1.1. Finding Life in Ancient Rocks

The presence of undisturbed laminations or microbands is frequently linked to the absence of bioturbation and thus, absence of life; however, biofilms are living organisms forming thin sediment traps at almost any temperature or salinity environment. Mud drapes, ripple and current structures are seen in BIF’s indicating that many laminations were primary and were derived from the transport and deposition of sediments. However, preservation of laminae may require cementation by microbial communities. Deep water formations remain, at least in part, enigmatic however, biological processes are known to precipitate and preserve sedimentary varves. Stromatolites or cyanobacteria incorporate sediment into their biological framework through enhanced precipitation of cements.

Precipitation by cyanobacteria or microbially induced sedimentary structures (MISS) requires a metabolic or enzyme-mediated process that extracts and speeds up the transfer of energy from the environment to an organism (photosynthesis or chemosynthesis, citric acid cycle or fermentation). Solar, geothermal or chemical energy, along with nutrients must be systematically sequestered, enabled by catalysts to facilitate growth, reproduction, and repair mechanisms required for sustainability.

The earliest known sedimentary rock sequences of Australia, Greenland, Canada and Africa demonstrate the presence of life and oxygenation in some form. Proliferation of biotic organisms
globally enhances atmospheric oxygen concentrations (pO$_2$) and is essential to sustain levels of atmospheric oxygen above 1%. The stability of O$_2$ in Earth’s atmosphere, at present-day levels, is only possible with input of an extensive biosphere.

The Carawine Dolomite of the Oakover Syncline, an outlying stratigraphic equivalent for the Wittenoom Dolomite which underlies the Dales Gorge Member, contains stromatolites. Isotope values from early studies $^{87}$Sr/$^{87}$Sr show non-marine components (Becker and Clayton 1976; Nelson et al. 1992). Oxygen fixing anaerobes from deep water sources are likely to play a dominant role in precipitating iron in a more distal environment (Anbar et al. 2007; Farquhar et al. 2007a; Goldblatt et al. 2006). Silica precipitates in the presence of iron creating a dual shuttle for both iron and silica (Fischer and Knoll 2009)

A symbiotic relationship between purple and green bacteria make use of similar pathways (Heising and Schink 1998; Heising et al. 1999; Widdel et al. 1993). The existence of iron-oxidizing anoxygenic phototrophs (Kappler et al. 2005) thus forms a tempting explanation for the existence of iron-rich bands in BIFs. In the presence of free oxygen, oxidation of Fe$^{2+}$ can also be performed by chemolithoautotrophic organisms (Kappler et al. 2005; Kerrich and Fryer 1988). This mechanism has the obvious advantage of allowing for sub-photonic zone oxidation, on par with empirical evidence via the following pathway:

$$6\text{Fe}^{2+} + 0.5\text{O}_2 + \text{CO}_2 + 16\text{H}_2\text{O} \rightarrow [\text{CH}_2\text{O}] + 6\text{Fe(OH)}_3 + 12\text{H}^+$$

Laboratory experiments with *Gallionella ferruginea*, which makes use of the above pathway, indicate rates of iron oxidation $>60$ times faster than abiotic reactions (Sogaard et al. 2000).

Photosynthetic cyanobacteria and MISS are not apparent in the Dales Gorge Member. These findings do not negate the possible link to global anoxia, but may explain the fluctuations within a continuous succession of alternating FeII and FeIII oxide sediments. Chemical interactions in
the sediment/water interface (Ewers and Morris 1981; Morris 1993; Trendall and Blockley 1970) may result in diagenic changes in valence electron configurations for FeII and FeIII. Biological mechanisms account for the precipitation of iron out of solution in a variety of environments, ranging from an anoxic photic zone to a locally oxygenated sub-photic zone. Production of oxygen at depths anticipated for BIF deposition remains enigmatic and may require a complex microbial ecosystem.

Contrary to early beliefs, the availability of iron and silica of sufficient quantity to deposit huge iron formations does not appear to be a problem for iron-rich formations. Using the extensive Hamersley Basin as a model, at only 10 ppm Fe saturation (100-400 ppm are possible, Morris and Horwitz 1983), with a 7 ppm outflow and approximately 15% of the basin water volume, the potential for large iron reservoirs is easily derived (Trendall 2002). The corresponding drop in the global-ocean dissolved iron content would only be .00002 ppm (Trendall 2002). Suspended sediments are transported in higher velocity currents and deposited in lower velocity currents.

