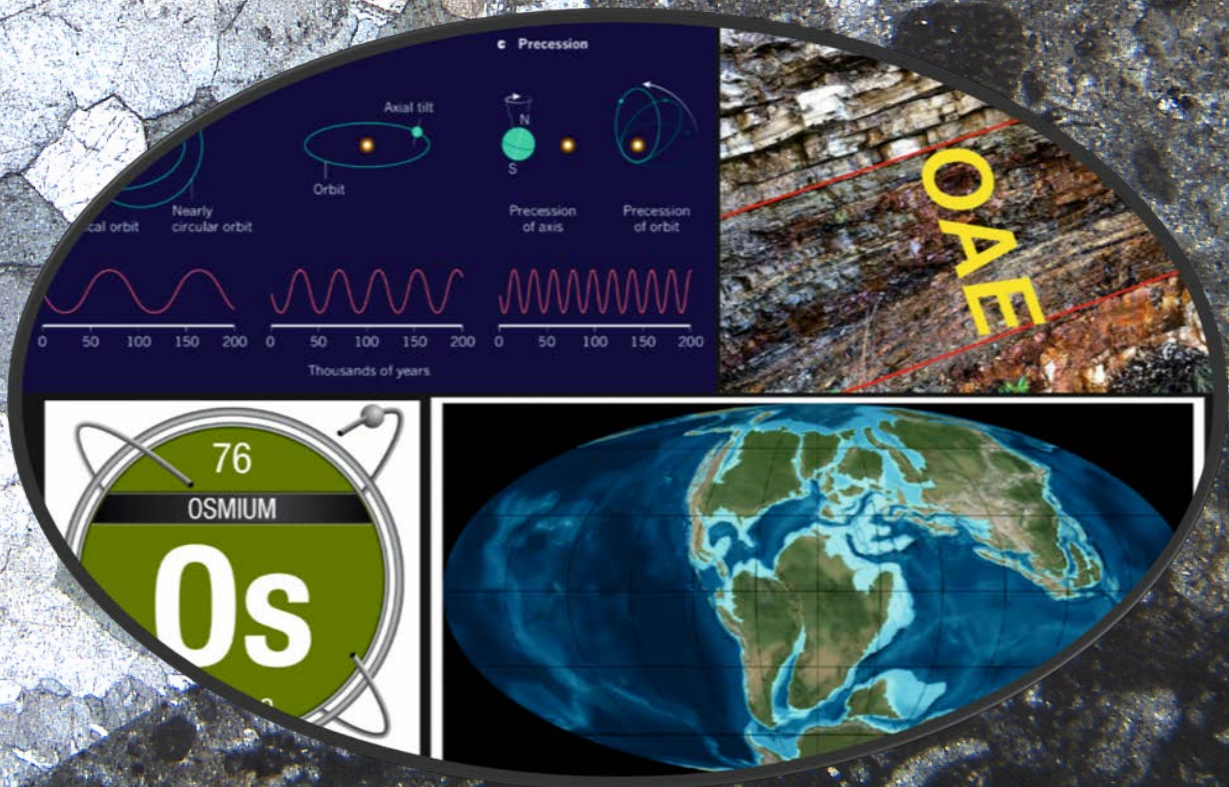




Universidad de Jaén

**RECORD OF ENVIRONMENTAL CHANGES DURING
THE APTIAN OF THE PREBETIC (BETIC EXTERNAL
ZONES). CHARACTERIZATION, CORRELATION AND
CONTROL FACTORS**



RAFAEL MARTÍNEZ RODRÍGUEZ

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DOCTORAL THESIS

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RECORD OF ENVIRONMENTAL CHANGES DURING THE APTIAN OF THE PREBETIC (BETIC EXTERNAL ZONES). CHARACTERIZATION, CORRELATION AND CONTROL FACTORS

PH. D. CANDIDATE:
RAFAEL MARTÍNEZ RODRÍGUEZ

**SUPERVISED BY:
JOSÉ MANUEL CASTRO JIMÉNEZ
GINÉS ALFONSO DE GEA GUILLÉN
LUIS MIGUEL NIETO ALBERT**

JAÉN, December 2021

RAFAEL MARTÍNEZ RODRÍGUEZ

UNIVERSITY OF JAÉN

**DEPARTMENT OF GEOLOGY · CENTER FOR ADVANCED STUDIES IN
EARTH SCIENCES, ENERGY AND ENVIRONMENT**



PH. D. THESIS

RECORD OF ENVIRONMENTAL CHANGES DURING THE APTIAN OF THE PREBETIC (BETIC EXTERNAL ZONES). CHARACTERIZATION, CORRELATION AND CONTROL FACTORS

**Thesis submitted to the University of Jaén for the degree of Philosophiae
Doctor (PhD), with International Mention, within the Doctoral Program in
Science and Technology of the Earth and the Environment.**

This Thesis has been supervised by the Drs. José Manuel Castro Jiménez, Senior Lecturer within the Stratigraphy Area at the Department of Geology, Faculty of Experimental Sciences of the University of Jaén; Ginés Alfonso de Gea Guillén, Senior Lecturer within the Stratigraphy Area at the Department of Geology, Faculty of Experimental Sciences of the University of Jaén, and Luis Miguel Nieto Albert, Senior Lecturer within the Stratigraphy Area at the Department of Geology, Faculty of Experimental Sciences from the University of Jaén.

This research is postulated for the International Mention, for which has been advised under the supervision of Dr. Sietske J. Batenburg, Researcher at the Department of Earth Sciences from the University of Oxford (United Kingdom), and Dr. David Selby, Professor of Earth Sciences from the Department of Earth Sciences at the University of Durham (United Kingdom).

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OVERWIEV

This memory is the result of five years of work within the research group RNM-200 of Basin Analysis and Environmental Geology, under the main Project “The Aptian of the Prebetic: Environmental and biotic changes, and control factors”. In this thesis, 6 outcrop sections and 1 core, from 3 different basin zones, have been analyzed, with a total 855 m of thickness. 464 field samples were collected from the outcrop sections and analyzed in the petrographic microscope. The core analysis involved the collection of 2,000 powder samples for inorganic geochemistry, 1,400 hard samples for paleontological and organic geochemistry, 4,000 measures for magnetic susceptibility, 99 analyses for Re-Os isotopes, and 58 analyses for μ -XRF. Collectively, 6 research papers will be published using this work. Methodologies developed on this training program include: field mapping and sampling of sedimentary carbonate sections; microscopic analysis of carbonate rocks; description and sampling of a core drilling; use of X-Ray fluorescence (μ -XRF) for elemental analysis; cyclostratigraphic analysis of physical and chemical signals; and systematics of the Re-Os isotope system, from geochemistry laboratory preparation to use of Thermal Ionisation Mass Spectrometer (TIMS).

The academic training of the PhD candidate included the realization of 6 international poster collaborations (EGU 2017, 2018, 2019, 2020, MIA 2018, IAS 2019), participation in 2 international workshops (IGCP-652 at Bremen, Germany, and IGCP-655 at Jaén, Spain), 1 national conference talk (SGE 2018 at Ávila, Spain), 1 international congress talk (IAS 2019 at Rome, Italy), and 2 long research stays in the United Kingdom (during 2018 and 2019 in the Departments of Earth Sciences at the University of Oxford and the University of Durham, respectively). Visit to Oxford University took place within the Stratigraphy and Sedimentology Research Group with Prof. Stuart Robinson as mentor. Visit to Durham University took place under NP Visiting Research - Earth Sciences YAF630 Programme, as a student belonging to St. Aidan's College. As a post-graduate teacher, he assisted in practice module teachings during academic courses of 2018/2019 and 2019/2020. Complementary, he has been member of the CEACTEMA Scientific Committee, Representative for the PhD-students in the Commission for Internal Quality Assurance of the Earth Sciences PhD Program of the University of Jaén, and member of the Council in the Department of Geology of the University of Jaén.



Universidad de Jaén

Escuela de Doctorado

TESIS DOCTORAL

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**REGISTRO DE CAMBIOS
AMBIENTALES EN EL APTIENSE DEL
PREBÉTICO (ZONAS EXTERNAS
BÉTICAS). CARACTERIZACIÓN,
CORRELACIÓN Y FACTORES DE
CONTROL**

**PRESENTADA POR:
RAFAEL MARTÍNEZ RODRÍGUEZ**

DIRIGIDA POR:
JOSÉ MANUEL CASTRO JIMÉNEZ
GINÉS ALFONSO DE GEA GUILLÉN
LUIS MIGUEL NIETO ALBERT

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Introducción

Se presenta un proyecto de tesis doctoral que se centra en el estudio del registro de los cambios ambientales ocurridos durante el Aptiense (121.4-113.2 Ma, según Gradstein et al., 2020). Este intervalo de tiempo despierta mucho interés en la comunidad científica por la diversidad de eventos y procesos geológicos que acaecieron durante el mismo: desarrollo y finalización del depósito de plataformas de carbonatos, desarrollo de Eventos Anóxicos Oceánicos (OAEs) registrados por la sedimentación de materiales con facies oscuras ricas en materia orgánica, crisis bióticas (crisis de biocalcificación, crisis de los nannoconus, extinción de caprinidos) y cambios climáticos asociados tanto al incremento de las temperaturas como a la activación del ciclo hidrológico (Skelton y Gili, 2012). Este enorme interés queda reflejado por el hecho de que el Aptiense es objeto de estudio de numerosos grupos de investigación tanto nacionales como internacionales en diferentes cuencas sedimentarias a (Collignon *et al.*, 1979; García Mondéjar, 1982a, 1982b, 1989, 1990; Pascal, 1985, 1987; Erba *et al.*, 1994, 1999; Vilas *et al.*, 1995; Menegatti *et al.*, 1998; Mutterlose, 1998, 2014; Larson, 1999; Masse, 2000; de Gea *et al.*, 2003; Dumitrescu *et al.*, 2006; Tejada *et al.*, 2009; Millán *et al.*, 2011; Najarro *et al.*, 2011; Moreno-Bedmar *et al.*, 2012; Peropadre *et al.*, 2012a, 2012b; Quijano *et al.*, 2012; Lorenzen *et al.*, 2013; Naafs *et al.*, 2016; Socorro *et al.*, 2017; entre otros), a escala global.

El estudio de varias sucesiones de carbonatos marinos datados como Cretácico Inferior de la Zona Prebética (Zonas Externas Béticas) se ha realizado, hasta ahora, desde una perspectiva fundamentalmente estratigráfica. Este estudio está enfocado en el reconocimiento de facies y sus cambios verticales y laterales, con el fin de poder establecer modelos de evolución de plataformas de carbonatos desde un punto de vista sedimentario y paleontológico, así como desde la perspectiva del análisis de cuencas (Castro, 1998; Ruiz-Ortiz y Castro, 1998; Aguado *et al.*, 1999; Castro *et al.*, 2008; Nieto *et al.*, 2012; Löser *et al.*, 2013; Castro *et al.*, 2014; Ruiz-Ortiz *et al.*, 2014, entre otros). Estas investigaciones han permitido establecer modelos de plataformas desarrolladas en contextos de *rifting*, con basculamiento de bloques y desarrollo de grábenes o semigrábenes, en los que se acumularon potentes sucesiones sedimentarias. No obstante, recientemente, el análisis de determinadas secciones estratigráficas se ha realizado con el fin de reconocer cambios ambientales en: condiciones climáticas, características tróficas del medio, productividad orgánica, composición de las comunidades bióticas, condiciones de oxigenación de los fondos marinos, o concentración de gases de efecto invernadero; con el objetivo de correlacionarlos con otros eventos contemporáneos reconocidos en otras áreas de la paleocuenca del Tethys y de otras cuencas sedimentarias (e.g. Hochuli *et al.*, 1999; de Gea *et al.*, 2003; Erba *et al.*, 2010; Weissert, 2011; Quijano *et al.*, 2012, Masse *et al.*, 2013; Aguado *et al.*, 2014; Moullade *et al.*, 2015, Naafs *et al.*, 2016). Los estudios estratigráficos, bioestratigráficos y geoquímicos realizados en materiales de esta edad en diferentes cuencas sedimentarias han permitido deducir que los cambios ambientales que ocurrieron en el Aptiense pueden ser considerados como análogos antiguos de los posibles efectos de corta y larga duración del impacto antropogénico global actual (p. ej. Norris *et al.*, 2013).

Resumen

La tesis doctoral se encuadra en el campo de la Estratigrafía, en concreto aborda el análisis de cuencas de un sector del Prebético (Zonas Externas Béticas, ZEB), y pretende obtener resultados que aporten conocimiento sobre episodios de cambio climático registrados en sucesiones sedimentarias marinas. El aspecto más relevante de esta tesis es el desarrollo de una investigación centrada en la caracterización, desde una perspectiva multidisciplinar, de los notables y variados cambios ambientales que sucedieron durante el Aptiense, de gran interés para la comunidad científica, en tanto que pueden ser considerados como análogos del cambio climático actual.

Los objetivos generales del trabajo son caracterizar, datar y correlacionar los cambios ambientales y bióticos registrados en las sucesiones estratigráficas seleccionadas de rocas sedimentarias de origen marino del Aptiense del Prebético, aplicando las técnicas más avanzadas en análisis secuencial, cicloestratigrafía y estratigrafía de alta resolución, geoquímica sedimentaria de isótopos estables y de elementos mayores, menores y traza. Con el análisis y discusión de los resultados obtenidos se pretende realizar una discusión sobre los factores de control que los regularon, así como sus consecuencias.

Se han estudiado las facies de plataformas someras de carbonatos en las sierras de Mariola (Alicante) y Bedmar-Jódar (Jaén), lo que ha permitido establecer la arquitectura estratigráfica, la evolución de la plataforma, y la discusión sobre los factores de control. Finalmente, con el apoyo del estudio de los isótopos de Carbono en la Sierra de Mariola, se ha establecido la relación entre la evolución de la plataforma y el Evento Anóxico Oceánico (OAE) 1^a.

Para profundizar en el estudio del Aptiense del Prebético, se ha llevado a cabo un estudio multidisciplinar usando un sondeo de un contexto sedimentario diferente, una rampa carbonatada (Cau, Alicante). Se ha realizado un estudio multidisciplinar, a partir fundamentalmente de isótopos (de Carbono, Oxígeno y Osmio), e incluyendo toma de muestras, análisis de la sedimentología, testificación geofísica del sondeo, y calcimetrías, que ha permitido establecer una estratigrafía de alta resolución basada en segmentos del perfil de isótopos de carbono calibrado con datos bioestratigráficos.

Se ha realizado un análisis cicloestratigráfico del sondeo del Cau, aplicando técnicas de análisis de series temporales, que ha permitido reconocer un control orbital en una parte significativa de la sucesión.

Los análisis isotópicos de Osmio han permitido confirmar datos de otras secciones del Aptiense inferior, y aportar por primera vez datos sobre el Aptiense superior. Estos resultados han llevado a proponer una discusión sobre el papel del vulcanismo a escala global sobre el ciclo del Carbono y los cambios ambientales y climáticos acontecidos a escala global durante el Aptiense.

Los resultados obtenidos han supuesto un avance en el conocimiento de los procesos sedimentarios y cambios ambientales que sucedieron en el Cretácico Inferior en la zona de estudio, en el contexto de los cambios globales que acontecieron en esta época. Además, el análisis detallado de la evolución de este sistema en el pasado puede contribuir a incrementar el conocimiento sobre el funcionamiento del Sistema Tierra bajo condiciones de elevados niveles de CO₂ en un contexto de calentamiento global.

Conclusiones

- Resumen de resultados
- Capítulo 3 – El sondeo del Cau

El registro del $\delta^{13}\text{C}_{\text{carb}}$ de alta resolución del sondeo de Cau se propone como una nueva sección de referencia global para la correlación estratigráfica del Aptiense basal al Aptiense superior medio, incluido el OAE 1a, debido a su carácter expandido, la continuidad del registro, y la sólida preservación de las señales geoquímicas y bioestratigráficas.

La combinación de estratigrafía de isótopos de C, testificación del sondeo, litoestratigrafía y bioestratigrafía integrada proporciona una resolución estratigráfica muy alta (0.5-11 ka), lo que ha permitido el reconocimiento de segmentos de isótopos de C previamente definidos y la subdivisión de algunos de estos en subunidades con potencial para incrementar la resolución de la correlación con secciones en todo el mundo. Fundamentalmente, la correlación detallada basada principalmente en registros de $\delta^{13}\text{C}_{\text{carb}}$ y calibrada utilizando marcadores bioestratigráficos demuestra que el registro de isótopos C de Cau refleja predominantemente una señal global y, por lo tanto, proporciona una base sólida para más análisis paleoambientales y paleobióticos de alta resolución temporal.

El registro de isótopos de C del inicio de OAE 1a en el sondeo de Cau se caracteriza por una caída de larga duración de los valores de isótopos de C. El análisis de ultra-alta resolución revela una sucesión marcada por picos negativos en los isótopos de C. La principal (-1.8‰) variación negativa de corta duración (< 10 ka) en el registro isotópico del C, marca la base del OAE 1a (base del segmento C3/Ap3) y el inicio del depósito de materiales ricos en materia orgánica. Este registro de ultra-alta resolución muestra un elevado grado de correlación con secciones pelágicas, y proporciona nuevas perspectivas en los procesos y tasas de cambio del ciclo global del carbono. El Aptiense superior exhibe una gran excursión negativa-positiva de larga duración de carácter global.

- Capítulo 4 – Sierra Mariola

El estudio de cuatro secciones de la Fm Llopis, distribuidas en el afloramiento de la Sierra Mariola, permite el reconocimiento de facies y asociaciones de facies de ambientes de plataforma abierta, barrera y plataforma interna, de una plataforma urgoniana carbonatada del Aptiense inferior, formada en el Margen Sudibérico.

Ocho parasecuencias son reconocidas en la plataforma urgoniana de Sierra Mariola, describiendo una evolución sedimentaria de fase regresiva para las dos primeras parasecuencias, mientras que el resto de plataformas presentan un carácter transgresivo.

La duración de la sedimentación de los materiales estudiados se piensa que abarcan ca. 0.8-1 Ma, incluyendo aproximadamente dos ciclos orbitales de excentricidad larga, con cada parasecuencia representando aproximadamente ciclos de 100-ka de excentricidad corta.

Los datos del $\delta^{13}\text{C}$ del Mb Medio de la Fm Llopis confirma que esta unidad registra el segmento isotópico de C Ap2, que predata el OAE 1a. El comienzo del OAE 1a es coetáneo con la Capa de Agres (Mb Superior), que es la expresión sedimentaria del comienzo del OAE 1a, lo cual,

finalmente, condujo a la finalización de la plataforma de carbonatos de la Fm Llopis, con la sedimentación de las margas hemipelágicas suprayacentes de la Fm Almadich.

La discusión sobre los factores que controlaron el desarrollo y el fin de la plataforma de carbonatos del Aptiense inferior señala una interacción compleja entre la tectónica extensional regional (subsistencia), el clima, y los cambios ambientales, los cuales condujeron a diferentes modos de producción de carbonatos controlados por variaciones en la entrada de siliciclásticos y cambios del nivel relativo del mar. El cambio ambiental más importante se considera estrechamente vinculado y es coetáneo al OAE 1a, una gran perturbación que finalmente produjo el final de la plataforma, desembocando en sedimentación hemipelágica.

- Capítulo 5 – Sierra de Bedmar-Jódar

El estudio de un afloramiento de la plataforma somera de carbonatos de la Fm Llopis del Aptiense inferior en la Sierra de Bedmar-Jódar, basado en diez secciones estratigráficas de alta resolución y un mapa de facies de detalle, ha revelado la arquitectura de facies de este sector de la plataforma.

Las facies descritas están organizadas en una sucesión de estratos de espesor muy variable, presentando localmente clinoformas con un sentido de buzamiento medio hacia el E.

Se han diferenciado hasta siete tipos de litofacies, una siliciclástica y cinco carbonatadas, con texturas que abarcan desde grainstones a packstones a wackestones y mudstones. Dos facies incluyen macrofósiles (estromatopóridos y rudistas).

Las litofacies L1 a L6 se organizan en dos distintos tipos de secuencias elementales que difieren en la presencia de estromatopóridos o rudistas. Se interpretan como secuencias de somerización, desarrolladas en una plataforma de carbonatos muy somera, con un lagoon delimitado hacia la costa por barras clásticas/ooidales, y limitado hacia el mar por bioconstrucciones de estromatopóridos (biohermos y biostromas) o rudistas.

El techo de estas secuencias algunos rasgos revelan una somerización de las bioconstrucciones, con probable emersión, con barras costeras superpuestas sobre las anteriores. Esta somerización pudo estar controlada por la tectónica local.

En conjunto, estas 8 secuencias elementales presentan un carácter progradante, con un avance de la plataforma hacia el Este.

La asociación de facies define tres tipos de secuencias elementales, claramente descritas en las secciones estratigráficas y en el mapa de facies: (1) areniscas y calcarenitas, depositadas en un ambiente marino abierto somero proximal, (2) areniscas, calcarenitas y calizas de estromatopóridos, depositadas en un lagoon semi-protegido, y (3) areniscas, calcarenitas y facies de rudistas, interpretadas como un lagoon de tipo urgoniano. Estas secuencias están frecuentemente coronadas por discontinuidades, que podrían estar asociadas a una combinación de agradación sedimentaria y/o caídas del nivel relativo del mar, producidas ocasionalmente por basculamiento tectónico vinculado al régimen extensional del *rifting* que afectó al Margen Continental Sudibérico.

La sucesión vertical de la plataforma estudiada ha sido dividida en dos parasecuencias

progradantes, las cuales representan dos fases:

- (1) instalación de la plataforma somera, con desarrollo de estromatopóridos;
- (2) desarrollo de una plataforma urgoniana dominada por rudistas.

La correlación con los carbonatos someros coetáneos de la plataforma en Mariola (Alicante), respaldados por la bioestratigrafía, revela interesantes características comunes en la evolución sedimentaria en ambos sectores de la plataforma prebética. Esto indica un episodio de escala regional de instalación y desarrollo de una plataforma somera de carbonatos, controlada por condiciones ambientales óptimas para la producción de carbonatos.

Durante el Aptiense inferior, la plataforma de Bedmar-Jódar estuvo probablemente aislada o parcialmente aislada del resto de la plataforma prebética, con una progradación diferente hacia el NE, mientras que la tendencia general de progradación de la plataforma del Prebético presenta un sentido hacia el SE o S. La sedimentación estaba principalmente controlada por tectónica extensional, favoreciendo pulsos de emersión que inclinaron el bloque de la plataforma, produciendo un sentido de progradación diferente. Las entradas de terrígenos ocasionales y la presencia de caráceas en los materiales indican que la plataforma aislada se encontraba, a veces, muy cerca del continente.

- Capítulo 6 - Ciclicidad en Cau

A partir de datos de alta resolución de rayos gamma, CaCO_3 y susceptibilidad magnética del sondeo de Cau, se propone una cronología calibrada astronómicamente para el Aptiense, a partir de esta sección de cuenca intra-plataforma. La influencia de la oblicuidad y la precesión modulada por excentricidad se refleja en una jerarquía de ciclos revelados por el análisis de series temporales de propiedades físicas y datos elementales. Sin embargo, esta cronología es menos fiable a base y techo del registro, donde la ciclicidad no es clara y no se puede excluir una astrocronología más joven. Aunque la incertidumbre en las dataciones en la base del sondeo dificultan el anclaje del registro, las duraciones sugeridas por la ciclicidad para intervalo de 70 a 120 m pueden considerarse robustas.

En comparación con las estimaciones del estudio de Malinverno et al. (2010), la duración del OAE 1a estimada en este estudio (1.4 Ma) es mayor que la calculada por el estudio anterior (1.1 Ma). Los resultados para el segmento Ap3 (C3) proporcionan una duración más larga, de 247 ka, en comparación con los 47 ka estimados por Malinverno et al. (2010). La duración del segmento Ap4 (C4) es similar en ambos estudios, con 240 y 239 ka, respectivamente. El segmento Ap5 (C5) también es más largo en este estudio (768 ka) en comparación con Malinverno et al. (2010) (510 ka). Por el contrario, el segmento Ap6 (C6) es más largo en el estudio de 2010 (349 ka), frente a los 142 ka de duración derivados de este trabajo. Por último, el segmento Ap7 (C7) es mucho más largo en el estudio anterior, con 1.59 Ma frente a los 477 ka de este estudio. Este trabajo es el primero en cuantificar la duración de los segmentos Ap8 a Ap13.

- Capítulo 7 – Isótopos de Re-Os en Cau

Este estudio presenta la primera evidencia directa de que la actividad volcánica continuó más

allá del OAE 1a durante el Aptiense superior. Los nuevos datos de isótopos de Os del sondeo de Cau confirman un marco de tiempo extendido para la entrada volcánica de Os no radiogénico durante el Aptiense, probablemente debido al emplazamiento de grandes provincias ígneas y su actividad continua, lo que influyó en la composición del Os de agua de mar durante ~ 2.8 Ma.

Los datos de Os_i de Cau proporcionan una fuerte evidencia para establecer con mayor precisión un registro de alta resolución de episodios magmáticos y pulsos de ciclo hidrológico acelerado, y muestran la inestabilidad climática que ocurrió antes (segmento Ap2) y durante el inicio del OAE 1a (segmento Ap3). Este estudio confirma la relación temporal del magmatismo de grandes provincias ígneas con el OAE 1a, demostrando que el magmatismo estuvo activo durante 550-750 ka antes del evento Selli, se mantuvo durante todo el OAE y cesó ~ 300 ka después del final del evento. La duración máxima calculada a partir de la excursión de Os_i vinculada a la fase principal del Ontong-Java Plateau es de 1.6 a 1.75 Ma. La inferencia de los datos de Os_i sugiere una duración mínima y máxima del magmatismo de grandes provincias ígneas de 2.8 y 3.6 Ma. La secuencia de eventos registrados en Cau comienza con un primer pulso volcánico anterior al OAE 1a, reflejado en un cambio negativo abrupto en los isótopos C que puede haber sido provocado por un pulso de emisiones de metano. Este primer evento fue seguido por el principal cambio abrupto en Os_i no radiogénico, seguido por el depósito de sedimentos marinos ricos en materia orgánica, lo que indica un aumento en la productividad y una reducción de la oxigenación debido al inmenso vulcanismo a través de la entrada de CO_2 , el aumento de la temperatura y la activación del ciclo hidrológico, que dio lugar a aguas ricas en nutrientes. Este registro confirma la relación entre la acumulación de materia orgánica, el desarrollo de anoxia/disoxia y el aumento de la productividad, con los pulsos iniciales de vulcanismo que preceden a la fase principal, como se mostró anteriormente para otros registros del OAE 1a (Tejada et al., 2009 ; Bottini et al., 2012). Durante el Aptiense superior, el ciclo del carbono experimentó un cambio lento reflejado en la excursión isotópica a largo plazo del registro $\delta^{13}C$, aunque el registro de Os_i permaneció relativamente estable, mostrando solo cambios puntuales asociados a pulsos volcánicos. El extenso registro del Aptiense en Cau permite destacar el comportamiento variable del ciclo del carbono a lo largo del intervalo de tiempo registrado. En el Aptiense inferior, el inicio de OAE 1a se asocia con una rápida excursión de isótopo de carbono negativo producida en menos de 25.000 años, que fue seguida por un fuerte cambio en la composición de Os_i y perturbaciones registradas en muchos otros proxies. En comparación, la excursión de isótopo de carbono negativa durante la transición Aptiense inferior-Aptiense superior, tuvo lugar durante una duración de aproximadamente ~ 1 Ma, tiempo en el que la composición de Os_i y otros proxies permanecieron estables. El desfase entre la desgasificación del CO_2 volcánico en el océano y la intensa meteorización continental debido al aumento de la pCO_2 debe tenerse en cuenta al evaluar diferentes pulsos episódicos y el reflejo de estos cambios en el registro del $\delta^{13}C$.

- Conclusiones generales

Esta investigación es un estudio estratigráfico y sedimentológico dentro de las ZEB, centrado en el Aptiense del Prebético. Los materiales estudiados pertenecen a tres contextos sedimentarios:

muy somero – proximal (Bedmar-Jódar); somero – intermedio (Mariola); y hemipelágico – distal (Cau).

En el Prebético, el Aptiense está registrado por las Fms Llopis y Almadich. La Fm Llopis carbonatada somera está presente en sectores proximales de la cuenca, como Bedmar-Jódar y Mariola, y registra solo una parte del Aptiense inferior. En Bedmar-Jódar, la Fm Llopis solo registra una parte del Mb Medio, aunque con un espesor mayor que en Mariola, indicando una mayor tasa de subsidencia para ese sector de la plataforma. En Mariola, los Mbs Medio y Superior de la Fm Llopis registran la parte baja del Aptiense inferior, incluyendo el comienzo del OAE 1a. En Cau, la hemipelágica Fm Almadich registra el Aptiense inferior, y la parte baja y media del Aptiense superior.

Las principales conclusiones que emergen del estudio de afloramientos de Bedma-Jódar y Mariola son:

- las facies Urgonianas de Jódar son parte de una plataforma aislada registrando solo una parte de lo registrado en Mariola, pero indicando una subsidencia mayor para este sector de la plataforma.
- las facies Urgonianas en Mariola registran extensivamente el intervalo previo al OAE 1a, como ejemplo de los cambios en las condiciones que precedieron al Evento Selli en un contexto de plataforma.

El estudio del sondeo del Cau ofrece una imagen de alta resolución del Aptiense. La quimioestratigrafía de Carbono y Osmio describe rápidos y abruptos cambios durante el Aptiense inferior, mientras que el Aptiense inferior es mucho más estable, con tendencias suaves y cambios de ritmo lento.

Del estudio cicloestratigráfico del sondeo del Cau, la característica más relevante que se desprende es la duración del segmento Ap3 (C3) dentro del CIE, que proporciona una duración bastante más larga (272 ka) respecto a cálculos previos (47 ka). El retraso entre la base del segmento Ap3 (comienzo del OAE 1a) y la base del segmento D de Os_i (comienzo de la fase principal del OJP) usando la astrocronología de este estudio, es de ca. 20-ka. Por tanto, para mantener el $\delta^{13}\text{C}$ en 1.5 ‰ durante ese intervalo, la entrada de carbono ligero debe haber sido producida por una fuente distinta al CO₂ volcánico.

La composición de Os_i marino permaneció dramáticamente no-radiogénica durante ~1.8 Ma, señalando la gran entidad de la fase magmática principal de Ontong-Java, mientras que el CIE termina justo 0.4 Ma después del comienzo del evento volcánico. Durante 1.4 Ma, los ciclos del C- y Os- fueron totalmente opuestos, sugiriendo que la cantidad de materia-orgánica enterrada superó a la influencia volcánica.

- Trabajo futuro

El conocimiento actual del impacto del OAE 1a en sectores proximales del dominio Prebético

podría ser expandido por la caracterización de los perfiles de $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ en la Fm Almadich en Sierra Mariola. Por otro lado, se plantean muchas cuestiones cuando se analiza el OAE 1a. El principal desencadenante del comienzo del OAE 1a no está claro aún entre la interacción del vulcanismo, la disociación de hidratos de gas, y/o la intrusión de magma en sedimentos ricos en materia orgánica. Se pueden llevar a cabo más estudios en el sondeo del Cau, como difracción de rayos-X y análisis de muestras en el SEM, para comprender mejor la mineralogía de los materiales, así como un estudio de XRF de mayor resolución, para disponer de otro set de datos para análisis de series temporales. Además, el uso de isótopos de He podría ayudar a situar el tiempo de los distintos eventos a una resolución sub-Milankovitch. Otros estudios que se están llevando a cabo en el sondeo involucran el análisis de palinología y dinoflagelados, para una mejor caracterización del ecosistema. Estudios futuros incluyendo biomarcadores e isótopos de Nd podrían arrojar luz sobre las condiciones climáticas regionales paleoambientales y paleoclimáticas.

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1 Introduction

This doctoral thesis project focuses on the study of the record of environmental changes that occurred during the Aptian (121.4-113.2 Ma, after Gradstein et al., 2020). This time interval arouses much interest in the scientific community due to the diversity of geological events and processes that occurred during it: development and demise of carbonate platforms, occurrence of Ocean Anoxic Events (OAEs) recorded by the sedimentation of materials with rich dark facies in organic matter, biotic crises (biocalcification crisis, nannoconus crisis, extinction of caprinids) and climatic changes related both to the increase in temperatures and to the activation of the hydrological cycle (Skelton and Gili, 2012). This enormous interest is reflected by the fact that the Aptian is the object of study of numerous national and international research groups in different sedimentary basins (Collignon et al., 1979; García Mondéjar, 1982a, 1982b, 1989, 1990; Pascal, 1985, 1987; Erba et al., 1994, 1999; Vilas et al., 1995; Menegatti et al., 1998; Mutterlose, 1998, 2014; Larson, 1999; Masse, 2000; de Gea et al., 2003; Dumitrescu et al., 2006; Tejada et al., 2009; Millán et al., 2011; Najarro et al., 2011; Moreno-Bedmar et al., 2012; Peropadre et al., 2012a, 2012b; Quijano et al., 2012; Lorenzen et al., 2013; Naafs et al., 2016; Socorro et al., 2017; among others), at a global scale.

The study of several successions of marine carbonates dated as lower Cretaceous from the Prebetic Zone (Betic External Zones) has been carried out, so far, from a fundamentally stratigraphic perspective. This study is focused on the recognition of facies and their vertical and lateral changes, in order to be able to establish models of evolution of carbonate platforms from a sedimentary and paleontological point of view, and from the perspective of basin analysis (Castro, 1998; Ruiz-Ortiz and Castro, 1998; Aguado et al., 1999; Castro et al., 2008; Nieto et al., 2012; Löser et al., 2013; Castro et al., 2014; Ruiz-Ortiz et al., 2014, among others). These investigations have made it possible to establish platform models developed in rifting contexts, with tilting of blocks and development of grabens or semi-grabens, in which powerful sedimentary successions were accumulated. However, recently, the analysis of certain stratigraphic sections has been conducted to detect environmental changes such as: climatic conditions, trophic characteristics of the environment, organic productivity, biotic communities, oxic conditions of the sea water, or concentration of greenhouse gases; in order to correlate them with the record of contemporaneous events recognized in other areas of the Tethys paleobasin and other sedimentary basins (e.g., Hochuli, et al., 1999; de Gea et al., 2003; Erba et al., 2010; Weissert, 2011; Quijano et al., 2012; Masse et al., 2013; Aguado et al., 2014; Moullade et al., 2015; Naafs et al., 2016). Stratigraphic, biostratigraphic and geochemical studies carried out on materials of this age in different sedimentary basins have allowed to deduce that the environmental changes that occurred during the Aptian can be considered as ancient analogues of the possible short- and long-duration effects of the current global anthropogenic impact (e.g. Norris et al., 2013).

1.1 Summary

This doctoral thesis is framed in the field of Stratigraphy, specifically it addresses the analysis of basins of a sector of the Prebetic (External Betic Areas, ZEB), and aims to obtain results that provide knowledge about episodes of climate change registered in marine sedimentary successions. Its most relevant aspect is the development of a research focused on the characterization, from a multidisciplinary perspective, of the notable and varied environmental changes that occurred during the Aptian, of great interest to the scientific community, insofar as they can be considered as analogs of current climate change.

The general objectives of the work are to characterize, date and correlate the environmental and biotic changes recorded in the selected stratigraphic successions of sedimentary rocks of marine origin from the Prebetic Aptian, applying the most advanced techniques in sequential analysis, cyclo-stratigraphy, and high-resolution stratigraphy and geochemistry of stable isotopes and major, minor and trace elements. With the analysis and discussion of the results obtained, it is intended to carry out a discussion on the control factors that regulated them, as well as its consequences.

Shallow carbonate platform facies have been studied in Sierra Mariola (Alicante) and Sierra de Bedmar-Jódar (Jaén), which permitted to establish the stratigraphic architecture, the evolution of the platform, and the discussion on the control factors. Finally, with the support of the study of carbon isotopes at Sierra Mariola, the relationship between the evolution of the platform and the Oceanic Anoxic Event 1a (OAE 1a) has been determined.

To deepen into the study of the Aptian of the Prebetic, a multi-proxy study has been performed using a core from a different sedimentary context, a carbonate ramp (Cau, Alicante). Based mainly on isotopes (carbon, oxygen and osmium), sedimentology, core logging, and carbonate content, which led to establish a high-resolution stratigraphy based on segments from the C-isotope profile, calibrated with biostratigraphic data. A cyclostratigraphy study has been carried out in the Cau Core, applying time series analysis techniques, which allowed the recognition of orbital control in a significant part of the series.

The osmium analysis have permitted to confirm data from other early Aptian sections, and have contributed for the first time with data from the upper Aptian. These results led to the proposal of a discussion on the vulcanism at global scale over the carbon cycle, and the environmental and climatic changes that happened globally during the Aptian.

The results obtained represent an advance in the knowledge of the sedimentary processes and environmental changes that occurred during the lower Cretaceous in the study area, in the context of the global changes that occurred at this time. In addition, the detailed analysis of the evolution of this system in the past contributes to increase the knowledge of the Earth System under conditions of high levels of CO₂ and global warming.

1.2 Hypothesis and objectives

- **HYPOTHESIS:** During the Aptian, important environmental changes took place in the Betic sedimentary basin sector, some of a global nature, which were recorded in the sedimentary successions, specifically in the facies, chemical composition and fossil content. Therefore, the detailed stratigraphic, sedimentological, geochemical and chronostratigraphic study of the selected stratigraphic successions will allow to explore the imprint of these environmental changes in the selected sedimentary successions, and the analysis and discussion of the data obtained will allow to elaborate models of the sedimentary and environmental evolution on the Prebetic platform during the Aptian, at a high resolution timescale.

- **GLOBAL OBJECTIVE:** To study the environmental changes that occurred during the Aptian, recorded in the selected sections, and generate models that explain these environmental changes, within the global context of high atmospheric CO₂ concentrations and temperatures.

To achieve the global objective, a detailed study that includes high-resolution stratigraphic and sedimentological analysis, biostratigraphic and geochemical, is required. The resolution of the temporal model obtained from biostratigraphy can be increased from the development of

temporal models based on the integration of biostratigraphy, geochemistry and cyclostratigraphy. From the results of these studies, it is possible to establish the sedimentary and environmental evolution of the part of the Prebetic domain studied during this time interval. The investigation has been carried out on sedimentary successions from three different contexts: a shallow isolated carbonate platform, represented by the Sierra de Bedmar-Jódar, a shallow carbonate platform with a transition from the lagoon to open marine environments, in the Sierra de Mariola, and a distal ramp, represented by the Sierra del Cau materials. In addition, previous works have shown (e.g., de Gea et al., 2003; Castro et al., 2008; Naafs et al., 2016) that at least some of the events recorded in the sections studied in this work and others close to the same basin, have a regional character, in some cases global, which gives greater interest to their study, reinforcing the global objective indicated above. In order to confirm the starting hypothesis and reach the global objective, the following general objectives (O) are:

OBJECTIVE 1. Study the stratigraphy, sedimentology, biostratigraphy and geochemistry of the selected sections.
OBJECTIVE 2. Characterize and interpret the environmental changes recorded, determine their local, regional or global character, and discuss the environmental control factors in the sedimentary basin.
OBJECTIVE 3. Establish regional paleogeographic evolutionary models for the Prebetic Domain, and integration in paleogeographic, paleoenvironmental and tectonic models on a global scale.

In order to achieve these objectives, a series of research activities have been carried out:

OBJECTIVE 1

- A. Analysis at a high-resolution scale of stratigraphic, biostratigraphic, sedimentological and cyclostratigraphic data from the Llopis and Almadich formations.
- B. Establishment of high-resolution profiles of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ for the Aptian, in both formations.
- C. Characterization of the early Aptian anoxic event (OAE 1a).
- D. Accurate dating of the most significant environmental and biotic changes.

OBJECTIVE 2

- A. Integration of results according to the principles of high-resolution event stratigraphy (HIRES sensu Kauffman, 1988). Sequence correlation.
- B. Integration of chemostratigraphic results.
- C. Integration of biostratigraphic results.
- D. Integration of cyclo-stratigraphic results.
- E. Stratigraphic correlation between the studied sections.
- F. Stratigraphic correlation with other sections on a global scale, from data published in the bibliography.

OBJECTIVE 3

- A. Analysis, integration, discussion and modelization of the obtained results.

2. Methodology

Abstract

A list of techniques and procedures applied in the execution of the activities listed above is detailed. These are of diverse application according to the classical work methodology in geological sciences, field methods, laboratory and cabinet.

a. Field methods:

- Survey of detailed stratigraphic sections.
- Detailed sampling of the different sections.
- Analysis of lateral and vertical facies changes.
- Analysis of clinoforms and limit surfaces of sedimentary bodies.

b. Laboratory methods:

- Detailed description of the cores of the surveys carried out in the Cau section, to obtain sedimentological and icnological data.
- High resolution sampling of Cau cores to obtain magnetic susceptibility data, biostratigraphy and chemostratigraphy (geochemistry of stable isotopes, major, minor and trace elements).
- Study of thin films, microfacies and micropaleontological studies, to complement the data obtained from the application of the previous methods.
- Geochemical analysis from the samples taken in the high resolution sampling.
- Analysis of samples by X-ray microfluorescence spectrometer (XRF).
- Isotopic analysis methodologies applied to the Re-Os isotope system.

c. Cabinet methods:

- Background analysis and bibliographic review.
- Preparation of stratigraphic sections and stratigraphic correlation.
- Preparation of correlation panels.
- Cyclo-stratigraphic analysis.
- Processing of geochemical data.
- Sequential analysis.
- Integration, discussion and preparation of results. Drafting of the final research report.

The application of the described methodology has been done at the Department of Geology and at the Center for Scientific Instrumentation, both at the University of Jaén. In addition, cyclostratigraphy methodologies were learnt and applied at the Department of Earth Sciences at the University of Oxford, and Re-Os systematics were learnt and applied at the Arthur Holmes Laboratories of the Department of Earth Sciences at the University of Durham.

Sites studied are indicated between brackets.

2.1 Field work [Mariola – Cau – Jodar]

The specific tools and instruments used for fieldwork used were the classic geology tools; geologic hammer to take rock samples in fresh cut, compass with clinometer to measure the orientation and inclination of surfaces and lines of geological interest (Fig. 2.1), hand-held magnifying glass with a minimum of 10-15 increases to be able to make a first approximation to the microfacies of the samples taken in the field, in addition to a monocular or binocular prismatic tool, scales for photographic representations and meters to measure the power or thickness of the layers.



Figure 2.1 Measurement at field. Bioclast in the Barranco del Tejar section (Jodar, Spain).

In addition, computer applications for portable geological equipment, such as cartography, GPS or online databases such as Google Earth have been used.

2.2 Microfacies analysis on thin section [Mariola – Jodar]

The realization of the thin sections, with the standard thickness of 30 μm , was carried out in the laboratory of the Department of Geology of the Faculty of Experimental Sciences of the University of Jaén and in the Center of Scientific and Technical Instrumentation of the same College. The thin sheet preparation process is standard, first cutting the rocks into dowels with a maximum size of approximately 3x2 cm (dimensions of a slide) in a refrigerated system water, for subsequent polishing. Then, the sample plugs are embedded in EPOXY resin and then the humidity is eliminated by leaving the samples in an oven at 40°C for 4 days. Subsequently, they are introduced into a vacuum chamber together with the EPOXY resin to replace the porosity air with it and thus achieve greater competition in the samples. Finally, it is possible to dye some sheets totally or partially using a stain, in this case, alizarin red for carbonates, according to some of the usual procedures, such as that of Lindholm and Finkelman (1972). The slides are studied using a transmitted light optical microscope, which can optionally have a built-in camera with which to take microphotographs with image processing software, in this case Leica brand and model MP04, with an integrated digital camera, Firewire brand (type B) Leica and DFC300FX model. The microscope is connected to a computer on which the Leica Application Suite (LAS) image management software is installed, which includes image calibration and database for

microfacies photography and preliminary treatment. The purpose of making these sheets fulfills a purpose of vital importance in the petrological and microfacies characterization of the samples from which they come, describing their components, the textural relationships and the petrographic features of each one of them. Likewise, the fossil content of the samples was studied to obtain sedimentological and paleoecological information and to carry out dating by determining benthic foraminifera, especially orbitolinids.

2.3 C and O stable isotopes [Cau – Mariola]

Stable isotope ratios from 885 carbonate samples were measured with a ThermoScientific MAT253 Isotope Ratio Mass Spectrometer connected to a Kiel IV Carbonate Device at the Stable Isotope Laboratory of the Instituto de Geociencias, Universidad Complutense de Madrid. Isotopic values for carbon and oxygen were calibrated against carbonate standards (NBS-19, NBS-18, and in-house standards).

2.4 High resolution core sampling [Cau]

The instruments used to study the cores of the borehole carried out in the Sierra del Cau in the CEA-Tierra laboratory are made up of (Fig. 2.2): PVC gutters where to place the borehole core; drilling system for taking samples; widia drill bits 2 cm wide diameter that are inserted in the system that makes the holes; digital scale; colorimetry tables (Munsell chart); tables to calculate the bioturbation index according to the Drosser-Bottjer procedure (1986); and agate mortars. Continuous control measurement of the magnetic susceptibility was made using a Burdington MS2E Core Logging Sensor model, controlled by the BarSoft software, installed in a Toshiba Satellite laptop.

While the magnetic susceptibility was measured with a standard interval of 5 cm, the sampling for stable isotopes of C and O was carried out according to a standard spacing of 10 cm, those used for the study of nanofossils and elemental geochemistry were taken with a 20 cm spacing; finally, samples for organic geochemistry, which must have a minimum weight of 10 g, were taken every 50 cm. For intervals of special interest, a higher resolution sampling was carried out.

2.4.1 Biostratigraphy

Calcareous nannofossils were investigated on smear slides for 129 samples from the Cau cores: 32 from D1; 32 from D2; 28 from D3; and 37 from D4. Sample selection was based on carbonate content, previous biostratigraphic data from the outcrop section (Aguado et al., 1999), and the needs of biostratigraphic correlation between cores D1–D4. Simple smear slides (Bown & Young, 1998) of the selected samples were prepared and mounted with adhesive (Canada balsam) as uniformly as possible, so that particle density in different slides would be comparable. The smear slides were examined at 1250 × magnification using polarizing light microscopes (Olympus BHSP and Leica DM4P). At least two longitudinal traverses (1 traverse = 200 fields of view; 1 field of view = 2.37×10^{-2} mm² in the Olympus microscope; and 1 traverse = 180 fields of view; 1 field of view = 2×10^{-2} mm² in the Leica microscope) were investigated for each sample in order to record the rare species. The taxonomic framework employed was based on Perch-Nielsen (1985), Bown et al. (1998), Bown (2005), Aguado et al. (2014a), Aguado et al. (2014b) and the Nannotax website (<http://www.mikrotax.org/Nannotax3/index.php?dir=Coccolithophores>).



Figure 2.2. Laboratory C6-006 of core sampling in dependencies of CEACTEMA (former CEACTIERRA) at University of Jaén.

Fifty-four samples were selected for the determination of the planktonic foraminifera assemblages. Sample selection was based on previous data from the outcrop section (e.g., Aguado et al., 1999; de Gea et al., 2003) in order to study the key intervals of biostratigraphic significance. Each sample (200 g dry weight) was treated with dilute 30–35% H₂O₂ for several hours to remove the OM, and subsequently washed through sieves. The residue was separated into three fractions (>200 µm, 100 – 200 µm, 50 – 100 µm), dried in an oven at 50 °C for 10 – 12 hours, and finally investigated using Olympus SZX16 and Leica M205C stereoscopic microscopes. For planktonic foraminifera, the taxonomic classification used was based on Ando et al. (2013), Moullade et al. (2002), Verga & Premoli-Silva (2002, 2003a,b, 2005) and the Mikrotax website (http://www.mikrotax.org/pforams/index.php?dir=pf_mesozoic).

2.4.2 Carbonate content

An automatic calcimeter manufactured by DREAM Électronique SAS (Pessac, France) (unique model, n.r.), housed in the laboratories of the CEACTierra (University of Jaén), was used to determine the carbonate content of samples. Carbonate contents were calculated based on the measurement of carbon dioxide pressure emitted after HCL injection (method based on ASTM D4373-02). After automatic calibration, 250 to 300 mg of each sample was reacted with 5.3 M HCl within an enclosed bottle. A total of 1867 samples (average vertical spacing of 10 cm) were analysed with a measurement accuracy $\pm 4\%$.

2.4.3 Natural gamma ray logging and magnetic susceptibility

Gamma Ray levels were measured with a wire-line QL40 sensor probe at a 3 cm spacing and reported as API (American Petroleum Institute) radioactivity units. Magnetic Susceptibility (MS)

was measured on the cut core-surface using a cylindrical Bartington MS2E core logging sensor device, with the BartSoft program. Measurements were performed manually at a 5 cm spacing under atmospheric conditions at 25°C temperature.

2.4.4 Total Organic Carbon (TOC)

TOC analyses were performed in the IRNAS laboratories (CSIC, Sevilla), using a Shimadzu TOC-V CSH. Total Carbon (TC) was determined by catalytic oxidation at high-temperature followed by CO₂ infrared non-dispersive detection. Total inorganic carbon (TIC) was measured after treatment with HCl to remove carbonates. The TOC content of the samples was obtained from the difference of TC-TIC by the loss-on-ignition method (Nelson & Sommers, 1996), with a measurement accuracy of coefficient of variation (CV) 1.5% max. A total of 101 samples were analysed, with an average sampling interval of 140 cm.

2.5 X-ray Microfluorescence Spectrometry [Cau]

X-ray Microfluorescence (μ FRX) is a non-destructive elemental analysis technique that does not require special sample preparation. This technique allows the user to perform quick analyzes and, in addition, has the advantage of analyzing a great variety of sample shapes and sizes, being able to obtain spatial distributions of elements (mapping).

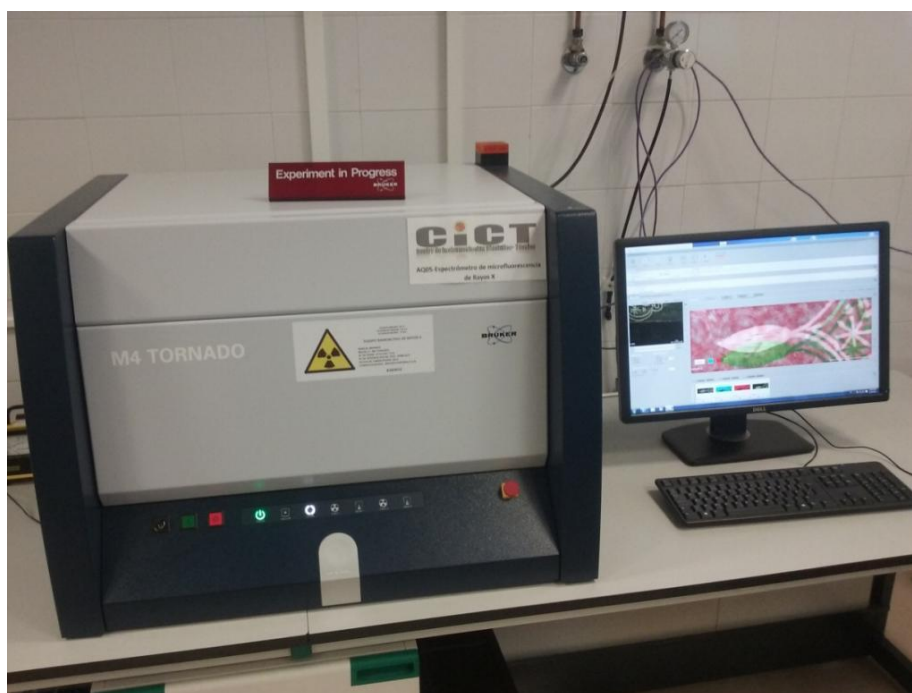


Figure 2.3. AQ05 Micro-X-ray fluorescence spectrometer at the CICT (University of Jaén).

The equipment used is a Bruker M4 Tornado X-ray energy dispersive microfluorescence spectrometer (Fig. 2.3). Sample excitation is carried out by an X-ray tube with Rh anode, with a maximum excitation intensity of 50 kV, 600 μ A (30W). X-ray optics are based on polycapillary tubes that offer a small spot of up to 25 μ m, which allows the size of the excitation beam to be restricted and the beam to be focused on a small point on the surface of the sample. In this way, elemental composition studies can be carried out in very small and localized sample areas, with a measurement range that goes from Na to U. The fluorescence emitted by the sample is captured by an energy dispersive detector (SDD), with 30 mm² of active area, processed and translated into information on the elemental composition.

2.6 Re-Os isotope geochemistry [Cau]

For each sample, 20 g pieces were extracted from the core, stored at the Department of Geology of Jaén University, and preparation of samples was made at sample processing laboratory (Rock Lab). First, the samples were washed with distilled water, and polished using a diamond polishing wheel to remove drill marks. Then they were dried at 50°C overnight to remove water, powdered using a RM 200 agate mortar mill, stored in plastic vials, and sent to Durham University for whole rock Re-Os analysis.

Chemical processing of samples was conducted at the Analytical Geochemistry Preparation Laboratory, in the Department of Earth Sciences of Durham University (Laboratory for Source Rock and Sulfide Geochronology and Geochemistry).

2.6.1 High temperature acid dissolution of samples for Re-Os isotope analysis

To separate the Re-Os fraction from the rest of geologic materials of the sample, CrO_3 -sulphuric acid was used, following the method established for black shales by Selby and Creaser in 2003. Whole rock powders were reacted with a digestion medium of CrO_3 in 4 N H_2SO_4 (0.2 g CrO_3 per ml of 4 N H_2SO_4). The sample loading was made using 1g, weighted using a precision scientific balance, and spiked in pre-cleaned Carius Tubes (5% H_2O_2 – 8N HNO_3 – Milli-Q water process) with a calculated amount of spike (previously derived from Re-test). The samples were then placed into an ice slurry mixture of dry ice and ethanol, and added 8 ml of CrO_3 - H_2SO_4 to dissolve the black shales. Tube sealing was done using a light torch technique melting the neck of the Carius tubes. After cooling, tubes were placed into steel pipe jackets and closed for introduction in the oven, heated at 220°C during 48 hours.

2.6.2 Solvent extraction for Re-Os isotope analysis

Using chloroform from an acid mixture, the Os was separated from the geologic materials. After opening of Carius tubes, 3 ml of CHCl_3 was added over the frozen (thawing) contents inside the tubes. Once thawed, samples were transferred in to 50 ml centrifuge tubes, and agitated using a vortex for a minute and placed into a room temperature water bath for 15 minutes. Then, the contents of the tubes were agitated again in the vortex for 1 minute, and centrifuged for 1 minute too. The CHCl_3 was settled to the base of the centrifuge tube, so for back reduction the CHCl_3 was transferred to a 22 ml glass vial previously filled with 3 ml of 9N HBr. The solvent extraction was repeated twice to totally rinse the Os acid solution from the carius tubes. Glass vials were sealed with teflon caps and placed on a rocker overnight. After the removal of CHCl_3 along the sides and towards the top of the glass vials from these CrO_3 - H_2SO_4 digested samples, the Os-bearing HBr was transferred into clean 8 ml glass vials and evaporated at 80°C overnight. Dry Os from the glass vials was transferred to their lids using 2*30µl 9N HBr to help meticulously dissolve and remove the entire Os fraction from the vial. HBr was evaporated on the lids at 70°C for 1 hour.

2.6.3 Micro-distillation for Re-Os isotope analysis

Micro-distillation to separate Os from geologic materials was made using CrO_3 - H_2SO_4 and 9N HBr. The followed protocol was based on the physical property of cohesion and surface tension that allows the surface of a liquid to resist an external force, in this case, the force of gravity. 20 µl of 9N HBr was placed directly to the base of Tri-star vials, and then turned up side down. Dried caps of the vials containing OsBr_6^{2-} were added 30 µl of CrO_3 – 12N H_2SO_4 solution making sure no air bubbles were left. The caps were carefully sealed with the Tristar vials and placed up side

down on to a hot digital plate at 80°C during 3-4 hours. Caps were removed, and Os-bearing HBr samples were dried down in the Tristar vials until 1 µl remained, parafilmed and ready to mass spec loading.

2.6.4 Re acetone solvent extraction for Re-Os isotope analysis from $\text{CrO}_3\text{-H}_2\text{SO}_4$ digested samples

To isolate Re from $\text{CrO}_3\text{-H}_2\text{SO}_4$ digested samples 5N NaOH was made from pellets – per 10 mL of MQ water, 2g of NaOH was added. Each 5 mL of NaOH was pre-cleaned individually with 2 mL of acetone in a 15 mL centrifuge tube, mixed for 2 minutes, and centrifugated for 10 minutes, then, the acetone was discarded. The resulting 5 mL of cleaned 5N sodium hydroxide solution was added to the dried samples, and placed on a hotplate at 50°C for up to 30 minutes. The sodium hydroxide was transferred to 15 ml centrifuge tubes, and then added 5 mL of acetone. After agitating the sodium hydroxide/acetone mix for 2 minutes, and centrifuging for 10 minutes, acetone separates from sodium hydroxide by density, so it was pipetted-off to new MQ pre-cleaned vials and evaporated at 60°C a few hours. Finally, 1 mL of 6N HCl was added and left to evaporate overnight at 80°C.

2.6.5 Re extraction from hydrochloric acid for Re-Os isotope analysis

For Re purification, single bead method was used, modified after Selby and Creaser (2003). Dried Re-bearing 6N HCl was dissolved with 0.5 mL of 0.05N HCl, and left for 15 minutes. After transferring the Re solution to 1.5 mL centrifuge vials, each sample was added a single bead, capped, and shaken for 1 hour. Then, solution was removed, leaving the Re on the bead. The single beads were washed with 2 x 1 mL of 0.05N HCl, capped and shaken for 5 minutes. To elute Re from the beads, 1 mL of 6N HNO_3 was added, capped and shaken for 1 hour. Finally, 6N HNO_3 was removed evaporating at 85°C.

2.6.6 Mass spectrometry

The purified Os and Re fraction was loaded onto previously crimped and degassed Pt and Ni filaments, respectively. Re loading was made adding Re activator solution directly to the sample and transferred to Ni wire. Os loading was made first loading the sample to Pt wire, and adding the Os activator later. Measures were analysed by Negative Thermal Ionization Mass Spectrometry (NTIMS) on a Thermo Scientific TRITON mass spectrometer (Fig. 2.4).

2.7 Cyclicity [Cau]

Cyclostratigraphy was studied using time series analysis techniques based on the Astrochron R software framework with additional support of Past software for timeseries wavelet transform, QAnalySeries for filtering and Redfit for spectral analysis. However, the explanation of this process is not the aim of the thesis so it is not included.

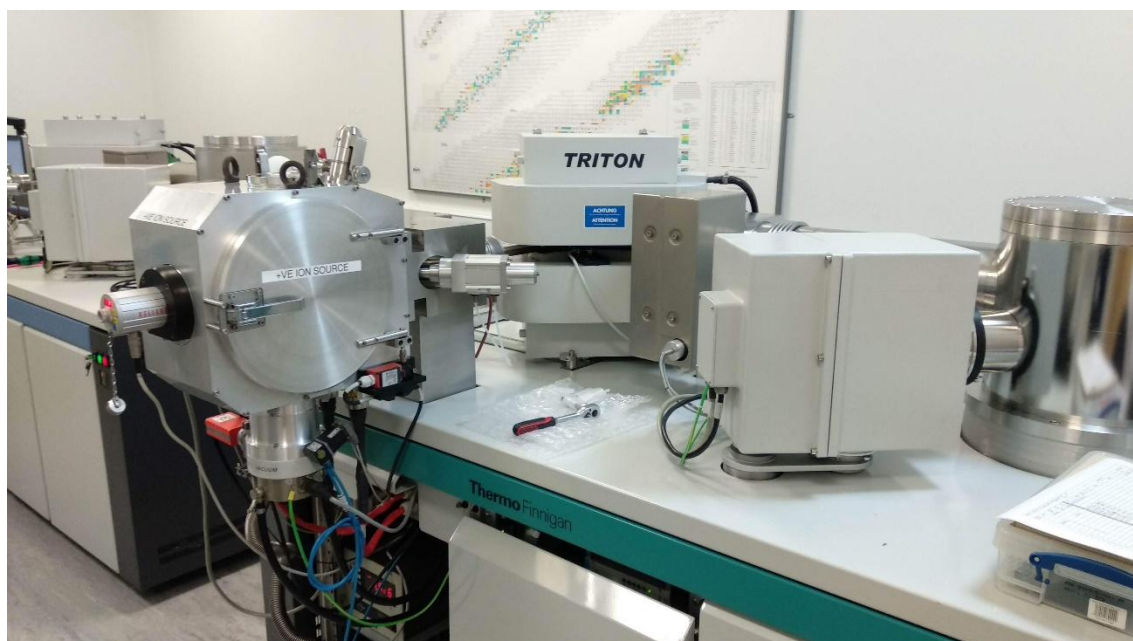


Figure 2.4. TRITON mass spectrometer at the University of Durham (UK).

3 The CAU core: preliminary results and C-isotope stratigraphy

The next chapter is partially based on the following published article, with added sections:

Paleoceanography and Paleoclimatology



RESEARCH ARTICLE

10.1029/2020PA004004

Key Points:

- A high-resolution $\delta^{13}\text{C}_{\text{carb}}$ record from Cau (Spain) is proposed as a new global reference for stratigraphic correlation of the Aptian
- The ultrahigh-resolution record of the onset of OAE 1a documents a long-term negative excursion in C-isotope values, punctuated by several marked negative spikes
- Evidence for the importance of OM burial as a feedback mechanism in response to increased carbon inputs into the ocean-atmosphere system

Supporting Information:

- Supporting Information S1

High-Resolution C-Isotope, TOC and Biostratigraphic Records of OAE 1a (Aptian) From an Expanded Hemipelagic Cored Succession, Western Tethys: A New Stratigraphic Reference for Global Correlation and Paleoenvironmental Reconstruction

José M. Castro¹, Pedro A. Ruiz-Ortiz¹, Ginés A. de Gea¹, Roque Aguado¹, Ian Jarvis², Helmut Weissert³, José M. Molina¹, Luis M. Nieto¹, Richard D. Pancost⁴, María L. Quijano¹, Matías Reolid¹, Peter W. Skelton⁵, Carmina López-Rodríguez⁶, and Rafael Martínez-Rodríguez¹

¹CEACTEMA and Department of Geology, University of Jaén, Campus Universitario, Jaén, Spain, ²Department of Geography, Geology and the Environment, Kingston University London, Kingston upon Thames, UK, ³Department of Earth Sciences, ETH Zürich, Zürich, Switzerland, ⁴Organic Geochemistry Unit, School of Earth Sciences, School of Chemistry and Cabot Institute for the Environment, University of Bristol, Bristol, UK, ⁵Independent Researcher, Milton Keynes, UK, ⁶Centro Oceanográfico de Málaga, Spanish Institute of Oceanography (IEO), Fuengirola, Spain

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Abstract: A high-resolution carbonate C-isotope stratigraphy for the Aptian is presented for the Cau core (Spain). The biostratigraphically calibrated C-isotope stratigraphy of the core is used to refine the previously defined C-isotope segments of the Aptian. Thirteen C-isotope segments have been identified and correlated, and further subdivisions are presented. Correlation with other sections worldwide demonstrates the robustness of the C-isotope stratigraphy of the Cau core. The studied succession includes a continuous record of the early Aptian Oceanic Anoxic Event (OAE 1a). Its onset has been studied at an ultrahigh-resolution scale (0.2–0.5 kyr spacing), revealing a succession of sharp $\delta^{13}\text{C}_{\text{carb}}$ negative spikes, interpreted as a record of pulses of volcanism and methane emissions. The largest spike was rapid (<10 kyr) and marks the base of OAE 1a, which occurs within a longer-term falling $\delta^{13}\text{C}_{\text{carb}}$ trend. The C-isotope profile across OAE 1a perfectly records the negative (C3/Ap3), positive (C4/Ap4), steady (C5/Ap5), and positive (C6/Ap6) segments that were defined from Cismon (Italy) and subsequently identified worldwide. The Ap7 to Ap14 segments record a C-isotope negative excursion, coupled with high TOC contents, probably related to regional paleogeography. The links with global environmental changes, episodes of widespread deposition of organic matter, and ultimately to major volcanic episodes are discussed. We propose the Cau core as a new reference section for the Aptian, and specifically for OAE 1a, based on its expanded and well-preserved sedimentary, geochemical and biotic archives, which provide further insights into the environmental and biotic changes that occurred during this time interval.

