Chapter from the book *Seismic and Sequence Stratigraphy and Integrated Stratigraphy - New Insights and Contributions*

Chapter 1

Introductory Chapter: An Introduction to the Seismic and Sequence Stratigraphy and to the Integrated Stratigraphy: Concepts and Meanings

Gemma Aiello

Additional information is available at the end of the chapter

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1. Introduction

This is the introductory chapter of the book "Seismic and sequence stratigraphy and integrated stratigraphy - new insights and contributions." In this chapter, the research themes studied in this book have been introduced referring to the seismo-stratigraphic and sequence stratigraphic techniques and methodologies, pertaining, in particular, the fine-grained shales and the alluvial systems, the seismo-stratigraphic features of Late Miocene deposits offshore the northern Taiwan and to the integrated stratigraphic studies, including the stratigraphy of the Jurassic deposits in the Irkutsk sedimentary basin studied through lithologic and paleobotanical data, the disconformities in stratigraphy, reviewing their theoretical concepts and studying selected examples from Paleozoic successions and the integrated stratigraphy of the foreland basin of the Andean fold and thrust belt.

The topics and the research themes developed in this book are of the great actuality and should have a good impact on the scientific research community. In fact, the sequence stratigraphic studies and the seismo-stratigraphic concepts have been typically developed on the deposits pertaining to the marine environment in a geodynamic context of a passive, Atlantic-type continental margin [1–13]. In this book, instead, emphasis is given to the sequence stratigraphic studies performed on the alluvial systems and on the fine-grained shales.

The passive margins are characterized by thick successions of clastic and carbonate deposits, mainly of shallow water depositional environments, constituting sedimentary wedges thickening toward the ocean. The sedimentary wedge overlies a continental lithosphere segmented in horst and graben structures and tends to be prograding on the newly formed continental lithosphere. The sedimentary successions of a passive continental margin may reach thicknesses in the order of 14 kilometers and accumulate during and after the continental rifting and the formation of oceanic lithosphere. In a well-developed Atlantic-type continental margin, a continental shelf, continental slope and rise and basin occur [14–28].

Sequence stratigraphic interpretations of the alluvial systems and of the fine-grained shales, studied in this book, may be considered as both a counterpart and an integration of sequence stratigraphic analyses of marine deposits in continental shelf, slope and basin environments. The sequence stratigraphic setting of the fluvial depositional systems has been studied by several authors in different geological frameworks [29–35]. The distributive fluvial systems (DFS) [35], which have been investigated in this book, are a particular type of fluvial system, which is characterized by a downstream whose size decreases, is not bounded from valleys and shows a pattern of different rays coming from an apex. The sequence stratigraphy of the fine-grained shales is an interesting research topic of this book, and theoretical aspects applied to several geological settings have been pointed out by several papers [36–40]. In particular, the sequence stratigraphy of the Barnett Shale and subordinately of the Woodford Shale is among the most studied research topics regarding the shales and has been coupled with other geological methodologies, including the geochemistry and the evaluation of the gas content for petroleum studies [41–45].

In this book, different case studies located in China have been presented. To this aim, it should be useful to clarify the type of geological structure of the Chinese-type basins. The present-day geological setting of the Asia continent and, in particular, of China has been controlled by the amalgamation of several Paleozoic continental blocks and many insular arcs. Ziegler et al. [46] have attempted to follow the traces of the migration of some of these blocks up to their unification in the Laurasia continent of the Pangea. The paleogeographic reconstructions of the Chinese region at the end of the Paleozoic have allowed to distinguish three Precambrian platforms, which have been captured during the growth processes in the Paleozoic (i.e., the Tarim platforms, Northern China, and Southern China) [47]. During the formation of the Meso-Cenozoic megasuture belt, a new set of plates was produced, with the capture of the blocks of the Lut, Iran, Tibetan block, and Indochinese platform, merging with the initial Paleozoic nucleus. In the time interval ranging from the Upper Cretaceous to the Pliocene, the collision of the Asia with the Arabian block occurred, while during the Cenozoic, the collision of the Asia with the Indian block occurred [48]. The Chinese basins include the Ordos, Pre-Nan Shan, Tsaidam, Tarim, Turfan, and Dzungarian and are characterized by the occurrence of Mesozoic-Tertiary continental successions deformed by both strike-slip and reverse faults involving the Paleozoic basement [49]. Their individuation appears to be related to compressional stresses [50]. Three types of basins, hosting important oil and gas resources, have been distinguished in China, namely the extensional basins, the compressional basins, and the transitional basins [50]. The extensional basins prevail in the Eastern China, including the Songliao and Bohai Gulf basins (the second one has been investigated in this book). The compressional basins are mainly located in the Western China, including the Tarim and Junggar basins, while the transitional ones are mainly located in the Central China, including the Sichuan and Ordos basins [50].

