Doctoral Thesis

**Late jurassic paleoceanography evidence from stable isotopes and carbonate sedimentology**

**Author(s):**
Padden, Maureen

**Publication Date:**
2001

**Permanent Link:**
https://doi.org/10.3929/ethz-a-004200330

**Rights / License:**
In Copyright - Non-Commercial Use Permitted

This page was generated automatically upon download from the ETH Zurich Research Collection. For more information please consult the Terms of use.
Late Jurassic Paleoceanography:
Evidence from Stable Isotopes and Carbonate Sedimentology

A dissertation submitted to the
SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZÜRICH

for the degree of
Doctor of Natural Sciences

presented by
Maureen Padden
Master of Science, University of Waterloo, Waterloo, Ontario, Canada

born January 30, 1969
citizen of Canada

accepted on the recommendation of
Prof. Dr. Helmut Weissett   examiner
Dr. Hanspeter Funk   co-examiner
Prof. Hugh Jenkyns   co-examiner

2001
For Mike and my parents

In memory of Sean
Table of Contents

Summary .......................................................................................................................................................... v
Zusammenfassung ........................................................................................................................................ vii
Acknowledgements .................................................................................................................................... ix

CHAPTER 1 Introduction ............................................................................................................................ 11
1.1 Why study ancient sediments? .............................................................................................................. 11
1.2 Late Jurassic setting and archives ......................................................................................................... 12
1.3 Summary of Research Objectives and Main Results ........................................................................... 13

CHAPTER 2 Late Jurassic lithological evolution and carbon isotope stratigraphy of the western Tethys ........................................................................................................................................ 16
Abstract ...................................................................................................................................................... 16
2.1 Introduction ........................................................................................................................................... 16
2.2 Methods ............................................................................................................................................... 18
2.3 Site Descriptions .................................................................................................................................. 19
  2.3.1 Jura Mountains ................................................................................................................................. 19
  2.3.2 Helvetic Nappes ............................................................................................................................... 21
  2.3.3 Ultrahelvetic Nappes ......................................................................................................................... 30
  2.3.4 Vocontian basin ................................................................................................................................. 33
  2.3.5 Southern Alps .................................................................................................................................. 35
2.4 Stable-Isotope Results ............................................................................................................................. 36
  2.4.1 Carbon ............................................................................................................................................ 36
  2.4.2 Oxygen .......................................................................................................................................... 37
2.5 Discussion .............................................................................................................................................. 37
  2.5.1 Diagenesis ...................................................................................................................................... 37
  2.5.2 Carbon Isotope Stratigraphy ........................................................................................................... 39
2.6 Conclusions .......................................................................................................................................... 40
References ..................................................................................................................................................... 41

CHAPTER 3 Evidence for Late Jurassic release of methane from gas hydrate ......................................... 46
Abstract ....................................................................................................................................................... 46
Introduction .................................................................................................................................................. 46
Geologic Setting .......................................................................................................................................... 47
Methods ....................................................................................................................................................... 48
Carbon Isotope Results ............................................................................................................................... 49
Discussion .................................................................................................................................................... 50
References Cited .......................................................................................................................................... 54
Summary

Stable isotopic records were produced from 12 Upper Jurassic carbonate sections deposited in the Tethys and Atlantic Oceans in depositional environments ranging from restricted/lagoonal to open ocean. The high-resolution carbonate δ¹³C curve can be separated into three main phases: a negative excursion in the middle Oxfordian, positive values throughout the Late Oxfordian and Kimmeridgian with the most positive δ¹³C values occurring in the Late Kimmeridgian and a gradual decline throughout the Tithonian towards the Jurassic - Cretaceous boundary.

The positive δ¹³C excursion discussed in Chapter 2 occurs in the Kimmeridgian and is likely related to higher organic carbon burial rates. Calculating the percentage of Late Jurassic source rocks deposited at any given time produces a strong correlation with the δ¹³C record; the most productive times occur in the Oxfordian and Kimmeridgian. The relatively muted amplitude of the δ¹³C record to such a significant amount of organic carbon burial is likely due to the ‘buffering’ effect of carbonate production. High sea levels and extensive carbonate producing shelves may have acted as an isotopic balance of organic burial, reducing the expected isotopic excursion.

The Oxfordian δ¹³C negative excursion is examined in detail in Chapter 3. This rapid, widespread excursion is likely due to a massive release of methane hydrate. The opening of a gateway between the ancient Tethys and Pacific Oceans may have triggered such a release. Warm, saline Tethyan water would immediately sink upon entering the Pacific, warming the continental margins of the Americas. Higher temperatures would have destabilized trapped methane and the addition of isotopically light (~ - 60‰) methane into the ocean/atmosphere carbon pool would account for the rapid 3‰ shift recorded in both marine carbonates and marine organic matter.

Chapter 4 examines the potential effect that depositional environment has upon δ¹³C records. A transect along a carbonate ramp from inner platform to purely pelagic
environments revealed that inner platform samples are isotopically depleted by as much as 3 \% compared to samples deposited beyond the shelf break. This offset may be related to a lateral evolution of seawater, whereby lighter carbon isotopes become concentrated in the low energy proximal regions due to remineralization of organic matter, rapid calcification and/or freshwater input. The implication of these results is that all records basinward of the shelf break mirror changes in open ocean $\delta^{13}$C.

Chapter 5 explores the oxygen-isotope stratigraphy of selected sections and the connection with sea level and temperature changes in the Tethyan and neighbouring regions. A comparison of carbonate $\delta^{18}$O ($\delta^{18}$O$_{\text{carb}}$) records from the unrecrystallized calcite of well-preserved belemnite fossils and bulk carbonate at Auenstein suggests that belemnite habitat was significantly deeper than previously thought and that temperature reconstructions based on belemnite $\delta^{18}$O may need to be reexamined.

Bulk carbonate $\delta^{18}$O records from the Tethys/Atlantic display anomalously positive $\delta^{18}$O values, which produce anomalously low paleotemperatures according to a calcite equilibrium equation. Because faunal distributions clearly indicate warm tropical temperatures and diagenesis would tend to cause a shift of $\delta^{18}$O values in the negative direction, the anomalous data cannot be explained by either anomalously low equatorial temperatures or by burial diagenesis. The most likely cause of the enriched $\delta^{18}$O$_{\text{carb}}$ values is intense evaporation at low latitudes creating a higher latitudinal $\delta^{18}$O gradient in Late Jurassic oceans. A possible implication of these findings is the formation of warm, saline intermediate or deep water during the Late Jurassic.
Zusammenfassung

In Spät-Jurassischen Karbonatserien aus lagunär bis offen marinen Milieus der Tethys und des Atlantiks wurden zwölf stabile Isotopen-Profile gemessen. Die hochauflösende Karbonat-$\delta^{13}C$-Kurve weist drei Hauptabschnitte auf: eine negative Exkursion im mittleren Oxford, positive Werte während des Späten Oxford und Kimmeridge mit den positivsten $\delta^{13}C$-Werten im Späten Kimmeridge, gefolgt von einem graduellen Abfall gegen die Jura - Kreide Grenze während des Tithons.

Die positive $\delta^{13}C$-Exkursion im Kimmeridge ist wahrscheinlich auf erhöhte Vergrabungsraten des organischen Kohlenstoffs zurückzuführen. Die Berechnung der prozentualen Anteile Spätjurassischer Muttergesteine bezüglich der Zeit ergibt eine gute Korrelation mit der $\delta^{13}C$-Kurve. Die produktivste Zeit ist während des Oxfords und Kimmeridges. Die geringe Amplitude der $\delta^{13}C$-Kurve ist wahrscheinlich auf den "Pufferungseffekt" der Karbonatsedimentation zurückzuführen. Hohe Meeresspiegel und ausgedehnte karbonatproduzierende Schelfe könnten die erhöhte Sedimentation an organischem Kohlenstoff bezüglich der Kohlenstoffisotopen kompensiert und daher die erwartete $\delta^{13}C$-Exkursion vermindert haben.


Kapitel 4 untersucht den potentiellen Einfluss, den das Ablagerungsmilieu einer
Probe auf deren isotopische Zusammensetzung ausübt. Ein Transekt, der sich vom inneren Plattform- bis zum rein pelagischen Bereich erstreckt, deckte auf, dass die δ¹³C-Werte von Proben aus dem inneren Plattformbereich um bis zu 3 % c abgereichert sind im Vergleich zu Proben, die ausserhalb der Schelfkante abgelagert wurden. Dieser Unterschied dürfte auf eine laterale Entwicklung des Meerwassers zurückzuführen sein, wobei durch die Remineralisierung von organischem Material, durch schnelle Kalzifizierung und/oder durch Süßwasserzufuhr die leichten Kohlenstoffisotope in niedrigenergetischen, proximalen Regionen angereichert werden. Die Folgerung aus diesen Resultaten ist, dass alle Profile ausserhalb der Schelfkante Aenderungen im δ¹³C des offenen Ozeans widerspiegeln.


δ¹⁸O-Analysen an Gesammtgesteins-Proben aus Tethys und Atlantik ergeben aussergewöhnlich hohe Werte, die, in eine Kalzitequilibrierungs-Gleichung eingesetzt, unerwartet tiefe Palaeotemperaturen ergeben. Weil die fossile Faunenverteilung jedoch eindeutig auf warme tropische Temperaturen hinweist und diagenetische Vorgänge die Isotopen-Werte in negativer Richtung verschieben würden, können die hohen δ¹⁸O-Werte weder durch aussergewöhnlich tiefe aequatoriale Temperaturen noch mit Vergrabungsdiaogenese erklärt werden. Die wahrscheinlichste Ursache für die hohen δ¹⁸O_{carb}-Werte ist intensive Evaporation in tiefen Breiten, die einen stärkeren δ¹⁸O-Gradient der Jurassischen Meere bewirkte. Eine mögliche Folge dieser Befunde ist die Bildung warmer, saliner Intermediär- oder Tiefenwässer während des Spätjuras.
Acknowledgements

I would like to thank Prof. Helmut Weissert and Dr. Hanspeter Funk who initiated this project and provided guidance at every stage of this thesis. I’m grateful to have had the opportunity to work with the SPOC group at the ETH. I would also like to thank the external co-examiner of this thesis, Prof. Hugh Jenkyns from Oxford University, for the time and effort spent correcting this work and for his detailed review of Chapter 3 during publication.

Special thanks to Prof. Judy McKenzie whose enthusiastic approach to science sets the tone for the entire Earth System Science group at the ETH and who made many helpful suggestions during the course of this thesis. Discussions with Lukas Wissler, Dr. Stefano Bernasconi, Hilary Paul and Dr. Uli Wortman greatly improved and clarified the interpretations presented here.

I was lucky to have had the help of the following people who cheerfully collected samples in all sorts of weather: Mike Fox, Dr. Hans Mohr, Prof. Helmi Weissert, Lukas Wissler and Dr. Uli Wortman. Claude Colombie from the University of Fribourg kindly shared her samples with me. Core sediment from three DSDP legs was provided by the Ocean Drilling Program. Dr. Hanspeter Luterbacher from Tübingen University generously provided washed foraminiferal samples from DSDP Legs 11 and 27.

I’d like to thank Dr. Stefano Bernasconi for generously sharing his laboratory expertise and for keeping cool throughout every lab crisis. Thanks to Hilary Paul for helping with the $\delta^{13}C_{org}$ and C/N measurements. I’m grateful to Daniela Schmidt for identifying and photographing the forams used in this study and to Jorijntje Henderiks for taking the SEM photos. Moritz Lehmann and Adrian Gilli were a big help to me in the coulomat lab. I thank Geoffrey Ruiz for teaching me how to use the cathode luminescence microscope and Urs Gerber for explaining how best to photograph thin sections under CL and for taking care of the processing. The tricky AAS measurements were made with the help of Andri Stefansson and Dr. Bruce Mountain.
Thanks to everyone at the Geological Institute who made me feel welcome, showed me the ropes when I first arrived and generally made living in Zürich fun, especially Andreas, Bill, Daniela, Diana, Giulio, Jane, Jorjntje, Mario and Paolo. Andreas and Giulio kept the office lively for several years and were always ready to take time for a story, a laugh or a coffee. Many thanks to the Valkyries rugby club of Zurich for keeping my off hours in the past few months entertaining in spite of the occasional bruises.

I’m very grateful to Lukas Wissler who translated the summary of this thesis, saving me hours of work, and whose sense of humour and enthusiasm helped me over some of the rough spots of this project. Special thanks go to Hilary Paul who was always ready to listen to the ups and downs of work and life; but mostly I’d like to thank Hilary for laughing with me (and often at me) every day for four years. It’s been fun - thanks.

I thank my parents for their continual encouragement and support. And to Mike, the most patient man in the world, my thanks for putting up with a complicated, trans-Atlantic life and for never doubting that good things would come of it all.
Chapter 1
Introduction

1.1 Why study ancient sediments?

As modern atmospheric CO₂ levels continue to rise, there is an increasing urgency to understand how the global carbon cycle and climate will react to changing atmospheric conditions. One way of testing both conceptual and numerical forecasts is to apply the same reasoning backward in the geological record and compare model results with environmental reconstructions based on geological observations. Of particular interest are those times in the geologic past in which atmospheric CO₂ levels were elevated and the globe supported little or no glaciation. If the geologic record can be read as the result from a natural, global climate experiment, these 'greenhouse' climates form the warm endmember of a climatic spectrum.

Past perturbations in the carbon cycle can be traced by analysing the stable-isotope composition of ancient marine deposits of calcium carbonate and organic matter. Because carbon atoms experience isotopic fractionation as they pass through the global carbon cycle, any changes in the size of a given reservoir are recorded in the large dissolved carbon pool of the ocean. These changes in the isotopic composition of the dissolved oceanic carbon pool are then passed on to carbonate minerals and organic matter formed in ocean water. Potential carbon cycle perturbations include volcanic injections of CO₂ into the atmosphere, methane input into the ocean/atmosphere from buried gas hydrates and changes in the rate of carbon burial in the sediments, in the form of carbonate and organic matter and changes in weathering flux.

Sudden releases of methane due to dissociation of buried gas hydrates have been postulated for the Paleocene (Dickens et al. 1995; Dickens et al. 1997; Bains et al. 1999), the Aptian (Jahren and Arens 1998) and the Toarcian (Hesselbo et al. 2000). The climatic implications of a large release of methane into the ocean/atmosphere system are intriguing because both methane and its oxidation product CO₂ are very effective greenhouse gases. The very depleted δ¹³C signature of methane (~ -60 ‰) ensures that a large methane release event will appear as a significant negative δ¹³C excursion and will therefore be readily identifiable in the geologic record.

Increases in the burial of isotopically light organic carbon (~ -22 ‰) tends to cause a
positive shift in the residual reservoirs if all other variables remain constant. For this reason, the isotopic composition of marine carbonates ($\delta^{13}C_{\text{carb}}$) has been used as a proxy for global organic carbon ($C_{\text{org}}$) burial rates (e.g. Arthur et al. 1985 and many others). The association of widespread anoxia with positive isotopic excursions has generally confirmed this approach. However, recent high resolution studies (e.g. Weissert and Mohr 1996; Menegatti et al. 1998) have suggested that the relationship between positive $\delta^{13}C$ values and high global $C_{\text{org}}$ burial rates may not be as straightforward as previously thought.

1.2 Late Jurassic setting and archives

The Late Jurassic is an interesting time in which to examine the dynamics of the global carbon cycle because previous investigations suggest that while substantial deposits of organic matter were deposited during this time, the isotopic response was relatively muted (Scholle and Arthur 1980; Jenkyns 1996; Weissert and Mohr 1996; Bartolini et al. 1999). The balance between organic and inorganic carbon 'sinks' is examined in Chapter 2.

Sedimentary sequences were chosen from a Late Jurassic carbonate ramp deposited along the northern Tethyan margin. These sedimentary archives are preserved in the Jura Mountains and Helvetic alpine nappes of Switzerland and in the Vocontian Basin of southwestern France. Other northern Tethyan carbonate shelf archives sampled for comparison with the carbonate ramp transect include two sections from western Portugal and a section from southern Germany. Southern Tethyan margin deposits from a submarine high are found in a Southern Alpine section of northern Italy. Previous efforts to correlate these deposits were complicated by the scarcity of index fossils in the Helvetic sections (Kugler 1987). Carbon-isotope data have been used in the present study to fine-tune the traditional stratigraphy of this region, providing a reliable means of correlation between the various depositional environments. The resulting high-resolution composite $\delta^{13}C$ curve provides a chronological framework in which to examine the lithological development of this region as well as providing valuable insight into the Late Jurassic global carbon cycle.
1.3 Summary of Research Objectives and Main Results

One of the main research objectives of this study was to apply high-resolution sampling to Late Jurassic pelagic carbonate strata in order to obtain a precise record of \( \delta^{13}C \) changes which could then be used for stratigraphical purposes. Chapter 2 provides a summary of the lithology of the studied region as well as the highest resolution \( \delta^{13}C \) data available for the Late Jurassic. A high sampling resolution was especially important for this time interval because of the mostly low-amplitude fluctuations.

The high-resolution sampling strategy was also instrumental in revealing a previously unknown, relatively short-lived negative isotope excursion in the Oxfordian. This excursion is discussed in detail in Chapter 3 and was likely caused by a release of methane from buried gas hydrate. The proposed mechanism for this release involves the opening of a gateway from the Tethys to the Pacific. Export and sinking of the Tethyan water into the Pacific may have destabilized frozen gas hydrates buried within continental margin sediments on the west coast of the Americas.

Another research objective was to investigate the role played by depositional environment and discern whether or not carbonate transport compromises \( \delta^{13}C \) records of periplatform sediments compared to sediments deposited exclusively in pelagic settings. This question is addressed in Chapter 4. Although carbonate records from very restricted paleoenvironments appear to record local, rather than open ocean conditions, all sedimentary units which were deposited oceanward of the carbonate platform display \( \delta^{13}C \) values which follow the same trends as those from the open ocean settings.

The final objective of this study, which is discussed in Chapter 5, was to determine whether Late Jurassic oxygen isotope (\( \delta^{18}O \)) records revealed any information about climate changes or paleoceanographic conditions. The oxygen-isotope signal of carbonates is much more sensitive to post-burial conditions and much less likely than \( \delta^{13}C \) to retain its original value. However, some information was gleaned from bulk carbonate \( \delta^{18}O \) data by constraining the most likely
direction of diagenetic alteration. The anomalously high δ¹⁸O values (and therefore low calculated paleotemperatures) are not likely to be due to either cool tropical temperatures in the Late Jurassic or by burial diagenesis. The high δ¹⁸O values are most likely caused by intense evaporation at low latitudes and a larger latitudinal δ¹⁸O gradient in Late Jurassic oceans compared to modern conditions.


Jenkyns, H.C., 1996, Relative sea-level change and carbon isotopes; data from the Upper Jurassic (Oxfordian) of central and southern Europe: Terra Nova, v. 8, p. 75-85.


CHAPTER 2

Late Jurassic lithological evolution and carbon isotope stratigraphy of the western Tethys

Prepared for publication in Eclogae Geologicae Helvetiae by M. Padden, H. Weissert, H. Funk, C. Kugler, S. Schneider and C. Gansner

ABSTRACT

Carbon isotope analysis was used as a stratigraphic tool in Late Jurassic carbonate successions from the western Tethys Ocean. Portions of the northern Tethyan margin are preserved in the Helvetic nappes of the Swiss Alps. The two Late Jurassic formations present in the Helvetic nappes, the Schilt and Quinten Formations, are poorly dated biostratigraphically. To improve this chronostratigraphy, carbon isotopes from the Schilt and Quinten Formations are compared to similar records from well-dated sections in the Jura Mountains, the Southern Alps and the Vocontian Basin. This comparison produces greatly improved age control for the Helvetic sections and a more detailed composite $\Delta^{13}C$ curve for the Late Jurassic than has been published previously. The composite $\Delta^{13}C$ curve features two short-lived negative excursions in the Oxfordian, a $\Delta^{13}C$ maximum in the Late Kimmeridgian and steadily decreasing $\Delta^{13}C$ values throughout the Tithonian. These $\Delta^{13}C$ events are consistent with previous, lower resolution data sets and are valuable tie-points which can be used for correlating Late Jurassic carbonaceous sediments among different lithologies and across different depositional settings.

2.1 INTRODUCTION

Carbon isotope records of marine carbonate and organic matter can be used both as a
Chapter 2

Lithology and $\delta^{13}$C

Figure 1

Map a) shows the location of sites discussed in text. Map b) is a paleogeographic reconstruction (redrawn from Ziegler 1988) of the western Tethys Ocean. Dark grey areas are deep-marine settings, light grey areas are shallow-marine settings and white represents exposed land surfaces during the Late Jurassic. In b) indicates the Iberian Peninsula and F; indicates France. The two black lines are an indication of modern coasts of northern Spain and northwestern France. Figure c) presents lithological units discussed in text in a chronostratigraphic framework.
stratigraphic and a paleoenvironmental tool (e.g. Arthur et al. 1985; Weisser 1989 and many others). In the present study, δ13C records are used primarily as a stratigraphic tool to correlate poorly dated lithological units with sections dated biostratigraphically. The extensive Late Jurassic carbonate rocks present in the Helvetic nappes of the Swiss Alps have been dated with a limited amount of biostratigraphic information (e.g. Rod 1937; Kugler 1987). In order to improve these age models, the present study compared stable isotope records of several Helvetic nappe sections with biostratigraphically and, in some cases, magnetostratigraphically dated sections from the Jura Mountains of northern Switzerland, the Southern Alps of northern Italy and the Vocontian Basin of southeastern France.

2.2 METHODS

Samples were taken at intervals ranging from less than 10 cm to tens of meters and with a range of resolutions from approximately 1 k.y. to 2 M.y. Fine-grained micrite samples were drilled with a diamond-tipped drill to produce a fine powder. This powder was reacted with phosphoric acid at 90 °C and the resulting CO2 analyzed with a VG PRISM mass spectrometer following the standard procedure of Sharma and Clayton (1965). All isotope results are reported relative to the standard Vienna PeeDee Belemnite and measurement precision based on standards is better than ±0.2 ‰. Relative abundances of total and inorganic carbon were measured on a UIC CM5012 Coulomat and expressed as % carbon. Organic-carbon abundance was calculated from the difference of these two measurements. Precision for carbonate carbon measurements is ±0.1 % for standards and ±0.9 % on natural samples, and organic carbon measurements have a precision of ±0.1 % measured on standards and ±0.3% measured on natural samples. The precision of the calculated organic-carbon content is ±0.14 based on standards and ±0.95 based on samples. For organic carbon isotope analyses, samples were decarbonated with 37% HCl overnight. Organic carbon isotopes and carbon and nitrogen abundance were measured on a Carlo
Erba elemental analyzer coupled in continuous flow to a VG Optima mass spectrometer. The standard NBS 22 was used for organic isotopic analyses with a reproducibility of ± 0.3‰. The elemental standard Atropina was used for carbon and nitrogen measurements with a reproducibility of ± 1.8% for carbon and ± 0.06% for nitrogen.

2.3 SITE DESCRIPTIONS

The area of study is located in Switzerland in France and in Italy. One section is presently located in the Jura mountains of northern Switzerland, five sections are found in the Helvetic nappes of the Swiss Alps, another outcrops in the Ultrahelvetic nappes of western Switzerland and two southern Alpine sections are located in northern Italy (figure 1). The Jurassic sediments from the Jura Mountains and from the helvetic nappes were deposited along the northern margin of the alpine Tethys. They form a north-south transect from an inner platform to a basinal environment in the Alpine Tethys. For comparison, two sections deposited along the southern Tethyan margin as well as a section from the Vocontian Basin in southeastern France are also considered. Samples were collected from sections where previous sedimentologic and chronostratigraphic work had been done (e.g. Rod 1937; Guillaume 1957; Gygi and Persoz 1987; Kugler 1987; Weissert and Channell 1989; Mohr 1992; Schneider 1998; de Rafelis 2000; Gansner 2000).

2.3.1 Jura Mountains

The Jura mountains form a crescent-shaped fold belt in northern Switzerland. The Auenstein section is found in a quarry in the eastern Jura fold belt, near the town of Wildegg and is the type section of the Wildegg Formation as defined by Gygi (1969). The Wildegg Formation originally consisted of three members (Gygi 1969) but was later redefined to include only two members, the Birmenstorf Member and the Effingen Member (Gygi and Persoz 1987). The sediments at Auenstein were deposited in an inner ramp environment along the northern Tethyan continental margin (figure 1; Gygi 1969; Gygi 2000a). The
Birnenstorf Member is approximately 6 m thick at Auenstein. The base is formed by a marine hardground containing up to 2% glauconite, 5% sand as well as iron ooids (Kugler 1987). Overlying marls and fine-bedded micritic limestones become less glauconitic and

Figure 2
sandy (–0.5% each) towards the Effingen Member boundary (Kugler 1987). Birkenstorf limestone beds range between 10 and 50 cm in thickness.

A rich macrofauna is preserved in the Birkenstorf Member including sponges (10-20%), ammonites, belemnites, echinoderms (crinoids and echnoids) and brachiopods (terebratulids and rhyynchonellids) (Kugler 1987). Carbonate content in the Birkenstorf Member ranges from 60 to 97% and organic carbon (C$_{org}$) is less than 1% (figure 2).

The Effingen member consists of 210 m of interbedded marls and limestone beds; the limestone beds in the lowermost 20 m are laterally discontinuous at this site (figure 2; Kugler 1987). Most limestone beds are 10 to 20 cm thick with some beds reaching thicknesses of 70 cm. Fossil-rich horizons in the lower Effingen Member contain ammonites, sponges, belemnites, brachiopods and echinoderms (Kugler 1987). The macrofauna present in the lowermost 30 m is extremely sparse in the upper Effingen Member. The Late Jurassic carbonate sequences outcropping in the Jura Mountains of northern Switzerland have been studied extensively and this paper cannot do justice to the entire literature. Gygi (2000a) provides a useful summary of the Late Jurassic chronostratigraphic framework of this region. Ammonite chronology (Gygi and Persoz 1987; Gygi 2000b) produces a robust correlation of the Birkenstorf and Effingen members of the Wildegg Formation throughout northeastern Switzerland. The time scale of Gradstein and Ogg (1996) is used to assign radiometric ages to ammonite zones and magnetostratigraphic zones. Isotopic samples were collected from limestone beds in the lowermost 60 m of the Effingen Member.

2.3.2 Helvetic Nappes

Schilt Formation

Nissibach and Ortstock are located in the Gonzen Nappe and the Axen Nappe respectively which belong, tectonically, to the Helvetic nappe unit of the Swiss Alps (Kugler 1987). The Schilt Formation (Middle to Late Oxfordian), outcropping at Nissibach and Ortstock, represents a time-equivalent to the Wildegg Formation. A detailed examination of
the sedimentary and faunal characteristics of the Schilt formation and comparison to the Wildegg Formation is described in Kugler (1987). The Schilt Formation represents an outer ramp paleoenvironment along the northern Tethyan continental margin (figure 1). Based on the descriptions of Kugler (1987), we divide the Schilt Formation into four members: Seeztal Mb., Schilt Limestone Mb., Schilt Marl Mb. and Mürtschen Mb.

Figure 3
Stratigraphy of the Schilt Formation at Nissibach. For lithological legend, see Figure 2.
The Seeztal Member is 3 m thick at Nissibach and 15 m thick at Ortstock and is composed of silty-sandy shales with carbonate content <35% and detrital quartz abundance between 20 and 40% (Kugler 1987). Organic-carbon content is < 1% throughout the entire Schilt Fm. Bioturbation is present in the Seeztal Member and phosphate nodules are frequently associated with ammonites (Kugler 1987). Quartz abundance decreases towards the contact with the Schilt Limestone Member (Kugler 1987). At Nissibach and Ortstock, the upper part of the Seeztal Member becomes increasingly calcareous and contains chamositic Fe
oooids and echinoderm spines.

The Schilt Limestone member is 8 m thick at Nissibach and 10 m thick at Ortstock. This micritic, bioturbated and locally nodular limestone succession contains minor amounts of dolomite and is virtually free of detrital material (Kugler 1987). Non-dolomitzed limestone is dark grey, micritic, and weathers to a light grey colour. The Schilt Limestone member contains a rich, though poorly preserved cephalopod fauna which can form calcareous nodules in a marly matrix (Kugler 1987). Echinoderm remains are also present in this member.