DOI: <https://doi.org/10.1029/2020PA004004>

4. Development and demise of a carbonate platform in the Western Tethys – Links with the OAE 1a – the Early Aptian of Sierra Mariola (South Iberian Palaeomargin)

4.1 Introduction

The episodic growth and demise of carbonate platforms in the Tethys domain during the Aptian is broadly connected to remarkable oceanic, climatic and biotic changes, within the context of the greenhouse world in the Early Cretaceous (Skelton, 2003; Skelton and Gili, 2012; Hay et al., 2019). The study of the factors that control the development of carbonate successions in the face of eustatic, climatic, and tectonic processes, represents an important tool for delineating the evolutionary trends of carbonate platforms (Enos and Moore, 1983; James and Mountjoy, 1983; Eberli and Ginsburg, 1989; Schlager, 1992; Simo et al., 1993; Graziano, 2000; Wissler et al., 2003; Föllmi et al., 2006; Reijmer, 2021). The Aptian carbonate platforms of the Western Tethys are characterized by a notable development of rudist bivalves, and present transient episodes of mass orbitolinid-rich facies occurrences. This study provides an excellent case to investigate the complex evolution of a carbonate platform in a rifting geological setting interacting with global and basinal environmental changes, and therefore to observe and evaluate the sedimentary record of the past (Millán et al., 2011; Godet et al., 2011; Huck et al., 2011; Huck and Heimhofer, 2015).

This work presents a high-resolution stratigraphy and sedimentology study based mostly on four carbonate sections that range from very shallow lagoonal facies to open marine outer platform environments, exposed over a large-scale continuous outcrop. The quality and extension of the outcrops have helped to correlate the studied sections, and to analyze the evolution of the platform both vertically and laterally. Different facies associations and variable stacking patterns provide a picture of the stratigraphic architecture of the carbonate framework throughout the shelf. Lateral facies changes and stratal patterns, particularly clinoforms, have been analyzed in order to characterize the morphology and structure of the strata at large scale. The facies analysis and their small-scale cyclicity have been the base for the characterization of the sedimentary model of the platform, whereas the analysis of the stratigraphic architecture and the different scales of cyclicity have been conducted to decipher the sedimentary evolution. Based on observations made over panoramic views across the outcrops and taking into account the stratal geometries and the analysis of trends in facies and microfacies, we propose a sequence-stratigraphic framework. The integration of these results within the tectonic, eustatic and environmental context has led to the discussion on the factors that controlled the development of the platform. This paper is focused on the study of a shallow-water carbonate platform affected by tectonics, biotic crises and ecological stress near the onset of the Early Aptian Oceanic Anoxic Event (OAE 1a), which has been investigated with stable isotope analyses. One specific focus of this work is to obtain clues about how a carbonate platform evolves in a context of environmental change and how was the interaction with the onset of the major cycle carbon perturbation associated to the OAE 1a.

4.2 Geological setting

The successions studied in this work encompass the early part of the Early Aptian (middle to upper members of the Llopis Formation, Castro, 1998; Castro et al., 2008). The materials studied are located in the Sierra Mariola (N province of Alicante, SE Spain). This range contains one of the Lower Cretaceous outcrops in the province of Alicante that are part of the Internal Prebetic (Fig. 4.1A) (e.g., Vera, 2004; Vilas et al., 2004; Martín-Chivelet et al., 2019). Together with the External Prebetic and the Subbetic, they form the External Zones of the Betic Cordillera, an Alpine Iberian chain. The External Zones of the Betic Cordillera are made of sedimentary units

deposited from Triassic to Early Miocene on the Southern Iberian Palaeomargin (SIP), during the Alpine tectonic cycle (Vera, 2001) (Fig. 4.1B). The development of wide and thick carbonate platforms in the shallow areas of the SIP was favored by large subsidence rates under an extensional tectonic regime (García-Hernández et al., 2001, 2003; Martín-Chivelet et al., 2019) (Fig. 4.1C).

Basin analysis of the Prebetic platform made by Vilas et al. (1993), allowed the recognition of several tectonosedimentary episodes for the Early Cretaceous. The Aptian represents a main tectonosedimentary episode (K4, Alonso-Chaves et al., 2004) limited by two major discontinuity horizons linked to extensional tectonic events that resulted in significant changes in basin palaeogeography and subsidence patterns. This Aptian tectonosedimentary episode corresponds to a second-order sedimentary cycle in the sense of Hardenbol et al. (1998), composed by a succession of third order cycles that define a general transgressive-regressive evolution (Castro, 1998; Ruiz-Ortiz and Castro, 1998; Castro et al., 2008).

Previous studies on the lower Aptian of Sierra de Mariola

The earliest work on the urgonian facies from the Sierra Mariola was published by Fallot (1943). Darder (1945) analyzed the geology of the northern region of Alicante and the south of Valencia, revealing the broad structural, stratigraphic and paleontological features. Fallot (1948) made a synthesis on the Betic Cordilleras, concluding that the different tectonic domains previously proposed (Betic, Subbetic and Prebetic Zones) have a different stratigraphy and thus, they represent different palaeogeographic evolutions. Busnardo et al. (1968) studied in detail the urgonian facies of the Sierra Mariola, with special attention to the ammonoids and orbitolines faunas. They divided the urgonian facies in two units, Barremian-lower Aptian and upper Aptian-lower Albian, separated by marls with ammonites from the Bedoulian-Gargasian transition. Relevant studies by Azéma et al. (1975) and Company et al. (1982) greatly contributed to the knowledge of biostratigraphy, and the tectonosedimentary and palaeogeographic evolution of the region during the Cretaceous. More recent studies on the lower Aptian of Sierra Mariola include the papers by Castro (1998), Castro et al. (2008, 2014), Martínez-Rodríguez et al. (2018) and Skelton et al. (2019), that made new advances mainly in biostratigraphy, basin analysis, sequence stratigraphy, geochemistry, and their correlation and integration in the global geodynamic and environmental context.

4.3 Material and methods

Lithostratigraphy

The lower Aptian of the Prebetic of Alicante is represented by the Llopis Fm., which is subdivided into three members (Castro, 1998; Castro et al., 2008). This work is focused on the study of the Middle and Upper members of the Llopis Fm. The Lower Member is made of limestones and marlstones, of Late Barremian age, and represents a regressive phase (Castro et al., 2008). Over these deposits, the Middle and Upper Member correspond to a new T-R sequence (Castro et al., 2008; Martín-Chivelet et al., 2019). These two members have an Early Aptian age, the Middle Member is composed of shallow marine grey limestones with rudists and corals, the Upper Member (Agres Bed) comprises bioclastic and sandy limestones, interbedded with marls with orbitolines. The Almadich Fm (Fig. 4.1C) is a rhythmic alternation of marls and marly limestones with ammonites and planktonic fauna, overlying the Llopis Fm, which was deposited in outer-ramp environments under hemipelagic conditions.

Methods

Four detailed logs recording lithostratigraphy and facies have been carried out, including sampling for petrographic, microfacies and, biostratigraphic characterization, along with C and O isotopes. The methodology of this study has its base on the fieldwork. At field, 318 samples

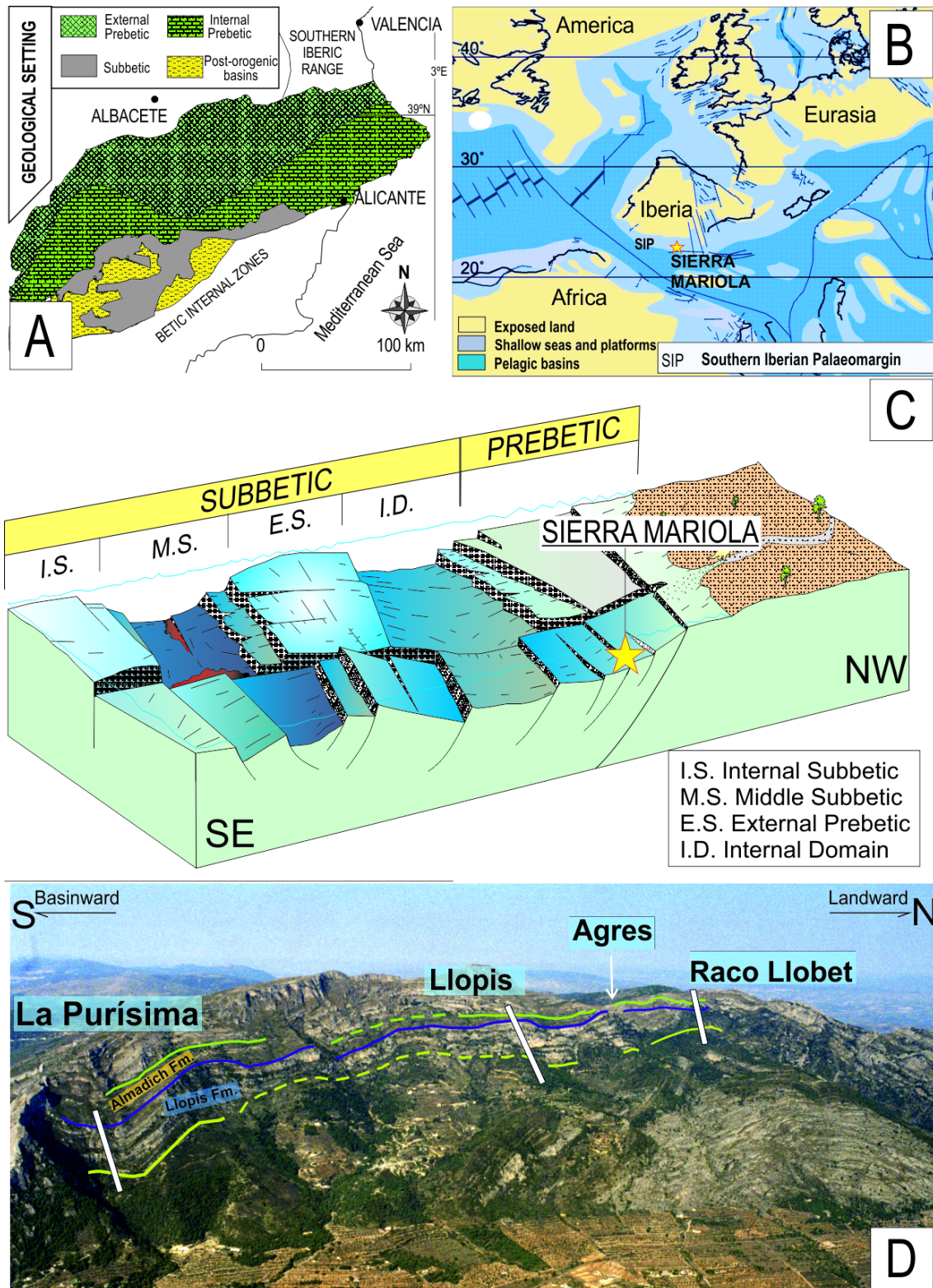


Figure 4.1. A. Regional geological setting of the Betic External Zones in the E of the Iberian Peninsula (modified from Castro et al., 2008). B. Palaeogeography of the Iberian Plate during the Aptian (simplified from Masse et al., 1993). C. Reconstruction of the tectonosedimentary context for the External Betic Zones during the Early Aptian (modified from Ruiz-Ortiz, 2010). D. Aerial view of eastern slope of Sierra Mariola, studied in this paper. Drawn lines highlight Llopis and Almadich Fms., The location of the four sections studied in this work are indicated.

were collected in the four sections studied, to make a total of 318 thin sections in order to describe the petrography and microfacies. The interval of sampling is variable, the mean value is 410 m / 318 samples = 1.29 m/sample. The size of sampling interval is dependent to the thickness of bed or set of beds, usually selected to document each level, or, in case of beds thicker than 1 m, to see the variation between its lower and upper part. In stretches with dolomitization, sampling has been usually avoided. The study of petrography and microfacies has been made using a polarized microscope Nikon Eclipse E600pol, and a binocular polarized microscope Olympus SXZ16 and SZPT mounted with photography lenses Nikon-DS-L1 and Olympus BX-40, respectively. Monographies by James and Dalrympe (2010) and Flügel (2010) has been used as a reference for facies and microfacies characterization. For stable isotope analyses, 130 samples were selected from two of the sections, 15 from La Purísima (distal section) and 115 from Racó Llobet (proximal section). Hard hand-samples were carefully micro-drilled to extract the micritic-matrix, in order to obtain a sedimentary C-isotope signal. Carbon isotope measurements were made with a ThermoScientific MAT253 Isotope Ratio Mass Spectrometer connected to a Kiel IV Carbonate Device at the Stable Isotope Laboratory of the Instituto de Geociencias (CSIC, Complutense University of Madrid). $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}$ values of the carbonate carbon were calibrated against certified carbonate standards (NBS-19). All the isotope data are reported in per mil (‰) versus Vienna-Pee Dee Belemnite (V-PDB) standard. The analytical precision of repeated standard measurements is always better than 0.025‰ for both carbon and oxygen. The cross-plots of $\delta^{13}\text{C}$ vs $\delta^{18}\text{O}$ (Fig. 4.9) of Racó Llobet and La Purísima show a low degree of correlation, indicating no intense post-depositional diagenetic alteration or influence of groundwater or meteoric water on the isotopic signature. The four sections presented are a compilation of different outcrops analyzed and correlated, used to make the direct physical correlation possible. Helicopter aerial views taken in 2007, provided by J.M. Castro, have been used to generate large panoramic, compound images, in order to adjust precision for the stratigraphic correlation, and to analyze the geometric disposition of strata packets to refine the stratigraphic architectural framework based on the study of the outcrops. Principles and terms of sequence stratigraphy (e.g., Catuneanu et al., 2011; Catuneanu, 2020) have been applied to the analysis of the record.

4.4 Results

4.4.1 Stratigraphy

La Purísima section (Fig. 4.1D, WGS84 coordinates: bottom 38°44'56.37"N 0°27'49.72"W; top 38° 44'59.208"N 0°28'18.751"W) is 159 m thick, and is mainly composed of limestones with less abundant intercalated marl levels. This section shows marked vertical facies changes between grainstones, floatstones/rudstones with corals and rudists, and mudstones (Dunham, 1962) (see Fig. 4.2). The location of the Llopis section (Fig. 4.1D) is South to the “Balcón de Llopis”, a steep wall in the centre of the East side of Sierra Mariola (WGS84 coordinates: 38°45'27.7"N 0°28'45.7"W) (Fig. 4.1D). The Llopis section is 53 m thick (Fig. 4.2), and its position is key to connect distal (outer) and proximal (inner) parts of the Aptian carbonate platform that developed at Sierra Mariola, and contains the upper part of the Llopis clinoforms where the carbonate beds present progradational geometries southwards. The Racó Llobet section (Fig. 4.1D) WGS84 coordinates are: Bottom; Lat. 38.7676670; Long. -0.4926540; Top; Lat. 38.7643143; Long. -0.4923775. The section is 118 m thick (Fig. 4.2). The first 38 m are characterized by the presence of calcarenites. The middle part consists of nodular and often bioturbated marly limestones. Its lower part (from 38 to 50 m) contains abundant brachiopods, whereas the upper part (from 50 to 60 m) is very rich in orbitolinids. The upper part, from 60 to 118 m, is composed mainly of well-bedded limestones with rudists. The Agres section is 18 m thick (Fig. 4.2). This section is located on the northern face of Sierra Mariola (Fig. 4.1D). Its

position is the most proximal of the four, and it was selected to study the transition from the Middle Member of the Llopis Formation to the Upper Member of the formation, the Agres Bed. This Upper Member displays an enrichment in quartz content and shows a very particular microfacies association of conical and planar orbitolinids, with abundant rudists (caprinidae) in recumbent position (Gili et al., 1995; Skelton et al., 2019). The top of this member is a planar surface with borings and ostreids that represents the demise of the platform (Skelton et al., 2019).

4.4.2 Biostratigraphy – Age constraints

Caprinidae rudists *Offneria interrupta* has been found at the base of the Racó Llobet section, and *Caprina douvillei* at the top (Skelton et al., 2019). The lower part of La Purísima section has *Sabaudia* sp., *Derventina* sp., and *Choffatella decipiens* (Fig. 4.3C-D) benthonic foraminifera. Also orbitoline *Dictyoconus maynci* has been found at the lower part of La Purísima. Other orbitolinids found are *Orbitolinopsis kiliani*, *O. buccifer* (Fig. 4.3A), and *O. cuvillieri*, the presence of the last one in this association is indicative of an Early Aptian age (*D. sarasini*-*D. oglanlensis* zones, Bonvallet et al., 2019). Planktonic foraminifera *Hedbergella sigali* have been recovered in the middle part of the Racó Llobet section. Collectively, these data indicate a lower Aptian (lower Bedoulian) age, which is consistent with previous data (e.g., Busnardo et al., 1968; Company et al., 1982; Castro et al., 2008; 2014; Skelton et al., 2019). Associations of orbitolinids have permitted the recognition of two biostratigraphic units (Castro et al., 2001): with *Orbitolinopsis killiani* and *O. cuvillieri*, recorded in the lower part, and with *Orbitolinopsis praesimplex* (Fig. 4.3B), whose first record occurs at the middle part of the unit.

Consequently, the time interval represented by the studied succession is correlated with the following planktonic foraminifera and ammonite biozones (Castro et al., 2001; Martín-Chivelet et al., 2019) (see Table 1):

- *Martelites sarasini* ammonite zone, corresponds to the part lacking *O. praesimplex*, and *D. oglanlensis* and *D. forbesi* ammonite zones corresponds to the part in which *O. praesimplex* is present. Collectively, this corresponds to the uppermost part of *Globigerinelloides blowi* zone. The base of the Agres Bed is coincident with the negative peak that marks the onset of the OAE 1a (Skelton et al., 2019). This horizon is placed between the FO of *Rhagodiscus angustus* and the FO of *L. cabri* (Castro et al., 2021), which corresponds to lowermost part of *D. forbesi* biozone (Gradstein et al., 2020).

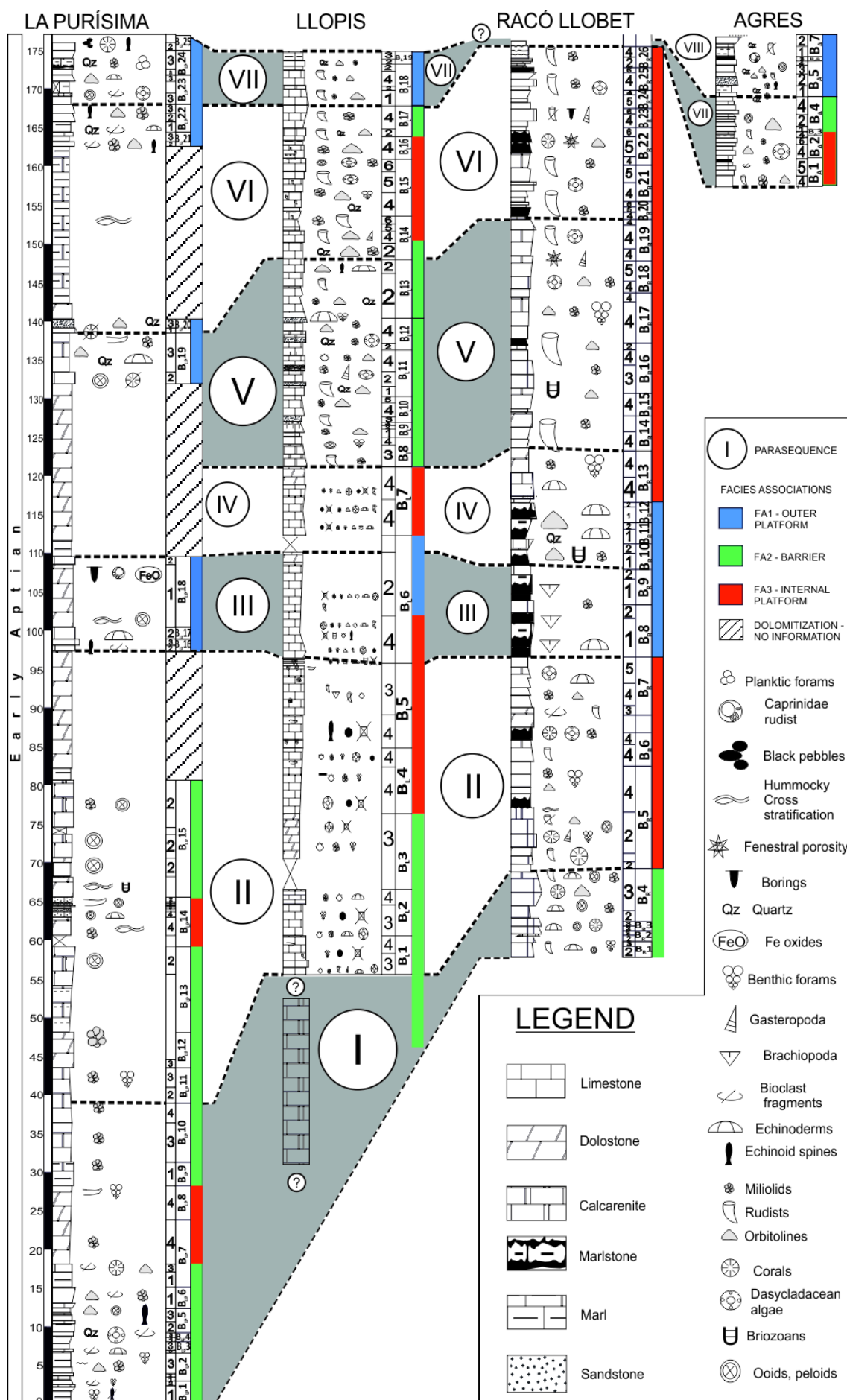
4.4.3 Sedimentology

4.4.3.1 Facies analysis

The combined field and microfacies detailed study have led to the differentiation of six main facies types (see Table 2 and figs. 4.4 and 4.5), based on the systematic established by Dunham (1962).

Facies 1 (Fig. 4.4B, Fig. 4.5.1A and 4.5.1B) contains with small skeletal matrix, planktic foraminifera and association of echinoids and planar orbitolines. Facies 1 corresponds to packstones and wackestones almost entirely composed of orbitolinids (orbitolinite). The orbitolinids are mostly planar. Less common grains are brachiopods, cortoids, crinoids, scarce rudist fragments, bryozoans and gastropods. The matrix is a peloidal micrite with fine quartz grains. This facies represent the outer or open marine platform.

Figure 4.2 (below). Correlation scheme for the studied sections. From left to right, the four stratigraphic columns are: La Purísima, Llopis, Racó Llobet, and Agres. Facies types are indicated with numbers, bundles are indicated as upside arrows, super bundles are indicated with roman numbers.



(Gradstein et al., 2020)	Marine Macrofossils	Planktonic Foraminifers	Calc. nanno.	LITHO- STRATIGRAPHY
Ma	Tethyan Ammonoids	Sub-Tropical Zone		
120.6	<i>Deshayesites forbesi</i>	<i>Globigerinelloides blowi</i>	NC6A	UPPER MB
	<i>Deshayesites oglanlensis</i>			MIDDLE MB
121.4	<i>Martelites sarasini</i>			LLOPIS FM

Table 1. Chronostratigraphic chart for the studied materials.

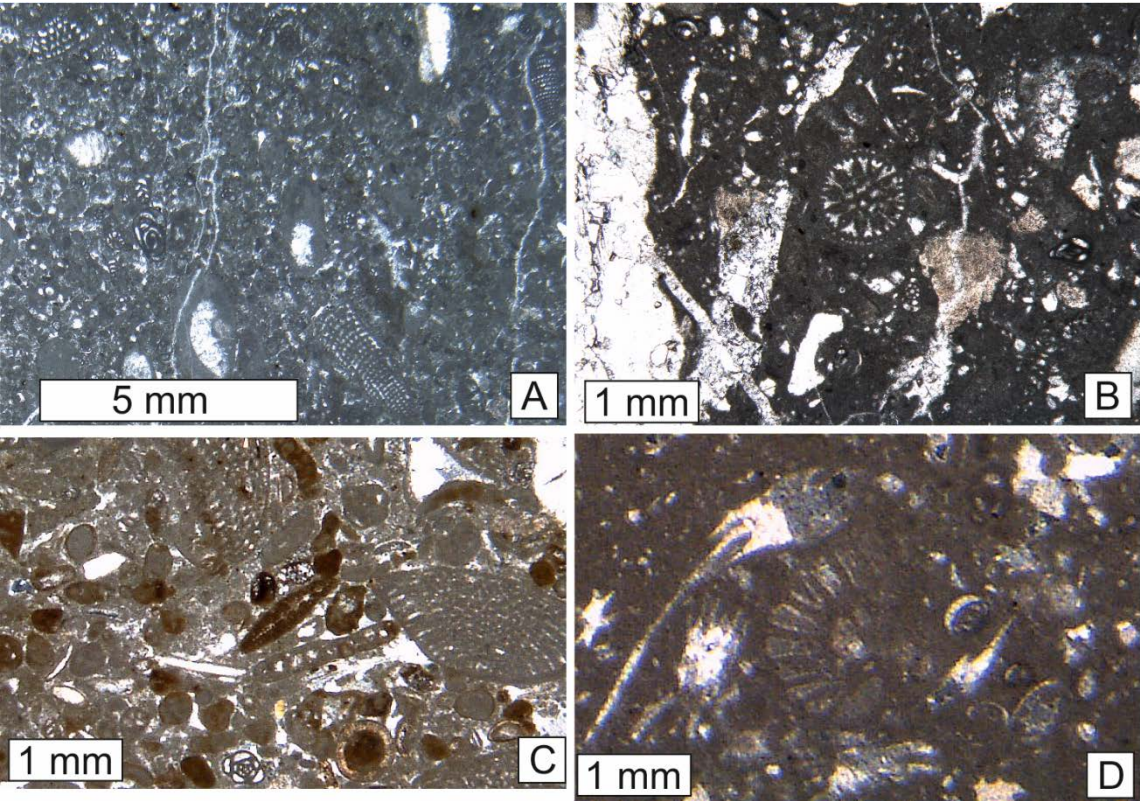


Figure 4.3. A. Microphotograph of sample SCL-14, showing *Orbitolinopsis buccifer*, *Dictyoconus maincy* and *O. praesimplex*. B. Detail of *Orbitolinopsis praesimplex* (sample SCL-9). C. Axial section of *Choffatella decipiens* (sample SCL-23). D. Oblique subequatorial section of *Choffatella decipiens* (sample LA-2).

Facies 2 (Fig. 4.5.1C and 4.5.1D) is represented mainly by coarse brownish grey calcarenites which are arranged in m-thick beds with local, small-scale cross-stratification. The microfacies are bioclastic grainstones with 1 mm mean sized grains and sparry cement. Grains are mostly coated, in some cases completely micritized. They are intraclasts, peloids, ooids, cortoids, and some bioclasts such as molluscs, red algae, echinoid spines, crinoids and benthic foraminifera. Some grains contain Fe-oxide. The intraclasts are poorly-sorted and sub-angular to sub-rounded in shape. This facies is interpreted as represent the outer or open marine platform.

Facies 3 (Fig. 4.5.1E-F-G-H) corresponds to grey limestones and marlstones with scleractinian corals, usually with packstone texture. The corals are small (cm-size) irregular bioclasts often encrusted by red algae, with micrite coatings and borings filled with sediment. The matrix is mudstone to wackestone with bioclasts and benthic foraminifera (mostly miliolids and orbitolinids), along with some lime mudstone intraclasts intensely burrowed. This facies has grainstone texture when related to shoals or external barrier, usually with fragmented and rounded bioclasts, and packstone texture and peletoidal matrix with rudists more linked to the internal part of the barrier, or open-circulation lagoonal environments.

Facies 4 (Fig. 4.5.1I and 4.5.1J) corresponds to floatstones and packstones with rudists, along with ostreids, chondrodonta, other bivalves, coral fragments, and another vagile organisms like echinoderms and gastropods. The matrix is a bioclastic wackestone (locally packstone), with small skeletal debris, including benthic foraminifera (miliolids and orbitolinids with conical morphology), and dasycladalean algae. This facies was deposited in shallow environments with low energy and moderate water circulation, in lagoon environments.

Facies 5 (Fig. 4.5.2K) is represented by wackestones and packstones with abundant benthic foraminifera, as miliolids and orbitolinids, among other planispiral, trochospiral and biserial benthonic foraminifera. This facies represent restricted lagoon environments.

Facies 6 (Fig. 4.5.2L) is represented by mudstones with scarce small miliolids and undifferentiated bioclasts. The micrite displays small (mm-size) pores (Fig. 4.5.2L). This facies are interpreted to be deposited under very shallow, low energy, very restricted lagoon environments.

4.4.3.2 Elementary cycles and facies associations

The described facies are stacked in meter-scale elementary cycles, formed mainly by three different vertical associations of facies (FA1, FA2 and FA3). By application of Walther's law, these vertical associations of facies indicate a 1-2-3-4-5-6 lateral facies relationship during deposition (Fig. 4.6). The first facies association (FA1, facies 1 and 2) is composed of packstones with orbitolinids, wackestone/packstone with brachiopods, and marlstones with corals, present in the middle part of the sections (parasequences III and IV, Fig. 4.2). The second association (FA2, facies 2 and 3) is represented by cycles of calcarenites followed by marlstones with corals, and it is mainly present in the lower part of the sections (parasequences I and II, Fig. 4.2). The third facies association (FA3, facies 4, 5, and 6) is composed of calcarenites, rudist floatstones and wackestones or mudstones with burrowed or bored tops, and dominates the upper part of the sections (parasequences IV, V and VI, Fig. 4.2). The elementary cycles are interpreted as shallowing-upwards cycles, that are stacked in groups of bundles separated by marly levels, which result in seven units considered as parasequences (e.g. Catuneanu et al., 2011; Catuneanu, 2020).

4.4.4 Cyclicity

One of the most pervasive characters of the succession is the vertical cyclicity defined by the elementary cycles of facies, and the higher scale cycles making up to seven defined parasequences. The succession of facies recorded in each elementary cycle is considered to be deposited under continuous sedimentation with gradual changes in the sedimentary conditions. These elementary cycles are limited by neat surfaces, considered to represent sharp changes in the sedimentary conditions, likely hiatuses, specially when features as iron crusts or borings appear in these surfaces. Bundles (B) have been defined here as sets of beds that begin with a determined type of facies, and together with field observations and petrography analysis, they describe a follow-up succession that generally goes from deeper or distal facies to shallower or proximal ones. The analysis of facies and their associations permits the determination of bundles across the sections. At larger scale, these bundles can be seen at field and on aerial images as packets that are laterally continuous through the outcrops, defined as Parasequences (SP), following the definition of Catuneanu and Zecchin (2020). Collectively, the analysis of cyclicity reveals three orders, from smaller to larger scale, named here as elementary cycles, bundles and parasequences. The sequence-stratigraphic terminology follows Vail et al. (1991) and Catuneanu (2020).

Table 2. Lithofacies, facies associations and environmental interpretation of the studied materials.

Facies	F.A.	Lithofacies description	Environmental interpretation
1	Facies Association 1	1a: Packstone and wackestone almost entirely composed of orbitolinids (orbitolinite), mostly planar. Less common grains are brachiopods, cortoids, crinoids, scarce rudist fragments, bryozoans and gastropods. The matrix is a peloidal micrite with fine quartz grains. 2a: This subfacies differs from facies 1a in the lower abundance of planar orbitolinids, and the presence of small bioclasts and planktic foraminifera.	Distal open platform. Shallow open marine environments with moderate to high energy.
2		Bioclastic grainstones with 1 mm mean sized grains and sparry cement. Grains are coated bioclasts, exhibit micrite envelopes or are completely micritized. It contains intraclasts, micritized grains, peloids, ooids, cortoids, and some bioclasts such as molluscs, red algae, echinoid spines, crinoids and benthic foraminifera. Some grains contains Fe-oxide. The intraclasts are poorly-sorted and sub-angular to sub-rounded in shape.	Barrier open platform closest to some small corals build-ups. Shallow marine environments with moderate energy, representing sandy (barrier) shoals.
3	Facies Association 2	Grey limestones and marlstones with scleractinian corals, with packstone texture. The corals are small (cm-size) irregular bioclasts often encrusted by red algae, with micrite coatings and borings filled with sediment. The matrix is mudstone to wackestone with bioclasts and benthic foraminifera (mostly miliolids and orbitolinids), along with some lime mudstone intraclasts intensely burrowed.	Build-ups located in the platform barrier.
4	Facies Association 3	Floatstones and packstones with rudists, along with ostreids, other bivalves, coral fragments, and another vagile organisms like echinoderms and gastropods. The matrix is a bioclastic wackestone (locally packstone), with small skeletal debris, including benthic foraminifera (miliolids and orbitolinids with conical morphology), and dasycladacean algae.	Lagoon environment of the inner platform. Low energy, shallow lagoon, with moderate water circulation.
5		Wackestones and packstones with abundant miliolids and orbitolinids, among other planispiral, trochospiral and biserial benthonic foraminifera. The matrix is homogeneous micrite.	Marginal lagoon environment. Shallow low-energy environment corresponding to a lagoon with restricted water circulation.
6		Mudstones with scarce small miliolids and undifferentiated bioclasts. The micrite displays small (mm-size) fenestral pores.	Very shallow low-energy environment with restricted circulation.

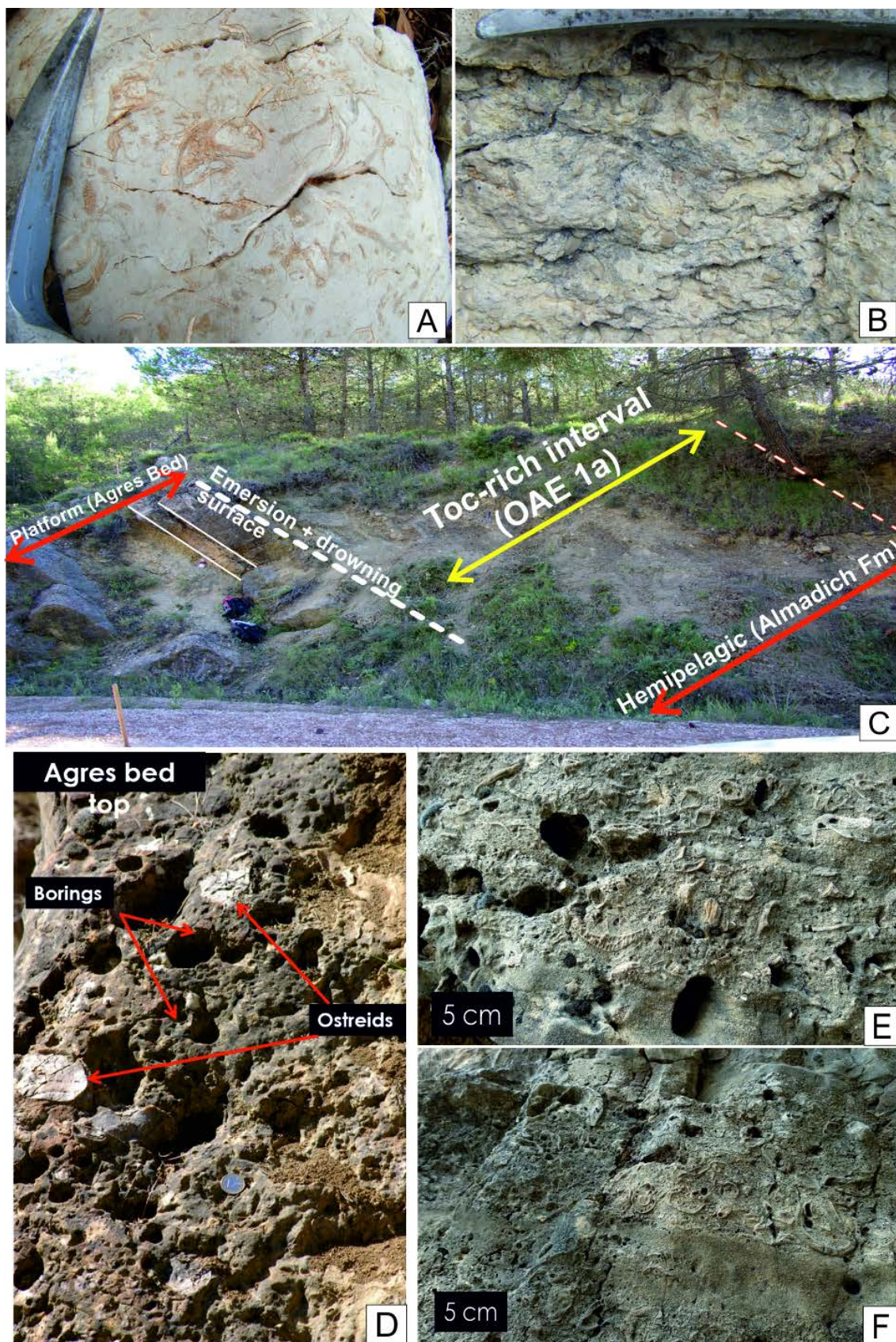


Figure 4.4. A. Rudist floatstone facies. B. Orbitolinite facies. C. Outcrop photography at Agres section showing the top of the Agres Bed and the base of Almadich Fm. D. Top horizon of Agres Bed. E-F. Detail of rudist-rich calcarenitic level from the uppermost part of the Agres Bed.

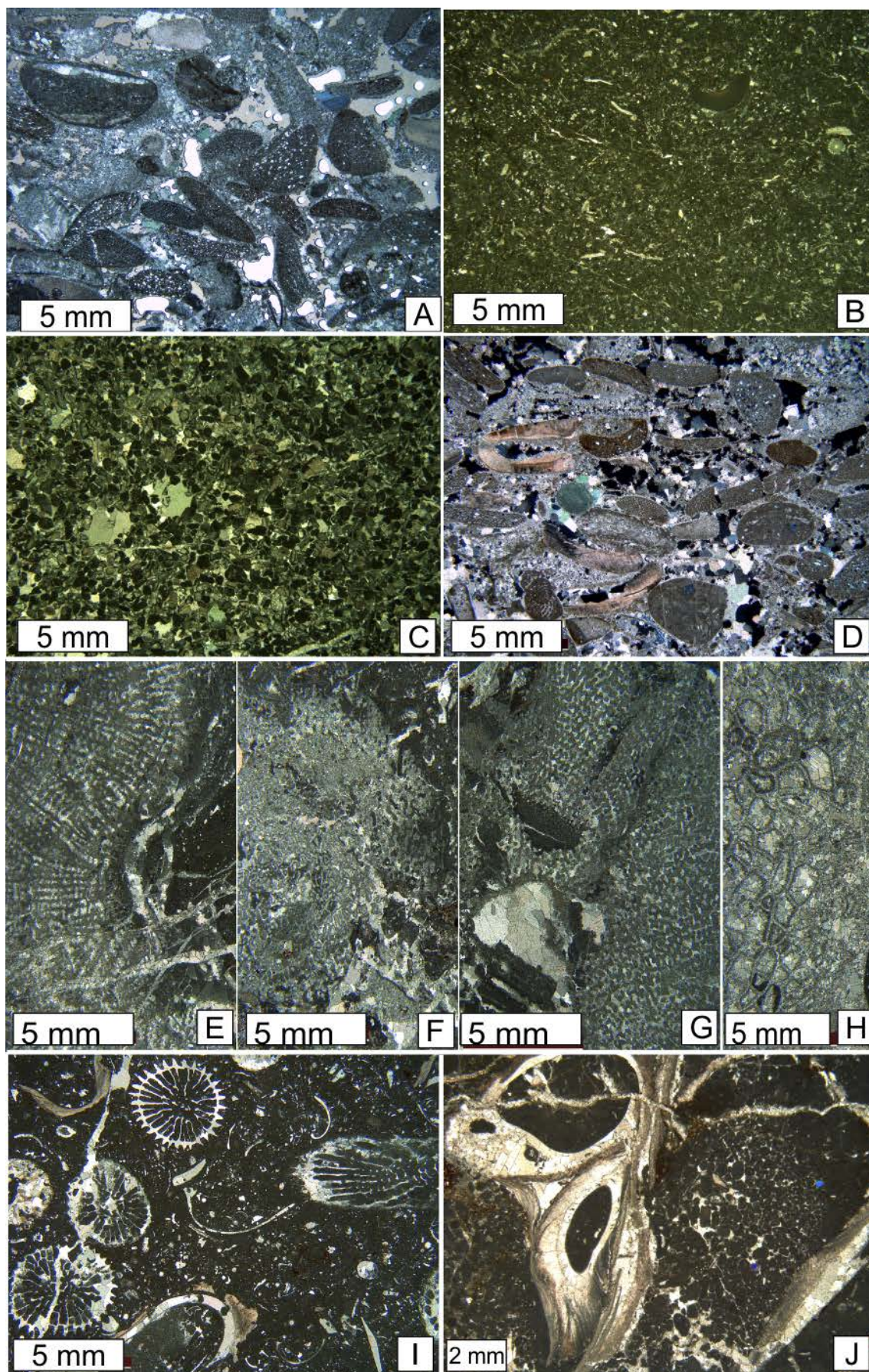


Figure 4.5.1 (up). Microfacies. A. Type 1a “orbitolinite” facies. B. Type 1b facies. C. Grainstone texture of calcarenitic facies type 2. D. Type 2 facies, on this sample showing sparry cemented matrix with accumulation of bioclasts, mostly planar orbitolines, parallel-oriented. E-F-G-H. Boundstone of coral facies type 3. I-J. Facies type 4, showing solitary corals (I) and rudists (J).

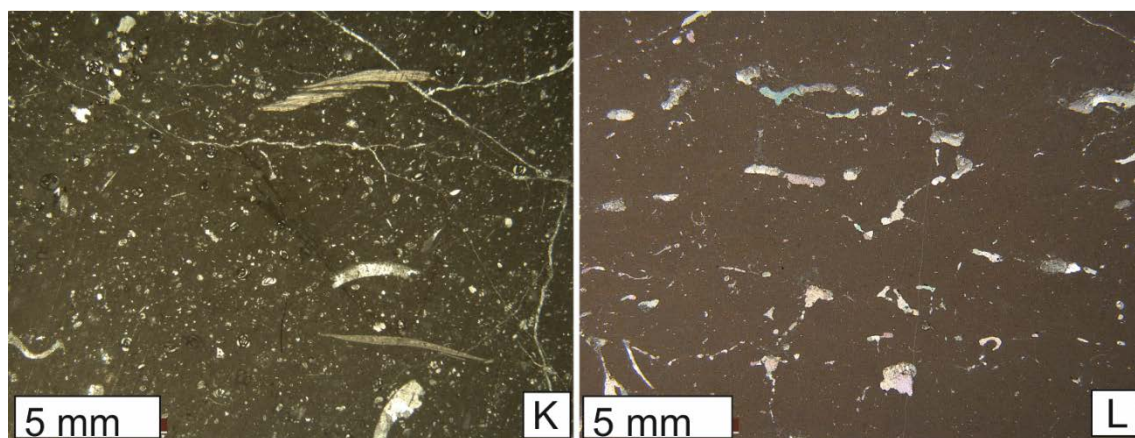


Figure 4.5.2. Microfacies. K. Facies type 5 wackestone with miliolids and other benthic foraminifera. L. Facies type 6, mudstone with fenestral porosity.

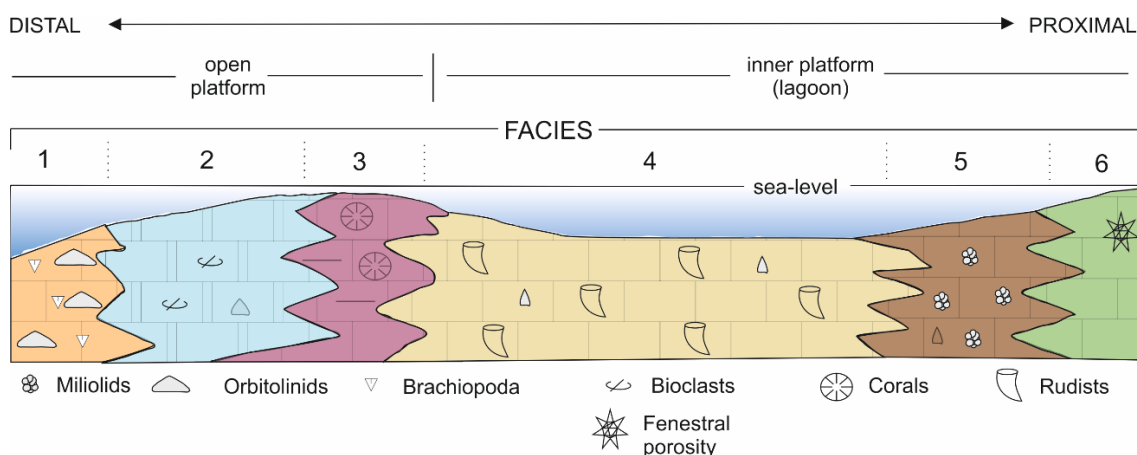


Figure 4.6. Facies model. Distribution of the facies in a schematic transect through the Mariola platform. Modified from Martínez-Rodríguez et al., (2018).

In La Purísima section, at least 25 bundles (B_{LP1} to B_{LP25}) have been recognized; nevertheless, due to dolomitization, it is difficult to observe the original sedimentary features at some parts of the section, where more bundles are probably present. In the Llopis section, 19 bundles (B_L1 to B_L19) have been recognized.

The Racó Llobet section shows 27 bundles (B_R1 to B_R26) that have different thickness between 2-3 m to more than 10 m. The lower four bundles belong to parasequence I (SP I), and the following three make the parasequence II (SP II). Parasequence III is formed by 3 bundles. 13 bundles have been recognized in the upper part of Racó Llobet section. The 6 lower bundles of the parasequence IV (SP V), are, in general, thicker (having 5-7 m) than the 7 upper bundles of parasequence V (SP VI), which are generally organized in packages of 2-3 m, in a thinning-upward trend. Only the base of parasequence VII is well exposed in this section.

The Agres section has 7 cycle-bundles (B_A1 to B_A7) (Fig. 4.7). The first 4 bundles are part of the parasequence VII (SP VII), while the 3 upper bundles are part of the Agres Bed (or parasequence VIII – SP VIII) (Fig. 4.7).

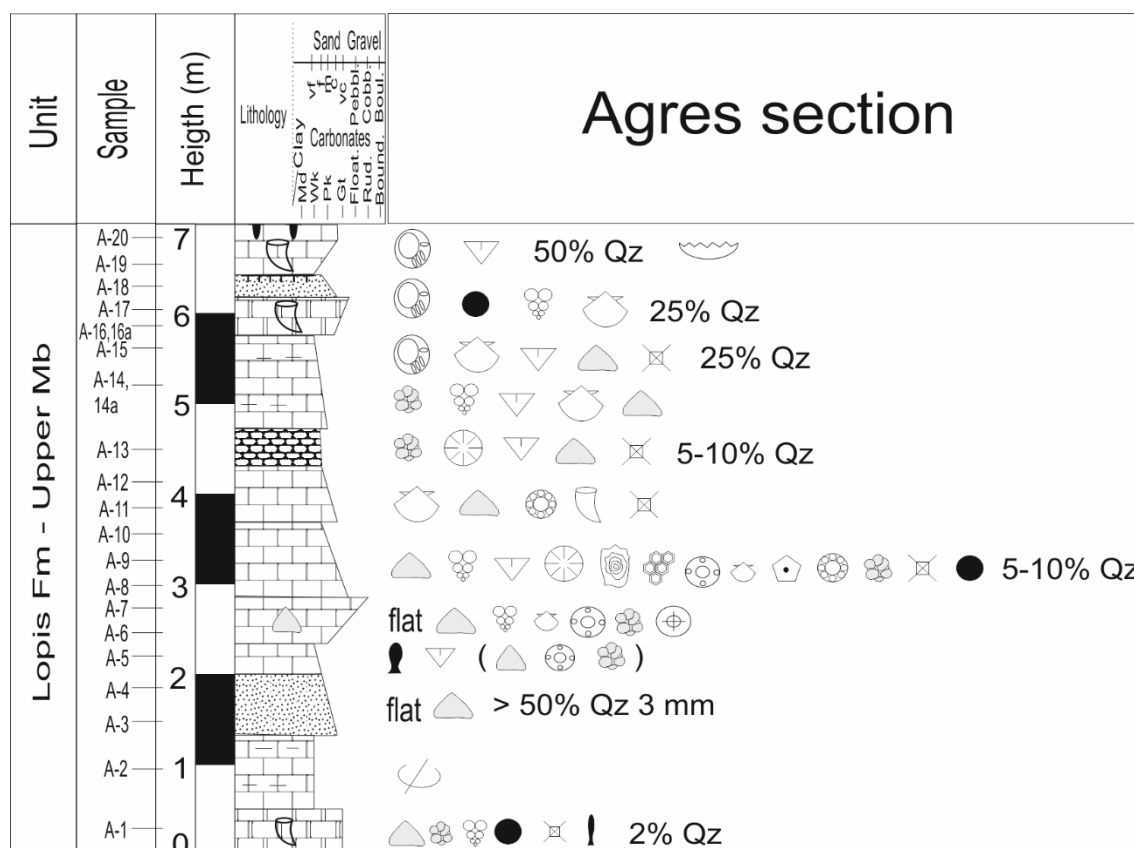


Figure 4.7. Detail of the Agres Section showing the Agres Bed, that corresponds to the parasequence VIII of this study.

4.4.5 Stratigraphic architecture

One of the key aspects of the Middle Member of Llopis Formation at Sierra Mariola is its great lateral continuity, constituting an almost continuous outcrop. The eastern slope of the range offers a large-scale natural cross section cutting the carbonates through 1650 m at NNE-SSW direction. The correlation of sections has been made taking reference horizons as marly levels or ferruginous surfaces, with the help of aerial views and helicopter images. This allowed to divide the Middle and Upper Members into eight parasequences (Fig. 4.8A). These parasequences can be seen in the panoramic views from the outcrops and are recognized in the cyclicity analysis of each studied section. To correlate the parasequences, we have integrated strata morphology data obtained from the field with the analysis of aerial photography.

- Parasequence I – SP I

The first parasequence crops out in the lowermost part of La Purísima and Racó Llobet sections, with a thickness of 15 and 12 m respectively. It has been recognized below the Llopis section, although the outcrop conditions hampered a detailed logging. It is formed by grey calcarenites showing small-scale cross-stratification and grainstone microfacies with crinoids, brachiopoda and small benthic forams (FA 2).

- Parasequence II – SP II

This parasequence is present in La Purísima, Llopis and Racó Robet sections. The thickness in La Purísima is 30 m, 40 m in Llopis, whereas in Racó Llobet is 60 m. The predominant facies are grey to white limestones with macrofossils (rudists and chondrodonta) (facies 4). This packet is aggradational, presenting clinoforms at the Llopis section, that confer it a sigmoidal shape

showing incipient progradational morphology (Fig. 4.8C). Facies change laterally from micritic packstones with corals at Raco Llobet (proximal) to calcarenitic grainstones at La Purísima (distal) (Fig. 4.2). The lateral facies change is recorded in the Llopis section, where clinoforms records the shift between the barrier or shoal complex at their upper (northern) part to the platform-slope at their lower (southern) part (Fig. 4.8C).

- Parasequence III – SP III

Parasequence III is present at La Purísima, Llopis and Raco Llobet sections. This parasequence is 10 m thick at Raco Llobet, passing to 15 m at Llopis and 13 m at La Purísima. This parasequence is composed of aggradational beds with inner platform facies in Raco Llobet and Llopis sections, whereas in La Purísima is represented by aggradational beds with external platform facies.

- Parasequence IV – SP IV

This parasequence is 15 m thick at Raco Llobet, and 11 m thick at Llopis, passing to 12 m at La Purísima. It contains parallel strata (Fig. 4.8D) with nodular levels with planar orbitolines and echinoids in Raco Llobet and Llopis, whereas in La Purísima is mostly represented by dolostones.

- Parasequence V – SP V

This package is prograding to the South, strongly dolomitized at La Purísima, with calcarenites in the upper part. At Llopis and Raco Llobet sections is composed of well stratified rudist limestones, which alternate with calcarenites at Llopis. The rudist facies are very well exposed at Raco Llobet, where this parasequence reaches 30 m thick (Fig. 4.8E).

- Parasequence VI – SP VI

This package is 30 m thick at La Purísima, 20 m at Llopis, and 23 m at Raco Llobet. A notable lateral facies change can be observed between them, from the Raco Llobet packstones, that are rich in rudists and dasycladacean algae, characteristic of inner platform environments, to calcarenites with hummocky cross stratification and marlstones at La Purísima (Fig. 4.8B).

- Parasequence VII – SP VII

This set represents the uppermost part of the Middle Member, shown at La Purísima, Llopis and Agres. It is composed of distal external platform facies at La Purísima (nodular and micritic limestone with biserial benthic forams). In Llopis and Agres it is represented by a particular association of external and internal platform facies, without clear presence of barrier facies. At the Raco Llobet section this parasequence is poorly exposed and dolomitized, and has not been logged in detail.

- Upper Member (Agres Bed) – SP VIII

The Agres Bed is the Upper Member of the Llopis Formation, it crops-out at the Agres section, and is 8 m thick. The Agres Bed has a more siliciclastic character than the underlying middle member of the Llopis Fm. as it contains some marly and sandy levels between 40-80 cm thick and 5-50 % of quartz content. Caprinid rudists have been distinguished in the uppermost level of this member (Skelton et al., 2019), with a marked planar surface atop of it, displaying 4-5 cm diameter sub-spherical borings, and it is colonized by ostreids.

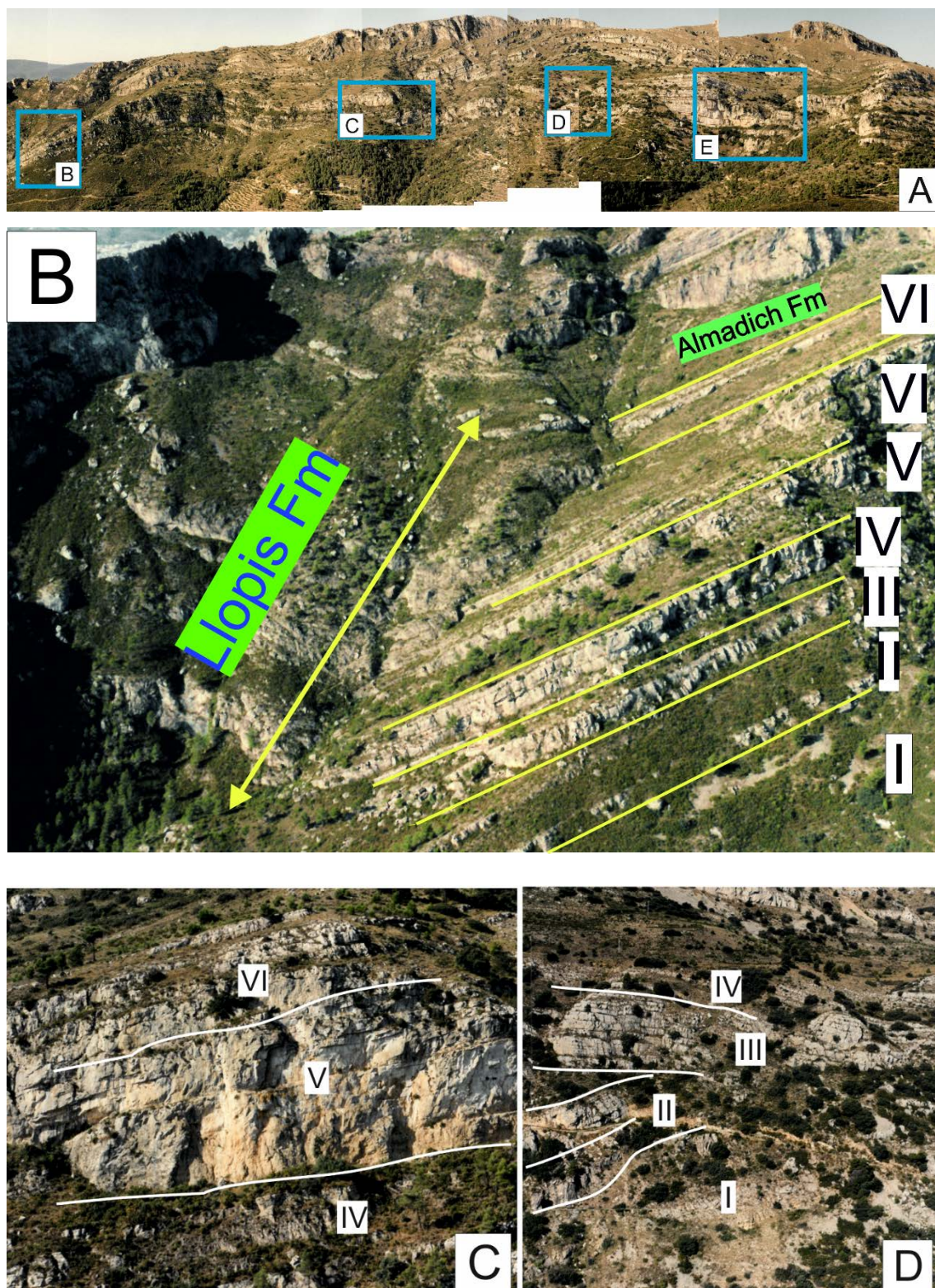
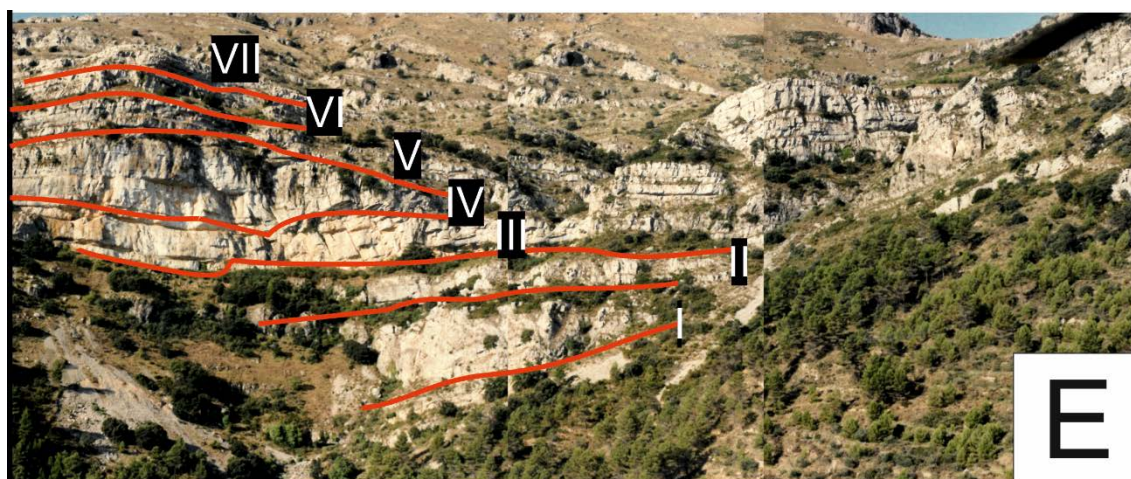


Figure 4.8 (up and down). Images from La Purísima section taken from helicopter flight, in which the parasequences or parasequences of the Middle Mbr of the Llopis Fm can be seen, separated by lines and indicated by numbers. 8A. Aerial view of the Eastern slope of Sierra Marriola, B-C-D-E indicate outcrop positions referred following this figure. 8B. Parasequences or parasequences of the middle member of the Llopis Formation at La Purísima section. The location can be seen in figure 8A. 8C. Stratigraphic relations between parasequences I and II, dipping SW, while III and IV are horizontal. These outcrops are located close to the Llopis section. 8D. Stratigraphic relations between parasequences III and IV in the Llopis section area. 8E. Stratigraphic relations between parasequences I, II, III, IV, V, VI and VII, close to the Racó Llobet section.



4.4.6 Carbon isotopes

The carbon-isotope record of the Racó Llobet section (Fig. 4.9) shows pronounced variability along the column, with values ranging from $+0.04\text{‰}$ to $+4.08\text{‰}$. The Racó Llobet curve starts with values around $+1\text{‰}$ from the base to 15 m, these are grainstones and facies with corals, then, from 15 to 30 m values are a little higher, around $+2\text{‰}$, but with a variance from $+3.53\text{‰}$ to $+0.42\text{‰}$, at 20 m, which constitutes a negative trend of -3.11‰ . The values then go from $+3.12\text{‰}$ to almost 0 (0.04‰ - minimum value of the curve), and then until $+3.34\text{‰}$ (around 50 m), in a negative-positive trend. After this, from 50 to 75 m, the three-point mean curve is steady around $+2\text{‰}$, even with sharp peaks at 55 m ($+4.08\text{‰}$ – maximum value of the curve, to 0.41‰). From 60 m to 75 m approximately the microfacies drilled have grainstone texture again. From 75 to 105 m the values seem higher around $+3\text{‰}$, lower 25 m packstones microfacies dominate within the lower 25 m (75 to 100 m) of this interval, while the upper 5 m (100 to 105 m) are dominated by wackestones. The uppermost part of the section (105 m to top) shows values around $+2\text{‰}$, with a high-frequency variability of 2‰ amplitude (between $+1\text{‰}$ and $+3\text{‰}$). The carbon isotopic signal at the uppermost part of La Purísima section (Fig. 4.9) ranges from $+0.43\text{‰}$ to $+3.13\text{‰}$. In the lowermost part of the section, the curve makes a negative ($+1.98\text{‰}$ to $+0.43\text{‰}$) followed by a positive ($+0.43\text{‰}$ to $+2.83\text{‰}$) trend. From 125 to 145 m the marlstone interval was not sampled. The uppermost part of the curve (from 150 m to the top) ends with a negative excursion from $+3.13\text{‰}$ (maximum value of the curve) to $+1.93\text{‰}$.

The Racó Llobet profile describes, from base to top, a generalized positive trend from $+1\text{‰}$ to $+3\text{‰}$, this type of behavior before the onset of the OAE 1a has been observed in other carbonate platform records during the Early Aptian as the Santa Maria (Abruzzi Region) and Monte Faito (Campania Region) sections from the Central Tethys archives (Amodio and Weissert, 2017).

To connect the C-isotope data of this study with previously published data of the same study area (Castro et al., 2014), the C-isotope curve from Skelton et al., (2019) is presented (Fig. 4.9). The correlation uses the top of the Racó Llobet section, as top of SP VI, that ties-up with the base of SP VII, present in La Purísima, and the top of SP VII, that is overlain by the SP VIII (Agres Bed) in Agres (Fig. 4.9).

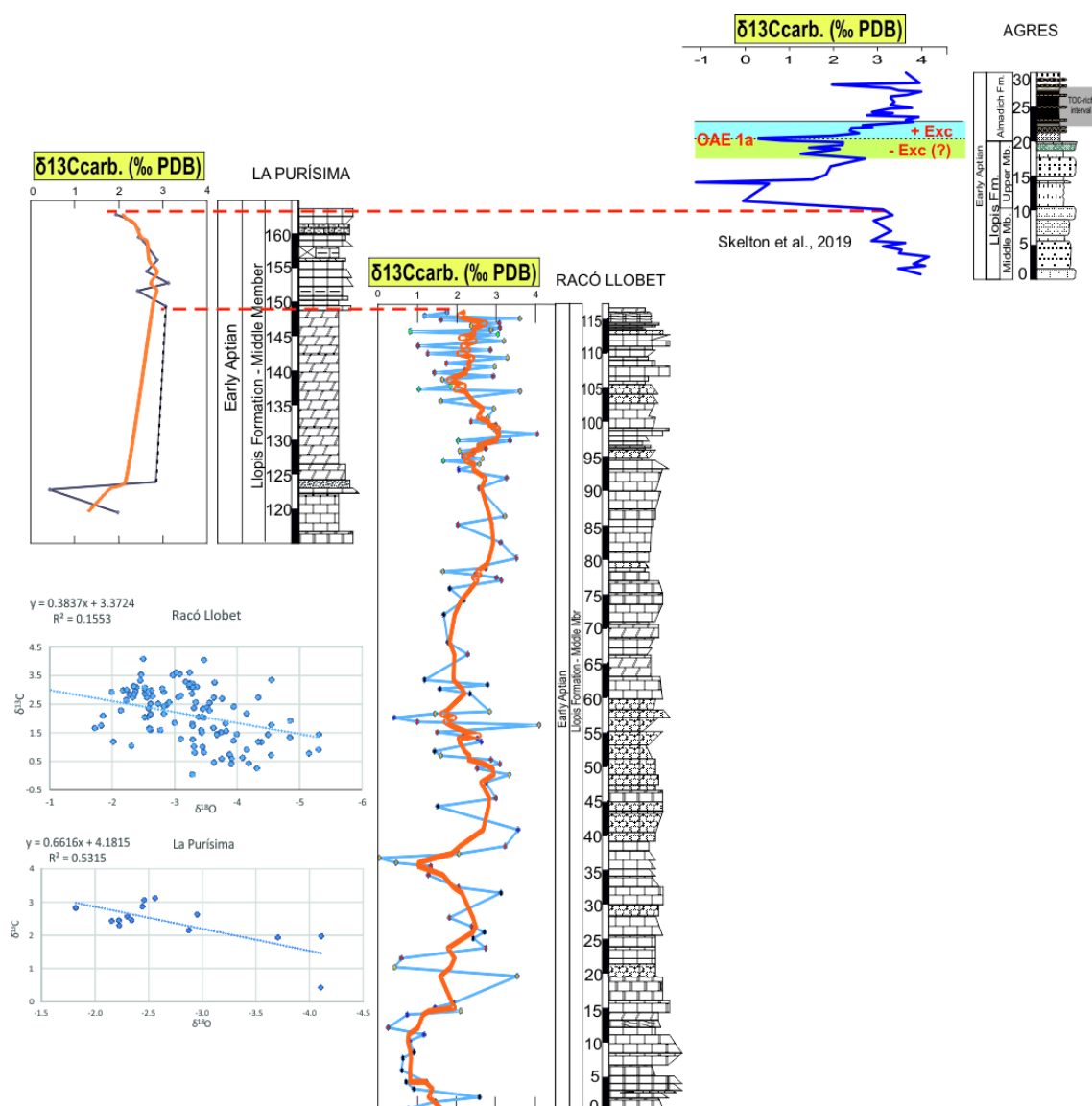


Figure 4.9. C-13 profiles from La Purísima, Racó Llobet and Agres sections. Orange coloured line indicates the three-point moving average. Cross-plots of $\delta^{13}\text{C}$ vs $\delta^{18}\text{O}$ from La Purísima and Racó Llobet are shown on the lower left part.