In this book, another important research topic is represented by the Andean foreland basin, whose age is Cenozoic and located in northern Argentina. Its formation has been modeled from a geodynamic point of view, finding a coefficient of erosional transport of 3000 m^2/year and a coefficient of depositional transport of 20,000 m^2/year [51]. These parameters have predicted the basin geometry of the Andean foreland basin [51]. It is a belt of foreland basins located eastwards of the Central Andes and extending into different regions, including the eastern Bolivia, the northern Argentina, the Paraguay and the southwestern sector of Brazil. Perhaps, this belt is characterized by several depocenters, whose regional sediment distribution has been reconstructed by Horton and deCelles [52]. According to the obtained results [52], the sedimentary basin filling strongly varies in the depocentral zones including the wedge-top, the foredeep, the forebulge and the back-bulge depocentral zones. This variation is accompanied by significant variations in elevation and gravimetric anomalies [52]. Significant variations in the crustal thickness of Andes have been previously pointed out by geological studies [53]. Moreover, the lithospheric flexure of the central Andes and the corresponding bending of stratigraphic sequences have been investigated in detail [54].

2. Seismic stratigraphy

In this book, the seismo-stratigraphic setting of the Northern Taiwan offshore has been reconstructed based on the geologic interpretation of seismic sections (see Chapter 3). Moreover, in Chapter 5, significant results on the stratigraphic unconformities have been shown, focusing on examples of Paleozoic successions. Perhaps, it should be useful to clarify some seismo-stratigraphic concepts and methods.

While the stratigraphic analysis was previously based on the field geological survey, on the measurement of stratigraphic sections and on the lithologic and paleontologic descriptions, aimed at reconstructing the depositional environments and at correlating the stratigraphic sequences among them, this work methodology has been deeply changed after the onset of the seismic stratigraphy, which has allowed for obtaining detailed seismic records of the stratigraphic successions.

The approach to the seismic stratigraphy is based on the key concept that the seismic reflectors may be compared with the strata plans and, perhaps, the geometry of the seismic reflectors corresponds to the depositional geometry [55]. In this sense, the seismic stratigraphy represents a geological and geophysical approach to the stratigraphic analysis and interpretation.

The seismic reflectors occur in correspondence with significant contrasts of the acoustic impedance, which is a significant parameter in seismic stratigraphy. When an acoustic wave meets the interface separating two media having a different acoustic impedance, a part of the wave is transmitted to the other medium, while another part is reflected on the interface among the two media. The concept of the acoustic impedance allows for the calculation of the quantity of transmitted and reflected acoustic energy.

If we consider U as the energy of the wave crossing the media M_1 and M_2 and we suppose that Z_1 is the acoustic impedance of the medium M_1 and Z_2 is the acoustic impedance of the medium M_2, the transmitted energy U_t can be calculated through the following equation:

$$U_t = \frac{2\,Z_1}{Z_1 + Z_2}\,.\,U \tag{1}$$

while the reflected energy U_r can be calculated through the following equation:

$$U_r = \frac{Z_2 - Z_1}{Z_1 + Z_2}\,.\,U \tag{2}$$

The contrasts of acoustic impedance controlling the individuation of the seismic reflectors are located along surfaces corresponding to strata surfaces or to other discontinuities having a chronostratigraphic meaning. The strata surfaces represent the old surfaces of deposition, and then, they are coeval in the depositional area. The discontinuities are old erosional or non-depositional surfaces corresponding to significant stratigraphic gaps. Also if they represent events varying during the geological time, the discontinuities are considered as chronostratigraphic surfaces, since all the strata overlying the discontinuity are younger than the underlying strata [2, 9–12]. When identified on a seismic section, the discontinuities let to identify the most important lateral variations in the deposition of a stratigraphic succession. Moreover, they offer a geological basis in order to subdivide the stratigraphic successions in depositional sequences, which are the basic stratigraphic units of seismic stratigraphy [2, 9–12].