The Schilt Marl member is extensive at both Nissibach and Ortstock (27 and 55 m respectively) and features dark grey marls with carbonate content between 35 and 75% as well as isolated beds of dark, micritic limestone (figures 3 and 4). This member contains few fossils and no coarse detrital material (Kugler 1987). Small calcareous nodules in a marly matrix can be seen in the basal layers of the Schilt Marl member at Nissibach and in the uppermost Schilt Marl at Ortstock (Kugler 1987).

The Mürtschen Member consists of well-bedded, grey limestones interbedded with marls and is 42 m thick at Nissibach and 8 m thick at Ortstock. Bedding is irregular and individual beds are between 15 and 35 cm thick. Fossils and detrital matter are both absent in the limestone beds. Small, dark, calcareous nodules are present in both the limestone and marl beds. There is a gradual transition to the overlying Quinten Formation as the limestone beds become more frequent and interbedded marls become thinner. Kugler (1987) defined the contact between the Mürtschen Member and the Quinten Formation to be where the marly interbeds of the Mürtschen Member are reduced to less than 2 cm thickness.

Several nodular limestone beds occur in the studied sections. In the Schilt limestone and Mürtschen members, nodules are often associated with ammonite molds or are irregular in shape. Nodules range in size from 0.5 mm - 2 cm and are randomly oriented and unsorted in a micritic to microsparitic and slightly marly matrix. The nodules are composed of tightly packed, uniform micrite which is usually about 2 mm in size. There is no sparite
present in the nodules and nodules with diffuse and clear boundaries may occur in the same sample. The boundary is often much easier to see macroscopically than microscopically.

The Seeztal, Schilt Limestone and Schilt Marl members are dated with ammonite stratigraphy (Kugler 1987). The Seeztal Mb. spans the Lamberti zone of the late Callovian to the Densiplicatum zone of the middle Oxfordian (Kugler 1987). The Schilt Limestone Mb. and Schilt Marl Mb. cover the Transversarium zone and perhaps part of the Bifurcatus zone; however the boundary between the Schilt Marl and the Mürtschen Mb. is poorly dated due to lack of fossils (Kugler 1987). The Mürtschen Mb. itself is fossil-poor throughout and therefore difficult to date with biostratigraphic methods (Kugler 1987). A minimum age is provided by the presence of Bimammatum in the overlying Quinten Formation (Kugler 1987).

---

**Figure 5**

*Stratigraphy of the Quinten Formation at Gemmi. For lithological legend, see Figure 2.*
Quinten Formation

Previous sedimentological observations and isotopic analysis of the Quinten Formation are reported from other sites in the Helvetic nappes at Guppen-Heuberg (Mohr 1992; Funk et al. 1993; Weissert and Mohr 1996), Melchsee (Schneider 1998) and Gemmi Montsalvens (575.500 / 161.750; Kanton Fribourg, Switzerland).

Figure 6
Stratigraphy of the Late Jurassic succession at Montsalvens. For lithological legend, see Figure 2.
The lowermost 160 m of the Quinten Formation crop out at Melchsee and the entire formation can be observed at Guppen-Heuberg (415 m) and Gemmi (210 m). The Quinten Formation is divided by most authors into the Lower Quinten Limestone (LQL), the Marlstone member (MM), Upper Quinten Limestone (UQL) and the Troskalk member (e.g. Rod 1937; Mohr 1992). The lowermost Quinten Limestone is a series of regularly-bedded (20-50 cm), dark grey, micritic limestones with low (<1%) organic content. Bedding becomes indistinct towards the contact to the Marlstone Member at Gemmi and Guppen (Mohr 1992; Gansner 2000). Carbonate content ranges from 93-100 % and nodular limestones are present in the LQL at Guppen (Mohr 1992). There is significant dolomitization associated with these nodules (Mohr 1992) whereas dolomite appears in the UQL at Gemmi (Gansner 2000) and is completely absent in the Quinten Formation at Melchsee. Horizons with abundant belemnite and ammonite remains occur in the LQL at Melchsee (Schneider 1998). At Guppen-Heuberg, dolomitized or silicified belemnites, ammonites, bivalves and echinoderm fragments also occur along isolated horizons (Mohr 1992). The LQL at Gemmi appears to be relatively fossil-poor (Gansner 2000).

The lower Quinten formation at Melchsee contains nodular limestone classified by Schneider (1998) into two different types according to colour. The first type which occurs just above the Schilt Formation displays predominantly ammonitic nodules which are usually about 0.5 to 2 cm in diameter although some reach sizes of 7 cm (Schneider 1998). These round to oval nodules are filled with light-coloured micrite. There is usually a sharp boundary between the nodule and the matrix although there are some examples of diffuse boundaries. Once again, the boundary between nodule and matrix is difficult to distinguish under the light microscope (Schneider 1998). This type of nodular limestone grades into the next type containing less well-rounded, dark grey nodules which do not appear to be predominantly associated with ammonite molds (Schneider 1998).

The Marlstone Member of the Quinten Formation contains marl at Guppen-Heuberg (Mohr 1992; Weissert and Mohr 1996) but no marls at either Gemmi or Melchsee (Schneider...
1998; Gansner 2000). At Guppen-Heuberg, this member consists of fossil-poor, thin-bedded (10-20 cm) dark grey micritic limestones interbedded with 2cm thick dark grey marls (Mohr 1992). At Gemmi, the MM contains 10% bioclasts including belemnites, bivalves, echinoderms ammonites and *Saccocoma* and 2% silt-sized quartz (Gansner 2000). Chert nodules and minor amounts of dolomite and pyrite are also present (Gansner 2000). A thin-bedded (5-10 cm), fossil-poor unit forms the MM at Melchsee (Schneider 1998).

Dolomitized nodules reappear in the Upper Quinten Limestone member at Guppen (Mohr 1992). They are especially common along fossil-rich horizons At Gemmi, nodular
intervals often take the form of 'pseudobreccia' (Gansner 2000) which consists of dark nodules in a light grey matrix. The UQL is only partially preserved at Melchsee and consists of thin (3-10 cm) micritic beds. Bed-parallel chert bands are also present in the UQL at Guppen and continue throughout the uppermost Troskalk member (Mohr 1992).
The Troskalk member, present at Gemmi and Guppen, is a thick-bedded (~1m) unit rich in platform-derived fossil remains (Mohr 1992; Funk et al. 1993; Gansner 2000). Faunal elements represent up to 19% of the limestone and include echinoderms, bivalves, benthic foraminifera, gastropods, bryozoa, brachiopods and serpulids (Mohr 1992; Gansner 2000). Fist-sized coral fragments were also found at Guppen (Mohr 1992; Funk et al. 1993).

Ammonites representing the *Bimammatum zone* are found in the LQL (Kugler 1987). The MM, also dated by ammonite stratigraphy, occurs in the *Pseudomutabilis zone* of the Late Kimmeridgian (Rod 1937). The age control for the Late Tithonian UQL is provided by calpionellids (Mohr 1992).

### 2.3.3 Ultrahelvetica Nappes

The Montsalvens section is located in the Ultrahelvetica nappes of western Switzerland (figure 1). The carbonate sequence outcropping at the Montsalvens gorge along the Jogne river was studied in great detail by Guillaume (1957) and divided into four lithological units: Calcaire concrétionné, Calcaire schisteux, Calcaire en grumeaux and Calcaire lité.

Calcaire concrétionné refers to a series of alternating 5-10cm nodular marls and 15-20 cm thick micritic limestones. At the Montsalvens site 7 m of Calcaire concrétionné is exposed. Nodules are dark grey, calcareous and are commonly associated with ammonites (Guillaume 1957). Carbonate content of the limestones ranges from 80 to 100% (figure 6). Organic carbon constitutes less than 1% throughout the Montsalvens section.

The abrupt disappearance of interbedded marls signals the contact to the Calcaire schisteux, an 18 m series of regularly-bedded dark grey micritic limestones (Guillaume 1957). Bedding ranges from 10-40 cm and siliceous nodules are locally isolated and can occur as narrow (<10cm) bands. Carbonate content ranges between 65-94% and preserved fossils are rare.

A switch to wavy bedding marks the transition to the Calcaire en grumeaux (Guillaume
1957). The name is related to the French word for curdled and refers to the occasionally mottled appearance of these limestones due to calcareous and siliceous nodules forming irregular ovoids in a micritic matrix. The limestones contain 80-96% CaCO₃ with less chert than the Calcaire schisteux. Bedding is generally 5-15cm thick although some beds
Chapter 32: Lithology and δ13C

Reach thicknesses of 40-50 cm. An 8 m series of very finely bedded (<10 cm) micritic limestones forms the base of the Calcaire lith. Bedding thickness in the upper part of the Calcaire lith averages 10 cm. These regularly bedded limestones contain 87-94% CaCO3.

Figure 10
Summary of correlation of Kimmeridgian-Tithonian δ13C records. Dashed line represents δ13C correlations. Solid line based on magnetostratigraphic measurements and Calpionellids found at Xausa and Valle del Mis.
with no discernible chert. Belemnite and ammonite aptychi remains are rare although some ammonites are found at the base of the Calcaire lité (Guillaume 1957).

At Montsalvens, there are nodular episodes in the Calcaire concrétionné and in the Calcaire en grumeaux (Guillaume 1957). The main difference between the two members is the presence of marl in the Calcaire concrétionné. The calcareous nodules tend to be dark grey, irregular ovoids and, in the Calcaire concrétionné, are commonly associated with ammonite molds (Guillaume 1957).

Based on ammonite associations and lithological comparisons to the Quinten Formation, Guillaume (1957) provided the following age estimates for the limestone succession at Montsalvens. The Calcaire concrétionné was estimated to be of middle Oxfordian age, the Calcaire schisteux and Calcaire en grumeaux of late Oxfordian to early Kimmeridgian age and the Calcaire lité of Kimmeridgian to early Tithonian age.

2.3.4 Vocontian basin

A 150 m section of the upper Terres Noires outcrops near the town of Vergons in southeastern France (figure 7). Sequence stratigraphic work at this site incorporated lithology, trace-element (Mn, Sr) analyses, palynological data and isotopic analysis (de Rafelis 2000; Jan du Chene et al. 2000). For the present study, the Vergons section was resampled at a higher resolution and sampling was extended down the section. Both isotopic records are shown in figure 7. In the lower part of the section, dark grey marly limestones, 10-40 cm thick, are interbedded with dark grey marls reaching thicknesses of 150 cm. Limestones become more frequent and the marly intervals thinner upwards in the section (figure 7). Carbonate content of the upper portion ranges between 66 and 97%. Organic carbon was measured on five samples; it is less than 0.25%. Preserved fauna include belemnites and ammonites (Jan du Chene et al. 2000; pers. obs.). Grainstones with well-rounded bioclasts and slump deposits are common above the sampled section where marl beds disappear completely (Jan du Chene et al. 2000).
The Vergons section is dated by ammonites, dinoflagellates and sequence stratigraphy (Jan du Chene et al. 2000). The Transversarium/Bifurcatus transition is present in the upper part of the section; however, the lower Transversarium/Densiplicatum transition was not found at this site. We assume, therefore, that the lower part of the section lies
within the *Transversarium* zone.

### 2.3.5 Southern Alps

Isotopic data from two southern Alpine sections, Valle del Mis located in the Belluno Basin, and Xausa located on the Trento Plateau, are reported in Weissert and Channell (1989). The 60 m Tithonian/Berriasian section at Valle del Mis was first described by Casati and Tomai (1969) and Weissert (1979) and contains the transition from the Rosso Ammonitico Superiore (RAS) to the Maiolica Formation. At this location, the RAS is a red-gray nodular marly limestone. Chert occurs as reddish-brown nodules and bands. The overlying Maiolica Formation consists of white to grey thin-bedded (5-40 cm) limestones interbedded with dark marls (Weissert 1979). Evidence of sporadic redeposition includes sorting of pelagic bivalves, current lamination and, rarely, carbonate turbidites (Weissert and Channell 1989).

The same formations are also present at Xausa. The 15m exposure of the RAS displays a reddish nodular limestone with marly interbedding (Weissert and Channell 1989). Towards the contact with the Maiolica Formation, there is a gradual decrease in nodularity and a colour shift from red to alternating pink and white limestone beds (Weissert and Channell 1989). The 50m Maiolica Formation at this site is similar to that of Valle del Mis.

![Figure 12](image-url)

*Figure 12*  
Crossplots of $\delta^{13}C$ vs $\delta^{18}O$ data. The most negative $\delta^{18}O$ values occur at Nissibach and Ortstock, pointing to significant burial and recrystallization in the Helvetic nappes.
although evidence of resedimentation is lacking. Faunal elements present in the limestone beds of the Maiolica Formation include coccoliths, calpionellids, calcispheres, radiolarians and ammonite aptychi (Weissert 1979). Isotopic data from the Xausa section, presented in Weissert and Channell (1989), has been augmented for the present study (figure 8). The RAS was sampled at a higher resolution and the record extended to a lower stratigraphic level (figure 8).

A combination of magnetostratigraphy and nannofossil analysis constrains the age of the section at Xausa and Valle del Mis (Channell et al. 1987; Channell and Grandesso 1987; Weissert and Channell 1989). The Tithonian is represented by magnetic anomalies M19 through M22 and the Calpionella alpina zone (figure 8). A summary of the correlation of magnetostratigraphy and nannofossil zones with ammonite zones is given in Gradstein and Ogg (1996; figure 1).

2.4 STABLE-ISOTOPE RESULTS

2.4.1 Carbon

The presented bulk carbonate $\delta^{13}C$ data fluctuate between 0.3 and 3.3‰ (figures 9-11). There is a negative excursion, of 2 to 6‰ in magnitude, which is dated as Transversarium age at Auenstein (Gygi and Persoz 1987) and Vergons (de Rafelis 2000; figure 9). A second, more subdued (< 1‰ in magnitude) negative excursion is dated at Auenstein to occur in the Bifurcatus zone (Gygi and Persoz 1987). The composite carbon isotope curve then rises steadily and reaches a maximum of about 3‰ in the Late Kimmeridgian (figure 10), dated at Guppen and Melchsee according to Rod (1937). There is a steady decrease in $\delta^{13}C$ values throughout the Tithonian, an interval dated at Xausa and Valle del Mis (Weissert and Channell 1989). The carbonate $\delta^{13}C$ record reaches values of approximately 1.5‰ at the Jurassic/Cretaceous boundary.

Organic carbon $\delta^{13}C$ ($\delta^{13}C_{org}$) data measured at Ortstock and Vergons range from -26.5 to -21.5‰ (figure 9). A negative $\delta^{13}C_{org}$ excursion, of 2 to 3‰ in magnitude, coincides
with the *Transversarium* excursion in the carbonate records at both sites.

### 2.4.2 Oxygen

The oxygen isotope data presented here range between -7.2 and 0.7 ‰. In addition to a much higher range of values, the oxygen isotope data display very poor agreement between sections. The most negative δ¹⁸O values occur at Nissibach and Ortstock, intermediate values occur at Gemmi, Guppen and Melchsee and the most enriched δ¹⁸O values in the sections at Auenstein, Montsalvens, Xausa and Vergons. The marly sediments at Nissibach, Ortstock and in the lowermost Vergons section also display relatively depleted δ¹⁸O values. There is no consistent stratigraphic trend in the δ¹⁸O data among the sections.

### 2.5 DISCUSSION

#### 2.5.1 Diagenesis

Many studies have demonstrated the value of carbon isotopes as a stratigraphic tool in carbonate successions (e.g. Scholle and Arthur 1980; Weissert and Lini 1991; Jenkyns et al. 1994; Jenkyns 1996; Ferreri et al. 1997; Menegatti et al. 1998 and many others). In alpine settings, carbon isotopes are much less susceptible than oxygen isotopes to resetting during recrystallization at high burial temperatures (e.g. Matter et al. 1975). A comparison of the Late Jurassic δ¹³C records shows an excellent correlation across depositional environments and lithologies (figures 2-8; figure 11). The good correlation between nodular and non-nodular sediments in the carbon isotope record (figure 11) indicates that the effect of nodule formation appears to have had little or no impact on the isotope record. In a similar way, dolomitization does not appear to have adversely affected the carbon isotope records since the dolomitized and non-dolomitized sections correlate very well (figure 11). The generally good agreement between the presented data and previous records by Jenkyns (1996) and especially the δ¹³C record from a series of cherty limestones by Bartolini
et al. (1999) confirms the robustness of the presented carbon-isotope signal among different lithologies.

Oxygen isotopes, on the other hand, are subject to re-equilibration with interstitial water at high burial temperatures and tend to become more depleted than the original value (e.g. Früh-Green et al. 1990). The robustness of the δ¹³C signal in the studied sections is supported by the overlapping curves of the 7 different sections which have been subject to different degrees of metamorphism and whose δ¹⁸O curves show an expected negative offset with increasing burial temperature (figure 12). The very low organic carbon content of the samples also reduces the likelihood of post depositional exchange of carbon atoms (figures 2-8). The application of carbon isotope stratigraphy in condensed sediments is justified by the preservation of the Oxfordian negative excursion in the series of condensed beds at Auenstein.

The oxygen-isotope values of cherty limestones also show a tendency towards negative values. More detailed study is called for, but a speculative explanation of this phenomenon is exchange of oxygen atoms between SiO₂, CaCO₃ and a fluid phase during chert nodule formation. This effect can be seen in the Montsalvens data where anomalously negative δ¹⁸O values occur in chert-rich intervals (figure 6). The δ¹⁸O values from the cherty limestones of the Appenines (Bartolini et al. 1999), are also relatively negative although the depth of tectonic burial is equal to or less extreme than at Montsalvens or in the Helvetic nappes. The potential effect of marly sedimentation on δ¹⁸O values is best illustrated in the Vergons section. The lower part of the section is very marly and shows the most depleted δ¹⁸O values. Depleted δ¹⁸O carb at Nissibach and Ortstock may be due to the marly lithology as well as recrystallization during burial. Therefore oxygen isotopes may be compromised in cherty carbonates and marls even when carbon-isotope signals appear to be preserved.
2.5.2 Carbon Isotope Stratigraphy

Carbon-isotope stratigraphy is an excellent tool to fine-tune platform-basin correlations because many studies have shown that original carbon-isotope values are preserved even after tectonic burial (Früh-Green et al. 1990; Kuhn 1996; Menegatti et al. 1998) and peri-platform sediments have the same isotopic compositions as concomitant pelagic sediments (e.g. Wissler et al. 1999; chapter 4). In the present data set, the distinct $\delta^{13}C$ fluctuations are subtle, which allows for a detailed correlation among the sections sampled at a high resolution (figure 11) and a more speculative correlation of lower-resolution data.

The Transversarium negative $\delta^{13}C$ excursion is present in four sections: Auenstein, Nissibach, Ortstock and Vergons. This isotopic signature is securely dated in the Birmenstorf Mb. at Auenstein and at Vergons and corroborates the chronological scheme proposed by Kugler (1987) for the Schilt Marl Mb. of the Schilt Fm. at Ortstock and Nissibach. Negative $\delta^{13}C$ shifts of similar magnitude have also been reported for Transversarium-aged limestones in the western Jura Mountains (Bill et al. 1995) and in mid-Oxfordian sediments in the Gulf of Mexico (Humphrey et al. 1986). This corroboration supports the contention that carbon isotopes produce a global signal.

The Bifurcatus negative excursion is present in the Effinger Mb. at Auenstein, in Schilt Marl Mb. at Ortock, in the Mürtschen Mb. at Nissibach, and in the Calcaire en grumeaux at Montsalvens. This excursion is well-dated only in the Effinger Mb. at Auenstein, but the time-frame is consistent with chronologies proposed for the Helvetic sections (Kugler 1989) and Montsalvens (Guillaume 1957) based on biostratigraphy. The positive Late Oxfordian $\delta^{13}C$ values which occur between the two negative excursions have also been reported from sediments in northern Italy and southern France by Jenkyns (1996) and in the Southern Alps by Bartolini et al. (1999). The $\delta^{13}C$ maximum in the late Kimmeridgian (Pseudomutabilis zone) is well-dated in the MM of the Quinten Fm. at Guppen (Weissett and Mohr 1996), Gemmi and Melchsee (Rod 1937) and can be correlated to the Calcaire...
lité at Montsalvens (figure 11). A positive δ¹³C excursion in the Late Kimmeridgian has also been found in the north Atlantic by Scholle and Arthur (1986) and in the Southern Alps by Bartolini et al. (1999). No biostratigraphic control is available between the negative δ¹³C excursion in the Bifurcatus zone and the late Kimmeridgian δ¹³C maximum in the Pseudomutabilis zone, therefore a constant sedimentation rate must be assumed between these two control points.

The Tithonian trend towards more depleted δ¹³C values is dated by magneto- and biostratigraphy at Xausa and Valle del Mis (Weissert and Channell 1989) and can be correlated with a similar trend at Montsalvens providing age control for the Montsalvens section during the Tithonian (figure 11). The trend toward more depleted δ¹³C throughout the Tithonian has also been documented by Letolle et al. (1978), Scholle and Arthur (1980) and Weissert and Channell (1989).

The overall agreement between the Late Jurassic carbon isotope stratigraphy described in this study and that of previous authors confirms that δ¹³C stratigraphy is a valuable stratigraphic tool with potential for resolving relatively fine-scaled stratigraphic problems. However, high resolution sampling is needed when correlating a carbon isotope record as subtle as that of the Late Jurassic.

2.6 CONCLUSIONS

The presented carbon isotope stratigraphy improves the chronological control of the carbonate successions of the Helvetic nappes. The comparison of carbon isotope stratigraphy from the Helvetic nappes with well-dated sections in the Jura Mountains, the Southern Alps and the Vocontian Basin revealed several key ‘tie-points’ in the Late Jurassic δ¹³C curve which can be used for stratigraphic correlation. A negative excursion in the Oxfordian Transversarium ammonite zone is well-dated at both Auenstein, in the Jura Mountains, and at Vergons, in the Vocontian Basin. A second negative δ¹³C excursion, in the Bifurcatus ammonite zone, is dated at the Auenstein section. The positive δ¹³C values in Late Oxfordian,
which are bracketed by these negative excursions, have also been reported in other global sections (Scholle and Arthur 1980; Jenkyns 1996; Bartolini et al. 1999). A Late Kimmeridgian positive $\delta^{13}$C excursion is dated in the Helvetic nappe sections (Weissert and Mohr 1996; this study) and provides time control for the Montsalvens section in the Ultrahelvetic nappes. The final distinctive feature of the Late Jurassic $\delta^{13}$C curve is the relatively smooth shift to depleted values towards the Jurassic/Cretaceous boundary which is well-dated in the Southern Alpine sections (Weissert and Channel 1989) and is used to constrain the upper portion of the Montsalvens section.

REFERENCES


Channell, J.E.T., and Grandesso, P., 1987, A revised correlation of Mesozoic polarity
chrons and calpionellid zones: Earth and Planetary Science Letters, v. 85, p. 222-
240.

de Rafelis, M., 2000, Apport de l’étude de la spéciation du manganese dans les carbonates
pélagiques à la comprehension du controlé des séquences eustatiques de 3ème ordre

Ferreri, V., Weissert, H., D’Argenio, and Buonocunto, P., 1997, Carbon-isotope stratigraphy:
A tool for basin to carbonate platform correlation: Terra Nova, v. 9, p. 57-61.

Früh-Green, G.L., Weissert, H. and Bernoulli, D., 1990, A multiple fluid history recorded
in Alpine ophiolites: Journal of the Geological Society of London, v. 147, p. 959-
970.

Gansner, 2000, Geologische Untersuchungen im Gebiet Gemmipass - Lämmeralp - Kummen,

platform along the northern Tethyan margin, eastern Helvetic Alps, in Simo, J.A.T.,
Scott, R.W., and Masse, J.P., eds., Cretaceous carbonate platform: AAPG Memoir:
Tulsa, OK, United States, American Association of Petroleum Geologists, p. 387-
407.


Guillaume, H., 1957, Géologie du Montsalvens (Préalpes fribourgeoises) [unpublished

und des süddeutschen Grenzgebietes: Beiträge Geologische Karte der Schweiz 139.

Gygi, R.A., 2000a, Integrated Stratigraphy of the Oxfordian and Kimmeridgian (Late Jurassic)
in northern Switzerland and adjacent southern Germany: Memoirs of the Swiss

Gygi, R.A., 2000b, Zone boundaries and subzones of the Transversarium Ammonite Zone
(Oxfordian, Late Jurassic) in the reference section of the zone, northern Switzerland:
Advances in Jurassic research 2000; proceedings of the Fifth international symposium
on the Jurassic system, in Hall Russell, L., and Smith Paul, L., eds.: GeoResearch
Forum: Zurich, Switzerland, Trans Tech Publications, p. 77-84.

in correlation of the Oxfordian (Late Jurassic) formations of the Swiss Jura range:

Humphrey, J.D., Ransom, K.L., and Matthews, R.K., 1986, Early meteoric diagenetic control
of upper Smackover production, Oaks Field, Louisiana: American Association of

Jan du Chene, R., Atrops, F., Emmanuel, L., de Rafelis, M., and Renard, M., 2000, Palynology
and sequence stratigraphy in the Tethyan Upper Oxfordian - Lower Kimmeridgian,
S-E France: Bulletin du Centre de Recherches Exploration Production Elf -
Aquitaine, v. 22.

Jenkyns, H.C., 1996, Relative sea-level change and carbon isotopes; data from the Upper
Jurassic (Oxfordian) of central and southern Europe: Terra Nova, v. 8, p. 75-85.

of the English Chalk and Italian Scaglia and its paleoclimatic significance: Geological

Kugler, C., 1987, Die Wildegg-Formation im Ostjura und die Schilt-Formation im östlichen
Helvetikum: ein Vergleich [unpublished Ph.D. thesis]: Universität Zürich, Zürich,
Switzerland, 209 p.

Kuhn, O., 1996, Der Einfluss von Verwitterung auf die Paläozeonographie zu Beginn des
Kreide-Treibhausklimas (Valanginian und Hautrivial) in der West-Tethys

Letolle, R., Renard, M., Bourbon, M., Filly, A., Benson, W.E., Sheridan, R.E., Pastouret,
L., Enos, P., Freeman, T., Murdmaa, I.O., Gradstein, F., Schmidt, R.R., Weaver,


CHAPTER 3
Evidence for Late Jurassic release of methane from gas hydrate

Accepted for publication in *Geology* by
M. Padden, H. Weissert, M. de Rafelis

**Keywords:** Late Jurassic, gas hydrate, carbon cycle, paleoclimate

**ABSTRACT**

Four Late Jurassic carbonate successions deposited in the Tethys-Atlantic Ocean record a negative carbon isotope excursion of at least 2‰. The excursion is present in both organic and carbonate carbon records and is comparable in magnitude and duration to isotopic changes during the late Paleocene thermal maximum. Our results indicate that during the Late Jurassic, long considered a warm greenhouse time, additional greenhouse gas was input to the atmosphere by a sudden release of methane from buried gas hydrate. A potential triggering mechanism may have been the opening of an oceanic gateway through the early Atlantic between the ancient Tethys and Pacific Oceans.

**INTRODUCTION**

The presence of methane hydrates along continental margins and in permafrost regions has spurred new research into the possible climatological effects of this as yet poorly defined carbon reservoir (Kvenvolden, 1988). Massive, rapid release of CH₄ (δ¹³C ≈ -60‰) has been invoked to explain a negative δ¹³C excursion in Paleocene foraminiferal, bulk marine carbonate (Bains et al., 1999; Dickens et al., 1995, 1997), soil carbonate and tooth apatite isotope records (Koch et al., 1992), an Aptian bulk-carbonate δ¹³C (δ¹³C_carb) excursion (Jahren and Ahrens, 1998; Jenkyns and Wilson, 1999), and a Toarcian excursion recorded in bulk carbonate, marine organic matter and terrestrial organic matter (Hesselbo et al., 2000). All of these isotopic excursions were accompanied by widespread climatic warming. The distinctive δ¹³C "signature" of methane release opens up the possibility of recognizing other methane-release events through
geologic history as suggested by Dickens et al. (1995). Here, we present evidence of methane release during the Late Jurassic, a time of major climate reorganization, related to changes in ocean circulation patterns (Weissert and Mohr, 1996).