4.5 Discussion

4.5.1 Facies model

The Mariola platform, as an autotrophic style or tropical T-factory of carbonates, biotically controlled (Schlager, 2003, 2005) likely had an “empty bucket” depositional geometry (Reijmer, 2021), with a rim, reef barrier present at the edge of the platform defining a protected lagoon, as a result to carbonate production mode controlled by light and water-temperature. Facies 1 is characteristic of shallow open marine environments with moderate to high energy. The accumulation of planar orbitolinids has been considered as related to transgressive trends, occurred at the end of an important episode of terrigenous input (Vilas et al., 1995). Terrigenous runoff could have increased nutrient supply favoring fast growing organisms with asexual reproduction, providing a possible scenario for large benthic foraminifera as planar orbitolines (Birkeland, 1988). The laterally related facies 2 represents shallow marine environments with moderate energy, probably representing calcarenitic (barrier) shoals (Flügel, 2010), as indicated by the grainstone texture and the dominance of cortoids. Facies 3 corresponds to shallow

agitated areas with coral growth and bioerosion (James and Dalrymple, 2010), in open platform environments. Facies 1, 2 and 3 collectively represent the outer platform, and facies 2 and 3 represent the barrier system that separated the highly dynamic open ocean waters from the more quiet, low-energy and shallow-water environments of the inner platform (Reijmer, 2021). The reef barrier was probably better developed during sea-level highstands, when the carbonate factory was able to follow the pace of relative sea-level rise (Reijmer, 2021). In addition, higher sediment production occurred when the top of the platform was flooded, a process called highstand shedding (Reijmer et al., 1988; Schlanger et al., 1994). Facies 4, dominated by rudists and including ostreids, dasycladalean algae and miliolids, was deposited in a low energy, shallow lagoon, with moderate water circulation. Facies 5 indicates a shallow low-energy environment corresponding to a lagoon with moderate water circulation (Flügel, 2010). Facies 6 is interpreted to be deposited in a very shallow low-energy environment with restricted circulation and probable subtidal areas, as indicated by the mudstone texture and presence of fenestral porosity (James and Dalrymple, 2010). Therefore, the described elementary cycles are interpreted as shallowing-upwards cycles.

This model applies to the middle member of the Llopió Fm, whereas the upper member (Agres Bed) corresponds to a sedimentary model of mixed siliciclastic-carbonate platform with redeposited rudist and other shallow carbonate materials, alternated with sands and shales deposited in open marine conditions, affected by storms. Shales were deposited during intervals of low energy, whereas sands represent pulses of higher energy with terrigenous inputs and shoal migration.

4.5.2 Sedimentary evolution

The middle and upper members of the Llopió Fm at Mariola describe a general regressive-transgressive evolution that corresponds to a 3rd order sequence, as parasequences SP I and II develop a regressive organization of the sedimentary bodies, while parasequences SP III to SP VIII (Agres Bed) record a transgressive evolution. The regressive track of the system involves the installation of an urgonian rimmed platform (parasequence SP I), followed by aggradation and progradation of the internal and barrier environments over the open platform (parasequence SP II), in a southwards direction (Fig. 4.10). Limestones from parasequence I that basically present an aggradational structure, are fossilized by the regressive limestones of parasequence SP II, showing a progradation pulse of more than 1 km southwards; this progradational trend is maintained in the highstand part of parasequence SP II (Fig. 4.10). Parasequences SP III and IV record a northward migration of the facies belt, defining a transgressive phase. Parasequences V, VI and VII record the second major phase of installation of the urgonian shallow carbonate platform. The general trend is a retrogradation of the facies belt, as there is retrogradation between parasequences V and VI, and a more pronounced step between parasequences V and VII. At the top of the succession, the Upper Member (Agres Bed) represents the terrigenous input that harbingers the demise of the platform, eventually drowned by the hemipelagic deposits of the Almadich Fm.

All the eight parasequences of the Llopió Fm at Mariola can be considered as parasequences (Posamentier and James, 1993; Catuneanu and Zecchin, 2020). Enrichment in quartz on the outer platform facies in relation with laterally equivalent inner facies, indicates siliciclastic inputs during the lowstand stages (Catuneanu, 2019). Aggradational phases resulted in parallel bedding developed in lagoonal as well as in outer platform environments, whereas progradational episodes generate clinoforms in the high energy barrier systems separating the lagoon from the outer platform environments.

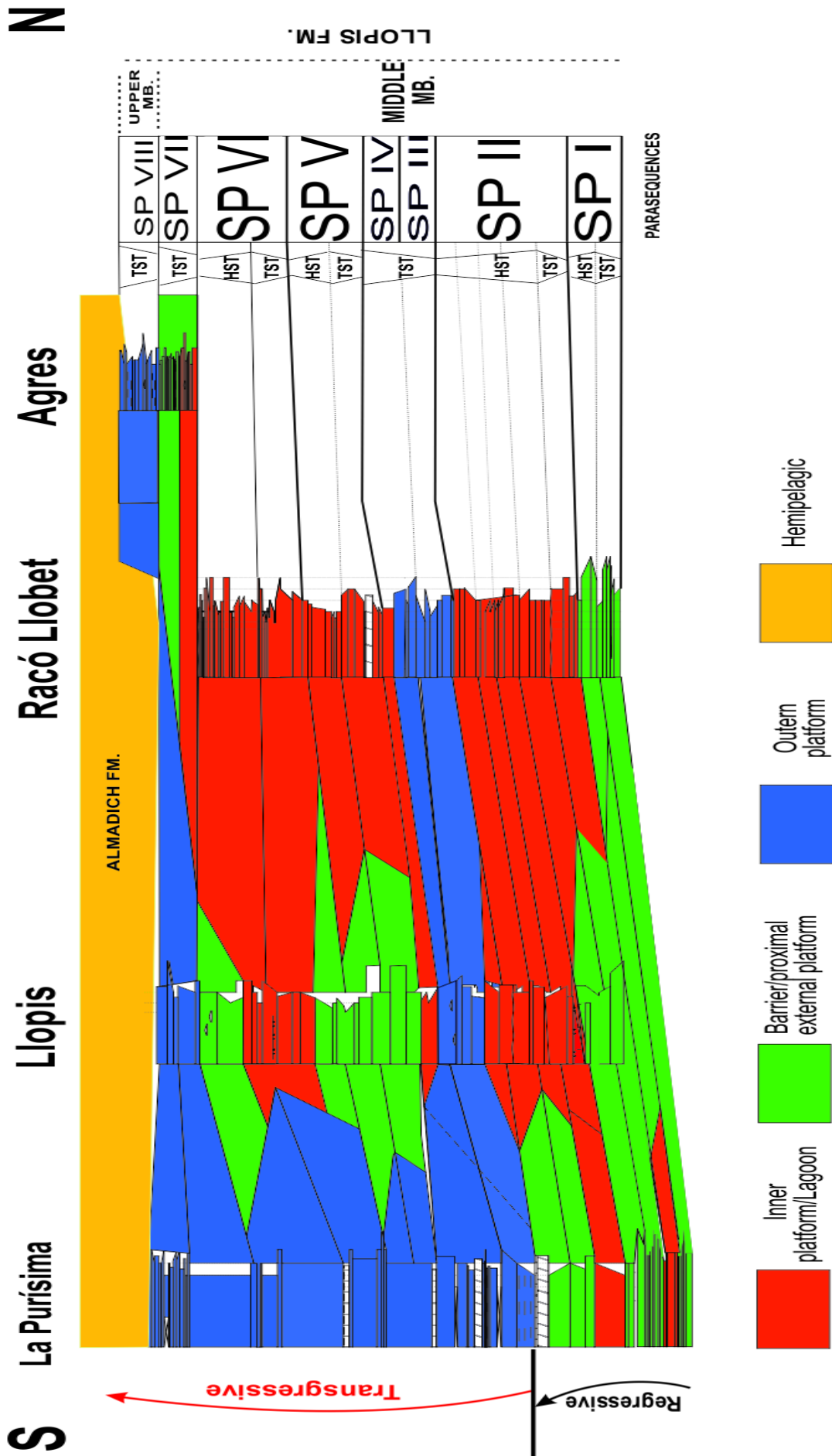


Figure 4.10. Sedimentary model for the Sierra Mariola during the Early Aptian.

4.5.3 Cyclostratigraphy – time duration

The Llopis platform presents a marked cyclicity that may have an autogenic, allogenic, or mixed origin. In this section we discuss the possible origin of this cyclicity and the factors that may have affected it. Milankovitch forcing of sea-level change due to celestial mechanics is one of the factors that determines the available accommodation space, via celestially driven changes in solar radiation (Ruddiman, 2014). Such sea-level changes are arguably the main cause, along with the autogenic shallowing-upwards cyclicity of these carbonates in a subsiding platform (e.g., Reijmer, 2021). The age of the Middle and Upper Mbs of the Llopis Fm is considered to comprise from the earliest Aptian (from the base of *M. sarasini* ammonite zone, equivalent to upper *G. blowi* planktonic foraminifera biozone), to middle Bedoulian (middle early Aptian), including *D. ogilensis* and the lowermost part of *D. forbesi* ammonite biozone (equivalent to the top of *G. blowi* planktonic foraminifera biozone). This would entail a duration of about 0.8-1 My, following the time scale by Gradstein et al., (2020) (Table 1). This duration would involve two 405-kyr long eccentricity metronome cycles and, consequently, the short component of eccentricity periodicity (100-kyr) would coincide with the number (8) of parasequences (4th order Super-Bundles) described. Considering the smaller-scale cycles, a total maximum of 33 bundles build-up the 8 parasequences, 26 bundles from Racó Llobet for SP I to SP VI, plus 8 bundles from Agres (4 bundles from SP VII, and 3 bundles from SP VIII). If we take into account shorter periodicities as obliquity (40-kyr) and precession (20-kyr), considering a constant sedimentation, the 0.8-1 My recorded by these materials would include about 20 obliquity cycles and 40 precession cycles. The total maximum stratigraphic cycles of 5th order found (33), might indicate that cyclicity at this order may be related to an orbital forcing response due to precession, instead of obliquity, as obliquity is expected not to have substantial influence in variation of insolation received at tropical realms (as Mariola was at a palaeolatitude of about 20°N in the Aptian) (Ruddiman, 2014). Furthermore, as 33 bundles have been distinguished, the lack of 7 bundles to reach the ideally 40 cycles, corresponds to minima in eccentricity (100-kyr) that could be producing a disguise in cycle detection (Hilgen et al., 2020). Nevertheless, given the uncertainty in the time model available for the early Aptian and specifically the base of the Aptian (e.g., Frau et al., 2017, 2018; Olierook et al., 2019; Martinez et al., 2021; Castro et al., 2021).

Thereupon, 6th order elemental cycles that makes up the bundles would correspond to auto-cyclic processes within the sedimentary basin, controlled by the interplay between carbonate production and subsidence (e.g. Schlager 2005).

4.5.4 Control factors over sedimentation and cyclicity

The first parasequence (SP I) is composed of external platform facies in all sections studied (from the Racó Llobet section to La Purísima). The calcarenites at Llopis showing very well selected ooids indicate agitated, shallow waters. This parasequence shows a marked cyclicity, especially in bundles B_R1 to B_R4 at Racó Llobet (Fig. 4.2), which represent a highstand phase with thinning- and shallowing-upwards sequences (e.g., Fragoso et al., 2021). Each bundle top is a planar surface, associated to bioturbation, borings, reddish colors and an irregular morphologies, indicating a sedimentary interruption, probably linked to a drop in relative sea-level. At the southern part of the outcrops, in La Purísima section, SP I presents ten bundles (B_{LP}1 to B_{LP}10) (Fig. 4.2). Higher quartz content and marly levels, overall in the lower part (bundles B_{LP}1 to 6) could reflect a rising sea-level phase (Fig. 4.10). These carbonates deposited under high turbidity waters, rich in nutrients, and therefore limited carbonate production, favoured the thriving of ecologically opportunistic organisms, such as planar orbitolines (Vilas et al., 1995). Bundles from the upper part (B_{LP}7 to 10) show inner platform facies (Fig. 4.2) and are related to a more stable phase of sea-level without significant siliciclastics inputs (Fig. 4.10).

The second parasequence (SP II) has a similar development than the first one, the three bundles B_R5 to B_R7 of internal platform at Racó Llobet laterally correlate to seven bundles B_{LP}8 to B_{LP}15 of a more distal character at La Purísima (Fig. 4.2). Between the Racó Llobet and La Purísima section, the Llopis section records a change from open platform environments (B_L1 to B_L3) to inner platform conditions (B_L4 and B_L5), recorded by lateral facies change across clinoforms (Fig. 4.8C). As the regression progressed, the decreasing turbidity and a better connection to more open marine waters drove a change to optimum environmental conditions for carbonate production, under a warm climate, stimulating the carbonate factory and producing higher sedimentation rates (SP II doubles the thickness of SP I at Racó Llobet, while at La Purísima SP I and SP II are 40 m thick) (Fig. 4.2); however, an increase in subsidence rates may be also taken into account to explain such increase in thickness. The lower half of SP II at Racó Llobet is mainly formed by the B_R5 cycle, with calcarenitic coral-rich rudstone and grainstone facies, deposited mostly under sea-level rise conditions or a transgressive episode (Fig. 4.10). The upper half of SP II at Racó Llobet is composed of one thick cycle (B_R6 and B_R7), limited to micritic limestones with rudist and miliolid fauna, reflecting a general trend to slightly more restricted environments, likely associated to an episode of highstand sea-level (Fig. 4.10). This step from corals to rudists is considered to be linked to an environmental change, as corals live in oligotrophic conditions, while rudists tolerate higher nutrient and turbidity conditions (e.g., Gili et al., 1995; Pittet et al., 2002). This vertical facies change is interpreted as the result of a shallowing-upward evolution. The increase in the restriction of the waters might be linked to an aggradation in the barrier/margin zone (Llopis), that would difficult the connection between the lagoon and the external platform. This change is also reflected in the distal sector of La Purísima: in SP II the bundles B_{LP}11 to B_{LP}13 display open barrier platform facies (association of *Derventina*, *Sabaudia* and *Choffatella*, along with planar orbitolinids). With this information, during the lower part of SP II, the barrier should be placed between the Llopis and Racó Llobet sections. In the upper part of SP II, the cycles B_{LP}14 and B_{LP}15, are generally thicker than the lower cycles (Fig. 4.2), with dominance of ooid-rich calcarenites, reflecting the progradation of the barrier facies over the outer platform facies (Fig. 4.10).

Parasequences SP III and IV are key to understand the general evolution of the platform, with a marked transgressive character. SP III is intensely dolomitized at La Purísima, whereas at Llopis bundle B_L6 shows an open platform association of facies 1 and 2, with *Choffatella decipiens* and *P. sunnilandensis elongata* (Castro, 1998). At Racó Llobet, SP III is composed of 2 bundles, B_R9 and B_R10, both of them with abundant brachiopoda in the lower part and calcarenite beds at the top. SP III has a transgressive character, with nodular limestones and brachiopods, that represent an increase in the bathymetry. These cycles are interpreted as shallowing-upwards, with a progressive increase in water energy (nodular limestones to calcarenites). This parasequence represents the beginning of a new T-R depositional sequence for the whole Middle Mb., from progradational in the lower half to retrogradational in the upper half (Fig. 4.10).

Parasequence SP IV represents a homogeneous sedimentary episode, with dominance of open platform facies. At Racó Llobet, bundle B_R11 presents open marine facies association dominated by miliolids, whereas B_R12 shows facies 1 dominated by orbitolines, and B_R13 has abundant echinoderms and quartz (Fig. 4.2). Collectively, these marly lithofacies plenty of planar orbitolines with crinoids, indicate open marine conditions, with moderate energy, and they are associated to a transgressive episode, resulting in homogeneous sedimentation within the studied area.

At a higher scale, the change in peritidal and shallow subtidal cycles from SP I and II to more distal facies in SP III and SP IV is considered to be linked to an increase in the siliciclastic input in

the platform, probably coeval to increased subsidence rates, that affected the carbonate production and reduced or removed the barrier system at the edge of the platform. Under these conditions, external platform deposits were dominant in all the studied area. At La Purísima, cycles B_{LP}16, B_{LP}17 and B_{LP}18 displays hummocky cross stratification and planar orbitolines (Fig. 4.2). At Llopi, B_L7 contains grainstone and packstone limestones with *O. buccifer* (Fig. 4.2). Bundles B_L4 and B_L5 show a mixing of globular and conical orbitolines (*Dictyoconus maynci* with *O. praesimplex* and *buccifer*) and some sandy brecciated deposits (Fig. 4.2), fine grained and well sorted, which might represent the proximal sedimentary expression of the storm deposits from La Purísima. Collectively, this “orbitolinite” facies enriched in siliciclastics, represent an important change in the carbonate production (from oligotrophic to mesotrophic conditions) and could be attributed to intensified hydrological cycle and continental weathering under warm and more humid conditions (Heimhofer et al., 2008; Tejada et al., 2009; Stein et al., 2012; Bottini et al., 2015; Lechler et al., 2015), probably combined with a relative rising sea level and transgressive conditions (e.g. Vilas et al., 1995). This episode may be linked to a regional climatic event, related to the environmental changes heralding the OAE 1a (e.g., Föllmi, 2012; Amodio and Weissert, 2017; Martínez-Rodríguez et al., 2021).

Within parasequence SP V, only bundle B_{LP}19 has been recognized at La Purísima, at the uppermost part, which contains facies 2 and 3 with *Orbitolinopsis praesimplex* and cortoids (Fig. 4.2). At Llopi, SP V displays facies 1, 2, 4 and 5. In detail, bundle B_L8 contains a calcarenitic association with *Orbitolinopsis cuvillieri*, while B_L9 contains also orbitolinids, and B_L10 contains *Orbitolinopsis praesimplex* (Fig. 4.2). Bundles B_L11 and B_L12 present some levels enriched in quartz (Fig. 4.2), indicating an intermittent clastic input. At Racó Llobet, the lower part of the parasequence contains *O. buccifer*, quartz and echinoids, whereas the upper part is dominated by micritic facies 4 and 5, with abundant dasycladacean algae and biserated benthic foraminifera (Fig. 4.2). On this parasequence, the cyclicity of strata starts to be more marked than below, with thinner beds, probably due to a reduction in the accommodation space, in a context of highstand.

In La Purísima, at the base of parasequence SP VI, bundle B_{LP}20 records the presence of sandy orbitolines (Fig. 4.2). Quartz is also found at Llopi in bundles B_L14 to B_L17 (Fig. 4.2), confirming that the terrigenous input is being produced not only in the lower transgressive part of the parasequence, but also during the highstand stage. At this moment, all the sections studied are dominated by rudists facies (*Toucasia* and *Caprina douvillei* are present), despite the stressed environment as inferred from the presence of terrigenous sediments.

During deposition of parasequence SP VII the lagoonal and internal platform environments were progressively replaced by platform-barrier and open platform environments, as facies 1 and 3 with arenaceous orbitolines and intraclasts dominate (Fig. 4.2). This is interpreted as the result of a retrogradation (Fig. 4.10), in which the facies belts retract as a response to a relative sea-level rise, probably related to a combination of climatic and tectonic factors, with the initiation of an extensional tectonic event with activation of listric faults, and an increase in humidity in the continent with the subsequent terrigenous input to the platform, processes that culminate in the next parasequence.

The parasequence SP VIII (Agres Bed) testifies a definitive change in the Urgonian platform. High detrital input and the installation of open marine facies marks the end of favourable environmental conditions for the Urgonian platform, resulting in a low carbonate productivity. Sandstone levels with fragments of large caprinids (*Offneria interrupta*) (Figs. 4.2, 4.7) deposited during storms, under high energy conditions, indicate a complex evolution with quiet phases of high carbonate production, which alternated with higher energy episodes in which important

terrigenous input hampered the carbonate production. These rapid fluctuations are typical of unstable and unpredictable environments characterized by significant changes in trophic resources produced by hyperthermals (Posenato et al., 2018).

The main result from the new C-isotope stratigraphy of the middle member of the Llopis Fm (Racó Llobet section, Fig. 4.9) is the confirmation that the Agres Bed coincides with the base of Ap3 segment, as proposed by Skelton et al. (2019) from the study of the overlying Agres bed and Almadich Fm. Thus, this major sedimentary change is interpreted as the local expression of the onset of the OAE 1a. As a hyperthermal, the facies found in the Agres section are consistent with intensified global greenhouse climatic pattern occurred in response to a major perturbation in the C-cycle (e.g., Menegatti et al., 1998; Jenkyns, 2010; Bottini and Erba, 2015; Erba et al., 2015; Castro et al., 2021; Martinez-Rodriguez et al., 2021).

4.6 Conclusions

The study of four sections of the Llopis Fm distributed in the outcrops of Sierra Mariola allows the recognition of facies and association of facies of open platform, barrier and inner platform environments from the lower Aptian urgonian carbonate platform formed in the southern Iberian margin.

The time interval of the sedimentation of the studied succession is considered to span ~0.8-1 Myr, encompassing approximately two long eccentricity orbital cycles, with each parasequence representing ~100-kyr short eccentricity cycles.

Eight parasequences are recognized in the urgonian platform of Sierra Mariola, describing a regressive sedimentary evolution for the two first parasequences, followed by a succession of six parasequences with a transgressive evolution.

The $\delta^{13}\text{C}$ data from the Middle member of the Llopis Fm confirms that this unit records the Aptian Ap-2 C-isotope segment, that predates OAE 1a. The onset of OAE 1a is coeval to the Agres Bed (Upper Mb), which represents the local sedimentary expression of the onset of the OAE 1a which eventually led to the demise of the Llopis Fm carbonate platform with the deposition of the hemipelagic marls of the overlying Almadich Fm.

The discussion about the factors controlling the development and the demise of the Early Aptian carbonate platform points out to a complex interplay between regional extensional tectonics (subsidence), climate, and environmental changes leading to different modes of carbonate production controlled by variations in the siliciclastics inputs, and relative sea-level changes. The utmost environmental change is considered closely linked and coeval with the global OAE 1a, a major perturbation that demised the carbonate platform, resulting in hemipelagic sedimentation.

5. Progradation of a shallow carbonate platform developed in an isolated block of the Western Tethys (lower Aptian, Sierra de Bedmar-Jódar, Prebetic of Jaén, Spain)

5.1 Introduction

The early Aptian of the Internal Prebetic, that belongs to the Southern Iberian Continental Margin (SICM, Figs. 5.1A, 5.1C), is characterized by the development of a carbonate platform that extends continually from the Tiscar Fault (province of Jaén, Fig. 5.1B) to Cabo de la Nao (province of Alicante; Fig. 5.1A). West of the Tiscar Fault, the Internal Prebetic crops out in several isolated blocks that constitute the Prebetic of Jaén (Vera, 2004; Fig. 5.1B). The episodic growth of carbonate platforms in the Tethys domain during the early Aptian is broadly connected to the context of the greenhouse world in the Early Cretaceous (Skelton, 2003; Skelton and Gili, 2012; Hay et al., 2019), with dominance of terrigenous deposition in proximal sectors of the Prebetic and lateral development of an extensive shallow marine carbonate platform, with maximum coastal transgression (Vilas et al., 2001; Martín-Chivelet et al., 2002, 2019; Vera, 2004; Castro et al., 2008). The study of the factors that control the development of carbonate successions in the face of eustatic, climatic, and tectonic processes, represents an important tool for delineating the evolutionary trends of carbonate platforms (Enos and Moore, 1983; James and Mountjoy, 1983; Eberli and Ginsburg, 1989; Schlager, 1992; Simo et al., 1993; Graziano, 2000; Wissler et al., 2003; Föllmi et al., 2006). The lower Bedoulian carbonate platforms of the Western Tethys are characterized by a notable development of rudist bivalves. This study provides an excellent example to investigate the evolution of a carbonate platform in a rifting geological setting. Additionally, this work represents a case of study of stromatoporoid development in Aptian facies, organisms that has been studied mainly in the Jurassic (Millán et al., 2011; Godet et al., 2011; Huck et al., 2011; Huck and Heimhofer, 2015).

In this work, a study of stratigraphy and sedimentology is shown based on a carbonate outcrop (Barranco del Tejar, Sierra de Bedmar-Jódar; Fig. 5.1D) that presents well preserved carbonate platform facies, valuable to analyze the evolution of the platform both vertically and laterally. Lateral facies changes and stratal patterns have been analyzed in order to characterize the facies architecture. The facies analysis and their cyclicity have been a base for the characterization of the sedimentary model of the platform, whereas the analysis of the stratigraphic architecture and the different scales of cyclicity have been conducted to decipher the sedimentary evolution. The integration of these results within the tectonic, eustatic and environmental context has led to the discussion on the factors that controlled the development of the platform.

5.2 Geological setting

The Sierra of Bedmar-Jódar succession belongs to the Prebetic of Jaén (see Molina et al., 2012 and references therein) (Figs. 5.1A, 5.1B). This subdomain is constituted by several isolated outcrops west to the Tiscar Fault, a tectonic feature that interrupts SW of the Prebetic of Sierra de Cazorla and Segura. Each isolated unit of the Prebetic of Jaén is part of the betic thrust front and is disposed over the Neogene of the Guadalquivir Basin, that was thrust by the subbetic units between the Burdigalian and the Messinian, with a net tectonic displacement towards the N-NW and W (Sanz de Galdeano et al., 2013). The structure of the Sierra de Bedmar-Jódar is an anticline tilted to the NW; the southern flank shows a mean dip of 45°, while the northern flank is subvertical or is slightly inverted. The axis of the fold is curved, convex to the NW-W, with an average strike of N30°E (Fig. 5.1D).

Molina et al. (2012) and Ruiz-Ortiz et al. (2014) studied the general features of the litho- and biostratigraphy of the Sierra de Bedmar-Jódar. The older materials that crop out are marly limestones, marls, marlstones and sands, with some levels of sandy dolostones interbedded. These lithofacies are part of the Los Villares Formation (Fm), dated as upper part of lower Valanginian/lower part of upper Valanginian (Ruiz-Ortiz et al., 2014). Overlying these materials are the carbonates of the Llopis Fm, of early Aptian age (Ruiz-Ortiz et al., 2014). Between both lithostratigraphic units there is a hiatus that encompasses the Hauterivian and the Barremian (Molina et al., 2015). The Seguilí Fm overlies the Llopis Fm, dated late Aptian (Molina et al., 2015). The Albian is represented by the shallow platform limestones, locally dolomitized, from the Sácaras and Jumilla Fms. The top of the sequence is formed by massive dolostones attributed to the Caliza de Jaén Fm, deposited during the Cenomanian (Molina et al., 2015).

5.3 Materials and methods

5.3.1 Lithostratigraphy

This work is focused on the study of the shallow carbonate platform of the Llopis Fm. This lithostratigraphic unit is made up by three members (Castro, 1998; Castro et al., 2008). The Lower Member (Mb; upper Barremian) is marly; it represents a regressive phase. Over these deposits, the Middle and Upper Mbs of the Llopis Fm corresponds to a Transgressive-Regressive (T-R) sequence. These two Mbs have been dated as lower Aptian. The Middle Mb is made up by shallow marine grey limestones with rudists and corals, the Upper Mb (Agres Bed) comprises bioclastic and sandy limestones, interbedded with marls with orbitolines. In the Bedmar-Jódar unit, the Lower Mb is not present, as there is an unconformity detected between Los Villares and Llopis Fms. Besides, no material could be correlated with the Agres Bed, recognized in the Prebetic of Alicante (see chapter 3). Other significant difference with the Prebetic of Alicante is that the hemipelagic Almadich Fm is not present in the Sierra de Bedmar-Jódar, where the Llopis Fm. is overlain by the Seguilí Fm (Ruiz-Ortiz et al., 2014; Nieto et al., 2022) (Fig. 5.2).

5.3.2 Methods

Ten partial sections have been studied with a total thickness of 250 m, with a detailed logging of stratigraphy and facies, and collection of 170 samples. 6 sections were logged in the top part of the outcrop, previously studied by Nieto et al. (unpublished) (Fig. 5.3), whereas 4 sections were studied in the ravine slope, where the main outcrop is located (Fig. 5.4). Each rock sample was used to make a thin section for petrographic and microfacies characterization, as well as benthic foraminifera determination for dating. The microfacies study was made using a Leica M205 C stereoscopic microscope. The average sampling interval is 1.47 m (250 m / 170 samples), although each sampling interval is variable. The size of sampling interval is dependent to the thickness of bed or set of beds, usually selected to register each level, or, in case of beds thicker than 1 m, to assess the variation between its lower and upper part. 76 measurements of dip and angle of dip were taken at field with a clinometer compass to characterize the structure of the outcrop (see Appendix). A facies map was made from the integration of field and microscopic observations (Fig. 5.6).

5.4 RESULTS

5.4.1 Biostratigraphy

The presence of two species of orbitolines, *Orbitolinopsis killiani* and *Orbitolinopsis cuvillieri*, attributed to the biostratigraphic unit 1 of Castro et al. (2001), indicate an early Aptian age. This biostratigraphic unit has been partially correlated with the upper part of *M. sarasini* and *D. oglanlensis* ammonite biozones, attributed an early Aptian age.

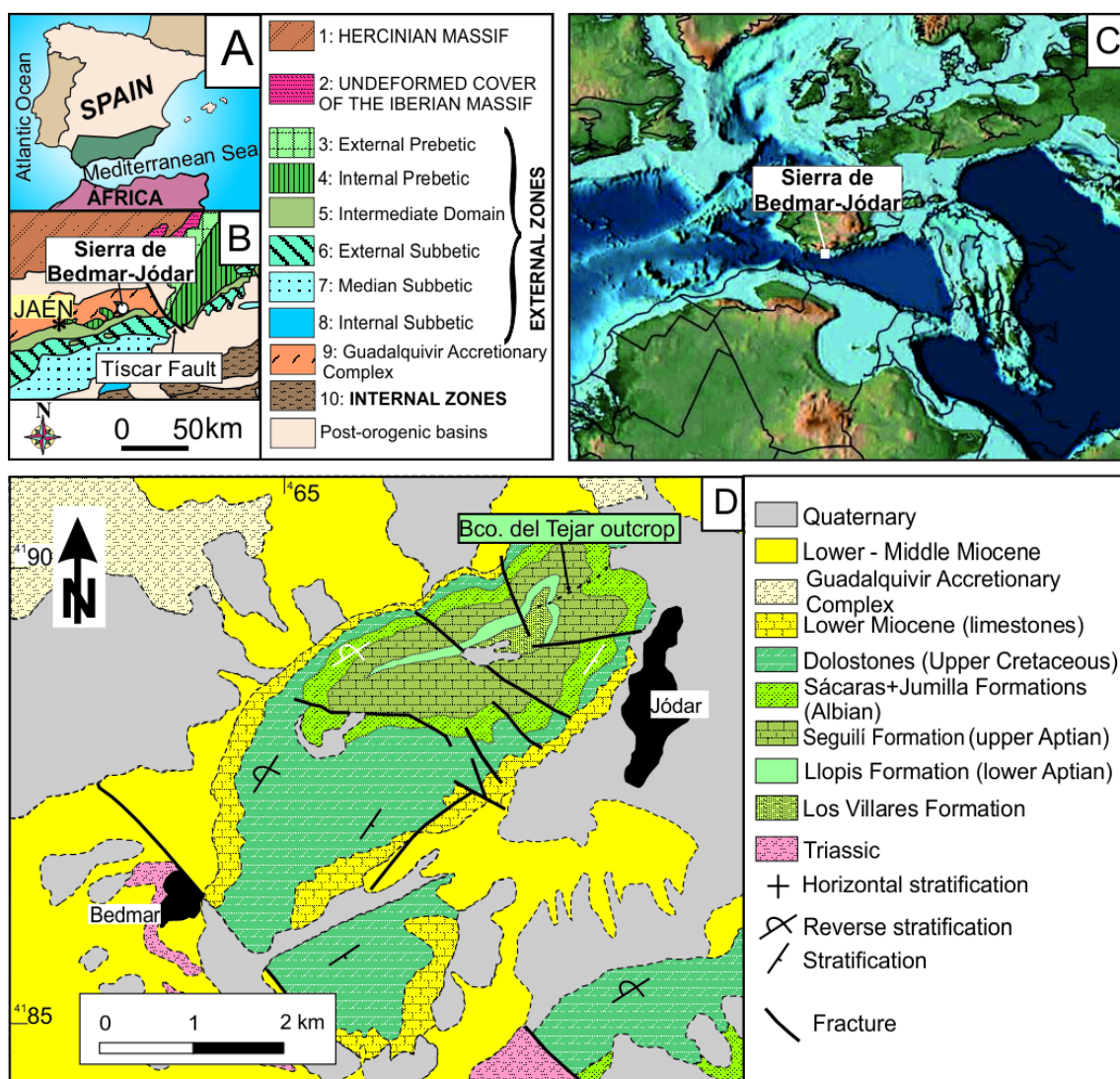


Figure 5.1. A. Location of the Betic Cordilleras in the Iberian Peninsula. B. Geologic scheme with location of the Sierra de Bedmar-Jódar, East from the city of Jaén. C. Palaeogeography of the Western Tethys domain, from 120 Ma ago (Scotese et al., 2016). D. Simplified geologic map of the Sierra de Bedmar-Jódar.

5.4.2 Facies analysis

From the study of the stratigraphic sections and the thin sections microfacies analysis, seven lithofacies associations (L1 to L7) and ten microfacies have been recognized (Table 1).

Lithofacies association 1 (L1): sandstone with peloids and bioclasts. These materials form bodies of mounded geometry with planar cross lamination. They can be defined as sandy bars with decreasing-upwards granulometry, in which coarse sand microfacies predominate in the lower part of the bar (microfacies 1A, Table 1; Fig. 5.5A; Fig. 5.6A), whereas the upper parts are dominated by fine grain sands (microfacies 1B, Table 1; Fig. 5.5B; Fig. 5.6B). Laterally, there is a change from L1 facies to L2 facies (Table 1).

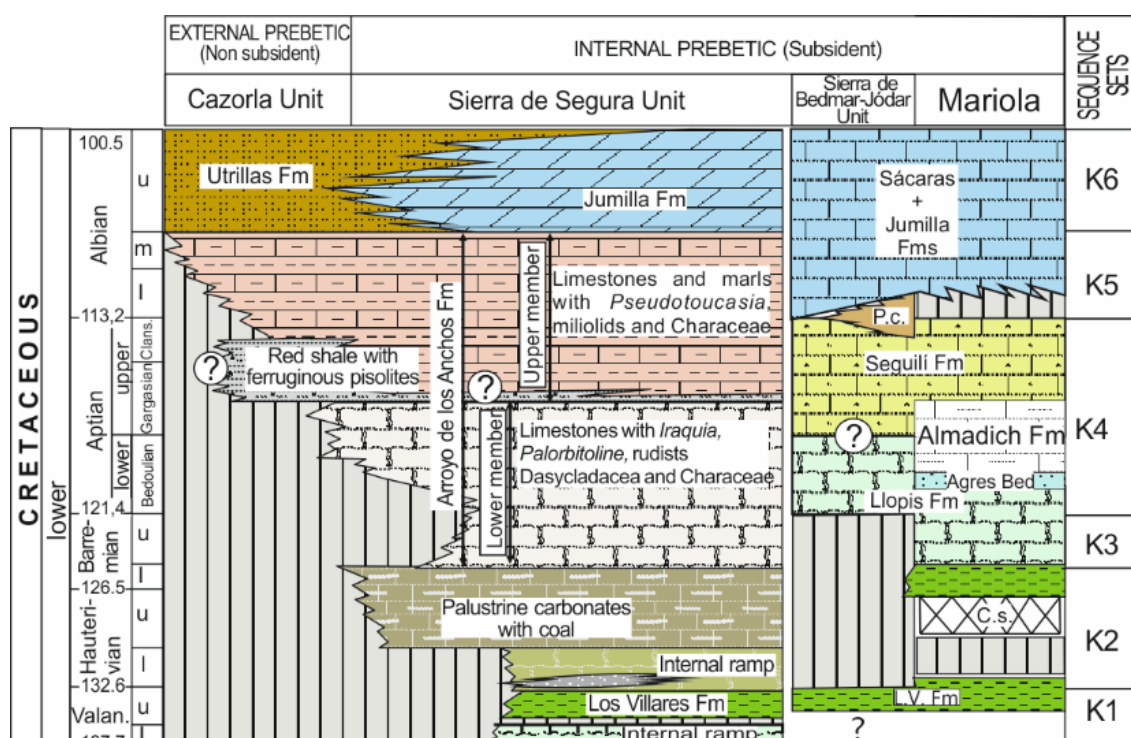


Figure 5.2. Chronostratigraphic chart for the Prebetic of the Sierra de Jódar-Bedmar Unit correlated with the chronostratigraphy of the Cazorra and Segura Units and the sequence sets determined considered in Vera et al. (2004) for the Early Cretaceous of Prebetic. Ages from Gradstein et al. (2020), GTS-2020. P.c.: palustrine carbonates. C.s.: condensed sediments.

Lithofacies association 2 (L2): limestone with ooids, bioclasts and/or peloidal grainstone textures (Table 1; Fig. 5.5C). As in lithofacies 1 (L1), these materials form oolitic bars with planar cross-lamination and planar cross-stratification, with predominance of oolites (microfacies 2A, Table 1; Fig. 5.6C) in the lower part of the sedimentary body, whereas the peloids (microfacies 2B, Table 1; Fig. 5.6D) are present mainly in the upper part. As indicated in L1, there is a lateral change between both facies, so that L2 end up being arranged over L1.

Lithofacies association 3 (L3): limestone with peloids and / or bioclastic packstone texture (Table 1; Fig. 5.5D). It is a lithofacies with abundant bioclasts, mainly bivalves, including some rudists. In some samples the ooids are abundant, as well as quartz grains with irregular shape (Fig. 5.6E). Orbitolines (*Orbitolinopsis killiani*, *O. cuvillieri*) and carophytes are also present (Table 1). This association is interpreted to be deposited in the transition zone between the inner and outer shelf, between the fair-weather wave base and the storm wave base. Ooids are more abundant in the outer shelf, whereas peloids are more abundant in the inner platform.

Lithofacies association 4 (L4): limestone with peloids, bioclasts and/or miliolids with mudstone/wackestone textures. Three microfacies have been distinguished into this lithofacies (Table 1). All of these have a micritic matrix but different kinds of carbonate grains, peloids and bioclasts (microfacies 5A; Fig. 5.6G), miliolids and orbitolines, algae and some rudists (Table 1; microfacies 5B); and peloids, miliolids and/or bioclasts (microfacies 5C, Table 1) with fenestrae.

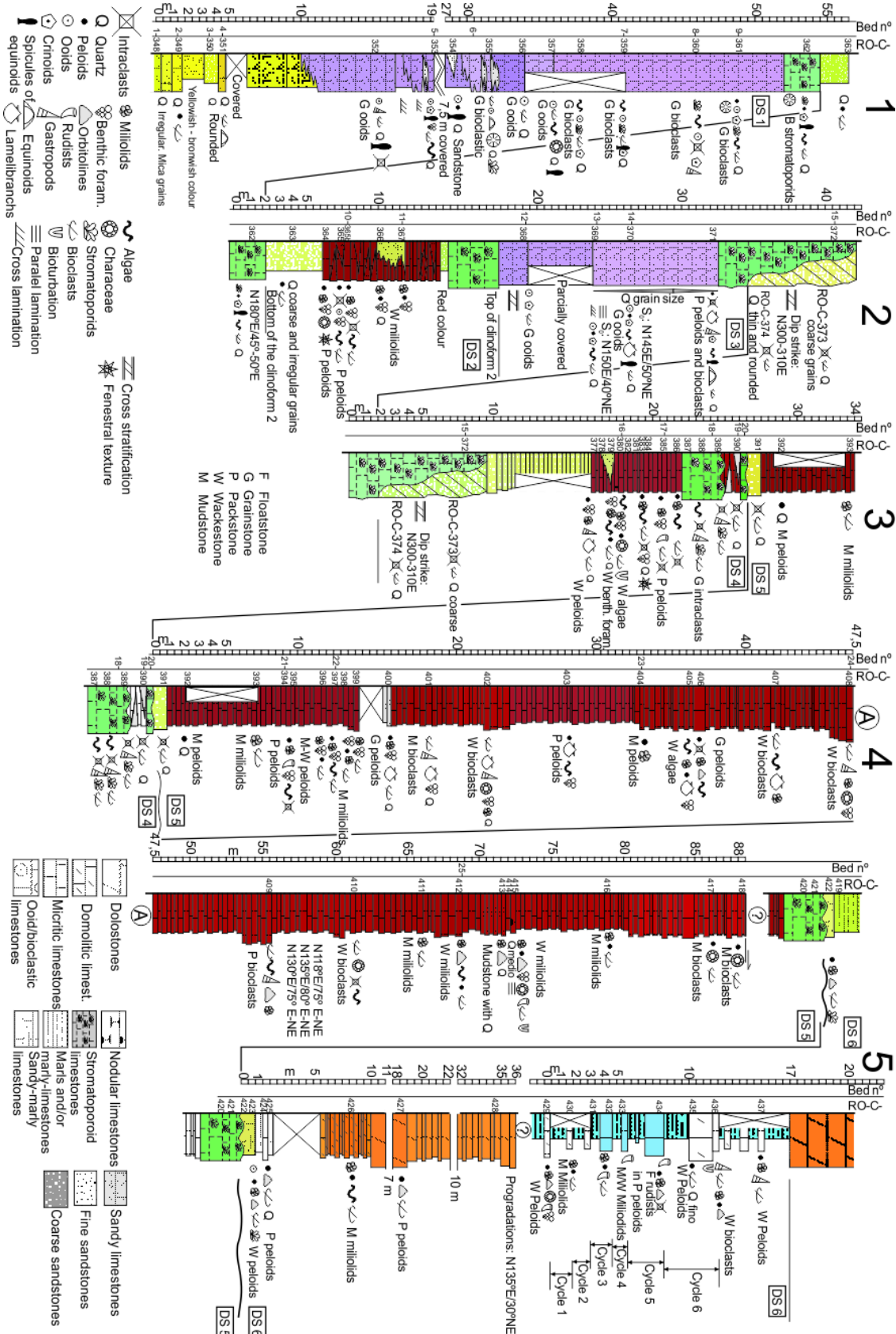


Figure 5.3. Stratigraphic columns on the top transect from the Barranco del Tejar section. Modified from Nieto et al., (unpublished).

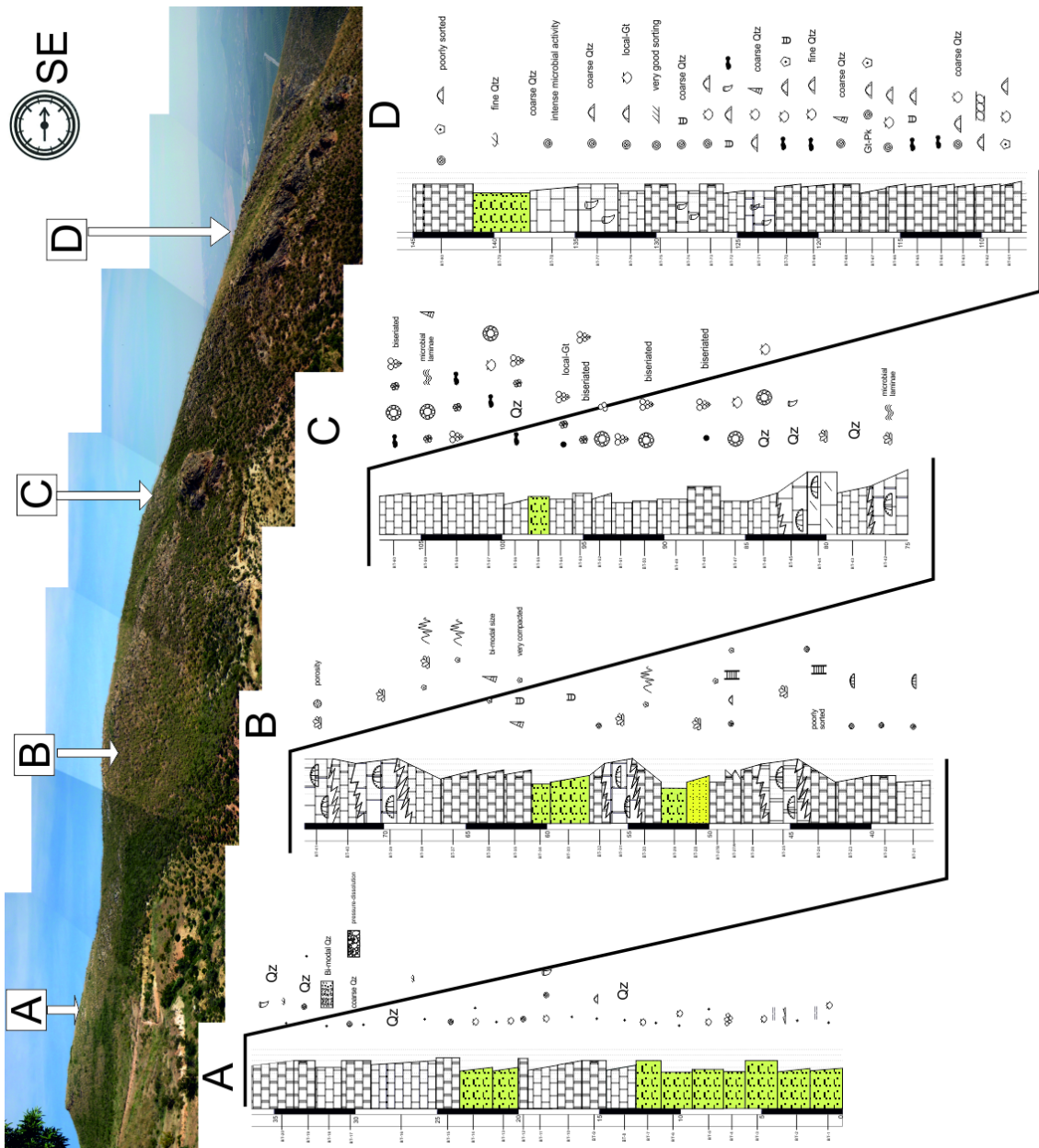


Figure 5.4. Stratigraphic sections on the lateral transect from Barranco del Tejar. A panorama of the outcrop can be observed above the stratigraphic columns.

Lithofacies association 5 (L5): stromatoporid limestone (Fig. 5.5E; Fig. 5.6I). These limestones are arranged in bodies of metric scale and sub-spherical morphology, arranged longitudinally according to the stratification (Fig. 5.7). In the outcrop, the stromatoporids are present in the form of bioherms and biostromes. When forming bioherms, they appear as individual mound masses. When forming a biostrome, they can be followed in a laterally expanded body. The stromatoporids are found locally in life position, embedded in a limestone matrix, strongly recrystallized and locally dolomitized, stained by Fe oxides. These bodies of stromatoporids present locally staggered morphologies. Atop of this facies it is possible to observe abundant traces of *Glossifungites* up to 3 cm deep.

Lithofacies association 6 (L6): rudist limestone (Table 1; Fig. 5.5F; Fig. 5.6J). It is arranged in elementary sequences with a thickness that vary between 1.25 m and 3.30 m. Each sequence is

composed of a basal marly or marlstone level, overlain by a limestone level with rudists, especially abundant in its upper part. Microfacies are mostly packstone and grainstone with ooids and bioclasts, with embedded rudists that can form decimeter-scale biostromes.

Lithofacies L7, dolostones: they are made up by dolostones, probably formed during late diagenetic stages that overprinted the depositional texture of the limestones (Table 1).

5.4.3 Stratigraphic architecture

The lithofacies described in the previous section and shown in Table 1 are organized in elemental sequences of decametric scale that are repeated throughout the studied outcrop (Fig. 5.7). The base of each sequence is made of sandstones with microfacies 1A or 1B, which change laterally to type L2 facies (limestones with ooids, bioclasts and/or peloids with grainstone texture; Table 1), which, in turn, also change laterally to lithofacies L3 (limestones with peloids and/or bioclasts with packstone texture; Table 1). The cartographic differentiation between the L2 and L3 lithofacies is complex, therefore they have been mapped as a single unit (L2 + L3; Fig. 5.7). In certain parts of the outcrop, the cartographic differentiation between the L3 and L4 facies is also complex, and they have been mapped as a single unit (L3 + L4; Fig. 5.7).

The L5 lithofacies (stromatoporid limestones, Table 1; Fig. 5.7) are placed on the L2 + L3 or L3 + L4 lithofacies. This facies can be arranged either as a continuous succession of bodies of reef morphology that act as a barrier or as bioherms of metric dimensions, arranged discontinuously (Fig. 5.7). Generally, within the L5 facies bodies there are materials attributed to the L1 facies (sandstones with peloids and bioclasts).

In the eastern part of the studied area (Fig. 5.7), within the upper part of the succession, elementary metric sequences are observed, consisting of centimetric to metric levels of L2 facies (limestones with ooids, bioclasts and/or peloids with grainstone texture, Table 1) over which there are beds of similar thickness to the previous ones composed by facies L6 (rudist limestones with grainstone texture). Rudists are arranged in small bioherms or in continuous lateral levels. Three main types of shallowing-upward elementary sequences can be differentiated (Fig. 5.8): Type 1: they have a lower division with terrigenous deposits (facies L1), which gradually transition upwards to oolitic carbonate facies, grainstone (L2) and finally packstones (L3).

Type 2: they have a lower part as type 2 sequences, which can be overlain by wackestones-mudstones with miliolids (L4) and have an upper division of stromatoporid bioconstructions (L5). Generally, the top surface of the stromatoporid bioconstructions presents an erosive morphology and, locally, remains of Fe oxides.

Type 3: These elementary sequences have a succession of L1 (sandstones), L2 (limestones), L4 (limestones) and L6 (rudist). Both elementary sequence types are shown in Figure 5.8.

In the studied area, a total of 8 overlapping sequences have been recognized in the succession (Fig. 5.7).

The analysis of the outcrops reveals that the general succession presents a general dip towards the E-NE, with development of clinoforms in the uppermost part of the elementary sequences, especially in the stromatoporoid levels. This is interpreted as the result of a progradation towards the E-NE, that differs from the general palaeogeographic trends of the SICM dipping to the SE, and has been explained as a result of the tilting of this sector of the Prebetic, related to the extensional rifting tectonics affecting the margin during the Aptian (e.g. Martín-Chivelet et al., 2002, 2019; Vera, 2004; Nieto et al., 2022).

Lithofacies		Microfacies		Grains and fossils	Key features	Environment
No.		No.				
L1	Sandstone with peloids and bioclasts	1A	Sandstone with coarse grain	Some peloids and/or bioclasts. Some samples show serpulids, bryozoan and clasts of stromatoporids	Planar cross – lamination	Inner shallow platform – with influence of waves. Sediments from the continent.
		1B	Sandstone with fine grain			
L2	Limestone with ooids, bioclasts and/or peloidal grainstone textures	2A	Grainstone with ooids and/or bioclasts	Ooids, bioclasts, quartz, echinoderms, benthic foraminifera, gastropods, algae (<i>Salpingoporella</i> sp., <i>Triploporella</i> sp.), rudist bioclasts, corals, crinoids, bryozoan, stromatoporida, micritized grains	Planar cross – lamination and planar cross – bedded Stylolites	Inner shallow platform – with no influence of waves. This lithofacies laterally change to sandstone facies (nº 1 lithofacies)
		2B	Grainstone with peloids	Peloids, intraclasts, orbitolines (<i>Orbitolinopsis killiani</i> , <i>O. cuvillieri</i>), miliolids, algae	Quartz, echinoids, crinoids	
L3	Limestone with peloids and/or bioclastic packstone texture	3	Packstone with peloids and/or bioclasts	Peloids, nondetermined bioclasts, algal bioclasts, rudist bioclasts, intraclasts, benthic foraminifera (<i>Cuneolina</i> sp., <i>Debarina</i> sp.), miliólids, algae (Dasycladaceae, <i>Salpingoporella</i> sp., <i>Bacinella</i> sp.), bivalves, stromatoporida, orbitolines (<i>Orbitolinopsis killiani</i> , <i>O. cuvillieri</i>)	Charophytes	Shallow platform with low to moderate energy with episodic fresh water influence
L4	Limestone with peloids, bioclasts and/or miliolids wackestone/mudstone texture	4A	Wackestone with peloids and/or bioclasts	Peloids, bioclasts, intraclasts, quartz, benthic foraminifera (<i>Pseudotextularia</i> sp., <i>Cuneolina</i> , sp.), miliolids, gastropods, bivalves, algae (<i>Triploporella</i> sp., <i>Pithonella</i> sp., Characeae), stromatoporida,	Charophytes	Lagoon. Very shallow
		4B	Wackestone with miliolids	Peloids, bioclasts, quartz, miliolids, orbitolines (<i>Orbitolinopsis killiani</i> , <i>O. cuvillieri</i>), <i>Debarina</i> sp., <i>Choffatella</i> sp.), algas (<i>Bacinella</i> sp.), rudists	Charophytes Fenestrae	
		4C	Mudstone with peloids or miliolids or bioclasts	Peloids, bioclasts (gastropods, bivalves), benthic foraminifera (<i>Cuneolina</i> sp., <i>Debarina</i> sp.), algae (Dasycladaceae, Characeae), miliolids	Fenestrae	
L5	Stromatoporid limestone	5	Floatstone with stromatoporida	Peloids, echinoids, quartz, stromatoporida, red algae, solitary corals, rudist bioclasts	Colonial corals partially dolomitized	Stromatoporoid biostromes. Barrier. High energy environment
L6	Rudist limestone	6	Grainstone / packstone with rudists	Ooids, bioclasts, echinoids, gastropoda, bryozoan, coarse grains of quartz		Small rudist biostromes in high energy environment (outer part of the platform)
L7	Dolostones	The dolomitization affected any one of the previous lithofacies.				

Table 1. Facies from the Barranco del Tejar outcrop, and sedimentary environments deduced.

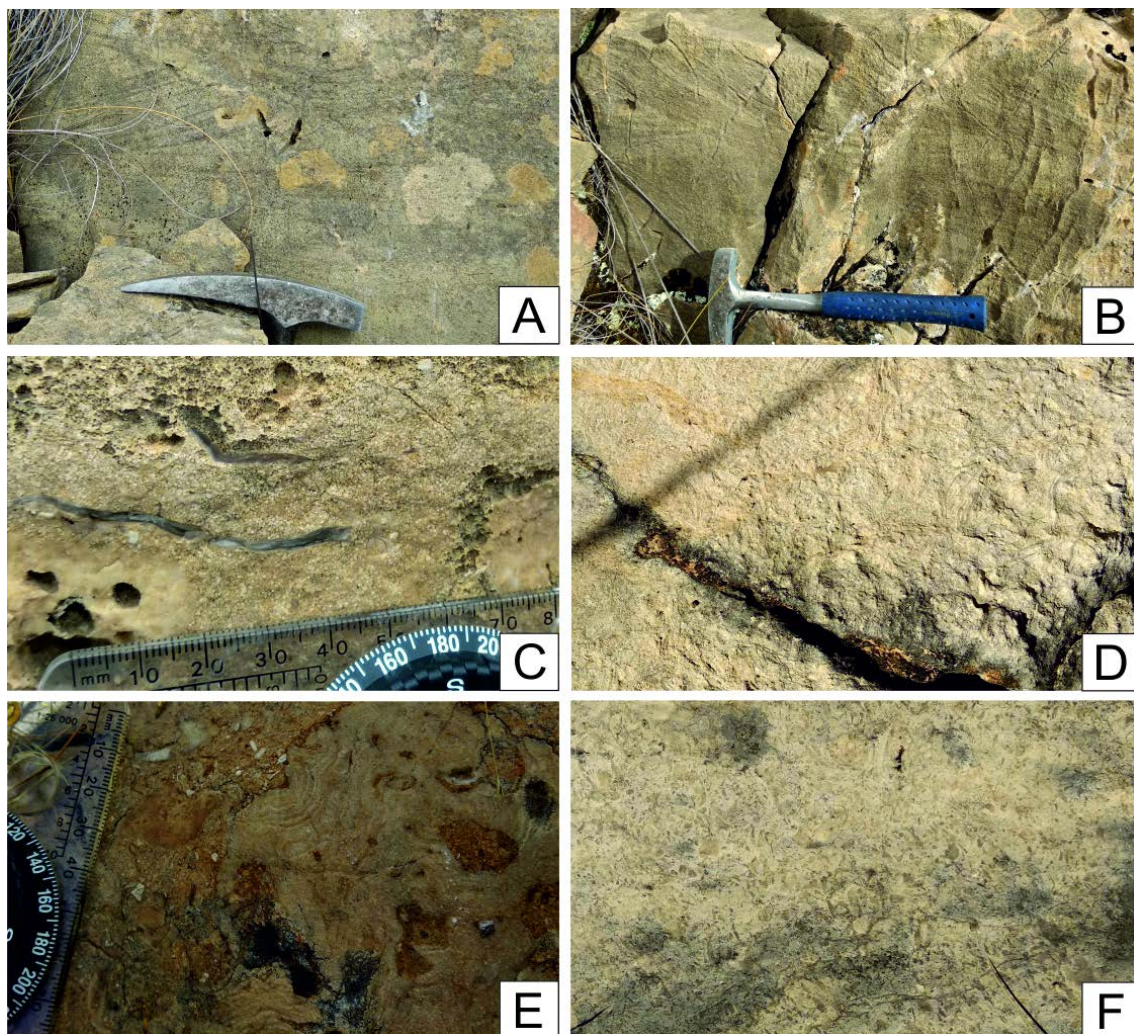
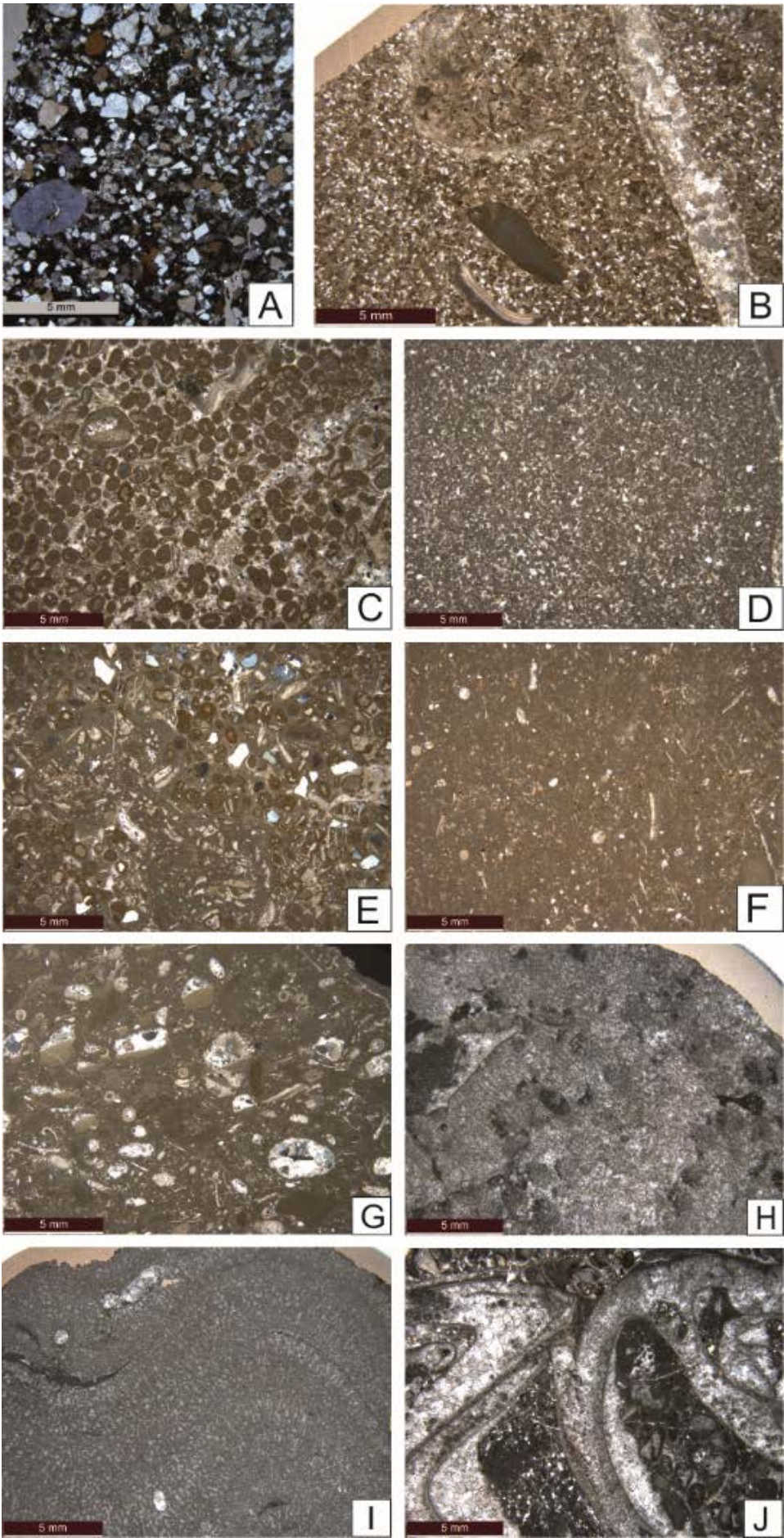


Figure 5.5. Lithostratigraphic facies of Llopis Fm in the Barranco del Tejar outcrops. A: Sandstone with coarse grain and cross-planar lamination (facies L1-1A, Table 1). B: Sandstone with fine grain and planar-cross lamination (facies L1-1B, Table 1). C: Limestone with ooids (facies L2, Table 1). D: Limestone with bioclastic fragments, mainly of bivalves (facies L3, Table 1). E: Stromatoporida limestone (facies L5, Table 1). F: Rudist limestone (facies L6, Table 1).

Figure 5.6 (following page). Microfacies of the Llopis Fm from the Barranco del Tejar outcrops. A: Sandstone with coarse grain, mainly quartz (microfacies 1A, Table 1). B: Sandstone with fine grains, mainly quartz (microfacies 1B, Table 1). C: Grainstone with ooids (microfacies 2A, Table 1). D: Grainstone with peloids (microfacies 2B, Table 1). E: Packstone with peloids (microfacies 3, Table 1). F: Packstone with peloids and bioclasts (microfacies 3, Table 1). G: Wackestone with peloids and charophytes (microfacies 4A, Table 1). H: Floatstone of stromatoporida (microfacies 5, Table 1). I: Detail of internal structure of a stromatoporida (microfacies 5, Table 1). J: Grainstone and packstone of ooids and peloids with rudists (microfacies 6, Table 1).