Mechanisms for Fe$^{2+}$ oxidation include diffusion, photochemical, sedimentallogical, and biological. Numerous microorganisms use iron as a metabolic agent, thus the hypothesis that the banding in BIF may be microbial mediated is attractive. Banding in chert, with only minor iron content, is common as well. Earliest fossil evidence for life has been linked to banded-chert formations (Schopf 1993). Although Cloud’s model for a biogenic origin of BIF remains valid, linking solely abrupt steps in biochemical evolution with increasing oxygen content of the atmosphere is now not widely accepted. A recent hypothesis (Goldblatt et al. 2006) suggests that “bistability” of (Lavvas et al. 2011) oxygen levels mediated first by UV and alternately by ozone
may account for the chemical evolution of the ocean and atmosphere. Two distinct stability ranges exist, one at 21% and the other at less than 1%.

1.2 Martian Life

The question of life’s origin may be extended to our closest potentially habitable planet, Mars. Mars, the “Red Planet,” has high concentrations of iron and silicate minerals at its surface, stratified layers, and, in the past, potentially large reservoirs of water or brines. Iron mineral precipitation and weathering on the Martian surface may provide insights into the early Earth iron formations. In addition, many scientists believe that life in some form, past or present, is possible for Mars (Allen et al. 2000; Allen et al. 2004; Fallacaro and Calvin 2006; McKay et al. 1996a; Sagan et al. 1973). Lack of oxygen or a UV light filter is a great hindrance to the emergence of life on Mars, but these conditions were also problems for an early Earth. Modeling early life conditions on Earth must include overcoming extreme UV light concentrations in absence of oxygen/ozone in Earth’s atmosphere and alternating oxic and anoxic or pH conditions. Investigations of Martian surface may provide a better understanding of a prebiotic Earth.

Time-sequential layers on Mars provide possible evidence of climate change, early life, and changes in orbital mechanics – rotation, obliquity, eccentricity, and precession. The wide-range of image and spectral data indicate that water and ice were abundant on Mars in past epochs. Both water and ice have the potential to support life. Hematite blueberries on Earth are commonly mediated by bacteria.

However, recent spectrometry analyses determined that sandstones on Mars contained strong concentrations of salts (aw ≥ 0.78 – 0.86 salinity) – a fatal level for most terrestrial life (Tosca
and McLennan 2009; Tosca and Knoll 2009). On Earth, extremophiles flourish in low pH, however the combination of both low and high pH (acid and alkaline) would be a challenge for prebiotic, origin of life scenarios. Environments with extreme heterogeneity can result from microbial mediation or can allow for symbiosis of oxic and anoxic anaerobes. Sulfates and iron oxides are capable of preserving signatures of life as geochemical records in the form of chemical, structural, textural, isotoic, or microfossil remains.

The Noachian/Amazonian Martian surface geology and topography demonstrate the presence of liquid water, strong oxidation regimes, and high axial instability (obliquity) as evidenced by superposition and cross-cutting relationships of water-dependent features. Hematite is the most abundant ore of iron, and it is usually slightly magnetic. Significant quantities of hematite are found on Earth in banded iron formations and are found on the Martian surface. Layered strata found on Mars, however, may have links to microbial activity and to high iron concentrations in the early Martian oceans. Conditions on early Earth and Mars, in theory, are conducive to the presence of microbial life. On Earth, lunar tidal influence may have contributed to the formation of iron-rich banded surfaces in active tectonic basins and to the stabilization of the Earth’s orbital periodicities (Laskar et al. 1993). Orbital forcing and lack of stability could contribute to the ultimate demise of early life on Mars. On Mars, however, radically changing obliquity and the lack of a stabilizing moon have subjected surface environments to huge climate oscillations.
1.3 Titan Life

Titan’s surface provides interesting comparisons for surface and seasonal processes on exotic or extrasolar terrains and on a “snowball or prebiotic Earth.” Closed-basin temporal flows provide excellent records of changing environments. Flow channels deliver sediment from higher elevations. Lakes in closed basins and low-lying valleys provide the most promising area for the discovery of thick stratified layers in deltaic inflows, seasonal lagoons and wetlands, and deep-water fine sediment accumulations. Titan’s northern polar region exhibits the necessary topographic variability to produce a viable historical record.