**GEOLOGIC SETTING**

In the Oxfordian Stage of the Late Jurassic, the supercontinent of Pangea was bisected into a northern continent (Laurasia) and a southern continent (Gondwana) by the equatorial Tethys Ocean (Fig. 1). The westernmost arm of the Tethys was the newly opened Atlantic corridor through what is now the Caribbean. The proto-Pacific Ocean, known as Panthalassa, covered the rest of the globe.

We present bulk-carbonate and bulk-organic δ¹³C (δ¹³Corg) records from the northern continental margin of the Tethys. Three of these sections formed along a carbonate-ramp transect and are found in Switzerland today (Fig. 1). The hemipelagic Vergons section is located in southeastern France. The Auenstein section, from an inner carbonate ramp, is currently located in the Swiss Jura Mountains and features a series of marine hardgrounds followed by a thick series of alternating marl and thin micritic limestone beds (Fig. 2). Chronologic control is provided by ammonite stratigraphy (Gygi and Persoz, 1987). The other two sections, Nissibach and Ortstock, are located in the Helvetic nappes of eastern Switzerland and feature outcrops of the hemipelagic Oxfordian Schilt Formation deposited in an outer-ramp environment (Kugler, 1987). It consists of a lowermost sandy limestone member, which is succeeded by an extensive marly interval with isolated micritic limestone beds. The marly intervals become thinner and less frequent higher in the section, and the uppermost Schilt Formation features thin-bedded micritic limestones with relatively few marl stringers. The scarcity and poor preservation of index fossils at this site make biostratigraphic dating tentative. The Vergons section comprises a thick series of marls and marly limestones ("Terres Noires") containing < 1% organic carbon and dated primarily with ammonite assemblages, dinoflagellates, and sequence stratigraphy (Jan du Chêne et al., in press).
Figure 1. Location of Oxfordian sections discussed in text and geologic time scale of Middle and Late Jurassic (Gradstein and Ogg, 1996) with Oxfordian Stage highlighted. A: Reconstruction of Late Jurassic paleogeography (Smith et al., 1994) with location of published Oxfordian record discussed in text: L-Louisiana, USA (Humphrey et al., 1986). B: Close-up of northern Tethyan paleogeography (Ziegler, 1988) with position of sampled carbonate ramp transect. Sites: A-Auenstein, Switzerland, N-Nissibach, Switzerland, O-Ortstock, Switzerland, V-Vergons, France. Dark gray shading indicates deep-marine setting, light gray represents shallow-marine setting, and white indicates land masses. Paleolatitudes are approximate. C: Modern map indicates site locations at present day. D: Interpreted paleodepths and position along carbonate ramp of studied sections.

METHODS

Bulk-carbonate samples were powdered with a diamond-tipped drill and then reacted with phosphoric acid at 90 °C; the resulting CO₂ was analyzed with a VG PRISM mass spectrometer. Bulk-organic samples were decarbonated overnight in 37% HCl and δ¹³C орг and carbon and nitrogen abundance were analyzed on a Carlo Erba elemental analyzer coupled in continuous flow to a VG Optima mass spectrometer. All isotope results are reported in per mil (‰) deviation from the standard Vienna Peedee belemnite (VPDB). Measurement precision based on the laboratory-standard Carrara Marble is ±0.1‰ for carbonate analyses. The standard NBS 22 was used for organic analyses with reproducibility of ±0.3‰. Carbonate content was measured on a UIC CM5012 Coulomat.
CARBON ISOTOPE RESULTS

The best-dated section is located in the Swiss Jura Mountains (Auenstein, Fig. 2) where age is constrained by extensive ammonite assemblages (Gygi and Persoz, 1987). At this site, a negative $\delta^{13}C_{\text{carb}}$ excursion from $3\%e$ to $1\%e$ occurs within the Transversarium ammonite zone. The $\delta^{13}C$ excursion coincides with an episode of reduced carbonate sedimentation in which several marine hardgrounds mark times of platform-growth crisis. A less precisely dated Oxfordian negative excursion is also found in the more continuous alpine sections of Nissibach and Ortstock. The most negative $\delta^{13}C_{\text{carb}}$ values at these sites are $0.6\%e$. Bulk organic $\delta^{13}C$ values in the Ortstock profile display an excursion from $-22.5\%e$ to $-26\%e$ with C/N ratios less than 10, which suggests a predominantly marine origin of the organic matter. During the same stratigraphic interval in the Vergons section, $\delta^{13}C_{\text{carb}}$ values shift from $2\%e$ to about $-2\%e$; there is a single measurement of $-4.5\%e$. Vergons $\delta^{13}C_{\text{org}}$ shifts from $-23$ to $-26\%e$ and recovers to $-24\%e$. These data indicate that both organic and inorganic marine carbon reservoirs were affected by the isotopic shift.

On the basis of previous chronostratigraphic investigations (Gygi and Persoz, 1987; Jan du Chêne et al., in press), the negative excursions in the four studied sections (Fig. 2) occur within the same million-year interval. The synchronicity of both carbonate and organic excursions at Ortstock and Vergons and the well-established global nature of $\delta^{13}C$ excursions in the pelagic realm support the assumption that the $\delta^{13}C$ excursion is synchronous in all sections. Low resolution carbon-isotope data from the oil-bearing upper Smackover Formation in Louisiana features a similar shift in the middle Oxfordian from about $2.5\%e$ to $0.5\%e$ (Humphrey et al., 1986) that further supports the interpreted global nature of this negative excursion. In order to calculate a maximum duration of the Transversarium zone negative excursion, the ammonite-dated section at Vergons is chosen as a starting point (Fig. 1). If we assume that the Transversarium zone represents about 1 m.y. and that the entire zone has been sampled at Vergons, the negative isotopic excursion lasted on the order of 180 k.y. This is a conservative estimate because no
index fossils from the lower ammonite zone were found at Vergons (Jan du Chene, in press). Thus, it is unlikely that the entire million years of the *Transversarium* zone was sampled at Vergons, and the negative excursion probably represents less than 180 k.y. As a starting point for discussion, the Oxfordian carbonate excursion is taken to be 2‰ as recorded in three out of four sections. The shift of δ¹³C<sub>org</sub> is 3 to 4‰.

**DISCUSSION**

Although diagenesis may sometimes explain a negative excursion and indeed meteoric diagenesis was initially invoked to explain the Smackover δ¹³C<sub>carb</sub> results (Humphrey et al., 1986), the persistence of the δ¹³C excursion in both marine carbonate and organic matter provides evidence that diagenesis cannot account for the observed signatures. Another possible explanation is that, following a period of deep water anoxia, rapid oceanic turnover repartitioned
12C-enriched water from the deep ocean to surface waters and the atmosphere. However, there is no evidence for extensive anoxia in the Oxfordian Tethys-Atlantic Ocean.

Widespread organic oxidation may also cause an isotopically negative response in the oceanic carbon pool; however, it is unlikely to occur over such a short time scale (Dickens et al., 1995). A global-scale decline in oceanic productivity and/or preservation of organic matter (Kump and Arthur, 1999) seems equally unlikely to have occurred and recovered over such a short time span. A volcanic source of isotopically light CO2 is not a plausible explanation because there is no evidence for extensive Late Jurassic volcanic activity (e.g. Rampino and Stothers, 1988).

The widespread and short-lived nature of the Transversarium negative excursion can best be interpreted as a sudden addition of isotopically light carbon to the global carbon cycle. Increasing atmospheric CO2 levels in the Oxfordian are supported by higher-plant biomarker changes indicating a coeval expansion of conifer forests (van Aarssen et al., 2000). The Oxfordian negative excursion has a similar magnitude and duration as Paleocene (Fig. 3), Aptian, and Toarcian
events, which have been explained by a release of frozen methane hydrate along continental margins. The Paleocene-Eocene boundary is marked by a negative $\delta^{13}$C$_{\text{carb}}$ shift of $\sim$1.5‰ in foraminifera and 2‰ to 3‰ in bulk-carbonate records (Dickens et al., 1995; Bralower et al., 1997; Bains et al., 1999) (Fig. 3) and lasted between 180 to 200 k.y. (Katz et al., 1999; Norris and Röhl, 1999). Aptian bulk $\delta^{13}$C$_{\text{carb}}$ data display a negative shift of $\sim$1.5‰ in northern Tethyan sediments (Erba et al., 1998; Menegatti et al., 1998) and $\sim$-2.5‰ over $\sim$20 k.y. in the Pacific (Jenkyns and Wilson, 1999). The Toarcian negative excursion also varies in size and is recorded in marine carbonate (2‰ to 5‰ negative shift) and marine and terrestrial organic matter (4‰ to 7‰ shift) over a period of $\sim$80 k.y. (Hesselbo et al., 2000). Massive release of methane from dissociation of hydrate is the most reasonable explanation for all four global negative $\delta^{13}$C excursions.

There are several differences between the Oxfordian and other records. Extensive carbonate dissolution during the Paleocene and Toarcian negative $\delta^{13}$C excursions has been explained as a consequence of oxidation of released CH$_4$ (Katz et al., 1999; Hesselbo et al., 2000). There is no decrease in carbonate content across the negative $\delta^{13}$C excursion at any of the Late Jurassic sites studied, although the negative excursion occurs in a very condensed interval at Auenstein (Fig. 2) and Oxfordian pelagic deposits tend, in general, to be siliceous. Positive $\delta^{13}$C values within the Oxfordian negative excursion may be due to partial recovery of the carbon cycle after input of discrete methane pulses. The slower recovery of $\delta^{13}$C$_{\text{org}}$ after the negative excursion compared to $\delta^{13}$C$_{\text{carb}}$ may be related to pCO$_2$-dependent fractionation effects.

Marine seismicity, slumping, and instability of continental margins are ongoing processes that may cause methane hydrate release into the atmosphere. Late Jurassic tectonic activity may be directly responsible for destabilizing slopes during rifting. The westward migration of North America during the Oxfordian (Lancelot et al., 1972) may have contributed to sediment failure and subsequent CH$_4$ release; however, ocean-circulation changes likely played an important role.
During the Paleocene (Bains et al., 1999; Dickens, 2000) and the Toarcian (Hesselbo et al., 2000), ocean circulation changes may have caused warming of intermediate or deep water masses, which, in turn, warmed and destabilized gas hydrates trapped within the sediment. Sediment failure would release methane gas produced from dissociation of gas hydrate into the ocean/atmosphere system where it would oxidize to produce $^{12}$C-rich CO$_2$ (Katz et al., 1999). Atmospheric CO$_2$ from the Ontong Java large igneous province has been proposed as a source of middle Cretaceous warmth (Opdyke et al., 1999).

Methane hydrate destabilization in the Oxfordian may have been caused by oceanographic circulation changes following the first significant Tethyan-Atlantic connection with the Pacific. Biogeographic provinces indicate that sporadic interbasin exchange may have occurred as early as the Bajocian (Hallam, 1975; Westermann et al., 1992). Callovian and Oxfordian marine sediments were deposited over newly formed ocean basalt (Lancelot et al., 1972) and marginal salt deposits (Prather, 1992), signaling rising sea level and increasingly oceanic conditions in the corridor between North America and Gondwana. Late Callovian to Oxfordian sedimentary deposits call for at least temporary bottom currents and deep-water ventilation (Gradstein et al., 1983).

The opening of an oceanic gateway between the equatorial Tethys-Atlantic and Pacific Oceans in the Callovian-Oxfordian would have changed ocean circulation patterns. For example, there is evidence that the closing of the Panamanian Isthmus in the late Pliocene and early Miocene increased equatorial upwelling in the eastern Pacific (Ibaraki, 1997). We assume, therefore, that extensive upwelling occurred along the equatorial eastern Pacific before the final separation of the northern and southern halves of Pangea in the Oxfordian. Significant interbasin exchange between the Atlantic and Pacific would produce a westward flow of warm and saline Atlantic water, driven by equatorial easterly winds. Atlantic water most likely sank as it encountered the cooler, less saline Pacific Ocean just as the modern Mediterranean sinks to form intermediate water upon entering the Atlantic.
The descent of warm Tethyan water along the western margins of the Americas may have destabilized gas hydrates buried in the sediments along the western continental margins of the Americas. In analogy to the Dickens et al. (1995) model, resulting faulting and slumping would release large amounts of isotopically light methane into the water column and ultimately into the atmosphere; the effect would be a global shift of marine carbon-isotope signatures to more negative values. Bottom-water temperatures in the ice-free Jurassic ocean were likely warmer than present. Gas hydrate would thus tend to form deeper in the sediments, and its stability window would be narrower (Dickens et al., 1995). However, methane trapped below the hydrate level would also be released upon slope failure (Haq, 1998). We propose that the $2\%$ shift in Oxfordian $\delta^{13}C_{\text{carb}}$ values and the $3\%$ shift in marine $\delta^{13}C_{\text{org}}$ may have been due to rapid release of isotopically light methane into the global carbon pool.

ACKNOWLEDGEMENTS

We thank J. McKenzie, H. Paul and L. Wissler for comments on an earlier draft. Careful reviews by H. Jenkyns and G. Dickens greatly improved the manuscript. Field assistance by M. Fox, L. Wissler, and H. Mohr and technical assistance by H. Paul are gratefully acknowledged.

REFERENCES CITED


Paleocene: Simulating first-order effects of massive dissociation of oceanic methane 


Erba, E., Bartolini, A., Channell, J.E.T., Claps, M., Jones, C., Opdyke, B., Premoli Silva, I., 


Kump, L.R., and Arthur, M.A., 1999, Interpreting carbon-isotope excursions: carbonates and


Westermann, G.E.G., and International Geological Correlation Programme Project 171
Circumpacific Jurassic, 1992, The Jurassic of the circum Pacific: Cambridge, U.K.,
Cambridge University Press, 676 p.
CHAPTER 4

The Effect of Depositional Setting on Late Jurassic $\delta^{13}$C Records

Prepared for publication in *Journal of Sedimentary Research* by
M. Padden, H. Weissert, S. Schneider, C. Gansner, C. Colombié

ABSTRACT

A comparison of $\delta^{13}$C values of bulk carbonate from two transects in the Late Jurassic northern Tethyan Ocean reveals systematic differences between inner platform samples and samples from all other depositional environments. Inner platform carbonate is on average 3‰ more depleted than carbonate deposited beyond the platform break. A lateral evolution of seawater, linked to organic mineralization and rapid carbonate precipitation is the most likely cause of this isotopic offset. The results justify using reconstructions of the $\delta^{13}$C history of seawater from bulk carbonate records, even for geologic periods when there was an absence of widespread pelagic sedimentation. Samples in the presented data set containing platform-derived material have the same isotopic composition as purely pelagic limestones as long as the sampled sections were located basinward of the carbonate platform break.

4.1 INTRODUCTION

Carbon-isotope stratigraphy is a powerful stratigraphic tool used extensively for Phanerozoic sediments and provides information about past changes in oceanic primary productivity, carbonate platform growth and glacial cycles. Biogenic carbonate with known 'vital effects', i.e. biologically controlled fractionation factors (e.g. Wolf et al. 1999; Dongho and Carpenter 2001), and well-constrained habitats, are the most reliable isotopic archive. In older records, where extant fossils cannot be found, or for samples where fossils are scarce or hard to identify and separate, bulk carbonate is commonly analyzed. Cenozoic bulk carbonate $\delta^{13}$C records from calcareous
nannofossils reproduce all major shifts seen in foraminiferal records (Shackleton et al. 1993). Carbonate-producing nannofossils first evolved in the Triassic (Bown 1996) and conquered the open ocean in the latest Late Jurassic according to Roth (1986). Thus, although there are indications that nannofossils occurred in rock-forming quantities as early as the Triassic (Bown 1996), many Phanerozoic δ¹³C records stem from carbonate deposited on or near carbonate platforms located along continental margins, epicontinental seaways or on seamounts located above the relatively shallow CCD (e.g. Bartolini et al. 1999; Grossman et al. 1993 and many others). Recent investigations have documented a significant degree of seawater isotopic evolution along a transect on the modern Bahamian platform (Patterson and Walter 1994). These results demonstrate the need to test whether bulk micritic carbonate records from the Phanerozoic do indeed represent carbon isotope values from the oceanic carbon pool and how significant a role is played by the depositional environment. A depth-related δ¹³C gradient would severely limit reconstructions of δ¹³C changes from sediments deposited before the Late Jurassic. On the other hand, a carbon isotope signature of different environments would help to resolve questions of carbonate provenance in fine-grained sediments of the Mesozoic where it is not clear from textural evidence whether or not there has been significant transport from the platform.

In order to test the robustness of records from environments close to carbonate platforms, we have chosen to examine a carbonate ramp transect deposited along the northern Tethyan margin (figure 1) during the Late Jurassic. Pelagic deposits from the southern Tethyan margin and two sites from the Iberian peninsula are examined for comparison (figure 1). A good reason for choosing Late Jurassic records is the remarkable stability of δ¹³C values after the mid-Oxfordian (Bartolini et al. 1999; Chapter 2). The low degree of variability means that records with different sampling resolutions and time ranges can be compared. The extensive sedimentological literature available for Late Jurassic northern Tethyan carbonate platforms allows for detailed paleoenvironmental classification (e.g. Gygi and Persoz 1987a, 1987b; Pittet and Strasser 1998;
Chapter 4 61 Depositional Setting

Figure 1
Maps a) and b) Location of sites discussed in text. Numbers in brackets provide key to site locations in map c) and figure 3. Map c) is a paleogeographic reconstruction (redrawn from Ziegler 1988) of the western Tethys Ocean. Dark grey areas are deep marine settings, light grey areas are shallow marine settings and white represents exposed land surfaces during the Late Jurassic. Ib indicates the Iberian Peninsula and Fr indicates France and the two thin black lines are an indication of modern coastlines of northern Spain and northwestern France.

Colombié 1999; Gygi 2000).

4.2 METHODS

Samples were collected in the field at varying intervals according to ease of access to the outcrop. Because of the sensitivity of stable isotopes to early diagenetic processes, samples with
sedimentary textures such as emersion surfaces were carefully avoided. Coarse cements and fossils were likewise avoided during isotopic sampling. Fine-grained micrite samples were drilled with a diamond-tipped drill to produce a fine powder. This powder was reacted with phosphoric acid at 90 °C and the resulting CO\textsubscript{2} analyzed with a VG PRISM mass spectrometer. All isotope results are reported relative to the standard Vienna PeeDee Belemnite and measurement precision based on standards is +/- 0.2 %e.

The Sr and Ca elemental abundance of the carbonate phase was measured on an atomic absorption spectrometer. Samples were dissolved overnight in 20 % HCl and then decanted. Precision of repeated analyses was better than 2 %.

4.3 SITE DESCRIPTIONS

During the Late Jurassic, the tropical Tethys Ocean formed a wedge bisecting the former supercontinent of Pangea (figure 1). The northern margin of the western Tethys was a large carbonate ramp system with some local steepening (Leinfelder 1993). The southern margin featured a series of platforms, submarine highs and basins bound by listric faults related to Middle Triassic continental rifting (Bertotti et al. 1993). The Lusitanian basin on the west coast of Portugal was situated between the Berlenga Bank to the northwest and the Iberian Massif to the southeast (Werner 1985).

Ten Upper Jurassic sections from different depositional environments were examined (figure 1). Table 1 indicates interpreted depositional settings of the presented sections. The 180m Kimmeridgian section at Pichoux in the Swiss Jura mountains of western Switzerland consists of micrite with platform-derived debris. Bedding ranges from 50cm to 4m in thickness. Based on detailed paleoecological analysis, Colombié (1999) suggests a restricted, low-energy depositional environment at Pichoux became increasingly restricted from the early to the late Kimmeridgian during sea level regression. Age control is provided by ammonite zonation and sequence stratigraphy (Colombié 1999).

A 114m Late Jurassic carbonate succession has been sampled at Rawyl in the Jura mountains
of western Switzerland. Preliminary sedimentological analysis indicates a peri-platform setting with platform-derived debris in a micritic matrix (Colombié, pers. com.).

Wurmlingen is a 40 m outer ramp carbonate section deposited during the Oxfordian and preserved on the Swabian Alb. The light brown micritic limestone beds range from 10 cm to 1 m in thickness and are separated by thin marl stringers (Pittet 1996). Significant export of carbonate mud from the platform is inferred from the absence of bioerosion in the sponge reef and the scarcity of nannofossil remains in the basinal sediments (Pittet and Strasser 1998). Chronological control at Wurmlingen is provided by well-established ammonite zonation (Schweigert 1995a; 1995b).

Two hemipelagic sections, Gemmi (210 m) and Melchsee (160 m), were also deposited along the outer ramp of the northern Tethys (Gansner 2000; Schneider 1998). Both sections consist of the Quinten Limestone Fm, a predominantly micritic limestone deposited in the Kimmeridgian and Tithonian and preserved in the Helvetic nappes of the Swiss Alps (Gansner 2000; Schneider 1998; Chapter 2). This dark grey micritic limestone is relatively fossil-poor at Melchsee, although horizons rich in belemnite and ammonite remains occur in the lowermost part of the section (Schneider 1998). Bedding ranges from 3 to 50 cm. The more proximal nature of the Gemmi sediments is shown by a higher percentage of dolomitized levels, thicker bedding and beds of current-sorted crinoid and belemnite debris (Gansner 2000). The lower Quinten Limestone at Melchsee and the upper Quinten Limestone at Gemmi contain calcareous nodules and nodular bedding (Gansner 2000; Schneider 1998; Chapter 2). Carbon isotope stratigraphy is used for age control at these two sites (Chapter 2).

A 85 m pelagic section at the Montsalvens gorge, within the Ultrahelvetic nappes of western Switzerland, features a series of thin-bedded (~ 20 cm thick) micritic limestones with calcareous and siliceous nodules common in the lowermost 40 m (Guillaume 1957). Fossils are rare throughout the succession. Carbon isotope stratigraphy (Chapter 2) has been used to constrain earlier age models based on lithostratigraphy and ammonite assemblages (Rod 1937; Guillaume 1957).

For comparison with the northern Tethyan margin, two pelagic sections deposited along
the southern Tethyan margin and presently located in northern Italy (Weissert and Channell 1989), were also examined. The Xausa succession (65 m) was deposited on the Trento Plateau and Valle del Mis sediments (60 m) were deposited in the Belluno Basin. Both feature red nodular limestone ('Rosso ammonitico superiore') in the Kimmeridgian and grade into the interbedded white limestones and dark cherts of the Tithonian Maiolica Fm (Weissert and Channell 1989). Chronological control is provided by calpionellid stratigraphy and magnetostratigraphy (Weissert and Channell 1989).

Two sites from western Portugal were sampled for comparison with the Swiss/German/Italian data set. A lower Kimmeridgian series of calcareous silt- and sandstones was deposited at Consolação on the western coast of Portugal in a predominantly calm, shallow and restricted environment with marine to brackish water (Werner 1985). Fine-grained spiculitic limestones at Montejunto were deposited during the late Oxfordian in a basinal setting in the Lusitanian basin of central Portugal (Leinfelder 1993).

4.4 RESULTS
4.4.1 Carbon Isotopes

Most Late Jurassic δ¹³C records are remarkably constant with time (figure 2), with variations typically on the order of ±1 ‰ from the Late Oxfordian to the Tithonian. The two proximal
sections, Pichoux and Consolação, show significantly more depleted and more variable δ¹³C values (average ~ 0 ‰ VPDB; ranges 5.5 and 4 ‰ respectively) compared to concomitant values from sections deposited in more open settings (average ~ 2.5‰ VPDB; ranges < 2 ‰).

4.4.2 Oxygen Isotopes

Late Jurassic oxygen isotope values display greater variation between profiles than

![Diagram](image)

**Figure 2**
Plot of δ¹³C vs. time for all sections discussed in text. Chronological constraint is based on ammonites where available and δ¹³C stratigraphy. See chapter 2 for a detailed discussion of age correlations.
δ¹³C data (figures 3 and 4). Values for a single site typically range over a 2.5 %e interval with the exception of Pichoux where the range is greater than 5 %e (figures 3 and 4). A weak, but significant, positive correlation between δ¹⁸O and δ¹³C data is present at Pichoux (R² = 0.6) and Wurmlingen (R² = 0.7; figure 4). There are two general trends in the oxygen

![Diagram of Carbon and oxygen isotope data plotted against depositional environment. Schematic drawing represents a typical carbonate ramp environment. Numbers and names refer to sections discussed in text. Note different scales in δ¹⁸O and δ¹³C plots.](image_url)
isotope data: 1) a trend toward more depleted $\delta^{18}O$ with increasing tectonic burial depth and 2) a trend toward more depleted $\delta^{18}O$ approaching coastal environments (figure 5).

### 4.4.3 Sr/Ca

The ratio of Sr to Ca abundance for the carbonate phase of selected samples is shown in figure 6. The concentration of Sr is reported as a ratio of Ca in order to normalize the Sr

![Figure 4](image_url)  
**Crossplot of isotopic data.**

![Figure 5](image_url)  
**Oxygen isotope data plotted in order of degree of alpine diagenesis: Gemmi is the most likely to have experienced high burial temperatures and the top four sections are the least likely to have experienced high burial temperatures. The arrows indicate two trends discussed in the text Tectonic affiliations are indicated to the right.**
concentration in samples with different carbonate content.

4.5 DISCUSSION

There is a striking offset between $\delta^{13}C$ values of the inner platform and $\delta^{13}C$ values of all other sections (figures 2 and 3). We will examine five possible mechanisms which may be responsible for this apparent difference: 1) differences in burial history 2) differing amounts of early diagenetic cement, with or without freshwater influence 3) cementation during subaerial exposure 4) mineralogical differences and 5) different source water during primary precipitation, with or without freshwater mixing.

The anomaly seen in the carbon isotope data cannot be explained by burial diagenesis for two reasons: 1) Pichoux, Consolação, Wurmlingen and Rawyl all experienced minimal burial (Werner 1985; Trümpy 1980). The discrepancy between $\delta^{13}C$ values at Pichoux and Consolação and those at Wurmlingen and Rawyl indicates that burial history cannot explain the anomalous $\delta^{13}C$ values. 2) Many studies have demonstrated that in the absence of rare, carbon-rich interstitial fluids, there is minimal carbon atom exchange between rock and fluid during even deep burial (Matter et al. 1975; Früh-Green et al. 1990).
Cements formed shortly after burial are another potential mechanism to shift carbon isotopes from their original values (Veizer 1983). Although matrix was carefully sampled in the current data set and coarse cements were avoided, fine cements are impossible to exclude and may be present. One would expect early cements to be more depleted in $^{13}$C than bulk rock values because of organic decomposition in pore fluids (Veizer 1983). Cements formed in a brackish environment would also be expected to carry a depleted $^{13}$C signature (Lazar and Erez 1992); terrestrial carbon dissolved in meteoric water is isotopically depleted relative to dissolved carbon in oceanic water (Meyers 1994).

For a similar reason, cements formed in a meteoric environment during subaerial exposure also tend to have $^{13}$C values which are more depleted than those of marine cements. Again, we cannot exclude that some of the fine cement in the micrite is of meteoric origin. Exposure horizons are present at Pichoux although they were not sampled. Such horizons are not present at Consolaçâo (Werner 1985) and this explanation, therefore, is not likely.

Another factor investigated was the role played by mineralogical differences between pelagic and benthic carbonate. In the modern ocean, aragonite and high-Mg calcite are deposited on platforms while planktonic organisms primarily precipitate low-Mg calcite. Aragonite contains significantly greater amounts of Sr than calcite (Tucker and Bathurst 1990). The concentration of these substitute ions remains high even after the metastable aragonite has reverted to the more stable form of calcite (Tucker and Bathurst 1990). The Phanerozoic is divided into times which favoured calcite precipitation and times of aragonite precipitation (Sandberg 1983). Although the Late Jurassic was a ‘calcite time’, coprecipitation of aragonitic and calcitic ooids in the Oxfordian Smackover Fm. (Heydari and Moore 1994) demonstrates that aragonite may have precipitated over limited time intervals or in certain settings.

To test the possibility of using elemental analysis in the Late Jurassic transect to detect platform-derived sediment, Sr/Ca ratios were calculated for selected samples. At Rawyl
and Wurmlingen, faunal evidence indicates a significant amount of sediment was exported from the inner ramp (Pittet and Strasser 1998). The sections at Montsalvens and Xausa display no sedimentological evidence for the presence of platform material and are used as the pelagic endmember. There is a slight trend towards lower Sr/Ca values with greater depth of deposition (figure 6). However all Sr/Ca ratios are so small (< 0.006) compared to modern data (1 - 1.4; Graham et al. 1982) that this method seems unlikely to provide useful information about sediment genesis for this time period.