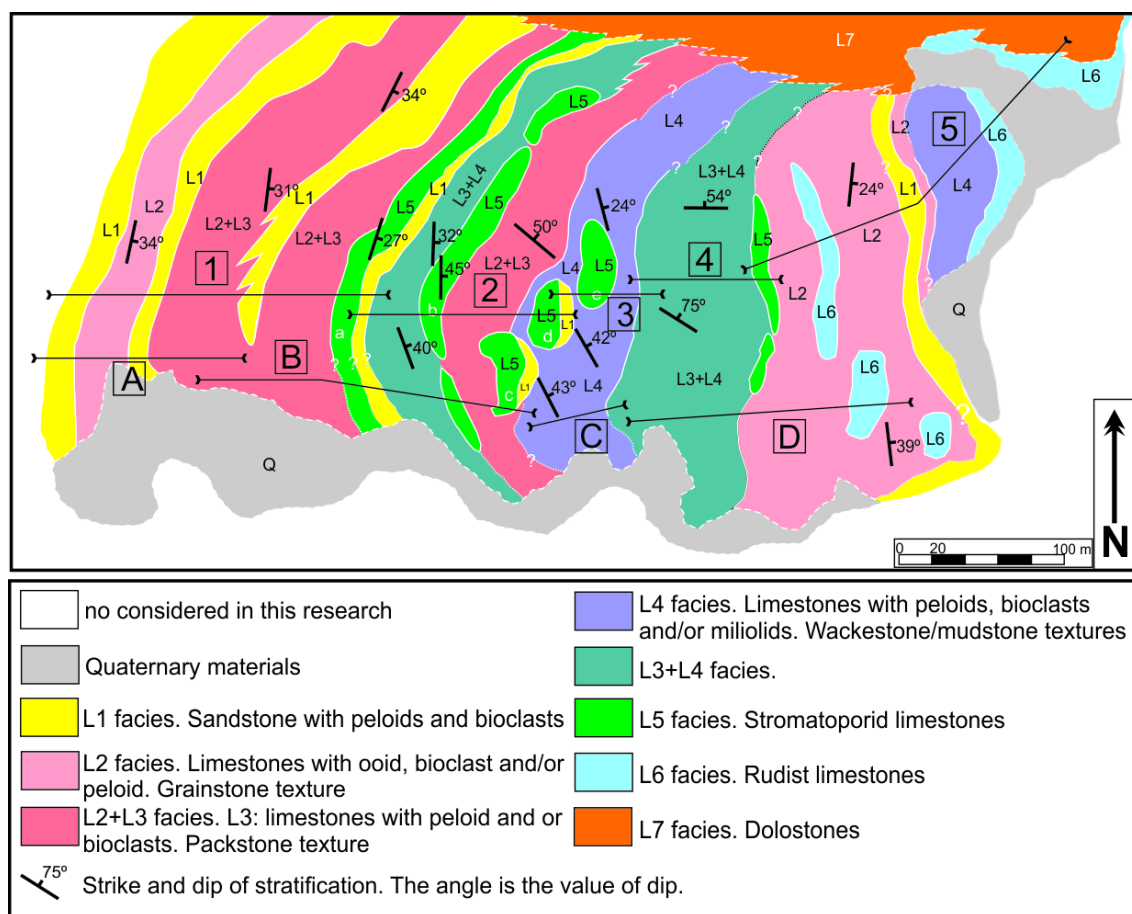


Figure 5.7. Lithofacies map of the Llopis Fm in the Barranco del Tejar outcrops. The position of the different stratigraphic sections considered and shown in this work are indicated.

5.5 Depositional model

L1 lithofacies were deposited on an inner shallow platform where the action of the waves produced sand-wave sedimentary bodies (James and Dalrympe, 2010) (Fig. 5.8). Towards more marine parts of this partially isolated platform, the L1 facies sands gradually pass towards the limestones of L2 and L3 facies, deposited on a shallow platform environment (Flügel, 2010), (Fig. 5.8). These calcarenitic bars delimit the lagoon, represented by limestones with L4 lithofacies (Reijmer, 2021). The lagoon is a low-energy shallow environment, episodically affected by currents providing with thin oolitic or peloidal levels (L2 or L3 facies), which are interfingered between the carbonates of L4 facies. Facies L3 and L4, with micritic matrix and benthonic microfauna were deposited in more quiet environments, in a relatively deep lagoon, probably protected from the open sea energy by sectors where stromatoporidae developed, without making a structured barrier, as demonstrated by their patchy distributions (Fig. 5.7). Towards the proximal sectors the lagoon was limited by the calcarenitic bars, whereas towards the external platform the limit of the lagoon was marked by bioconstructions of stromatoporidae, which acted as relatively deep reef barriers, in marine contexts slightly deeper than those of the lagoon (Leinfelder et al., 2005). Stromatoporidae would grow in highly abrasive, energetic marine environments and, perhaps, in superheated waters, typical of oligotrophic marine environments (Leinfelder et al., 2005). The presence of erosive surfaces and thin iron crusts at the top of the stromatoporidae bioconstructions indicate that the end of the growth of these bioconstructions was related to an erosive phase, perhaps due to a higher wave energy, or

relative sea level drops, probably reaching occasional short-term emersions (e.g. Pomar, 2001). Over the irregular surface on top of bioconstructions, new sandstone beds (L1 facies) are disposed, with development of subsequent sequences. The replacement of stromatoporoids by rudists in type 3 sequences in the upper part of the succession could be related to a reduction in the terrigenous inputs and, therefore, a change in the environmental conditions favouring the carbonate production, and leading to the development of a shallower urgonian carbonate platform with a shallow lagoon dominated by rudists. Due to the limited extension of the outcrop there is no data about the facies that would represent the border of the lagoon.

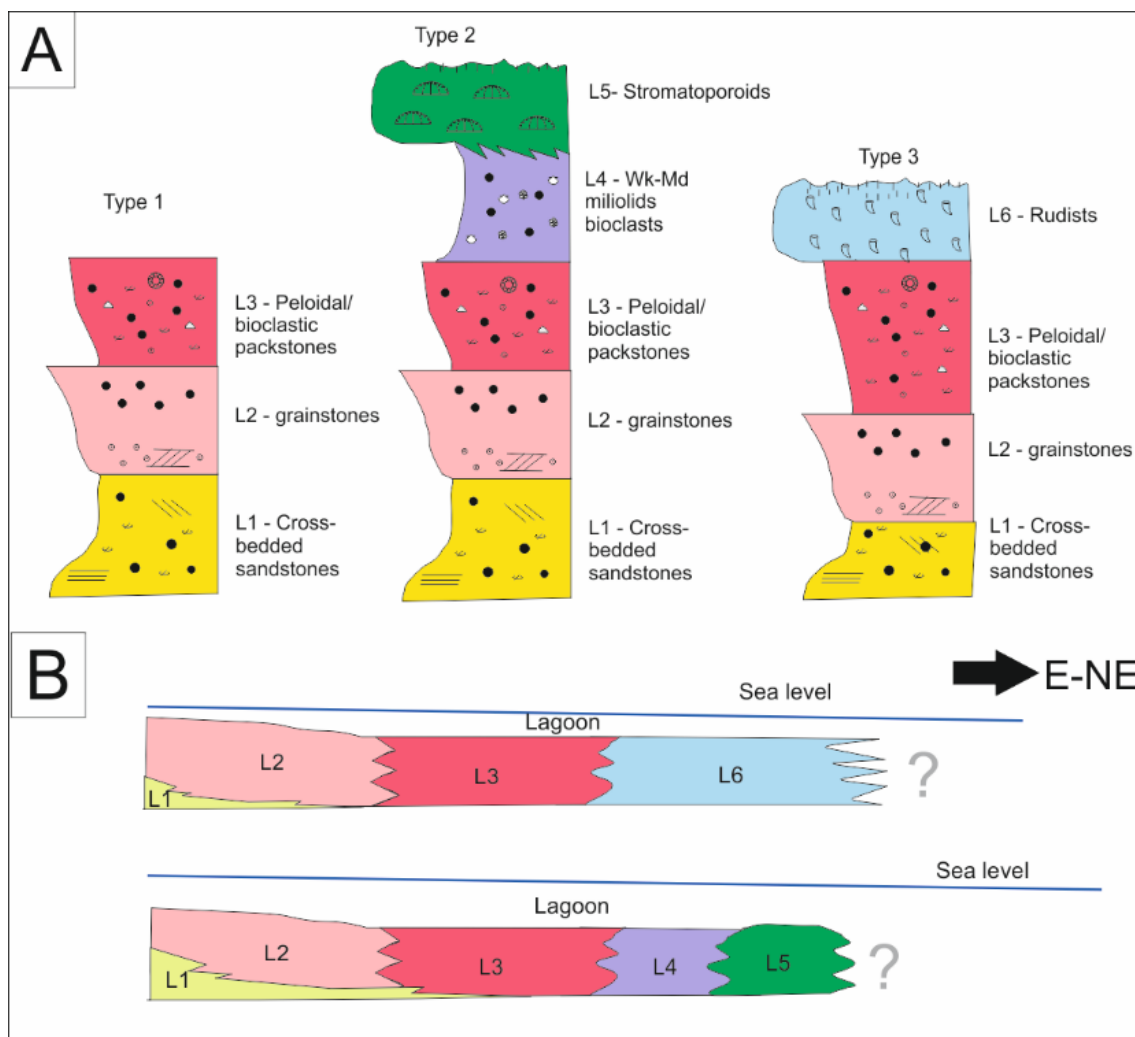


Figure 5.8. A. Elementary sequence types deduced from the facies analysis. B. Depositional model of Bedmar-Jódar shallow carbonate platform.

5.6 Cyclicity and sedimentary evolution

The detailed successions and mapping (Figs. 5.3, 5.4 and 5.7) allow to distinguish up to eight elementary sequences, which are arranged in a succession of Type 1 (2 sequences), Type 2 (4 sequences) and Type 3 (2 sequences) (Fig. 5.8A). This succession of elementary sequences represents a replacement of facies, both vertical and lateral: the lower part of the succession is mostly sandy and calcarenitic, without noticeable macrofossils, the middle part is marked by the presence of stromatoporoids, and the upper part witnesses the disappearance of stromatoporoids and facies L3 (packstones), and development of rudistid and wakestone-

mudstone facies L4. This succession is interpreted to represent three phases in the evolution of the platform:

Phase 1 of installation: with dominance of terrigenous sediments from the continent and mixed carbonate-siliciclastic sediments under a weak development of the carbonate factory, probably limited by the presence of siliciclastics in a transgressive context.

Phase 2 of early development of a lagoon-barrier system: with development of a relative deep barrier with stromatoporoids, bounding a lower energy sector with deposition of micritic sediments and small benthic fauna.

Phase 3 of development of a lagoon dominated by rudists (urgonian facies): with wider and shallower lagoon, probably protected by a barrier system located beyond the studied area.

At a higher scale, this succession can be subdivided into two major units, that could be considered as parasequences (Catuneanu and Zecchin, 2020). The first unit is composed by the 6 lower elementary sequences, and the second unit is made up by the 2 upper elementary sequences, collectively representing the installation and development of a shallow carbonate platform in the first unit, followed up by a well-developed urgonian facies under optimal environmental conditions for carbonate production in the second unit.

5.7 Correlation with Sierra Mariola

The materials of this study correlate with the Middle Mb of the Llopis Fm at Sierra Mariola. The eight elementary sequences organized in two parasequences present a progradation of the platform towards the E-NE. This organization is equivalent to that parasequences I and II defined at Mariola (see Chapter 4), with a marked progradational evolution, also with a lower parasequence mostly calcarenitic and a parasequence II with development of rudist facies. Additionally, biostratigraphy based on benthonic foraminifers (biostratigraphic unit with *O. Killiani* and *O. cuvillieri*) is consistent with a correlation between the Bedmar-Jódar succession and the lower part of the Mariola succession.

Therefore, the episode of installation and consolidation of the shallow platform through a marked progradation has been recorded in two distant sites of the Prebetic platform. This points out to a regional episode of high carbonate production under optimal environmental conditions, and probably reduced subsidence rates leading to reduced accommodation space and subsequent progradation of the shallow platform deposits (Catuneanu et al., 2011).

5.8 Conclusions

The study of an outcrop from the early Aptian Llopis Fm shallow carbonate platform in the Sierra de Bedmar-Jódar, has been based on ten high-resolution stratigraphic sections and a detailed facies map has revealed the facies architecture of this sector of the platform.

The facies described are arranged in a succession of strata of highly variable thickness, locally with clinoforms with a mean E dip direction.

Up to seven lithofacies have been differentiated, one with siliciclastics, five of carbonate facies ranging from grainstones and packstones to wackestones and mudstones. Two facies include macrofossils (stromatoporoids and rudists).

Lithofacies L1 to L6 are organized in two different types of elementary sequences that differ in the presence of stromatoporoids or rudists. They are interpreted as shallowing-upwards sequences, developed in a very shallow carbonate platform, with a lagoon limited to the shore by clastic/ooidal bars, and limited to the sea by stromatopod bioconstructions (bioherms and biostromes) or rudists.

Atop of these sequences some features reveal a shallowing of the bioconstructions, with probable emersion, overlaid by coastal bars. This shallowing may be controlled by local tectonics.

Collectively, the 8 elementary sequences present a progradational character, with an advance of the platform to the East.

The associations of facies define three types of elementary sequences, clearly depicted in the stratigraphic sections and in the facies map: (1) sandstones and calcarenites, deposited in shallow open marine proximal environments, (2) sandstones, calcarenites and stromatoporoid limestones, deposited on a semi-protected lagoon, and (3), sandstones, calcarenites and rudist facies, interpreted to represent an urgonian-type lagoon. These sequences are frequently capped by discontinuity surfaces, which might be related to a combination of sediment aggradation, and or relative sea-level drops, occasionally driven by tectonic tilting linked to the extensional regime of the rifting affecting the SICM.

The vertical succession of the platform studied has been divided into two progradational parasequences, which represent two phases:

- (1) installation of the shallow platform, with development of stromatoporoids;
- (2) development of an urgonian platform dominated by rudists.

Correlation with the coeval shallow carbonate platform in Mariola (Alicante), supported by biostratigraphy, reveals interesting common features in the sedimentary evolution in both sectors of the Prebetic platform. This indicates a regional scale episode of installation and development of a shallow carbonate platform controlled by optimal environmental conditions for carbonate production.

During the early Aptian, the Bedmar-Jódar platform was likely isolated or partially isolated from the rest of the Prebetic platform, with a different progradation movement towards the NE, whereas the general trend of the Prebetic platform presents progradation to the SE or S. The sedimentation was mainly controlled by extensional tectonics, favouring emersion pulses that tilted the platform block, producing a different orientation of the progradation. Occasional terrigenous inputs from the continent and the presence of *characeae* in the materials indicates that this isolated platform was, sometimes, very proximal to the continent.

6. Cyclostratigraphy of the Cau core

6.1 Orbital theory

Cyclostratigraphy is the study of the stratigraphic record with the aim of recognizing a periodic pattern that could be linked to any or all of the earth periodic orbital movements. Solar insolation received by the earth is dependent on the gravitational interaction with other celestial bodies. The study of celestial mechanics started in the 17th century, when the studies by Kepler and Newton discovered the functioning of the Solar system. Subsequent advances in the knowledge of the movement of the different celestial bodies were introduced by Laplace (1775, 1776) and Lagrange (1778, 1783 and 1784), that enabled astronomy to flourish during the 18th and 19th centuries. Cyclostratigraphy is a relatively young discipline that started in the 20th century after the seminal publication made by Milutin Milankovitch (Milankovitch, 1941), who calculated the duration of the different orbital movements of the Earth. Such astronomical solutions have been widely developed in the last decades mainly due to the works by Jacques Laskar (e.g. Laskar, 1989, 1990; and Laskar et al., 2004, 2011). The discipline is based on understanding astronomical climate forcing and reading geological time in sedimentary sequences, provided that an imprint of insolation variations caused by Earth's orbital eccentricity, obliquity and/or precession is preserved in the sedimentary successions (Milankovitch forcing). In order to obtain an interpretation of cyclicity, proxies and models of stratigraphy, paleoclimate, and astronomy are combined, following data-model comparison methodologies, using a visual approach and time-series analysis, to ultimately calibrate to astronomical solutions with the goal of obtaining a floating or astrochronologically tuned time scale (Fig. 6.1). Understanding climate dynamics and constraining geologic time and geologic correlation are the main applications of cyclostratigraphy, as part of an integrated stratigraphic approach (Schwarzacher, 1993; Hilgen et al., 2004; Strasser et al., 2006; Hinnov and Hilgen, 2012). The interaction of the planet Earth with Mars, Venus and other celestial bodies in the Solar system has a profound impact on insolation, the amount of energy the Earth receives from the Sun. As these gravitational interactions are semi-periodic, they can result in a cyclic pattern than can be recorded in sediments.

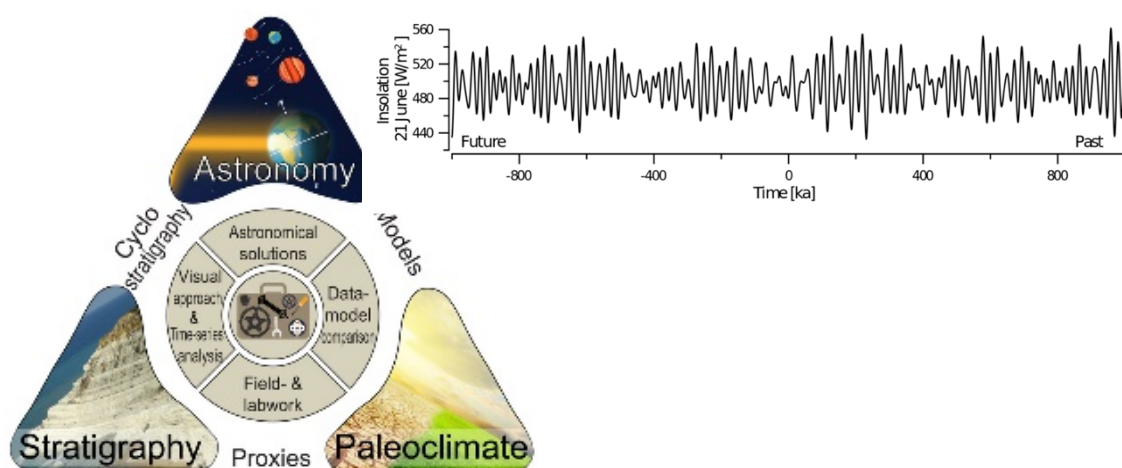


Figure 6.1. Left: diagram showing the different fields that are connected with the cyclostratigraphy discipline. Right: Time series of incoming solar radiation on June 21st (Northern Hemisphere summer solstice) at 65°N, between 1 million year ago (right-hand scale) and 1 million year in the future (left-hand scale). ka = thousand years ago. Source: www.cyclostratigraphy.org.

Astronomical tuning

The key aspect of cyclostratigraphy is the identification of the astronomical parameters that force cyclicity in the sedimentary record, and the development of a detailed understanding of astronomical climate forcing (Berger et al., 1993, 2010). Correlating cyclic sedimentary records with precision to quantitative astronomical models has been done for the Neogene (Hilgen et al., 2012) and the Paleogene (Westerhold et al., 2012, 2014, 2015; Boulila et al., 2018), though extending this procedure through the Mesozoic is difficult. To capture cyclic climate variations through stratigraphic successions, cyclostratigraphy uses different proxies at high resolution, such as paleontological abundance, isotopic ratios and sediment composition.

The calibration of geologic time by the Earth's astronomical parameters is called Astrochronology. When a section seems to display cyclicity, high-resolution data is collected from the section, which could be in the form of different proxies, such as chemostratigraphic data (C and O stable isotopes, elements or chemical compound abundances, measured directly or indirectly) or physical property variations, such as gamma ray or magnetic susceptibility. The collected data is tested for cyclicity using time series analyses, using signal processing tools to determine spectral density, such as the periodogram or the multitaper method to decompose the expressed signal. The astronomical tuning is always constrained to an independent age control, that can be absolute (radioisotopic dating) or relative (bio-, magneto-, chemostratigraphy). Once the hierarchy of cycles is established, the phase relationship can be deduced, and only then cycles extremes can be tied to an astronomical solution.

Due to the chaotic nature of the solar system, in part caused by the asteroids Ceres and Vesta, it is not possible to use the astronomical solutions beyond 52 Ma, although the presence of the stable component of 405 kyr allows cyclostratigraphic interpretations that can be anchored to the absolute time scale throughout the Mesozoic and Paleozoic. There are different tuning targets: astronomically tuned stratigraphic reference datasets (De Vleeschouwer et al., 2017), glacial models (Imbrie and Imbrie, 1980), insolation curves (Milankovitch, 1941; Laskar et al., 2004) and astronomical solutions that consist of one or more astronomical parameters (Lourens et al., 1996; Hinnov, 2018a).

Other strategies include establishing floating astrochronologies based on the ratio of frequencies (Meyers and Sageman, 2007), the amplitude modulation of the precession index by eccentricity (Meyers, 2019), or a combination of these (Meyers, 2019). To yield an anchored astrochronology from the floating astrochronology, a numerical age must be established through an integrated stratigraphic approach based on independent methods of correlation, preferably by high-precision radioisotopic geochronology (Meyers, 2019).

Nevertheless, astrochronology and cyclostratigraphy remain controversial to some extent, due to issues such as: the diagenetic imprint of cycles in sedimentary successions; uncertainties in the astronomical parameters of the deep-time geologic past; independent age control in cyclostratigraphy; the relationship between the stratigraphic record, climate-forced sedimentary response and astronomically forced climate; and the completeness of the stratigraphic record (e.g. the presence of hiatuses) (Sinnesael et al., 2019).

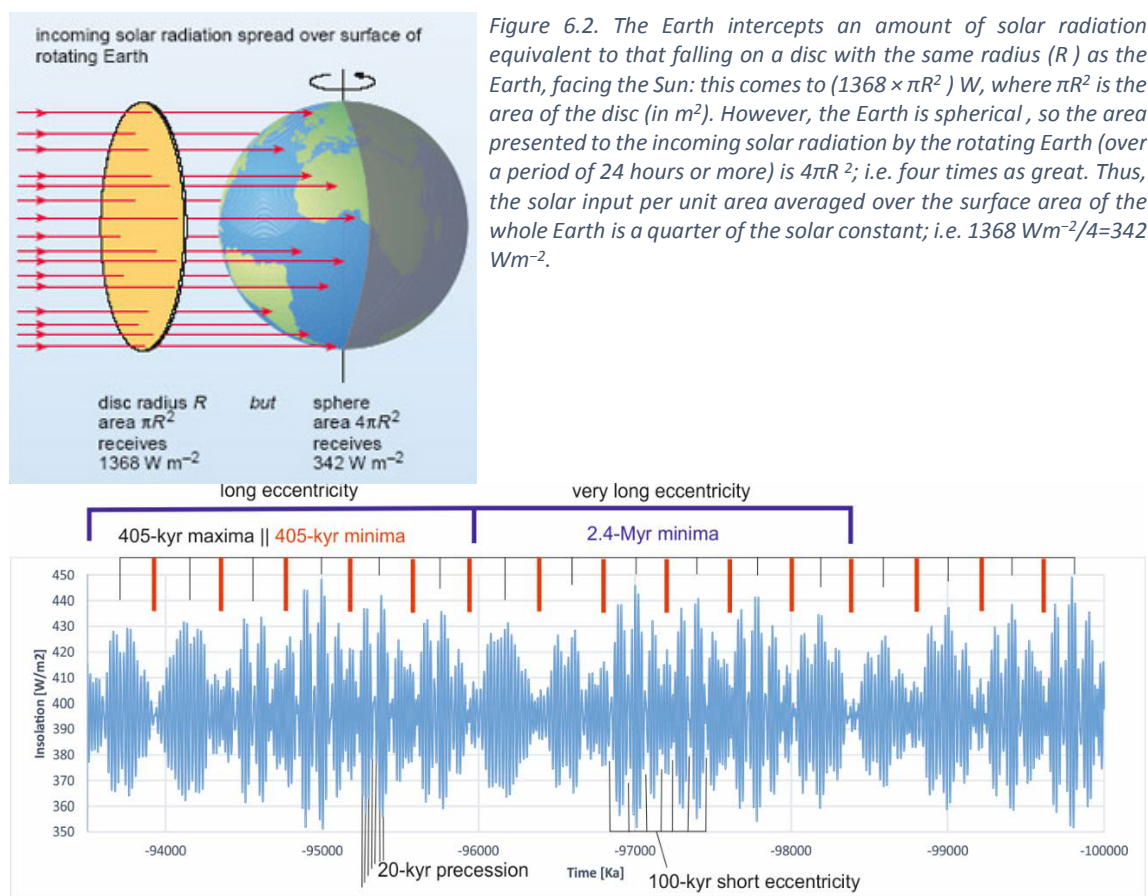
6.2 Principles of cyclostratigraphy applied to the Cau Section

Radiation is emitted by the Sun at the rate of 3.85×10^{26} W. Located at an average distance from the Sun of some 150×10^6 km, the Earth intercepts only a fraction of this - an amount equivalent

to the solar radiation falling on the flat, circular disc depicted in Fig. 6.2. The solar input *per unit area* of this disc is called the solar constant. Measurements from satellite-borne radiation sensors give the solar constant an average value over recent years of 1368 W m^{-2} . When averaged over the surface of the whole globe, the solar input per unit area at the top of the atmosphere comes down by a factor of four, to 342 W m^{-2} .

Insolation received at Cau during the Aptian may resemble a pattern like that plotted in Fig. 6.3, showing the calculated insolation based on the astronomical solution La2004 (Laskar et al., 2004).

In the insolation profile, the three orbital parameters are included, precession (21-kyr), obliquity (41-kyr) and both components of eccentricity, short (100-kyr) and long (405-kyr), whereas there are other minor components, as precession varies between 19-kyr and 23-kyr, obliquity also presents two components, and short-eccentricity has various different periodicities. All the former periodicities are combined and interplay in multiple and complex ways altering the ideal insolation curve that is received by the Earth, and that could be ultimately reflected in the geological record. In Fig. 6.3, at this scale, the more easily seen cycles are the long eccentricity (405-kyr) and short eccentricity (100-kyr) ones, while within a short eccentricity cycle, the individual oscillations reflect the influence of precession, with each short eccentricity cycle presenting five 20-kyr cycle oscillations of the signal. The final goal of time series analysis is the application of statistical tools to test whether periodic signals are present in a time series, and how periodic signals behave over the dataset, to obtain profiles similar to that shown in Fig. 6.4.



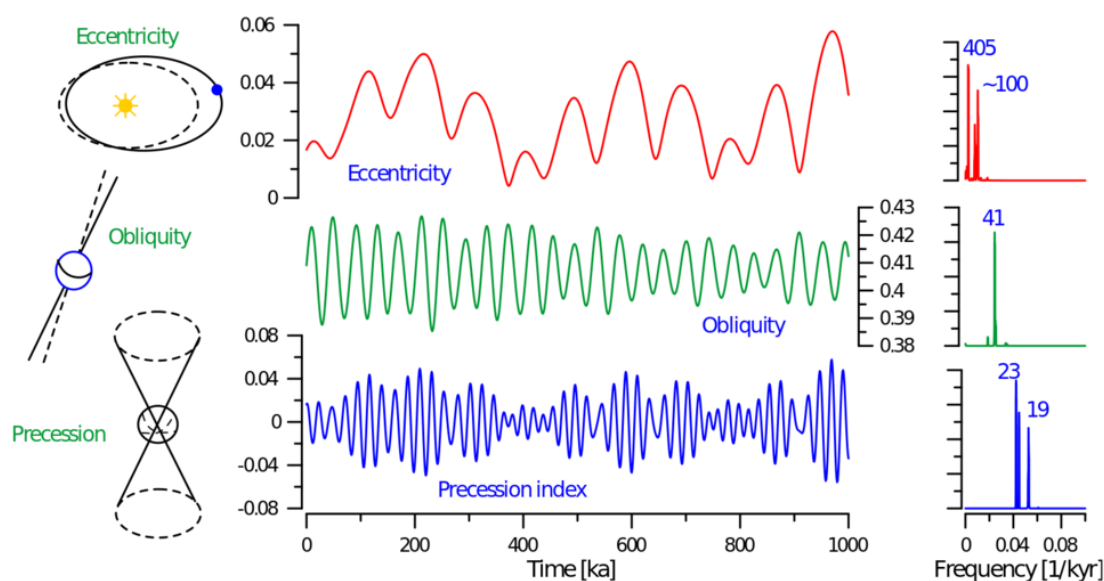


Figure 6.4. The evolution of the three astronomical parameters (eccentricity, obliquity and precession) over the last 1 million year, in the time-domain (middle panels), as well as in the frequency domain (right-hand panels). The representation of the astronomical parameters in the frequency domain is particularly useful to discern their main periodic components: 405 and ~100 kyr for eccentricity, 41 kyr for obliquity and 23, 21 and 19 kyr for precession. ka = thousand years ago. kyr = thousand years duration. Source: www.cyclostratigraphy.org.

The next part of the chapter is currently in preparation for publication with the following article structure:

Integrated stratigraphy of the Cau Core (SE Spain) provides a timescale for the Aptian

6.3 Introduction

The mid-Cretaceous (Aptian-Turonian, 124.4 to 89.8 ± 0.3 Ma) was characterized by intermittent super-greenhouse conditions and a generally warm climate, with an absence of ice sheets and weak latitudinal temperature gradients (e.g. Föllmi, 2012; Friedrich et al., 2012; Bodin et al., 2015 and O'Brien et al., 2017). During the Aptian (121.4 to 113.2 Ma), temperatures and sea-levels were rising, and recurrent anoxic conditions in the Tethys Ocean led to the deposition of several organic-rich beds, including the Selli, Noir, Fallot, and Jacob levels (Föllmi et al., 2006; Renard et al., 2005). One of the most studied Oceanic Anoxic Events (OAEs) is the early Aptian OAE (OAE 1a) (see Arthur et al., 1990; Erba 1994; Mehay et al., 2009; Erba et al., 2010; Stein et al., 2011). The main imprint of this event is a negative excursion in carbon isotope records, followed by a pronounced positive excursion. Both excursions in $\delta^{13}\text{C}$ have been observed worldwide (e.g. Bralower et al., 1999; De Gea et al., 2003; Ando et al., 2008; Heldt et al., 2008; Kuhnt et al., 2011; Elkhazri et al., 2012; Hu et al., 2012; Castro et al., 2021). The OAE 1a is associated with major global climatic and paleoceanographic changes (Millán et al., 2009), linked to increased continental runoff and weathering (Najarro et al., 2010), mass occurrences of *Lithocodium-Bacinella* (incrusting organisms of unknown taxonomic origin), sea level rise (Menegatti et al., 1998; Bralower et al., 1999; Erba et al., 1999) and carbonate platform drowning (e.g. Föllmi et al., 1994, 2006; Weissert et al., 1998; Skelton et al., 2003, 2019; Castro et al., 2008; Huck et al., 2010). The cause of these paleoenvironmental changes is thought to be an increase in atmospheric $p\text{CO}_2$ through volcanic activity from one or more Large Igneous Provinces (LIP) (Kerr, 2005; Erba, 2004). The intense volcanic activity of the Ontong Java Plateau (OJP) during the early phase of anoxia of the OAE 1a triggered a maximum warming of about 1.5-2 °C (Bottini et al., 2015). The weak constraints on the timing of causal mechanisms triggering

events culminating in oceanic anoxia during OAE 1a limits our understanding of the drivers of this climatic perturbation, although the OAE 1a itself has been extensively studied (Weissert and Lini, 1991; Jenkyns, 1995; Menegatti et al., 1998; Bralower et al., 1999; Erba et al., 1999; Luciani et al., 2001; Bellanca et al., 2002; Price, 2003; van Breugel et al., 2007; Ando et al., 2008; Méhay et al., 2009; Millán et al., 2009; Malkoc et al., 2010; Mahanipour et al., 2011; Stein et al., 2011; Bottini et al., 2012; Hu et al., 2012; Quijano et al., 2012; Aguado et al., 2014; Castro et al., 2019, 2021).

Although it is considered that the OAE 1a was characterized by a major warming, there is some evidence that cooler intervals or “cold snaps” occurred during the event. Three possibly global cooling episodes have been documented through high-resolution studies within the OAE 1a. Cooling has tentatively been ascribed to lower atmospheric CO₂ levels (Jenkyns, 2018) possibly through weakened volcanic activity in combination with an increase in global burial of organic matter leading to a drawdown of CO₂ (Gröcke et al., 1999).

Despite its rich sedimentary record of environmental change, a complete picture of climatic evolution during the Aptian is not available, because most successions cover only limited portions of the estimated 13-Myr long stage (Li et al., 2008; Malinverno et al., 2010; Lorenzen et al., 2013, and others). In particular, the upper part of the lower and the upper Aptian lack a sufficiently constrained chronology, limiting paleoclimatic studies.

A proposal is underway for a new definition for base of the Aptian (Global Boundary Stratotype Section and Point, GSSP). Meanwhile, different definitions of the stage boundaries and differences in dating efforts result in a range of ages and durations suggested for the Aptian and the OAE 1a. The International Chronostratigraphic Chart (ICC) sets the base of the Aptian at ~125.0 Ma (Cohen et al., 2013; v2020/20), whereas the GTS2020 (Gradstein et al., 2020) provides an age of 121.4 ± 0.6 Ma for the Barremian/Aptian boundary (Zhang et al., 2019). This younger age is in close agreement with a recently published cyclostratigraphic calibration of the Barremian (Martínez et al., 2020), suggesting an age of the Barremian/Aptian boundary of 121.40 ± 0.34 Ma, as well as Ar⁴⁰/Ar³⁹ geochronological estimation between 123.4 and 121.2 Ma (Olierook et al., 2019). The top of the Aptian is set at ~113.0 Ma in the ICC (Cohen et al., 2013; v2020/20) and at 113.2 ± 0.3 Ma in the GTS2020 (Gradstein et al., 2020), based on a U-Pb date of a basal Albian volcanic ash layer in north-west Germany (Selby et al., 2009). The duration estimates in the ICC and GTS 2020 for the Aptian stage are 11 and 8.4 Myr, respectively. A longer duration for the Aptian stage of 13.4 Myr was suggested by an astrochronology from the Piobbico core which recovered 33.7 m of the Fucoid marls near Piobbico, central Italy (Huang et al., 2010). A correlation with the nearby Cismon core was used to extend the duration for the Aptian by ~0.5 Myr to ~13.9 Myr, because the Piobbico core did not recover the base of reversed magnetic chron M0r. Several studies have focussed on estimating the duration of OAE 1a in the early Aptian, including Li et al. (2008), Huang et al. (2010), Malinverno et al. (2010), Lorenzen et al. (2013) and Moullade et al. (2015), resulting in estimated durations ranging from 1.15 to 1.4 Myr. Following OAE 1a, the return of better ventilated conditions in the water column coincided with pronounced cooling and the end of the main phase of volcanic activity (Tejada et al., 2009; Bottini et al., 2012), although a recent study by Martínez-Rodríguez et al. (2021) (Chapter 7) confirmed that volcanism continued after the OAE 1a and during the Late Aptian.

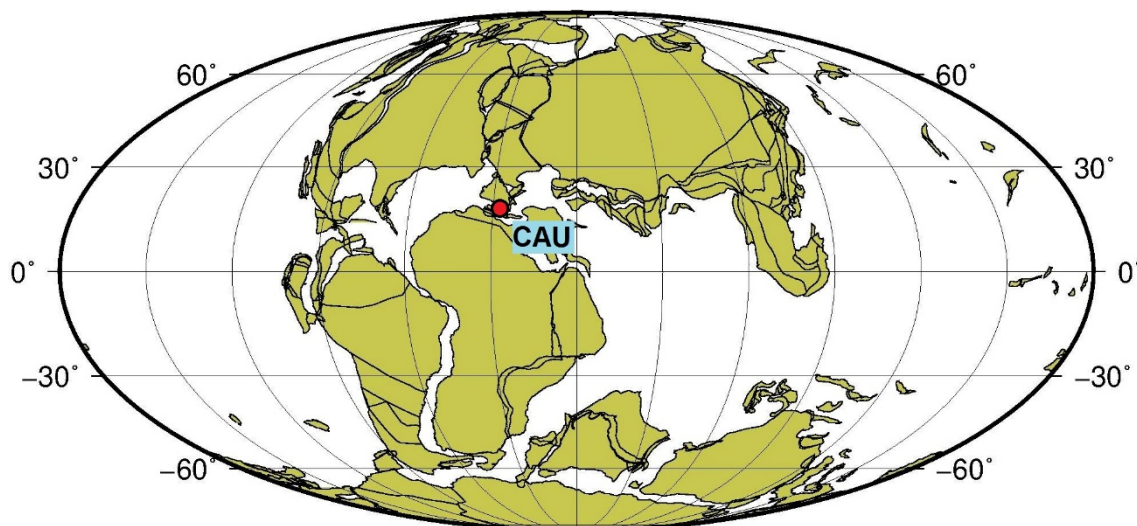
Unravelling the sequence of events leading to episodes of oceanic anoxia requires constraints on the tempo and mode of climate change by studies of well-dated sedimentary successions. The newly-drilled Cau core in south-eastern Spain presents an exceptional archive of past

environmental change during the early and late Aptian. The Cau Core is particularly suitable for the study of OAE 1a as it provides an expanded succession from a relatively shallow marine environment, in comparison to deeper and/or condensed sections from the Tethyan domain.

6.4 Materials and methods

6.4.1 Geological setting

At Cau, hemipelagic marls with varying amounts of organic carbon were deposited a tropical climate at a palaeolatitude of about 22.5°N (Fig. 6.5), on a margin that experienced extensional rifting as the Western Tethys was opening (e.g. de Gea et al., 2003; Castro et al., 2008; 2021).



120.0 Ma Reconstruction

Figure 6.5: Palaeogeographic reconstruction (based on www.osdn.de; Hay et al., 1999) for the Early Aptian (120 Ma) showing location of the Cau section.

The Cau Core was drilled in the Cau hill (Lat. 38.70°; Long. -0.00° WGS84) located in the SE of Spain, in the province of Alicante. Four boreholes were drilled in the Cau hill to obtain an almost continuous record of the Almadich Fm (Ruiz-Ortiz et al., 2016; Castro et al., 2019).

The sediments of the Almadich Fm at Cau are marls, with intercalated beds of marly limestones less than one metre thick. Alternations between marls and limestones are more easily observed in the field than in the core. The materials represent the distal expression of a shallow carbonate ramp with hemipelagic sedimentation. Palaeographically, the area is located in the Southern Iberian Palaeomargin (SIP, see Vera, 2001), which is currently represented by the External Zones of the Betic Cordillera, specifically in the platform settings of the margin, the Prebetic Zone. During OAE 1a, the Aptian prebetic platform drowned under a transgressive regime.

The composite record of the core has been constructed comparing the gamma ray signal between cores, correlating the $\delta^{13}\text{C}$ data and faunal data from biostratigraphy. The drilled materials of the core from the Cau hill have a mean dip angle of 20°, but some sections display 10° of dip while others have 30°, so a dip correction was applied over 5 m intervals. Hole D4 overlaps D3 by 15.4 m, D3 and D2 overlap by 6.4 m, there is no overlap between D1 and D2, and a gap of 1 m has been assigned. For a more detailed report on the extraction, logging, biostratigraphy and lithology of the core see Ruiz-Ortiz et al., (2016) and Castro et al. (2021).

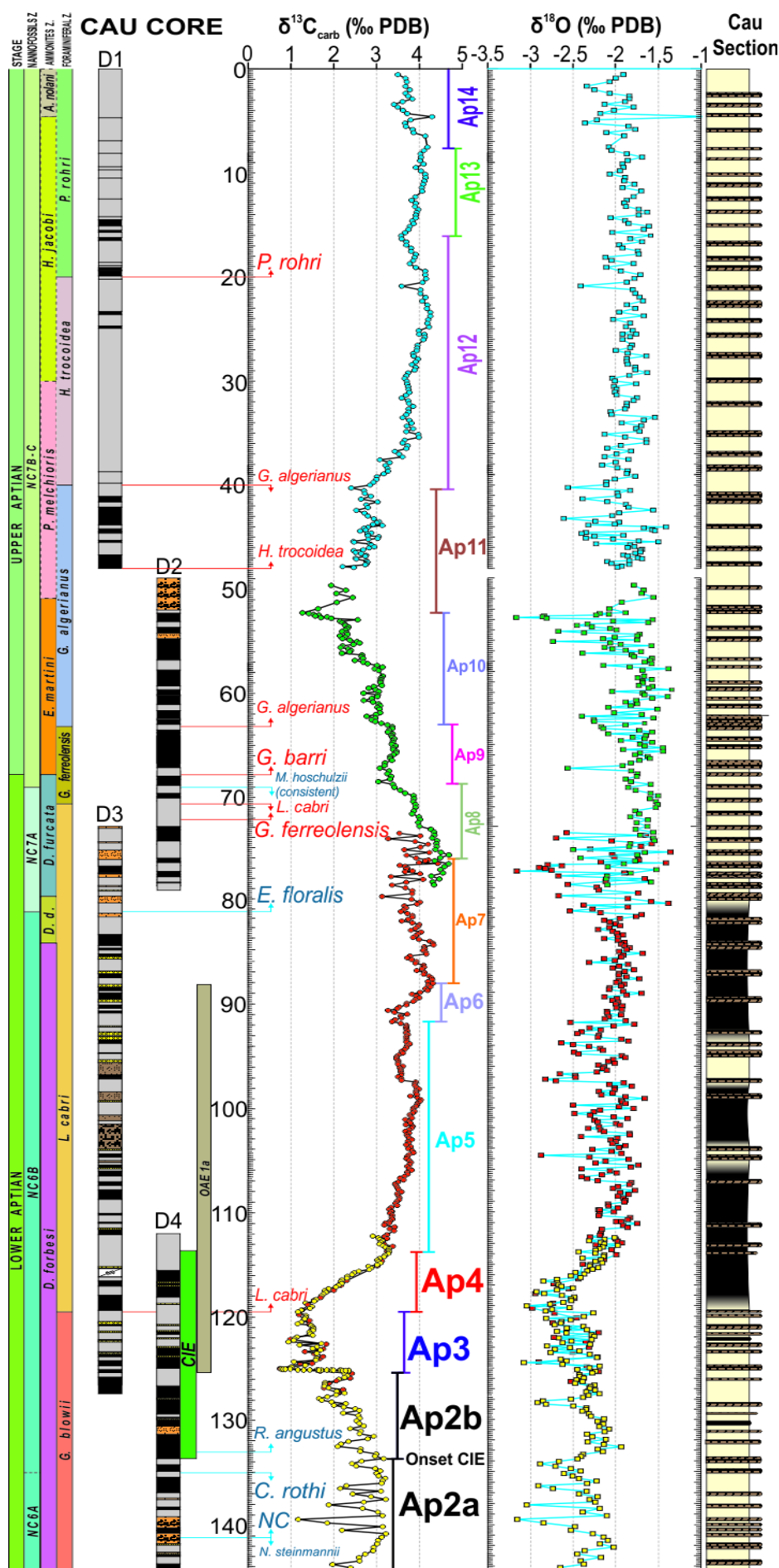
6.4.2 Biostratigraphy

The record of the Cau core begins in nannofossil Zone NC6A (Fig. 6.6), characterized by the coexistence of the nannofossil markers *Hayesites irregularis*, *Braarudosphaera hockwoldensis*, *Nannoconus truttii* and *Conusphaera rothii*, found at the base of the core. Also recorded in the lowermost part of the core is the highest occurrence (HO) of *Nannoconus steinmanii*, used to define the Nannoconid crisis event (Fig. 6.6). Besides, the absence of forms assignable to *Leupoldina cabri* and the assemblages of *Globigerinelloides blowi*, *Globigerinelloides aptiensis* and small-size trochospiral hedbergellids, allowed to situate the base of the core within the planktic foraminifera biozone of *Globigerinelloides blowi*. The Cau core ranges through the Aptian until its top, where the lower part of *Paraticinella rohri* zone was identified, coincident with the uppermost part of the NC7 zone, which correlates to the lowermost part of *Hypacanthoplites jacobi* ammonite biozone (Fig. 6.6). The biostratigraphic information provides a framework for a first-order estimate of sedimentation rate variability across the cored interval (Table 1).

Foraminifera zones	Depth (m)	Ages from Gradstein et al., 2020 (Ma)	Sed. rate (cm/kyr)	Ages from Malinverno et al., 2010 & Coccioni, 2019* (Ma)	Sed. Rate (cm/kyr)
<i>G. blowi</i>	Base: 144.4 Top: 119.5	Base: 120.7 Top: 120.6	24.90		
<i>L. cabri</i>	Base: 119.5 Top: 70.6	Base: 120.6 Top: 118.6	2.45	Base: 120.80* Top: 118.74	2.37
<i>G. ferreolensis</i>	Base: 70.6 Top: 63.2	Base: 118.6 Top: 118.2	0.53	Base: 118.74 Top: 117.64	0.67
<i>G. algerianus</i>	Base: 63.2 Top: 40.0	Base: 118.2 Top: 116.8	1.66	Base: 117.64 Top: 115.74	1.22
<i>H. trocoidea</i>	Base: 40.0 Top: 20.0	Base: 116.8 Top: 116.6	10.00	Base: 115.74 Top: 115.26	4.17
<i>P. rohri</i>	Base: 20.0 Top: 0.0	Base: 116.6 Top: 114.2	0.83		

Ammonites zone	Depth (m)	GTS2020 Age (Ma)	Sedimentation rate (cm/kyr)
<i>D. forbesi</i>	Base: 144.4 Top: 84.4	Base: 120.7 Top: 120.0	8.57
<i>D. deshayesi</i>	Base: 84.4 Top: 79.9	Base: 120.0 Top: 119.1	0.50
<i>D. furcata</i>	Base: 79.9 Top: 67.9	Base: 119.1 Top: 118.8	4.00
<i>E. martini</i>	Base: 67.9 Top: 50.9	Base: 118.8 Top: 117.5	1.31
<i>P. melchioris</i>	Base: 50.9 Top: 30.0	Base: 117.5 Top: 116.8	2.99
<i>A. nolani</i>	Base: 30.0 Top: 4.6	Base: 116.8 Top: 114.4	1.06
<i>H. jacobi</i>	Base: 4.60 Top: 0.0	Base: 114.4 Top: 114.2	2.30

Table 1. Identified biozones in the Cau Core, with base and top depths, corresponding estimated ages from Malinverno et al., (2012), Coccioni (2019), Gradstein et al. (2020), and resulting sedimentation rates.



Estimated sedimentation rates vary according to the numerical ages applied, with the starkest difference for the planktic foraminifera. The main difference in the sedimentation rate tendency from the two provided foraminifera zone age sets is found in the *H. trocoidea* zone, with estimated sedimentation rates of 10.00 cm/kyr (using ages from Gradstein et al., 2020) and 4.17 cm/kyr (using ages from Malinverno et al., 2010). However, this biozone only spans 20.0 m of the 144.4 long series. The Cau Core is biostratigraphically complete, yielding a weighted average sedimentation rate of 5.42 cm/kyr (forams) and 2.45 cm/kyr (ammonites) for the early Aptian, whereas for the late Aptian, the sedimentation rates are 0.98 cm/kyr (forams) and 1.04 cm/kyr (ammonites). The sedimentation rate was generally higher in the early Aptian than in the late Aptian, due to a decrease in regional rifting activity. The variation of sedimentation rates with time and depth can be observed in Fig. 6.7.

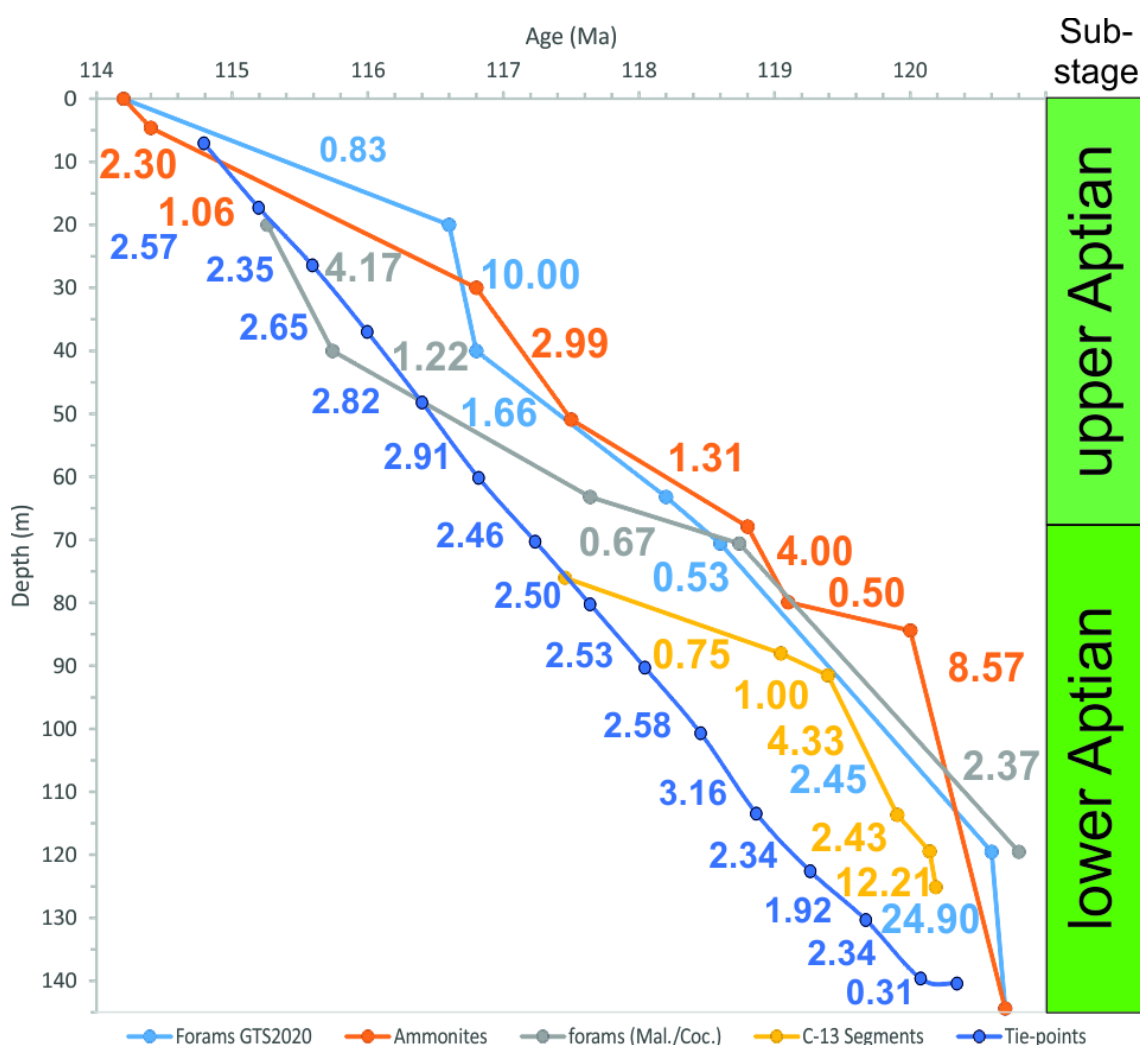


Figure 6.7. Range of ages (Ma) for the different biozones from the Cau Core, listed in Table 1. In light blue, planktic foraminifera from GTS2020 (Gradstein et al., 2020); in orange, ammonite zones from GTS2020; in grey, planktic foraminifera from Malinverno et al., 2010, and Coccioni et al., 2019; in yellow, $\delta^{13}\text{C}$ segments from Malinverno et al., 2010; in dark blue, tie-points for the cyclostratigraphic model of this study. Sedimentation rates are indicated in cm/kyr with the corresponding colours in the plot.

6.4.3 Stable isotopes and correlation

Stable carbon- and oxygen-isotope ratios of bulk carbonates have been analysed at a ~30 cm resolution throughout the four individual cores to generate a composite record. Figure 6.6 shows 755 values along the 144.4 m composite of the Cau Core. Stable isotopes were measured

with a ThermoScientific MAT253 Isotope Ratio Mass Spectrometer connected to a Kiel IV Carbonate Device at the Stable Isotope Laboratory of the Instituto de Geociencias (CSIC, Complutense University of Madrid). All the isotope data are reported in per mil (‰) versus Vienna-Pee Dee Belemnite (V-PDB) standard. For both systems (carbon and oxygen), the standard deviation was always between 0.00 and 0.03 ‰ and the average CO₃ sample weight was 95 µg.

6.4.4 Natural gamma ray logging and magnetic susceptibility

Gamma Ray levels were measured with a wire-line QL40 sensor probe at a 3 cm spacing and reported as API (American Petroleum Institute) radioactivity units (Fig. 6.8). Magnetic Susceptibility (MS) was measured on the cut core-surface using a cylindrical Bartington MS2E core logging sensor device, with the BartSoft program. Measurements were performed manually at a 5 cm spacing under atmospheric conditions at 25°C temperature. Each point was measured three times and averaged to reduce errors, and reported in IU (instrumental units), although the lower part of the data from 144.4 to 110 m has been removed due to measurement errors (Fig. 6.8).

6.4.5 Carbonate content

The Cau Core has been sampled with a standard spacing of 10 cm for powder samples, and 250 to 300 mg of each sample was reacted with 5.3 M hydro-chloric acid. Emitted carbon dioxide was measured with an automatic calcimeter (DREAM Électronique SAS, Pessac, France) to determine the carbonate content (Fig. 6.8).

6.4.6 Micro-X-ray fluorescence

To assess the elemental variations over the marl/limestone alternations that are present throughout the core, a boundary between these two lithologies was mapped using micro-XRF. The equipment used is a Bruker M4 Tornado X-ray energy dispersive microfluorescence spectrometer, and the elements analyzed were Ca, Si, Mg, Al, S, K, Ti, Fe, Sr, Zr, Mn and Rb.

6.4.7 Sedimentary cyclicity

To test for a potential orbital imprint on sedimentation at Cau, the high-resolution physical property and carbonate data were subjected to time series analyses. For this purpose, gamma ray, CO₃Ca concentrations and magnetic susceptibility data were linearly interpolated and detrended using the Astrochron software package (v0.9; Meyers, 2014) in R-Studio (RStudio Team, 2015). A wavelet transform using the PAST (PAleontological STatistics, v4.05; Hammer et al., 2001) software, and a harmonic analysis conducted in Astrochron, were used to investigate periodicities in the records. The program Redfit, designed to work with unevenly spaced series (v3.8e; Schulz and Mudelsee, 2002), was used to generate power spectra.

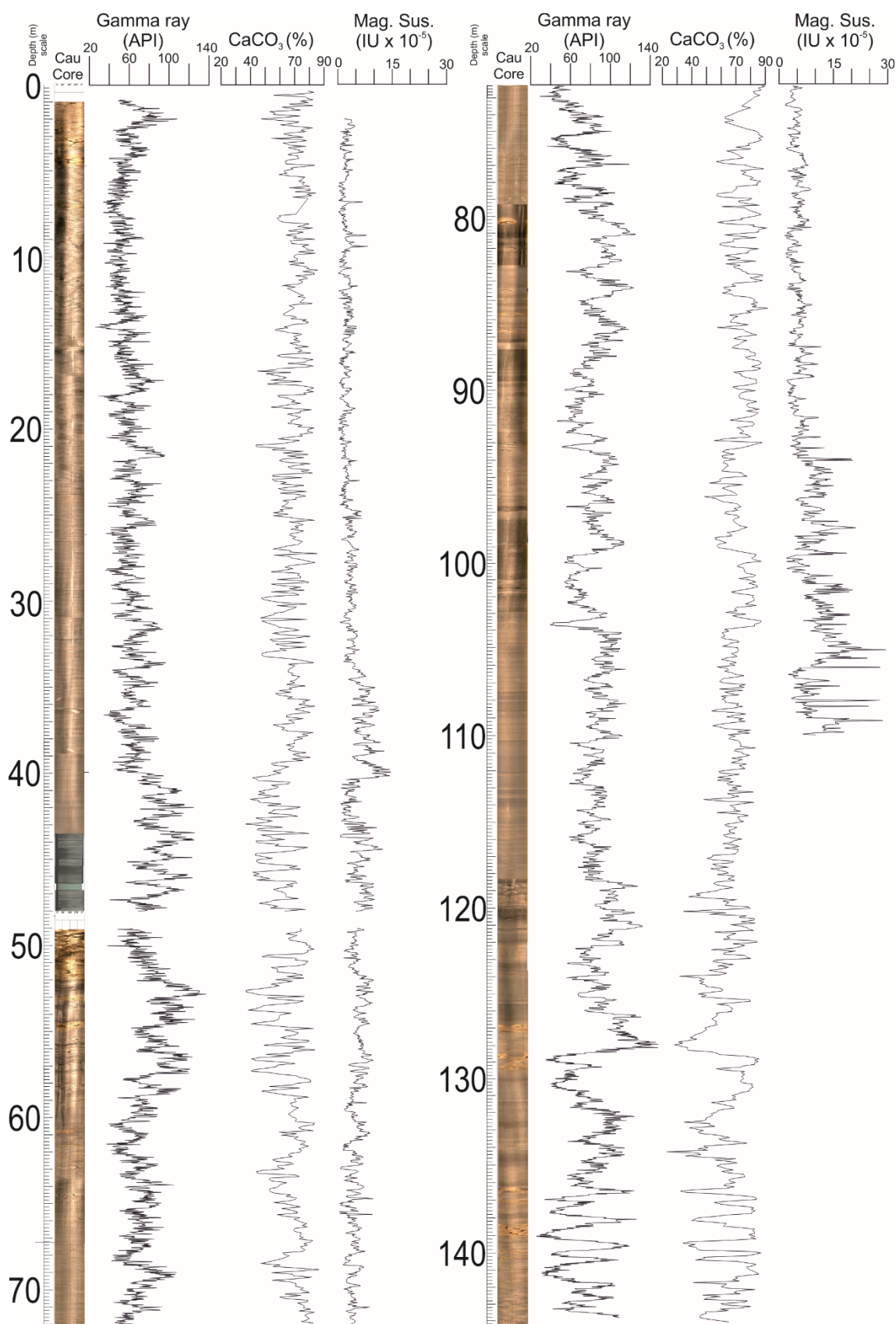


Figure 6.8. High-resolution data from the Cau Core. In the left part: depth scale in meters, flanked by the composite image from the Cau drill holes, the data of gamma ray (API units), CaCO₃ content (%) and magnetic susceptibility (IU, instrumental units). Reliable magnetic susceptibility information is not available below 110 m depth. From 43.3 to 49 m depth the scanned image of the core is used, as the drill hole pictures were disturbed due to reaching the phreatic zone.

6.5 Results

6.5.1 Cyclicity

There are two main lithologies in the Cau core, marlstones (hereafter “marls”) and limestones. Marls present higher API values in the gamma ray and higher magnetic susceptibility, while they are lower in CaCO_3 . Limestones present lower API values in gamma ray, and lower values in magnetic susceptibility, while they present higher content CaCO_3 contents (Fig. 6.9).

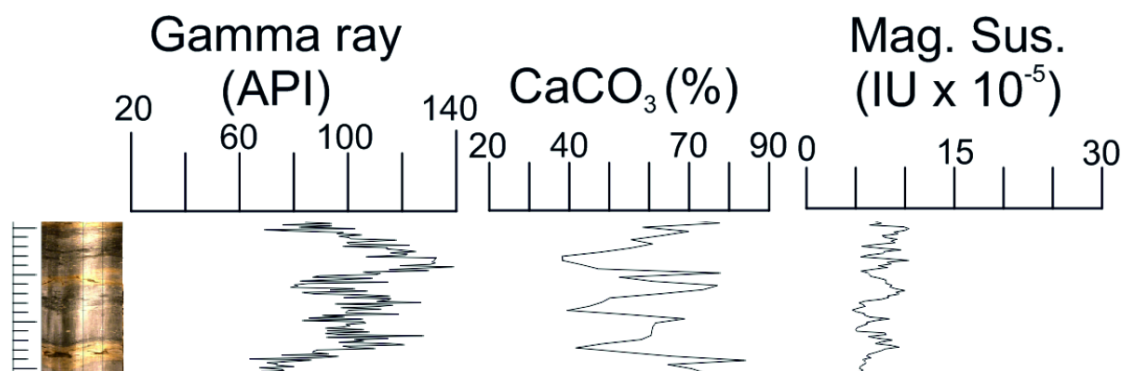


Figure 6.9. 3-m interval of core lithology, gamma ray, CaCO_3 and MS. Three darker bands display higher values of gamma ray, MS, and lower values of calcium carbonate. Clear lithologic intervals show the opposite behaviour in the physical and chemical data, showing minima in gamma ray, MS, and maxima in CaCO_3 .

In the gamma ray record, main periodicities are detected at 10.50 m and 5.88 m (above 99% confidence), at 2.00 m, 1.43-1.36 m and 79 cm (above 95% confidence), with additional periodicities above 90% confidence at 2.44 and 1.80 m, and 99 and 84 cm (Fig. 6.10A). For the CaCO_3 content record, the main periodicities above 99% are at 12.50 and 10.30 m, 47, and 37-34 cm, above 95% confidence at 5.56 m, 96-89-79 and 50 cm, with additional periodicities above 90% confidence, at 7.69, 1.96 and 1.03 m, and at 84 cm, and above 80% confidence at 2.70 m (Fig. 6.10B). Periodicities above 99% for the MS record are at 10.00 and 8.30 m, above 95% confidence at 4.35 and 3.85 m, and 42.50 cm, and above 80% confidence at 1.59 m, 1.12 m and 96 cm (Fig. 6.10C).

To investigate the behavior of dominant periodicities over the record, and to identify potential changes in sedimentation rates, the wavelet and evolutive spectra of the gamma ray, carbonate and MS records are displayed in the lower part of figure 6.10 and in figure 6.11, showing periodicities on different spatial scales. The continuous wavelet transform of the gamma ray record (Fig. 6.10A) shows a concentration of power around the main periodicity of 10 m, and power in a band around the 5 m periodicity. The wavelet transform of the carbonate record (Fig. 6.10B) shows power concentrated around periodicities of 10 and 5 m, whereas the higher frequencies show power around a 1-m period. The wavelet of the MS record (Fig. 6.10C) shows power at periodicities of 10 and 5 m, similar to the wavelets of the gamma ray and carbonate data. Gamma ray and CaCO_3 wavelets show minor power at 110 and 75 m depth, whereas the MS spectra lacks power between 60-70 m depth. Across the records, a shift in the duration of the dominant periodicity around 10 m is observed from approximately 9 m in the lowermost 40 m of the composite record to 12–15 m in the rest of the record. This shift is more clearly expressed in the evolutive harmonic analyses (EHA) of the different datasets. The EHA of gamma ray data (Fig. 6.11A) shows a shift in spectral power at 110 m depth from a 6.66 m periodicity (frequency of 0.15 cycles/m) to 12.5 m periodicity (0.08 cycles/m). Parallel to the decametric periodicity there is power at 5.88 m periodicity (0.17 cycles/m) until 40 m depth. The EHA of

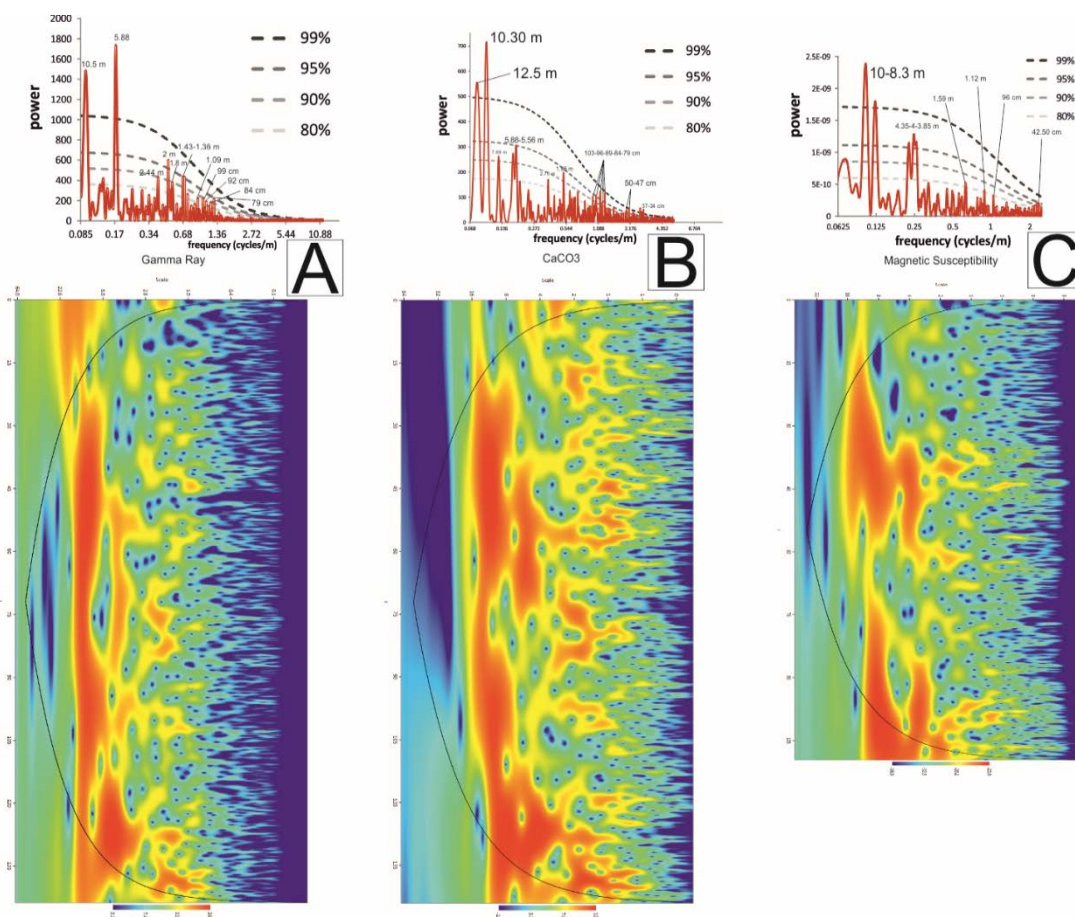


Figure 6.10. Redfit power spectra and continuous wavelet transform of the complete record of gamma ray (A), CaCO_3 content (B) and magnetic susceptibility (C). Spectral analyses have a configuration of: OFAC = 6, HIFAC = 1, $n50 = 1$, $lwin = 1$, $Nsim = 1,000$; and a Welch window. Black to grey dashed lines indicate the χ^2 confidence levels compared to red noise. Continuous wavelet analyses were run using the Past software based on the Lomb-Scargle Fourier transform using the Morlet function as the mother wavelet with 0 lag.