Recent confirmation of hydrogen cyanide (HCN) abundance in Titan’s atmosphere (Lavvas et al. 2011; Mayo and Samuelson 2005) provides additional promise for comparative studies of early Earth and Titan atmospheres (Tian et al. 2011). HCN is an important molecule and possible precursor to a biologic world. As a source of fixed nitrogen, the early Earth surface temperatures appear to offset the faint Sun paradox (Sagan and Mullen 1972), suggesting that strong greenhouse gas concentrations must be invoked to satisfy these conditions. To reach appropriate concentrations of greenhouse gases, atmospheric conditions must be conducive for the formation of the necessary components, such as methane and ammonia. If methane and atomic nitrogen are available, photolysis of HCN is possible through the chemical reactions:

\[ CH_3 + N \rightarrow HCN + H_2 \quad \quad \quad \quad \quad 3CH_2 + N \rightarrow HCN + H \]
At the surface, hydrolysis converts HCN to ammonium – a source of ammonia. The process can result in production of methane and oxygen in the following reactions:

\[ 2 \text{HCN} + 6 \text{H}_2\text{O} \rightarrow 2 \text{CH}_4 + 2 \text{NH}_3 + 3 \text{O}_2 \]

Methane photolysis include CH₃ and ³CH₂. Titan’s nitrogen rich atmosphere produces hydrogen cyanide, HCN, a precursor to ammonia at the surface. Production of HCN is a theoretical constituent of early Earth atmosphere; however, it is a known constituent for Titan’s atmosphere. HCN is the most abundant nitrile in Titan’s atmosphere and is super-saturated to saturated at all altitudes below the tropopause. Near Titan’s surface, contributions from ethane are negligible. An atmosphere rich in ammonia has long been proposed for a prebiotic Earth (Bada and Miller 1968); however, EUV photolysis is destructive to ammonia preservation. Wolf and Toon (2010) proposed that Titan’s fractal organic rich haze may provide a model for Earth’s necessary conditions to shield ammonia from EUV photolysis (Wolf and Toon 2010a; Wolf and Toon 2010b). These findings, as well as early research into Titan’s organic haze, parallel current astrobiology research work searching for pathways in the emergence of life on Earth.

The limited availability of surface liquids on Titan and the apparent sink of hydrocarbon volumes at the equator could potentially spell doom for ongoing surface evolution of Titan. To be perpetuated, hydrocarbons must be renewable. Titan’s geology, and its ability to create a sequential sedimentary record, will suffer from stagnation and eventual death if the present trend persists without an internal source of recharge to Titan’s surface. While it’s true that the Goldilock’s conditions are present now, it’s apparent that the timing was “just right” for us (the intruders) to catch a glimpse of a living planet before it’s life blood (liquid methane) is all gone.
2. Astronomical Clocks

Geologic features and sedimentary sequences are commonly interpreted in context with transgressive-regressive sea-level cycles, glacial minimum or maximums, and Milankovitch periodicities. These features are climate driven and include enhanced seasonal fluctuations. Planetary motion is an astronomical timekeeper for the past, present, and future. For early man, astronomical motion (apparent or actual) was the only keeper of time. As technology evolved, cultural dependency on orbital periodicities waned.

Rather than appealing to an Earth analog in an attempt to understand other planetary surfaces, as noted in the introduction, the conclusion from this research is an acknowledgement that other worlds may expose past epochs for Earth. Planetary motion operates like clockwork with mathematical equations serving as the hands of time. Repeating patterns and basic laws are frequently overlooked in the quest for more complex data or for status quo (i.e., no reinterpretation). How many scientists overlooked background radiation before Penzias and Wilson were stuck with it by mistake, or Einstein miss evidence for an expanding universe? If the patterns of astronomical or radiative forcing are clearly significant on other planets, perhaps these patterns need greater attention in reconstructing Earth’s planetary surfaces.