Whether or not mineralogy plays a role in the δ¹³C isotopic shifts at Pichoux and Consolação remains an open question. Positive isotopic shifts on the order of 1 ‰ can be traced to aragonite precipitation in modern settings (Andrews et al. 1997). Although mineralogy may play a minor role, the anomalously negative δ¹³C values of Pichoux and Consolação are unlikely to be due solely to mineralogical differences.

Primary calcite that is precipitated in a brackish environment would tend to be more depleted relative to calcite precipitated in the open ocean (Lazar and Erez 1992). However, modern carbonates display an isotopic offset between open ocean and platform-derived carbonate even in the absence of freshwater influence (Patterson and Walter 1994). Carbon-isotope depletion in modern proximal settings may be traced to carbon isotope depletion of the platform water mass. Under conditions of extreme evaporation and high alkalinity, bacterial mat formation may cause δ¹³C of dissolved inorganic carbon (δ¹³C DIC) in water masses to reach values down to -9 ‰ (Lazar and Erez 1992). Patterson and Walter (1994) describe progressive depletion of δ¹³C in dissolved inorganic carbon from the open ocean towards the carbonate banks of the Bahamas and Florida Bay. This lateral evolution of seawater is comparable to the vertical evolution of dissolved carbon in the open ocean and involves significant organic matter remineralization and CaCO₃ precipitation. In a modern setting, these processes cause preferential accumulation of the light carbon isotope ¹²C in the dissolved inorganic carbon pool (Patterson and Walter 1994).

Sea water from the most restricted settings of the Bahamian transect displays δ¹³C values depleted by as much as 4 ‰ relative to sea water from the open ocean (Patterson and Walter
The Late Jurassic ²³⁴C offset from an inner platform average to an outer platform average is on the order of 2.5‰ (figure 3). The highly variable nature of platform water evolution, with or without freshwater input, leads to ²³¹C ranges of 9‰ in modern platform water samples (Patterson and Walter 1994).

In order to distinguish between the two most likely possibilities, i.e. that the depleted ²³⁴C values at Pichoux and Consolação are due to either early diagenetic cement or due to differences in the primary calcite itself (and thus to water mass differences), it is helpful to consider the ²³⁸O data. The trend toward more depleted ²³⁸O values with increasing burial depth is seen in sections with very similar ²³¹C values. This reinforces the contention that oxygen isotopes are much more sensitive to recrystallization after burial than carbon isotopes (e.g. Früh-Green et al. 1990). Oxygen-isotope values of carbonate rocks become more negative when recrystallized at high burial temperatures (Früh-Green et al. 1990). When oxygen atoms in carbonate exchange with interstitial water molecules at higher temperatures than the original precipitation, carbonate becomes increasingly depleted due to the strongly temperature-dependent fractionation factor of water and calcite (~ 0.25‰/°C; Romanek et al. 1992).

The second trend in the oxygen isotope data displays increasingly depleted values in coastal environments. Once again, either primary or secondary calcite would be expected to be less enriched in the heavy isotope under subaerial or brackish conditions (e.g. Veizer 1983). Since meteoric water is isotopically lighter than ocean water (Rozanski et al. 1993), carbonate minerals precipitated from a freshwater mixture show oxygen isotopes significantly more depleted than open marine carbonates (Veizer, 1983). The weak correlation between ²³⁸O and ²³¹C in the Pichoux data (figure 4) may argue for the presence of early diagenetic cements (e.g. Veizer 1983). However, the complete absence of correlation in the Consolação data (figure 4) suggests this mechanism cannot explain anomalous values at this site. Furthermore, if a secondary cement is responsible for this second trend in the ²³⁸O data, we would expect ²³¹C values at Rawyl and Wurmlingen to be intermediate between the depleted ²³¹C values of Consolação/Pichoux and those from open ocean settings. Since the ²³¹C values at Wurmlingen and Rawyl are firmly
within the typical Late Jurassic range (figure 2), the anomalous δ¹³C values in the restricted sections must, to some extent, reflect primary conditions.

The susceptibility of oxygen to diagenesis during deep burial is well documented (e.g. Früh-Green et al. 1990). Results from the present analysis suggest that oxygen isotopes are also more likely to change during early diagenesis. Oxygen isotope records at Rawyl and Wurmlingen point clearly to diagenetic overprinting (figure 5) while carbon isotope values appear well-preserved. In contrast, the very depleted carbon isotope values at Pichoux and Consolação suggest that primary precipitation of calcite occurred under very different conditions from those at Rawyl, Wurmlingen and the other sections.

Similar results were reported from an Early Cretaceous ramp transect in the Arabian Gulf (Vahrenkamp, 1996) where oxygen isotopes were affected in shallow settings by diagenesis and carbon isotope fluctuations were so well preserved that they were used for correlating pelagic limestones with platform limestones. An isotopic investigation of a Greek carbonate platform (Grötsch et al. 1998) produced results which appear to fall between those of the present study and those of Vahrenkamp (1996). Platform limestones displayed carbon isotope values which were offset from pelagic values but fluctuations in the shallow-water carbon records were sufficiently preserved for stratigraphic correlation (Grötsch et al. 1998).

4.6 CONCLUSIONS

The comparison of δ¹³C values along a Late Jurassic carbonate ramp transect reveals that δ¹³C values are identical within 0.6‰ in all depositional settings basinward of the most restricted locations (figure 2). Carbon isotope values of two inner platform sites are up to 4‰ more negative and more variable than all other sections. Oxygen isotope values show greater variation between sites than carbon isotopes and display a trend toward more negative values with increasing burial depth as well as approaching the platform.

The anomalously negative δ¹³C values of the two inner platform sites may be due to source water differences and/or early diagenesis. Both explanations are possible although evidence from
oxygen isotopes suggests that a primary difference in source water $\delta^{13}C$ may be the more likely of the two. Two sites, situated in a peri-platform setting and on the outer ramp display depleted $\delta^{18}O$ values but ‘normal’ open ocean $\delta^{13}C$ values. One explanation of the data is that $\delta^{18}O$ values have been compromised during early diagenesis and $\delta^{13}C$ reflects primary values. While the susceptibility of $\delta^{18}O$ to recrystallization and the robustness of $\delta^{13}C$ during burial are well established (e.g. Fruh-Green 1990), the present data set indicates that oxygen isotopes may also be more susceptible than $\delta^{13}C$ to early diagenesis. Carbon isotope depletion of the source waters in the restricted environments of the inner platform are documented along modern platforms (Patterson and Walter 1994) and therefore provide a reasonable mechanism to explain the anomalously depleted carbon values at Pichoux and Consolacao.

Carbon isotope values from the two inner platform settings do not reflect Late Jurassic open ocean values and such sites should be avoided for both paleoenvironmental and stratigraphic studies due to the potential effects of isotopic depletion of inner platform waters as well as early diagenesis. Sections in outer ramp settings appear to have maintained primary $\delta^{13}C$ signatures although $\delta^{18}O$ values have experienced some post-depositional shifts. Such settings are good candidates for paleoenvironmental reconstructions, especially when open ocean sites are not available.

REFERENCES

Bown, P.R., 1996, Recent advances in Jurassic calcareous nannofossil research: Advances in Jurassic research, in Riccardi, A.C., ed.: GeoResearch Forum: Zurich, Switzerland, Transtec Publications, p. 55-66.


Gygi, R.A., 2000, Integrated Stratigraphy of the Oxfordian and Kimmeridgian (Late Jurassic)


Pittet, B., 1996, Contrôles climatiques, eustatiques et tectoniques sur des systèmes mixtes carbonates-siliciclastiques de plate-forme: exemples de l’Oxfordien (Jura suisse,


Schweigert, G., 1995a, Amoebopeltoceras n.g., eine neue Ammonitengattung aus dem Oberjura (Ober-Oxfordium bis Unter-Kimmeridgium) von Süedwestdeutschland und Spanien:


CHAPTER 5

Oxygen isotope evidence of enhanced tropical evaporation in the Late Jurassic

Prepared for publication in *Paleoceanography* by
M. Padden, H. Weissert and D. Schmidt

ABSTRACT

Three Late Jurassic oxygen isotope records from marine carbonates deposited in the western Atlantic and along the northern and southern margins of the Tethys Ocean record anomalously high values. The lowest paleotemperatures calculated from δ¹⁸O_carb are 15 °C and are at least 5 °C cooler than temperature minima predicted from faunal assemblages and paleoclimatic models. Diagenetic alteration during burial and alpine deformation tend to cause a δ¹⁸O_carb shift in the negative direction and therefore cannot account for these anomalous values. Intense evaporation at low latitudes and large equator-to-pole δ¹⁸O_sw gradients may explain the anomalously high δ¹⁸O_carb. A possible implication of high tropical evaporation is export of warm, saline Tethyan/Atlantic waters as intermediate or deep water.

5.1 INTRODUCTION

Marine δ¹⁸O records have been used extensively to document glacial/interglacial cycles, sea water temperature variations and oceanic circulation changes. The high potential for diagenetic alteration of Mesozoic carbonate rocks and the difficulty of interpreting δ¹⁸O records from shells of extinct organisms pose additional challenges when applying δ¹⁸O stratigraphy to older records. However, several recent studies have highlighted the importance of δ¹⁸O data for Mesozoic paleoceanographic reconstructions (Podlaha et al. 1998; Clarke and Jenkyns 1999; Stoll and Schrag 2000) as well as the need to consider the effects of diagenesis and the problem of constraining habitats of extinct species. High resolution isotope data from Late Jurassic deposits in southern Europe and DSDP site 105 in the eastern Atlantic provide an excellent opportunity to explore the limits and potential of δ¹⁸O stratigraphy in ancient deposits.
5.2 GEOLOGICAL SETTING OF ARCHIVES

In the Oxfordian stage of the Late Jurassic, the supercontinent of Pangea was bisected into a northern continent (Laurasia) and a southern continent (Gondwana) by the equatorial Tethys Ocean (Figure 1). The westernmost arm of the Tethys was the newly opened Atlantic corridor through the present Caribbean. The proto-Pacific Ocean was known as Panthalassa and covered the rest of the globe. For this study we investigated a) carbonate ramp sediments from a Northern Tethys transect. The section Auenstein was deposited in an outer ramp environment and the section at Montsalvens was deposited in the Helvetic Basin. b) pelagic sediments from the southern margin of the Alpine Tethys preserved in the section at Xausa. c) pelagic sediments from the central Atlantic cored at site 105 during DSDP Leg 11.

5.2.1 Auenstein

A 70 m section was sampled at a quarry near Auenstein, situated in the Jura fold belt in north eastern Switzerland (figure 1). Two members of the Wildegg Formation are present
at Auenstein, the Birmenstorf Member and the Effinger Member (Gygi and Persoz, 1987). The 6m thick Birmenstorf Member consists of a basal condensed series of glauconitic hardgrounds and an upper series of glauconitic marls and micrites (Gygi 2000; Gygi and Persoz, 1987). The Effinger Mb. is a 210 m thick rhythmically alternating marl and limestone sequence. Limestone beds are on average 20cm thick although some reach thicknesses of 75cm. Belemnite samples were collected from fossil-rich horizons in the lower Effinger Mb. The lowermost 70m of the Effinger Mb were sampled at Auenstein. A comprehensive ammonite stratigraphy has been proposed for the Auenstein site (Gygi and Persoz 1987). The glauconitic hardground in the lowermost Birmenstorf Member and the distinct ~3m thick marly interval at the Birmenstorf Mb-Effinger Mb boundary were used to correlate the isotopic data with previous biostratigraphic work.

Figure 2.
Stratigraphy and correlation of studied sections. Solid lines represent chronological control points and dotted lines represent correlations based on C-isotope stratigraphy.
5.2.2 Montsalvens

A 100 m limestone succession was sampled at a gorge along the Jogne River in the Ultrahelvetic nappes of western Switzerland (figure 2). Guillaume (1957) described four different members at this site: Calcaire concrétionné, Calcaire schisteux, Calcaire grumeaux, Calcaire lité. The Calcaire concrétionné member is 7m thick at Montsalvens and consists of chert concretions in a marly matrix interbedded with dark grey micritic limestones. There is a sharp contact with the next highest member, the 18m thick Calcaire schisteux member. This member contains 10 to 40cm thick non-nodular planar bedded limestone. The Calcaire grumeaux member is 29m thick with 5 to 15cm thick beds and is very similar to the Calcaire schisteux member except for the presence of wavy bedding and calcareous and chert nodules. Overlying the Calcaire grumeaux is the 32m thick Calcaire lité member with non-nodular, fine-bedded (~ 10 to 20cm thick) micritic limestones. Two intervals, each approximately 10m thick, in the lowermost Calcaire lité display thinner bedding (< 10cm) than the rest of the Calcaire lité (figure 2). The lower 36m of the Montsalvens section are not used for oxygen isotope stratigraphy because of the prevalence of chert nodules and the potential for oxygen exchange between silica-rich interstitial fluids and calcite. Carbon isotope values are less likely to be affected by interaction with SiO₂-rich fluids.

Chronological control of the Montsalvens section is based on the ammonite framework of Guillaume (1957), the lithostratigraphy of Rod (1937) and carbon isotope stratigraphy. The Montsalvens section is situated in the Ultrahelvetic nappes and burial was deeper than at Auenstein (e.g. Trümpy 1980).

5.2.3 Xausa

The transition between the Rosso Ammonitico Formation and the Maiolica Formation outcropping near the northern Italian town of Xausa was first sampled for isotope analysis by Weissert and Channell (1989). Results from additional sampling of the lower Rosso Ammonitico member are presented here. The Rosso Ammonitico Fm is a red nodular pelagic limestone,
in which, as the name suggests, abundant poorly preserved ammonite fossils are found. At Xausa, there is a gradual transition between the upper 19m of the Rosso Ammonitico Formation to the ~ 36m exposure of the overlying Maiolica Formation featuring alternating white coccolithic limestones and black radiolarites (Weissert and Channell 1989). Magnetostratigraphy and nannofossil stratigraphy provide age control (Weissert and Channell 1989; Erba et al. 1998) and δ¹³C stratigraphy was used to incorporate the new isotopic data into the existing set. Chronologic ages were recalculated from magnetostratigraphic and nannofossil zones according to the time scale of (Gradstein and Ogg 1996).

5.2.4 DSDP Leg 11, Site 105

A Late Jurassic red and green clayey limestone was cored during the final phase of DSDP drilling at site 105 in the western Atlantic during Leg 11 (Lancelot et al. 1972). Bernoulli (1972) and Luterbacher (1972) suggest a bathyal environment for site 105 sediments with some inferred transport from submarine highs into the basin. Sediment from cores 34 to 39 was sampled for stable isotope analysis. Site 105 was situated in a submarine basin created by the irregular topography of the underlying basalt (Lancelot et al. 1972). Intervals with slumping were avoided during isotopic sampling, however the authors note the possibility that small or subtle deformational features may have gone undetected. Faunal and floral assemblages include ammonite aptychi, calcareous nannofossils, calpionellids, the planktic crinoid Saccocoma, benthic foraminifera and ostracods (Hollister et al. 1972). The calcareous nannofossil *Stephanolithion bigoti* is present throughout cores 35-39 (Thierstein 1975) and denotes an Oxfordian to Tithonian age (Thierstein 1975; Bown 1996). The first appearance of the calpionellid *Calpionella alpina* in core 33 indicates an age of latest Tithonian (Erba et al. 1998) and provides a minimum age for the sampled interval. The good preservational state of coccoliths and benthic foraminifera in the site 105 samples can be seen in plates 1 and 2.
5.3 METHODS

All bulk carbonate samples were drilled with a diamond bit into a fine powder. Isotope samples were reacted with phosphoric acid at 90 °C and the resulting CO$_2$ analyzed with a VG PRISM mass spectrometer following the standard procedure of Sharma and Clayton (1965). All isotope results are reported in delta notation relative to the standard Vienna PeeDee Belemnite and measurement precision based on standards is better than +/- 0.2 ‰.

Belemnite thin sections were cut perpendicular to the long axis and photographed under cold cathode luminescence (CL) in order to differentiate between primary and secondary calcite. A diamond-tipped drill was used to selectively sample the non-luminescent portion of the belemnite rostra (‘non-luminescent belemnites’ in following discussion and in plate 3 and figure 3). Three belemnites were sampled to include both luminescent and non-luminescent calcite (‘luminescent belemnites’ in plate 3 and figure 3).
Figure 4.
Composite isotope records from Montsalvens (black circles), Xausa (grey circles) and DSDP site 105 (open circles). A) Carbon isotope data B) Oxygen isotope data C) Composite curve of all $\delta^{18}O$ values (with no smoothing).

Benthic foraminifera from DSDP site 105 were prepared by washing in a calgon solution and sieving at the University of Tübingen (Luterbacher, pers. com.). Individual foraminifera were hand-picked and all isotopic measurements were made with a minimum of 10 specimens. Measurements were made at the Genus level because of the difficulty differentiating species and, where species identification was possible, to an insufficient number of individuals. All analyzed specimens were photographed under a light microscope and additional foraminiferal samples were examined with a scanning electron microscope.
5.4 RESULTS

Bulk carbonate samples from Montsalvens display \( \delta^{13}C \) values (\( \delta^{13}C_{\text{carb}} \)) that range from 1.7 to 2.8\%\text{e} and \( \delta^{18}O \) values (\( \delta^{18}O_{\text{carb}} \)) range from -5.1 to 0.1\%\text{e} (figures 4). The range of isotopic values at Xausa is similar to that of Montsalvens with \( \delta^{13}C_{\text{carb}} \) ranging between 1.2 and 2.5\%\text{e} and \( \delta^{18}O_{\text{carb}} \) ranging between -3.5 and -0.3\%\text{e} (figure 4).

The carbon isotope record from DSDP site 105 is noisier than at Montsalvens or Xausa (figure 4) although the absolute \( \delta^{13}C_{\text{carb}} \) range is similar. Bulk carbonate \( \delta^{13}C \) values lie between 1.2 and 2.6\%\text{e} and \( \delta^{18}O \) between -4 and -0.3\%\text{e}. Foraminiferal \( \delta^{13}C \) and \( \delta^{18}O \) values are more depleted than bulk carbonate except for the uppermost three *Spirillina* spp. samples, which are equal to or more enriched than bulk \( \delta^{13}C \) and \( \delta^{18}O \) values (figure 5). Foraminiferal group \( \delta^{13}C \) records are offset from each other by 1-2 per mil in most samples and \( \delta^{18}O \) records are offset by up to 2-4\%\text{e}. 

*Figure 5.* Bulk carbonate and foraminiferal isotopic data for DSDP site 105. Depth represents depth below sea floor.
Table 1 Estimated paleolatitudes for studied sites and corresponding $\delta^{18}$O.

<table>
<thead>
<tr>
<th>Age</th>
<th>Site</th>
<th>Paleolatitude$^1$</th>
<th>$\delta^{18}$O$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Kimmeridgian</td>
<td>Xausa</td>
<td>18</td>
<td>-0.158</td>
</tr>
<tr>
<td>Early Kimmeridgian</td>
<td>DSDP site 105</td>
<td>20</td>
<td>-0.176</td>
</tr>
<tr>
<td>Early Kimmeridgian</td>
<td>Montsalvens</td>
<td>26</td>
<td>-0.270</td>
</tr>
<tr>
<td>Late Tithonian</td>
<td>Xausa</td>
<td>22</td>
<td>-0.201</td>
</tr>
<tr>
<td>Late Tithonian</td>
<td>DSDP site 105</td>
<td>28</td>
<td>-0.312</td>
</tr>
<tr>
<td>Late Tithonian</td>
<td>Montsalvens</td>
<td>30</td>
<td>-0.360</td>
</tr>
<tr>
<td>Late Jurassic Average</td>
<td>Xausa</td>
<td>20*</td>
<td>-0.176***</td>
</tr>
<tr>
<td>Late Jurassic Average</td>
<td>DSDP site 105</td>
<td>24*</td>
<td>-0.233***</td>
</tr>
<tr>
<td>Late Jurassic Average</td>
<td>Montsalvens</td>
<td>28*</td>
<td>-0.312***</td>
</tr>
</tbody>
</table>

1 Paleolatitudes estimated from paleogeographic reconstructions of (Dercourt and Commission for the Geological Map of the World 1993).
2 $\delta^{18}$O calculated from equation 2.
* Average of Early Kimmeridgian and Late Tithonian paleolatitudes for each site.
** $\delta^{18}$O values to calculate paleotemperatures used in Figure 8B.

Bulk carbonate samples from Auenstein display $\delta^{13}$C values between 1.2 and 3.2‰ and $\delta^{18}$O values range from -4.5 to -0.2‰. Belemnite samples from Auenstein fall into two distinct groups according to petrographic analysis under CL. Calcite which is luminescent (yellow-orange in plate 3) is seen in plate 3A concentrated around the perimeter, in the central axis and in so-called ‘growth bands’. Other belemnite samples display this luminescent calcite only around the perimeter and in fractures. Elsewhere there is only non-luminescent calcite (dark blue in plate 3). Non-luminescent belemnites display $\delta^{13}$C and $\delta^{18}$O values that are distinctly different from bulk values from the same bed (figure 3). Luminescent belemnites generally have $\delta^{13}$C values that are intermediate between the more depleted non-luminescent belemnites and $\delta^{13}$C_{carb}, although one luminescent belemnite has a $\delta^{13}$C value similar to non-luminescent samples. The oxygen isotope values of luminescent belemnites fall within the range of $\delta^{18}$O_{carb}, whereas non-luminescent samples are distinctly more enriched in the heavy oxygen isotope.
5.5 DISCUSSION
5.5.1 Age Correlation between sites

The available \( \delta^{18}O \) records were correlated by \( \delta^{13}C \) stratigraphy, within the bounds of biostratigraphic and magnetostratigraphic data (Ch 2, figure 2). The minor negative \( \delta^{13}C \) excursion in the Bifurcatus ammonite zone at Auenstein is correlated to an excursion of similar magnitude at Montsalvens and at site 105. At Montsalvens, this excursion occurs in the Calcaire grumeaux, which is estimated by (Guillaume 1957) and (Rod 1937) to be of Oxfordian age according to ammonite assemblages and sequence stratigraphy respectively. The Montsalvens record was correlated with the Xausa data using two tie points: the relatively positive \( \delta^{13}C \) excursion in the early Tithonian and the small negative \( \delta^{13}C \) excursion

![Plot of modern \( \delta^{18}O \) and salinity vs. latitude from Zachos et al. (1994). Dotted line indicates the regression curve derived by Zachos et al. (1994; equation 2) which best fits the available data.](image)

in the Bifurcatus ammonite zone at Auenstein is correlated to an excursion of similar magnitude at Montsalvens and at site 105. At Montsalvens, this excursion occurs in the Calcaire grumeaux, which is estimated by (Guillaume 1957) and (Rod 1937) to be of Oxfordian age according to ammonite assemblages and sequence stratigraphy respectively.
in the mid-Tithonian (figure 2). Sedimentation rates between δ¹³C tie points are always assumed to be constant. The timescale of (Gradstein and Ogg 1996) was used to calculate absolute ages and all literature data used for comparison have been recalculated according to this most recent time scale.

5.5.2 Temperature calculation
Paleotemperatures are calculated from δ¹⁸O data using the calcite-water equation of (Craig 1965), modified by (Anderson and Arthur 1983):

\[ T \, (^°\text{C}) = 16 + 4.14 \, (\delta^{18}\text{O}_{\text{carb}} - \delta^{18}\text{O}_{\text{sw}}) - 0.13 \, (\delta^{18}\text{O}_{\text{carb}} - \delta^{18}\text{O}_{\text{sw}})^2 \]  

where \( \delta^{18}\text{O}_{\text{carb}} \) is the δ¹⁸O value of calcite with respect to the VPDB standard and \( \delta^{18}\text{O}_{\text{sw}} \) is the δ¹⁸O value of seawater relative to VSMOW. Late Jurassic seawater δ¹⁸O is taken to be -1‰ SMOW (= -1.2‰ VPDB) according to the estimate of (Shackleton and Kennett 1975) for an ice-free world ocean. In the modern ocean, δ¹⁸O sw varies with latitude by approximately 1.5‰ (Zachos et al., 1994; figure 6). This variation is caused by high evaporation in the tropics and progressively more depleted rainfall in higher latitudes. Zachos et al. (1994) derived a regression equation that fits data from the modern southern hemisphere:

\[ \delta^{18}\text{O}_{\text{sw}} = 0.576 + 0.041 \, y - 0.0017 \, y^2 + 1.35 \times 10^{-3} \, y^3 \]  

Although this relationship has almost certainly changed in the past, it provides a starting point to correct for latitudinal differences in δ¹⁸O sw (table 1). Paleolatitudes of DSDP site 105, Montsalvens and Xausa are estimated from the paleogeographic constructions of (Dercourt et al., 1993; figure 1).

5.5.3 Diagenesis
Distinguishing between a paleoceanographic signal and diagenetic overprinting is central to the interpretation of stable isotope records of sediments. In general, the older the sediments, the more important is the need to assess the degree of diagenesis. Carbon isotope stratigraphy has proven to be relatively robust and appears unaffected by tectonic overprinting
and burial history (e.g. Matter et al. 1975); correlations can also be made across depositional environments (e.g. Ferreri et al. 1997; Chapter 4). Interstitial fluids tend to be carbon-poor and this fluid-rock exchange of carbon atoms is usually minimized (e.g. Früh-Green et al. 1990).

Oxygen isotopes are much more susceptible to exchange with interstitial waters. Isotopic fractionation of $\delta^{18}O_{\text{carb}}$ during precipitation is dependent on both temperature and the oxygen isotope composition of water (Friedman et al. 1977). Reequilibration of carbonate at a different temperature and/or with water of different isotopic composition results in altered $\delta^{18}O_{\text{carb}}$. This effect has been documented in pelagic carbonate deposits at the sediment-water interface in low latitudes where cooler temperatures are encountered relative to the environment of original precipitation (Schrag 1999), as well as during deep burial and alpine orogenesis when higher temperatures are encountered relative to those of original precipitation (Früh-Green et al. 1990). Recrystallization and exchange of oxygen may also occur during mineralogical changes from meta-stable carbonate minerals such as aragonite and high-Mg calcite to the more stable form of low-Mg calcite (Veizer 1983). Sedimentary texture may play a key role in determining the degree of fluid-rock interaction. Fossils with open pore spaces and grain-supported rocks are more likely to encounter substantial fluid circulation than fine-grained matrix-supported carbonates. Thick, dense low-Mg calcite shells are also good candidates for maintaining a relatively unaltered isotopic composition. Petrographic and/or geochemical methods may be used to identify alterations.

In spite of the potential for diagenetic alteration, many Mesozoic $\delta^{18}O$ records from marine carbonates have been used to reconstruct paleoceanographic conditions (e.g. Podlaha et al. 1998; Clarke and Jenkyns 1999; Stoll and Schrag 2000; Veizer et al. 2000). Oxygen isotope analysis of well-preserved belemnite rostra has been used to infer ocean water paleotemperatures and secular changes in $\delta^{18}O_{\text{sw}}$ (see Podlaha et al. 1998; Veizer et al. 2000 for review and summary of available literature). Belemnites are particularly good candidates for isotopic analysis because they precipitate low-Mg calcite which is a much
more stable mineral phase than aragonite or high-Mg calcite and are therefore less prone to
recrystallization over long periods of geological time. The dense, thick construction of the
belemnite shell is also less susceptible to diagenetic fluids and the internal structure aids the
identification of diagenetic alteration. Secondary calcite appears yellow-orange under cathode
luminescence (e.g. plate 3), whereas low-Mg calcite is non-luminescent with a dull blue
color (e.g. plate 3; Veizer, 1983). However, as Veizer (1983) noted, early-stage low-Mg
calcite cements would be indistinguishable from original calcite under CL. Barbin et al.
(1991) have suggested from studies of modern carbonates that some shells are luminescent
regardless of the degree of alteration. Clearly, cathode luminescence is a useful tool for
identifying diagenetic alteration, but it must be used in combination with other information.
The stable isotope data also provide insight into the degree of recrystallization in the
Auenstein belemnites and more particularly into the belemnite habitat.

