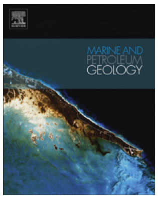
Marine and Petroleum Geology 86 (2017) 1417–1430

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo



Research paper

The Wheeler diagram, flattening theory, and time

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ARTICLE INFO

Article history:
Received 26 April 2017
Received in revised form
26 July 2017
Accepted 28 July 2017
Available online 29 July 2017

Keywords:
Sequence stratigraphy
Chronostratigraphy
Timelines
Wheeler diagrams
Base level

ABSTRACT

Wheeler diagrams are excellent tools to represent time stratigraphy. These diagrams are produced by considering interpreted surfaces as snapshots of geologic times linked with transit cycles of the base level. The base level, defined in the nineteenth century, can be regarded as an ultimate 'time' reference for stratigraphic units. The application of the base level concept to deep marine settings is a more recent development, even though the same definition applies to all depositional environments. Flat timelines are also known as flattening theories can produce similar looking diagrams and have an edge that they operate in 3D. However, flattening of a dataset can be achieved with various techniques, which are reviewed and the optimum algorithm, which has a future application for hydrocarbon and research communities, is improved to honor geological constraints such as faults and horizons. A secondary aspect of the Wheeler diagrams is the dual nature of geological timelines. The diagrams are originally plotted on a relative geological time scale and no formal technique has yet been recommended for time calibration. In this paper, a nomogram approach is proposed to calibrate the timelines. The representation of unconformities that are parallel to bedding planes is another important idea presented in this paper.

1. Introduction

Wheeler's time stratigraphy is fundamentally based on two chief concepts: base level and geologic timelines (Wheeler, 1958, 1964). The base level is generally considered as a reference for lithospheric variations and the development of time-stratigraphic units (Powel, 1875; Barrell, 1917). The maximum rise or fall in base level is often linked to time, which indirectly influences the construction as well as interpretation of the Wheeler's time stratigraphy. Wheeler set a new journey for stratigraphy by providing thought-provoking ideas, following geometrical laws and establishing relationships between successive stratigraphic intervals. He built on Barrell's idea by stating that the cyclicity in a sedimentary record is controlled by an ever changing and an undulating abstract surface known as a 'base level'. The *ultimate* base level for deposition and erosion is the sea level and its extension into the subsurface of continents (Bates and Jackson, 1987). However, *temporary* base levels operate over shorter time scales, and explain processes of deposition and erosion in all depositional environments (Bates and Jackson, 1987; Posamentier and Allen, 1999; Catuneanu, 2006, in press). Recent advances in deepwater research have shown many elements that link sedimentary processes to the concept of base level (Stow, 1985; Stow et al., 2002; Viana et al., 2007; Rebesco and Camerlenghi, 2008; Hernández-Molina et al., 2011; Rebesco et al., 2014; Hübscher et al., 2016). In many cases, the observed changes in the deep water sedimentation are not solely controlled by sea level fluctuations, but by a multitude of factors that influence processes of deposition or erosion of the sea floor (e.g., accumulation of contourites irrespective of sea level rise and fall at a given site).

Perhaps the most valuable contributions from Wheeler are the representation of a stratigraphic succession in a time-space framework and its interpretation with reference to base level. The charts utilizing his concept of time stratigraphy are named as *Wheeler diagrams*. This is the point where the modern day flattening theory began and the definition of time was formalized in stratigraphic interpretation schemes. He identified a three-fold system of nomenclatures such as time, time-rock, and rock units in the field of stratigraphy. Forming time stratigraphy as a new discipline, he criticized the problems associated with lithostratigraphy and biostratigraphy. His work was published in a series of writings, which lasted for more than a decade explaining the need for time-stratigraphic units (Wheeler and Beesley, 1948; Wheeler

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http://dx.doi.org/10.1016/j.marpetgeo.2017.07.034

and Murray, 1957; Wheeler, 1958, 1959, 1964).

Wheeler's effort achieved a remarkable success and earned popularity when the researchers from Exxon started utilizing the ideas for hydrocarbon exploration (Payton, 1977). They developed methods using 2D seismic data and introduced how to produce chronostratigraphic (Wheeler) charts. Their work was similar to Wheeler's approach, i.e. the geological timelines are horizontal when plotted in chronostratigraphic charts. However, it was a labor-intensive approach and the interpreters started looking for a semi-automated solution. The advances in computer science gave a new light to the Wheeler diagrams and the scientific community faced a flood of algorithms to produce semi-automated Wheeler diagrams with minimal efforts. This rapid advancement in technology has not only increased the competition but has also introduced new edicts, errors, and problems. The introduction of flattening theory and automated approaches has provided enough reputation to Wheeler that the work of Grabau (1906), who produced a similar diagram to represent time stratigraphy, remains overlooked.