With climate change indicated in the ancient Martian surface, with ongoing seasonal processes on Titan, and with banded-iron formations, it’s clearly evident that patterns of astronomical or orbital forcing are visible. Predictable rhythmic patterns are consistent with changes in celestial positions in orbit about the Sun, with oscillations in insolation and with the resulting changes in sedimentary processes. Like the spring rain, the summer drought, the monsoons, and the annual flooding of the Nile – seasons dominate the rock record on Earth and on any planet with axial tilt and oscillating orbital positions that produce dramatic changes in solar radiation.
The problem lies not in noting the possibility; many scientists have suggested seasonal varves as potential candidates for the formation of sedimentary layers in submarine settings. However, the comprehensive work of fitting the sequences into known patterns and chronologies that match the setting, the mineralogy, and the present-day processes have thus far been meager. Paleontologist, chronostratigraphers, and marine biologists use the growth rhythms from invertebrates to date or package time. As a caveat, essentially all marine and terrestrial life respond to and demonstrate behavior befitting astronomical rhythms. Therefore, our quest to understand and interpret these rhythms is essential. This work too is unfinished, indicative of insufficient evidence, and should not be viewed as affirmation that sedimentary sequences in banded-iron formations are primarily a result of tidal and seasonal processes.

Tidalites or rhythmites demonstrate orbital patterns in with better resolution than BIF’s. Ice cores and glacial varves, which are seasonally driven, provide another example of astronomical rhythms. Individual varves or couplets should not be interpreted without additional contextual support – many warm days and cool nights produce sedimentary laminae; however, a distinct change should be perceivable between the starved winter trickle and stronger flows at the onset of spring. While Earth, Titan, and Mars experience diurnal, semidiurnal, seasonal, and longer-period climate (Milankovitch) cycles, and other processes operate to form rock layers, erosion patterns, and geomorphic features.

Banded-iron formations are similar to many sedimentary sequences in repetition. In this context, the environment was relatively stable and long standing, based on the vast thickness of many formations. Depositional environments must include vast supplies of iron, energy oscillations, and a mechanism for changing mineralogy. Mineralogy alternations are consistent with changing directions and source of sediment, mineral alignment to achieve thermodynamic
stability, and/or changing chemistry. The most visible patterns of change in oceans are tides and currents – both produced in part or whole by orbital cycles. Weather patterns creating storms, seasonal flooding, enhanced or dampened erosion and deposition are also seasonal, but much less predictable. Their signature can be seen in thickness anomalies, in the outliers, and in the non-repetitive sequences.

Climate cycles bring strong geologic changes to planetary surfaces and in many instances, destroy rather than create or preserve rhythmic depositional patterns. The Dales Gorge drill core records 18 potential tectonic, climate, or ocean basin cycles in macrobands. The Ophthalmia Thrust Belt is indicative of major tectonic change in the region including cycles of uplift, compression, and downwarping. Mesobands, representing current patterns and seasons, correlate well with changing sediment supply, velocities, and rhythms. Microbands, resulting from mixing with daily, tidal, spring/neap or other bidirectional flow periodicities, also correspond to slow diagenesis and lateral migration of minerals. Changing water chemistry is also implied for microband precipitation and diagenesis.

The most revealing principle observed is that to some degree ancient surfaces are shaped by their orbital forcing mechanisms. Based on this research, most planets capable of preserving sedimentary records will first and foremost record changing seasons. In addition, strong control is asserted by regional geology and hydrogeology. The presence of volatile liquid reservoirs is also essential. Without these important components, effects of seasons, weather patterns, and erosion are effectively dampened. In addition to seasonal patterns, tidal signatures rank high for planetary bodies with large moons, like Earth and possibly the Saturn/Titan system. Driving repetitive, predictable geologic processes on planetary surfaces are the distinct results of the orbital dynamics of that system.
The Noachian/Amazonian Martian surface geology and topography demonstrate the potential of high axial instability (obliquity) as evidenced by superposition and cross-cutting relationships of water-dependent features. Axial tilt creates seasons capable of melting polar caps and sublimating CO₂ into the atmosphere. The presence of liquids, including sufficient liquid to produce sedimentary sequences, appears to be evidenced in numerous regions on Mars based on its geomorphology. Seasonal change drives sedimentary processes by mobilizing or depositing sediments, by changing flow directions, velocities, or mineralogy, by altering the environment, and by leaving evidence in sequential and, hopefully, definable patterns. Surface processes and conditions, long extinct on Earth or other planets, must also be extracted from past sedimentary records, both terrestrial and extraterrestrial. This research suggests that seasonal sedimentary processes are dominant on Titan and Mars, and have played a significant role in the formation of ancient surfaces capable of preserving a record of life, which includes banded-iron formations (BIF’s) on Earth.