Reconstructions of belemnite paleoecology and habitat remain controversial (Doyle 1992).
Morphological similarities to the extant species Loligo opalescens, a Mediterranean squid, led
Jarvis (1980) to conclude that belemnites may have lived at depths of 120-330 m and moved to
shallower waters when feeding or mating. Anderson and Arthur (1983) concluded on the basis
of isotopic studies of different mollusk shells that belemnites lived at greater depths than ammonites.
Cool Kimmeridgian to Tithonian paleotemperatures (~13 -16 °C) calculated from well-preserved
belemnites on Mallorca led Price and Sellwood (1994) to conclude that belemnites were recording
cool subsurface water masses. The distribution of Late Jurassic corals suggests that surface
water temperatures along the northern margin of the Tethys, including the sites on Mallorca and
at Auenstein, were between 20 and 30 °C.

Non-luminescent belemnites display distinctly different δ13C values from bulk δ13C (figure
3), indicating precipitation in separate water masses. The relatively negative δ13C values of well-
preserved belemnites are consistent with an intermediate-to-deep water habitat where δ13C values
of the dissolved inorganic carbon pool become depleted as the result of oxidation of sinking
organic matter. The intermediate values of the partially recrystallized belemnites indicate a mixture
of original calcite (negative $\delta^{13}$C) and secondary calcite precipitated in equilibrium with bulk values (positive $\delta^{13}$C). Positive $\delta^{18}$O values of the well-preserved belemnites are also consistent with a habitat in cool intermediate or deep waters (figure 3). The complete resetting of the luminescent belemnite $\delta^{18}$O values to those of the bulk sediment illustrates the greater susceptibility of oxygen isotopes to diagenetic overprinting compared to carbon isotopes.

Bulk $\delta^{18}$O$_{\text{carb}}$ has also been used for paleoceanographic investigations even when some diagenetic overprinting is suspected (Clarke and Jenkyns 1999; Stoll and Schrag 2000). The reasoning behind this approach is that isotopic excursions in excess of $\sim 1\%\epsilon$ in a $\delta^{18}$O record at any given site cannot be attributed solely to diagenesis without a significant lithological change. This hypothesis is supported by the models of Stoll and Schrag (2000). Although an original $\delta^{18}$O value cannot be determined from these studies, the relative change in $\delta^{18}$O provides information about changing temperature (Clarke and Jenkyns 1999) and/or changing seawater $\delta^{18}$O ($\delta^{18}$O$_{\text{sw}}$) due to glaciation (Stoll and Schrag 2000).

In the present study, although original $\delta^{18}$O$_{\text{carb}}$ values cannot be determined for any of the presented data sets, the direction of diagenetic change, i.e. whether isotopic values are likely to become more negative or more positive, can be constrained. Bulk carbonate records from open marine settings, where most of the carbonate was likely precipitated by calcareous organisms living in the photic zone, are used in the present study in order to avoid a ‘mixed’ $\delta^{18}$O signal with shallow water carbonates and pelagic carbonates mixed in unknown proportions (Chapter 4).

Assuming that $\delta^{18}$O$_{\text{sw}}$ and temperature were similar at Montsalvens, Xausa and site 105, the overlap of $\delta^{18}$O$_{\text{carb}}$ records suggests that a similar degree of postdepositional diagenesis took place in all three sections (figure 4). Several lines of evidence indicate that $\delta^{18}$O$_{\text{carb}}$ at Montsalvens, Xausa and at DSDP site 105 are minimum estimates. Extensive early diagenesis at the sediment-water interface causes precipitation of calcite at much cooler bottom water temperatures and
thus shifts $\delta^{18}O_{\text{carb}}$ to higher values (e.g. Schrag, 1999). Later reequilibration of calcite $\delta^{18}O$ at higher temperatures during burial tends to drive $\delta^{18}O_{\text{carb}}$ towards more negative values (Matter et al. 1975). The unreasonably high benthic foraminifera temperatures from site 105 (figure 5) are an excellent example of this phenomenon. Large pore spaces in the foraminiferal chambers may have facilitated calcite-water exchange whereas less fluid

\[
\delta^{18}O_{\text{SW}} = -1 \quad \delta^{18}O_{\text{SW}} = -0.16, -0.18, -0.27 \quad \delta^{18}O_{\text{SW}} = 0.5
\]

Figure 7. Figure is based on oxygen isotope curve of figure 4. Paleotemperature calculations using equation 1. Shaded region represents most reasonable paleotemperature range for Tethys-Atlantic based on coral reef distribution (Moore et al. 1992). A) Paleotemperatures calculated using $\delta^{18}O_{\text{sw}} = -1%$ for a homogeneous, ice-free world ocean. B) Paleotemperatures calculated using $\delta^{18}O_{\text{sw}}$ corrected according to equation 2 assuming $\delta^{18}O$-latitude slope identical in Late Jurassic and recent times. Paleolatitudes of the sites represent an average between Early Kimmeridgian and Late Tithonian values according to the paleogeographic reconstructions of (Dercourt and Commission for the Geological Map of the World 1993) C) Paleotemperatures calculated using $\delta^{18}O_{\text{sw}} = 0.5%$ (for all sites) provide the best fit to the paleotemperature range inferred from coral reef distribution.
circulation may have penetrated the coccolith ooze resulting in lower rates of recrystallization and cementation. Isotopic analysis of calcite veins in the basalt underlying the sediments at site 105 suggests that pore fluids became increasingly depleted over time according to a diagenesis model by (Brenneke 1977). Significant interaction between the sediments at site 105 with such pore fluids would also tend to cause more depleted \( \delta^{18}O \) values (Brenneke 1977).

Alpine diagenesis causes a negative shift in \( \delta^{18}O \) values with increasing burial depth and metamorphic grade (Früh-Green et al. 1990). This effect is clearly seen in the Late Jurassic carbonate records of the Helvetic nappes (Chapter 2, Chapter 4). Thus, since the most likely effect of diagenesis would be to shift \( \delta^{18}O_{\text{carb}} \) towards more negative values and resulting paleotemperature calculations towards higher values, paleotemperatures calculated from Montsalvens, Xausa and site 105 \( \delta^{18}O_{\text{carb}} \) may be regarded as maximum estimates.

### 5.5.4 Paleotemperature and \( \delta^{18}O_{\text{sw}} \)

The puzzling aspect of the composite bulk paleotemperature estimates in (figure 7) is why temperatures of two sub-tropical sites record such low temperatures. Modern sea water temperatures between 30 °N and 30 °S have temperatures between 20 °C and 30 °C (Laboratory 1999) and in an equable Late Jurassic world without sea ice or glaciers, lower sea surface temperatures at low latitudes is unlikely. Coral reef distributions for the Kimmeridgian (Beauvais 1973) and the Tithonian (Sellers 1985) suggest that temperatures of ~ 20 °C to 30 °C (the temperature tolerance of modern coral reefs; CMC, 1988a; CMC, 1988b) were encountered between latitudes of about 35 °N and S. A general circulation model of the Late Jurassic, which compares favorably with the coral distribution, predicts paleotemperatures even higher than 30 °C across a narrow equatorial band (Moore et al. 1992). Moore et al. (1992) noted that ammonites, which were widespread throughout this region, were generally restricted to temperatures <30 °C. A recent compilation of paleotemperature data from belemnite \( \delta^{18}O \) indicates a tropical seawater temperature
anomaly of \(-2 \, ^\circ \text{C}\) compared to modern values (Veizer et al. 2000). Aside from the uncertainties involved in belemnite records, the anomaly cited by (Veizer et al. 2000) is too small to account for the apparent paleotemperatures of the present data set. In any case, coral distribution is inconsistent with significantly lower tropical sea surface temperatures and therefore provides a framework in which to investigate the curiously low paleotemperatures calculated from $\delta^{18}$O$_{\text{carb}}$.

One possible explanation for the bulk $\delta^{18}$O data is $\delta^{18}$O$_{\text{sw}}$ that were higher in the tropics during the Late Jurassic. Evaporation of seawater causes both isotopic enrichment of $\delta^{18}$O and increased salinity as remaining waters become more concentrated (figure 6). The $\delta^{18}$O$_{\text{sw}}$ gradient from the tropics to polar regions may have been higher during ‘greenhouse’ climates featuring accelerated hydrologic cycles. By similar reasoning, high salinity contrasts in Late Cretaceous ocean models result have been attributed to higher precipitation and evaporation rates accompanying higher global temperatures (Hay 1995). The Late Jurassic $\delta^{18}$O is estimated to have been $-1 \, \%_\text{e}$ (VSMOW) according to the calculations of Shackleton.
and Kennett (1975) for an ice-free world ocean. However the $\delta^{18}O_{sw}$ value which produces the most reasonable temperatures for the composite $\delta^{18}O_{carb}$ data set at ~25 °N is 0.5‰ (figure 7) and this value may have been higher. No upper boundary can be placed on the value of $\delta^{18}O_{sw}$ at this latitude because of uncertainty about the amount of diagenetic overprinting. The lower boundary for paleo-$\delta^{18}O_{sw}$ can be inferred from figure 7: Paleo-$\delta^{18}O_{sw}$ cannot have been as low as the modified $\delta^{18}O_{sw}$-latitude equation of Zachos et al. (1994) predicts (figure 7) because temperatures calculated from the composite $\delta^{18}O_{carb}$ data represent maximum temperatures and half of the paleotemperature curve lies below 20 °C when paleotemperature is calculated with latitude-corrected $\delta^{18}O_{sw}$ values (equation 2).

### 5.5.5 Oceanic Circulation and Paleosalinity

High evaporation rates over the Tethys-Atlantic seaway and higher latitudinal gradients of $\delta^{18}O_{sw}$ have important implications for oceanic circulation in the Late Jurassic. In figure 8 it is clear that salinity and $\delta^{18}O_{sw}$ covary with evaporative and dilution processes in the modern ocean. If, as the Late Jurassic $\delta^{18}O_{sw}$ data imply, evaporation at low latitudes was intensified, latitudinal salinity gradients were likely higher in Late Jurassic oceans. However, estimating absolute paleosalinities from inferred $\delta^{18}O_{sw}$ is very difficult because of probable changes in the $\delta^{18}O_{sw}$/salinity relationship and in the total oceanic salinity over time. In modern oceans, the relation between $\delta^{18}O_{sw}$ and salinity ranges from ~0.61‰/practical salinity units (psu) in the North Atlantic to 0.35‰/psu in the Mediterranean and Red Seas (figure 8). Changes in the isotopic composition of high latitude runoff during ice-free times and the absence of sea ice as a salinizing agent may have caused considerable changes in the $\delta^{18}O$-salinity relationship. High average salinity of the Late Jurassic world ocean, which has been estimated to be approximately 40 psu (i.e. ~5 psu higher than modern values of 34.7 psu) according to a sediment cycling model constructed by Hay and Wold (1997), would shift the $\delta^{18}O_{sw}$-salinity slopes to higher salinities and may also have caused changes in the slope (figure 8).
Although absolute salinity cannot be calculated, the δ¹⁸O data do suggest that the Tethys-Atlantic was the site of intense evaporation, as shown by the relatively high inferred δ¹⁸Osw, and was therefore probably considerably more saline than average ocean values. This may have had an effect on the location of bottom water formation during the Late Jurassic. The formation of sea ice is the most effective cause of high latitude bottom water in the modern ocean and is furthermore the most energy-efficient method of forming bottom water when average salinities are less than 35 psu (Hay et al. 1999). As mentioned, Late Jurassic paleosalinities have been estimated to have been approximately 40 psu on average (Hay and Wold 1997) and there is no strong geological evidence of continental glaciation (Frakes and Francis 1988). Hay et al. (1999) noted that simple cooling of deep water at high latitudes is the most energy efficient method of forming deep water at salinities above 40 psu.

However, there are two reasons to suppose that low latitude deep-water formation played a significant role in Late Jurassic paleoceanography. The first is that relatively high precipitation rates at high latitudes, evidenced by Late Jurassic coal distributions (e.g. Hallam, 1984; Parrish, 1992), likely resulted in relatively fresh polar waters. In the absence of sea-ice formation as a concentration mechanism, freshening of high latitude waters inhibits deep-water formation. Deep-water formation by simple cooling at high latitudes, as suggested by Hay et al. (1999) is less effective if high latitude water masses are relatively fresh. The second line of reasoning concerns conditions at low latitudes. Brass et al. (1982a and b) noted that a concentrated basin just before salt deposition would be the most effective source of warm saline bottom water (WSBW) and emphasized the role of paleogeography, suggesting that a prerequisite of WSBW formation is the location of epicontinental seas within the zone of net evaporation (10 to 40° latitude) under the descending Hadley cells. The time of highest Late Jurassic Tethyan salinity would likely have been just before Tithonian-aged evaporites were deposited in southern Europe and the Middle East (e.g. Hallam, 1984).

The increasing apparent-temperature trend in figure 7 during the latest Tithonian may
Chapter 5  

5.6 CONCLUSIONS

The Late Jurassic carbonate archives from Auenstein, DSDP site 105, Montsalvens and Xausa provided an opportunity to investigate the use of oxygen isotope records of both belemnite and bulk carbonate. The belemnite δ¹⁸O and δ¹³C results from Auenstein highlight the importance of belemnite habitat and a multiproxy approach to paleoceanographic reconstructions.
Comparison of recrystallized with well-preserved belemnites confirms earlier studies that δ¹³C calcite is a relatively robust parameter, which is preserved even in completely recrystallized calcite. Oxygen isotopes, on the other hand, are much more sensitive to post-burial diagenetic processes and recrystallized belemnites displayed the δ¹⁸O values which were completely reset to bulk carbonate δ¹⁸O values.

The bulk carbonate δ¹⁸O data from DSDP site 105, Montsalvens and Xausa suggest that latitudinal δ¹⁸Oₘₚ gradients may have changes over geologic time. This has important implications for paleotemperature reconstructions based on δ¹⁸O measurements of both carbonates and phosphates because of the dependence of the fractionation factors on the isotopic composition of water. During times of accelerated hydrologic cycling, such as the Late Jurassic, intense tropical evaporation and extensive precipitation at high latitudes may lead to greater equator-to-pole δ¹⁸Oₘₚ gradients.

Another, more speculative, implication of high equator-to-pole δ¹⁸Oₘₚ gradients is the possible presence of warm, saline, intermediate or bottom water. The presence of highly saline tropical waters, due to intense evaporation, and relatively fresh high latitude waters with no sea ice formation would tend to promote deep-water formation in the tropics. A wider distribution of Late Jurassic δ¹⁸O records, especially from high latitude sites and/or oceanic modeling may help to resolve the question of Atlantic/Tethyan bottom water formation.

REFERENCES

Chapter 5

99

Oxygen Isotopes

of Economic Paleontologists and Mineralogists, p. 1-151.


Bown, P.R., 1996, Recent advances in Jurassic calcareous nannofossil research: Advances in Jurassic research, in Riccardi, A.C., ed.: GeoResearch Forum: Zurich, Switzerland, Transtec Publications, p. 55-66.


Chapter 5

102 Oxygen Isotopes


Chapter 5

103 Oxygen Isotopes


Veizer, J., Godderis, Y., and François, L.M., 2000, Evidence for decoupling of atmospheric
Plate 1.
SEM photomicrographs of DSDP site 105 Late Jurassic sediments reproduced from (Bernoulli 1972). Scale: x2000. Sediment consists primarily of coccolith fragments and clay minerals. A) sample 11-105-3-1, 40cm B) 11-105-34-4, 120cm C) 11-105-37-2, 85-87cm

Plate 2.
Examples of benthic forams from DSDP site 105 which were used for isotopic analysis. A) *Lenticulina muensteri* (Roemer) from sample 11-105-37-1, 100cm. Light microscope. B) *Nodosaria destructa* (Schwager) SEM photomicrograph from sample 11-105-37-1. C) *Spirillina* sp. (Luterbacher) as in Luterbacher 1972 SEM photomicrograph from sample 11-105-37-1.

Plate 3.
Belemnite thin sections under CL. A) belemnite from 7.8m in Auenstein profile. Example of 'luminescent belemnite' with yellow-orange recrystallized calcite concentrated in 'growth rings'. B) example of 'non-luminescent belemnite' from 26m in the Auenstein profile with recrystallized, luminescent calcite found only along the perimeter and in the central axis. Other parts of the belemnite feature dark blue low-Mg calcite. C) a 'non-luminescent belemnite' at 26m showing the uniform, dark blue colour of the original calcite and secondary crystals forming along the perimeter.
Chapter 5

Oxygen Isotopes
APPENDIX
### Site Locations

<table>
<thead>
<tr>
<th>SECTION NAME</th>
<th>SWISS NAT. COORDINATES</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auenstein</td>
<td>653.900 / 252.400</td>
<td>39° 18' N</td>
<td>9° 20' W</td>
</tr>
<tr>
<td>Consolação</td>
<td>500 / 230</td>
<td>34° 54' N</td>
<td>69° 10' W</td>
</tr>
<tr>
<td>DSDP leg 11, site 105</td>
<td>34° 54' S</td>
<td>12° 56' S</td>
<td>117° 53' E</td>
</tr>
<tr>
<td>DSDP leg 27, site 261</td>
<td>32° 24' N</td>
<td>156° 36' E</td>
<td></td>
</tr>
<tr>
<td>DSDP leg 6, site 49.1</td>
<td>613.370 / 138.230</td>
<td>39° 9' N</td>
<td>9° 13' W</td>
</tr>
<tr>
<td>Gemmi</td>
<td>613.370 / 138.230</td>
<td>39° 9' N</td>
<td>9° 13' W</td>
</tr>
<tr>
<td>Montejunto</td>
<td>575.500 / 161.750</td>
<td>39° 9' N</td>
<td>9° 13' W</td>
</tr>
<tr>
<td>Montsalvens</td>
<td>575.500 / 161.750</td>
<td>39° 9' N</td>
<td>9° 13' W</td>
</tr>
<tr>
<td>Nissibach</td>
<td>742.980 / 221.940</td>
<td>39° 9' N</td>
<td>9° 13' W</td>
</tr>
<tr>
<td>Ortstock</td>
<td>716.350 / 198.870</td>
<td>39° 9' N</td>
<td>9° 13' W</td>
</tr>
<tr>
<td>Pichoux</td>
<td>584.150 / 237.230</td>
<td>39° 9' N</td>
<td>9° 13' W</td>
</tr>
<tr>
<td>Rawyl</td>
<td>584.150 / 237.230</td>
<td>39° 9' N</td>
<td>9° 13' W</td>
</tr>
<tr>
<td>Vergons</td>
<td>584.150 / 237.230</td>
<td>39° 9' N</td>
<td>9° 13' W</td>
</tr>
<tr>
<td>Wurmlingen</td>
<td>48° 1' N</td>
<td>6° 22' E</td>
<td></td>
</tr>
<tr>
<td>Xausa</td>
<td>45° 16' N</td>
<td>6° 22' E</td>
<td></td>
</tr>
<tr>
<td>Valle del Mis</td>
<td>46° 9' N</td>
<td>6° 22' E</td>
<td></td>
</tr>
</tbody>
</table>
## II Isotopic and Geochemical Data

<table>
<thead>
<tr>
<th>ORSTOCK</th>
<th>( \delta^{13}C_{\text{carb}} )</th>
<th>( \delta^{18}O_{\text{carb}} )</th>
<th>( \delta^{13}C_{\text{org}} )</th>
<th>Total C</th>
<th>CaCO(_3) %</th>
<th>TOC %</th>
<th>C/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>2.01</td>
<td>-1.93</td>
<td></td>
<td>0.68</td>
<td>2.8</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>5.00</td>
<td></td>
<td></td>
<td></td>
<td>0.45</td>
<td>1.7</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>7.00</td>
<td></td>
<td></td>
<td></td>
<td>0.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.50</td>
<td>2.64</td>
<td>-3.08</td>
<td></td>
<td>11.52</td>
<td>94.2</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>21.50</td>
<td>2.45</td>
<td>-5.24</td>
<td></td>
<td>11.42</td>
<td>94.9</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>23.50</td>
<td>2.47</td>
<td>-5.68</td>
<td></td>
<td>11.38</td>
<td>95.8</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>24.50</td>
<td>2.25</td>
<td>-5.70</td>
<td></td>
<td>10.75</td>
<td>89.7</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>32.80</td>
<td>1.59</td>
<td>-7.07</td>
<td></td>
<td>2.40</td>
<td>19.0</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>32.70</td>
<td>1.95</td>
<td>-6.80</td>
<td>-21.94</td>
<td>1.90</td>
<td>14.8</td>
<td>0.12</td>
<td>4.81</td>
</tr>
<tr>
<td>33.25</td>
<td>1.94</td>
<td>-7.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33.75</td>
<td>1.83</td>
<td>-6.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34.25</td>
<td>1.50</td>
<td>-7.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34.50</td>
<td>1.77</td>
<td>-6.24</td>
<td>-21.90</td>
<td>1.16</td>
<td>9.4</td>
<td>0.04</td>
<td>3.40</td>
</tr>
<tr>
<td>34.75</td>
<td>2.02</td>
<td>-7.52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35.25</td>
<td>1.80</td>
<td>-6.99</td>
<td>-21.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36.25</td>
<td>1.87</td>
<td>-7.13</td>
<td>-23.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36.50</td>
<td>0.63</td>
<td>-6.90</td>
<td>-23.55</td>
<td>13.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36.75</td>
<td>1.11</td>
<td>-7.44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.25</td>
<td>1.67</td>
<td>-7.17</td>
<td>-25.83</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.75</td>
<td>1.74</td>
<td>-7.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38.25</td>
<td>1.59</td>
<td>-7.02</td>
<td>-21.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38.50</td>
<td>1.63</td>
<td>-6.78</td>
<td></td>
<td>4.64</td>
<td>39.8</td>
<td>0.00</td>
<td>5.67</td>
</tr>
<tr>
<td>38.75</td>
<td>1.92</td>
<td>-7.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39.25</td>
<td>2.07</td>
<td>-6.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.25</td>
<td></td>
<td>-22.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42.50</td>
<td>2.29</td>
<td>-6.91</td>
<td></td>
<td>7.55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44.50</td>
<td>2.08</td>
<td>-6.90</td>
<td></td>
<td>7.64</td>
<td>64.2</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>46.50</td>
<td>2.38</td>
<td>-6.74</td>
<td></td>
<td>7.46</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48.50</td>
<td>2.38</td>
<td>-6.85</td>
<td></td>
<td>5.74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50.50</td>
<td>2.61</td>
<td>-6.60</td>
<td></td>
<td>8.19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>52.30</td>
<td>2.20</td>
<td>-6.82</td>
<td></td>
<td>7.09</td>
<td>55.1</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>52.70</td>
<td>2.16</td>
<td>-6.26</td>
<td></td>
<td>6.35</td>
<td>52.7</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>53.50</td>
<td>2.13</td>
<td>-6.28</td>
<td></td>
<td>6.45</td>
<td>52.1</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>54.20</td>
<td>2.62</td>
<td>-6.86</td>
<td></td>
<td>7.04</td>
<td>57.2</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>54.70</td>
<td>2.09</td>
<td>-6.60</td>
<td>-22.55</td>
<td>6.39</td>
<td>52.1</td>
<td>0.13</td>
<td>3.75</td>
</tr>
<tr>
<td>55.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>56.30</td>
<td>2.69</td>
<td>-6.40</td>
<td></td>
<td>9.48</td>
<td>78.3</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>56.70</td>
<td>2.13</td>
<td>-6.21</td>
<td></td>
<td>8.95</td>
<td>73.6</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>57.50</td>
<td>2.06</td>
<td>-6.15</td>
<td></td>
<td>6.19</td>
<td>49.4</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>58.30</td>
<td>2.56</td>
<td>-6.44</td>
<td>-22.69</td>
<td>6.27</td>
<td>49.7</td>
<td>0.31</td>
<td>1.65</td>
</tr>
<tr>
<td>58.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>59.50</td>
<td>2.00</td>
<td>-6.17</td>
<td></td>
<td>9.20</td>
<td>82.7</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>60.30</td>
<td>2.16</td>
<td>-6.70</td>
<td></td>
<td>6.00</td>
<td>50.5</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>60.70</td>
<td>2.02</td>
<td>-6.20</td>
<td></td>
<td>7.54</td>
<td>63.7</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>61.50</td>
<td>1.76</td>
<td>-6.13</td>
<td></td>
<td>7.35</td>
<td>61.2</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>62.50</td>
<td>1.84</td>
<td>-6.05</td>
<td></td>
<td>8.66</td>
<td>70.9</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>66.75</td>
<td>1.75</td>
<td>-6.04</td>
<td></td>
<td>6.61</td>
<td>56.0</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>68.75</td>
<td>1.78</td>
<td>-5.86</td>
<td>-22.54</td>
<td>5.76</td>
<td>45.4</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>69.75</td>
<td>1.81</td>
<td>-5.97</td>
<td></td>
<td>7.42</td>
<td>61.9</td>
<td>0.00</td>
<td>1.73</td>
</tr>
</tbody>
</table>
### ORTSTOCK

<table>
<thead>
<tr>
<th>meters</th>
<th>$\delta^{13}$C$_{carb}$</th>
<th>$\delta^{18}$O$_{carb}$</th>
<th>$\delta^{13}$C$_{org}$</th>
<th>Total C</th>
<th>CaCO$_3$ %</th>
<th>TOC %</th>
<th>C/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>71.75</td>
<td>1.81</td>
<td>-5.86</td>
<td></td>
<td>6.64</td>
<td>58.2</td>
<td>0.00</td>
<td>3.27</td>
</tr>
<tr>
<td>72.75</td>
<td>1.80</td>
<td>-5.81</td>
<td></td>
<td>5.95</td>
<td>50.4</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>73.75</td>
<td>1.77</td>
<td>-6.19</td>
<td></td>
<td>8.98</td>
<td>75.8</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>75.75</td>
<td>2.17</td>
<td>-5.70</td>
<td></td>
<td>10.63</td>
<td>89.0</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>76.75</td>
<td>1.89</td>
<td>-5.79</td>
<td>-21.58</td>
<td>8.06</td>
<td>62.8</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>77.75</td>
<td>2.28</td>
<td>-5.53</td>
<td></td>
<td>10.46</td>
<td>87.3</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>78.75</td>
<td>2.20</td>
<td>-5.32</td>
<td></td>
<td>8.46</td>
<td>68.5</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>79.75</td>
<td>2.21</td>
<td>-5.30</td>
<td></td>
<td>8.18</td>
<td>67.2</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>80.75</td>
<td>2.17</td>
<td>-5.57</td>
<td></td>
<td>7.47</td>
<td>62.9</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>82.25</td>
<td></td>
<td></td>
<td></td>
<td>8.12</td>
<td>67.4</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>84.25</td>
<td>2.38</td>
<td>-4.99</td>
<td></td>
<td>9.79</td>
<td>81.0</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>85.25</td>
<td>2.43</td>
<td>-5.18</td>
<td></td>
<td>9.21</td>
<td>80.1</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>86.25</td>
<td>2.51</td>
<td>-5.23</td>
<td></td>
<td>10.93</td>
<td>91.5</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>87.25</td>
<td>2.46</td>
<td>-5.01</td>
<td>-21.98</td>
<td>8.90</td>
<td>70.8</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td>88.25</td>
<td>2.69</td>
<td>-4.74</td>
<td></td>
<td>8.06</td>
<td>66.8</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>89.25</td>
<td>2.42</td>
<td>-4.92</td>
<td></td>
<td>8.44</td>
<td>67.8</td>
<td>0.30</td>
<td></td>
</tr>
</tbody>
</table>