CaCO_3 (Fig. 6.11B) shows main spectral power at the 11.76-10 m periodicities (0.085-0.1 cycles/m), and some spectral power at a periodicity of 5.88 m (0.17 cycles/m), and a decrease in overall power at a depth of 90 m. In the EHA of MS (Fig. 6.11C), a periodicity of 9 m (0.11 cycles/m), seems to transition to 10-m periodicity (0.1 cycles/m) from 80 m depth upwards, and then to a 12.5-m periodicity (0.08 cycles/m), which could indicate a progressive increase in the sedimentation rate. A parallel transition is observed in a band centred on a 3.3-m periodicity (0.3 cycles/m) to a band centred on a 4.1 m periodicity (0.24 cycles/m), supporting the idea of an increase in the sedimentation rate between 75-70 m depth, spanning the lower-upper Aptian transition, although such a change in sedimentation rate is not suggested by biostratigraphy.

The gamma ray and CaCO_3 records were cut to produce two partial records (Fig. 6.12), at 75 m, where they show less power in the wavelets (Figs. 6.10A, 6.10B), and MS was cut at 65 m for the same reason (Fig. 6.10C). The lower partial records of CaCO_3 , gamma ray and MS show the longest periodicity at 10, 8.3 and 9 m, respectively (Figs. 6.12B, 6.12D, 6.12F). The rest of main periodicities of interest in the lower partial record of the gamma ray (75-144.4 m; Fig. 6.12D) at 5.9, 1.8, 1.1 m and 82 cm, are different from the same interval in the carbonate record (Fig. 6.12B) at 7.7, 5, 2.7, 1.7 m, 88, 54, 50 and 37 cm. The low frequencies in the carbonate record are longer than in the gamma ray, being the main difference that CaCO_3 presents more power in the high frequencies. The MS lower partial interval (65-110 m; Fig. 6.12F) presents a relatively

clean spectrum with the main periodicity at 9 m, and smaller periodicities of 77, 69, 61 and 45 cm.

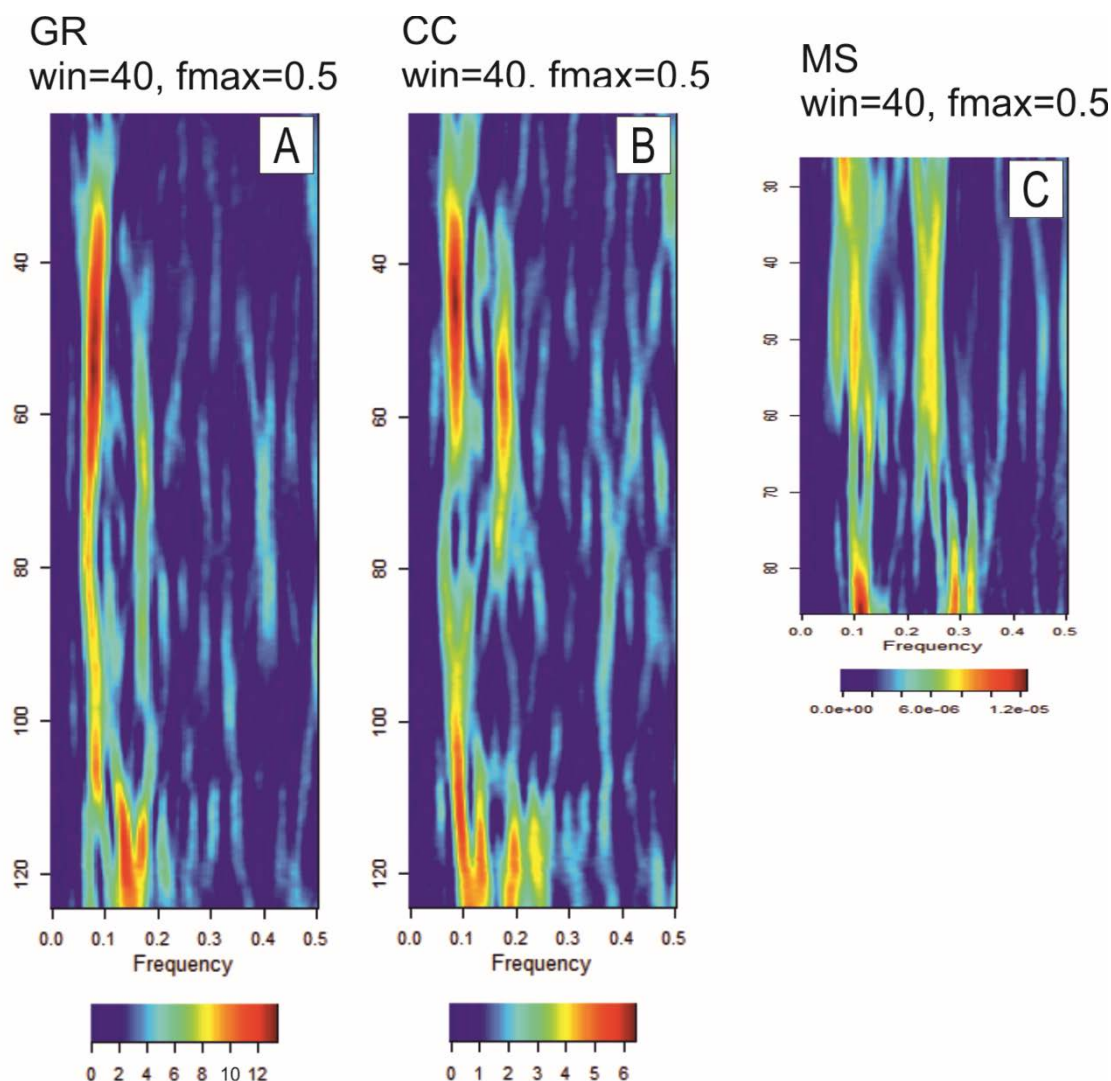


Figure 6.11. Evolutive harmonic analyses with a multitaper method time-bandwidth product of 2, padded with 10,000 zeros, $f_{\min} = 0$ and $f_{\max} = 0.5$. A. Gamma ray, step size = 0.014 m, 40-m width windows. B. CaCO_3 content, step size = 0.045 m, 40-m width windows. C. Magnetic susceptibility, step size = 0.019 m, 40-m width windows.

The upper interval of the CaCO_3 record (75-0 m; Fig. 6.12A) also presents a clean spectrum, with main periodicities above 99% confidence at 12.5 m, 96, 79, 40, 36 and 32 cm. However, in the same interval, the gamma ray (Fig. 6.12C) displays a lack of power, with only two periodicities above 99% confidence, at 95 and 37 cm. Redfit analysis of MS over the upper interval (0-65 m; Fig. 6.12E) exhibits a clean spectrum, with main periodicities above 99% confidence at 4 m, 51 and 44 cm. The hierarchy of cycles, with short alternations at a scale of 32 to 54 cm, and longer periodicities of about 2 m, may correspond to the periodicities of precession and short eccentricity. The 9-m cycles, varying between 12.5-10 m and 8.30-7.69 m may represent the 405-kyr component of long eccentricity. The 10, 9, 8.30 and 7.69 m periodicities correspond to the lower Aptian, yielding sedimentation rates of 2.5-1.9 cm/kyr, that are more in agreement with calculated sedimentation rates from ammonites (2.45 cm/kyr) than from forams (5.42 cm/kyr). The 12.5 m periodicity occurs in the upper Aptian, yielding a higher sedimentation rate of 3.1 cm/kyr. That differs more from calculated sedimentation rates from biostratigraphy of 0.98 cm/kyr (forams) and 1.04 cm/kyr (ammonites). Applying the ammonites sedimentation

rates results in durations of 408 to 314 kyr for the 7.7-10 m periodicity, and a duration of 1202 kyr for the 12.5 m periodicity.

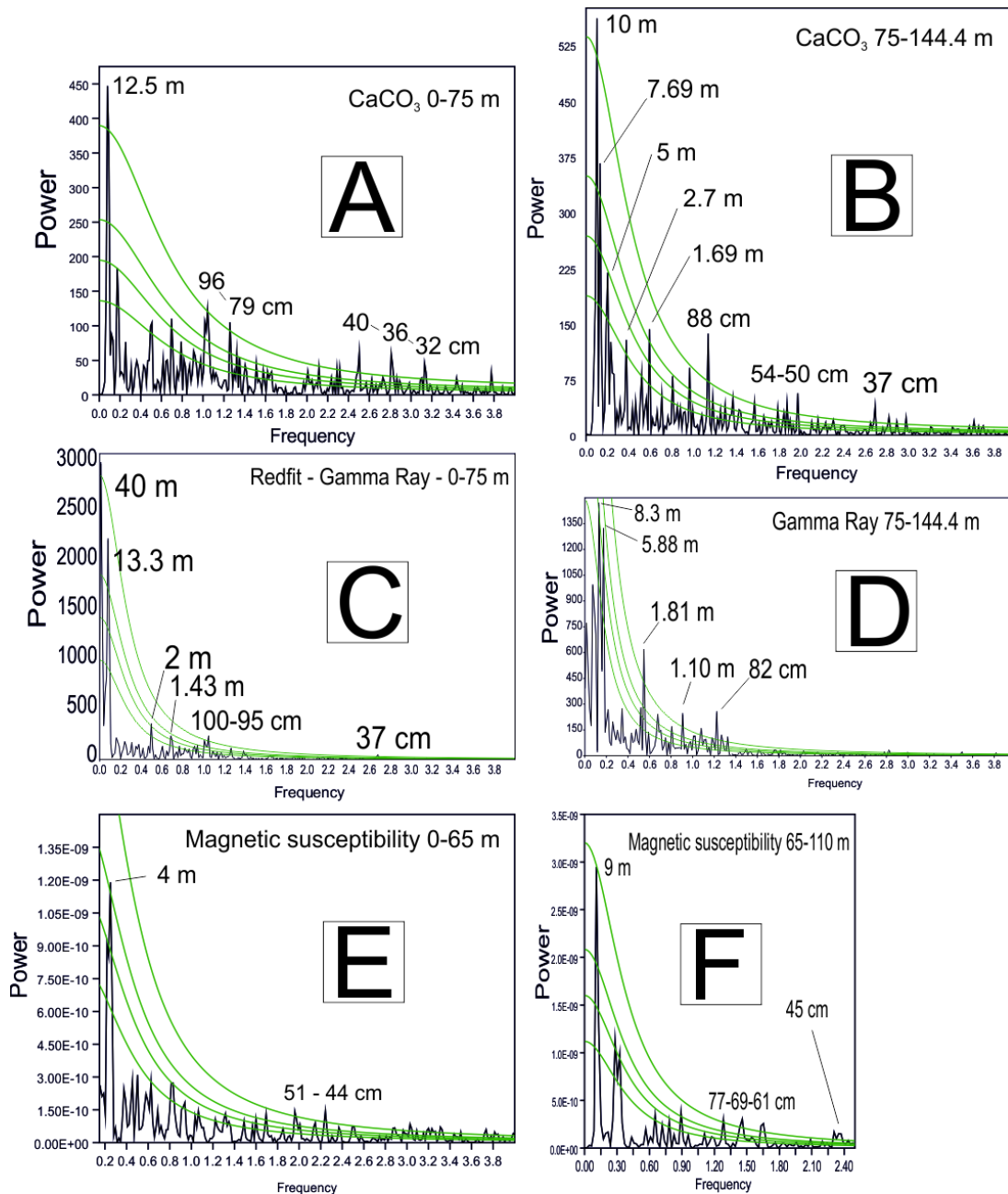


Figure 6.12. Left panels (A, C, E) show red power spectra of gamma ray, CaCO_3 (0-75 m) and magnetic susceptibility (0-65 m) partial records of the upper part of the Cau core. Right panels (B, D, F) show red power spectra of gamma ray, CaCO_3 (75-144.4 m) and magnetic susceptibility (65-110 m) partial records of the lower part of the Cau core. Window used is Welch type, with an oversample of 1 and using 1 segment.

6.5.2 Sedimentary response

The Cau Core presents an alternation of light and dark colored bands or levels, usually on a decimeter scale. Marls levels are darker in colour, opposite to limestone calcareous levels that have lighter tones. A close up of a limestone-marl transition is shown in Fig. 6.13, which displays a portion of the core and a micro X-ray fluorescence ($\mu\text{-XRF}$) mapping image (generated using a

Bruker M4 Tornado spectrometer). The limestone is enriched in Ca, whereas the marl is enriched in other elements such as Al, Si, Ti, S, K, Fe, Sr and Zr.

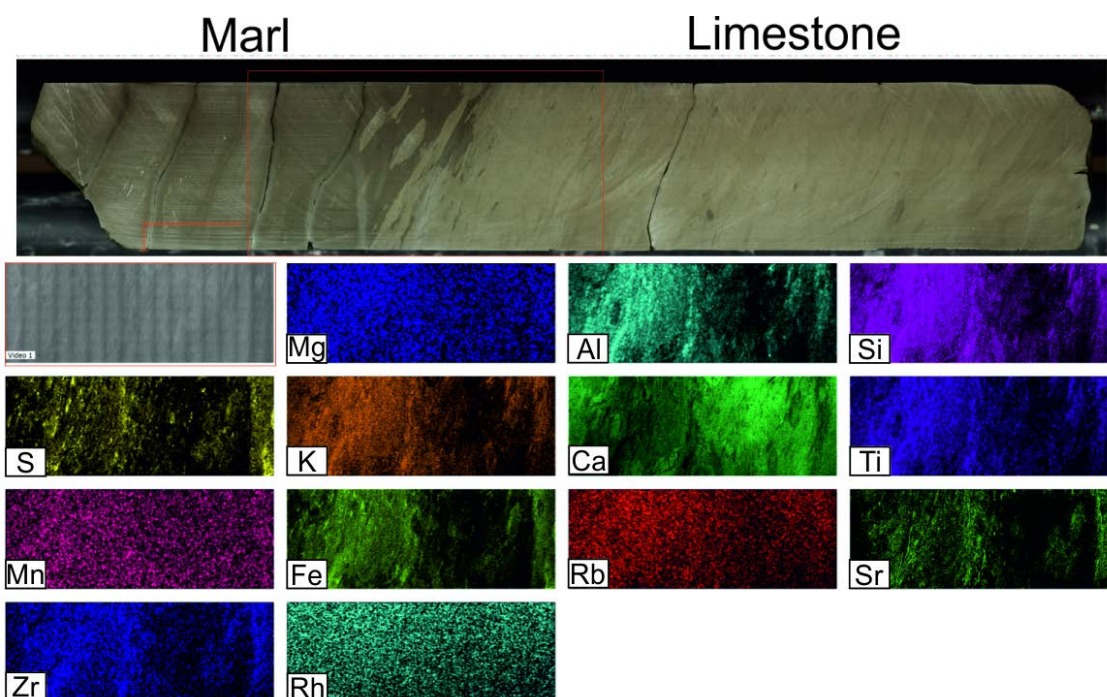


Figure 6.13. Photography of the core in which a marl/limestone transition can be seen. Micro X-ray fluorescence (μ -XRF) mapping images of this type of transition is displayed below the lithologic photography, from left to right, elements are: upper row - Mg, Al, Si; mid-upper row - S, K, Ca, Ti; mid-lower row - Mn, Fe, Rb, Sr; lower row - Zr, Rh. Elements that show an enrichment in the left part (marl) and deficiency in the right part (limestone) are Al, Si, S, K, Ti, Fe, Sr and Zr. The contrast in S and Sr are less marked. Only Ca shows the opposite heterogeneity. Mg, Rb and Mn show a diffuse difference. Rh is the target X-ray tube.

6.5.3 Astrochronology

The record was isolated from 70 to 120 m depth as this interval shows the clearest cyclicity, and displays the dark facies associated with OAE 1a. A Redfit analysis was conducted on this interval to investigate the present periodicities (Fig. 6.14). The two longest periodicities above 95% confidence are at 10 m and 2-1.8 m, respectively. Periodicities of 1.4 and 1.1 m may result from an interference of the 2-1.8 periodicity with the one at 83-78 cm (above 99% confidence). The smallest periodicity above 99% confidence is at 36 cm. Collectively, the ratios of periodicities of 2-1.8 m : 83-78 cm : 36 cm is 5.3:2.2:1, correspond to the hierarchy of the frequencies of the orbital parameters of short eccentricity, obliquity and precession, respectively. Evolutive harmonic analysis over the complete gamma ray record, using a window of 20 m (Fig. 6.15), displays an undulating line of spectral power from 70 m depth to the base, at a frequency of 0.5-0.55 (2-1.8 m), suggesting a dominant influence of short eccentricity forcing. Bandpass filters were applied to the 70-120 m interval (Fig. 6.16) using a Gaussian window, at a frequency of 0.1 ± 0.03 (bandwidth of 1/3 of the target), and at frequency of 0.5 ± 0.17 (bandwidth of 1/3 of the target), using AnalySeries.

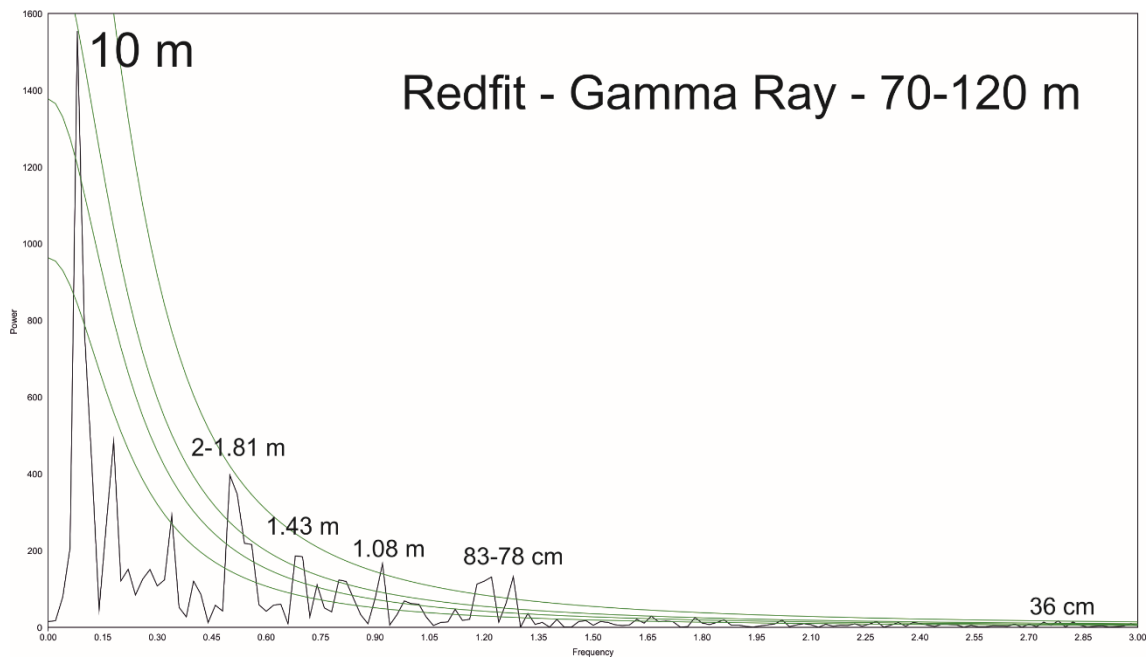


Figure 6.14. Red power spectra of the gamma ray record between 70 and 120 m depth.

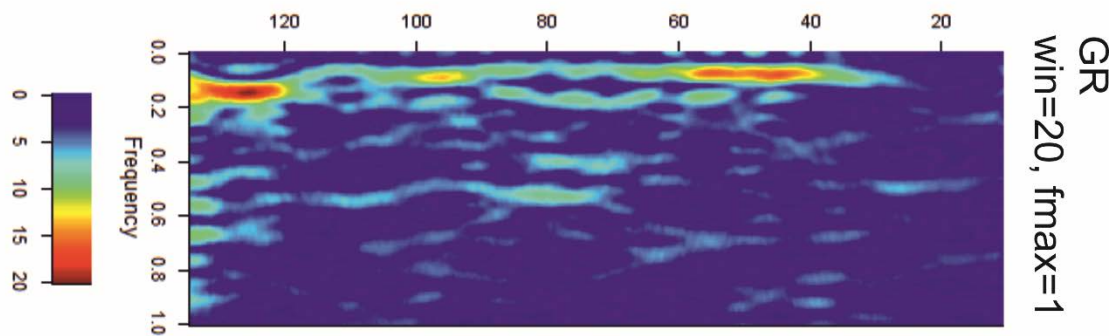


Figure 6.15. Evolutive harmonic analysis of gamma ray record, with a window of 20 m. In the middle of the graphic, higher power can be observed at frequency of 0.5-0.55.

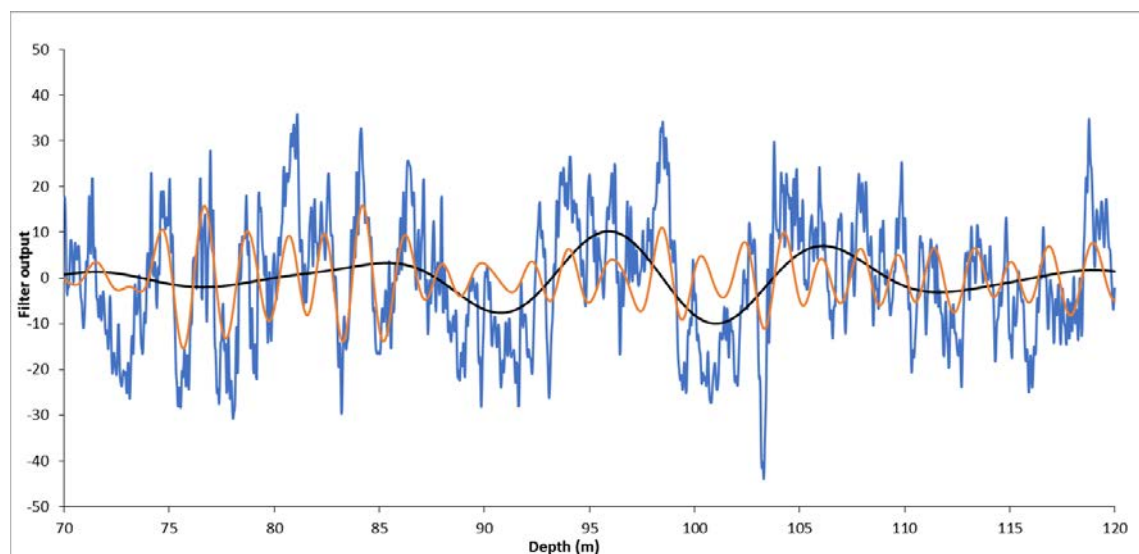


Figure 6.16. Band-pass filter of the gamma ray data between 70 and 120 m depth, at frequencies of 0.1 and 0.5, with a bandwidth of 1/3 of the target frequency, using a Gaussian window in the AnalySeries software.

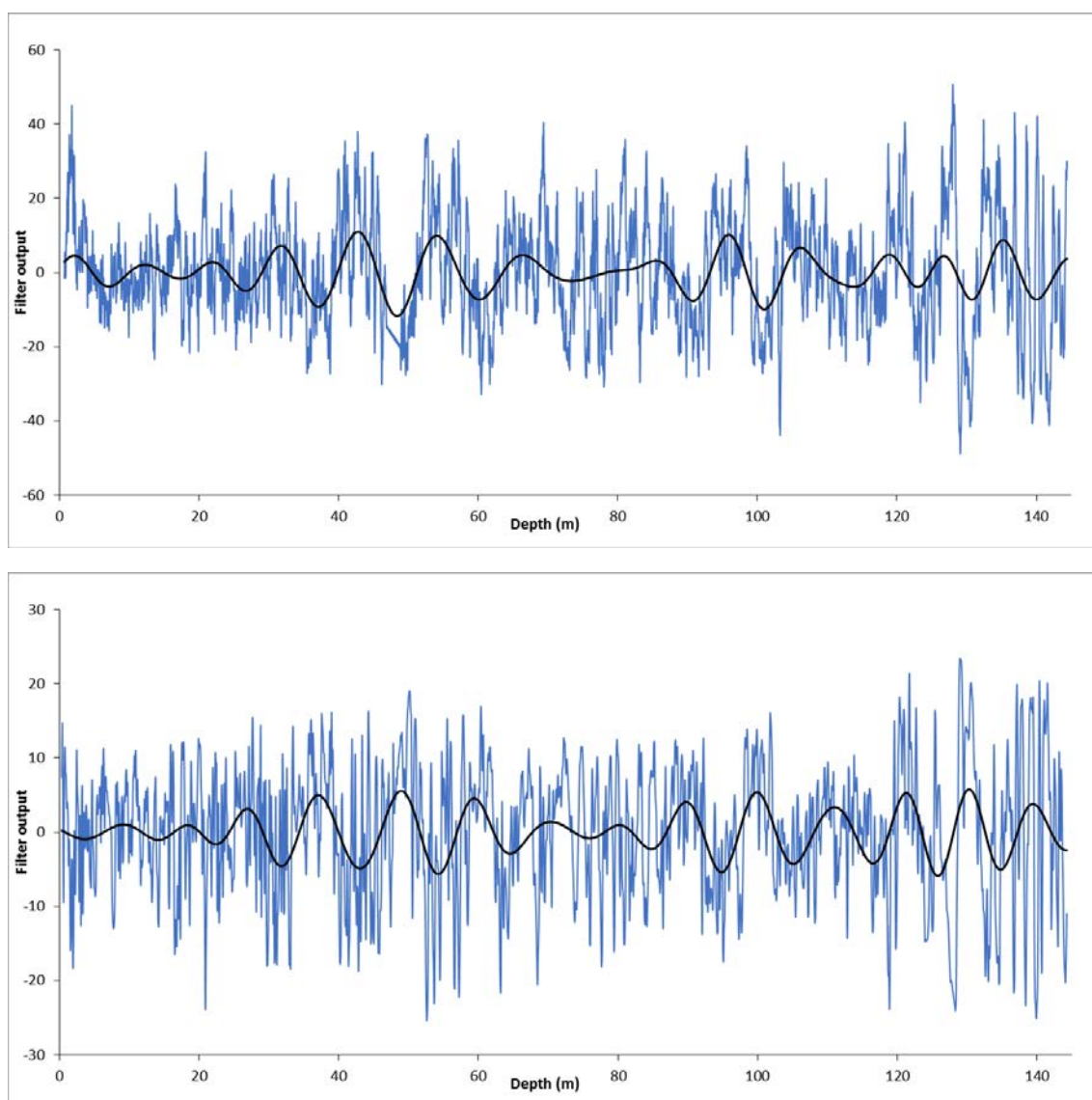


Figure 6.17. Gamma ray (upper panel) and CaCO_3 (lower panel) data filtered to a frequency of 0.1, with a bandwidth of $1/3$ of the target frequency, using a Gaussian window in the *AnalySeries* software.

6.6 Discussion

The gamma ray and magnetic susceptibility records mirror the CaCO_3 data, likely reflecting variations in the terrigenous input of clay leading to the deposition of marls, and in the supply of carbonate by marine productivity leading to the formation of limestones.

The marls present increased concentrations in detrital elements Al, Si and Fe, while limestones present higher content of Ca. Increased Al, Si and Fe in marls are likely due to abundance of kaolinite, smectite and illite clay minerals, whereas the higher content of Ca in limestones reflects the higher abundance of calcium carbonate. The driver of the observed sedimentary cyclicity may be variations in the amount of run-off and weathering influencing the amount of clay input and carbonate productivity. Climate variations forced by cyclic changes in the insolation pattern may have resulted in these alternations of limestones and marl. This may be driven by changes in seasonality, with a high amplitude of precession causing increased seasonality and stronger monsoon-like precipitation and increased run-off and clay input (Ruddiman, 2014). The higher sedimentation rate in the lower Aptian ($\sim 4\text{cm/kyr}$) compared to

the upper Aptian (~1 cm/kyr) indicates more presence of siliciclastics in the lower Aptian, and more presence of carbonate in the upper Aptian.

On a ~10 m scale, intervals with a strong contrast between limestones and marls alternate with intervals characterized by a less marked contrast. Intervals of strong lithologic contrast likely correspond to 405 kyr eccentricity maxima with a higher amplitude of the short eccentricity cycles (100 kyr) and the precessional cycles with an average duration of 18.395 and 22.16 kyr in the Aptian (Berger et al., 1992). Contrastingly, intervals with less contrast likely represent long eccentricity (405 kyr) minima, in which seasonal extremes did not occur.

6.6.1 Phase-relationship

To establish an age model based on cyclostratigraphy, the phase relationship between the 405-kyr periodicity of eccentricity-modulated precession and the variability in the data records must be resolved.

At 22.5° N, the estimated palaeogeographic position of Cau (Fig. 6.18A), the current seasonal difference in insolation is 250 W/m² (Fig. 6.18B), mostly driven by eccentricity-modulated precession. The Cau core materials encompass multiple periods of different orbital variations, but eccentricity-modulated precession exerts a major control on insolation variation, from a seasonal contrast of 290 W/m² (Fig. 6.18C) to 395 W/m² (Fig. 6.18D), a difference of more than 100 W/m². At tropical latitudes, the variability of the obliquity does not affect the absolute values greatly (Figs. 14D and 14E, 395 W/m²). Variations in precession mostly affect the time pattern of the distribution of insolation, but when eccentricity and obliquity are at maximum values and the precession is at 0° (Fig. 6.18F), the seasonal contrast reaches 407 W/m². That value represents the orbital configuration that produces the maximum seasonal contrast of received insolation, which ultimately exert a major control on climate variations. In this way, the alternation of marls and limestones is expected to be more marked during long eccentricity (405-kyr) maxima, that correspond to periods of maximum amplitude of precession and short eccentricity (100-kyr periodicity).

During overall minima in CaCO₃ and maxima in Gamma Ray and MS, the records present higher variability. In Fig. 6.17 (upper panel), maxima of the 10 m filter presents higher amplitude variability of the data, in comparison with minima of this periodicity. This high variability is the sedimentary response caused by large amplitude of the precessional forcing during eccentricity maxima. Dark bands can be observed when minima in CaCO₃ and maxima in Gamma Ray and MS (Figs. 6.8, 6.19), indicating a major contrast in the limestone/marl rhythmic pattern. During eccentricity maxima, increased variability of the hydrological cycle may be driven by precessional forcing, and minima in CaCO₃ would reflect increased carbonate dilution due to higher siliciclastic input. Based on the former sedimentary response to eccentricity-modulated precession, minima in this record that occur near minima in the band-pass filters are assigned to the ages of minima in the 405-kyr component of eccentricity from the La2010b solution (Laskar et al., 2011).

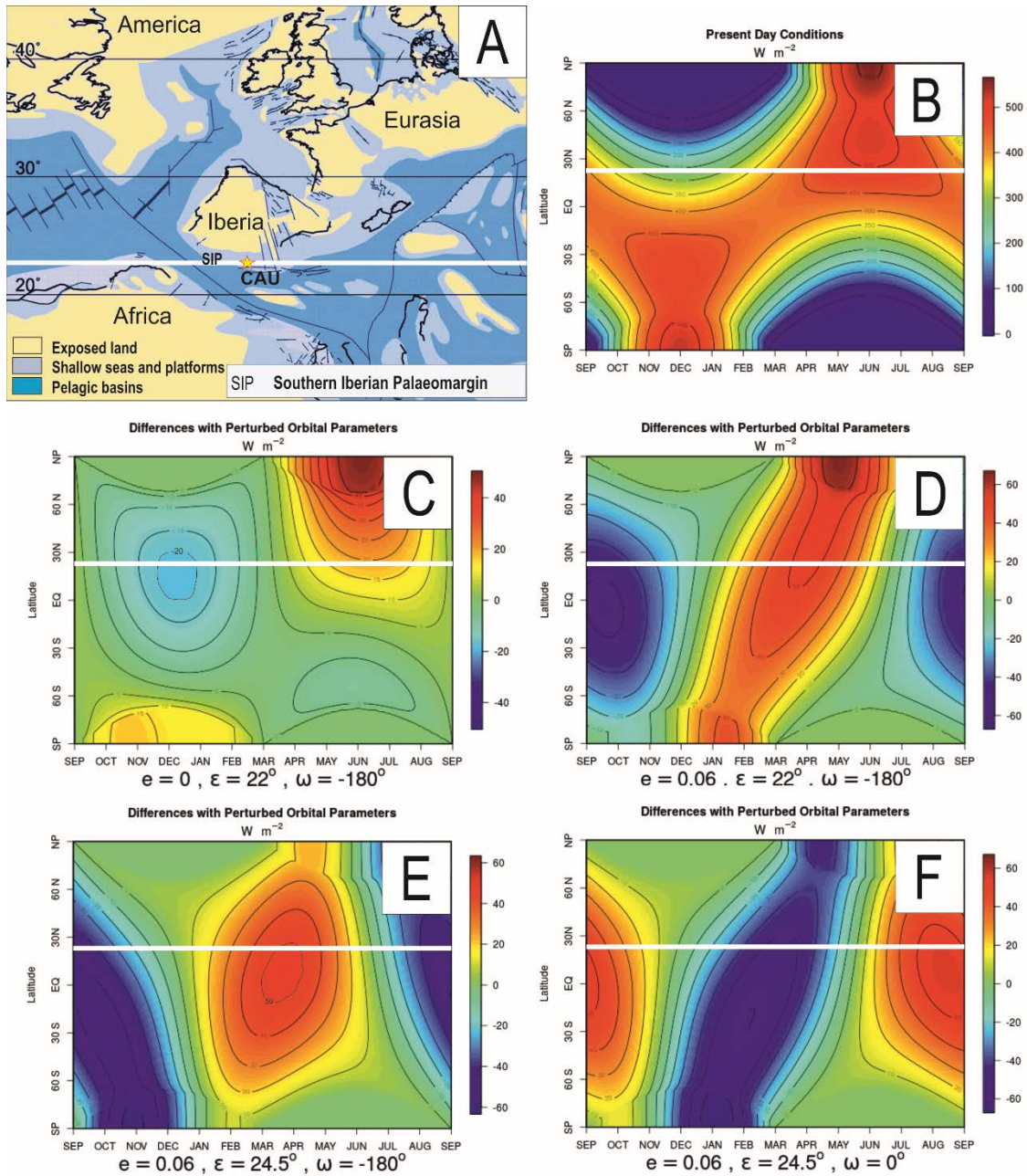


Figure 6.18. A. Palaeogeography of the Iberian Plate during the Aptian (simplified from Masse et al., 1993). B. Global seasonal distribution of insolation (W m^{-2}) at present day orbital configuration. At 20°N , the difference maxima is 250 W m^{-2} (500 W m^{-2} at summer solstice – 250 W m^{-2} at winter solstice). C. Difference with eccentricity and obliquity minima. At 20°N , the winter and summer solstices have a difference of -20 W m^{-2} and $+20 \text{ W m}^{-2}$ respectively, so the seasonal difference is 290 W m^{-2} . D. Difference with eccentricity maxima and obliquity minima. At 20°N , the winter and summer solstices have a difference of -45 W m^{-2} and $+50 \text{ W m}^{-2}$ respectively, so the seasonal difference is 395 W m^{-2} . E. Difference with eccentricity and obliquity maxima. At 20°N , the winter and summer solstices have a difference of -45 W m^{-2} and $+50 \text{ W m}^{-2}$, so the seasonal difference is 395 W m^{-2} . F. Difference with eccentricity and obliquity maxima, and precession of 0° . At 20°N , the winter and summer solstices have a difference of -52 W m^{-2} and $+55 \text{ W m}^{-2}$, so the seasonal difference is 407 W m^{-2} . A-F. The white line is the latitude of Cau during the Aptian at 22.5°N , e : eccentricity, ξ : obliquity (degrees), ω : precession (degrees). Figures and data from <https://biocycle.atmos.colostate.edu/shiny/Milankovitch/>.

Peaks at 5.88-5.4 m in the redfits analyses of this study (Fig. 6.12) could be the result of an interference between long- and short-components of eccentricity (Liebrand et al., 2017) and might reflect peaks and troughs of the long eccentricity periodicity that spans for 200-kyr. Short eccentricity is represented by periodicities of 2.7, 1.8 and 1.7 m (Figs. 6.12, 6.14), only present in the lower part of the record. For some reason, short eccentricity has a loss of power during

the upper Aptian record. Obliquity is represented by periodicities of 61, 69, 77, 79, 82, 88, 95, 96 cm and 1.1 m (Fig. 6.12). Precession is represented by periodicities of 32, 36, 37, 40, 44, 45, 50, 51 and 54 cm (Fig. 6.12).

From the base of the core to 136.5 m depth, the highest amplitude observed in the gamma ray and carbonate records is shown by cycles of 0.61-1.1 m, interpreted as obliquity cycles (Fig. 6.19). This high amplitude suggests a strong influence of variations in the tilt of Earth's axis on climate. This obliquity dominance coincides with eccentricity maxima, associated with more variability in seasonality. From 136.5 to 128 m depth (Fig. 6.19), in the gamma ray record, the amplitude of the 0.61-1.1 m cycle, thought to reflect obliquity, attenuates and the variation is controlled by longer cycles interpreted as short eccentricity (1.7-2.7 m). Additionally, periodicities of 0.32-0.54 m are recognized in the carbonate record, from 136.5 to 132.5 m depth, which are interpreted as precession. The frequency of the obliquity cycles seems to be higher in the lower part of this portion of the core (base to 136.5 m), indicating a lower sedimentation rate, than in the upper part (136.5 to 128 m). Power spectra peaks at 88 and 82 cm in the partial redfits from CaCO_3 and gamma ray (75-144.4 m) support a constant obliquity whereas peaks at 1.69, 1.81 and 2.70 m shows more variability in the short eccentricity domain (Fig. 6.12). From 128 to 118.4 m (Fig. 6.19) the signal is dominated by obliquity-paced cycles and long-eccentricity. This part of the record corresponds to the onset of the OAE 1a, when variable sedimentation rates and increase in clastics from the continent through intensification of weathering may have transferred power from short to long eccentricity.

From 118.4 to 104 m (Fig. 6.19), precession cycles can be observed in the CaCO_3 record, as the partial redfit of CaCO_3 (75-144.4 m) shows spectral peaks at 54, 50 and 37 cm (Fig. 6.12). The gamma ray record shows highest amplitude in the obliquity cycles. The development of the OAE 1a led to the deposition of dark marls. The reduction of limestone levels in this interval is associated with a reduced influence of long eccentricity pacing, likely due to a stable sedimentation rate.

From 104 to 79-80 m (Fig. 6.19) the gamma ray signal presents a low-frequency undulation of the signal preserving the 405-kyr long eccentricity cyclicity, with the 100-kyr short eccentricity cycles superimposed. Influence of obliquity paced cycles can be observed intermittently from 104 to 89 m within the first two 405-kyr cycles. The first 405-kyr long eccentricity cycle is 10 m thick (Fig. 6.12, spectral peak in CaCO_3 at 10 m) whereas the second and third long eccentricity cycles are thinner (7.5 and 7.7 m respectively) and indicate a decrease in the sedimentation rate, associated with the end of OAE 1a and a progressive decrease in TOC contents. The CaCO_3 record does not preserve the long eccentricity modulation, except in the uppermost part. The carbonate record shows a stronger influence of obliquity than of precession, likely as a consequence of the absence of carbonate levels.

From 79 to 53 m (Fig. 6.19) the gamma ray record shows 3 low-frequency long eccentricity cycles, and the higher frequencies show the highest amplitudes in both short eccentricity and obliquity cycles (96 and 79 cm peaks in gamma ray spectral power from 0-75 m; Fig. 6.12). The three periodicities are variable in thickness, as this part of the record includes the transition from the lower to the upper Aptian. CaCO_3 record shows precession cycles (Fig. 6.12, peaks at 40-30-32 cm on the 0-75 m power spectra) likely due to recurrence of limestone beds, with an increased amplitude from meter 71, probably due to a change in the sedimentation coincident with the onset of the *G. ferreolensis* zone. The decrease in the carbonate content and increase in clay can be continued up to meter 40, as this interval is linked to a relatively high TOC content and associated with the low sedimentation rate of the *algerianus* zone.

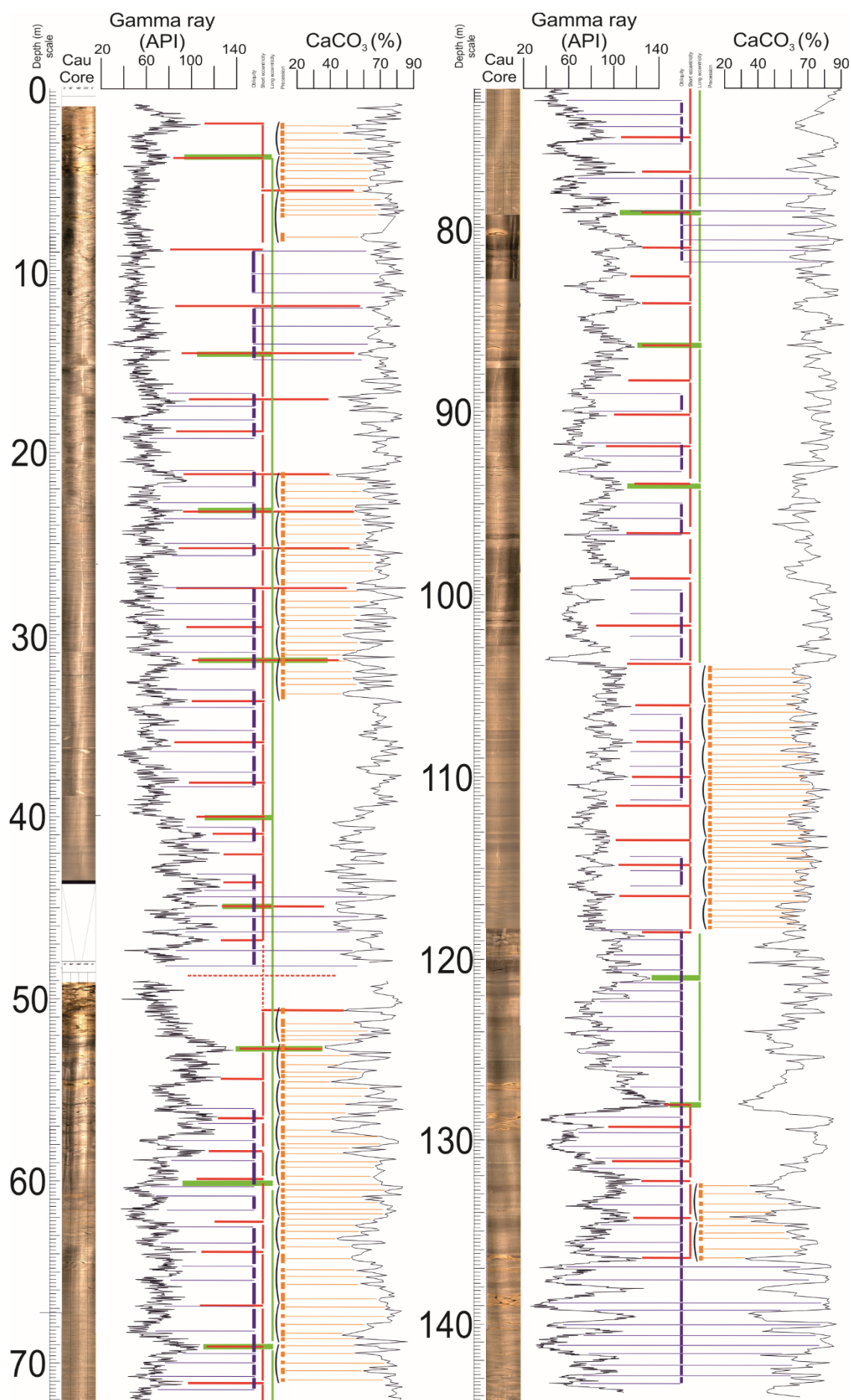


Figure 6.19 (up). Composite image of the *Cau* core flanked with estimated orbital cycles recognized in the gamma ray and CaCO_3 records. Estimated orbital periodicities are represented by lines in different colours: orange for precession; purple for obliquity; red for short-eccentricity, and green long-eccentricity.

From 53 to 40 m (Fig. 6.19) the gamma ray record shows two oscillations reflecting long eccentricity cycles and the highest amplitude is detected for obliquity and short eccentricity periodicities with variable frequencies, whereas in the CaCO_3 record, the highest amplitude is displayed by several obliquity oscillations. From 40 to 33.7 m (Fig. 6.19) the obliquity and short eccentricity periodicities have the highest amplitude and the CaCO_3 record presents higher values probably associated with a decrease in sedimentation rate. From 33.7 to 21 m (Fig. 6.19) the CaCO_3 record shows highest amplitude at a frequency that corresponds to precession cycles. An increase in the sedimentation rate (from 1.22-1.66 cm/kyr of the *algerianus* zone to the 4.77-10.00 cm/kyr of the *trocoidea* zone) could have enhanced the marl/limestone contrast. From 21 to 8.6 m (Fig. 6.19) the precession signal in the carbonate record fades out, and even obliquity and short eccentricity periods are sometimes difficult to distinguish in the gamma ray record. This could be the result of a drop in the sedimentation rate (from 10.00 cm/kyr of the *trocoidea* zone to 0.86 cm/kyr of the *rohri* zone). From 8.6 m to the top of the core (Fig. 6.14), the CaCO_3 record again displays the precession periodicity, indicating an increase in the sedimentation rate (from 1.06 cm/kyr of *nolani* zone to 2.30 cm/kyr of the *jacobi* zone).

6.6.2 Timescale

To calibrate the astronomical tuning for the complete record we have selected the Nannoconid Crisis (NC – 141.2 m depth, Fig. 6.6) biostratigraphic event anchored at 120.34 Ma, based on datings by Erba (1996, 2004) and Channell et al. (2000). Using Astrochron, a 405-kyr band-pass filter was applied to the La2010b solution, which is the best fit for geological data beyond 52 Ma (Westerhold et al., 2020). Then, ages of consecutive minima of the La2010b 405-kyr filter have been assigned to minima in the 10 m band-pass filter of gamma ray data as tie-points for the orbital age model (Table 2). Minima at 80.75 and 70.77 m depth have been selected using maxima in the 10 m band-pass filter of CaCO_3 (Fig. 6.17; lower panel), as in the gamma ray data the minima are not clear in that interval.

Using the control-points frame from Table 2, the dataset was tuned in Astrochron, using piecewise linear interpolation (Fig. 6.20). With this interpretation, the investigated core would span from 114.60 Ma to 121.36 Ma (6.76 Ma, Fig. 6.20), and would encompass fourteen long eccentricity 405-kyr cycles in total (Figs. 6.17, 6.20). In Fig. 6.21, a power spectral analysis using the redfit method shows the most powerful periodicities above 99% confidence at periods of 400 kyr, above 95% confidence at 105-kyr, and above 99% at a range of 90-kyr and at 40 kyr, that would be representing the long and short components of eccentricity, and obliquity, respectively. In the evolutive harmonic analysis (Fig. 6.22), the spectral power is concentrated in a band centered around a 0.4-Myr periodicity (frequency of 2.5 cycles/Myr – Fig. 6.22A), representing the long eccentricity periodicity. In Fig. 6.22B, two bands of power can be observed at frequencies of 9-12.5 cycles/Myr, within the range of short eccentricity. Figure 6.22C displays a stable band around 23-kyr (42.5 cycles/Myr) that falls in the range of precession.

Depth (m)	Age (Ma)	Sed. Rate (cm/kyr)
141.2	120.340	
140.38	120.080	0.31
131.05	119.677	2.34
123.29	119.272	1.92
114.1	118.88	2.34
101.29	118.474	3.16
90.84	118.069	2.58
80.75	117.67	2.53
70.77	117.271	2.50
60.61	116.858	2.46
48.58	116.445	2.91
37.34	116.047	2.82
26.75	115.648	2.65
17.55	115.257	2.35
7.29	114.858	2.57

Table 2. Tie-points for constructing the orbital age model and resulting linear sedimentation rates.

6.7 Conclusions – Preliminary results

Based on the high-resolution data from gamma ray, CaCO_3 and MS from the Cau Core, we propose a new astronomically calibrated chronology for the Aptian of this intra-shelf basin site (Tables 3.1 and 3.2; Fig. 6.23). The influence of obliquity and eccentricity-modulated precession is reflected in a hierarchy of cycles revealed by time series analysis of physical property and elemental data. However, this chronology has less confidence in the uppermost and lowermost part of the record, where the cyclicity is not clear, and an older tuning can not be excluded. Although the uncertainty on the dating of the base of the core causes difficulty for anchoring the record, the durations suggested by the cyclicity in the interval from 70 to 120 m can be considered robust.

In comparison with the estimates from Malinverno et al. (2010), the duration of the OAE 1a estimated in this study (1.4 Myr) is longer than calculated by the previous study (1.1 Myr). Our results for Segment Ap3 (C3) give a markedly longer duration of 272 kyr, in comparison to 47 kyr estimated by Malinverno et al. (2010). Duration of segment Ap4 (C4) is similar in both studies, with 240 and 239 kyr, respectively. Segment Ap5 (C5) is again longer in this study (768 kyrs) in comparison to 510 Kyrs from Malinverno et al. (2010). In contrast, segment Ap6 (C6) is longer in the study from 2010 (349 kyr), compared to the 142 kyr duration derived from this study. Finally, segment Ap7 (C7) is much longer in the previous study, with 1.59 Myr as compared to 477 kyr (this study) (Table 3.2 and Fig. 6.23). This study is the first to quantify the duration of the segments Ap8 to Ap13.

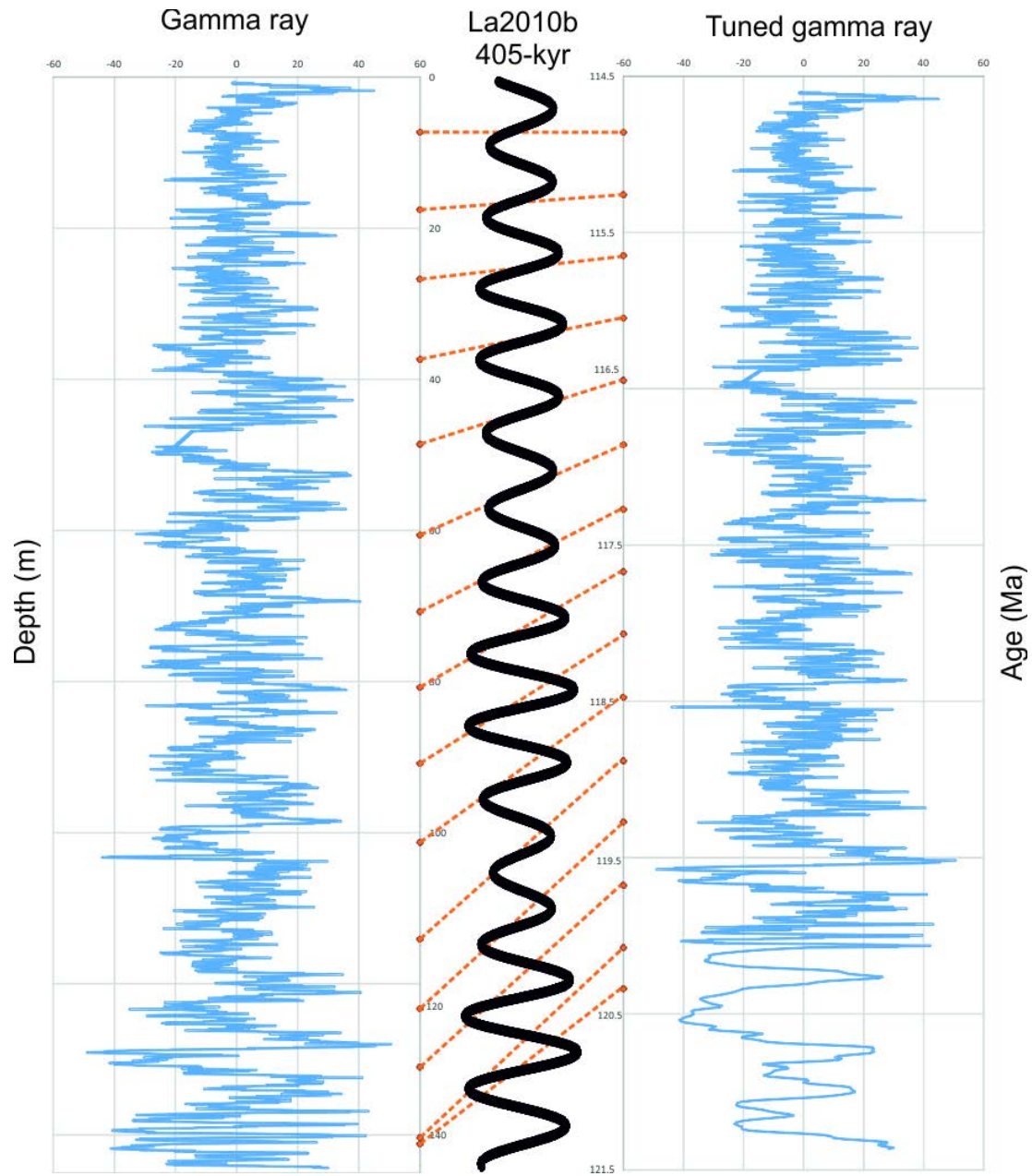


Figure 6.20. The gamma ray record in the depth domain (left panel, y-axis is depth in meters) and in time domain (right panel, y-axis is age in Ma). Orange dots indicate tie-points. 405-kyr filter of the La2010b eccentricity solution from Laskar et al. (2011) (central panel), applied in Astrochron, using a Gaussian window and a bandwidth of 1/3 of the target frequency (0.0025). In the time domain, the filter is centered at 405 kyr with bandwidth limits of 303-kyr and 588-kyr.

Figure 6.21 (below). Redfit spectral analysis, using a Welch window, showing the power spectrum of the tuned gamma ray record.

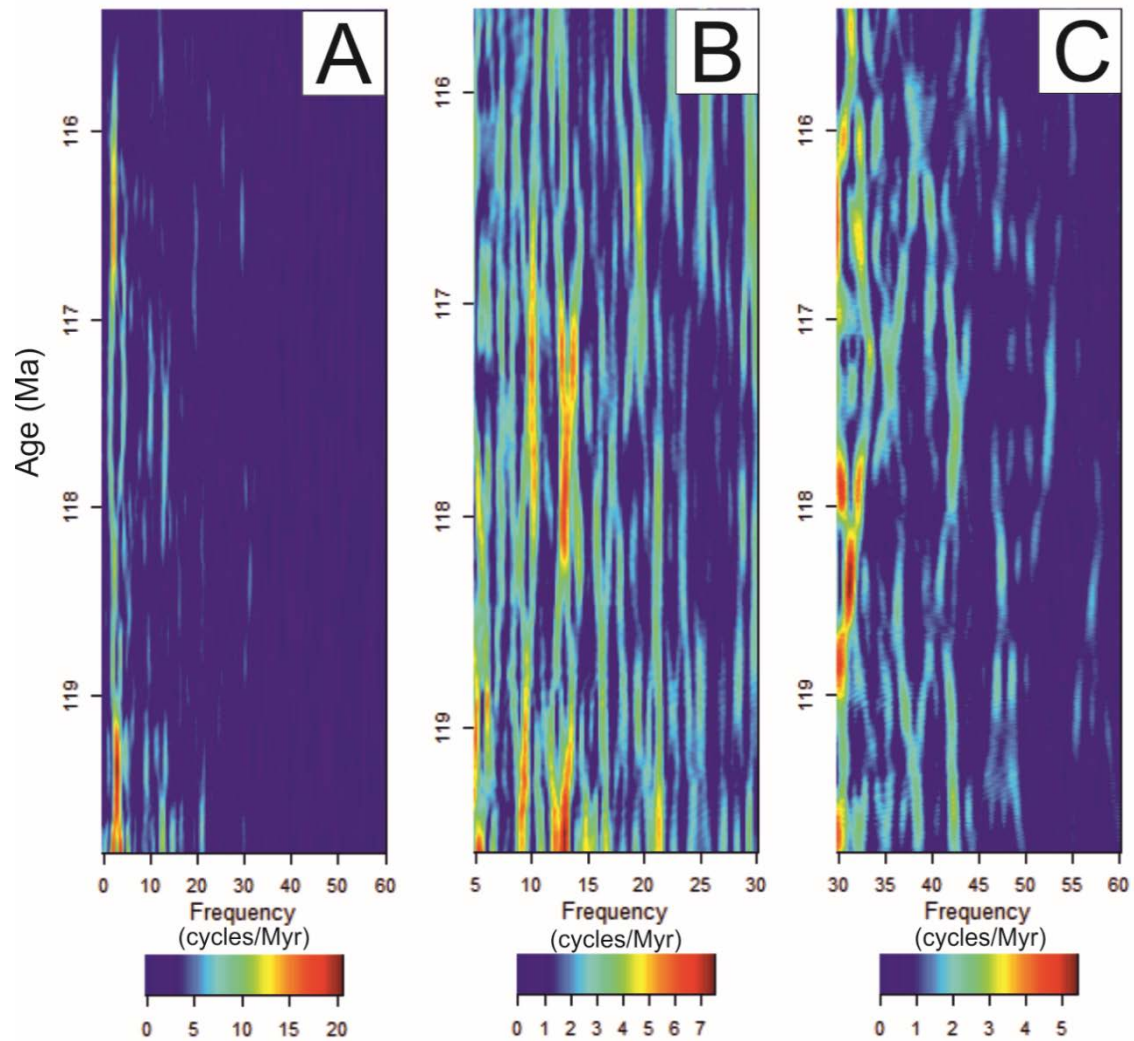
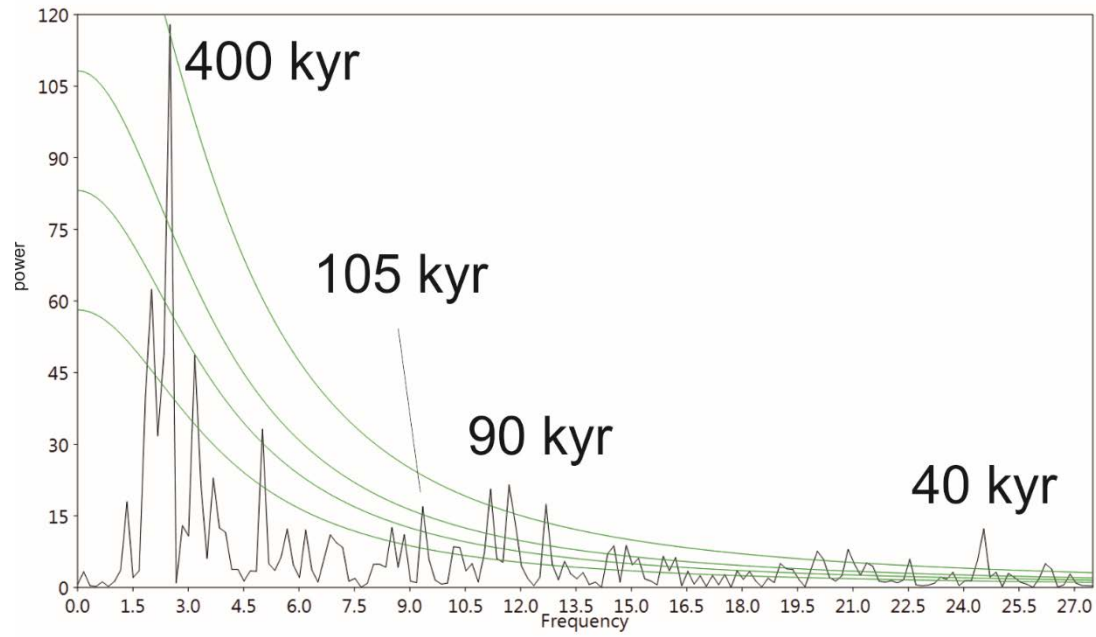


Figure 6.22. Evolutionary harmonic analysis of the tuned gamma ray record, on different frequency axes. The window used in A and C is 1, window used in B is 1.5.

Horizon	Depth (m)	Age (Ma)
NC - Nannoconid crisis	141.20	120.34
Ap2a-Onset CIE-Ap2b	133.70	119.79
Ap2-Ap3 - OAE 1a onset	125.40	119.38
Ap3-Ap4	119.50	119.11
Ap4-End CIE-Ap5	113.80	118.87
Ap5-Ap6	91.70	118.10
Ap6-Ap7 - OAE 1a end	88.10	117.96
Ap7-Ap8	76.10	117.48
Ap8-Ap9	68.70	117.19
Ap9-Ap10	63.00	116.96
Ap10-Ap11	52.30	116.57
Ap11-Ap12	40.40	116.16
Ap12-Ap13	16.10	115.20
Ap13-Ap14	7.60	114.87

Table 3.1. Estimated age for the most prominent stratigraphic horizons present in this study.

$\delta^{13}\text{C}$ Stage	Duration (kyr)		
	This study	Malinverno	
Ap2b	408.21		
Ap3	271.79	46.7 $\pm$ 13.7	C3
Ap4	239.85	239 $\pm$ 39	C4
CIE	919.84		
Ap5	768.16	510 $\pm$ 70	C5
Ap6	141.68	349 $\pm$ 47	C6
OAE 1a	1421.47	1110 $\pm$ 110	
Ap7	476.56	1590 $\pm$ 70	C7
Ap8	297.24		
Ap9	231.70		
Ap10	382.44		
Ap11	417.36		
Ap12	954.74		
Ap13	330.56		

Table 3.2. Estimated duration for the most prominent stratigraphic features present in this study and the duration of $\delta^{13}\text{C}$ events by Malinverno et al., (2010).

