

INTRODUCTION

The website www.orbitalscale.com documents the application of the periodic time scale of Matthews and Al-Husseini (2010) to stratigraphic data sets that are proxies for glacio-eustasy. The application of the scale to sequences in the Arabian Plate is discussed in articles and case studies in the open-access module “Study” in this website and summarized in the Arabian Orbital Stratigraphy (AROS) Chart in the module “Home”. The AROS Chart is updated on an ongoing basis with new data and interpretations.

THE STRATON

The Orbital Scale of glacio-eustasy is constructed with *stratons* – chronostratigraphic units that are tuned by the long-eccentricity 405,000-year orbital cycle (0.405 Myr E-Cycle) (Figure 1, Matthews and Frohlich, 2002; Matthews and Al-Husseini, 2010), and referred to g2-g5 in the astronomical model of the Solar System (Laskar et al., 2004; Laskar, 2020). The E-cycle represents continuous changes of the Earth’s orbit around the Sun from nearly circular to elliptical, which are caused by the gravitational *tug-of-war* between Venus (g2) and Jupiter (g5) over the Earth’s position relative to the Sun.

Stratons have an average duration of c. 0.4 Myr and represent climate and glacio-eustatic cycles that correspond to transgressive-regressive (T-R) depositional sequences. Candidate stratons are interpreted throughout the Phanerozoic, and are generally referred to fourth-order sequences (e.g., Haq, 2014, 2018; Haq and Schutter, 2008; Simmons, 2020). Many candidate stratons are also referred to as high-frequency sequences or cycles, medium- or small-scale sequences or cycles, cycles or cycle sets, parasequences or parasequence sets, etc. In cases where these units are calibrated by empirical geologic time scales and have an average duration of c. 0.4 Myr they are most likely stratons. To avoid ambiguity resulting from the various synonyms for these sequences, the c. 0.4 Myr time-rock unit was named the “straton” (Matthews and Al-Husseini, 2010).

CALIBRATING E-CYCLES AND STRATONS

E-Cycles are numbered between the maxima of the 0.405 Myr sinusoidal component of the Fourier representation of eccentricity (Laskar et al., 2004; Laskar, 2020). Base/start Cycle E1 occurred at 192,125 years before present (Figure 1); base/start Cycle E2 at $0.0192125 + 0.405$ Ma (million years before present), and base/start Cycle EN = $.0192125 + N \times 0.405$ Ma (Hinnov, 2018). The 0.405 Myr E-Cycle is resolved by cyclostratigraphic analyses of rhythmic stratigraphic series and used to calibrate biozones and stages in the Astronomical Time Scale (ATS, e.g., Hinnov, 2018; Huang, 2018). It is referred to as the *tuning fork* or *astronomical metronome* of stratigraphy (Hinnov, 2018; Laskar, 2020).

Stratons are numbered as integers between the minima of eccentricity with base/start of Straton 1 calibrated at 371,000 years before present (Figure 1); base/start of Straton 2 is $0.371 + 0.405$ Ma, and base/start Straton N is $0.371 + (N-1) \times 0.405$ Ma (Figure 2). The base/start of any straton differs by 23,625 years from the mid-point of an E-Cycle. For example base/start of Straton 1 at 0.371 Ma differs by 0.023625 Myr from the mid-point of E-Cycle 1 at 0.394625. Most chronostratigraphic calibrations carry uncertainties of ± 0.1 to ± 1.0 Myr that far exceed the difference of c. 0.02 Myr between mid-point E-cycles and base stratons.

ORBITONS AND DOZONS

Correlating an individual straton calibrated in astronomical time to a candidate fourth-order sequence dated in a biozone or stage is difficult because the latter are rarely dated to the numerical age resolution of a straton by radiometric and cyclostratigraphic techniques. This problem was addressed by considering how eccentricity variations cause groups of stratons to form T-R sequences that may be recognized as million-scale third-order sequences.

The first six Fourier terms of the eccentricity equation (Laskar et al., 2004) beat at periods of c. 0.1, 0.4 and 2.4 Myr (see Figs. 7 and 8 in Matthews and Frohlich, 2002). These beats produce sequences that are still too short to establish accurate correlations to sequences that are dated with accuracies that can be incorrect by several million years.