### WURMLINGEN

<table>
<thead>
<tr>
<th>meters</th>
<th>$\delta^{13}$C$_{carb}$</th>
<th>$\delta^{18}$O$_{carb}$</th>
<th>CaCO$_3$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td></td>
<td></td>
<td>95.88</td>
</tr>
<tr>
<td>0.88</td>
<td></td>
<td></td>
<td>84.08</td>
</tr>
<tr>
<td>1.58</td>
<td></td>
<td></td>
<td>95.73</td>
</tr>
<tr>
<td>2.18</td>
<td></td>
<td></td>
<td>94.50</td>
</tr>
<tr>
<td>3.38</td>
<td>2.48</td>
<td>-4.85</td>
<td>96.00</td>
</tr>
<tr>
<td>4.30</td>
<td>2.98</td>
<td>-4.18</td>
<td>97.91</td>
</tr>
<tr>
<td>5.58</td>
<td>2.66</td>
<td>-4.51</td>
<td>96.74</td>
</tr>
<tr>
<td>7.10</td>
<td>2.66</td>
<td>-4.53</td>
<td></td>
</tr>
<tr>
<td>7.92</td>
<td>2.61</td>
<td>-4.39</td>
<td>96.27</td>
</tr>
<tr>
<td>8.47</td>
<td>2.93</td>
<td>-3.60</td>
<td>97.42</td>
</tr>
<tr>
<td>9.53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.73</td>
<td>2.98</td>
<td>-4.05</td>
<td></td>
</tr>
<tr>
<td>9.80</td>
<td>2.90</td>
<td>-3.97</td>
<td>97.53</td>
</tr>
<tr>
<td>9.93</td>
<td>2.93</td>
<td>-4.21</td>
<td>97.82</td>
</tr>
<tr>
<td>10.01</td>
<td>2.77</td>
<td>-4.11</td>
<td></td>
</tr>
<tr>
<td>10.21</td>
<td>2.81</td>
<td>-4.09</td>
<td>96.49</td>
</tr>
<tr>
<td>name</td>
<td>meters</td>
<td>$\delta^{13}$C</td>
<td>$\delta^{18}$O</td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>---------------</td>
<td>---------------</td>
</tr>
<tr>
<td>A1</td>
<td>0.00</td>
<td>1.50</td>
<td>-3.30</td>
</tr>
<tr>
<td>A2</td>
<td>0.10</td>
<td>1.23</td>
<td>-2.86</td>
</tr>
<tr>
<td>A3</td>
<td>0.40</td>
<td>1.24</td>
<td>-0.66</td>
</tr>
<tr>
<td>A4</td>
<td>0.40</td>
<td>1.27</td>
<td>-0.22</td>
</tr>
<tr>
<td>A5</td>
<td>0.50</td>
<td>2.72</td>
<td>-1.31</td>
</tr>
<tr>
<td>A6</td>
<td>0.60</td>
<td>2.93</td>
<td>-2.16</td>
</tr>
<tr>
<td>A7</td>
<td>0.66</td>
<td>3.11</td>
<td>-1.06</td>
</tr>
<tr>
<td>A9</td>
<td>0.78</td>
<td>3.11</td>
<td>-1.44</td>
</tr>
<tr>
<td>A8</td>
<td>0.89</td>
<td>2.99</td>
<td>-1.76</td>
</tr>
<tr>
<td>A10</td>
<td>1.35</td>
<td>2.88</td>
<td>-1.96</td>
</tr>
<tr>
<td>A11</td>
<td>1.45</td>
<td>3.11</td>
<td>-1.49</td>
</tr>
<tr>
<td>A12</td>
<td>1.60</td>
<td>2.95</td>
<td>-1.28</td>
</tr>
<tr>
<td>A13</td>
<td>1.75</td>
<td>2.83</td>
<td>-2.11</td>
</tr>
<tr>
<td>A15</td>
<td>1.98</td>
<td>3.07</td>
<td>-2.47</td>
</tr>
<tr>
<td>A14</td>
<td>2.18</td>
<td>3.02</td>
<td>-2.28</td>
</tr>
<tr>
<td>A16</td>
<td>2.35</td>
<td>2.58</td>
<td>-3.80</td>
</tr>
<tr>
<td>A17</td>
<td>3.08</td>
<td>2.58</td>
<td>-4.50</td>
</tr>
<tr>
<td>A18</td>
<td>3.43</td>
<td>2.86</td>
<td>-4.08</td>
</tr>
<tr>
<td>A19</td>
<td>3.86</td>
<td>2.61</td>
<td>-2.72</td>
</tr>
<tr>
<td>A20</td>
<td>3.96</td>
<td>2.58</td>
<td>-2.75</td>
</tr>
<tr>
<td>AF2</td>
<td>7.86</td>
<td>-0.91</td>
<td>-2.15</td>
</tr>
<tr>
<td>A21</td>
<td>8.09</td>
<td>2.47</td>
<td>-2.81</td>
</tr>
<tr>
<td>A22</td>
<td>8.57</td>
<td>2.62</td>
<td>-1.33</td>
</tr>
<tr>
<td>A23</td>
<td>9.88</td>
<td>2.60</td>
<td>-2.42</td>
</tr>
<tr>
<td>A24</td>
<td>10.66</td>
<td>2.80</td>
<td>-1.04</td>
</tr>
<tr>
<td>A25</td>
<td>12.83</td>
<td>2.89</td>
<td>-2.85</td>
</tr>
<tr>
<td>A26</td>
<td>13.98</td>
<td>2.43</td>
<td>-3.06</td>
</tr>
<tr>
<td>A27</td>
<td>14.08</td>
<td>2.98</td>
<td>-3.37</td>
</tr>
<tr>
<td>A28</td>
<td>16.73</td>
<td>2.90</td>
<td>-3.17</td>
</tr>
<tr>
<td>A29</td>
<td>17.63</td>
<td>2.80</td>
<td>-3.21</td>
</tr>
<tr>
<td>A30</td>
<td>18.18</td>
<td>3.17</td>
<td>-3.17</td>
</tr>
<tr>
<td>A31</td>
<td>20.01</td>
<td>2.58</td>
<td>-2.69</td>
</tr>
<tr>
<td>A32</td>
<td>20.51</td>
<td>2.53</td>
<td>-2.88</td>
</tr>
<tr>
<td>A33</td>
<td>21.06</td>
<td>2.85</td>
<td>-3.49</td>
</tr>
<tr>
<td>A34</td>
<td>21.61</td>
<td>2.76</td>
<td>-3.34</td>
</tr>
<tr>
<td>A35</td>
<td>24.36</td>
<td>2.54</td>
<td>-2.44</td>
</tr>
<tr>
<td>A36</td>
<td>25.61</td>
<td>2.56</td>
<td>-2.68</td>
</tr>
<tr>
<td>A37</td>
<td>26.13</td>
<td>2.55</td>
<td>-2.53</td>
</tr>
<tr>
<td>A38</td>
<td>27.88</td>
<td>2.55</td>
<td>-3.39</td>
</tr>
<tr>
<td>A39</td>
<td>31.28</td>
<td>2.54</td>
<td>-2.98</td>
</tr>
<tr>
<td>A40</td>
<td>31.53</td>
<td>2.48</td>
<td>-3.06</td>
</tr>
<tr>
<td>A41</td>
<td>32.03</td>
<td>2.49</td>
<td>-3.34</td>
</tr>
<tr>
<td>A42</td>
<td>32.33</td>
<td>2.54</td>
<td>-3.23</td>
</tr>
<tr>
<td>A43</td>
<td>32.78</td>
<td>2.42</td>
<td>-3.44</td>
</tr>
<tr>
<td>A44</td>
<td>34.96</td>
<td>2.19</td>
<td>-4.23</td>
</tr>
<tr>
<td>A45</td>
<td>35.69</td>
<td>2.39</td>
<td>-3.61</td>
</tr>
<tr>
<td>A51</td>
<td>36.14</td>
<td>2.28</td>
<td>-3.46</td>
</tr>
<tr>
<td>A46</td>
<td>36.34</td>
<td>2.40</td>
<td>-2.88</td>
</tr>
<tr>
<td>A50</td>
<td>36.69</td>
<td>1.88</td>
<td>-3.72</td>
</tr>
</tbody>
</table>
### AUENSTEIN Bulk

<table>
<thead>
<tr>
<th>name</th>
<th>meters</th>
<th>$\delta^{13}C_{\text{carb}}$</th>
<th>$\delta^{18}O_{\text{carb}}$</th>
<th>Total C</th>
<th>CaCO$_3$ %</th>
<th>TOC %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A52</td>
<td>37.74</td>
<td>2.53</td>
<td>-3.38</td>
<td>73.26</td>
<td>65.74</td>
<td></td>
</tr>
<tr>
<td>A53</td>
<td>39.99</td>
<td>2.55</td>
<td>-3.68</td>
<td>8.50</td>
<td>64.88</td>
<td>0.54</td>
</tr>
<tr>
<td>A54</td>
<td>41.06</td>
<td>2.80</td>
<td>-3.50</td>
<td>9.15</td>
<td>59.74</td>
<td>0.48</td>
</tr>
<tr>
<td>A55</td>
<td>43.89</td>
<td>2.49</td>
<td>-3.36</td>
<td>66.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A56</td>
<td>47.61</td>
<td>2.46</td>
<td>-3.38</td>
<td>66.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A57</td>
<td>49.36</td>
<td>2.16</td>
<td>-3.26</td>
<td>82.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A58</td>
<td>51.36</td>
<td>2.20</td>
<td>-3.39</td>
<td>8.35</td>
<td>60.96</td>
<td></td>
</tr>
<tr>
<td>A59</td>
<td>52.91</td>
<td>2.05</td>
<td>-3.23</td>
<td>68.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A60</td>
<td>53.46</td>
<td>2.38</td>
<td>-3.34</td>
<td>55.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A61</td>
<td>54.21</td>
<td>2.19</td>
<td>-3.24</td>
<td>70.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A62</td>
<td>54.81</td>
<td>2.19</td>
<td>-3.20</td>
<td>8.87</td>
<td>69.57</td>
<td></td>
</tr>
<tr>
<td>A63</td>
<td>55.24</td>
<td>2.32</td>
<td>-1.96</td>
<td>9.43</td>
<td>72.15</td>
<td></td>
</tr>
<tr>
<td>A64</td>
<td>55.74</td>
<td>2.64</td>
<td>-1.95</td>
<td>9.44</td>
<td>72.36</td>
<td></td>
</tr>
<tr>
<td>A65</td>
<td>56.06</td>
<td>2.73</td>
<td>-1.95</td>
<td>9.95</td>
<td>79.32</td>
<td>0.43</td>
</tr>
<tr>
<td>A66</td>
<td>56.69</td>
<td>2.66</td>
<td>-1.94</td>
<td>9.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A67</td>
<td>57.41</td>
<td>2.80</td>
<td>-1.93</td>
<td>10.05</td>
<td>79.18</td>
<td>0.55</td>
</tr>
<tr>
<td>A68</td>
<td>59.26</td>
<td>2.89</td>
<td>-1.93</td>
<td>10.09</td>
<td>81.18</td>
<td>0.35</td>
</tr>
<tr>
<td>A69</td>
<td>59.75</td>
<td>2.89</td>
<td>-1.92</td>
<td>10.87</td>
<td>87.05</td>
<td>0.43</td>
</tr>
<tr>
<td>A70</td>
<td>60.84</td>
<td>1.70</td>
<td>-4.02</td>
<td>11.25</td>
<td>91.37</td>
<td>0.29</td>
</tr>
<tr>
<td>A71</td>
<td>62.29</td>
<td>0.50</td>
<td>0.39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A72</td>
<td>63.31</td>
<td>0.63</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A73</td>
<td>64.33</td>
<td>0.67</td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A74</td>
<td>65.33</td>
<td>0.60</td>
<td>-0.21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A75</td>
<td>66.16</td>
<td>0.35</td>
<td>-0.22</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### AUENSTEIN Belemnites

<table>
<thead>
<tr>
<th>name</th>
<th>meters</th>
<th>$\delta^{13}C_{\text{carb}}$</th>
<th>$\delta^{18}O_{\text{carb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF2a</td>
<td>7.86</td>
<td>-0.09</td>
<td>-0.03</td>
</tr>
<tr>
<td>AF2d</td>
<td>7.86</td>
<td>0.65</td>
<td>-3.23</td>
</tr>
<tr>
<td>AF2d</td>
<td>7.86</td>
<td>1.01</td>
<td>-1.99</td>
</tr>
<tr>
<td>AF2d</td>
<td>7.86</td>
<td>0.98</td>
<td>-2.10</td>
</tr>
<tr>
<td>AF1b</td>
<td>8.27</td>
<td>-0.40</td>
<td>0.04</td>
</tr>
<tr>
<td>AF1a</td>
<td>8.27</td>
<td>-0.50</td>
<td>0.39</td>
</tr>
<tr>
<td>AF4a</td>
<td>14.48</td>
<td>1.70</td>
<td>-4.02</td>
</tr>
<tr>
<td>AF4b</td>
<td>14.48</td>
<td>0.14</td>
<td>0.47</td>
</tr>
<tr>
<td>AF4c</td>
<td>14.48</td>
<td>-0.21</td>
<td>0.05</td>
</tr>
<tr>
<td>AF8c</td>
<td>26.03</td>
<td>0.95</td>
<td>-0.42</td>
</tr>
<tr>
<td>AF8b</td>
<td>26.03</td>
<td>0.81</td>
<td>0.29</td>
</tr>
<tr>
<td>AF7a</td>
<td>27.78</td>
<td>-0.07</td>
<td>0.22</td>
</tr>
<tr>
<td>AF7b</td>
<td>27.78</td>
<td>0.10</td>
<td>-0.06</td>
</tr>
<tr>
<td>AF7b</td>
<td>27.78</td>
<td>-0.15</td>
<td>-0.08</td>
</tr>
<tr>
<td>AF7c</td>
<td>27.78</td>
<td>0.48</td>
<td>-0.60</td>
</tr>
<tr>
<td>AF7d</td>
<td>27.78</td>
<td>0.15</td>
<td>-0.33</td>
</tr>
<tr>
<td>AF7e</td>
<td>27.78</td>
<td>0.21</td>
<td>0.07</td>
</tr>
<tr>
<td>AF6a</td>
<td>28.48</td>
<td>0.35</td>
<td>-0.10</td>
</tr>
<tr>
<td>AF6b</td>
<td>28.48</td>
<td>0.70</td>
<td>-0.19</td>
</tr>
<tr>
<td>AF6c</td>
<td>28.48</td>
<td>0.38</td>
<td>-0.19</td>
</tr>
<tr>
<td>AF6d</td>
<td>28.48</td>
<td>0.21</td>
<td>-0.22</td>
</tr>
<tr>
<td>meters</td>
<td>$\delta^{13}C_{\text{carb}}$</td>
<td>$\delta^{18}O_{\text{carb}}$</td>
<td>$\delta^{13}C_{\text{org}}$</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>0.00</td>
<td>3.19</td>
<td>-5.00</td>
<td>20.82</td>
</tr>
<tr>
<td>0.08</td>
<td>2.74</td>
<td>-5.41</td>
<td>-20.82</td>
</tr>
<tr>
<td>0.33</td>
<td>2.43</td>
<td>-5.47</td>
<td></td>
</tr>
<tr>
<td>0.41</td>
<td>2.77</td>
<td>-5.07</td>
<td></td>
</tr>
<tr>
<td>0.58</td>
<td>2.53</td>
<td>-4.98</td>
<td></td>
</tr>
<tr>
<td>0.70</td>
<td>2.24</td>
<td>-5.70</td>
<td></td>
</tr>
<tr>
<td>0.87</td>
<td>2.60</td>
<td>-5.24</td>
<td>-22.00</td>
</tr>
<tr>
<td>1.08</td>
<td>2.48</td>
<td>-5.02</td>
<td></td>
</tr>
<tr>
<td>1.45</td>
<td>2.30</td>
<td>-5.24</td>
<td></td>
</tr>
<tr>
<td>1.65</td>
<td>2.15</td>
<td>-3.42</td>
<td>-19.44</td>
</tr>
<tr>
<td>2.11</td>
<td>2.36</td>
<td>-5.01</td>
<td></td>
</tr>
<tr>
<td>2.35</td>
<td>2.25</td>
<td>-4.84</td>
<td></td>
</tr>
<tr>
<td>2.68</td>
<td>2.35</td>
<td>-4.74</td>
<td></td>
</tr>
<tr>
<td>2.91</td>
<td>2.19</td>
<td>-4.80</td>
<td></td>
</tr>
<tr>
<td>2.96</td>
<td>2.18</td>
<td>-4.96</td>
<td></td>
</tr>
<tr>
<td>3.18</td>
<td>2.35</td>
<td>-5.02</td>
<td></td>
</tr>
<tr>
<td>3.41</td>
<td>2.20</td>
<td>-4.98</td>
<td></td>
</tr>
<tr>
<td>3.51</td>
<td>2.00</td>
<td>-5.13</td>
<td></td>
</tr>
<tr>
<td>3.71</td>
<td>1.94</td>
<td>-5.06</td>
<td>-26.16</td>
</tr>
<tr>
<td>3.94</td>
<td></td>
<td>-4.69</td>
<td></td>
</tr>
<tr>
<td>4.06</td>
<td>2.64</td>
<td>-4.69</td>
<td></td>
</tr>
<tr>
<td>4.16</td>
<td>1.91</td>
<td>-5.51</td>
<td>-21.43</td>
</tr>
<tr>
<td>8.33</td>
<td>1.89</td>
<td>-4.65</td>
<td></td>
</tr>
<tr>
<td>8.84</td>
<td>1.85</td>
<td>-4.85</td>
<td>-21.76</td>
</tr>
<tr>
<td>9.04</td>
<td></td>
<td>-4.10</td>
<td></td>
</tr>
<tr>
<td>9.64</td>
<td>2.27</td>
<td>-4.91</td>
<td>-23.07</td>
</tr>
<tr>
<td>10.24</td>
<td>1.80</td>
<td>-4.91</td>
<td>-23.07</td>
</tr>
<tr>
<td>11.14</td>
<td>0.76</td>
<td>-6.16</td>
<td>-19.87</td>
</tr>
<tr>
<td>12.34</td>
<td>1.85</td>
<td>-4.93</td>
<td>-20.56</td>
</tr>
<tr>
<td>12.94</td>
<td>1.39</td>
<td>-4.80</td>
<td>-20.23</td>
</tr>
<tr>
<td>14.14</td>
<td>1.20</td>
<td>-5.27</td>
<td>-22.53</td>
</tr>
<tr>
<td>14.74</td>
<td>0.69</td>
<td>-5.37</td>
<td>-20.36</td>
</tr>
<tr>
<td>16.54</td>
<td>1.86</td>
<td>-4.95</td>
<td>-20.70</td>
</tr>
<tr>
<td>18.79</td>
<td>2.09</td>
<td>-4.66</td>
<td>-23.25</td>
</tr>
<tr>
<td>19.74</td>
<td>2.25</td>
<td>-7.22</td>
<td></td>
</tr>
<tr>
<td>20.49</td>
<td>1.65</td>
<td>-5.38</td>
<td>-23.64</td>
</tr>
<tr>
<td>24.49</td>
<td>2.27</td>
<td>-3.76</td>
<td></td>
</tr>
<tr>
<td>29.69</td>
<td>2.41</td>
<td>-4.28</td>
<td>-21.08</td>
</tr>
<tr>
<td>35.09</td>
<td>2.19</td>
<td>-3.19</td>
<td>-19.42</td>
</tr>
<tr>
<td>39.49</td>
<td>2.74</td>
<td>-3.19</td>
<td>-19.42</td>
</tr>
<tr>
<td>50.09</td>
<td>2.61</td>
<td>-3.26</td>
<td></td>
</tr>
<tr>
<td>53.69</td>
<td>2.66</td>
<td>-3.36</td>
<td>-22.73</td>
</tr>
<tr>
<td>57.29</td>
<td>2.66</td>
<td>-2.79</td>
<td></td>
</tr>
<tr>
<td>60.29</td>
<td>2.25</td>
<td>-3.93</td>
<td></td>
</tr>
<tr>
<td>63.69</td>
<td>2.31</td>
<td>-4.13</td>
<td></td>
</tr>
<tr>
<td>65.09</td>
<td>2.11</td>
<td>-4.24</td>
<td>-21.50</td>
</tr>
<tr>
<td>69.09</td>
<td>1.57</td>
<td>-4.44</td>
<td></td>
</tr>
<tr>
<td>71.69</td>
<td>1.46</td>
<td>-5.31</td>
<td></td>
</tr>
<tr>
<td>75.49</td>
<td>1.80</td>
<td>-4.68</td>
<td></td>
</tr>
<tr>
<td>78.49</td>
<td>1.77</td>
<td>-5.02</td>
<td>-24.67</td>
</tr>
<tr>
<td>meters</td>
<td>$\delta^{13}$C$_{\text{carb}}$</td>
<td>$\delta^{18}$O$_{\text{carb}}$</td>
<td>Total C</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>--------</td>
</tr>
<tr>
<td>0.00</td>
<td>2.51</td>
<td>-1.87</td>
<td>9.70</td>
</tr>
<tr>
<td>0.50</td>
<td>2.57</td>
<td>-1.36</td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td>2.63</td>
<td>-2.35</td>
<td></td>
</tr>
<tr>
<td>1.50</td>
<td>2.67</td>
<td>-1.47</td>
<td></td>
</tr>
<tr>
<td>2.00</td>
<td>2.53</td>
<td>-3.46</td>
<td></td>
</tr>
<tr>
<td>2.50</td>
<td>2.54</td>
<td>-2.31</td>
<td></td>
</tr>
<tr>
<td>3.00</td>
<td>2.63</td>
<td>-1.55</td>
<td>11.15</td>
</tr>
<tr>
<td>3.50</td>
<td>2.41</td>
<td>-2.47</td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>2.42</td>
<td>-2.80</td>
<td></td>
</tr>
<tr>
<td>4.50</td>
<td>2.62</td>
<td>-1.52</td>
<td></td>
</tr>
<tr>
<td>5.00</td>
<td>2.61</td>
<td>-2.25</td>
<td></td>
</tr>
<tr>
<td>5.50</td>
<td>2.57</td>
<td>-2.19</td>
<td></td>
</tr>
<tr>
<td>6.00</td>
<td>2.57</td>
<td>-2.31</td>
<td></td>
</tr>
<tr>
<td>6.50</td>
<td>2.57</td>
<td>-3.14</td>
<td></td>
</tr>
<tr>
<td>7.00</td>
<td>2.33</td>
<td>-1.81</td>
<td></td>
</tr>
<tr>
<td>7.10</td>
<td>2.41</td>
<td>-1.24</td>
<td></td>
</tr>
<tr>
<td>7.50</td>
<td>2.46</td>
<td>-1.28</td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>2.44</td>
<td>-1.75</td>
<td></td>
</tr>
<tr>
<td>8.50</td>
<td>2.49</td>
<td>-1.80</td>
<td></td>
</tr>
<tr>
<td>9.00</td>
<td>2.37</td>
<td>-1.59</td>
<td></td>
</tr>
<tr>
<td>9.50</td>
<td>2.68</td>
<td>-1.63</td>
<td></td>
</tr>
<tr>
<td>10.00</td>
<td>2.24</td>
<td>-1.50</td>
<td></td>
</tr>
<tr>
<td>10.50</td>
<td>2.37</td>
<td>-1.84</td>
<td>9.17</td>
</tr>
<tr>
<td>11.00</td>
<td>2.26</td>
<td>-3.12</td>
<td></td>
</tr>
<tr>
<td>11.50</td>
<td>2.32</td>
<td>-2.43</td>
<td></td>
</tr>
<tr>
<td>12.00</td>
<td>2.33</td>
<td>-1.95</td>
<td></td>
</tr>
<tr>
<td>12.50</td>
<td>2.50</td>
<td>-2.41</td>
<td></td>
</tr>
<tr>
<td>13.00</td>
<td>2.57</td>
<td>-2.32</td>
<td></td>
</tr>
<tr>
<td>13.50</td>
<td>2.54</td>
<td>-2.72</td>
<td></td>
</tr>
<tr>
<td>14.00</td>
<td>2.37</td>
<td>-2.55</td>
<td></td>
</tr>
<tr>
<td>14.50</td>
<td>2.50</td>
<td>-2.51</td>
<td>10.55</td>
</tr>
<tr>
<td>15.00</td>
<td>2.45</td>
<td>-2.47</td>
<td></td>
</tr>
<tr>
<td>15.50</td>
<td>2.46</td>
<td>-2.52</td>
<td></td>
</tr>
<tr>
<td>16.00</td>
<td>2.60</td>
<td>-1.90</td>
<td></td>
</tr>
<tr>
<td>16.50</td>
<td>2.48</td>
<td>-1.79</td>
<td></td>
</tr>
<tr>
<td>17.00</td>
<td>2.33</td>
<td>-3.25</td>
<td></td>
</tr>
<tr>
<td>17.50</td>
<td>2.28</td>
<td>-4.15</td>
<td></td>
</tr>
<tr>
<td>18.00</td>
<td>2.11</td>
<td>-3.22</td>
<td></td>
</tr>
<tr>
<td>18.50</td>
<td>2.37</td>
<td>-2.61</td>
<td></td>
</tr>
<tr>
<td>19.00</td>
<td>2.11</td>
<td>-3.21</td>
<td></td>
</tr>
<tr>
<td>19.50</td>
<td>2.33</td>
<td>-2.24</td>
<td></td>
</tr>
<tr>
<td>20.00</td>
<td>2.22</td>
<td>-2.38</td>
<td></td>
</tr>
<tr>
<td>20.50</td>
<td>2.31</td>
<td>-2.29</td>
<td>10.99</td>
</tr>
<tr>
<td>21.00</td>
<td>2.23</td>
<td>-2.24</td>
<td></td>
</tr>
<tr>
<td>21.50</td>
<td>2.29</td>
<td>-1.79</td>
<td></td>
</tr>
<tr>
<td>22.00</td>
<td>2.40</td>
<td>-2.09</td>
<td></td>
</tr>
<tr>
<td>22.50</td>
<td>2.18</td>
<td>-2.37</td>
<td></td>
</tr>
<tr>
<td>23.00</td>
<td>2.23</td>
<td>-2.42</td>
<td></td>
</tr>
<tr>
<td>23.50</td>
<td>2.25</td>
<td>-2.08</td>
<td></td>
</tr>
<tr>
<td>24.00</td>
<td>2.18</td>
<td>-2.77</td>
<td></td>
</tr>
<tr>
<td>24.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>meters</td>
<td>$\delta^{13}C_{\text{carb}}$</td>
<td>$\delta^{18}O_{\text{carb}}$</td>
<td>Total C</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-------</td>
</tr>
<tr>
<td>25.00</td>
<td>2.26</td>
<td>-3.05</td>
<td>10.52</td>
</tr>
<tr>
<td>25.50</td>
<td>2.55</td>
<td>-2.33</td>
<td></td>
</tr>
<tr>
<td>26.00</td>
<td>2.35</td>
<td>-1.85</td>
<td></td>
</tr>
<tr>
<td>26.50</td>
<td>2.27</td>
<td>-2.18</td>
<td></td>
</tr>
<tr>
<td>27.00</td>
<td>2.16</td>
<td>-1.94</td>
<td></td>
</tr>
<tr>
<td>27.50</td>
<td>2.18</td>
<td>-1.78</td>
<td></td>
</tr>
<tr>
<td>28.00</td>
<td>2.31</td>
<td>-1.46</td>
<td></td>
</tr>
<tr>
<td>28.50</td>
<td>2.12</td>
<td>-2.03</td>
<td></td>
</tr>
<tr>
<td>29.00</td>
<td>2.17</td>
<td>-1.49</td>
<td>11.30</td>
</tr>
<tr>
<td>29.50</td>
<td>2.12</td>
<td>-1.65</td>
<td></td>
</tr>
<tr>
<td>30.00</td>
<td>1.75</td>
<td>-5.05</td>
<td></td>
</tr>
<tr>
<td>30.50</td>
<td>1.78</td>
<td>-3.71</td>
<td></td>
</tr>
<tr>
<td>31.00</td>
<td>2.06</td>
<td>-1.94</td>
<td></td>
</tr>
<tr>
<td>31.50</td>
<td>1.93</td>
<td>-2.09</td>
<td></td>
</tr>
<tr>
<td>32.00</td>
<td>2.14</td>
<td>-1.63</td>
<td></td>
</tr>
<tr>
<td>32.50</td>
<td>2.16</td>
<td>-2.50</td>
<td></td>
</tr>
<tr>
<td>33.00</td>
<td>2.28</td>
<td>-2.25</td>
<td>10.76</td>
</tr>
<tr>
<td>33.50</td>
<td>2.39</td>
<td>-1.33</td>
<td></td>
</tr>
<tr>
<td>34.00</td>
<td>2.18</td>
<td>-2.17</td>
<td></td>
</tr>
<tr>
<td>34.50</td>
<td>1.87</td>
<td>-4.53</td>
<td></td>
</tr>
<tr>
<td>35.00</td>
<td>1.86</td>
<td>-3.85</td>
<td></td>
</tr>
<tr>
<td>35.50</td>
<td>1.94</td>
<td>-2.74</td>
<td></td>
</tr>
<tr>
<td>36.00</td>
<td>2.01</td>
<td>-1.97</td>
<td></td>
</tr>
<tr>
<td>36.50</td>
<td>1.98</td>
<td>-1.74</td>
<td></td>
</tr>
<tr>
<td>37.00</td>
<td>2.03</td>
<td>-1.02</td>
<td></td>
</tr>
<tr>
<td>37.50</td>
<td>2.16</td>
<td>-1.30</td>
<td>10.62</td>
</tr>
<tr>
<td>38.00</td>
<td>1.96</td>
<td>-1.37</td>
<td></td>
</tr>
<tr>
<td>38.50</td>
<td>1.96</td>
<td>-1.88</td>
<td></td>
</tr>
<tr>
<td>39.00</td>
<td>1.94</td>
<td>-1.79</td>
<td></td>
</tr>
<tr>
<td>40.00</td>
<td>1.96</td>
<td>-1.19</td>
<td></td>
</tr>
<tr>
<td>40.50</td>
<td>2.32</td>
<td>-1.91</td>
<td></td>
</tr>
<tr>
<td>41.00</td>
<td>2.44</td>
<td>-0.83</td>
<td>10.26</td>
</tr>
<tr>
<td>41.50</td>
<td>2.23</td>
<td>-0.95</td>
<td></td>
</tr>
<tr>
<td>42.00</td>
<td>2.10</td>
<td>-1.09</td>
<td></td>
</tr>
<tr>
<td>42.50</td>
<td>2.06</td>
<td>-1.46</td>
<td></td>
</tr>
<tr>
<td>43.00</td>
<td>2.38</td>
<td>-0.77</td>
<td></td>
</tr>
<tr>
<td>45.00</td>
<td>2.17</td>
<td>-1.30</td>
<td>11.16</td>
</tr>
<tr>
<td>47.00</td>
<td>2.28</td>
<td>-0.80</td>
<td></td>
</tr>
<tr>
<td>49.00</td>
<td>2.48</td>
<td>-0.99</td>
<td>11.78</td>
</tr>
<tr>
<td>51.00</td>
<td>2.55</td>
<td>-1.62</td>
<td></td>
</tr>
<tr>
<td>53.00</td>
<td>2.44</td>
<td>-1.87</td>
<td>11.61</td>
</tr>
<tr>
<td>54.50</td>
<td>2.13</td>
<td>-1.74</td>
<td>11.52</td>
</tr>
<tr>
<td>54.86</td>
<td>2.31</td>
<td>-1.11</td>
<td></td>
</tr>
<tr>
<td>55.07</td>
<td>2.31</td>
<td>-1.32</td>
<td>11.42</td>
</tr>
<tr>
<td>55.15</td>
<td>2.13</td>
<td>-1.32</td>
<td>11.59</td>
</tr>
<tr>
<td>55.23</td>
<td>2.22</td>
<td>-1.21</td>
<td>11.35</td>
</tr>
<tr>
<td>55.27</td>
<td>2.58</td>
<td>-0.43</td>
<td></td>
</tr>
<tr>
<td>55.41</td>
<td>2.41</td>
<td>-1.38</td>
<td>11.46</td>
</tr>
<tr>
<td>55.49</td>
<td>2.39</td>
<td>-1.48</td>
<td>11.28</td>
</tr>
<tr>
<td>55.76</td>
<td>2.62</td>
<td>-0.70</td>
<td>11.55</td>
</tr>
<tr>
<td>meters</td>
<td>$\delta^{13}$C$_{\text{carb}}$</td>
<td>$\delta^{18}$O$_{\text{carb}}$</td>
<td>Total C</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>--------</td>
</tr>
<tr>
<td>55.98</td>
<td>2.03</td>
<td>-1.67</td>
<td>11.72</td>
</tr>
<tr>
<td>56.09</td>
<td>2.63</td>
<td>-0.47</td>
<td>11.79</td>
</tr>
<tr>
<td>56.28</td>
<td>2.48</td>
<td>-0.52</td>
<td>11.59</td>
</tr>
<tr>
<td>56.57</td>
<td>2.68</td>
<td>-0.21</td>
<td></td>
</tr>
<tr>
<td>56.93</td>
<td>2.63</td>
<td>-0.53</td>
<td></td>
</tr>
<tr>
<td>57.11</td>
<td>2.61</td>
<td>-0.41</td>
<td></td>
</tr>
<tr>
<td>57.27</td>
<td>2.56</td>
<td>-0.57</td>
<td></td>
</tr>
<tr>
<td>57.54</td>
<td>2.35</td>
<td>-0.71</td>
<td></td>
</tr>
<tr>
<td>57.73</td>
<td>2.52</td>
<td>-0.39</td>
<td></td>
</tr>
<tr>
<td>58.21</td>
<td>2.72</td>
<td>-0.40</td>
<td></td>
</tr>
<tr>
<td>58.46</td>
<td>2.48</td>
<td>-1.08</td>
<td></td>
</tr>
<tr>
<td>59.20</td>
<td>2.30</td>
<td>-2.11</td>
<td></td>
</tr>
<tr>
<td>59.93</td>
<td>2.31</td>
<td>-2.04</td>
<td></td>
</tr>
<tr>
<td>60.51</td>
<td>2.27</td>
<td>-2.25</td>
<td></td>
</tr>
<tr>
<td>61.25</td>
<td>2.53</td>
<td>-1.13</td>
<td></td>
</tr>
<tr>
<td>61.46</td>
<td>2.64</td>
<td>-0.84</td>
<td></td>
</tr>
<tr>
<td>62.40</td>
<td>2.81</td>
<td>-0.94</td>
<td></td>
</tr>
<tr>
<td>62.73</td>
<td>2.79</td>
<td>-0.81</td>
<td></td>
</tr>
<tr>
<td>63.12</td>
<td>2.67</td>
<td>-1.05</td>
<td></td>
</tr>
<tr>
<td>64.22</td>
<td>2.75</td>
<td>-0.79</td>
<td></td>
</tr>
<tr>
<td>64.51</td>
<td>2.52</td>
<td>-1.78</td>
<td></td>
</tr>
<tr>
<td>64.59</td>
<td>2.22</td>
<td>-1.60</td>
<td>11.76</td>
</tr>
<tr>
<td>65.59</td>
<td>1.94</td>
<td>-1.57</td>
<td></td>
</tr>
<tr>
<td>66.51</td>
<td>2.21</td>
<td>-0.94</td>
<td></td>
</tr>
<tr>
<td>66.59</td>
<td>2.04</td>
<td>-1.50</td>
<td></td>
</tr>
<tr>
<td>67.59</td>
<td>2.16</td>
<td>-1.01</td>
<td></td>
</tr>
<tr>
<td>68.59</td>
<td>2.24</td>
<td>-0.58</td>
<td></td>
</tr>
<tr>
<td>69.59</td>
<td>2.58</td>
<td>-0.40</td>
<td></td>
</tr>
<tr>
<td>70.59</td>
<td>2.33</td>
<td>-0.47</td>
<td></td>
</tr>
<tr>
<td>71.51</td>
<td>2.32</td>
<td>-1.18</td>
<td>10.96</td>
</tr>
<tr>
<td>71.59</td>
<td>2.15</td>
<td>-1.12</td>
<td></td>
</tr>
<tr>
<td>72.59</td>
<td>2.18</td>
<td>-1.25</td>
<td></td>
</tr>
<tr>
<td>73.59</td>
<td>2.18</td>
<td>-0.66</td>
<td></td>
</tr>
<tr>
<td>74.59</td>
<td>2.11</td>
<td>-0.61</td>
<td></td>
</tr>
<tr>
<td>76.59</td>
<td>2.01</td>
<td>-1.75</td>
<td></td>
</tr>
<tr>
<td>77.59</td>
<td>2.12</td>
<td>-1.16</td>
<td></td>
</tr>
<tr>
<td>78.09</td>
<td>2.07</td>
<td>-1.28</td>
<td></td>
</tr>
<tr>
<td>78.59</td>
<td>2.07</td>
<td>-1.18</td>
<td></td>
</tr>
<tr>
<td>79.09</td>
<td>2.03</td>
<td>-2.16</td>
<td></td>
</tr>
<tr>
<td>79.59</td>
<td>2.02</td>
<td>-1.84</td>
<td></td>
</tr>
<tr>
<td>80.09</td>
<td>2.05</td>
<td>-1.29</td>
<td></td>
</tr>
<tr>
<td>80.59</td>
<td>1.96</td>
<td>-2.31</td>
<td></td>
</tr>
<tr>
<td>81.09</td>
<td>1.99</td>
<td>-2.39</td>
<td></td>
</tr>
<tr>
<td>81.59</td>
<td>1.91</td>
<td>-2.39</td>
<td></td>
</tr>
<tr>
<td>82.09</td>
<td>1.68</td>
<td>-2.58</td>
<td></td>
</tr>
<tr>
<td>83.09</td>
<td>2.04</td>
<td>-2.16</td>
<td></td>
</tr>
<tr>
<td>83.59</td>
<td>2.03</td>
<td>-2.00</td>
<td></td>
</tr>
<tr>
<td>84.09</td>
<td>1.92</td>
<td>-2.11</td>
<td></td>
</tr>
<tr>
<td>84.09</td>
<td>2.00</td>
<td>-2.35</td>
<td></td>
</tr>
<tr>
<td>84.59</td>
<td>1.96</td>
<td>-2.15</td>
<td></td>
</tr>
<tr>
<td>meters</td>
<td>$\delta^{13}$C$_{org}$</td>
<td>$\delta^{18}$O$_{carb}$</td>
<td>$\delta^{13}$C$_{carb}$</td>
</tr>
<tr>
<td>--------</td>
<td>------------------</td>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>2.30</td>
<td>1.36</td>
<td>-5.01</td>
<td>-23.11</td>
</tr>
<tr>
<td>3.10</td>
<td>1.94</td>
<td>-4.40</td>
<td>-23.23</td>
</tr>
<tr>
<td>4.70</td>
<td>1.63</td>
<td>-5.47</td>
<td>-22.86</td>
</tr>
<tr>
<td>6.10</td>
<td>2.34</td>
<td>-4.23</td>
<td>-23.36</td>
</tr>
<tr>
<td>7.30</td>
<td>1.64</td>
<td>-5.17</td>
<td>-22.86</td>
</tr>
<tr>
<td>8.80</td>
<td>2.02</td>
<td>-4.78</td>
<td>-23.35</td>
</tr>
<tr>
<td>10.30</td>
<td>1.91</td>
<td>-4.48</td>
<td>-23.28</td>
</tr>
<tr>
<td>11.30</td>
<td>2.32</td>
<td>-4.21</td>
<td>-23.32</td>
</tr>
<tr>
<td>12.80</td>
<td>1.08</td>
<td>-3.64</td>
<td>-23.46</td>
</tr>
<tr>
<td>14.58</td>
<td>1.97</td>
<td>-5.35</td>
<td>-23.53</td>
</tr>
<tr>
<td>16.28</td>
<td>1.88</td>
<td>-4.47</td>
<td>-23.25</td>
</tr>
<tr>
<td>18.23</td>
<td>2.34</td>
<td>-4.97</td>
<td>-23.22</td>
</tr>
<tr>
<td>19.53</td>
<td>1.91</td>
<td>-4.51</td>
<td>-22.50</td>
</tr>
<tr>
<td>20.83</td>
<td>2.38</td>
<td>-4.98</td>
<td>-22.98</td>
</tr>
<tr>
<td>22.03</td>
<td>2.27</td>
<td>-5.79</td>
<td>-23.16</td>
</tr>
<tr>
<td>23.13</td>
<td>2.53</td>
<td>-4.83</td>
<td>-22.97</td>
</tr>
<tr>
<td>24.28</td>
<td>2.33</td>
<td>-5.51</td>
<td>-23.19</td>
</tr>
<tr>
<td>26.28</td>
<td>2.37</td>
<td>-5.22</td>
<td>-23.87</td>
</tr>
<tr>
<td>27.58</td>
<td>1.29</td>
<td>-4.66</td>
<td>-23.52</td>
</tr>
<tr>
<td>29.38</td>
<td>2.10</td>
<td>-5.66</td>
<td>-22.84</td>
</tr>
<tr>
<td>30.78</td>
<td>2.10</td>
<td>-5.60</td>
<td>-22.52</td>
</tr>
<tr>
<td>32.58</td>
<td>2.23</td>
<td>-4.77</td>
<td>-23.42</td>
</tr>
<tr>
<td>37.20</td>
<td>2.75</td>
<td>-4.30</td>
<td>-23.19</td>
</tr>
<tr>
<td>38.25</td>
<td>1.70</td>
<td>-3.25</td>
<td>-23.09</td>
</tr>
<tr>
<td>38.84</td>
<td>2.35</td>
<td>-4.60</td>
<td>-23.81</td>
</tr>
<tr>
<td>39.48</td>
<td>2.13</td>
<td>-4.98</td>
<td>-23.12</td>
</tr>
<tr>
<td>40.05</td>
<td>2.34</td>
<td>-4.48</td>
<td>-23.42</td>
</tr>
<tr>
<td>36.95</td>
<td>1.32</td>
<td>-2.39</td>
<td>-24.39</td>
</tr>
<tr>
<td>38.25</td>
<td>0.71</td>
<td>-2.04</td>
<td>-23.33</td>
</tr>
<tr>
<td>40.25</td>
<td>2.06</td>
<td>-4.32</td>
<td>-24.69</td>
</tr>
<tr>
<td>41.45</td>
<td>0.40</td>
<td>-1.72</td>
<td></td>
</tr>
<tr>
<td>42.55</td>
<td>-1.96</td>
<td>-1.37</td>
<td>-25.86</td>
</tr>
<tr>
<td>43.85</td>
<td>1.12</td>
<td>-1.82</td>
<td></td>
</tr>
<tr>
<td>45.80</td>
<td>-0.34</td>
<td>-1.66</td>
<td>-24.17</td>
</tr>
<tr>
<td>47.57</td>
<td>-1.60</td>
<td>-0.63</td>
<td></td>
</tr>
<tr>
<td>48.31</td>
<td>-1.54</td>
<td>-0.91</td>
<td>-26.51</td>
</tr>
<tr>
<td>49.19</td>
<td>0.51</td>
<td>-1.81</td>
<td>-24.58</td>
</tr>
<tr>
<td>49.83</td>
<td>-0.56</td>
<td>-0.90</td>
<td>-23.11</td>
</tr>
<tr>
<td>50.67</td>
<td>-0.52</td>
<td>-0.65</td>
<td>-24.28</td>
</tr>
<tr>
<td>51.18</td>
<td>0.54</td>
<td>-1.65</td>
<td>-24.97</td>
</tr>
<tr>
<td>51.57</td>
<td>0.71</td>
<td>-0.75</td>
<td>-24.17</td>
</tr>
<tr>
<td>52.00</td>
<td>0.59</td>
<td>-1.38</td>
<td></td>
</tr>
<tr>
<td>53.32</td>
<td>1.08</td>
<td>-1.85</td>
<td>-26.12</td>
</tr>
<tr>
<td>54.17</td>
<td>1.55</td>
<td>-2.11</td>
<td>-24.44</td>
</tr>
<tr>
<td>55.16</td>
<td>1.38</td>
<td>-0.81</td>
<td>-26.13</td>
</tr>
<tr>
<td>56.74</td>
<td>1.70</td>
<td>-1.33</td>
<td>-25.05</td>
</tr>
<tr>
<td>57.48</td>
<td>1.37</td>
<td>-1.76</td>
<td>-24.78</td>
</tr>
<tr>
<td>58.38</td>
<td>1.99</td>
<td>-1.70</td>
<td>-24.00</td>
</tr>
<tr>
<td>59.66</td>
<td>2.08</td>
<td>-2.16</td>
<td></td>
</tr>
</tbody>
</table>
### Vergons