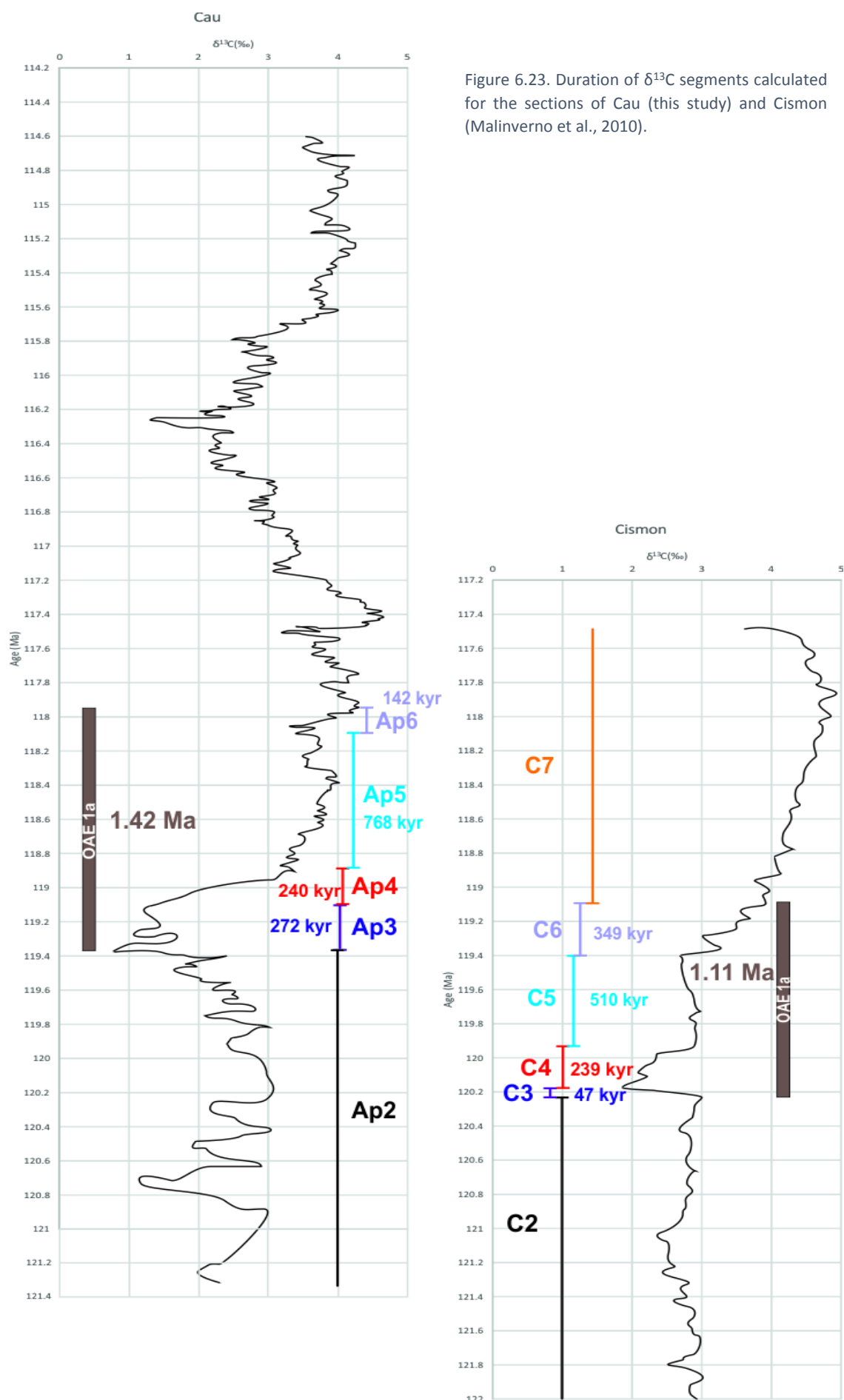
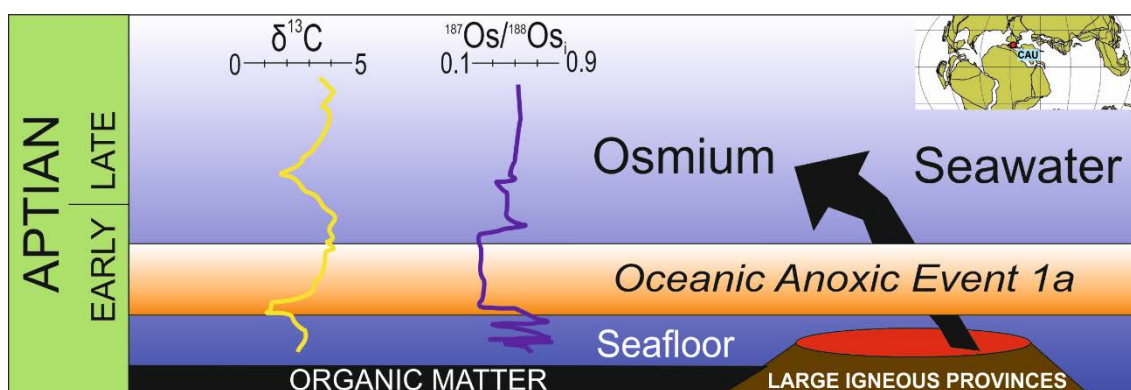
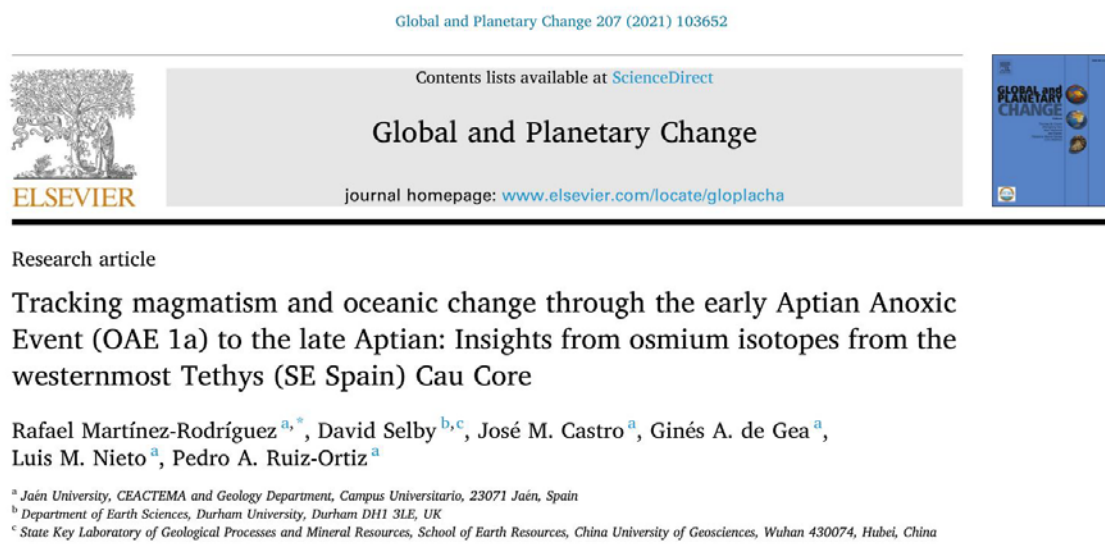


Figure 6.23. Duration of $\delta^{13}\text{C}$ segments calculated for the sections of Cau (this study) and Cismon (Malinverno et al., 2010).

7. Re-Os isotopes from the Cau core

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Abstract: Some of the major Carbon cycle perturbations of the Phanerozoic occurred during the Aptian, in relation to magmatism. The highest temperatures reconstructed for the Cretaceous Period correspond to the Oceanic Anoxic Event of the early Aptian (OAE 1a), an episode of accelerated global change. Here we present a chemostratigraphic study based on osmium isotopes integrated with high-resolution Carbon-Oxygen stable isotope data from the Cau Core (Western Tethys, SE Spain), including a 6.4 Ma record from the early to the late Aptian. This high-resolution study of the continuous and expanded Cau section permits a thorough understanding of the duration of the Aptian events, as well as an evaluation of the mechanisms triggering the abrupt changes of the global carbon and osmium cycles and their interdependence. Here we show that the Large Igneous Province (LIP) Aptian magmatism initiated 550–750 kyr prior to the OAE 1a, and persisted for 1.4 Myr after the event, influencing the composition of seawater for 2.8 Myr. We show a continuous Os isotope record encompassing the OAE 1a and the late Aptian for the first time, and demonstrate that the recovery from the exceptionally unradiogenic composition of seawater Os produced by the dominance of the Ontong Java Plateau volcanism, was slow. Our results demonstrate the different time duration of some events, and the asynchronous relationship between the carbon and osmium cycles.

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8. Conclusions

8.1 Summary of results

8.1.1 Chapter 3 – The Cau Core

The high-resolution $\delta^{13}\text{C}_{\text{carb}}$ record from the Cau core is proposed as a new global reference from a shelf setting for stratigraphic correlation of the lowermost Aptian to the mid-upper Aptian, including OAE 1a, due to its expanded character, the continuity of the record, and the robust preservation of geochemical and biostratigraphic signals.

The combination of C-isotope stratigraphy, core logging, lithostratigraphy and integrated biostratigraphy provides a very high stratigraphic resolution (0.5–11 kyr), which has permitted the recognition of previously defined C-isotope segments and the subdivision of some of these into subunits with potential for improved correlation to sections worldwide. Crucially, detailed correlation based primarily on $\delta^{13}\text{C}_{\text{carb}}$ records and calibrated using biostratigraphic markers demonstrates that the C-isotope record from Cau predominantly reflects a global signal and therefore provides a robust basis for further paleoenvironmental and paleobiotic analyses at high temporal resolution.

The C-isotope record of the onset of OAE 1a in the Cau core is characterized by a long-term decline in C-isotope values. The analysis at ultra-high resolution reveals a succession of marked negative C-isotope peaks. The major (-1.8 ‰) short term (< 10 kyr) shift in the C-isotope record marks the base of OAE 1a (base of C3/Ap3 segment), and the beginning of the deposition of organic-rich deposits. This ultra-high-resolution record is in agreement with observed patterns in pelagic sections, and provides new insights into the processes and rates of perturbations to the global carbon cycle.

The upper Aptian displays a major long-lasting negative-positive C-isotope excursion of global character.

8.1.2 Chapter 4 – Sierra Mariola

The study of four sections of the Llopis Fm distributed in the outcrops of Sierra Mariola allows the recognition of facies and association of facies of open platform, barrier and inner platform environments from the lower Aptian urgonian carbonate platform formed in the southern Iberian margin.

Eight parasequences are recognized in the urgonian platform of Sierra Mariola, describing a regressive sedimentary evolution for the two first parasequences, followed by a succession of six parasequences with a transgressive evolution.

The time interval of the sedimentation of the studied succession is considered to span ~0.8-1 Myr, encompassing approximately two long eccentricity orbital cycles, with each parasequence representing ~100-kyr short eccentricity cycles.

The $\delta^{13}\text{C}$ data from the Middle member of the Llopis Fm confirms that this unit records the Aptian Ap-2 C-isotope segment, that predates OAE 1a. The onset of OAE 1a is coeval to the Agres Bed (Upper Mb), which represents the local sedimentary expression of the onset of the OAE 1a which eventually led to the demise of the Llopis Fm carbonate platform with the deposition of the hemipelagic marls of the overlying Almadich Fm.

The discussion about the factors controlling the development and the demise of the Early Aptian carbonate platform points out to a complex interplay between regional extensional tectonics

(subsidence), climate, and environmental changes leading to different modes of carbonate production controlled by variations in the siliciclastics inputs, and relative sea-level changes. The utmost environmental change is considered closely linked and coeval with the global OAE 1a, a major perturbation that eventually led to the demise the carbonate platform, resulting in hemipelagic sedimentation.

8.1.3 Chapter 5 – Sierra de Bedmar-Jódar

The study of an outcrop from the early Aptian Llopis Fm shallow carbonate platform in the Sierra de Bedmar-Jódar, based on ten high-resolution stratigraphic sections and a detailed facies map has revealed the facies architecture of this sector of the platform.

The facies described are arranged in a succession of strata of highly variable thickness, locally with clinoforms with a mean E dip direction.

Up to seven lithofacies types have been differentiated, one with siliciclastics, five of carbonate facies ranging from grainstones and packstones to wakestones and mudstones. Two facies include macrofossils (stromatoporoids and rudists).

Lithofacies L1 to L6 are organized in two different types of elementary sequences that differ in the presence of stromatoporoids or rudists. They are interpreted as shallowing-upwards sequences, developed in a very shallow carbonate platform, with a lagoon limited to the shore by clastic/ooidal bars, and limited to the sea by stromatopod bioconstructions (bioherms and biostromes) or rudists.

Atop of these sequences some features reveal a shallowing of the bioconstructions, with probable emersion, overlain by coastal bars. This shallowing may be controlled by local tectonics.

Collectively, the 8 elementary sequences present a progradational character, with an advance of the platform towards the East.

The associations of facies define three types of elementary sequences, clearly depicted in the stratigraphic sections and in the facies map: (1) sandstones and calcarenites, deposited in shallow open marine proximal environments, (2) sandstones, calcarenites and stromatopod limestones, deposited on a semi-protected lagoon, and (3), sandstones, calcarenites and rudist facies, interpreted to represent an urgonian-type lagoon. These sequences are frequently capped by discontinuity surfaces, which might be related to a combination of sediment aggradation, and or relative sea-level drops, occasionally driven by tectonic tilting linked to the extensional regime of the rifting affecting the SICM.

The vertical succession of the platform studied has been divided into two progradational parasequences, which represent two phases:

- (1) installation of the shallow platform, with development of stromatoporoids;
- (2) development of an urgonian platform dominated by rudists.

Correlation with the coeval shallow carbonate platform in Mariola (Alicante), supported by biostratigraphy, reveals interesting common features in the sedimentary evolution in both sectors of the Prebetic platform. This indicates a regional scale episode of installation and development of a shallow carbonate platform controlled by optimal environmental conditions for carbonate production.

During the early Aptian, the Bedmar-Jódar platform was likely isolated or partially isolated from the rest of the Prebetic platform, with a different progradation movement towards the NE, whereas the general trend of the Prebetic platform presents progradation to the SE or S. The sedimentation was mainly controlled by extensional tectonics, favouring emersion pulses that tilted the platform block, producing a different orientation of the progradation. Occasional terrigenous inputs from the continent and the presence of *characeae* in the materials indicates that this isolated platform was, sometimes, very close to the continent.

8.1.4 Chapter 6 – Cyclicity of Cau

Based on the high-resolution data from gamma ray, CaCO_3 and MS from the Cau Core, we propose a new astronomically calibrated chronology for the Aptian of this intra-shelf basin site (Tables 3.1 and 3.2; Fig. 6.23). The influence of obliquity and eccentricity-modulated precession is reflected in a hierarchy of cycles revealed by time series analysis of physical property and elemental data. However, this chronology has less confidence in the uppermost and lowermost part of the record, where the cyclicity is not clear, and an older tuning can not be excluded. Although the uncertainty on the dating of the base of the core causes difficulty for anchoring the record, the durations suggested by the cyclicity in the interval from 70 to 120 m are considered robust.

In comparison with the estimates from Malinverno et al. (2010), the duration of the OAE 1a estimated in this study (1.4 Myr) is longer than calculated by the previous study (1.1 Myr). Our results for Segment Ap3 (C3) give a markedly longer duration of 272 kyr, in comparison to 47 kyr estimated by Malinverno et al. (2010). Duration of segment Ap4 (C4) is similar in both studies, with 240 and 239 kyr, respectively. Segment Ap5 (C5) is again longer in this study (768 kyrs) in comparison to 510 Kyrs from Malinverno et al. (2010). In contrast, segment Ap6 (C6) is longer in the study from 2010 (349 kyr), compared to the 142 kyr duration derived from this study. Finally, segment Ap7 (C7) is much longer in the previous study, with 1.59 Myr as compared to 477 kyr (this study) (Table 3.2 and Fig. 6.23). This study is the first to quantify the duration of the segments Ap8 to Ap13.

8.1.5 Chapter 7 - Cau Re-Os isotopes

The study presents the first direct evidence that volcanic activity continued beyond the OAE 1a during the late Aptian. Our new Os-isotope data from the Cau Core confirm an extended time frame for the volcanic input of unradiogenic Os during the Aptian, likely due to emplacement of LIP and their continued activity, influencing composition of seawater Os for ~2.8 Myr.

The Cau Os_i data provide strong evidence to more accurately establish a high-resolution record of magmatic episodes and pulses of accelerated hydrological cycle, and exhibits the climatic instability that occurred before (Ap2 segment) and during the onset of the OAE 1a (Ap3 segment). This study confirms the temporal relationship of LIP magmatism with the OAE 1a, demonstrating that the magmatism was active 550–750 kyr prior to the Selli Event, was sustained through the entire OAE, and ceased ~300 kyr after the end of the event. The maximum duration calculated from the Osi excursion linked to the main phase of the OJP is 1.6–1.75 Myr. Inference from the Osi data suggests a minimum and maximum duration of LIP magmatism of 2.8 and 3.6 Myr. The sequence of events recorded at Cau starts with a first volcanic pulse predating the OAE 1a, reflected in an abrupt negative shift in C-isotopes that may have been triggered by a pulse of methane emissions. This first event was followed by the main abrupt shift

in non-radiogenic Os_i , followed by deposition of marine organic-rich sediments, indicating an increase in productivity and reduction of oxygenation due to the immense volcanism via CO_2 input, temperature increase and activation of hydrological cycle, resulting in nutrient-rich waters. This record confirms the relation between the accumulation of organic matter, the development of anoxia/dysoxia and the productivity increase, with the initial pulses of volcanism that predate the main phase, as previously shown for other OAE 1a records (Tejada et al., 2009; Bottini et al., 2012). During the late Aptian, the carbon cycle underwent a slow-paced change reflected in the long-term isotope excursion of the $\delta^{13}C$ record, although the Os_i record remained relatively stable, showing only punctual changes associated to volcanic pulses. The expanded Aptian record at Cau highlights the different behaviour of the carbon cycle throughout the recorded time interval. In the early Aptian, the onset of the OAE 1a is associated with a rapid carbon negative isotope excursion produced in less than 25-kyr, which was followed by a strong change in the Os_i composition and perturbations recorded in multiple other proxies. In comparison, the negative carbon isotope excursion during the upper early Aptian-lower late Aptian transition, took place over a duration of ca. ~ 1 Myr, in which time, Os_i composition and other proxies remain stable. The delay between volcanic CO_2 outgassing in the ocean and enhanced continental weathering due to increased pCO_2 has to be considered when assessing different episodic pulses and the reflection of these changes in the $\delta^{13}C$ record.

8.2 General conclusions

This research is a stratigraphic and sedimentological study within the BEZ, focused on the Aptian of the Prebetic. The studied materials belong to three sedimentary contexts: very shallow – proximal (Bedmar-Jódar); shallow – intermediate (Mariola); and hemipelagic – distal (Cau).

In the Prebetic, the Aptian is recorded by the Llopis Fm and the Almadich Fm. The shallow carbonate Llopis Fm is present in proximal sectors of the basin, as Bedmar-Jódar and Mariola, and records only a part of the early Aptian. The Llopis Fm at Bedmar-Jódar records only a part of the Middle Mb, but with higher thickness than Mariola, indicating higher subsidence rate for this sector of the platform. In Mariola, the Middle and Upper Mbs of the Llopis Fm record the lower part of the early Aptian, including the onset of the OAE 1a. At Cau, the hemipelagic Almadich Fm records the early Aptian, and the lower and middle parts of the late Aptian.

The main conclusions that emerge from the study of the outcrops from Bedmar-Jódar and Mariola, are:

- the Urgonian facies of Jódar are part of an isolated platform recording only a part of what is recorded at Mariola, but indicating a higher subsidence for this sector of the platform.
- the Urgonian facies at Mariola extensively records the interval previous to the OAE 1a, as an example of the changes in the conditions that preceded the Selli Event in a platform context.

The study of the Cau Core offers a high-resolution frame of the Aptian. Carbon and Osmium chemostratigraphy describe rapid and abrupt changes during the early Aptian, whereas the late Aptian is much more stable with smooth trends and slow-paced changes.

From the cyclostratigraphic study of the Cau Core, the most relevant feature that follows is the duration of the Ap3 (C3) segment within the CIE, that yields a much longer duration (272 kyr) from previous calculations (47 kyr). The delay between the base of the Ap3 segment (onset of the OAE 1a) and the base of the D Os_i segment (onset of OJP main phase) using the astrochronology of this study is ca. 20-kyr. Therefore, to keep the $\delta^{13}C$ at +1.5 ‰ for that

interval, the input of light carbon must have been produced by a source different than volcanic CO₂.

Os_i marine composition remained dramatically unradiogenic during ~1.8 Myr, indicating the great entity of the Ontong-Java main magmatic phase, whereas the CIE ends just ca. 0.4 Myr after the onset of the main volcanic event. During 1.4 Myr, C-cycle and Os-cycle were totally opposite, suggesting that the amount of organic-matter burial surpassed the volcanism influence.

8.3 Future work

The current knowledge of the impact of the OAE 1a in proximal sectors of the Prebetic domain could be expanded by the characterization of the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ profiles of the Almadich Fm at Sierra Mariola. Besides, many questions arise when the OAE 1a is analyzed. The main trigger of the onset of the OAE 1a is still unclear between the interplay of volcanism, dissociation of gas hydrates and/or intrusion of magma into organic rich-sediments. More studies can be conducted in the Cau Core, such as X-ray diffraction and SEM analysis of samples, for a better understanding of the mineralogy of the materials, and a higher resolution XRF study, in order to provide another dataset for time series analysis. Furthermore, the use of He-isotopes would help to constrain the tempo of the different events at sub-Milankovitch resolution. Other studies undergoing currently in the core involve the analysis of palynology and dinoflagellates, for a better characterization of the ecosystem. Future studies involving biomarkers and Nd-isotopes could shed light on local and regional paleoenvironmental and paleoclimate conditions.

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Appendix

All samples remain stored at the Department of Geology in the University of Jaén.

List of Samples and Data Tables

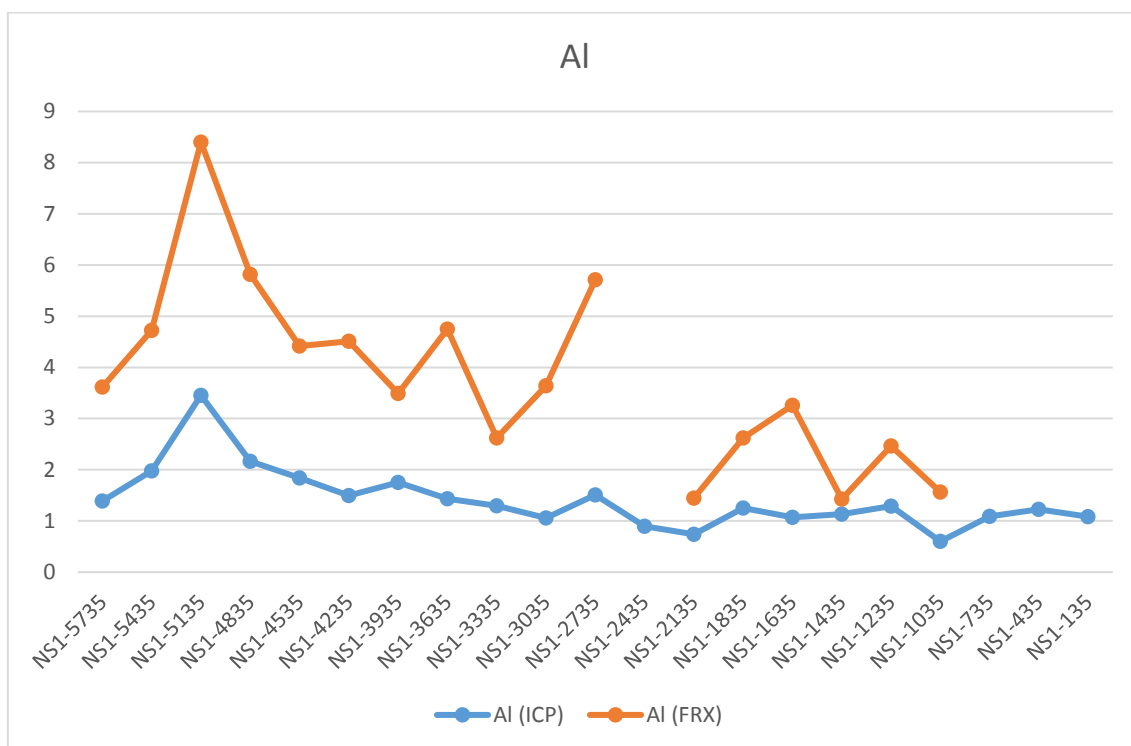
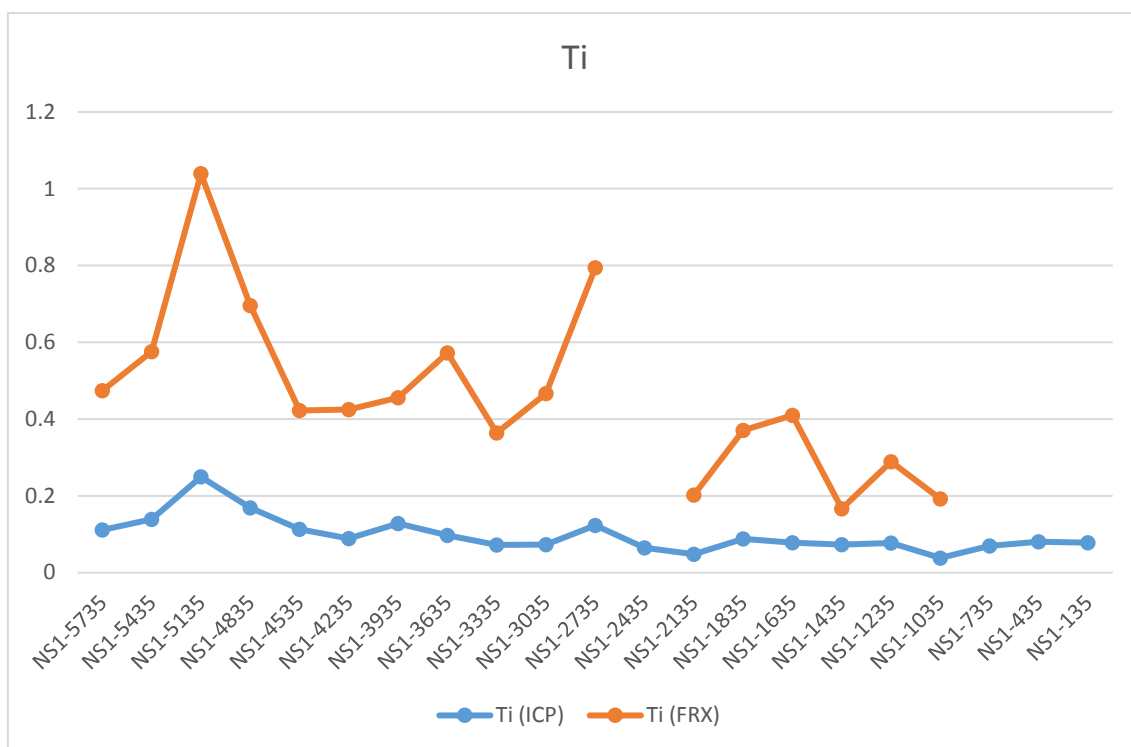
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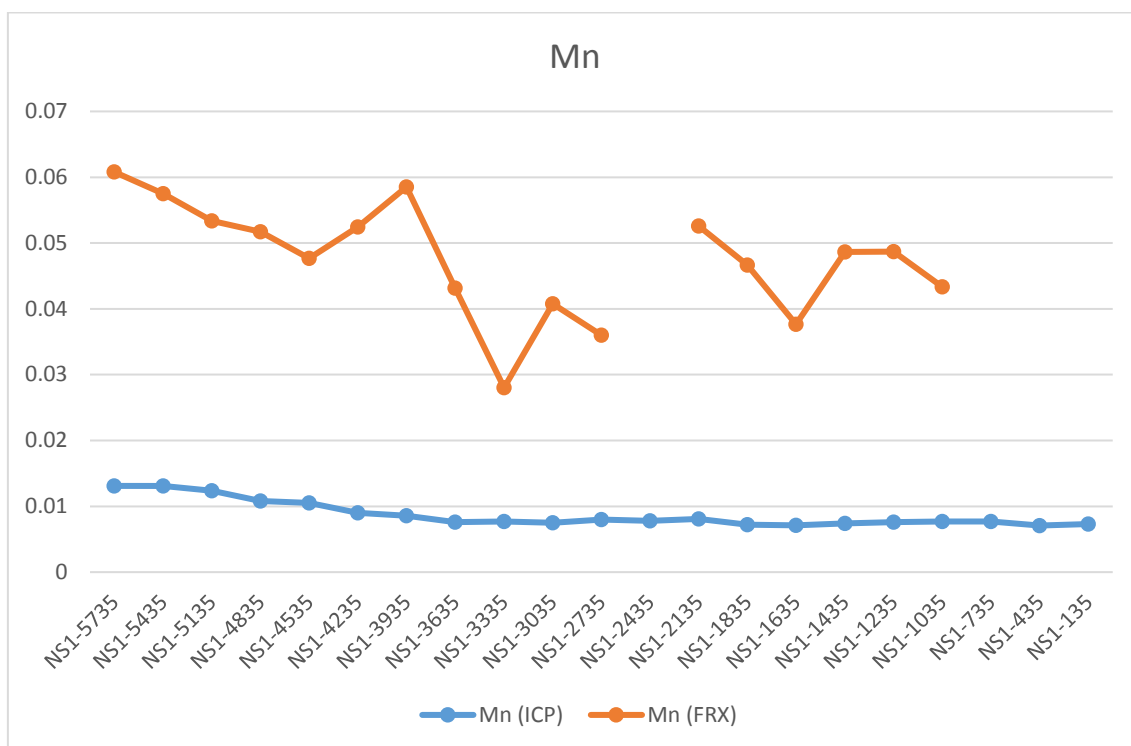
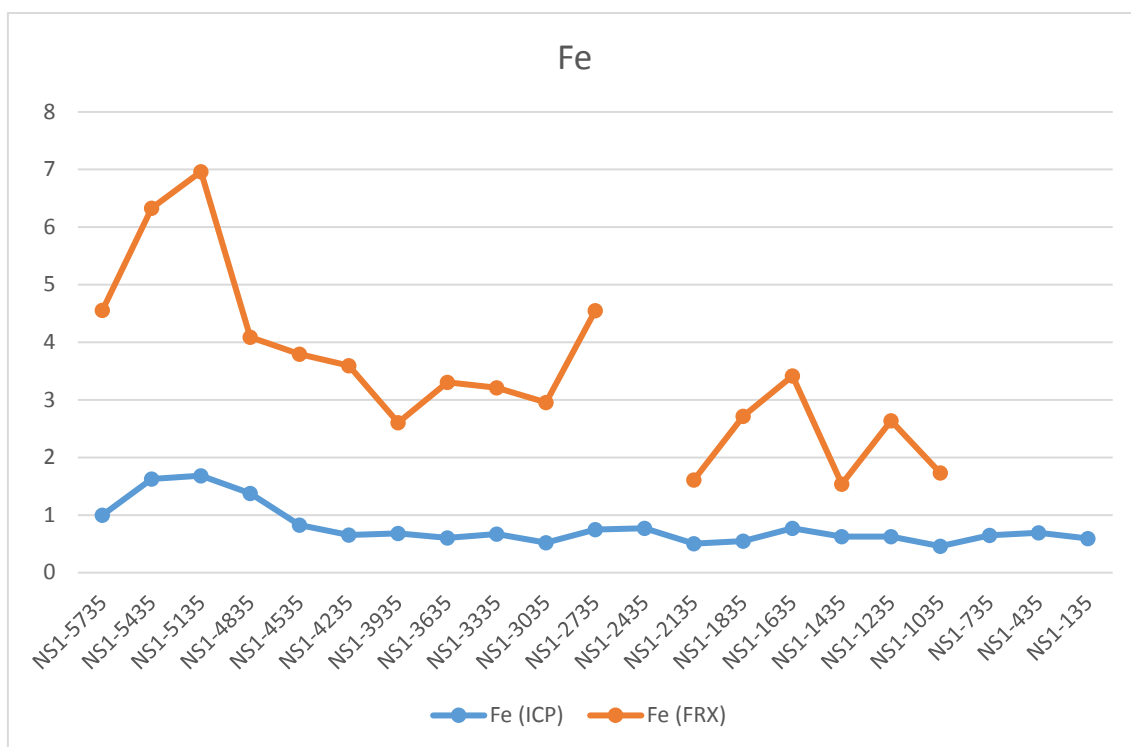
Core XRF DATA

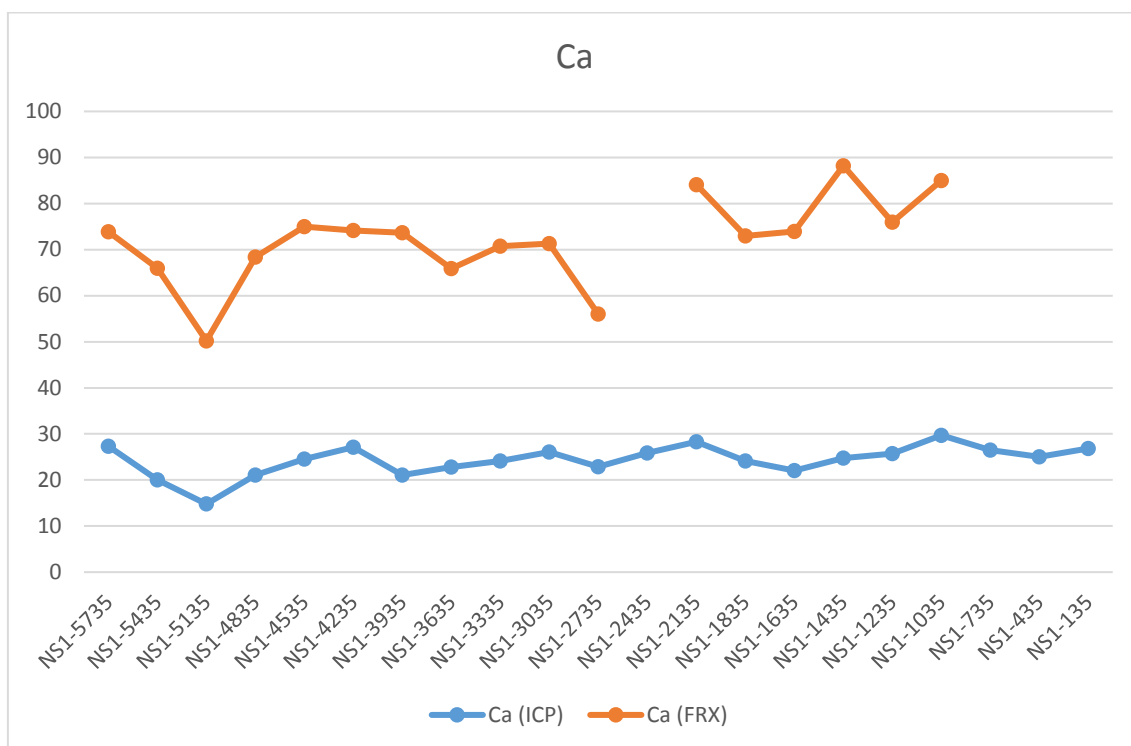
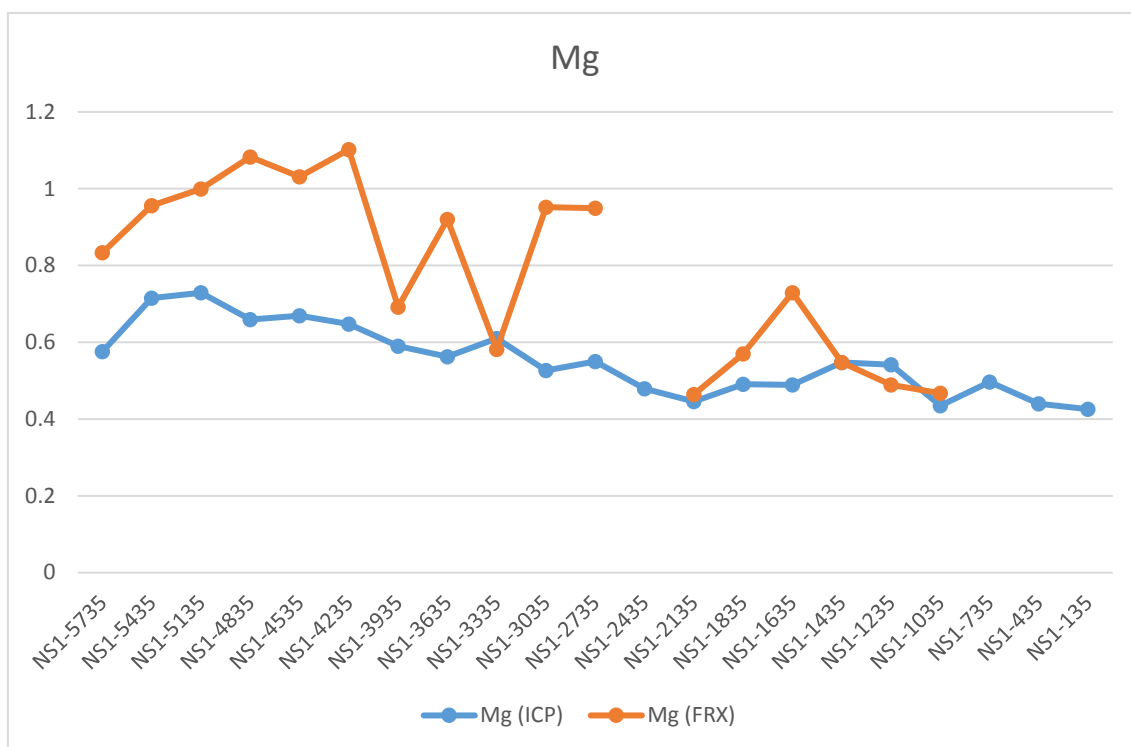
Core Ref	Core Depth (	True Depth (	Composite C	Ca	Si	Fe	Al	S	K	Mg	Sr	Ti	Mn	SUMA
XRF1-1035	10.35	8.005	8.005	84.9979874	7.16355442	1.73067243	1.56329731	1.57740078	0.7108493	0.46781786	1.0436558	0.192282	0.04334514	99.4908624
XRF1-1235	12.35	9.595	9.595	75.9271436	11.7116766	2.63706082	2.46723599	3.27604463	1.26784447	0.4895927	1.32186064	0.28880939	0.04869955	99.4359684
XRF1-1435	14.35	11.26	11.26	88.2197797	5.9436591	1.53923957	1.42783985	0.54490821	0.58121682	0.54793096	0.47236659	0.16681789	0.04866215	99.4924208
XRF1-1635	16.35	12.6975	12.6975	73.9133604	14.8571943	3.41773234	3.26008614	0.84809856	1.69292157	0.7294611	0.37101527	0.40989666	0.03764052	99.5374069
XRF1-1835	18.35	14.05	14.05	73.0056942	14.917235	2.71735923	2.62226358	2.44733952	1.66105502	0.56998379	1.081641	0.37055318	0.04663324	99.4397577
XRF1-2135	21.35	16.14	16.14	84.1075181	8.49787291	1.61154727	1.44716692	1.20543308	0.81637901	0.46427777	1.09040185	0.20222594	0.05261219	99.495435
XRF1-2735	27.35	21.215	21.215	56.0437639	23.3025566	4.55354429	5.71184372	3.25564302	3.36166838	0.94959177	1.95562437	0.79443853	0.03598653	99.9646611
XRF1-3035	30.35	23.74	23.74	71.3085916	15.474245	2.95484725	3.6399445	1.77202447	1.99803745	0.95176924	0.81553269	0.4666911	0.0407647	99.422448
XRF1-3335	33.35	26.37	26.37	70.7490277	14.3727929	3.21230574	2.62362852	4.25428132	1.63264501	0.58148202	2.15674483	0.3643698	0.02802711	99.9753049
XRF1-3635	36.35	29.03	29.03	65.8611321	19.5600875	3.30557237	4.74724943	1.12008888	2.68539156	0.92005229	0.5283402	0.57295544	0.04313202	99.3440018
XRF1-3935	39.35	31.7	31.7	73.6594988	14.9497296	2.60274222	3.48799563	1.09644721	2.07636977	0.69195482	0.32907002	0.45590351	0.05852281	99.4082344
XRF1-4235	42.35	34.4	34.4	74.1549442	12.0585321	3.59384347	4.50799979	1.06597792	2.00155189	1.10207819	0.42156232	0.42482112	0.05244016	99.3837512
XRF1-4535	45.35	37.1	37.1	74.9721621	11.5592819	3.79681192	4.41656095	0.90476	1.87476323	1.0311842	0.3520149	0.42277795	0.04766258	99.3779798
XRF1-4835	48.35	39.8	39.8	68.4019986	15.3914342	4.09033554	5.81624634	0.90150048	2.65075431	1.08250737	0.31966713	0.69579188	0.05173062	99.4019665
XRF1-5135	51.35	42.5	42.5	50.205675	24.5553041	6.96352743	8.40196478	2.3902661	4.25365489	0.99916472	0.23906582	1.03919782	0.05335727	99.1011779
XRF1-5435	54.35	45.2	45.2	65.9465659	16.7379042	6.33172235	4.72206831	1.31241699	2.51305522	0.95595075	0.24623768	0.57623115	0.05750106	99.3996537
XRF1-5735	57.35	47.9	47.9	73.8869162	11.8216213	4.55769649	3.61297088	2.07891368	1.82353508	0.83371275	0.27616112	0.47396515	0.06079602	99.4262844
XRF3-553	5.53	4.9	78.4	90.882579	3.9463701	2.11202664	1.47149088	0.13533028	0.50462877	0.47922488	0.17702382	0.21296589	0.05326555	99.9749058
XRF3-1453	14.53	12.96	86.46	68.9169715	9.49646693	4.927244	5.16939064	7.27024072	2.68043289	0.23827442	0.18078568	0.61750857	0.02582667	99.523142
XRF3-1753	17.53	15.58	89.35	80.8459097	7.76957255	3.64666698	4.41127994	0.39386689	1.67963785	0.50487238	0.2116005	0.46301719	0.03810061	99.9545245
XRF3-2053	20.53	18.2	91.07	82.7060728	6.82842843	3.57305766	3.60640132	0.45537018	1.44933929	0.7673946	0.19965285	0.38277355	0.02457329	99.993064
XRF3-2353	23.53	19.99	93.49	59.3278583	14.7526684	6.7005107	8.51298677	4.0750244	4.11689937	0.8504153	0.36948406	0.79996477	0.02086035	99.5266725
XRF3-2653	26.53	23.53	97.3	66.2595984	13.0630256	5.40715118	5.23058416	4.33024425	2.66063388	0.57258565	1.71963272	0.69247252	0.03446381	99.9703922
XRF3-2953	29.53	26.07	99.57	82.813197	5.39752249	3.92130708	2.22114401	2.81635623	1.01863489	0.55238013	0.91184928	0.29700737	0.03854904	99.9879475
XRF3-3253	32.53	28.48	102.25	62.600657	13.8062384	6.01179134	5.7697225	5.00132205	3.15526903	0.64533378	2.18666636	0.70337151	0.03576117	99.9355418
XRF3-3543	35.43	30.86	103.73	72.8584674	9.97158023	4.71501215	5.62480996	1.58753216	2.51871903	0.91883187	0.58000695	0.53321782	0.03645472	99.3446323
XRF3-3853	38.53	33.77	107.27	72.5837593	9.39614277	4.84473379	3.99219639	3.64704178	2.32213404	0.76510203	1.22893238	0.54053147	0.03537307	99.355947
XRF3-4053	40.53	35.65	109.42	71.3316017	10.1769315	4.8709769	4.53286751	3.28361454	2.50599745	0.74589376	1.30720936	0.54832456	0.02356847	99.3269858
XRF3-4153	41.53	36.58	109.45	78.7895772	7.98795554	4.11686249	3.73984569	1.22520622	1.68277458	0.88116536	0.53549711	0.45053266	0.04045669	99.4498736
XRF4-32	0.32	0.25	112.2	75.8399264	6.64066011	3.46074119	3.44238948	2.76989225	1.60216215	0.49453644	0.27097172	0.35759377	0.04006368	99.4189372
XRF3-4453	44.53	39.39	112.89	73.1213968	9.17800597	4.9182141	3.37971385	4.10733034	2.15060093	0.74946766	1.19953237	0.50874249	0.03374339	99.3467484
XRF4-332	3.32	2.54	114.49	66.0448261	6.2441586	4.02383417	3.16394126	17.0006198	1.99652631	0.34971781	0.28071919	0.37651226	0.01538457	99.49624
XRF4-432	4.32	3.31	115.26	67.92235	7.0483484	4.40601582	3.59526913	13.3509453	2.03003464	0.38493202	0.27668224	0.40437105	0.03604512	99.4549937
XRF3-4753	47.53	42.21	115.98	69.1158945	11.5487318	5.1871676	4.7792295	3.52769579	2.41195199	0.88117228	1.17504532	0.53815035	0.03901809	99.2040573
XRF4-632	6.32	4.97	116.92	56.9468003	12.1634299	6.84007082	4.64020501	12.3868929	3.4143788	0.70476032	2.15648294	0.6157218	0.03249955	99.9012423
XRF3-5053	50.53	45.96	118.83	46.2218816	21.6855105	8.6630776	10.1424955	3.84968873	5.38244369	1.19977533	0.98529857	1.0736876	0.0488274	99.2526866
XRF4-932	9.32	7.53	119.48	72.741069	9.29410881	4.6943194	3.50715577	5.20875772	2.03097468	0.72910804	1.18032274	0.49007574	0.0482431	99.924135
XRF4-1232	12.32	9.15	121.1	82.0172478	7.23850831	3.94325153	3.11898827	0.55293235	1.50759973	0.88750517	0.22265432	0.39107435	0.05591044	99.9356723
XRF3-5353	53.53	48.78	121.7	83.2238614	5.14178858	2.84668977	2.26621986	3.4730097	1.1456166	0.56691921	0.54651158	0.24002194	0.04858301	99.4992217
XRF4-1532	15.32	12.32	124.27	54.7983765	10.9037259	7.38836662	4.57349693	17.4414951	2.92124304	0.61803363	0.46320375	0.73765833	0.03628916	99.881889
XRF3-5653	56.53	51.6	124.5	56.3272462	17.5211476	8.79534478	7.59690619	2.11949674	3.90466328	1.38538796	0.76947082	0.87797504	0.05408299	99.3517215
XRF4-1832	18.32	14.83	126.78	51.0091867	21.3433727	9.12934683	8.52023013	2.03122305	4.2328905	1.80808578	0.18800906	1.04527691	0.07654605	99.3841677
XRF3-5953	59.53	54.41	127.28	44.7212413	23.7088788	9.87508957	9.32740853	2.8870406	5.03641751	2.08481041	0.46845481	1.134603	0.07070848	99.314653
XRF4-2134	21.34	17.33	129.28	61.4974277	17.2657334	5.90444458	7.19888034	2.45865927	3.64193709	0.89302498	0.21378312	0.8276202	0.04448737	99.945998
XRF4-2434	24.34	19.81	131.76	65.5080945	15.8117154	6.50949658	6.0710182	0.99811634	2.91399911	0.93654434	0.26663441	0.8308227	0.07132207	99.9177636
XRF4-2734	27.34	22.18	134.13	55.6347208	19.6386156	7.53433764	7.99464903	2.15729874	3.94558827	1.36308353	0.4804577	0.99960513	0.04868389	99.8150403
XRF4-3036	30.36	24.58	136.53	79.3828855	10.0068385	3.86372935	3.27608239	0.40785341	1.48575511	0.60385257	0.29776079	0.50500882	0.04996383	99.8797302
XRF4-3326	33.26	27.11	139.06	88.3224266	5.04001219	2.82329548	1.70271608	0.12650789	0.75589617	0.57369328	0.29377214	0.25568731	0.05853448	99.9525416
XRF4-3626	36.26	29.66	141.61	78.8720055	9.43204597	4.1050969	3.58069866	0.39810636	1.75066277	0.88252356	0.2745709	0.47956953	0.05923769	99.8345178
XRF4-3926	39.26	32.11	144.06	66.1283283	10.6213221	6.7151013	3.8365516	7.7924125	2.63829138	0.47215779	0.99491219	0.67656785	0.05889085	99.9345358

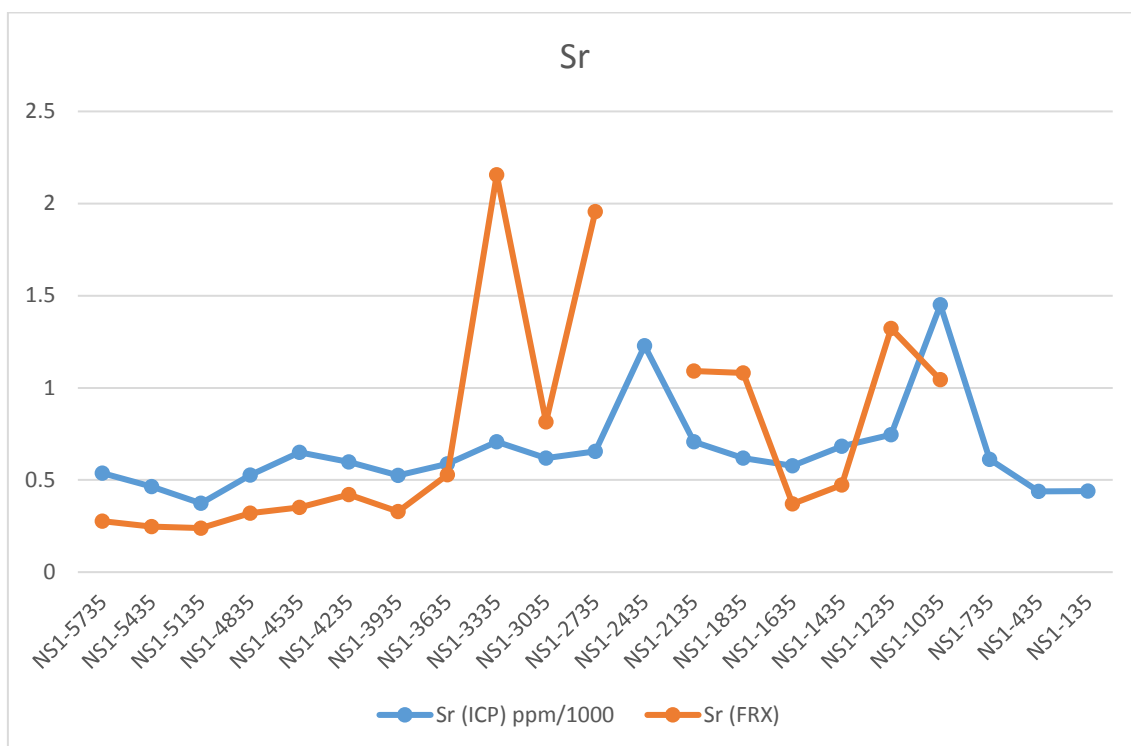
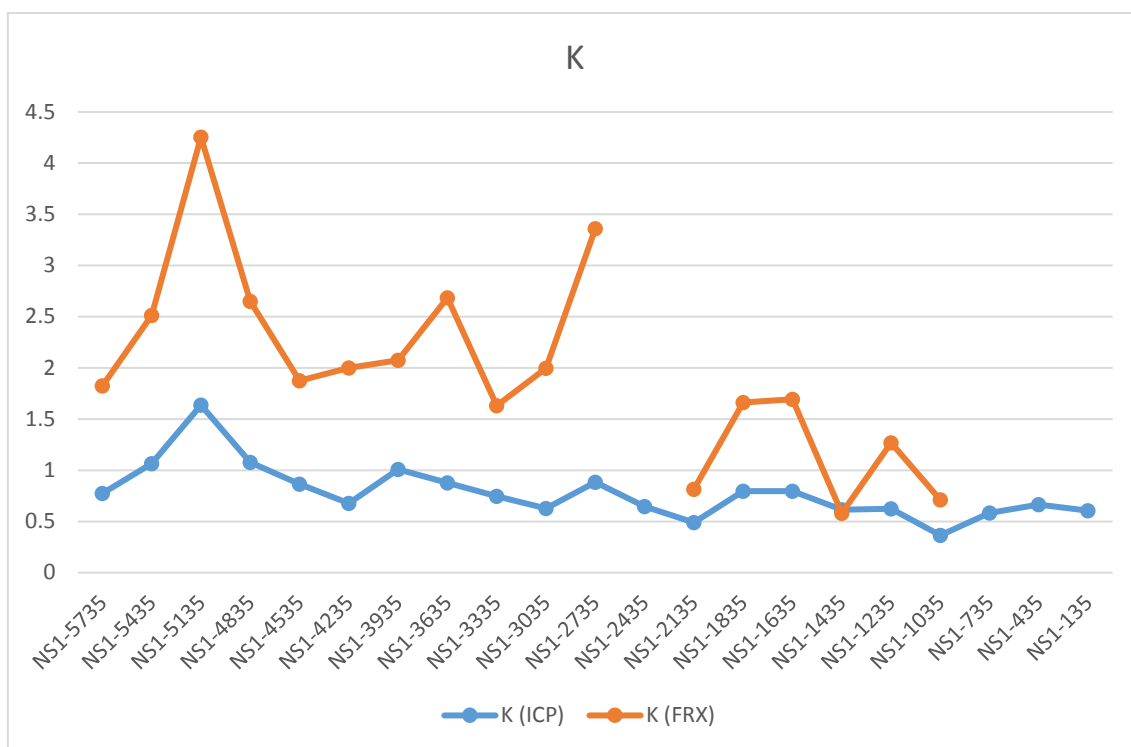
MUESTRA	Ti (ICP)	Ti (FRX)	Al (ICP)	Al (FRX)	Fe (ICP)	Fe (FRX)	Mn (ICP)	Mn (FRX)	Mg (ICP)	Mg (FRX)	Ca (ICP)	Ca (FRX)	K (ICP)	K (FRX)	Sr (ICP)	Sr (FRX)	Cr (ICP) ppm	Cr (ICP) ppm	Cr (FRX)	
NS1-5735	0.11137606	0.47396515	1.38770417	3.61297088	0.99716817	4.55769649	0.01310235	0.06079602	0.57572345	0.83371275	27.3367395	73.8869162	0.77470904	1.8235308	536.850678	0.53685068	0.27616112	19.409882	0.01940988	0.01087651
NS1-5435	0.13893997	0.57623115	1.97564524	4.7206831	1.62536141	6.33172235	0.01309581	0.05750106	0.71529573	0.95595075	20.0037053	65.9465659	1.06620498	2.51305522	463.651236	0.46365124	0.24623768	25.8282515	0.02582825	0.00765412
NS1-5135	0.24949631	1.03919782	3.45411226	8.40196478	1.68446267	6.96352743	0.01238736	0.05357277	0.72898155	0.99916472	14.7814493	50.205675	1.63641393	4.25365489	373.340358	0.37334036	0.23906582	44.6183816	0.04461838	0.01984926
NS1-4835	0.16918649	0.69579188	2.16812396	5.81624634	1.37719275	4.09033554	0.01079223	0.05173062	0.65914811	1.08250737	21.0836427	68.4019986	1.07701559	2.65075431	525.884379	0.52588438	0.31966713	30.5865894	0.03058659	0.01906842
NS1-4535	0.1127187	0.42277795	1.8371887	4.41656095	0.82851971	3.79681192	0.01050924	0.04766258	0.6696123	1.0311842	24.5584878	74.9721621	0.86591541	1.87476323	650.0106	0.6500106	0.3520149	25.3508157	0.02535082	0.01442129
NS1-4235	0.08877525	0.42482112	1.49683193	4.50799979	0.65312637	3.59384347	0.00899083	0.05244016	0.6479614	1.10207819	27.1198531	74.1549442	0.67798415	2.00155189	597.312268	0.59731227	0.42156232	21.5634366	0.02156344	0.01842045
NS1-3935	0.128	0.45590351	1.75	3.48799563	0.68	2.60274222	0.00855	0.05852281	0.59	0.69195482	21.1	73.6594988	1.01	2.07636977	525	0.525	0.32907002	22.875	0.022875	0.00768762
NS1-3635	0.09719967	0.57295544	1.43463639	4.74724943	0.60173955	3.30557237	0.00759301	0.04313202	0.56220214	0.92005229	22.8029705	65.8611321	0.87629488	2.68539156	586.925015	0.58692502	0.5283402	17.2224998	0.0172225	0.01207337
NS1-3335	0.07225107	0.3643698	1.29824954	2.62362852	0.67213133	3.21230574	0.00767988	0.02802711	0.61022225	0.58148202	24.1459074	70.7490277	0.74590867	1.63264501	706.817427	0.70681743	2.15674483	15.3969679	0.01539697	0.01030101
NS1-3035	0.07348588	0.4666911	1.05601947	3.6399445	0.5204474	2.95484725	0.00748637	0.0407647	0.5265598	0.95176924	26.0691533	71.3085916	0.62810189	1.99803745	618.995625	0.61899562	0.81553269	13.5096826	0.01350968	0.00427445
NS1-2735	0.1235	0.79443853	1.51	5.71184372	0.75	4.55354429	0.008	0.0398653	0.55	0.94959177	22.9	56.0437639	0.885	3.36166838	655	0.655	1.95562437	21	0.021	0.01427296
NS1-2435	0.06469649		0.89710827		0.77104576		0.00777031		0.47888716		25.8633976		0.64474268		1228.16008	1.22816008		12.8850369	0.01288504	
NS1-2135	0.04831012	0.20222594	0.74022204	1.44716692	0.50438067	1.61154727	0.00809336	0.05261219	0.44614952	0.46427777	28.3150154	84.1075181	0.49140461	0.81637901	707.555294	0.70755529	1.09040185	10.7853717	0.01078537	0.00289898
NS1-1835	0.08813339	0.37055318	1.25062305	2.62226358	0.54690777	2.71735923	0.00718835	0.04663324	0.49092162	0.5698379	24.0931381	73.0056942	0.79670575	1.66105502	619.557228	0.61955723	1.081641	15.8176917	0.01581769	0.00827673
NS1-1635	0.07789837	0.40989666	1.07320596	3.26008614	0.76862217	3.41773234	0.00709844	0.03764052	0.48900925	0.7294611	22.0150939	73.9133604	0.79696212	1.69292157	577.467548	0.57746755	0.37101527	15.7618476	0.01576185	0.00264654
NS1-1435	0.07351922	0.16681789	1.1343949	1.42783985	0.62815467	1.53923957	0.00739837	0.04866215	0.54769836	0.54793096	24.755733	88.2197797	0.61380448	0.58121682	682.43312	0.68243312	0.47236659	16.6996601	0.01669966	0.0022675
NS1-1235	0.0776768	0.28880939	1.29008277	2.46723599	0.62440531	2.63706082	0.00760137	0.04869955	0.54131607	0.4895927	25.7379272	75.9271436	0.62350058	1.26784447	745.855048	0.74585505	1.32186064	17.5365073	0.01753651	0.00756903
NS1-1035	0.0385	0.192282	0.6	1.56329731	0.46	1.73067243	0.0077	0.04334514	0.435	0.46781786	29.7	84.9979874	0.365	0.7108493	1450	1.45	1.0436558	10.7	0.0107	0.0043171
NS1-735	0.06978588		1.0900669		0.64819075		0.00769523		0.49680909		26.4699941		0.58304504		612.5768	0.6125768		16.0643614	0.01606436	
NS1-435	0.08056834		1.22832998		0.69497123		0.00708144		0.44016195		25.032897		0.6645184		438.890338	0.43889034		16.5798923	0.01657989	
NS1-135	0.0780262		1.08147414		0.59231523		0.00728674		0.42583964		26.8019309		0.60479556		440.609152	0.44060915		15.0898383	0.01508984	

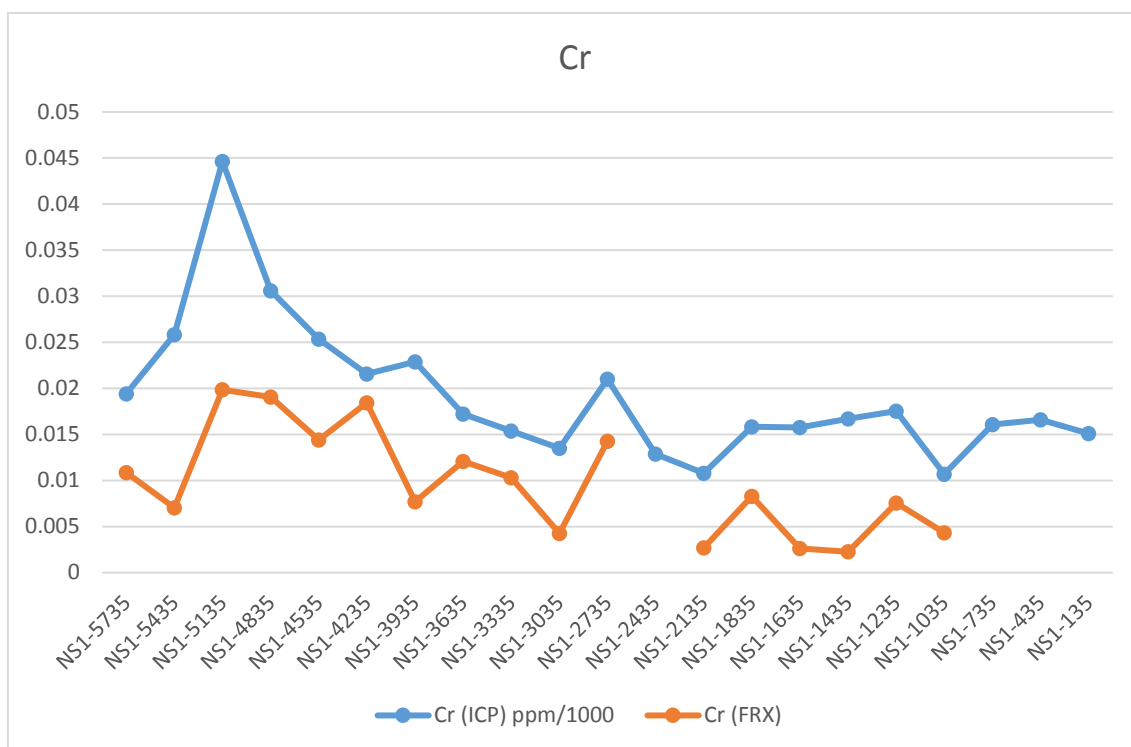
ICP-MS vs FRX
comparison



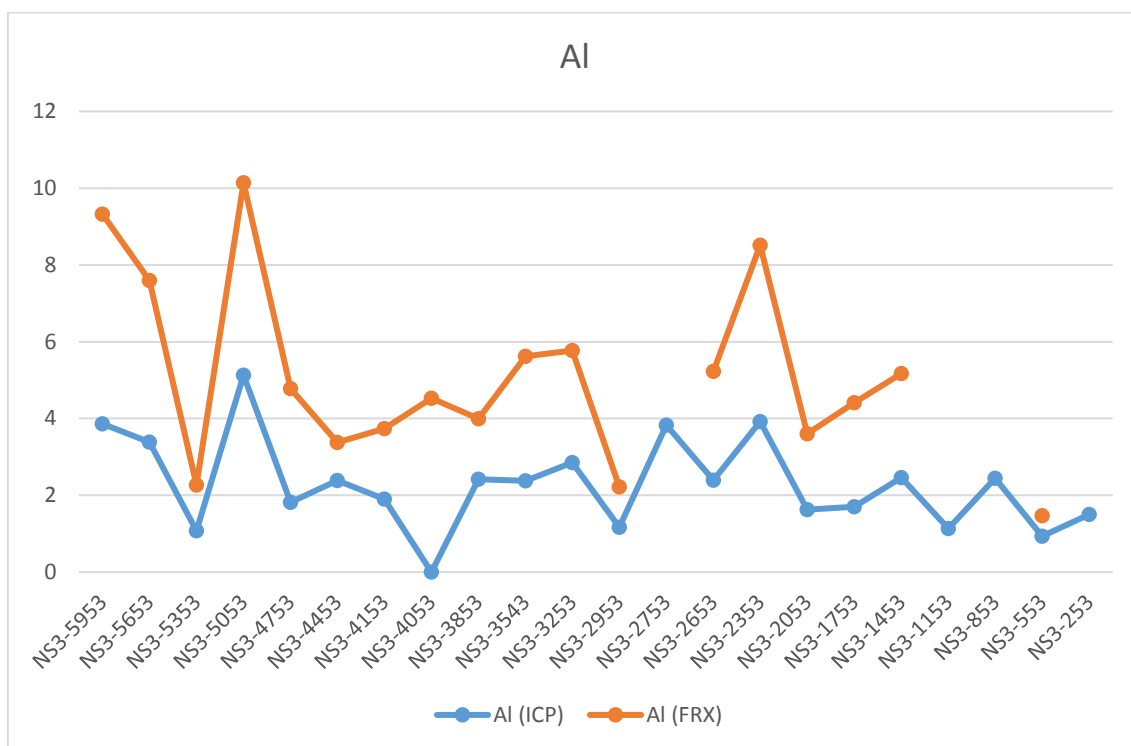
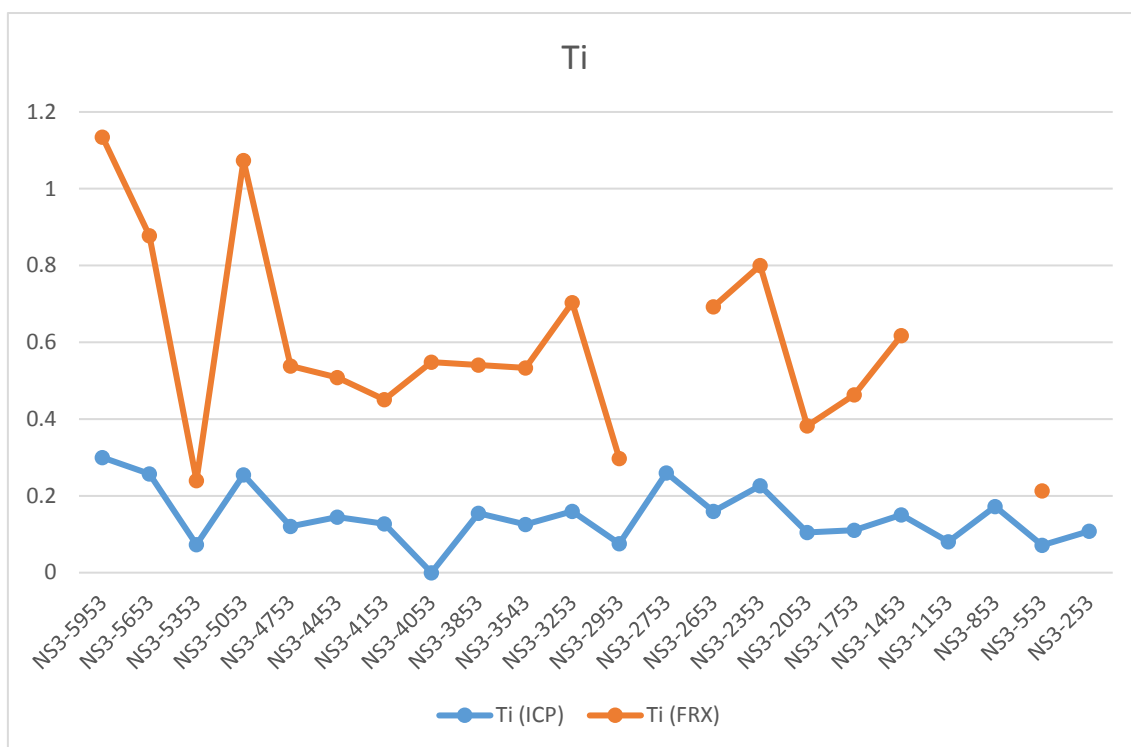