To extend the search for sequence architectures with much longer durations the periods of all 20 Fourier terms of the eccentricity equation (Laskar et al., 2004; see Table 1 in Matthews and Al-Husseini, 2010) were slightly rounded-off resulting in a tuned eccentricity that beats at 14.58 Myr, and contains 36 cycles of 0.405 Myr. The tuned eccentricity has a similar shape and magnitude to the untuned version, but its advantage is it repeats every 14.58 Myr and can be used in any Phanerozoic interval (see Fig. 5 in Matthews and Al-Husseini, 2010).

The time interval of 14.58 Myr defines an Orbiton (36 sets of stratons) bounded by significant lowstands. Orbiton 1 is predicted between sequence boundary SB 1 at 16.166 Ma and SB 0 (zero) at 1.586 Ma (Figure 2). Sequence boundaries represent the start of post-glacial sea-level rises (transgression). The interval between SB 1 at 1.586 Ma and SB 37 at 541.046 Ma consists of 37 orbitons, and the ages of SBs can be estimated by the arithmetical formula:

$$SB\ N = 1.586 + (N \times 14.58)\ \text{Ma}$$

Orbitons contain three 4.86 Myr stratigraphic units named “dozons” consisting of sets of 12 stratons (named A, B and C in ascending order) that are also bounded by major lowstands (Figure 2). The 12 stratons in a dozon are named in ascending order as A-1 to A-12, B-1 to B-12, and C-1 to C-12. Stratons A-12, B-12 and C-12 typically consist of major lowstands and are capped by SBs.

THIRD-ORDER TRANSGRESSIVE-REGRESSIVE SEQUENCES

The magnitudes of sea-level fluctuations and grouping patterns of stratons in third-order sequences vary significantly depending on prevailing conditions on Earth (e.g., continent-ocean configuration, ocean and atmospheric circulation, size of ice-prone polar continents, level of greenhouse gases, etc.). Similarly the types of glacial scenarios can range from stable ice caps with sea-level fluctuations of 10–20 m, to mid-size ice caps with very pronounced lowstands and sea-level changes of 40–50 m. Ice caps can be stuck for a long time and eventually transition to minimum ice caps (Matthews and Al-Husseini, 2010; Ruebsam and Al-Husseini, 2021).

The orbital scale predicts each straton may have a unique sea-level magnitude such that stratigraphic discontinuities can occur between any two stratons, or a group of several stratons. The most prominent discontinuities (stratigraphic unconformity) are most likely to occur between Stratons 5 and 6, 8 and 9, and 11 and 12; several unconformities may also occur within Stratons 6 and 12. The positions of prominent discontinuities imply dozons consist of a lower c. 2.03 Myr third-order sequence (from base-up Stratons 1 to 5), and an upper third-order c. 2.83 Myr sequence (Stratons 6 to 12) (Figure 2).

The orbital scale predicts the main flooding surface/interval (MFS, MFI) occurs in Straton 2 in the lower 2.03 Myr T-R sequence of a dozon. The sequence architecture of the upper 2.83 Myr T-R sequence is more complicated and will depend on the choice of parameters. Typically it will consist of a 1.21 Myr T-R sequence (Stratons 6 to 8) with an MFS in Stratons 7 or 8, and a 1.62 Myr T-R sequence (Stratons 9 to 12) with an MFS in upper Stratons 9 or 10.

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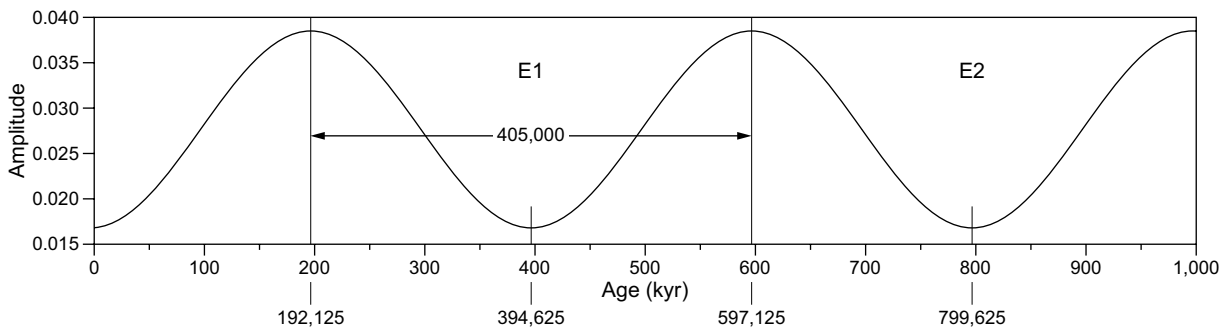
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(a) Astronomical Time Scale (ATS)