<table>
<thead>
<tr>
<th>meters</th>
<th>$\delta^{13}$C$_{\text{carb}}$</th>
<th>$\delta^{18}$O$_{\text{carb}}$</th>
<th>$\delta^{13}$C$_{\text{org}}$</th>
<th>Total C</th>
<th>CaCO$_3$ %</th>
<th>TOC %</th>
</tr>
</thead>
<tbody>
<tr>
<td>61.17</td>
<td>2.24</td>
<td>-1.90</td>
<td>-24.79</td>
<td>10.78</td>
<td>9.29</td>
<td></td>
</tr>
<tr>
<td>63.13</td>
<td>2.32</td>
<td>-2.10</td>
<td></td>
<td>9.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>64.87</td>
<td>2.49</td>
<td>-2.00</td>
<td>-24.44</td>
<td>10.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>67.40</td>
<td>2.47</td>
<td>-2.65</td>
<td></td>
<td>9.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>69.32</td>
<td>2.82</td>
<td>-2.04</td>
<td>-24.72</td>
<td>9.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>71.02</td>
<td>2.82</td>
<td>-2.01</td>
<td>-24.51</td>
<td>10.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72.47</td>
<td>2.83</td>
<td>-1.84</td>
<td>-25.21</td>
<td>9.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73.88</td>
<td>2.90</td>
<td>-1.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Consolacao

<table>
<thead>
<tr>
<th>meters</th>
<th>$\delta^{13}$C$_{\text{carb}}$</th>
<th>$\delta^{18}$O$_{\text{carb}}$</th>
<th>Total C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.73</td>
<td>-5.53</td>
<td>9.97</td>
</tr>
<tr>
<td>1.35</td>
<td>0.78</td>
<td>-6.55</td>
<td>5.92</td>
</tr>
<tr>
<td>4.05</td>
<td>-0.48</td>
<td>-5.51</td>
<td>5.01</td>
</tr>
<tr>
<td>4.90</td>
<td>0.67</td>
<td>-6.73</td>
<td>8.81</td>
</tr>
<tr>
<td>5.42</td>
<td>0.38</td>
<td>-5.54</td>
<td>6.45</td>
</tr>
<tr>
<td>8.47</td>
<td>1.02</td>
<td>-5.48</td>
<td>8.90</td>
</tr>
<tr>
<td>8.47</td>
<td>0.69</td>
<td>-5.85</td>
<td>7.96</td>
</tr>
<tr>
<td>8.57</td>
<td>1.38</td>
<td>-5.59</td>
<td>10.97</td>
</tr>
<tr>
<td>9.82</td>
<td>1.51</td>
<td>-6.45</td>
<td>11.33</td>
</tr>
<tr>
<td>11.42</td>
<td>-0.41</td>
<td>-5.47</td>
<td>4.32</td>
</tr>
<tr>
<td>11.87</td>
<td>0.42</td>
<td>-6.26</td>
<td>5.23</td>
</tr>
<tr>
<td>13.37</td>
<td>0.84</td>
<td>-5.95</td>
<td>11.69</td>
</tr>
<tr>
<td>14.02</td>
<td>1.51</td>
<td>-5.56</td>
<td>6.58</td>
</tr>
<tr>
<td>17.53</td>
<td>-1.42</td>
<td>-5.03</td>
<td>8.16</td>
</tr>
<tr>
<td>18.57</td>
<td>-2.19</td>
<td>-5.65</td>
<td>6.11</td>
</tr>
<tr>
<td>19.62</td>
<td>1.17</td>
<td>-5.70</td>
<td>4.12</td>
</tr>
<tr>
<td>21.24</td>
<td>-0.51</td>
<td>-6.62</td>
<td>4.58</td>
</tr>
<tr>
<td>22.14</td>
<td>-0.48</td>
<td>-4.91</td>
<td>8.02</td>
</tr>
<tr>
<td>25.79</td>
<td>-0.15</td>
<td>-5.29</td>
<td>8.00</td>
</tr>
<tr>
<td>32.89</td>
<td>0.77</td>
<td>-6.20</td>
<td>10.42</td>
</tr>
<tr>
<td>33.52</td>
<td>0.86</td>
<td>-5.50</td>
<td>10.12</td>
</tr>
<tr>
<td>43.77</td>
<td>-0.29</td>
<td>-6.47</td>
<td>5.66</td>
</tr>
</tbody>
</table>

### Montejunto

<table>
<thead>
<tr>
<th>meters</th>
<th>$\delta^{13}$C$_{\text{carb}}$</th>
<th>$\delta^{18}$O$_{\text{carb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>2.47</td>
<td>-3.52</td>
</tr>
<tr>
<td>2.00</td>
<td>2.35</td>
<td>-5.05</td>
</tr>
<tr>
<td>4.00</td>
<td>2.12</td>
<td>-4.49</td>
</tr>
<tr>
<td>6.00</td>
<td>2.07</td>
<td>-4.87</td>
</tr>
<tr>
<td>8.00</td>
<td>1.82</td>
<td>-4.90</td>
</tr>
<tr>
<td>10.00</td>
<td>1.76</td>
<td>-5.15</td>
</tr>
<tr>
<td>meters</td>
<td>$\delta^{13}C_{\text{carb}}$</td>
<td>$\delta^{18}O_{\text{carb}}$</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>0.79</td>
<td>-0.91</td>
<td>-6.66</td>
</tr>
<tr>
<td>4.43</td>
<td>0.77</td>
<td>-4.39</td>
</tr>
<tr>
<td>5.43</td>
<td>1.30</td>
<td>-3.35</td>
</tr>
<tr>
<td>7.36</td>
<td>1.32</td>
<td>-3.90</td>
</tr>
<tr>
<td>8.81</td>
<td>1.81</td>
<td>-2.81</td>
</tr>
<tr>
<td>11.90</td>
<td>0.30</td>
<td>-4.13</td>
</tr>
<tr>
<td>15.64</td>
<td>1.64</td>
<td>-3.12</td>
</tr>
<tr>
<td>18.64</td>
<td>0.51</td>
<td>-4.36</td>
</tr>
<tr>
<td>26.36</td>
<td>1.18</td>
<td>-4.06</td>
</tr>
<tr>
<td>29.76</td>
<td>1.91</td>
<td>-3.47</td>
</tr>
<tr>
<td>29.76</td>
<td>2.14</td>
<td>-3.65</td>
</tr>
<tr>
<td>35.07</td>
<td>2.18</td>
<td>-3.00</td>
</tr>
<tr>
<td>37.19</td>
<td>1.61</td>
<td>-4.10</td>
</tr>
<tr>
<td>39.79</td>
<td>0.50</td>
<td>-4.85</td>
</tr>
<tr>
<td>40.64</td>
<td>0.79</td>
<td>-4.62</td>
</tr>
<tr>
<td>44.50</td>
<td>0.66</td>
<td>-4.57</td>
</tr>
<tr>
<td>47.14</td>
<td>0.36</td>
<td>-4.02</td>
</tr>
<tr>
<td>50.14</td>
<td>0.88</td>
<td>-3.24</td>
</tr>
<tr>
<td>52.21</td>
<td>1.07</td>
<td>-4.64</td>
</tr>
<tr>
<td>55.29</td>
<td>0.96</td>
<td>-2.00</td>
</tr>
<tr>
<td>57.14</td>
<td>-0.48</td>
<td>-4.14</td>
</tr>
<tr>
<td>57.64</td>
<td>1.19</td>
<td>-3.77</td>
</tr>
<tr>
<td>61.21</td>
<td>1.51</td>
<td>-3.74</td>
</tr>
<tr>
<td>63.93</td>
<td>0.45</td>
<td>-3.66</td>
</tr>
<tr>
<td>68.47</td>
<td>1.23</td>
<td>-3.56</td>
</tr>
<tr>
<td>71.93</td>
<td>-0.97</td>
<td>-5.74</td>
</tr>
<tr>
<td>75.24</td>
<td>-1.24</td>
<td>-5.72</td>
</tr>
<tr>
<td>79.93</td>
<td>-0.59</td>
<td>-5.69</td>
</tr>
<tr>
<td>87.64</td>
<td>-0.50</td>
<td>-4.12</td>
</tr>
<tr>
<td>89.43</td>
<td>-2.09</td>
<td>-3.71</td>
</tr>
<tr>
<td>90.00</td>
<td>0.27</td>
<td>-4.57</td>
</tr>
<tr>
<td>93.50</td>
<td>-2.64</td>
<td>-5.50</td>
</tr>
<tr>
<td>106.43</td>
<td>-1.65</td>
<td>-5.69</td>
</tr>
<tr>
<td>109.50</td>
<td>-1.40</td>
<td>-5.67</td>
</tr>
<tr>
<td>113.07</td>
<td>-3.48</td>
<td>-5.95</td>
</tr>
<tr>
<td>117.14</td>
<td>-1.49</td>
<td>-6.55</td>
</tr>
<tr>
<td>119.64</td>
<td>-0.77</td>
<td>-6.74</td>
</tr>
<tr>
<td>122.86</td>
<td>-1.66</td>
<td>-6.74</td>
</tr>
<tr>
<td>125.93</td>
<td>-0.32</td>
<td>-5.38</td>
</tr>
<tr>
<td>129.43</td>
<td>-1.04</td>
<td>-5.11</td>
</tr>
<tr>
<td>132.93</td>
<td>-1.63</td>
<td>-5.35</td>
</tr>
<tr>
<td>135.07</td>
<td>0.98</td>
<td>-3.20</td>
</tr>
<tr>
<td>139.14</td>
<td>-0.39</td>
<td>-4.97</td>
</tr>
<tr>
<td>141.57</td>
<td>-1.02</td>
<td>-5.32</td>
</tr>
<tr>
<td>144.64</td>
<td>-0.53</td>
<td>-5.40</td>
</tr>
<tr>
<td>146.57</td>
<td>-0.72</td>
<td>-4.30</td>
</tr>
<tr>
<td>149.64</td>
<td>-0.88</td>
<td>-4.44</td>
</tr>
<tr>
<td>155.00</td>
<td>-2.07</td>
<td>-5.74</td>
</tr>
<tr>
<td>158.00</td>
<td>-1.97</td>
<td>-6.29</td>
</tr>
<tr>
<td>164.93</td>
<td>-3.30</td>
<td>-6.55</td>
</tr>
<tr>
<td>PICHOUX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>meters</td>
<td>(\delta^{13}C_{\text{carb}})</td>
<td>(\delta^{18}O_{\text{carb}})</td>
</tr>
<tr>
<td>172.21</td>
<td>-1.54</td>
<td>-5.94</td>
</tr>
<tr>
<td>174.03</td>
<td>-1.99</td>
<td>-5.43</td>
</tr>
<tr>
<td>175.40</td>
<td>-0.70</td>
<td>-6.00</td>
</tr>
<tr>
<td>177.93</td>
<td>-0.85</td>
<td>-4.56</td>
</tr>
<tr>
<td>178.64</td>
<td>-0.82</td>
<td>-4.53</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RAWYL</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>meters</td>
<td>(\delta^{13}C_{\text{carb}})</td>
<td>(\delta^{18}O_{\text{carb}})</td>
<td>Total C</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>2.77</td>
<td>-3.92</td>
<td>11.30</td>
<td></td>
</tr>
<tr>
<td>1.10</td>
<td>2.81</td>
<td>-3.55</td>
<td>11.62</td>
<td></td>
</tr>
<tr>
<td>3.50</td>
<td>2.69</td>
<td>-3.75</td>
<td>11.49</td>
<td></td>
</tr>
<tr>
<td>5.10</td>
<td>2.65</td>
<td>-3.40</td>
<td>11.70</td>
<td></td>
</tr>
<tr>
<td>7.00</td>
<td>2.55</td>
<td>-3.35</td>
<td>11.71</td>
<td></td>
</tr>
<tr>
<td>9.50</td>
<td>2.51</td>
<td>-3.51</td>
<td>11.01</td>
<td></td>
</tr>
<tr>
<td>10.00</td>
<td>2.42</td>
<td>-3.59</td>
<td>11.58</td>
<td></td>
</tr>
<tr>
<td>12.80</td>
<td>2.62</td>
<td>-3.55</td>
<td>11.44</td>
<td></td>
</tr>
<tr>
<td>15.75</td>
<td>2.82</td>
<td>-3.46</td>
<td>11.64</td>
<td></td>
</tr>
<tr>
<td>18.75</td>
<td>2.67</td>
<td>-3.50</td>
<td>11.59</td>
<td></td>
</tr>
<tr>
<td>19.50</td>
<td>2.66</td>
<td>-3.50</td>
<td>11.46</td>
<td></td>
</tr>
<tr>
<td>21.10</td>
<td>2.52</td>
<td>-3.28</td>
<td>11.48</td>
<td></td>
</tr>
<tr>
<td>26.50</td>
<td>2.71</td>
<td>-3.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.20</td>
<td>2.87</td>
<td>-3.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33.75</td>
<td>2.32</td>
<td>-2.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34.75</td>
<td>2.81</td>
<td>-3.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.40</td>
<td>2.89</td>
<td>-3.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41.10</td>
<td>2.94</td>
<td>-3.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>44.80</td>
<td>2.85</td>
<td>-3.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46.50</td>
<td>2.85</td>
<td>-3.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>47.20</td>
<td>2.74</td>
<td>-3.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50.10</td>
<td>2.57</td>
<td>-3.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>54.10</td>
<td>2.20</td>
<td>-3.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>58.50</td>
<td>2.74</td>
<td>-3.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>63.80</td>
<td>2.55</td>
<td>-3.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>85.25</td>
<td>2.04</td>
<td>-3.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>88.10</td>
<td>2.39</td>
<td>-3.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>92.10</td>
<td>2.06</td>
<td>-2.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>94.50</td>
<td>2.00</td>
<td>-3.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>105.10</td>
<td>2.15</td>
<td>-3.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>106.60</td>
<td>2.03</td>
<td>-2.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>107.20</td>
<td>2.01</td>
<td>-4.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>108.80</td>
<td>2.34</td>
<td>-4.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>111.75</td>
<td>1.85</td>
<td>-3.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>113.75</td>
<td>1.93</td>
<td>-3.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>meters</td>
<td>$\delta^{13}$C_{carb}</td>
<td>$\delta^{18}$O_{carb}</td>
<td>Total C</td>
<td>CaCO$_3$ %</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------</td>
<td>----------------------</td>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>0.00</td>
<td>2.53</td>
<td>-1.36</td>
<td>11.72</td>
<td>96.59</td>
</tr>
<tr>
<td>0.90</td>
<td>2.45</td>
<td>-1.20</td>
<td>11.70</td>
<td>95.54</td>
</tr>
<tr>
<td>1.50</td>
<td>2.39</td>
<td>-1.09</td>
<td>11.37</td>
<td>93.17</td>
</tr>
<tr>
<td>1.75</td>
<td>2.40</td>
<td>-2.15</td>
<td>11.79</td>
<td>97.06</td>
</tr>
<tr>
<td>3.05</td>
<td>2.21</td>
<td>-0.98</td>
<td>11.63</td>
<td>95.07</td>
</tr>
<tr>
<td>5.30</td>
<td>2.44</td>
<td>-1.63</td>
<td>11.65</td>
<td>95.00</td>
</tr>
<tr>
<td>5.60</td>
<td>2.20</td>
<td>-0.94</td>
<td>11.61</td>
<td>96.42</td>
</tr>
<tr>
<td>5.90</td>
<td>2.13</td>
<td>-1.10</td>
<td>11.37</td>
<td>95.19</td>
</tr>
<tr>
<td>6.40</td>
<td>2.03</td>
<td>-1.41</td>
<td>11.58</td>
<td>97.51</td>
</tr>
<tr>
<td>6.80</td>
<td>2.12</td>
<td>-1.66</td>
<td>11.48</td>
<td>95.63</td>
</tr>
<tr>
<td>7.30</td>
<td>2.06</td>
<td>-0.95</td>
<td>11.75</td>
<td>96.28</td>
</tr>
<tr>
<td>7.70</td>
<td>2.05</td>
<td>-0.60</td>
<td>11.68</td>
<td>95.83</td>
</tr>
<tr>
<td>8.50</td>
<td>1.95</td>
<td>-1.39</td>
<td>11.74</td>
<td>96.13</td>
</tr>
<tr>
<td>10.10</td>
<td>1.98</td>
<td>-0.34</td>
<td>11.81</td>
<td>98.84</td>
</tr>
<tr>
<td>11.00</td>
<td>1.89</td>
<td>-0.56</td>
<td>11.81</td>
<td>98.49</td>
</tr>
<tr>
<td>12.00</td>
<td>1.81</td>
<td>-1.39</td>
<td>11.69</td>
<td>98.41</td>
</tr>
<tr>
<td>12.50</td>
<td>1.71</td>
<td>-1.06</td>
<td>11.56</td>
<td>94.85</td>
</tr>
<tr>
<td>13.40</td>
<td>1.82</td>
<td>-1.18</td>
<td>11.62</td>
<td>96.06</td>
</tr>
<tr>
<td>13.90</td>
<td>1.65</td>
<td>-1.25</td>
<td>11.75</td>
<td>95.16</td>
</tr>
<tr>
<td>14.30</td>
<td>1.58</td>
<td>-1.04</td>
<td>11.88</td>
<td>99.17</td>
</tr>
<tr>
<td>15.00</td>
<td>1.53</td>
<td>-1.11</td>
<td>11.85</td>
<td>99.24</td>
</tr>
<tr>
<td>15.20</td>
<td>1.62</td>
<td>-1.30</td>
<td>11.92</td>
<td>98.61</td>
</tr>
<tr>
<td>15.90</td>
<td>1.64</td>
<td>-1.66</td>
<td>11.81</td>
<td>99.12</td>
</tr>
<tr>
<td>16.30</td>
<td>1.56</td>
<td>-1.56</td>
<td>11.69</td>
<td>97.06</td>
</tr>
<tr>
<td>17.00</td>
<td>1.67</td>
<td>-1.27</td>
<td>11.87</td>
<td>98.35</td>
</tr>
<tr>
<td>17.40</td>
<td>1.63</td>
<td>-1.53</td>
<td>11.85</td>
<td>99.10</td>
</tr>
<tr>
<td>17.80</td>
<td>1.52</td>
<td>-1.61</td>
<td>11.59</td>
<td>97.02</td>
</tr>
</tbody>
</table>
# DSDP LEG 27 SITE 261