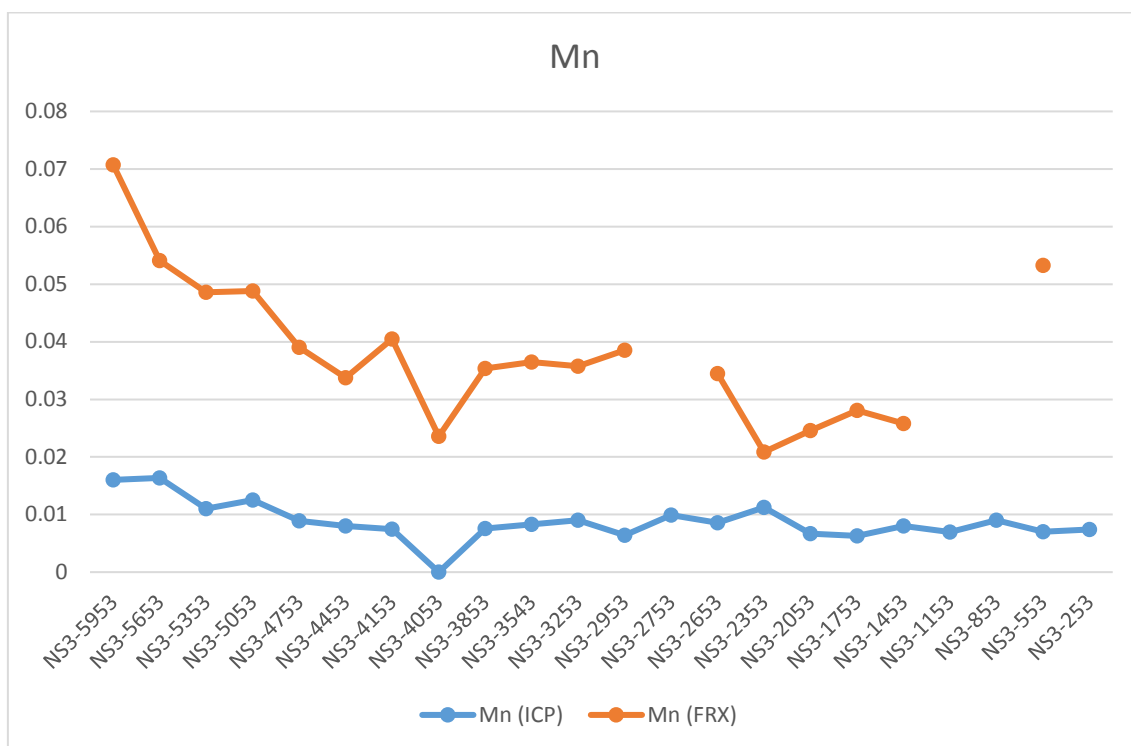
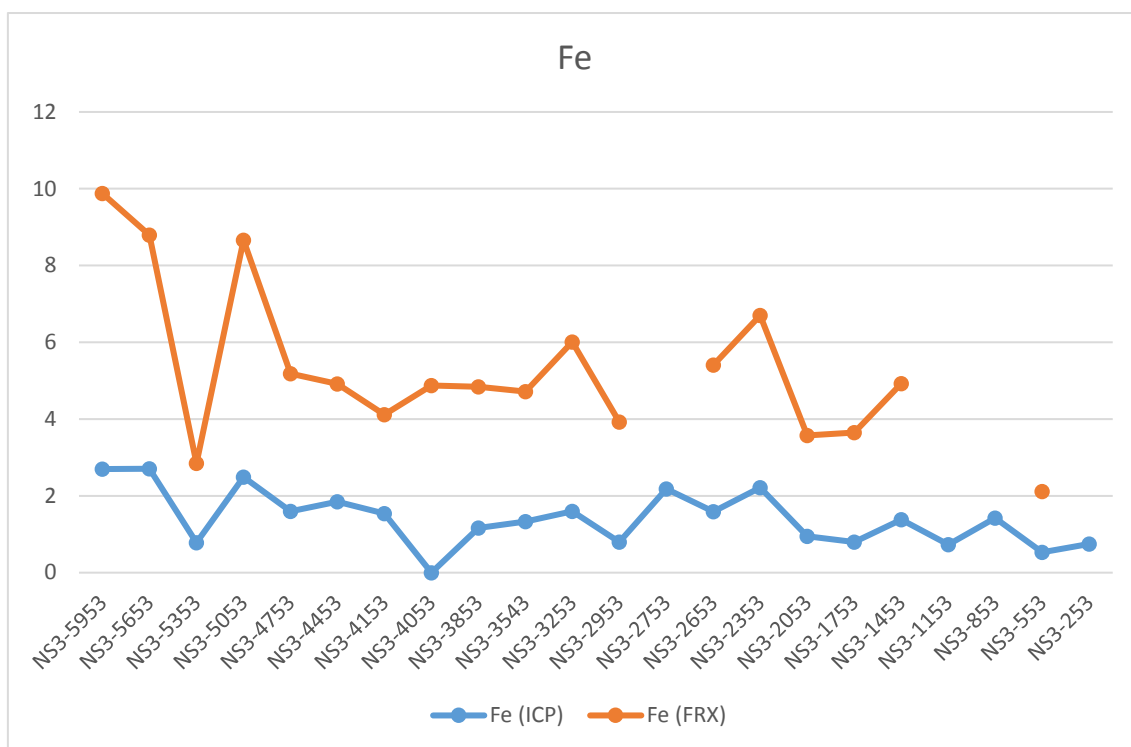


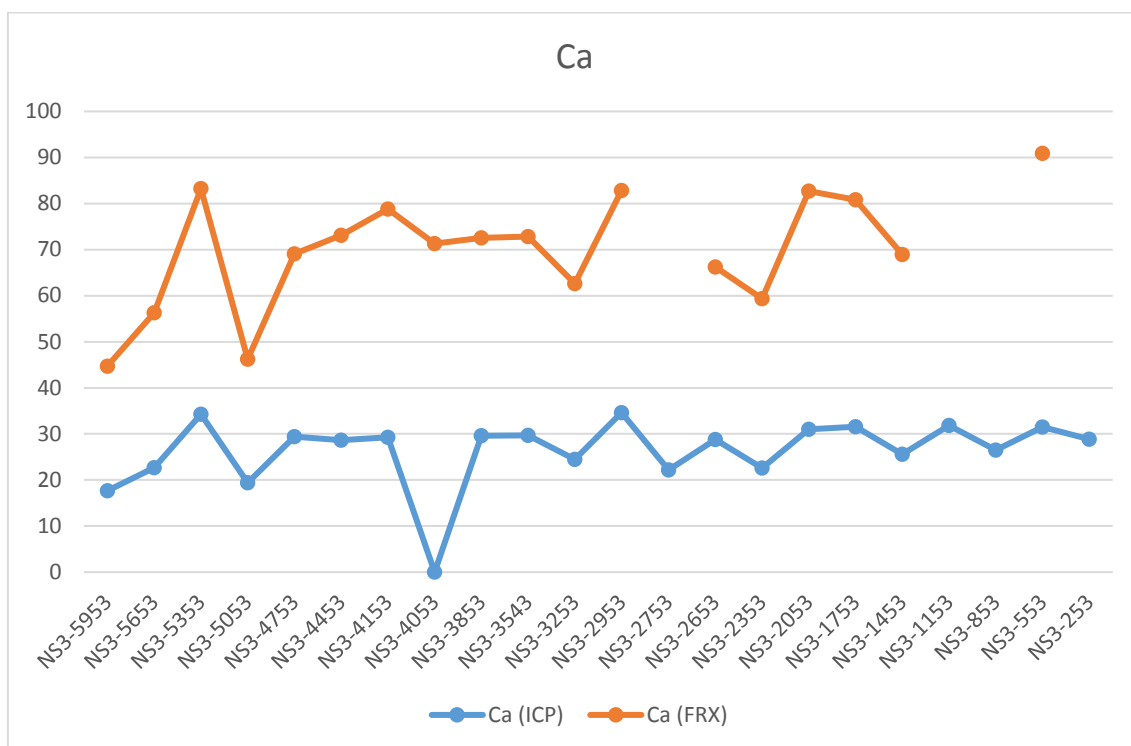
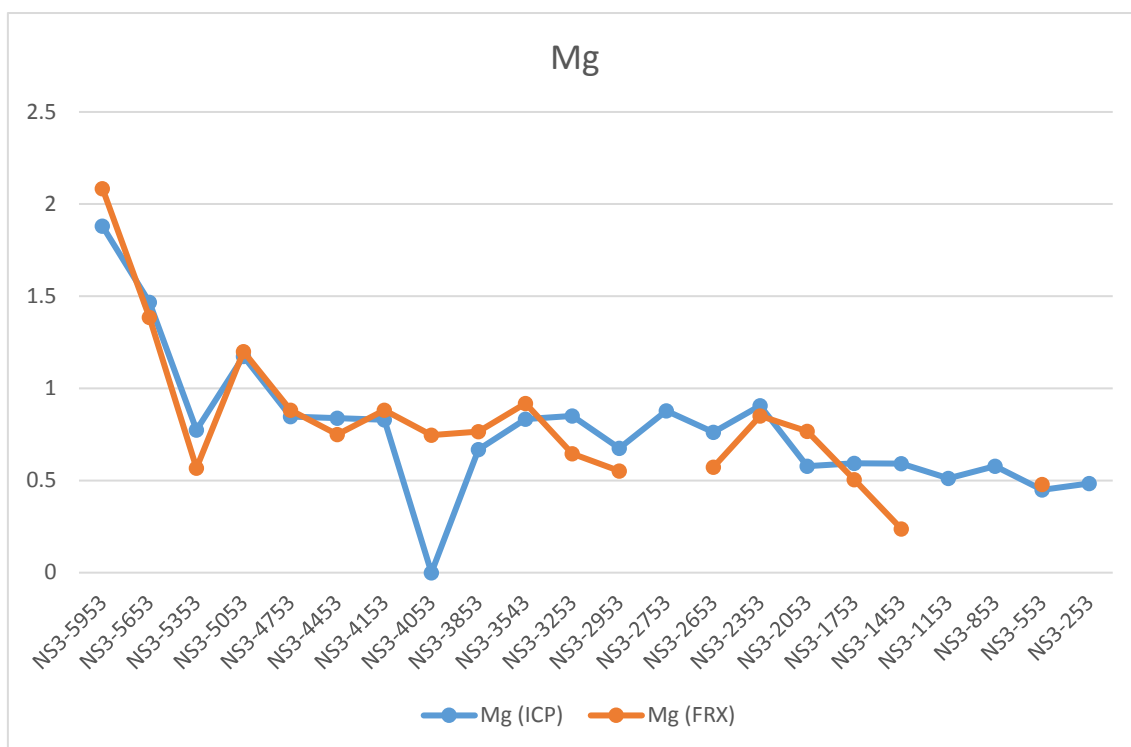


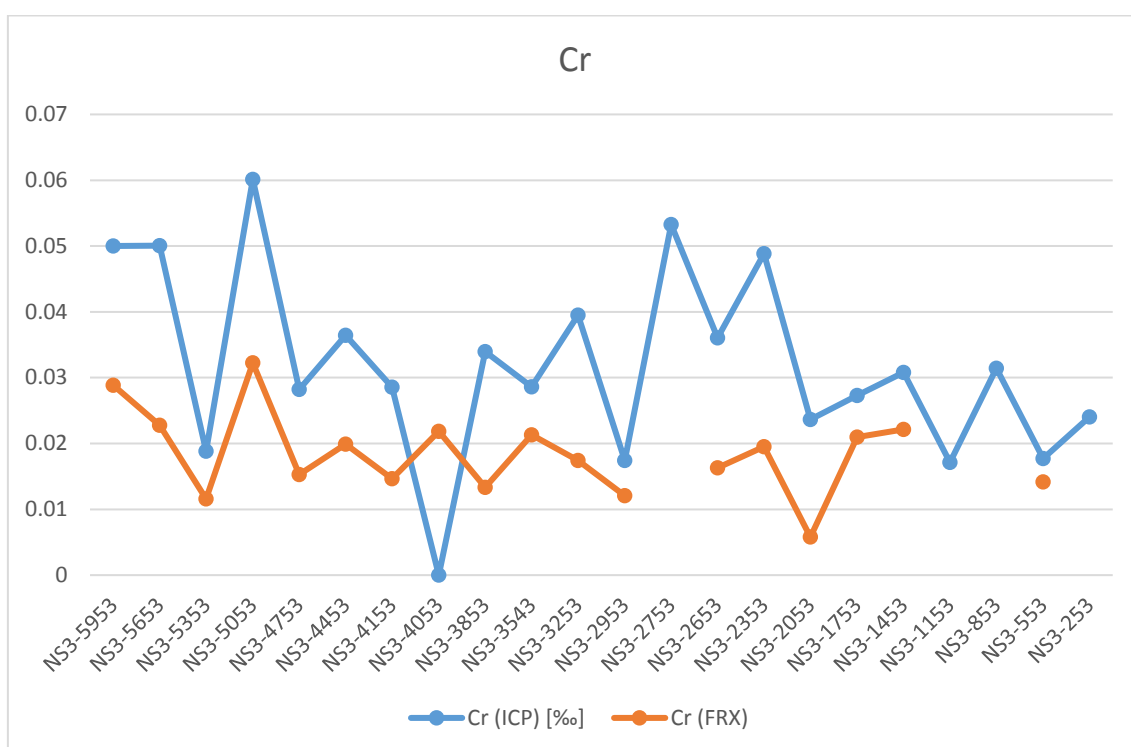
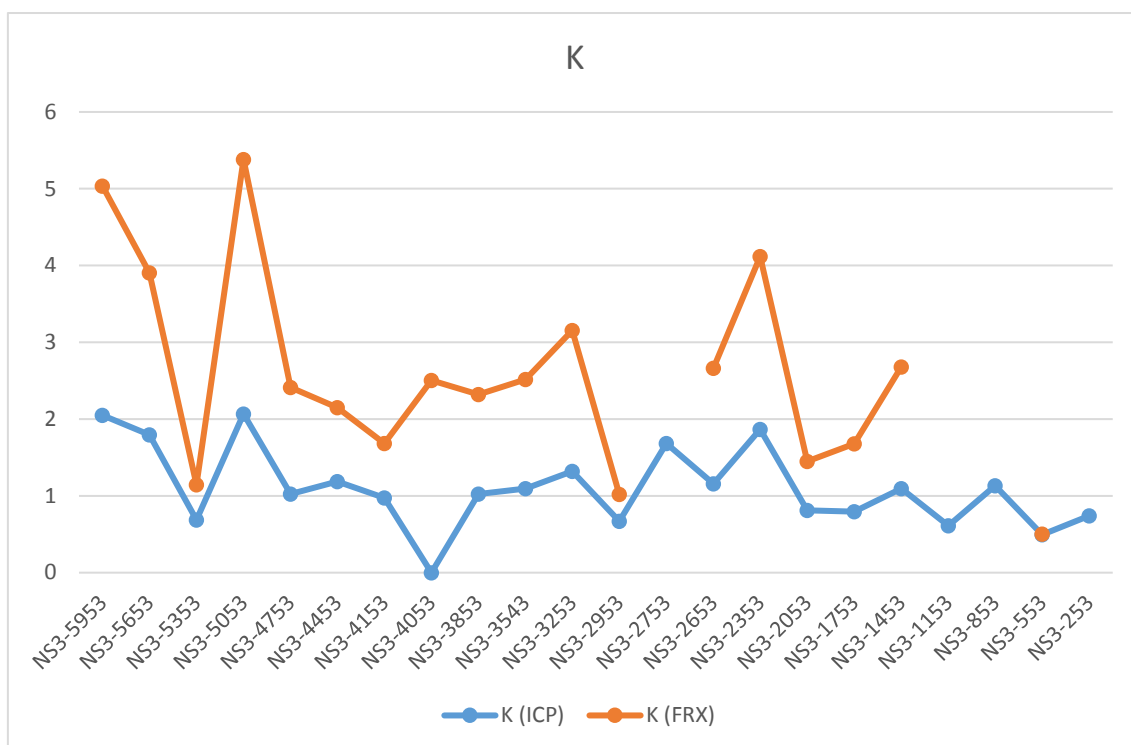


MUESTRA	Ti (ICP)	Ti (FRX)	Al (ICP)	Al (FRX)	Fe (ICP)	Fe (FRX)	Mn (ICP)	Mn (FRX)	Mg (ICP)	Mg (FRX)	Ca (ICP)	Ca (FRX)	K (ICP)	K (FRX)	Cr (ICP) [ppm]	Cr (ICP) [%]	Cr (FRX)
NS3-5953																	
NS3-5953	0.3	1.134603	3.865	9.32740853	2.7	9.87508957	0.016	0.07070848	1.88	2.08481041	17.65	44.7212413	2.05	5.03641751	50	0.05	0.02885097
NS3-5653	0.25738276	0.87797504	3.38603866	7.59690619	2.70641953	8.79534478	0.0163604	0.05408299	1.4672997	1.38538796	22.6570169	56.3272462	1.79460441	3.90466328	50.0508779	0.05005088	0.02276423
NS3-5353	0.07283279	0.24002194	2.26621986	0.78019751	2.84668977	0.01099868	0.04858301	0.77493369	0.56691921	0.56691921	34.2830113	83.2238614	0.68827621	1.1456166	18.8541146	0.01885411	0.01158261
NS3-5053	0.25449609	1.0736876	5.12977253	10.1424955	2.49362307	8.6630776	0.01249725	0.0488274	1.17428209	1.19977533	19.3934305	46.2218816	2.06797929	5.38244369	60.1389722	0.06013897	0.03223964
NS3-4753	0.12096691	0.53815035	1.819496	4.7792295	1.59935105	5.1871676	0.00888206	0.03901809	0.846619	0.88117228	29.3856908	69.1158945	1.02394931	2.41195199	28.2165669	0.02821657	0.015261
NS3-4453	0.14508983	0.50874249	2.38686186	3.37971385	1.85099728	4.9182141	0.00800224	0.0337439	0.83816354	0.74946766	28.6419586	73.1213968	1.18557416	2.15060093	36.4559368	0.03645594	0.01992527
NS3-4153	0.12749839	0.45053266	1.90085469	3.73984569	1.5394648	4.11686249	0.00748338	0.04045669	0.8301856	0.88116536	29.2553011	78.7895772	0.97387841	1.68277458	28.5711435	0.02857114	0.01463813
NS3-4053	0	0.54832456	0	4.53286751	0	4.8709769	0	0.02356847	0	0.74589376	0	71.3316017	0	2.50599745		0	0.02182494
NS3-3853	0.15460921	0.54053147	2.41581376	3.99219639	1.16143441	4.84473379	0.00759377	0.03537307	0.66887456	0.76510203	29.5975833	72.5837593	1.02455287	2.32213404	33.9398481	0.03393985	0.01332396
NS3-3543	0.12580382	0.53321782	2.38183118	5.62480996	1.32756009	4.71501215	0.00829734	0.03645472	0.83336202	0.91883187	29.667061	72.8584674	1.09446433	2.51871903	28.63341	0.02863341	0.02131185
NS3-3253	0.0756861	0.70337151	2.85	5.7697225	1.6	6.01179134	0.009	0.03576117	0.85	0.64533378	24.5	62.6200657	1.32	3.15526903	39.5	0.0395	0.01742504
NS3-2953	0.25978114		3.82720192	2.22114401	0.79977502	3.92130708	0.00639667	0.03854904	0.6744725	0.55238013	34.6313222	82.813197	0.66825466	1.01863489	17.4262869	0.01742629	0.01205251
NS3-2753					2.18198568		0.00988102		0.87764516		22.1644836		1.68264313		53.2807665	0.05328077	
NS3-2653	0.16000416	0.69247252	2.39613304	5.23058416	1.59238369	5.40715118	0.00858437	0.03446381	0.7627381	0.57258565	28.7683821	66.2595984	1.15666468	2.66063388	36.046117	0.03604612	0.01629412
NS3-2353	0.22626296	0.79996477	3.92269968	8.51298677	2.21560507	6.7005107	0.0112671	0.02086035	0.90568661	0.8504153	22.6289698	59.3278583	1.86596576	4.11689937	48.8443514	0.04884435	0.01952055
NS3-2053	0.10519438	0.38277355	1.62576863	3.60640132	0.94747554	3.57305766	0.00669919	0.02457329	0.57765057	0.7673946	30.9886561	82.7060728	0.81234551	1.44933929	23.6426357	0.02364264	0.00578196
NS3-1753	0.11076416	0.46301719	1.70523273	4.41127994	0.797175	3.64666698	0.00629987	0.02810061	0.59420857	0.50487238	31.5389524	80.8459097	0.79680916	1.67963785	27.305	0.027305	0.02098963
NS3-1453	0.15062341	0.61750857	2.46438297	5.16939064	1.37787887	4.927244	0.00799185	0.02582667	0.59251604	0.23827442	25.5665137	68.9169715	1.09541519	2.68043289	30.8201798	0.03082018	0.02214003
NS3-1153	0.0803644		1.13744698		0.72971764		0.00698589		0.51238264		31.8317872		0.61301357		17.1267465	0.01712675	
NS3-853	0.17245796		2.44245657		1.42585342		0.00900612		0.57811301		26.4808127		1.13283359		31.4330031	0.031433	
NS3-553	0.0715	0.21296589	0.935	1.47149088	0.535	2.11202664	0.007	0.05326555	0.45	0.47922488	31.5	90.882579	0.4955	0.50462877	17.7	0.0177	0.01418291
NS3-253	0.10799746		1.50152434		0.7513224		0.00737772		0.48345663		28.8736436		0.74249702		24.0289133	0.02402891	

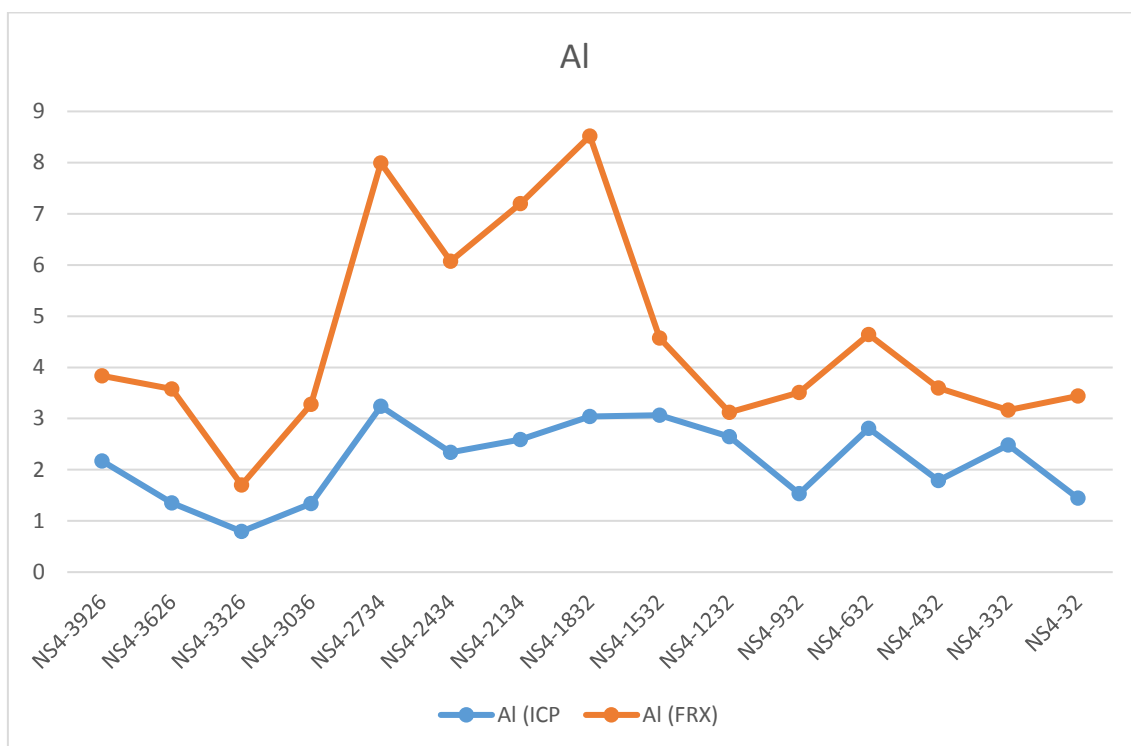
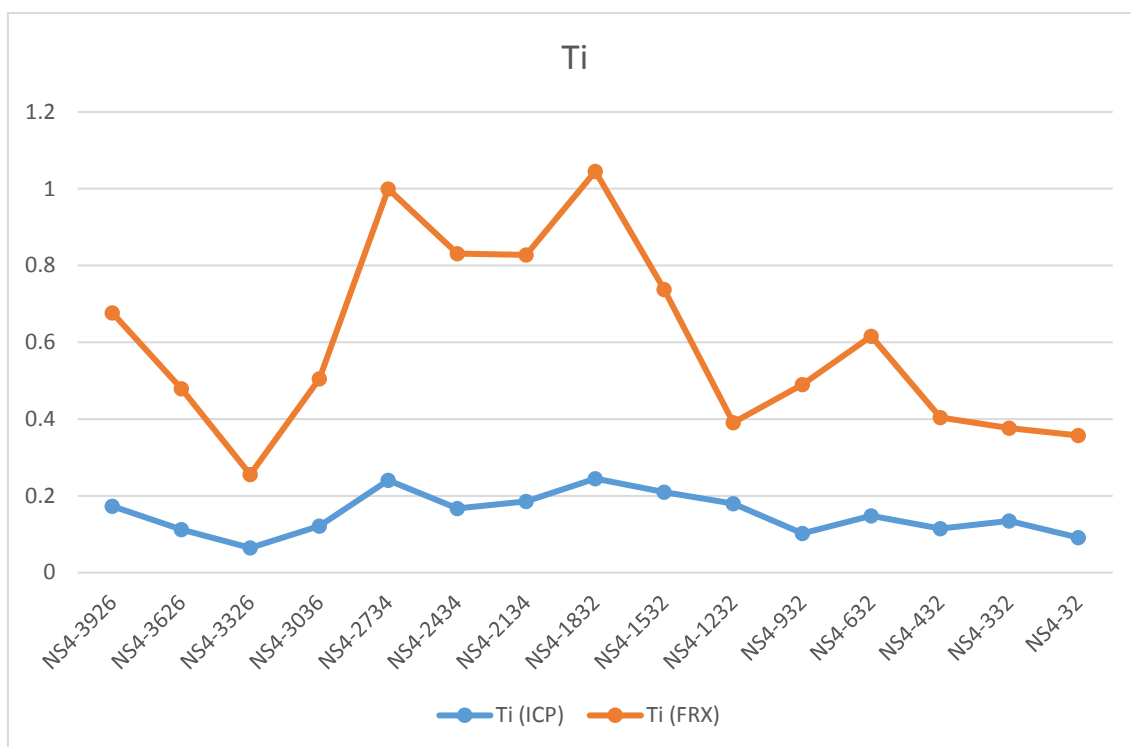


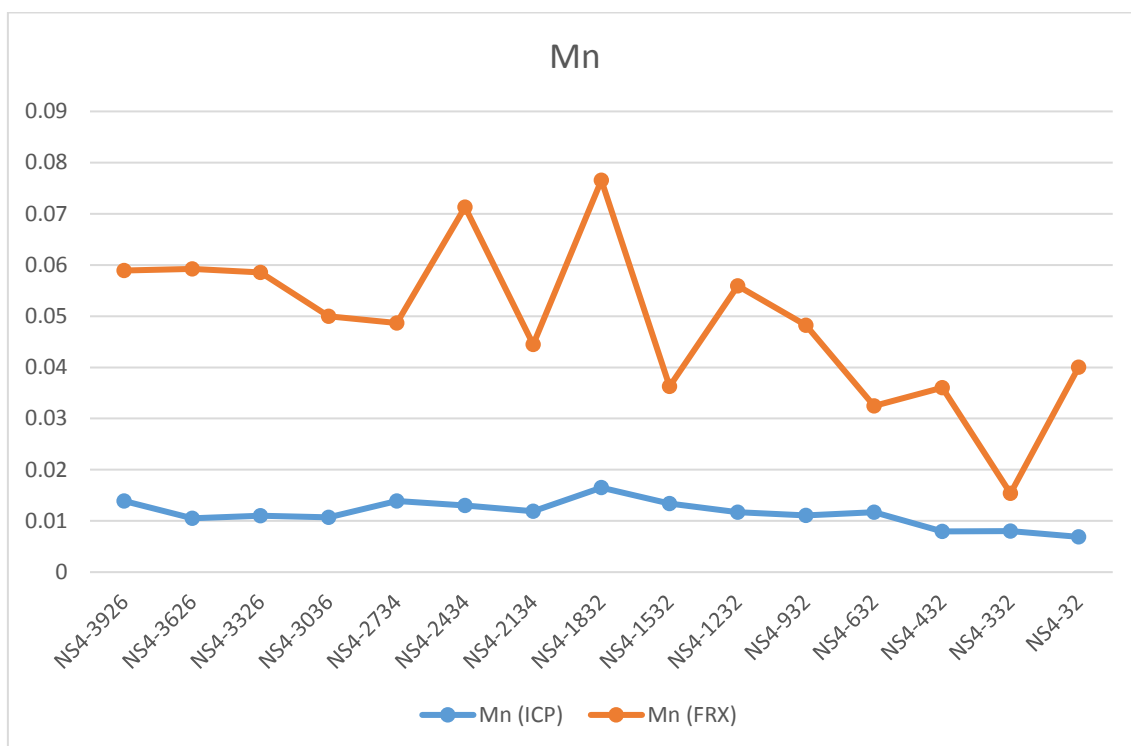
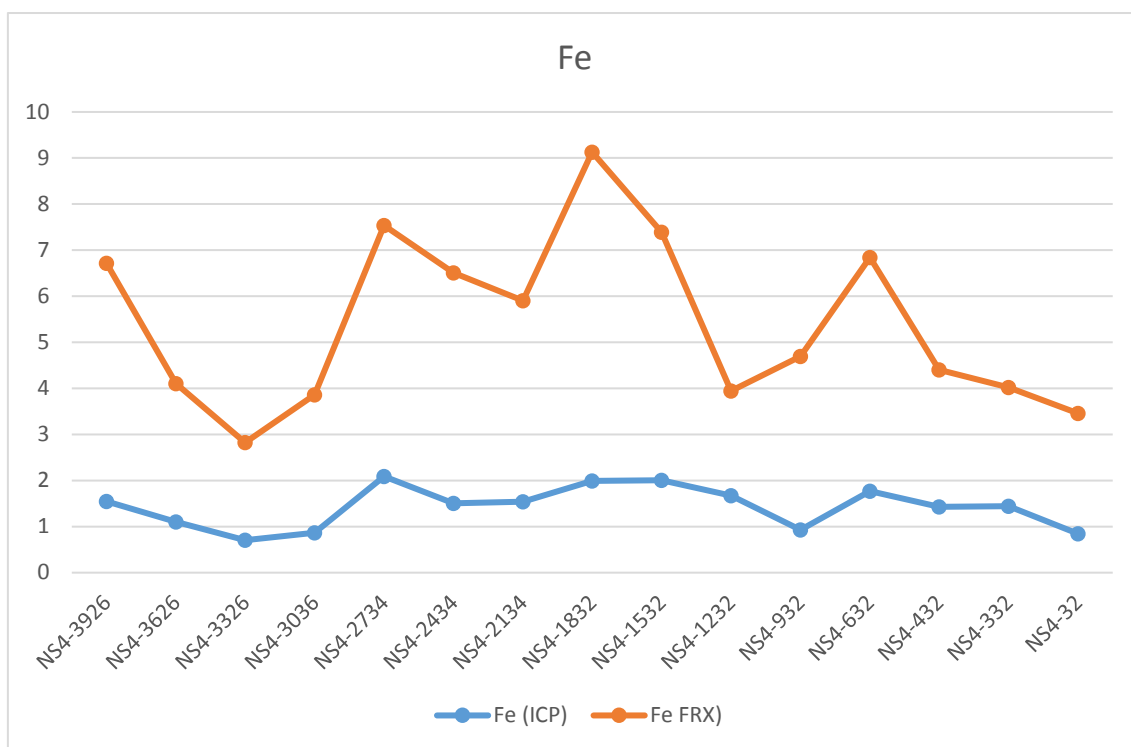


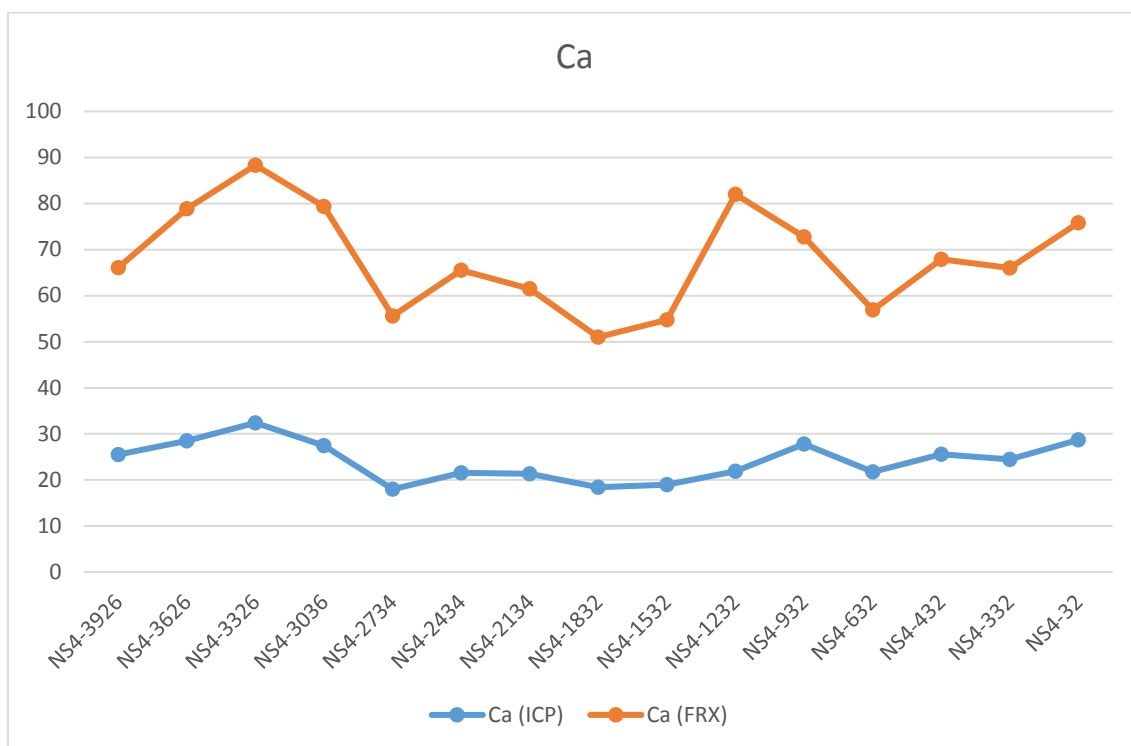
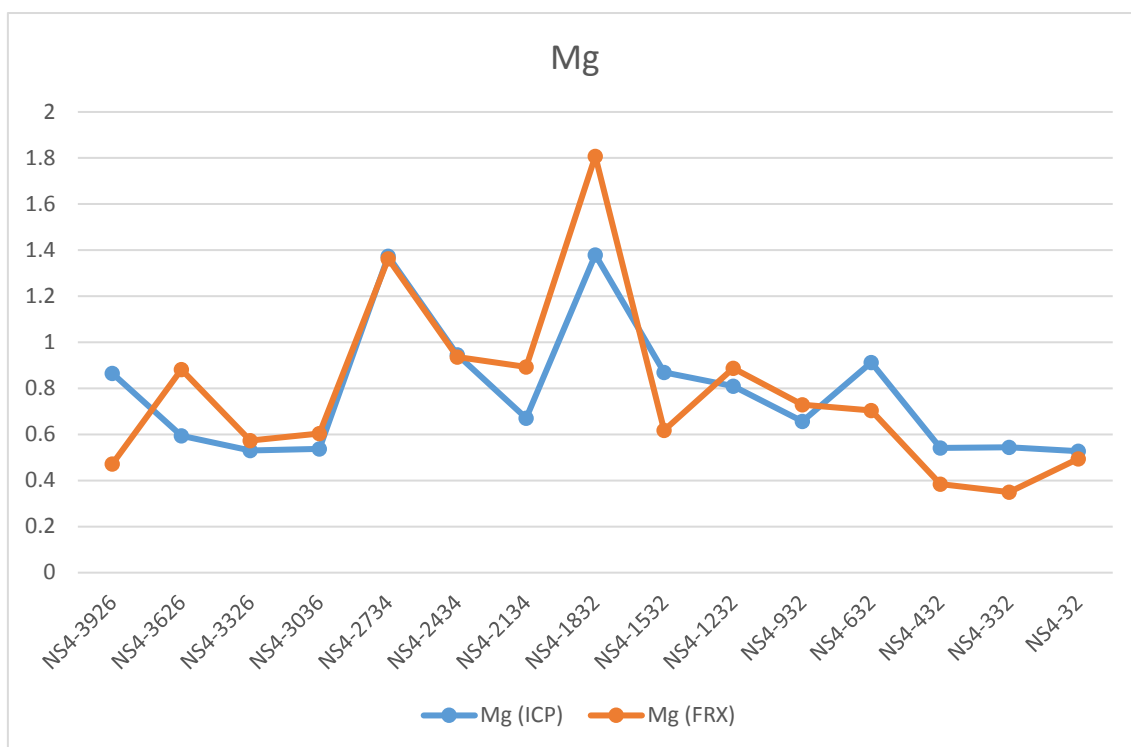


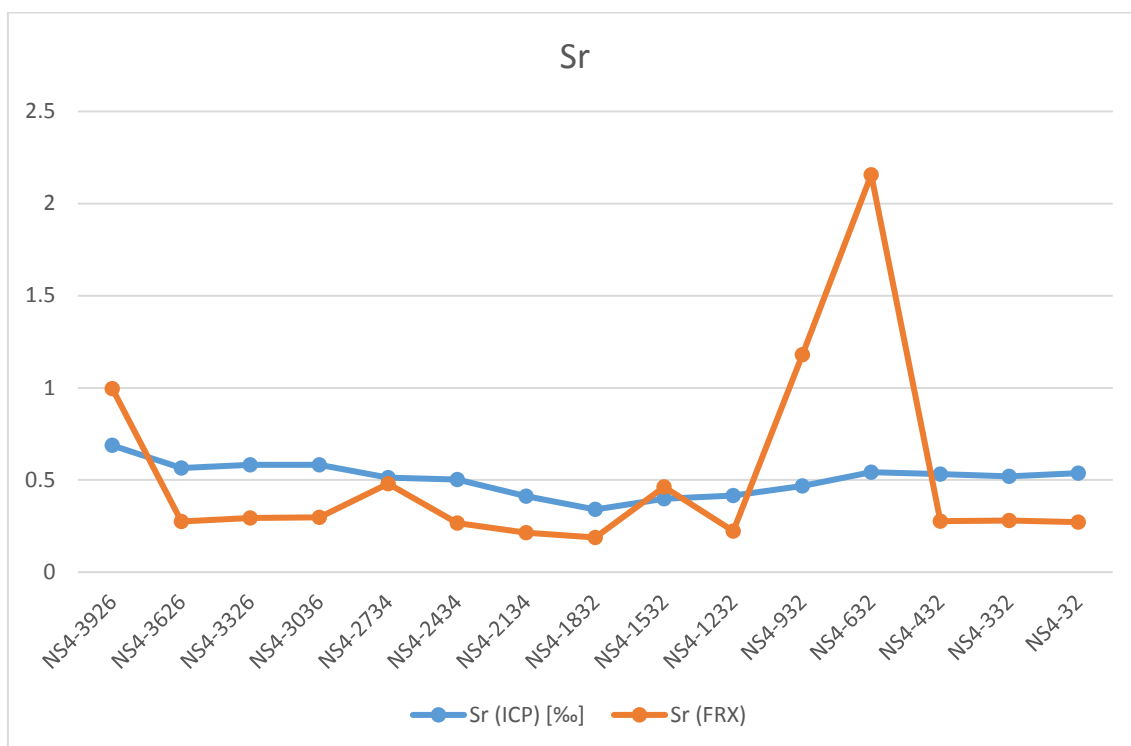
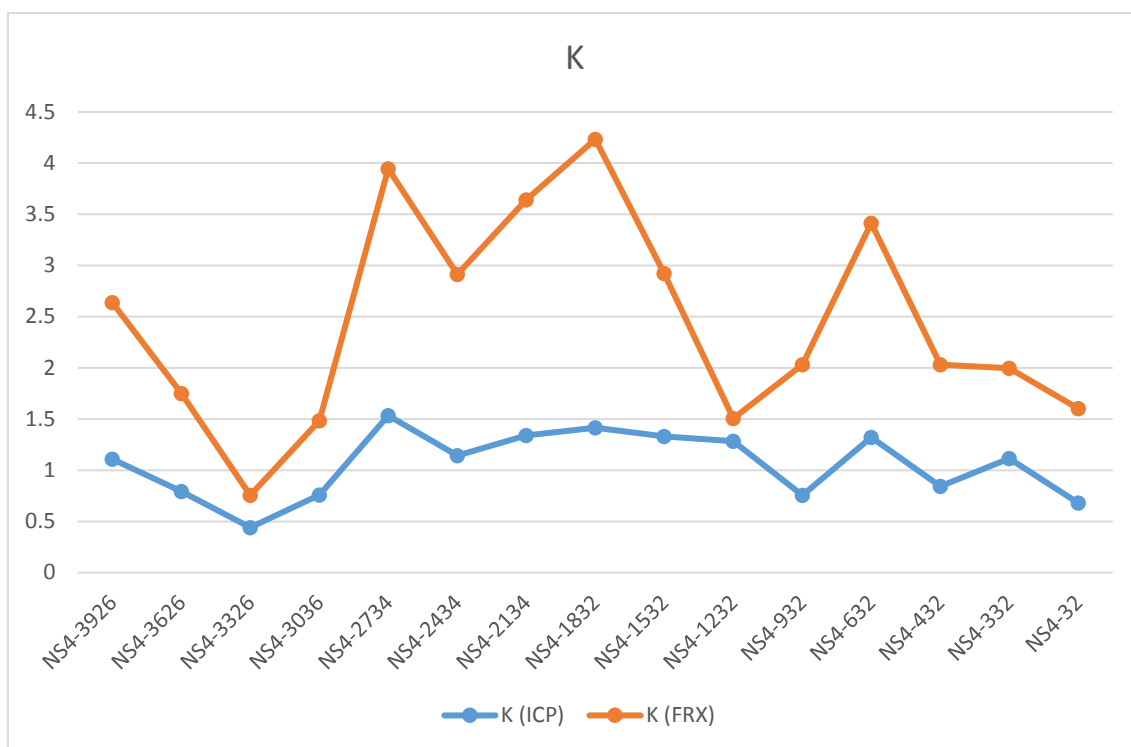


MUESTRA	Ti (ICP)	Ti (FRX)	Al (ICP)	Al (FRX)	Fe (ICP)	Fe FRX)	Mn (ICP)	Mn (FRX)	Mg (ICP)	Mg (FRX)	Ca (ICP)	Ca (FRX)	K (ICP)	K (FRX)	Sr (ICP)	Sr (ICP) [%]	Sr (FRX)
NS4-3926	0.17352624	0.67656785	2.17220067	3.8365516	1.5477845	6.7151013	0.01388029	0.05889085	0.86470191	0.47215779	25.5455166	66.1283283	1.10901381	2.63829138	0.06873984	0.68739836	0.99491219
NS4-3626	0.1125	0.47956953	1.355	3.58069866	1.105	4.1050969	0.01055	0.05923769	0.595	0.88252356	28.5	78.8720055	0.7935	1.75066277	0.0565	0.565	0.2745709
NS4-3326	0.06460541	0.25568731	0.79461525	1.70271608	0.7048779	2.82329548	0.01099978	0.05853448	0.53010765	0.57369328	32.4068484	88.3224266	0.44143102	0.75589617	0.05822495	0.58224945	0.28377214
NS4-3036	0.12158312	0.50500882	1.3369626	3.27608239	0.86393687	3.86372935	0.01071049	0.04996383	0.5377455	0.60385257	27.4917633	79.3828855	0.75938355	1.48575511	0.05826038	0.58260379	0.29776079
NS4-2734	0.24085335	0.99960513	3.23861445	7.99464903	2.08921663	7.53433764	0.01389694	0.04868389	1.37344513	1.36308353	17.9926173	55.6347208	1.53474543	3.94558827	0.05133466	0.51334662	0.4804577
NS4-2434	0.16711423	0.8308227	2.33941459	6.0710182	1.50820684	6.50949688	0.01300624	0.07132207	0.94548638	0.93654434	21.5560772	65.5080945	1.14495098	2.91399911	0.05031256	0.50312563	0.26663441
NS4-2134	0.18564717	0.8276202	2.5888198	7.19888034	1.53716831	5.90444458	0.01188906	0.04448737	0.67120561	0.89302498	21.3369968	61.4974277	1.3416705	3.64193709	0.04124227	0.41242269	0.21378312
NS4-1832	0.245	1.04527691	3.04	8.52023013	1.9923436	9.12934683	0.0165	0.07654605	1.38	1.80808578	18.45	51.0091867	1.415	4.2328905	0.034	0.34	0.18800906
NS4-1532	0.20994589	0.73765833	3.06402278	4.57349693	2.005	7.38836662	0.01341314	0.03628916	0.86888814	0.61803363	18.9671785	54.7983765	1.33069949	2.92124304	0.03976158	0.39761577	0.46320375
NS4-1232	0.17993111	0.39107435	2.64698632	3.11898827	1.67363488	3.94325153	0.01167874	0.05591044	0.80985397	0.88750517	21.9064657	82.0172478	1.2853562	1.50759973	0.04162747	0.41627466	0.22265432
NS4-932	0.10201954	0.49007574	1.53213126	3.50715577	0.93037522	4.6943194	0.01108315	0.0482431	0.6565247	0.72910804	27.8014675	72.741069	0.75538272	2.03097468	0.0466866	0.46686596	1.18032274
NS4-632	0.1480842	0.6157218	2.80876433	4.64020501	1.77219496	6.84007082	0.01168691	0.03249955	0.91290899	0.70476032	21.7485747	56.9468003	1.32127791	3.4143788	0.05423088	0.54230881	2.15648294
NS4-432	0.11466217	0.40437105	1.78885669	3.59526913	1.42759995	4.40601582	0.00798387	0.03604512	0.54162458	0.38493202	25.6076646	67.92235	0.84462765	2.03003464	0.05314135	0.53141354	0.27668224
NS4-332	0.135	0.37651226	2.485	3.16394126	1.445	4.02383417	0.008	0.01538457	0.545	0.34971781	24.5	66.0448261	1.115	1.99652631	0.052	0.52	0.28071919
NS4-32	0.09144055	0.35759377	1.44574831	3.44238948	0.84727195	3.46074119	0.0068909	0.04006368	0.52742197	0.49453644	28.7177324	75.8399264	0.68160236	1.60216215	0.05364881	0.53648814	0.27097172









Re-Os Study - Core Sampling

SAMPLES ReOs CAU CORE (DURHAM)		
99 SAMPLES		Analysed =
1	OS4-3926	x
2	OS4-3766	xx
3	OS4-3646	x
4	OS4-3566	x
5	OS4-3446	x
6	OS4-3326	x
7	OS4-3176	x
8	OS4-3056	x
9	OS4-2936	
10	OS4-2844	
11	OS4-2694	x
12	OS4-2484	x
13	OS4-2424	
14	OS4-2304	
15	OS4-2184	x
16	OS4-2054	x
17	OS4-1954	
18	OS4-1852	x
19	OS4-1752	
20	OS4-1632	
21	OS4-1612	x
22	OS4-1552	x
23	OS4-1472	
24	OS4-1392	
25	OS4-1352	x
26	OS4-1332	x
27	OS4-1152	x
28	OS4-1092	
29	OS4-1032	x
30	OS4-0802	
31	OS3-4993	x
32	OS3-4953	
33	OS3-4903	
34	OS3-4853	
35	OS3-4803	x
36	OS3-4783	
37	OS3-4753	
38	OS3-4723	
39	OS3-4653	
40	OS3-4553	x
41	OS3-4513	
42	OS3-4433	
43	OS3-4313	
44	OS3-4213	
45	OS3-4093	
46	OS3-4043	x
47	OS3-3873	
48	OS3-3773	

49	OS3-3673	
50	OS3-3553	
51	OS3-3413	
52	OS3-3293	
53	OS3-3193	
54	OS3-3073	x
55	OS3-2913	
56	OS3-2833	
57	OS3-2593	
58	OS3-2473	
59	OS3-2293	
60	OS3-2113	x
61	OS3-1713	xx
62	OS3-1193	xx
63	OS3-0663	x
64	OS2-3060	x
65	OS2-2601	x
66	OS2-2113	x
67	OS2-1575	x
68	OS2-1037	x
69	OS2-390	x
70	OS1-5735	x
71	OS1-5020	x
72	OS1-4735	
73	OS1-4225	x
74	OS1-3745	
75	OS1-3195	x
76	OS1-2715	
77	OS1-2155	x
78	OS1-1495	x
79	OS1-0795	x
80	OS1-0065	x
81	OS4-3686	x
82	OS4-3366	x
83	OS4-3206	x
84	OS4-3086	x
85	OS4-2140	x
86	OS4-1252	x
87	OS3-1023	x
88	OS3-3325	x
89	OS2-0907	x
90	OS2-0642	x
91	OS2-0300	x
92	OS2-0150	x
93	OS4-3500	x
94	OS4-3346	x
95	OS4-3286	x
96	OS4-3226	x
97	OS4-3146	x
98	OS4-3100	
99	OS4-2094	x

Re-Os Study – Analytical results

Depth	Core Sample	Core Reference	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	Re (ppt)	±	Os (ppt)	±	^{182}Os (ppt)	±	$^{187}\text{Re}/^{186}\text{Os}$	±	$^{187}\text{Os}/^{186}\text{Os}$	±	rho	% Re Blank	% ^{187}Os Blank	% ^{186}Os Blank	Os_i	±	Age
144.2	1	OS4-3926	2.32	-2.68	5.407	0.013	83.35	0.36	29.57	0.13	363.81	1.65	1.38	0.01	0.60	0.28	0.02	0.11	0.65	0.008	120.60
142.8	2*	OS4-3766	2.66	-2.48	4.765	0.012	84.36	0.38	30.41	0.13	311.77	1.56	1.24	0.01	0.59	0.31	0.02	0.11	0.61	0.008	120.54
142.2	81	OS4-3686	2.85	-2.05	1.850	0.005	70.21	0.30	26.30	0.12	139.89	0.76	0.91	0.01	0.61	0.81	0.03	0.12	0.63	0.006	120.51
141.8	3	OS4-3646	2.94	-2.21	2.887	0.007	79.81	0.30	29.65	0.11	193.68	0.89	0.98	0.01	0.60	0.08	0.03	0.14	0.59	0.005	120.49
141.1	4	OS4-3566	3.04	-2.16	2.585	0.007	53.95	0.23	19.71	0.08	260.98	1.30	1.13	0.01	0.62	0.58	0.03	0.16	0.60	0.007	120.46
140.7	93	OS4-3500	2.63	-2.42	3.791	0.002	97.34	0.41	35.99	0.15	209.56	0.90	1.02	0.01	0.69	0.45	0.02	0.11	0.60	0.007	120.44
140	5	OS4-3446	3.07	-2.51	1.775	0.005	29.32	0.15	10.83	0.07	325.94	2.31	1.03	0.01	0.70	0.14	0.09	0.37	0.37	0.010	120.41
139.6	82	OS4-3366	1.09	-3.20	4.564	0.011	89.62	0.39	32.93	0.15	275.73	1.43	1.08	0.01	0.62	0.33	0.02	0.10	0.52	0.007	120.40
139.4	94	OS4-3346	2.08	-2.66	3.127	0.002	60.88	0.27	22.29	0.10	279.10	1.31	1.11	0.01	0.71	0.54	0.03	0.18	0.54	0.008	120.39
139	6	OS4-3326	3.07	-2.13	0.578	0.002	80.53	0.35	30.03	0.14	38.28	0.24	0.95	0.01	0.52	0.41	0.03	0.13	0.87	0.006	120.37
138.8	95	OS4-3286	2.96	-2.41	4.447	0.002	75.17	0.32	27.68	0.12	319.64	1.43	1.06	0.01	0.70	0.38	0.03	0.15	0.81	0.007	120.36
138.4	83	OS4-3206	1.81	-3.08	3.533	0.009	82.97	0.36	30.48	0.14	230.56	1.20	1.08	0.01	0.63	0.42	0.02	0.11	0.61	0.007	120.34
138.2	96	OS4-3226	2.20	-2.65	3.154	0.002	66.89	0.30	24.40	0.11	257.19	1.17	1.14	0.01	0.71	0.54	0.03	0.16	0.62	0.007	120.33
137.8	7	OS4-3176	2.63	-2.26	2.839	0.007	100.97	0.37	39.12	0.17	144.36	0.74	0.63	0.00	0.61	0.08	0.04	0.10	0.34	0.004	120.32
137.6	97	OS4-3146	3.14	-2.33	2.861	0.002	39.22	0.18	14.49	0.07	392.85	2.04	1.03	0.01	0.74	0.59	0.05	0.28	0.24	0.008	120.31
137.2	84	OS4-3086	2.37	-2.46	2.902	0.007	73.12	0.32	27.15	0.13	212.62	1.14	0.98	0.01	0.63	0.52	0.02	0.12	0.56	0.007	120.29
136.8	8	OS4-3056	3.03	-2.37	0.370	0.002	77.71	0.36	29.17	0.16	25.24	0.21	0.89	0.01	0.48	0.65	0.04	0.14	0.84	0.007	120.27
134	11	OS4-2694	2.57	-2.70	1.755	0.005	60.42	0.30	22.44	0.13	155.63	0.99	0.98	0.01	0.65	0.14	0.05	0.18	0.67	0.008	120.15
132.6	12	OS4-2484	2.09	-2.16	3.155	0.008	61.70	0.31	22.51	0.12	278.87	1.63	1.14	0.01	0.61	0.08	0.04	0.18	0.58	0.009	120.09
131	15	OS4-2184	2.53	-2.16	3.758	0.009	64.40	0.32	23.73	0.13	315.09	1.94	1.05	0.01	0.65	0.06	0.04	0.17	0.42	0.009	120.01
129.8	85	OS4-2140	2.50	-2.32	2.754	0.007	40.35	0.19	14.96	0.08	366.36	2.14	1.00	0.01	0.66	0.54	0.04	0.22	0.26	0.008	119.96
129.4	99	OS4-2094	2.52	-2.42	1.495	0.002	87.43	0.36	32.56	0.14	91.35	0.42	0.96	0.01	0.67	1.13	0.03	0.12	0.78	0.006	119.94
128.7	16	OS4-2054	2.16	-2.37	0.692	0.003	125.83	0.79	47.26	0.42	29.12	0.28	0.89	0.01	0.65	0.35	0.02	0.08	0.83	0.011	119.91
127	18	OS4-1852	2.14	-2.27	2.232	0.006	55.32	0.28	20.24	0.12	219.38	1.38	1.11	0.01	0.65	0.11	0.03	0.20	0.67	0.009	119.84
125	21	OS4-1612	0.67	-2.48	4.193	0.014	89.40	0.47	32.94	0.20	253.20	1.66	1.05	0.01	0.63	0.06	0.03	0.12	0.54	0.010	119.75
124.5	22	OS4-1552	1.42	-2.65	5.765	0.014	92.39	0.44	32.89	0.15	348.66	1.81	1.35	0.01	0.62	0.04	0.02	0.12	0.65	0.009	119.73
122.8	25	OS4-1352	1.53	-2.57	15.053	0.037	144.16	0.72	48.90	0.21	612.39	3.05	1.79	0.01	0.63	0.03	0.02	0.16	0.56	0.012	119.65
121.9	26	OS4-1252	1.13	-2.84	11.269	0.028	153.58	0.71	54.70	0.23	409.89	2.02	1.35	0.01	0.61	0.02	0.01	0.07	0.53	0.009	119.61
121.7	86	OS4-1352	1.01	-2.31	9.146	0.022	487.37	1.35	194.04	0.73	93.77	0.41	0.41	0.00	0.58	0.16	0.01	0.02	0.22	0.002	119.60
121.4	27	OS4-1152	1.44	-2.72	18.210	0.045	1259.41	3.37	508.01	1.97	71.31	0.33	0.31	0.00	0.59	0.03	0.01	0.02	0.16	0.002	119.59
120.2	29	OS4-1032	1.36	-2.66	9.757	0.024	950.35	2.44	385.72	1.50	50.32	0.23	0.26	0.00	0.59	0.05	0.02	0.02	0.16	0.002	119.54
118.8	31	OS3-4993	1.54	-2.48	29.626	0.072	1128.10	3.20	447.83	1.62	131.61	0.57	0.43	0.00	0.58	0.02	0.01	0.02	0.17	0.003	119.47
116.8	35	OS3-4803	2.31	-2.44	7.728	0.019	305.14	0.98	120.65	0.51	127.44	0.63	0.47	0.00	0.61	0.03	0.02	0.03	0.21	0.003	119.39
113.6	40	OS3-4553	3.38	-2.23	22.298	0.055	632.26	1.99	247.49	0.93	179.24	0.80	0.55	0.00	0.58	0.02	0.01	0.03	0.19	0.003	119.24
108	46	OS3-4043	3.52	-1.91	17.364	0.043	274.81	1.12	103.30	0.44	334.40	1.65	0.88	0.01	0.58	0.03	0.02	0.08	0.21	0.007	119.00
100	54	OS3-3073	3.86	-1.96	8.523	0.021	295.30	0.93	117.34	0.50	144.50	0.71	0.43	0.00	0.61	0.03	0.02	0.03	0.14	0.003	118.64
91.7	60	OS3-2113	3.37	-1.88	21.688	0.053	535.66	1.77	207.96	0.80	207.48	0.94	0.61	0.00	0.59	0.02	0.02	0.04	0.20	0.004	118.27
88	61	OS3-1713	4.21	-1.90	8.288	0.020	231.30	0.75	90.26	0.34	182.69	0.83	0.57	0.00	0.58	0.03	0.02	0.04	0.21	0.004	118.11
83.5	62*	OS3-1193	3.85	-1.98	7.690	0.019	172.25	0.59	67.15	0.27	227.82	1.08	0.58	0.00	0.56	0.20	0.02	0.05	0.13	0.004	117.91
81.8	87	OS3-1023	3.71	-2.10	5.806	0.014	165.83	0.52	65.07	0.25	177.53	0.81	0.53	0.00	0.59	0.26	0.02	0.05	0.18	0.003	117.83
79	63	OS3-0663	3.67	-2.22	0.430	0.002	107.72	0.62	41.67	0.37	20.52	0.21	0.64	0.01	0.60	0.56	0.04	0.10	0.60	0.008	117.71
75.6	88	OS3-3325	3.79	-2.26	9.386	0.023	163.94	0.63	60.80	0.23	307.12	1.39	1.00	0.01	0.59	0.16	0.01	0.05	0.39	0.006	117.56
73.4	64	OS2-3060	4.39	-1.55	7.525	0.018	95.33	0.44	34.32	0.15	436.19	2.19	1.25	0.01	0.59	0.03	0.02	0.12	0.39	0.009	117.46
69.8	65	OS2-2601	3.84	-1.50	4.284	0.011	78.22	0.31	29.00	0.12	293.91	1.40	1.00	0.01	0.61	0.06	0.03	0.14	0.42	0.006	117.30
65.4	66	OS2-2113	3.41	-1.68	9.610	0.023	95.49	0.44	33.21	0.13	575.65	2.66	1.56	0.01	0.60	0.02	0.02	0.12	0.43	0.010	117.11
60.8	67	OS2-1575	2.97	-1.82	7.287	0.018	97.42	0.44	35.13	0.15	412.64	2.00	1.24	0.01	0.58	0.03	0.02	0.11	0.43	0.009	116.90
56.5	68	OS2-1037	2.65	-1.68	3.863	0.010	61.40	0.32	22.86	0.14	336.11	2.26	0.96	0.01	0.65	0.06	0.05	0.18	0.30	0.010	116.71
54.9	89	OS2-0907	2.15	-2.13	4.468	0.011	87.26	0.37	32.16	0.14	276.36	1.40	1.05	0.01	0.62	0.34	0.02	0.10	0.51	0.007	116.64
53.2	90	OS2-0642	2.30	-2.06	4.268	0.011	68.95	0.30	25.28	0.12	335.84	1.74	1.09	0.01	0.62	0.35	0.02	0.13	0.44	0.008	116.57
48	70	OS1-5735	2.47	-1.98	2.730	0.007	54.49	0.26	20.21	0.11	268.69	1.67	0.99	0.01	0.66	0.09	0.05	0.20	0.47	0.008	116.34
43.6	71	OS1-5020	2.84	-2.25	5.806	0.014	67.73	0.34	23.70	0.11	487.31	2.60	1.51	0.01	0.64	0.04	0.03	0.17	0.56	0.011	116.14
34.6	73	OS1-4425	3.71	-1.70	7.678	0.019	59.86	0.31	19.96	0.09	765.27	3.89	1.95	0.01	0.64	0.03	0.02	0.20	0.47	0.014	115.74
25.2	75	OS1-3195	3.99	-1.80	5.005	0.012	55.28	0.30	19.19	0.10	518.92	2.98	1.58	0.01	0.65	0.03	0.02	0.17	0.58	0.013	115.33
16.4	77	OS1-2155	3.59	-1.83	1.896	0.005	25.82	0.15	9.23	0.07	408.76	3.12	1.31	0.01	0.71	0.13	0.08	0.43	0.53	0.014	114.94
11.8	78	OS1-1495	4.07	-1.70	4.352	0.011	53.90	0.27	19.06	0.09	454.14	2.48	1.41	0.01	0.65	0.34	0.02	0.17	0.54	0.011	114.73
6.2	79	OS1-0795	3.87	-2.11	2.141	0.006	35.10	0.20	12.79	0.09	332.89	2.49	1.14	0.01	0.66	0.70	0.04	0.25	0.51	0.012	114.48