(b) Orbital Scale Glacio-Eustasy (OSGE)

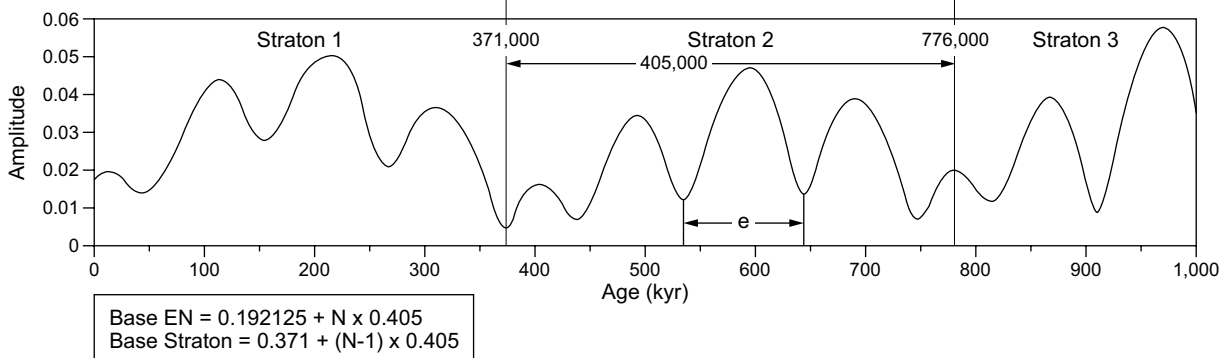


Figure 1: (a) The Astronomical Time Scale (ATS) subdivides time according to the 0.405 Myr sinusoidal component of the Earth’s eccentric orbit (E-Cycle) and numbers them between the maxima of the sine wave. (b) The Orbital Scale defines time-rock units named ‘stratons’ between the minima of the eccentricity curve and estimates their duration as 0.405 Myr, with Straton 1 starting at 371,000 years before present. Four c. 0.1 Myr short-eccentricity cycles (e) typically form a straton. The two scales differ by 23,625 years (Hinnov, 2018). Glacio-eustatic falls and stratigraphic breaks occur at eccentricity minima.