Conditions on early Earth and Mars may have been conducive to the survival or emergence of microbial life. Titan’s organic inventory contains potential ingredients for life. Seasonal varves, depositional couplets, a chronostratigraphic record, and catastrophic flood deposits are predicted for all three surfaces. Within these records, the history of our solar system and the history of life resides. Though none will be complete, each piece makes a valuable contribution to our knowledge of our solar system’s past. Recreating past events and conditions for planetary systems, in our own solar system or any other, requires both science and supposition. Stephen J. Gould aptly described this quandary in his book, *Wonderful Life*, as a conspiracy of time, location, events, and conditions (Westall 2003). All parameters and variables must be properly understood, correctly placed in time and space, or the interpretations are suspect.
Prospects for a habitable environment on Earth were dependent on the Earth-Moon-Sun system, the presence of water, greenhouse gases, and an oxygen-rich atmosphere. Iron-rich Archean formations demonstrate that uniformitarian processes of deposition, burial, and diagenesis, linked to orbital periodicities, have not changed as dramatically as Earth’s surface or atmosphere itself has changed. The same is likely true for Mars and Titan. By using both tools – a geologic record and knowledge of the “ways of the planets” (planetary motions) – our hope is to arrive at a better understanding of the two “big” questions posed to science: 1) Where and when did life begin on Earth? and 2) Is there other life out there? The answers derived from this research are small contributions.
Acknowledgements

Contributions from the science community, from the National Aeronautics and Space Administration (NASA) and Jet Propulsion Laboratories (JPL), and from associated missions – Cassini/Huygens, MRO, Spirit and Opportunity rovers, Mars Global Survey, Pheonix, HiRISE, and others – provide researchers ready access to data and images. Remote sensing and digital imaging technology led the way for orbiters and satellites, robotic rovers, and extraterrestrial probes to detect planetary surfaces with better precision and areal coverage than ever before. The study of planetary surfaces relies not only on these high profile missions, but also on open access of data to the science community. Cooperative efforts of NASA/JPL/ASU produced a wide cadre of imaging, altimetry, RADAR, IR thermal emission spectra, to name a few which have been used in this research. Recently made available climate, ocean, and atmospheric observations from the National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), National Climatic Data Center (NCDC), and the National Archive of Ocean Data (NODC) were also extensively searched. In addition, the Smithsonian National Museum of Natural History, Rock and Ore Collection provided open access to meticulously preserved records, including nearly 400 feet of drill core from ancient Australian BIF’s. The compilation of data from these sources is combined to demonstrate distinct correlations in planetary surfaces within our solar system which have undergone weathering, erosion, and subsequent deposition of sedimentary sequences in response to orbital patterns in our solar system. Data contributed from these collections and from the multiple sources acknowledged are contained in the following
References


Archer AW, Johnson TW (1997) Modelling of cyclic tidal rhythmites (Carboniferous of Indiana and Kansas, Precambrian of Utah, USA) as a basis for reconstruction of intertidal positioning and palaeotidal regimes. Sedimentology 44: 991-1010.


Girkin AN (2005) A computational study on the evolution of the dynamics of the obliquity of the Earth.


James HL, Trendall AF (1982) Banded iron formation; distribution in time and paleoenvironmental significance; Mineral deposits and the evolution of the biosphere; report of the Dahlem Workshop on Biospheric evolution and Precambrian metallogeny. 3.


Klein C (2005) Some Precambrian banded iron-formations (BIFs) from around the world: Their age, geologic setting, mineralogy, metamorphism, geochemistry, and origin. Am Mineral 90: 1473-1499.


Trendall AF, Blockley JG (1970) The iron formations of the Precambrian Hamersley group, Western Australia; with special reference to the crocidolite. 119.