MARIOLA – Field samples & Thin Sections

Agres				
A-1	A-12	LA-1	LA-12	LA-23
A-2	A-13	LA-2	LA-13	LA-24
A-3	A-14	LA-3	LA-14	LA-25
A-4	A-15	LA-4	LA-15	LA-26
A-5	A-16	LA-5	LA-16	LA-27
A-6	A-16a	LA-6	LA-17	LA-28
A-7	A-17	LA-7	LA-18	LA-29
A-8	A-18	LA-8	LA-19	LA-30
A-9	A-19	LA-9	LA-20	
A-10	A-20	LA-10	LA-21	
A-11	A-20a	LA-11	LA-22	
La Purísima		Llopis		
LP-0	LP-27	LP-56	SCL-1	SCL-34
LP-1	LP-28	LP-57	SCL-2	SCL-35
LP-2	LP-29	LP-58	SCL-3	SCL-36
LP-3	LP-30	LP-59	SCL-4	SCL-37
LP-4	LP-31	LP-60	SCL-5	SCL-38
LP-5	LP-32	LP-61	SCL-6	SCL-39
LP-6	LP-33	LP-62	SCL-7	SCL-40
LP-7	LP-34	LP-63	SCL-8	SCL-41
LP-7a	LP-35	LP-64	SCL-9	SCL-42
LP-7b	LP-36	LP-65	SCL-10	SCL-43
LP-8	LP-37	LP-66	SCL-11	SCL-43a
LP-9	LP-38	LP-67	SCL-12	SCL-44
LP-10	LP-39	LP-68	SCL-13	SCL-45
LP-11	LP-40	LP-69	SCL-14	SCL-46
LP-12	LP-41	LP-70	SCL-15	SCL-47
LP-13	LP-42	LP-71	SCL-16	SCL-48
LP-14	LP-43	LP-72	SCL-17	SCL-49
LP-15	LP-44	Techo-Llopis	SCL-18	SCL-50
LP-16	LP-45	Base-	SCL-19	SCL-51
LP-17	LP-46	Almadich	SCL-20	SCL-52
LP-18	LP-47		SCL-21	SCL-53
LP-19	LP-48		SCL-22	SCL-54
LP-20	LP-49		SCL-23	SCL-55
LP-21	LP-50		SCL-24	SCL-56
LP-22	LP-51		SCL-25	SCL-57
LP-23	LP-52		SCL-26	SCL-58
LP-24	LP-53		SCL-27	
LP-25	LP-54		SCL-28	
LP-26	LP-55		SCL-29	
			SCL-30	
			SCL-31	
			SCL-32	
			SCL-33	

Racó Llobet

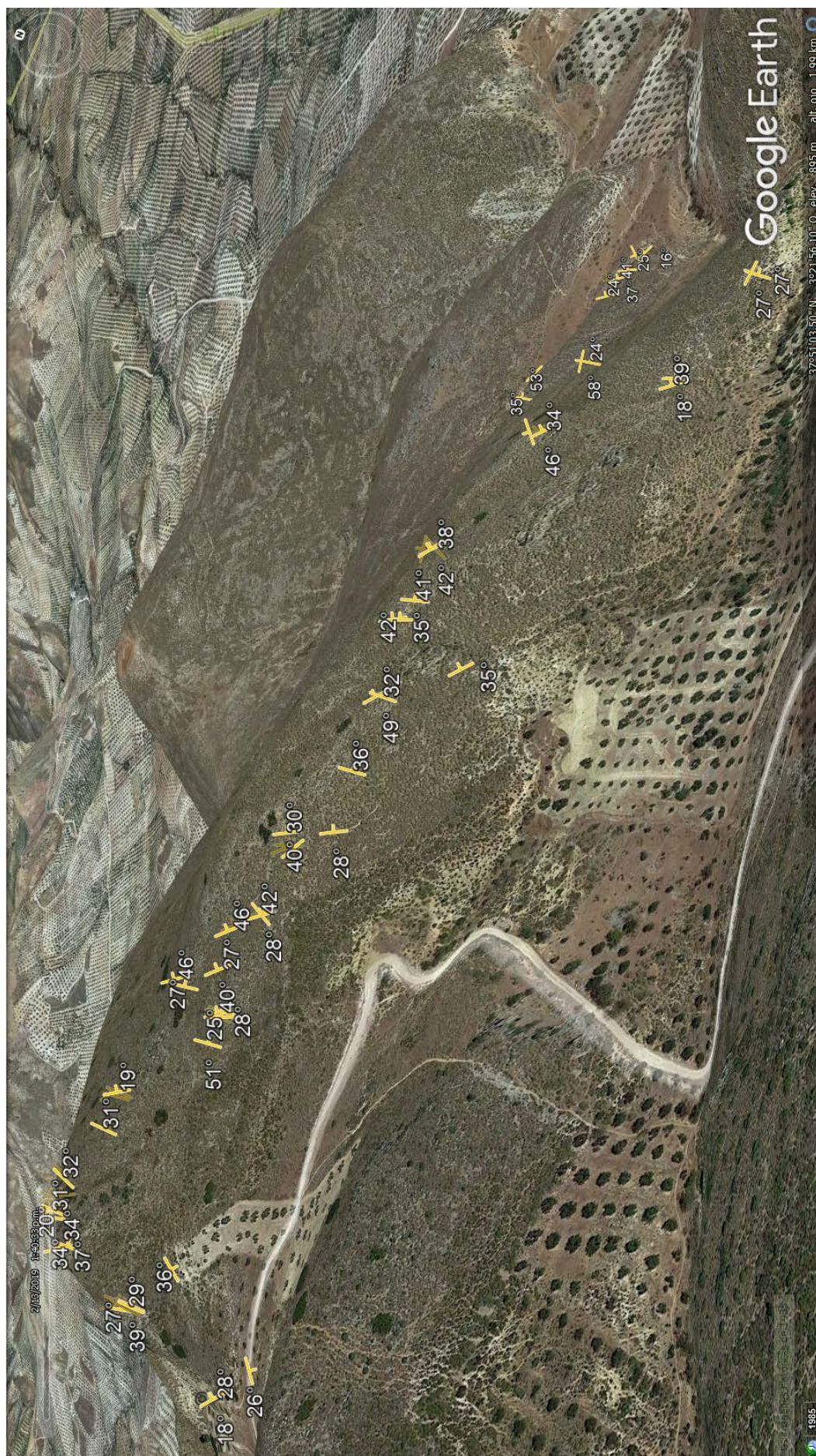
RL-1	RL-49	GS16-13
RL-2	RL-50	GS16-14
RL-3	RL-51	GS16-15
RL-4	RL-52	GS16-16
RL-5	RL-53	GS16-17
RL-6	RL-54	GS16-18
RL-7	RL-55	GS16-19
RL-8	RL-56	GS16-20
RL-9	RL-57	GS16-21
RL-10	RL-58	GS16-22
RL-11	RL-59	GS16-23
RL-12	RL-60	GS16-24
RL-13	RL-61	GS16-25
RL-14	RL-62	GS16-26
RL-15	RL-63	GS16-27
RL-16	RL-64	GS16-28
RL-17	RL-65	GS16-29
RL-18	RL-66	GS16-30
RL-19	RL-67	GS16-31
RL-20	RL-68	GS16-32
RL-21	RL-69	GS16-33
RL-22	RL-70	GS16-34
RL-23	RL-71	GS16-35
RL-24	RL-72	GS16-36
RL-25	RL-73	GS16-37
RL-26	RL-74	GS16-38
RL-27	RL-75	GS16-39
RL-28	RL-76	GS16-40
RL-29	RL-77	GS16-41
RL-30	RL-78	GS16-42
RL-31	RL-79	GS16-43
RL-32	RL-80	GS16-44
RL-33	RL-81	GS16-45
RL-34	RL-82	GS16-46
RL-34a	RL-83	GS16-47
RL-35	GS16-1	GS16-48
RL-36	GS16-2	GS16-49
RL-37	GS16-3	GS16-50
RL-38	GS16-4	GS16-51
RL-39	GS16-5A	GS16-52
RL-40	GS16-5B	GS16-53
RL-41	GS16-6	GS16-54
RL-42	GS16-7	GS16-55
RL-43	GS16-8	
RL-44	GS16-9	
RL-45	GS16-10A	
RL-46	GS16-10B	
RL-47	GS16-11	
RL-48	GS16-12	

BEDMAR-JÓDAR - Field samples & Thin Sections

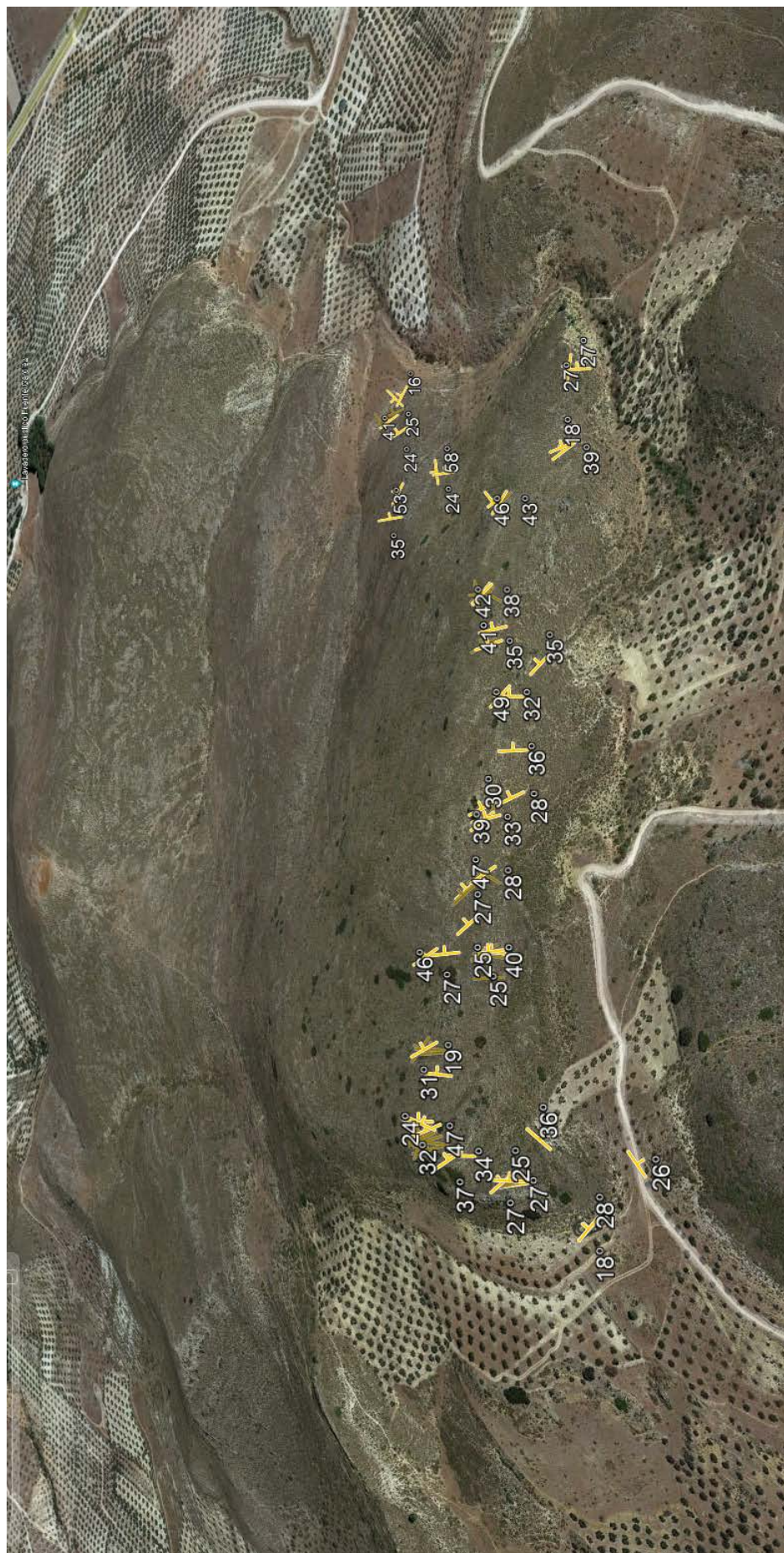
BT-1	BT-18	BT-34	BT-51	BT-68
BT-2	BT-19	BT-35	BT-52	BT-69
BT-3	BT-20	BT-36	BT-53	BT-70
BT-4	BT-21	BT-37	BT-54	BT-71
BT-5	BT-22	BT-38	BT-55	BT-72
BT-6	BT-23	BT-39	BT-56	BT-73
BT-7	BT-24	BT-40	BT-57	BT-74
BT-8	BT-25	BT-41	BT-58	BT-75
BT-9	BT-26	BT-42	BT-59	BT-76
BT-10	BT-27A	BT-43	BT-60	BT-77
BT-11	BT-27B	BT-44	BT-61	BT-78
BT-12	BT-28	BT-45	BT-62	BT-79
BT-13	BT-29	BT-46	BT-63	BT-80
BT-14	BT-30	BT-47	BT-64	BT-81
BT-15	BT-31	BT-48	BT-65	BT-82
BT-16	BT-32	BT-49	BT-66	
BT-17	BT-33	BT-50	BT-67	

BEDMAR-JÓDAR – Outcrop structure analysis

latitude	longitude	zone	altitude	horiz_precis	vert_precis	planeType	dip	dipAzimuth	strike
37.8534681	-3.36034419	30S	0	-1	-1	Bedding	53	26	296
37.8536221	-3.36055185	30S	0	-1	-1	Bedding	35	80	350
37.8530936	-3.36020875	30S	0	-1	-1	Bedding	58	82	352
37.8530848	-3.3601984	30S	0	-1	-1	Bedding	24	353	263
37.8519053	-3.35952171	30S	0	-1	-1	Bedding	27	8	278
37.8519149	-3.35953658	30S	0	-1	-1	Bedding	27	87	357
37.8518232	-3.36023529	30S	0	-1	-1	Bedding	18	68	338
37.851787	-3.36027846	30S	0	-1	-1	Bedding	39	53	323
37.8520879	-3.36068155	30S	0	-1	-1	Bedding	46	322	232
37.8520879	-3.36068155	30S	0	-1	-1	Bedding	43	32	302
37.8520811	-3.36067656	30S	0	-1	-1	Bedding	34	44	314
37.8519974	-3.36144821	30S	0	-1	-1	Bedding	42	45	315
37.8519961	-3.36144875	30S	0	-1	-1	Bedding	38	38	308
37.8520083	-3.36144946	30S	0	-1	-1	Bedding	38	120	30
37.8520063	-3.36145067	30S	0	-1	-1	Bedding	44	353	263
37.852008	-3.3614526	30S	0	-1	-1	Bedding	43	53	323
37.8520099	-3.36145318	30S	0	-1	-1	Bedding	38	59	329
37.8520048	-3.36145366	30S	0	-1	-1	Bedding	36	51	321
37.8520116	-3.36145464	30S	0	-1	-1	Bedding	24	113	23
37.8518844	-3.36174026	30S	0	-1	-1	Bedding	41	76	346
37.8518824	-3.36186149	30S	0	-1	-1	Bedding	35	70	340
37.8519051	-3.36186707	30S	0	-1	-1	Bedding	42	61	331
37.8515077	-3.36201919	30S	0	-1	-1	Bedding	35	43	313
37.8516837	-3.36226338	30S	0	-1	-1	Bedding	32	90	0
37.8516876	-3.36226215	30S	0	-1	-1	Bedding	49	42	312
37.8515793	-3.36266791	30S	0	-1	-1	Bedding	36	87	357
37.8515347	-3.36301879	30S	0	-1	-1	Bedding	28	64	334
37.8516918	-3.36309989	30S	0	-1	-1	Bedding	30	64	334
37.8516785	-3.36317393	30S	0	-1	-1	Bedding	39	75	345
37.8516743	-3.36319194	30S	0	-1	-1	Bedding	33	51	321
37.8516286	-3.3631677	30S	0	-1	-1	Bedding	40	31	301
37.8516504	-3.36358442	30S	0	-1	-1	Bedding	42	122	32
37.8516504	-3.36358442	30S	0	-1	-1	Bedding	31	58	328
37.8516636	-3.36394139	30S	0	-1	-1	Bedding	27	48	318
37.8516288	-3.36358076	30S	0	-1	-1	Bedding	28	55	325
37.8517319	-3.36373822	30S	0	-1	-1	Bedding	46	48	318
37.8517147	-3.36369263	30S	0	-1	-1	Bedding	47	48	318
37.8515385	-3.36412441	30S	0	-1	-1	Bedding	40	82	352
37.8515385	-3.36412441	30S	0	-1	-1	Bedding	25	97	7
37.8515385	-3.36412441	30S	0	-1	-1	Bedding	39	59	329
37.8515351	-3.36413002	30S	0	-1	-1	Bedding	28	56	326
37.8515245	-3.36414397	30S	0	-1	-1	Bedding	25	69	339
37.8515442	-3.36414992	30S	0	-1	-1	Bedding	34	99	9
37.8515203	-3.36430459	30S	0	-1	-1	Bedding	51	87	357
37.8519859	-3.36421558	30S	0	-1	-1	Bedding	46	55	325
37.851865	-3.36417848	30S	0	-1	-1	Bedding	27	84	354
37.8518671	-3.36486303	30S	0	-1	-1	Bedding	19	60	330
37.8518671	-3.36486303	30S	0	-1	-1	Bedding	28	93	3
37.8518671	-3.36486303	30S	0	-1	-1	Bedding	27	35	305
37.8518718	-3.36489325	30S	0	-1	-1	Bedding	34	86	356
37.8517686	-3.36501507	30S	0	-1	-1	Bedding	31	96	6
37.8518171	-3.36536652	30S	0	-1	-1	Bedding	32	115	25
37.8518509	-3.36535469	30S	0	-1	-1	Bedding	24	94	4
37.8517217	-3.36538889	30S	0	-1	-1	Bedding	47	67	337
37.8517386	-3.36540691	30S	0	-1	-1	Bedding	33	9	279
37.8517421	-3.36541226	30S	0	-1	-1	Bedding	23	49	319
37.8517368	-3.36544755	30S	0	-1	-1	Bedding	27	63	333
37.8517165	-3.36545402	30S	0	-1	-1	Bedding	33	75	345
37.8517033	-3.36546737	30S	0	-1	-1	Bedding	36	16	286
37.8517005	-3.3654701	30S	0	-1	-1	Bedding	31	95	5
37.8516954	-3.36548533	30S	0	-1	-1	Bedding	20	29	299
37.8517038	-3.36551787	30S	0	-1	-1	Bedding	34	76	346
37.851509	-3.36553995	30S	0	-1	-1	Bedding	37	56	326
37.851485	-3.36550642	30S	0	-1	-1	Bedding	34	91	1
37.8511858	-3.36561978	30S	0	-1	-1	Bedding	27	93	3
37.8511737	-3.36562769	30S	0	-1	-1	Bedding	25	49	319
37.8511617	-3.36563467	30S	0	-1	-1	Bedding	33	75	345
37.8511515	-3.3656419	30S	0	-1	-1	Bedding	27	81	351
37.8511228	-3.36561414	30S	0	-1	-1	Bedding	33	99	9
37.8511141	-3.36559622	30S	0	-1	-1	Bedding	29	95	5
37.8511146	-3.36558886	30S	0	-1	-1	Bedding	39	94	4
37.8511334	-3.36559523	30S	0	-1	-1	Bedding	31	98	8
37.8510497	-3.36532079	30S	0	-1	-1	Bedding	36	131	41
37.8504387	-3.36534716	30S	0	-1	-1	Bedding	26	146	56
37.8506974	-3.36585142	30S	0	-1	-1	Bedding	28	39	309
37.8506974	-3.36585136	30S	0	-1	-1	Bedding	18	44	314



Barranco del Tejar – FieldClino dip measurements .kmz file (Google Earth view).



CAU CORE – sample log

A sample log database is presented for information. Numbers in samples indicate perforation depth (uncorrected) in cm. This data is available at: Castro, Jose Manuel; Ruiz-Ortiz, Pedro A; de Gea, Ginés A; Aguado, Roque; Jarvis, Ian; Weissert, Helmut J; Molina, José M; Nieto, Luis M; Pancost, Richard D; Quijano, María L; Reolid, Matías; Skelton, Peter W; López-Rodríguez, Carmina; Martínez-Rodríguez, Rafael (2020): Geochemistry of the CAU core (drilled 2015-2017): C and O isotopes, TOC and CaCO₃ - Aptian - Betic Cordillera, Alicante, Spain. PANGAEA, <https://doi.org/10.1594/PANGAEA.920558>

Samples D4	True stratigraphic depth (m)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	TOC	CaCO ₃
GS4-0032	0.25	2.84	-2.04		76.71
GS4-0052	0.40	2.97	-2.15		75.95
GS4-0072	0.55	3.00	-2.34	1.2	68.30
GS4-0092	0.70	3.06	-2.20		68.92
GS4-0112	0.86	3.02	-2.15		70.27
GS4-0132	1.01	3.00	-2.00		73.91
GS4-0152	1.16	3.08	-2.17		71.29
GS4-0172	1.32	3.13	-2.22		67.73
GS4-0192	1.47	3.21	-2.26		67.48
GS4-0212	1.62	3.21	-2.46	1.1	61.89
GS4-0232	1.78	3.21	-2.26		62.91
GS4-0252	1.93	3.20	-2.15		60.62
GS4-0272	2.08	3.12	-2.16		67.14
GS4-0292	2.24	3.10	-2.42	0.2	60.54
GS4-0312	2.39	3.00	-2.20		64.26
GS4-0332	2.54	2.94	-2.26		68.33
GS4-0352	2.70	2.98	-2.18		58.93
GS4-0372	2.85	3.01	-2.32		60.70
GS4-0392	3.00	2.94	-2.33	1.6	62.82
GS4-0412	3.16	2.74	-2.23		59.86
GS4-0422	3.23	2.84	-2.19	0.7	
GS4-0432	3.31	2.80	-2.29		66.89
GS4-0452	3.46	2.75	-2.36		66.63
GS4-0472	3.62	2.51	-2.50		66.04
GS4-0492	3.77	2.40	-2.40	0.3	58.80
GS4-0512	3.94	2.36	-2.56		50.21
GS4-0532	4.11	2.24	-2.44		57.23
GS4-0552	4.28	2.23	-2.72		54.02
GS4-0572	4.45	2.11	-2.88		53.42
GS4-0592	4.62	2.09	-2.72	1.2	52.07
GS4-0612	4.79	2.11	-2.70		55.54

GS4-0622	4.88	1.95	-2.99	1.1	
GS4-0632	4.97	2.04	-2.67		56.30
GS4-0652	5.14	1.98	-2.53		61.30
GS4-0672	5.31	1.80	-2.72		54.78
GS4-0692	5.48	1.72	-2.97	1.2	46.31
GS4-0702	5.56	1.79	-2.62	1.5	54.10
GS4-0712	5.65	1.74	-2.88		61.21
GS4-0732	5.82	1.68	-2.66		59.77
GS4-0752	5.99	1.63	-2.52		57.90
GS4-0772	6.16	1.62	-2.55	1	49.53
GS4-0792	6.33	1.52	-2.55		39.80
GS4-0812	6.50	1.47	-2.65	1.2	41.91
GS4-0832	6.68	1.27	-2.80		41.23
GS4-0852	6.85	1.32	-3.08	1.3	69.85
GS4-0872	7.02	1.41	-2.57		62.40
GS4-0892	7.19	1.37	-2.78		59.18
GS4-0912	7.36	1.17	-2.86	1.6	74.76
GS4-0932	7.53	1.09	-2.29		35.73
GS4-0952	7.70			0.7	74.68
GS4-0972	7.87	1.28	-2.40		67.31
GS4-0992	8.04	1.27	-2.85		74.34
GS4-1012	8.20	1.25	-2.56	0.9	73.66
GS4-1032	8.36	1.36	-2.66		66.04
GS4-1052	8.52	1.16	-2.67		62.70
GS4-1072	8.67	1.08	-2.75	1.8	82.13
GS4-1092	8.83	1.40	-2.41		68.10
GS4-1112	8.99	1.44	-2.60		77.05
GS4-1132	9.15	1.45	-2.36		65.11
GS4-1152	9.30	1.44	-2.72	1.2	71.20
GS4-1172	9.46	1.36	-2.61		78.91
GS4-1192	9.62	1.38	-2.31		73.24
GS4-1212	9.78	1.43	-2.28		53.68
GS4-1222	9.86	1.39	-2.16	1	
GS4-1232	9.94	1.07	-2.70		56.56
GS4-1252	10.09	1.01	-2.31		53.68
GS4-1272	10.25	0.99	-2.55	0.8	56.81
GS4-1292	10.41	0.86	-2.65		72.98
GS4-1312	10.57	1.63	-2.33		49.87
GS4-1322	10.65	1.67	-2.10		
GS4-1332	10.72	1.13	-2.84	1.6	62.23
GS4-1352	10.88	1.53	-2.57		55.50
GS4-1372	11.04	1.43	-2.75	1.2	67.65

GS4-1392	11.20	1.62	-2.45		54.02
GS4-1412	11.36	1.25	-2.80		62.82
GS4-1432	11.51	1.53	-2.33		25.23
GS4-1452	11.67	-0.46	-3.65	0.4	69.68
GS4-1456	11.70				
GS4-1472	11.83	1.68	-2.24	0.8	43.35
GS4-1492	11.99	1.52	-2.68		43.52
GS4-1512	12.15	1.51	-2.61		48.94
GS4-1532	12.32	1.00	-3.12		53.85
GS4-1552	12.49	1.42	-2.65		53.59
GS4-1572	12.65	1.26	-2.21	1.5	49.70
GS4-1592	12.82	0.94	-2.33		37.34
HS4-1611	12.98	0.66	-2.45		
GS4-1612	12.99	0.67	-2.48		69.00
HS4-1613	12.997	0.56	-2.27		
HS4-1614	13.006	0.49	-2.46		
HS4-1615	13.014	0.52	-2.29		
HS4-1616	13.022	0.57	-2.31		
HS4-1617	13.031	1.46	-2.46		
HS4-1618	13.039	1.54	-2.31		
HS4-1618.5	13.043	1.69	-2.13		
HS4-1619	13.047	1.42	-2.39		
HS4-1620	13.056	1.71	-2.19		
HS4-1621	13.064	1.76	-2.22		
HS4-1622	13.072	1.77	-2.19		
GS4-1622	13.072	1.72	-2.29		
HS4-1623	13.081	1.97	-2.08		
HS4-1625	13.098	2.13	-2.01		
HS4-1626	13.106	2.15	-2.13		
HS4-1627	13.114	2.01	-2.08		
HS4-1628	13.123	2.25	-2.21		
HS4-1629	13.131	2.26	-2.10		
HS4-1630	13.139	2.25	-2.18		
HS4-1631	13.148	2.31	-2.12		
HS4-1632	13.156	2.31	-2.17		
GS4-1632	13.156	2.19	-2.26		70.19
HS4-1633	13.164	2.25	-2.21		
GS4-1652	13.32	2.26	-2.30		59.27
GS4-1672	13.49	2.18	-2.45	1	64.09
GS4-1682	13.57	2.19	-2.41		
GS4-1692	13.66	2.24	-2.45		63.08
GS4-1712	13.82	2.17	-2.40		60.79

GS4-1732	13.99	2.04	-2.49		57.66
GS4-1752	14.16	1.99	-2.42		44.10
GS4-1772	14.33	1.72	-2.50		54.27
GS4-1792	14.49	1.72	-2.27	0.1	55.71
GS4-1812	14.66	1.70	-2.32		53.00
GS4-1822	14.74	1.71	-2.10	1.5	
GS4-1832	14.83	1.81	-2.33		50.80
GS4-1852	14.99	2.14	-2.27		43.18
GS4-1872	15.16	1.99	-2.37		40.64
GS4-1892	15.33	2.18	-2.22		37.51
GS4-1912	15.50	1.98	-2.34		36.32
GS4-1934	15.68	1.78	-2.41		32.60
GS4-1954	15.85	1.58	-2.55		31.33
GS4-1974	16.01	1.64	-2.89		35.64
GS4-1994	16.18	1.87	-2.95		52.24
GS4-2014	16.35	2.21	-2.85		57.83
GS4-2034	16.51	1.93	-2.53		80.18
GS4-2054	16.68	2.16	-2.37		81.53
GS4-2074	16.84	2.43	-2.37		81.40
GS4-2094	17.00	2.52	-2.42		71.63
GS4-2124	17.25	2.15	-2.34	0.9	74.34
GS4-2154	17.50	2.50	-2.32		72.98
GS4-2184	17.75	2.53	-2.16		72.47
GS4-2214	17.99	2.46	-2.24		79.92
GS4-2244	18.24	2.52	-2.17		78.60
GS4-2274	18.49	2.62	-2.22		71.71
GS4-2304	18.74	2.31	-2.10		68.33
GS4-2334	18.98	2.56	-2.15		62.31
GS4-2364	19.23	2.53	-2.36		62.40
GS4-2394	19.48	2.86	-2.30		59.52
GS4-2424	19.73	2.72	-2.14	0.6	51.90
GS4-2454	19.97	2.27	-2.36		48.51
GS4-2484	20.22	2.09	-2.16		33.70
GS4-2514	20.45	2.02	-1.95		54.69
GS4-2544	20.69	2.55	-2.23		46.74
GS4-2574	20.92	2.54	-2.17	0.2	54.61
GS4-2606	21.17	2.92	-2.41		57.06
GS4-2634	21.39	2.89	-2.43		76.11
GS4-2664	21.63	3.09	-2.47		49.70
GS4-2694	21.86	2.57	-2.70		21.84
GS4-2724	22.10	2.35	-2.92	1.32	34.50
GS4-2754	22.33	2.45	-2.74		54.78

GS4-2784	22.57	2.89	-2.56		59.10
GS4-2814	22.80	3.01	-2.44		61.98
GS4-2844	23.03	2.92	-2.64		63.50
GS4-2876	23.28	2.97	-2.53		74.76
GS4-2906	23.52	3.13	-2.46		65.11
GS4-2936	23.75	3.07	-2.25		60.54
GS4-2966	23.99	3.05	-2.36	0.1	41.40
GS4-2996	24.22	2.22	-2.94		56.73
GS4-3026	24.49	2.08	-2.77		82.55
GS4-3056	24.75	3.03	-2.37		53.85
GS4-3086	25.01	2.37	-2.46		76.11
GS4-3116	25.27	2.80	-2.24		81.62
GS4-3146	25.53	3.14	-2.33		61.72
GS4-3176	25.80	2.63	-2.26		40.81
GS4-3206	26.06	1.81	-3.08		61.30
GS4-3246	26.41	2.60	-2.21		80.01
GS4-3286	26.76	2.96	-2.41		81.53
GS4-3326	27.11	3.07	-2.13	0	37.76
GS4-3366	27.46	1.09	-3.20	0.9	41.66
GS4-3406	27.81	1.77	-2.88		85.90
GS4-3446	28.16	3.07	-2.51		47.33
GS4-3486	28.51	2.12	-2.55		82.30
GS4-3526	28.84	3.14	-2.29		78.23
GS4-3566	29.16	3.04	-2.16		75.44
GS4-3606	29.49	2.96	-2.11		71.03
GS4-3626	29.66	2.70	-1.88	0.5	
GS4-3646	29.82	2.94	-2.21		58.84
GS4-3656	29.90			0.4	
GS4-3686	30.15	2.85	-2.05		67.50
GS4-3726	30.47	2.84	-2.39		49.44
GS4-3766	30.80	2.66	-2.48	0.3	58.50
GS4-3806	31.13	2.51	-2.19		58.00
GS4-3846	31.46	2.53	-2.44		45.21
GS4-3886	31.79	1.90	-2.40		63.92
GS4-3926	32.11	2.32	-2.68	1.3	75.5

Samples D3	True stratigraphic depth (m)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	TOC	CaCO_3
GS3-0073	0.64	3.53	-2.58		65.30
GS3-0103	0.91	4.02	-1.65		83.07
GS3-0133	1.17	3.27	-2.70		55.81

GS3-0163	1.44	3.90	-2.05		82.28
GS3-0193	1.70	4.20	-1.58		81.67
GS3-0223	1.97	4.02	-1.71		82.63
GS3-0253	2.23	3.65	-2.30		72.97
GS3-0273	2.41			0.6	
GS3-0283	2.50	4.23	-1.36		85.16
GS3-0313	2.76	3.70	-2.04		69.74
GS3-0343	3.03	3.92	-2.02		80.63
GS3-0363	3.20	4.21	-1.74		93.50
GS3-0373	3.29	4.14	-1.73		84.89
GS3-0393	3.47	3.99	-2.18		85.33
GS3-0403	3.56	4.43	-1.41		93.00
GS3-0423	3.73	3.54	-2.80		56.16
GS3-0433	3.82	3.67	-2.63	0.4	82.98
GS3-0453	4.00	3.72	-2.90		54.07
GS3-0463	4.09	3.69	-2.83		53.11
GS3-0483	4.26	3.84	-2.76		55.29
GS3-0493	4.35	3.67	-3.16		50.24
GS3-0513	4.53	4.02	-1.90		79.84
GS3-0543	4.81	3.34	-2.67		56.42
GS3-0553	4.90			0.2	
GS3-0573	5.08	4.09	-1.66		85.59
GS3-0603	5.35	3.69	-2.12		78.54
GS3-0633	5.63	3.36	-2.56		58.86
GS3-0663	5.90	3.67	-2.22		59.64
GS3-0693	6.17	3.83	-2.20		72.27
GS3-0723	6.44	3.83	-1.74	0.1	79.32
GS3-0753	6.72	3.13	-2.67		62.69
GS3-0783	6.99	3.81	-1.86		81.24
GS3-0813	7.26	4.01	-1.58		84.63
GS3-0833	7.45	3.95	-1.38		84.00
GS3-0853	7.63	3.65	-2.38	1.3	61.21
GS3-0873	7.81	3.69	-1.86		82.54
GS3-0893	7.99	3.63	-2.27		66.61
GS3-0913	8.17	3.57	-2.54		58.69
GS3-0933	8.35	3.72	-2.18		61.47
GS3-0953	8.54	3.83	-1.70		84.28
GS3-0973	8.72	3.84	-1.76		76.54
GS3-0993	8.90	3.74	-1.95		68.79
GS3-1003	8.99			0.8	
GS3-1013	9.17	3.59	-2.13		66.35
GS3-1033	9.34	3.84	-2.07	0.1	63.21
GS3-1053	9.52	4.00	-2.00		71.92

GS3-1073	9.70	3.96	-1.95		71.66
GS3-1093	9.87	3.91	-2.07		68.35
GS3-1113	10.05	3.80	-2.21		72.62
GS3-1133	10.23	4.04	-2.03		76.19
GS3-1153	10.40	3.97	-1.98	1.3	86.46
GS3-1173	10.58	3.91	-1.92		81.06
GS3-1193	10.76	3.85	-1.98		81.15
GS3-1213	10.93	3.99	-2.13		66.17
GS3-1233	11.11	4.24	-1.98	0.1	60.69
GS3-1253	11.29	4.31	-1.90	0.6	65.48
GS3-1273	11.46	4.33	-1.93		59.64
GS3-1293	11.64	4.12	-1.89		66.96
GS3-1313	11.82	4.12	-1.84		80.19
GS3-1333	11.99	4.09	-1.87		80.89
GS3-1353	12.17	4.15	-1.96		78.97
GS3-1373	12.35	4.16	-1.68		79.93
GS3-1393	12.52	3.79	-1.91		83.10
GS3-1413	12.70	3.72	-1.94		79.15
GS3-1433	12.88	3.82	-2.14		64.61
GS3-1453	13.05	3.93	-2.01	0.7	67.13
GS3-1473	13.23	3.91	-2.31		65.48
GS3-1493	13.41	4.10	-1.86		71.83
GS3-1513	13.58	4.11	-1.96		66.96
GS3-1533	13.75	4.06	-2.03		73.75
GS3-1553	13.93	3.94	-1.79		78.45
GS3-1573	14.10	4.12	-1.89		70.88
GS3-1593	14.28	4.10	-1.96		76.19
GS3-1613	14.45	4.23	-1.97		71.20
GS3-1633	14.62	4.29	-1.88		66.17
GS3-1653	14.80	4.30	-1.72		78.36
GS3-1673	14.97	4.20	-1.96		81.93
GS3-1693	15.15	4.31	-1.99		77.32
GS3-1713	15.32	4.21	-1.90		86.20
GS3-1733	15.49	4.26	-1.94		79.50
GS3-1753	15.67	4.14	-2.07	1.3	82.63
GS3-1773	15.84	4.19	-2.08		72.01
GS3-1793	16.02	4.02	-1.91		75.93
GS3-1813	16.19	3.82	-1.70		82.70
GS3-1833	16.36	3.92	-1.87		77.15
GS3-1853	16.54	4.00	-2.13		69.13
GS3-1873	16.71	3.91	-1.99		73.14
GS3-1893	16.89	3.86	-2.04		70.70

GS3-1913	17.06	3.71	-1.97		76.19
GS3-1933	17.23	3.70	-2.00		76.88
GS3-1953	17.41	3.53	-1.92		77.32
GS3-1973	17.58	3.48	-1.99		76.01
GS3-1993	17.76	3.27	-1.93		82.20
GS3-2013	18.02	3.42	-2.10	0.1	71.49
GS3-2033	18.20	3.71	-2.10		80.19
GS3-2053	18.38	3.56	-1.94		80.11
GS3-2073	18.56	3.58	-2.08		72.27
GS3-2093	18.74	3.44	-2.13		71.31
GS3-2113	18.91	3.37	-1.88		78.80
GS3-2133	19.09	3.56	-2.53		54.07
GS3-2153	19.27	3.70	-1.78		81.76
GS3-2173	19.45	3.69	-2.03		71.75
GS3-2193	19.63	3.70	-2.31		59.73
GS3-2213	19.81	3.71	-2.18		59.38
GS3-2233	19.98	3.69	-2.40		68.44
GS3-2253	20.16	3.73	-2.45	0.3	59.99
GS3-2273	20.34	3.70	-2.20		63.47
GS3-2293	20.52	3.70	-2.21		60.51
GS3-2313	20.70	3.70	-1.93		72.70
GS3-2333	20.88	3.70	-1.85		76.10
GS3-2353	21.06	3.77	-2.64		57.55
GS3-2373	21.23	3.71	-2.50		51.02
GS3-2393	21.41	3.70	-2.31		63.47
GS3-2413	21.59	3.66	-2.18		62.78
GS3-2433	21.77	3.59	-2.15		68.26
GS3-2453	21.95	3.61	-2.49		47.45
GS3-2473	22.13	3.51	-2.44		57.12
GS3-2493	22.30	3.47	-1.93		69.13
GS3-2513	22.48	3.47	-1.89		72.09
GS3-2533	22.66	3.51	-2.03	0.3	70.01
GS3-2553	22.84	3.51	-2.09		61.00
GS3-2573	23.02	3.50	-2.01		71.14
GS3-2593	23.20	3.61	-2.20		66.52
GS3-2613	23.37	3.54	-2.13		69.57
GS3-2633	23.54	3.56	-2.15		76.45
GS3-2653	23.70	3.57	-2.10		70.35
GS3-2673	23.87	3.58	-2.22		64.96
GS3-2693	24.04	3.58	-2.66		54.68
GS3-2713	24.21	3.50	-2.48		58.60
GS3-2733	24.38	3.58	-2.47		56.94

GS3-2753	24.55	3.58	-2.82		57.12
GS3-2773	24.72	3.91	-2.70		69.66
GS3-2793	24.89	3.90	-1.91		82.20
GS3-2813	25.06	3.90	-2.07		79.41
GS3-2833	25.23	3.93	-1.81		85.85
GS3-2853	25.40	3.99	-2.01		71.60
GS3-2873	25.57	3.92	-2.02		74.18
GS3-2893	25.74	3.92	-2.20		74.62
GS3-2913	25.91	3.94	-2.04		82.11
GS3-2933	26.08	3.79	-2.17		70.79
GS3-2953	26.24	3.96	-1.89		82.28
GS3-2973	26.41	4.03	-1.66		82.98
GS3-2993	26.58	4.01	-1.93	0.8	78.19
GS3-3013	26.74	3.96	-1.92		65.39
GS3-3033	26.90	3.95	-1.88		80.80
GS3-3053	27.06	3.92	-2.50		81.24
GS3-3073	27.22	3.86	-1.96		78.45
GS3-3093	27.38	3.85	-1.79		82.60
GS3-3113	27.54	3.88	-2.18		67.74
GS3-3133	27.70	3.85	-2.26		62.08
GS3-3153	27.86	3.77	-2.48		66.70
GS3-3173	28.02	3.80	-2.30		78.28
GS3-3193	28.18	3.83	-2.02		85.24
GS3-3213	28.34	3.67	-1.86		81.32
GS3-3233	28.50	3.76	-2.25		60.95
GS3-3253	28.66	3.79	-2.21	1.2	59.21
GS3-3273	28.81	3.68	-1.99		61.12
GS3-3293	28.97	3.84	-1.95		61.47
GS3-3313	29.13	3.82	-2.19		70.96
GS3-3333	29.29	3.76	-2.32		63.65
GS3-3353	29.45	3.68	-2.18		69.92
GS3-3373	29.61	3.76	-2.14	0.7	70.61
GS3-3393	29.77	3.71	-1.84		65.65
GS3-3413	29.93	3.73	-1.83		69.48
GS3-3433	30.09	3.76	-2.41		59.03
GS3-3453	30.25	3.82	-1.98		69.05
GS3-3473	30.41	3.73	-2.06		68.09
GS3-3493	30.57	3.75	-2.00		62.52
GS3-3513	30.76	3.69	-2.04		61.10
GS3-3533	30.94	3.80	-1.89		68.00
GS3-3553	31.13	3.74	-1.96		68.00
GS3-3573	31.32	3.83	-2.27		58.77

GS3-3593	31.51	3.86	-2.05		61.12
GS3-3613	31.70	3.76	-1.93		70.96
GS3-3633	31.88	3.72	-2.87		57.73
GS3-3653	32.07	3.70	-2.31		61.21
GS3-3673	32.26	3.76	-1.85	1.3	70.61
GS3-3693	32.45	3.81	-2.12		62.08
GS3-3713	32.63	3.77	-2.24		61.56
GS3-3733	32.82	3.72	-1.73		70.61
GS3-3753	33.01	3.76	-1.82		73.20
GS3-3773	33.20	3.82	-2.40		55.90
GS3-3793	33.39	3.72	-2.07		67.83
GS3-3813	33.57	3.73	-1.99		67.13
GS3-3833	33.76	3.65	-2.16		73.75
GS3-3853	33.95	3.55	-2.40		75.06
GS3-3873	34.14	3.63	-2.33		57.55
GS3-3893	34.33	3.50	-2.21		58.60
GS3-3913	34.51	3.43	-1.82		78.97
GS3-3933	34.70	3.46	-1.84		78.10
GS3-3953	34.89	3.49	-1.97	0.6	68.35
GS3-3973	35.08	3.52	-2.03		64.20
GS3-3993	35.26	3.58	-1.77		71.49
GS3-4013	35.45	3.48	-1.95		72.53
GS3-4033	35.64	3.51	-1.85		82.11
GS3-4053	35.83	3.53	-1.97		67.65
GS3-4073	36.01	3.53	-1.91		73.40
GS3-4093	36.20	3.47	-1.89		74.27
GS3-4113	36.39	3.44	-1.90		72.97
GS3-4133	36.58	3.48	-2.09	1.6	65.48
GS3-4153	36.76	3.34	-2.08	1.9	70.95
GS3-4173	36.95	3.30	-1.97		74.97
GS3-4193	37.14	3.36	-2.20		
GS3-4193	37.14	3.34	-2.18		57.21
GS3-4213	37.32	3.32	-2.02		70.90
GS3-4233	37.51	3.37	-2.19		56.16
GS3-4253	37.70	3.36	-2.20		56.07
GS3-4273	37.89	3.37	-1.83		62.78
GS3-4293	38.07	3.31	-1.86		72.53
GS3-4313A	38.26	3.29	-1.99		
GS3-4313B	38.26	3.21	-1.94		69.83
GS3-4333	38.45	3.18	-1.75		80.45
GS3-4353	38.64	3.42	-1.91		66.00
GS3-4373	38.82	3.30	-1.86	1.5	64.43

GS3-4393	39.01	3.41	-2.16		56.86
GS3-4433	39.38	3.25	-2.17		66.70
GS3-4453	39.57	3.18	-2.18		67.39
GS3-4473	39.76	3.24	-2.30		55.90
GS3-4493	39.95	3.14	-2.00		77.15
GS3-4513	40.13	3.15	-1.98		70.79
GS3-4533	40.32	3.18	-1.93		73.92
GS3-4553	40.51	3.38	-2.23	1.1	61.30
GS3-4603	40.98	3.24	-2.05		64.35
GS3-4653	41.45	3.19	-1.99		72.79
GS3-4703	41.92	3.13	-2.14		70.96
GS3-4723	42.10				70.35
GS3-4753	42.38	3.02	-2.38	0.1	68.44
GS3-4783	43.60				49.28
GS3-4803	43.79	2.31	-2.44		67.30
GS3-4853	44.26	2.17	-2.73	1.4	51.81
GS3-4903	44.73	2.00	-2.55		67.74
GS3-4953	45.20	1.73	-2.94		53.46
GS3-5003	45.67	1.54	-2.48	0.8	55.73
GS3-5033	45.95				44.49
GS3-5053	46.14	1.41	-2.73		49.98
GS3-5103	46.61	1.26	-2.98		61.47
GS3-5153	47.08	1.19	-2.72	0.3	62.08
GS3-5203	47.55	1.30	-2.45		80.98
GS3-5253	48.02	1.43	-2.74		76.27
GS3-5303	48.49	1.48	-2.55	0.1	65.74
GS3-5353	48.96	1.43	-2.20		83.07
GS3-5403	49.43	0.98	-2.72		52.16
GS3-5453	49.89	1.82	-2.35		76.01
GS3-5503	50.36	1.75	-2.31		67.04
GS3-5553	50.83	1.55	-2.50	0.8	56.07
GS3-5603	51.30	1.66	-2.21		47.45
GS3-5653	51.77	1.22	-2.90		48.41
GS3-5703	52.24	0.75	-2.34		43.01
GS3-5753	52.71	2.42	-2.20		78.54
GS3-5803	53.18	2.38	-2.39		66.70
GS3-5853	53.65	1.89	-2.53		55.64
GS3-5903	54.12	1.78	-2.30		54.77
GS3-5953	54.59	2.11	-2.32		45.54

Samples D2	True stratigraphic depth (m)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	TOC	CaCO_3
GS2-0090	0.70	1.93	-1.79		74.70
GS2-0150	1.16	2.27	-1.67		66.77
GS2-0190	1.47	2.05	-1.70		81.01
GS2-0240	1.86	2.43	-1.56		75.81
GS2-0300	2.32	2.06	-1.93		77.68
GS2-0380	2.94	1.62	-2.07	1.32	75.38
GS2-0430	3.33	1.26	-1.88		61.99
GS2-0440	3.41	1.41	-2.19		54.23
GS2-0450	3.49	1.52	-2.08		59.60
GS2-0460	3.56	1.64	-2.23		54.06
GS2-0470	3.64	1.56	-2.84		46.39
GS2-0480	3.72	1.84	-2.86		36.97
GS2-0490	3.80	1.69	-3.17		37.06
GS2-0500	3.87	1.93	-2.81		41.86
GS2-0520	4.00	2.55	-1.57		76.48
GS2-0540	4.14	2.14	-2.03		59.65
GS2-0560	4.28	2.19	-1.62		72.20
GS2-0580	4.42	2.25	-2.33		48.92
GS2-0600	4.55	2.26	-2.45		43.69
GS2-0620	4.69	2.33	-2.28		53.80
GS2-0642	4.84	2.30	-2.06		59.65
GS2-0662	4.98	2.26	-1.99		59.21
GS2-0682	5.12	2.18	-2.67	1.16	47.09
GS2-0702	5.25	2.29	-2.37		52.23
GS2-0722	5.39	2.31	-1.72		82.93
GS2-0744	5.54	2.13	-1.75		72.64
GS2-0764	5.68	2.25	-2.01		65.92
GS2-0784	5.82	2.19	-2.15		67.23
GS2-0804	5.95	2.36	-1.75		77.87
GS2-0824	6.09	2.53	-2.73		49.27
GS2-0844	6.23	2.59	-2.06		68.63
GS2-0864	6.37	2.45	-1.94		68.90
GS2-0884	6.50	2.19	-1.58		50.73
GS2-0907	6.66	2.15	-2.13		46.58
GS2-0927	6.80	2.33	-2.04		43.88
GS2-0947	6.94	2.39	-1.88		70.17
GS2-0967	7.07	2.36	-1.70		57.83
GS2-0987	7.21	2.18	-2.39		42.36
GS2-1007	7.37	2.65	-1.81		53.43
GS2-1027	7.53	2.64	-1.78	1.48	71.10

GS2-1047	7.70	2.67	-1.57		78.79
GS2-1072	7.90	2.48	-1.60		80.88
GS2-1092	8.06	2.67	-1.66		69.06
GS2-1112	8.22	2.78	-1.58		73.31
GS2-1132	8.38	2.99	-2.14		47.63
GS2-1152	8.54	3.13	-1.84		59.62
GS2-1172	8.71	2.94	-1.38		79.44
GS2-1192	8.87	3.04	-1.69		70.34
GS2-1259	9.41	3.13	-1.67		66.94
GS2-1279	9.57	3.09	-1.74		68.30
GS2-1299	9.73	3.09	-1.58		70.42
GS2-1319	9.89	3.08	-1.69		67.68
GS2-1339	10.05	3.08	-1.68	1.71	67.09
GS2-1370	10.30	3.11	-1.73		70.55
GS2-1382	10.40	2.92	-1.57		83.09
GS2-1402	10.56	2.80	-1.61		72.65
GS2-1422	10.72	2.97	-1.34		82.67
GS2-1442	10.88	3.04	-2.04		71.22
GS2-1462	11.05	2.68	-1.68		72.48
GS2-1482	11.21	3.02	-1.66		71.56
GS2-1502	11.38	3.01	-1.39		76.46
GS2-1522	11.54	2.88	-1.57		79.43
GS2-1545	11.74	2.69	-1.76		72.83
GS2-1565	11.90	2.90	-1.88	0.742	73.65
GS2-1585	12.07	3.04	-1.75		65.72
GS2-1605	12.24	3.07	-1.82		60.28
GS2-1625	12.41	3.01	-2.09		57.30
GS2-1645	12.58	3.05	-1.51		69.19
GS2-1687	12.93	3.07	-2.02		58.29
GS2-1707	13.10	2.97	-1.69		63.08
GS2-1727	13.26	2.76	-2.40		43.84
GS2-1747	13.43	2.96	-1.56		70.60
GS2-1767	13.60	2.87	-2.26	1.41	53.42
GS2-1787	13.77	2.96	-2.25		54.66
GS2-1807	13.93	3.09	-1.66		61.02
GS2-1827	14.10	3.24	-1.88		58.54
GS2-1847	14.27	3.36	-2.17		52.84
GS2-1867	14.44	3.35	-2.14		56.81
GS2-1887	14.61	3.28	-1.72		64.16
GS2-1907	14.77	3.25	-1.57		70.43
GS2-1927	14.94	3.36	-2.09		55.65
GS2-1947	15.11	3.33	-1.64		69.33

GS2-1967	15.28	3.35	-1.80		61.32
GS2-1983	15.41	3.40	-1.66		71.58
GS2-2003	15.59	3.37	-1.94		58.26
GS2-2023	15.76	3.36	-1.57		73.20
GS2-2043	15.94	3.34	-1.71		72.48
GS2-2063	16.11	3.43	-1.66	1.97	78.34
GS2-2083	16.28	3.37	-1.45		78.52
GS2-2103	16.46	3.37	-1.91		69.24
GS2-2123	16.63	3.45	-1.44		74.46
GS2-2140	16.78	3.44	-1.71		73.30
GS2-2160	16.96	3.38	-1.77		73.00
GS2-2180	17.13	3.31	-1.62		80.60
GS2-2200	17.30	3.31	-1.60		78.70
GS2-2220	17.48	3.35	-1.72		74.90
GS2-2250	17.74	3.18	-1.82		62.00
GS2-2280	18.00	3.17	-1.92		63.70
GS2-2308	18.25	3.06	-2.56	1.46	52.20
GS2-2338	18.51	3.28	-1.82		55.32
GS2-2368	18.77	3.24	-1.74		72.87
GS2-2398	19.03	3.32	-1.75		69.24
GS2-2428	19.29	3.30	-1.88		54.63
GS2-2456	19.54	3.03	-1.82		70.88
GS2-2486	19.80	3.37	-1.59	0.967	73.91
GS2-2516	20.08	3.40	-1.85		63.45
GS2-2546	20.36	3.54	-1.77		63.36
GS2-2576	20.65	3.65	-1.59		72.09
GS2-2601	20.88	3.84	-1.50		75.98
GS2-2631	21.16	3.86	-1.60		83.33
GS2-2661	21.45	3.84	-1.53	0.796	78.49
GS2-2691	21.73	3.89	-1.51		74.68
GS2-2721	22.01	3.89	-1.53		82.72
GS2-2756	22.34	3.86	-1.77		85.92
GS2-2786	22.62	3.81	-1.72		84.88
GS2-2816	22.91	3.97	-1.83		77.97
GS2-2846	23.19	4.00	-1.62		72.70
GS2-2876	23.47	3.95	-1.76		70.54
GS2-2913	23.82	3.99	-1.63		61.55
GS2-2943	24.10	4.25	-1.77		65.09
GS2-2973	24.38	4.33	-1.56		77.10
GS2-3003	24.66	4.33	-1.71		84.11
GS2-3013	24.76			0.536	86.87
GS2-3033	24.95	4.28	-1.56		86.27

GS2-3060	25.20	4.39	-1.55		77.80
GS2-3090	25.48	4.38	-1.83		62.15
GS2-3120	25.77	4.38	-1.84		71.40
GS2-3150	26.05	4.36	-2.50		55.41
GS2-3180	26.33	4.49	-1.66		79.01
GS2-3205	26.57	4.67	-1.75		75.46
GS2-3235	26.85	4.47	-2.41		80.74
GS2-3265	27.13	4.34	-1.77		83.16
GS2-3295	27.41	4.66	-1.90		69.50
GS2-3325	27.69	4.57	-2.09	1.22	56.19
GS2-3355	27.98	4.47	-1.52		79.35
GS2-3390	28.31	4.53	-1.83		71.57
GS2-3420	28.59	4.26	-2.10		59.38
GS2-3450	28.87	4.45	-2.11		76.33
GS2-3480	29.15	4.29	-1.59		83.93
GS2-3510	29.43	4.32	-2.10		72.18

Samples D1	True stratigraphic depth (m)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	TOC	CaCO_3
GS1-0065	0.56	3.50	-1.91		55.93
GS1-0095	0.81			0.207	82.44
GS1-0105	0.90	3.68	-2.00		73.80
GS1-0145	1.24	3.71	-2.07		61.32
GS1-0195	1.67	3.68	-2.34		55.42
GS1-0235	2.02	3.78	-2.25		59.86
GS1-0275	2.36	3.68	-2.07		70.13
GS1-0315	2.62	3.74	-1.84		77.65
GS1-0355	2.89	3.84	-1.84		70.98
GS1-0395	3.15	3.61	-1.89	0.306	78.25
GS1-0435	3.41	3.41	-2.13		66.62
GS1-0475	3.68	3.50	-1.79		73.29
GS1-0515	3.97	3.62	-2.02		65.42
GS1-0555	4.28	3.72	-2.18		65.85
GS1-0595	4.58	4.30	-0.88		83.64
GS1-0635	4.89	3.80	-2.22		63.03
GS1-0675	5.20	3.67	-2.36		66.20
GS1-0695	5.35			0.775	75.17
GS1-0715	5.51	3.69	-1.85		72.78
GS1-0755	5.81	3.85	-1.77		80.30
GS1-0795	6.12	3.87	-2.11		70.38
GS1-0835	6.43	4.14	-1.90		68.67
GS1-0975	7.50	4.19	-2.08		59.61

GS1-0995	7.66			0.344	58.24
GS1-1015	7.82	4.11	-2.05		60.04
GS1-1055	8.14	4.03	-1.87		72.27
GS1-1095	8.47	4.04	-1.69		75.94
GS1-1135	8.80	4.02	-1.86		69.27
GS1-1175	9.12	4.10	-1.92		67.99
GS1-1215	9.45	3.92	-1.91		78.17
GS1-1245	9.69			0.723	84.24
GS1-1255	9.77	4.04	-1.95		71.24
GS1-1295	10.10	4.14	-2.07		72.18
GS1-1335	10.42	4.15	-1.89		74.57
GS1-1375	10.75	4.12	-1.90		75.69
GS1-1415	11.07	4.09	-1.78		77.74
GS1-1455	11.40	4.06	-1.92		75.00
GS1-1495	11.72	4.07	-1.70		65.17
GS1-1545	12.13			0.009	73.72
GS1-1575	12.33	3.91	-1.79		77.23
GS1-1625	12.67	3.82	-1.87		81.76
GS1-1665	12.94	3.92	-1.90		69.87
GS1-1715	13.28	3.90	-1.88		62.34
GS1-1755	13.55	3.98	-1.73		67.65
GS1-1795	13.82	3.94	-1.63		78.34
GS1-1835	14.09	3.92	-1.73		65.42
GS1-1845	14.16			0.395	57.30
GS1-1875	14.36	3.92	-2.06		65.34
GS1-1915	14.64	3.84	-1.89		70.15
GS1-1955	14.91	3.87	-1.85		73.21
GS1-1995	15.18	3.78	-1.61		79.79
GS1-2035	15.48	3.75	-1.67		72.18
GS1-2075	15.77	3.67	-2.04		61.06
GS1-2115	16.07	3.58	-1.59		77.31
GS1-2145	16.30			1.10	82.61
GS1-2155	16.37	3.59	-1.83		76.75
GS1-2195	16.67	3.70	-1.69		67.65
GS1-2235	16.97	3.70	-1.96		64.48
GS1-2275	17.27	3.81	-1.92		58.67
GS1-2315	17.57	3.81	-1.74		83.08
GS1-2355	17.86	3.92	-1.73		76.28
GS1-2395	18.16	3.89	-2.12		65.85
GS1-2435	18.46	3.86	-2.05		74.06
GS1-2445	18.54			0.808	65.94
GS1-2475	18.76	3.78	-1.79		67.82

GS1-2515	19.12	3.92	-2.11		65.25
GS1-2555	19.48	4.14	-1.94		67.65
GS1-2595	19.84	4.14	-1.71		72.18
GS1-2635	20.20	4.16	-1.78		82.27
GS1-2675	20.56	4.08	-1.87		58.67
GS1-2715	20.92	3.59	-2.41		43.62
GS1-2745	21.19			0.648	54.90
GS1-2755	21.28	4.03	-1.80		75.94
GS1-2795	21.64	4.03	-1.77		76.11
GS1-2835	22.00	4.15	-1.72		80.48
GS1-2875	22.36	4.07	-1.68		80.05
GS1-2915	22.72	4.19	-1.87		54.99
GS1-2955	23.08	4.18	-1.77		64.57
GS1-2995	23.44	4.26	-1.96		59.10
GS1-3035	23.79	4.26	-1.67		73.12
GS1-3045	23.87			0.820	77.43
GS1-3075	24.14	4.21	-2.03		62.09
GS1-3115	24.49	4.19	-1.83		61.23
GS1-3155	24.84	4.23	-1.88		55.59
GS1-3195	25.19	3.99	-1.80		72.69
GS1-3235-A	25.54	4.00	-1.92		75.60
GS1-3235-B	25.54	4.12	-1.76		
GS1-3265	25.80	4.13	-1.83		67.39
GS1-3295	26.07	4.10	-1.92		67.22
GS1-3345	26.50			0.486	75.26
GS1-3355	26.59	3.96	-1.81		73.80
GS1-3385	26.85	3.95	-1.83		60.81
GS1-3415	27.12	3.94	-2.00		66.79
GS1-3445	27.38	3.86	-1.86		66.71
GS1-3475	27.64	3.87	-1.64		78.42
GS1-3505	27.91	3.97	-1.87		66.79
GS1-3535	28.18	3.92	-1.87		62.77
GS1-3565	28.44	3.83	-1.86		72.09
GS1-3595	28.71	3.92	-1.77		58.07
GS1-3625	28.98	3.89	-1.77		54.22
GS1-3645	29.16			0.284	74.15
GS1-3655	29.25	3.74	-1.63		66.19
GS1-3685	29.51	3.70	-1.84		70.13
GS1-3715	29.78	3.66	-2.04		47.46
GS1-3745	30.05	3.71	-2.01		60.72
GS1-3775	30.32	3.72	-1.76		71.15

GS1-3805	30.58	3.74	-2.02		63.29
GS1-3835	30.85	3.75	-1.99		50.80
GS1-3865	31.12	3.77	-2.01		47.64
GS1-3895	31.39	3.69	-1.99		57.56
GS1-3925	31.65	3.59	-1.75		73.04
GS1-3945	31.83			1.05	54.99
GS1-3955	31.92	3.74	-1.79		63.03
GS1-3985	32.19	3.76	-1.87		53.37
GS1-4015	32.46	3.86	-1.87		57.30
GS1-4045	32.73	3.75	-1.89		60.04
GS1-4075	33.00	3.75	-2.06		47.98
GS1-4105	33.27	3.70	-2.05		61.40
GS1-4135	33.54	3.61	-1.54		83.04
GS1-4165	33.81	3.77	-1.67		68.59
GS1-4195	34.08	3.82	-1.93		65.59
GS1-4225	34.35	3.71	-1.70		73.55
GS1-4235	34.44			1.38	71.84
GS1-4255	34.62	3.86	-1.76		67.05
GS1-4285	34.89	3.70	-1.72		77.23
GS1-4315	35.16	3.98	-2.13		59.78
GS1-4345	35.43	3.99	-1.89		59.86
GS1-4375	35.70	3.66	-1.64		80.48
GS1-4405	35.97	3.61	-1.64		72.61
GS1-4435	36.24	3.73	-1.94		70.04
GS1-4465	36.51	3.70	-2.10		69.10
GS1-4495	36.78	3.43	-1.82		76.03
GS1-4525	37.05	3.53	-1.99		69.79
GS1-4535	37.14			1.05	55.50
GS1-4555	37.32	3.61	-2.13		63.46
GS1-4585	37.59	3.08	-1.85		82.53
GS1-4615	37.86	3.31	-2.00		71.54
GS1-4645	38.13	3.21	-2.16		69.53
GS1-4675	38.40	3.26	-1.98		69.53
GS1-4705	38.67	3.27	-1.86		68.84
GS1-4735	38.94	3.17	-1.87		71.58
GS1-4765	39.21	3.01	-1.77		75.69
GS1-4795	39.48	3.00	-2.01		55.50
GS1-4825	39.75	2.93	-2.11		60.72
GS1-4835	39.84			0.692	55.16
GS1-4855	40.02	2.85	-2.11		55.95
GS1-4885	40.29	2.41	-2.56		44.21
GS1-4915	40.56	2.71	-1.83		65.85

GS1-4945	40.83	2.73	-1.98		57.04
GS1-4975	41.10	2.87	-1.97		49.69
GS1-5005	41.37	2.64	-2.39		49.17
GS1-5035	41.64	3.03	-2.10		46.01
GS1-5065	41.91	2.76	-1.88		73.89
GS1-5095	42.18	2.80	-1.85		54.82
GS1-5125	42.45	2.53	-1.56		72.27
GS1-5135	42.54			1.74	43.62
GS1-5155	42.72	2.72	-1.96		54.90
GS1-5185	42.99	2.80	-2.04		48.83
GS1-5215	43.26	2.94	-2.61		44.64
GS1-5245	43.53	3.06	-2.24		47.04
GS1-5255	43.62	3.01	-1.96		53.79
GS1-5275	43.80	2.92	-2.01		63.54
GS1-5285	43.89	3.14	-2.32		43.53
GS1-5305	44.07	2.80	-1.41		59.35
GS1-5315	44.16	2.71	-1.67		56.70
GS1-5335	44.34	2.75	-1.57		73.72
GS1-5345	44.43	2.62	-1.54		70.47
GS1-5365	44.61	2.88	-2.35		43.62
GS1-5375	44.70	2.79	-2.40		43.36
GS1-5395	44.88	2.80	-1.91		54.99
GS1-5405	44.97	3.05	-2.25		44.47
GS1-5425	45.15	3.03	-2.35		45.41
GS1-5435	45.24	2.81	-2.03	0.559	56.53
GS1-5455	45.42	2.46	-1.73		66.71
GS1-5465	45.51	2.48	-1.50		73.80
GS1-5485	45.69	2.85	-2.23		41.56
GS1-5495	45.78	2.88	-1.83		45.84
GS1-5515	45.96	2.95	-1.78		47.29
GS1-5525	46.05	2.83	-1.86		52.85
GS1-5545	46.23	2.69	-1.69		70.58
GS1-5555	46.32	2.47	-1.71		71.67
GS1-5575	46.50	2.51	-1.71		68.93
GS1-5585	46.59	2.64	-1.77		61.58
GS1-5605	46.77	2.76	-1.91		58.67
GS1-5615	46.86	2.74	-1.86		62.60
GS1-5635	47.04	2.51	-1.74		64.23
GS1-5645	47.13	2.53	-1.69		64.31
GS1-5665	47.31	2.77	-1.84		55.76
GS1-5675	47.40	2.79	-2.10		53.71
GS1-5695	47.58	2.77	-2.05		53.28

GS1-5705	47.67	2.74	-1.84		58.58
GS1-5725	47.85	2.21	-1.93		77.31
GS1-5735	47.94	2.47	-1.98	0.895	63.37