| Orbiton 1, Orbital Scale | | | | | Dozon | | | | | | |
|--------------------------|--------------|-----------------------------------|-------|-------------------------------------|------------------------|----------------------------------|---------------------------------------|--|--------------|---------|--------------|
| Orbiton | Dozon | 0.405 Myr Straton Age @ Base (Ma) | | Predicted Stratigraphic Observation | Orbital Sequence (Myr) | Glacio-Eustatic Signal ← High | Typical $\delta^{13}\text{C}$ Pattern | | | | |
| Orbiton 1 (14.58 Myr) | Orbiton Zero | 0A-4 | 1 | 0.371 | | | | | | | |
| | | 0A-3 | 2 | 0.776 | | | | | | | |
| | | 0A-2 | 3 | 1.181 | Highstand | | | | | | |
| | | 0A-1 | 4 | 1.586 | Transgression | | | | | | |
| | SB Zero | Dozon 1C (4.86 Myr) | 1C-12 | 5 | 1.991 | Major Lowstand | | Carbon-13 Isotope $\delta^{13}\text{C}$ - $\delta^{13}\text{C}$ + | | | |
| | | | 1C-11 | 6 | 2.396 | | | | 12 | Plateau | |
| | | | 1C-10 | 7 | 2.801 | Minor Highstand | | | | 11 | Rising Limb |
| | | | 1C-9 | 8 | 3.206 | Minor Lowstand | | | | 10 | Valley |
| | 1C-8 | 9 | 3.611 | Minor Highstand | | 9 | | | Inflection | | |
| | 1C-7 | 10 | 4.016 | | | 8 | | | Valley | | |
| | 1C-6 | 11 | 4.421 | Minor Lowstand | | 7 | | | Falling Limb | | |
| | 1C-5 | 12 | 4.826 | | | 6 | | | Plateau | | |
| | 1C-4 | 13 | 5.231 | | | 5 | | | Rising Limb | | |
| | 1C-3 | 14 | 5.636 | | | 4 | | | Broad Valley | | |
| | 1C-2 | 15 | 6.041 | Highstand | | 3 | | | | | |
| | SB 1C | Dozon 1B (4.86 Myr) | 1B-12 | 16 | 6.446 | Transgression | | | | 2 | Falling Limb |
| | | | 1B-11 | 17 | 6.851 | Major Lowstand | | 1 | | | |
| | | | 1B-10 | 18 | 7.256 | Minor Highstand | | | | | |
| | | | 1B-9 | 19 | 8.066 | Minor Lowstand | | | | | |
| | SB 1B | Dozon 1A (4.86 Myr) | 1B-8 | 20 | 8.471 | Minor Highstand | | | | | |
| | | | 1B-7 | 21 | 8.876 | Minor Highstand | | | | | |
| | | | 1B-6 | 22 | 9.281 | Minor Lowstand | | | | | |
| | | | 1B-5 | 23 | 9.686 | | | | | | |
| | SB 1A | Dozon 1A (4.86 Myr) | 1B-4 | 24 | 10.091 | | | | | | |
| | | | 1B-3 | 25 | 10.496 | | | | | | |
| | | | 1B-2 | 26 | 10.901 | Highstand | | | | | |
| | | | 1B-1 | 27 | 11.306 | Transgression | | | | | |
| | SB 1A | Dozon 1A (4.86 Myr) | 1A-12 | 28 | 11.711 | Major Lowstand | | | | | |
| | | | 1A-11 | 29 | 12.116 | | | | | | |
| | | | 1A-10 | 30 | 12.521 | Minor Highstand | | | | | |
| | | | 1A-9 | 31 | 12.926 | Minor Lowstand | | | | | |
| | SB 1A | Dozon 1A (4.86 Myr) | 1A-8 | 32 | 13.331 | Minor Highstand | | | | | |
| | | | 1A-7 | 33 | 13.736 | Minor Highstand | | | | | |
| | | | 1A-6 | 34 | 14.141 | Minor Lowstand | | | | | |
| | | | 1A-5 | 35 | 14.546 | | | | | | |
| | SB 1A | Dozon 1A (4.86 Myr) | 1A-4 | 36 | 14.951 | | | | | | |
| | | | 1A-3 | 37 | 15.356 | | | | | | |
| | | | 1A-2 | 38 | 15.761 | Highstand | | | | | |
| | | | 1A-1 | 39 | 16.166 | Transgression | | | | | |
| | SB1 | Orbiton 2 | 2C-12 | 40 | 16.571 | Major Lowstand | | | | | |
| 2C-11 | | | 41 | 16.976 | | | | | | | |

Figure 2: Orbital Scale of glacio-eustasy (Matthews and Al-Husseini, 2010) consists of stratons that tracked the long-eccentricity 0.405 Myr signal (Figure 1). Stratons form periodic orbitons (14.58 Myr), dozons (4.86 Myr) and third-order sequence consisting of multiples of 0.405 Myr (typically, 2.03 and 2.83 Myr). Stratons are numbered as consecutive integers as well as according to their positions in dozons A to C and Orbitons 1 to 37, and dated at their start/base. The scale predicts the ages of lowstand stratons containing major or minor unconformities, and highstands containing maximum flooding surfaces or intervals (MFS, MFI). Sequence boundaries (SB) correlate to the starts of post-glacial transgressions. In many Phanerozoic intervals carbon-13 isotope ($\delta^{13}\text{C}$) positive excursions (plateaus) correlate to sea level lows and negative excursions (valleys) to sea level highs. Decreasing (falling limb) and increasing (rising limb) $\delta^{13}\text{C}$ trends correlate to sea level rises and falls, respectively (Al-Husseini and Ruebsam, 2020).