<table>
<thead>
<tr>
<th>core</th>
<th>section</th>
<th>upper cm</th>
<th>lower cm</th>
<th>$\delta^{13}C_{\text{carb}}$</th>
<th>$\delta^{18}O_{\text{carb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>4</td>
<td>63</td>
<td>64</td>
<td>-0.33</td>
<td>-3.18</td>
</tr>
<tr>
<td>31</td>
<td>4</td>
<td>93</td>
<td>94</td>
<td>0.47</td>
<td>-3.68</td>
</tr>
<tr>
<td>31</td>
<td>5</td>
<td>140</td>
<td>141</td>
<td>1.36</td>
<td>-2.59</td>
</tr>
<tr>
<td>32</td>
<td>1</td>
<td>140</td>
<td>141</td>
<td>1.54</td>
<td>-1.71</td>
</tr>
<tr>
<td>32</td>
<td>2</td>
<td>44</td>
<td>45</td>
<td>1.69</td>
<td>-1.72</td>
</tr>
<tr>
<td>32</td>
<td>2</td>
<td>94</td>
<td>95</td>
<td>2.00</td>
<td>-1.36</td>
</tr>
<tr>
<td>32</td>
<td>3</td>
<td>11</td>
<td>12</td>
<td>1.45</td>
<td>-2.28</td>
</tr>
<tr>
<td>32</td>
<td>3</td>
<td>44</td>
<td>45</td>
<td>1.21</td>
<td>-2.70</td>
</tr>
<tr>
<td>32</td>
<td>3</td>
<td>86</td>
<td>87</td>
<td>1.24</td>
<td>-2.69</td>
</tr>
<tr>
<td>32</td>
<td>3</td>
<td>133</td>
<td>134</td>
<td>2.91</td>
<td>-1.71</td>
</tr>
<tr>
<td>32</td>
<td>4</td>
<td>47</td>
<td>48</td>
<td>2.61</td>
<td>-1.84</td>
</tr>
<tr>
<td>32</td>
<td>4</td>
<td>90</td>
<td>92</td>
<td>2.01</td>
<td>-2.61</td>
</tr>
<tr>
<td>32</td>
<td>4</td>
<td>138</td>
<td>140</td>
<td>2.35</td>
<td>-2.70</td>
</tr>
</tbody>
</table>

# DSDP LEG 6 SITE 49

<table>
<thead>
<tr>
<th>core</th>
<th>section</th>
<th>upper cm</th>
<th>lower cm</th>
<th>$\delta^{13}C_{\text{carb}}$</th>
<th>$\delta^{18}O_{\text{carb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>22</td>
<td>24</td>
<td>2.92</td>
<td>-1.47</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>51</td>
<td>53</td>
<td>2.79</td>
<td>-1.46</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>84</td>
<td>86</td>
<td>2.72</td>
<td>-1.35</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>110</td>
<td>112</td>
<td>2.84</td>
<td>-1.76</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>24</td>
<td>26</td>
<td>2.52</td>
<td>-1.02</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>52</td>
<td>54</td>
<td>2.46</td>
<td>-0.88</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>84</td>
<td>86</td>
<td>2.59</td>
<td>-1.90</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>108</td>
<td>110</td>
<td>2.86</td>
<td>-1.79</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>22</td>
<td>24</td>
<td>2.78</td>
<td>-1.43</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>56</td>
<td>58</td>
<td>2.70</td>
<td>-1.36</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>81</td>
<td>83</td>
<td>2.66</td>
<td>-1.32</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>111</td>
<td>113</td>
<td>2.41</td>
<td>-0.95</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>143</td>
<td>145</td>
<td>2.66</td>
<td>-1.61</td>
</tr>
<tr>
<td>core</td>
<td>section</td>
<td>upper cm</td>
<td>lower cm</td>
<td>δ¹³C&lt;sub&gt;carb&lt;/sub&gt;</td>
<td>δ¹⁵O&lt;sub&gt;carb&lt;/sub&gt;</td>
</tr>
<tr>
<td>------</td>
<td>---------</td>
<td>----------</td>
<td>----------</td>
<td>---------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>34</td>
<td>2</td>
<td>16</td>
<td>17</td>
<td>1.80</td>
<td>-0.65</td>
</tr>
<tr>
<td>34</td>
<td>cc</td>
<td>0</td>
<td>1</td>
<td>1.67</td>
<td>-1.08</td>
</tr>
<tr>
<td>35</td>
<td>1</td>
<td>118</td>
<td>119</td>
<td>1.52</td>
<td>-1.21</td>
</tr>
<tr>
<td>35</td>
<td>1</td>
<td>140</td>
<td>141</td>
<td>1.57</td>
<td>-1.25</td>
</tr>
<tr>
<td>35</td>
<td>2</td>
<td>32</td>
<td>33</td>
<td>1.65</td>
<td>-1.03</td>
</tr>
<tr>
<td>35</td>
<td>2</td>
<td>104</td>
<td>105</td>
<td>1.64</td>
<td>-1.09</td>
</tr>
<tr>
<td>35</td>
<td>2</td>
<td>134</td>
<td>135</td>
<td>2.45</td>
<td>-0.88</td>
</tr>
<tr>
<td>35</td>
<td>3</td>
<td>17</td>
<td>18</td>
<td>2.15</td>
<td>-2.28</td>
</tr>
<tr>
<td>35</td>
<td>3</td>
<td>46</td>
<td>47</td>
<td>1.97</td>
<td>-2.41</td>
</tr>
<tr>
<td>35</td>
<td>3</td>
<td>88</td>
<td>89</td>
<td>2.43</td>
<td>-0.80</td>
</tr>
<tr>
<td>35</td>
<td>3</td>
<td>117</td>
<td>118</td>
<td>2.39</td>
<td>-1.25</td>
</tr>
<tr>
<td>35</td>
<td>4</td>
<td>16</td>
<td>17</td>
<td>1.98</td>
<td>-1.54</td>
</tr>
<tr>
<td>35</td>
<td>4</td>
<td>48</td>
<td>49</td>
<td>2.18</td>
<td>-1.33</td>
</tr>
<tr>
<td>35</td>
<td>4</td>
<td>120</td>
<td>121</td>
<td>2.51</td>
<td>-1.16</td>
</tr>
<tr>
<td>35</td>
<td>4</td>
<td>143</td>
<td>144</td>
<td>2.09</td>
<td>-2.08</td>
</tr>
<tr>
<td>36</td>
<td>1</td>
<td>123</td>
<td>124</td>
<td>2.14</td>
<td>-1.64</td>
</tr>
<tr>
<td>36</td>
<td>2</td>
<td>8</td>
<td>9</td>
<td>1.86</td>
<td>-0.85</td>
</tr>
<tr>
<td>36</td>
<td>2</td>
<td>36</td>
<td>37</td>
<td>2.18</td>
<td>-0.97</td>
</tr>
<tr>
<td>36</td>
<td>2</td>
<td>62</td>
<td>63</td>
<td>2.16</td>
<td>-0.95</td>
</tr>
<tr>
<td>36</td>
<td>2</td>
<td>105</td>
<td>106</td>
<td>1.52</td>
<td>-2.23</td>
</tr>
<tr>
<td>36</td>
<td>2</td>
<td>140</td>
<td>141</td>
<td>1.93</td>
<td>-1.59</td>
</tr>
<tr>
<td>36</td>
<td>3</td>
<td>26</td>
<td>27</td>
<td>1.91</td>
<td>-1.27</td>
</tr>
<tr>
<td>36</td>
<td>3</td>
<td>52</td>
<td>53</td>
<td>1.67</td>
<td>-2.10</td>
</tr>
<tr>
<td>36</td>
<td>3</td>
<td>89</td>
<td>90</td>
<td>2.14</td>
<td>-1.81</td>
</tr>
<tr>
<td>36</td>
<td>3</td>
<td>112</td>
<td>113</td>
<td>2.09</td>
<td>-2.26</td>
</tr>
<tr>
<td>36</td>
<td>cc</td>
<td>0</td>
<td>1</td>
<td>2.06</td>
<td>-1.94</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>12</td>
<td>13</td>
<td>1.98</td>
<td>-1.86</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>44</td>
<td>45</td>
<td>1.70</td>
<td>-3.10</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>73</td>
<td>74</td>
<td>2.18</td>
<td>-1.37</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>105</td>
<td>106</td>
<td>1.57</td>
<td>-2.67</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>144</td>
<td>145</td>
<td>1.59</td>
<td>-2.67</td>
</tr>
<tr>
<td>37</td>
<td>2</td>
<td>18</td>
<td>19</td>
<td>1.15</td>
<td>-1.64</td>
</tr>
<tr>
<td>37</td>
<td>2</td>
<td>49</td>
<td>50</td>
<td>1.77</td>
<td>-1.74</td>
</tr>
<tr>
<td>37</td>
<td>2</td>
<td>76</td>
<td>77</td>
<td>2.31</td>
<td>-1.04</td>
</tr>
<tr>
<td>37</td>
<td>2</td>
<td>100</td>
<td>101</td>
<td>1.78</td>
<td>-1.92</td>
</tr>
<tr>
<td>37</td>
<td>2</td>
<td>137</td>
<td>138</td>
<td>1.96</td>
<td>-1.54</td>
</tr>
<tr>
<td>37</td>
<td>3</td>
<td>12</td>
<td>13</td>
<td>1.84</td>
<td>-1.49</td>
</tr>
<tr>
<td>37</td>
<td>3</td>
<td>45</td>
<td>46</td>
<td>1.76</td>
<td>-1.33</td>
</tr>
<tr>
<td>37</td>
<td>3</td>
<td>70</td>
<td>71</td>
<td>1.83</td>
<td>-1.20</td>
</tr>
<tr>
<td>37</td>
<td>3</td>
<td>120</td>
<td>121</td>
<td>1.76</td>
<td>-1.78</td>
</tr>
<tr>
<td>37</td>
<td>4</td>
<td>24</td>
<td>25</td>
<td>1.40</td>
<td>-0.49</td>
</tr>
<tr>
<td>37</td>
<td>4</td>
<td>52</td>
<td>53</td>
<td>1.83</td>
<td>-1.47</td>
</tr>
<tr>
<td>37</td>
<td>4</td>
<td>85</td>
<td>86</td>
<td>1.73</td>
<td>-1.27</td>
</tr>
<tr>
<td>37</td>
<td>4</td>
<td>119</td>
<td>120</td>
<td>1.16</td>
<td>-1.62</td>
</tr>
<tr>
<td>37</td>
<td>4</td>
<td>140</td>
<td>141</td>
<td>1.92</td>
<td>-1.37</td>
</tr>
<tr>
<td>37</td>
<td>5</td>
<td>22</td>
<td>23</td>
<td>1.88</td>
<td>-1.47</td>
</tr>
<tr>
<td>37</td>
<td>5</td>
<td>58</td>
<td>59</td>
<td>1.39</td>
<td>-1.18</td>
</tr>
<tr>
<td>37</td>
<td>5</td>
<td>116</td>
<td>117</td>
<td>1.27</td>
<td>-1.63</td>
</tr>
<tr>
<td>37</td>
<td>5</td>
<td>142</td>
<td>143</td>
<td>2.26</td>
<td>-1.37</td>
</tr>
<tr>
<td>core</td>
<td>section</td>
<td>upper cm</td>
<td>lower cm</td>
<td>$\delta^{13}\text{C}_{\text{carb}}$</td>
<td>$\delta^{18}\text{O}_{\text{carb}}$</td>
</tr>
<tr>
<td>------</td>
<td>---------</td>
<td>----------</td>
<td>----------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>37</td>
<td>6</td>
<td>24</td>
<td>25</td>
<td>1.91</td>
<td>-1.26</td>
</tr>
<tr>
<td>37</td>
<td>6</td>
<td>54</td>
<td>55</td>
<td>2.18</td>
<td>-0.81</td>
</tr>
<tr>
<td>37</td>
<td>6</td>
<td>113</td>
<td>114</td>
<td>1.99</td>
<td>-1.22</td>
</tr>
<tr>
<td>37</td>
<td>6</td>
<td>143</td>
<td>144</td>
<td>1.86</td>
<td>-1.03</td>
</tr>
<tr>
<td>38</td>
<td>1</td>
<td>104</td>
<td>105</td>
<td>1.95</td>
<td>-0.86</td>
</tr>
<tr>
<td>38</td>
<td>1</td>
<td>132</td>
<td>133</td>
<td>1.98</td>
<td>-0.88</td>
</tr>
<tr>
<td>38</td>
<td>2</td>
<td>19</td>
<td>20</td>
<td>1.96</td>
<td>-0.82</td>
</tr>
<tr>
<td>38</td>
<td>2</td>
<td>44</td>
<td>45</td>
<td>2.00</td>
<td>-0.58</td>
</tr>
<tr>
<td>38</td>
<td>2</td>
<td>77</td>
<td>78</td>
<td>1.81</td>
<td>-1.71</td>
</tr>
<tr>
<td>38</td>
<td>2</td>
<td>118</td>
<td>119</td>
<td>2.05</td>
<td>-0.92</td>
</tr>
<tr>
<td>38</td>
<td>2</td>
<td>141</td>
<td>142</td>
<td>2.07</td>
<td>-0.30</td>
</tr>
<tr>
<td>38</td>
<td>3</td>
<td>24</td>
<td>25</td>
<td>1.49</td>
<td>-0.99</td>
</tr>
<tr>
<td>38</td>
<td>3</td>
<td>50</td>
<td>51</td>
<td>1.66</td>
<td>-1.49</td>
</tr>
<tr>
<td>38</td>
<td>3</td>
<td>82</td>
<td>83</td>
<td>1.90</td>
<td>-1.20</td>
</tr>
<tr>
<td>38</td>
<td>3</td>
<td>121</td>
<td>122</td>
<td>1.64</td>
<td>-1.47</td>
</tr>
<tr>
<td>38</td>
<td>3</td>
<td>142</td>
<td>143</td>
<td>1.69</td>
<td>-1.63</td>
</tr>
<tr>
<td>38</td>
<td>4</td>
<td>24</td>
<td>25</td>
<td>2.26</td>
<td>-0.65</td>
</tr>
<tr>
<td>38</td>
<td>4</td>
<td>58</td>
<td>59</td>
<td>2.36</td>
<td>-1.03</td>
</tr>
<tr>
<td>38</td>
<td>4</td>
<td>84</td>
<td>85</td>
<td>2.48</td>
<td>-0.72</td>
</tr>
<tr>
<td>38</td>
<td>4</td>
<td>127</td>
<td>128</td>
<td>2.50</td>
<td>-1.10</td>
</tr>
<tr>
<td>38</td>
<td>4</td>
<td>145</td>
<td>146</td>
<td>2.48</td>
<td>-0.93</td>
</tr>
<tr>
<td>38</td>
<td>5</td>
<td>27</td>
<td>28</td>
<td>2.47</td>
<td>-0.56</td>
</tr>
<tr>
<td>38</td>
<td>5</td>
<td>55</td>
<td>56</td>
<td>2.40</td>
<td>-0.73</td>
</tr>
<tr>
<td>38</td>
<td>5</td>
<td>84</td>
<td>85</td>
<td>2.15</td>
<td>-1.38</td>
</tr>
<tr>
<td>38</td>
<td>5</td>
<td>122</td>
<td>123</td>
<td>2.45</td>
<td>-1.08</td>
</tr>
<tr>
<td>38</td>
<td>5</td>
<td>145</td>
<td>146</td>
<td>2.48</td>
<td>-0.64</td>
</tr>
<tr>
<td>38</td>
<td>6</td>
<td>22</td>
<td>23</td>
<td>2.33</td>
<td>-0.71</td>
</tr>
<tr>
<td>38</td>
<td>6</td>
<td>52</td>
<td>53</td>
<td>2.23</td>
<td>-1.15</td>
</tr>
<tr>
<td>38</td>
<td>6</td>
<td>80</td>
<td>81</td>
<td>1.66</td>
<td>-2.07</td>
</tr>
<tr>
<td>38</td>
<td>6</td>
<td>125</td>
<td>126</td>
<td>2.36</td>
<td>-0.86</td>
</tr>
<tr>
<td>38</td>
<td>6</td>
<td>141</td>
<td>142</td>
<td>1.65</td>
<td>-1.82</td>
</tr>
<tr>
<td>38</td>
<td>cc</td>
<td>0</td>
<td>1</td>
<td>2.25</td>
<td>-2.02</td>
</tr>
<tr>
<td>39</td>
<td>1</td>
<td>28</td>
<td>29</td>
<td>2.07</td>
<td>-1.30</td>
</tr>
<tr>
<td>39</td>
<td>1</td>
<td>58</td>
<td>59</td>
<td>2.04</td>
<td>-1.49</td>
</tr>
<tr>
<td>39</td>
<td>1</td>
<td>86</td>
<td>87</td>
<td>2.19</td>
<td>-1.35</td>
</tr>
<tr>
<td>39</td>
<td>1</td>
<td>128</td>
<td>129</td>
<td>2.31</td>
<td>-1.13</td>
</tr>
<tr>
<td>39</td>
<td>2</td>
<td>27</td>
<td>28</td>
<td>1.82</td>
<td>-3.97</td>
</tr>
<tr>
<td>39</td>
<td>2</td>
<td>51</td>
<td>52</td>
<td>1.88</td>
<td>-1.42</td>
</tr>
<tr>
<td>39</td>
<td>2</td>
<td>89</td>
<td>90</td>
<td>2.32</td>
<td>-1.49</td>
</tr>
<tr>
<td>39</td>
<td>2</td>
<td>110</td>
<td>111</td>
<td>2.59</td>
<td>-1.13</td>
</tr>
</tbody>
</table>
### DSDP LEG 11 SITE 105 NODOSARIIDS

<table>
<thead>
<tr>
<th>core</th>
<th>section</th>
<th>upper cm</th>
<th>lower cm</th>
<th>$\delta^{13}{\text{C}}_{\text{carb}}$</th>
<th>$\delta^{18}{\text{O}}_{\text{carb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>2</td>
<td>18</td>
<td>25</td>
<td>0.42</td>
<td>-5.49</td>
</tr>
<tr>
<td>34</td>
<td>cc</td>
<td></td>
<td></td>
<td>0.21</td>
<td>-6.07</td>
</tr>
<tr>
<td>35</td>
<td>2</td>
<td>20</td>
<td>40</td>
<td>0.20</td>
<td>-6.10</td>
</tr>
<tr>
<td>35</td>
<td>4</td>
<td>44</td>
<td>60</td>
<td>-0.02</td>
<td>-6.53</td>
</tr>
<tr>
<td>36</td>
<td>2</td>
<td>100</td>
<td>102</td>
<td>0.36</td>
<td>-6.24</td>
</tr>
<tr>
<td>36</td>
<td>cc</td>
<td></td>
<td></td>
<td>-0.61</td>
<td>-4.60</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>100</td>
<td>119</td>
<td>-1.49</td>
<td>-4.92</td>
</tr>
<tr>
<td>37</td>
<td>5</td>
<td>77</td>
<td>91</td>
<td>0.20</td>
<td>-4.22</td>
</tr>
<tr>
<td>37</td>
<td>cc</td>
<td></td>
<td></td>
<td>-0.62</td>
<td>-2.53</td>
</tr>
<tr>
<td>39</td>
<td>1</td>
<td>81</td>
<td>97</td>
<td>0.56</td>
<td>-6.74</td>
</tr>
<tr>
<td>39</td>
<td>cc</td>
<td></td>
<td></td>
<td></td>
<td>-6.68</td>
</tr>
</tbody>
</table>

### DSDP LEG 11 SITE 105 LENTICULINA

<table>
<thead>
<tr>
<th>core</th>
<th>section</th>
<th>upper cm</th>
<th>lower cm</th>
<th>$\delta^{13}{\text{C}}_{\text{carb}}$</th>
<th>$\delta^{18}{\text{O}}_{\text{carb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>2</td>
<td>20</td>
<td>40</td>
<td>-0.67</td>
<td>-3.25</td>
</tr>
<tr>
<td>35</td>
<td>4</td>
<td>44</td>
<td>60</td>
<td>-0.74</td>
<td>-3.71</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>100</td>
<td>119</td>
<td>-1.73</td>
<td>-2.32</td>
</tr>
<tr>
<td>37</td>
<td>5</td>
<td>77</td>
<td>91</td>
<td>-1.64</td>
<td>-2.09</td>
</tr>
<tr>
<td>37</td>
<td>cc</td>
<td></td>
<td></td>
<td>-1.53</td>
<td>-1.24</td>
</tr>
</tbody>
</table>

### DSDP LEG 11 SITE 105 SPIRILLINA

<table>
<thead>
<tr>
<th>core</th>
<th>section</th>
<th>upper cm</th>
<th>lower cm</th>
<th>$\delta^{13}{\text{C}}_{\text{carb}}$</th>
<th>$\delta^{18}{\text{O}}_{\text{carb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>2</td>
<td>18</td>
<td>25</td>
<td>1.71</td>
<td>0.29</td>
</tr>
<tr>
<td>35</td>
<td>2</td>
<td>20</td>
<td>40</td>
<td>1.65</td>
<td>0.31</td>
</tr>
<tr>
<td>35</td>
<td>4</td>
<td>44</td>
<td>60</td>
<td>1.94</td>
<td>-0.98</td>
</tr>
<tr>
<td>36</td>
<td>cc</td>
<td></td>
<td></td>
<td>0.57</td>
<td>-0.52</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>100</td>
<td>119</td>
<td>0.54</td>
<td>-4.69</td>
</tr>
<tr>
<td>37</td>
<td>5</td>
<td>77</td>
<td>91</td>
<td>0.72</td>
<td>-4.24</td>
</tr>
<tr>
<td>38</td>
<td>cc</td>
<td></td>
<td></td>
<td>1.74</td>
<td>-3.95</td>
</tr>
</tbody>
</table>
CURRICULUM VITAE

Maureen Padden

Date of birth: January 30, 1969

Place of birth: Chatham, Ontario, Canada

Citizenship: Canadian

Education:
1991 - 1994 Honours Bachelor of Science
Department of Earth Sciences
University of Waterloo
Waterloo, Ontario, Canada
Thesis title: A Paleohydrological Study of Chappice Lake using Stable Isotopes

1994 - 1996 Master of Science
Department of Earth Sciences
University of Waterloo
Waterloo, Ontario, Canada
Thesis title: Holocene Paleohydrology of the Palliser Triangle from Isotopic Studies of Lake Sediments

1997 - 2001 Doctor of Natural Sciences
Geological Institute
Swiss Federal Institute of Technology
Zürich, Switzerland
Thesis title: Late Jurassic Paleoceanography: Evidence from Stable Isotopes and Carbonate Sedimentology