This paper provides insights into the concepts that influence the construction and interpretation of Wheeler diagrams. Firstly, the application of the base level concept to deep water settings is discussed, in order to provide a framework for the understanding of current-controlled sedimentation and resultant deposits, such as contourites. Secondly, it provides explanations to treat conformities and unconformities equal when representing them on a relative time scale. This is a much-needed concept in the field of stratigraphy and for the development of a relative geologic time scale. The nature of an unconformity becomes pronounced when the relative surface is plotted on an absolute time scale. Thirdly, it assembles all this by providing a dedicated section to explain the properties of timelines. Fourthly, it completes the topic by proposing several solutions for the automated Wheeler diagrams. Importantly, an inversion-based algorithm from an open source community – which has a potential to become a worldwide tool for 3D Wheeler diagrams – is improved to utilize interpreted stratigraphic surfaces during the flattening process. The calibration step remains a missing subject of these automated diagrams and no adequate solution has been proposed. Therefore, we propose a simpler approach for performing calibration steps, which will assist the flattening algorithm to prepare calibrated Wheeler diagrams. The paper also addresses a solution of representing the unconformities that are formed parallel to a bedding plane. These new elements introduced in this paper will not only improve the concepts of Wheeler diagrams and their automation but also will enhance the application of these concepts beyond seismic solutions.

2. Base level and accommodation

The interpretational aspect of Wheeler diagrams is strongly influenced by the changes in base level and accommodation. The concept of base level was refined through time, and is relevant to the 'preservation' of geologic timelines represented on Wheeler diagrams in various depositional settings. The base level undergoes vertical motions i.e., rise and fall, which leads to the formation of stratigraphic sequences (Catuneanu, 2006; Miall, 2016). Powel (1875), who focused on fluvial successions, coined the term and stated that there exists an imaginary level below which a river or a stream cannot down cut (Fig. 1). He termed it as '*baselevel*' and further quotes that the base level of a plain is the level of the surface of the sea, lake or stream, into which the waters of the plain are discharged (Powel, 1895). His work was restricted to the erosional aspect of sedimentary processes and landmasses, with the sea level representing the ultimate level of continental denudation. Rice (1897) broadened and refined the definition of the base level as a surface of balance (equilibrium) between deposition and erosion, which remains a valid concept to the present day. Barrell (1917) further explained that the base level is a dynamic surface that oscillates over multiple timescales, thus explaining the formation of unconformities of different magnitudes, irrespective of controlling mechanisms (i.e., eustasy, climate, or tectonism; Fig. 2). Wheeler and Murray (1957) built on Barrell's (1917) work and exemplified the applications of the base level concept with the study of the Pennsylvanian cyclothems along the Mississippi River.

In a long term, the *ultimate* base level for subaqueous deposition and continental erosion is the sea level (Bates and Jackson, 1987). On shorter time scales, *temporary* base levels are established as 3D surfaces of equilibrium between sedimentation and erosion, which broadly follow the lithospheric surface (Bates and Jackson, 1987; Posamentier and Allen, 1999; Catuneanu, 2006, in press, Fig. 1). The position of the temporary base levels is constantly shifting in response to changing equilibrium conditions, which explains local to regional processes of sedimentation and erosion in all depositional environments. The temporary base level may be referred to as a 'graded profile' in continental environments (e.g., Cross, 1991; Cross and Lessenger, 1998; Jervey, 1988; Posamentier and Allen, 1999; Schumm, 1993; Holbrook et al., 2006) or as the 'deep base level' in subaqueous (particularly deep water) environments (e.g., Hübscher et al., 2016). In either case, the temporary base level describes the equilibrium profile towards which the depositional surface proceeds, via processes of sedimentation or erosion, in any depositional environment (Catuneanu, in press). Therefore, the concept of base level is a descriptor of 'sedimentation' (i.e., sedimentary processes that shape the landscape and the seafloor profiles: deposition = base-level rise; erosion = base-level fall; Catuneanu, 2006, in press), in contrast with 'accommodation' which defines the space created by basin-forming mechanisms (Jervey, 1988; Posamentier and Allen, 1999). The interplay between sedimentation and accommodation generates the stratal stacking patterns that define all sequence stratigraphic units and bounding surfaces from local to regional scales (e.g., Cross and Lessenger, 1998; Posamentier and Allen, 1999; Catuneanu, 2006, p. 84; Qayyum et al., 2015c, p. 338; Catuneanu et al., 2011; Catuneanu and Zecchin, 2013, 2016; Eriksson et al., 2013; Catuneanu, in press). At regional scales, out-of-phase changes in base level driven by tectonism can lead to the coeval development of stratigraphic sequences and unconformities between different portions of the same sedimentary basin (e.g. Catuneanu, 2004; Catuneanu et al., 1999; Csato et al., 2013; Menegazzo et al., 2016). By controlling processes of deposition and erosion, changes in base level are responsible for the 'preservation' or 'erosion' of timelines in the stratigraphic record (Table 1).

The concept of base level can be applied to any depositional environment, from continental to deep water, and from siliciclastic to evaporitic and carbonates. In some cases, e.g., shallow water evaporites and carbonates, the base level can be very close to the sea level, and therefore, the two concepts can be used interchangeably (Tucker et al., 1990; Schlager, 2007; Shahzad et al., 2017). In deep water setting, the base level is much below the sea level (e.g., Hübscher et al., 2016; and Fig. 1). For instance, the canyons and channels often cut through the sea floor with a water depth reaching a few km. The variations of sea level do not directly influence on the longitudinal gradient of canyons at such a greater depth, but the hydrodynamic conditions at the seafloor, which influence the position of the base level, do. Similarly, cool-water carbonates also grow at a depth 1 km below the sea level such as in the Porcupine Basin (De Mol et al., 2002). At such a depth, the sea level no longer plays a major role, and the base level is controlled by the nutrients availability.

Modern studies of the oceans and seas show that a water