The main steps of the seismo-stratigraphic analysis are represented by the identification of the discontinuities and consequently of the depositional sequences, by the reconstruction of the original geometry of the sedimentary bodies and related sedimentary environments and by the chronostratigraphic correlation [2, 9–12].

The seismic sequence analysis allows for the identification of the depositional sequences. The geometric relationships between the lateral terminations of the strata and the discontinuities or the correlative conformities define the boundaries of the depositional sequences [2]. The lateral terminations of the strata with respect to the sequence boundaries individuate the configurations of onlap, downlap, continuity (lower boundaries) and of erosional truncation, toplap and continuity (upper boundaries) [1, 2, 7–12].

The seismic facies analysis deals with both the individuation and the geologic interpretation of the geometry, continuity, amplitude, frequency and velocity of the seismic reflectors, more than the outer shape of the sedimentary bodies and the seismic facies associations in a depositional sequence [2, 56–61]. In the modern development of this methodology, one aim is represented by the recognition of clusters or groups, representative of significant variations in the properties of the rocks, in the lithology and in the content of fluids. The cluster analysis offers a significant instrument in order to perform the classification of the shapes of the seismic traces grouping them into clusters, often using an unsupervised process without a previous definition of the clusters [57, 60, 61].

The analysis of relative sea-level fluctuations is based on the construction of chronostratigraphic diagrams and of curves of relative sea-level cycles [1, 6–10, 62]. In a chronostratigraphic section, reporting the chronological units in the ordinates of the graph, each layer has an equal time duration. Both erosional and non-depositional hiatuses may occur among the time surfaces corresponding to the layers of the depositional sequences. Three-dimensional

Wheeler chronostratigraphic diagrams represent a useful tool in the geological interpretation of the seismic sections [63–65]. While the conventional Wheeler diagrams, which are usually made by hand, include sketch diagrams showing the extent of chronostratigraphic sequences, new methods have been recently developed in order to construct a Wheeler diagram for a seismic three-dimensional volume [63–65].

3. Sequence stratigraphy

The concepts of depositional sequence, isochronous boundaries, and characteristic correlation geometry, which have been typically developed in the seismic stratigraphy, may be applied in the stratigraphic analysis of outcrops, representing, in that case, the sequence stratigraphy. Some beautiful examples of progradation, toplap, and other stratigraphic relationships have been described by Bosellini [66], an Italian geologist who has applied the concepts of the sequence stratigraphy to significant outcrops of the Triassic carbonate platforms of the Dolomites (Northern Italy). Bosellini [66] has described several types of progradational geometries occurring in spectacular outcrops located in the Dolomites at an outcrop scale comparable with one of the seismic sections. In the Dolomites, an episodic progradation of the carbonate platform has been suggested based on outcrop analysis. During the periods of high debris input, the progradation of the carbonate platform occurred, which was evidenced by the widening of shallow water carbonate depositional environments. On the contrary, during the periods of low debris input, the basinal sedimentation prevailed on the shallow water carbonate deposition. The onlap of the basinal facies at the toe of the carbonate slope may be observed in outcrop [66]. The progradational geometries have been interpreted accordingly with two different models, which have been named as two periods of Triassic times. In the Ladinian model, the progradation and the aggradation of the carbonate platform took place contemporaneously, indicating a phase of a relative sea-level rise. In the Carnian model, toplap geometries have been observed in the carbonate platform, indicating a phase of relative sea-level stand [66].

Numerous are the sequence stratigraphic studies carried out on carbonate platform outcrops. Stafleu and Schlager [67] have carried out a sequence stratigraphic study in which pseudo-toplap geometries have been identified in the Schlern and Raibl Formations. Prograding clinoforms have been identified in the Schlern Formation coupled with topset geometries [67]. Two lithological models have been constructed to explain the geologic evolution of the carbonate platform, that is, (1) rapid progradation of the carbonate platform coupled with slow aggradation and (2) toplap of the prograding clinoforms against the topsets deposited in the inner platform. The seismic models have generated a pseudo-toplap, which is not coincident with a toplap in the outcropping sections [67].

The siliciclastic sequence stratigraphy, its concepts and application have been resumed by Posamentier and Allen [68]. The key concepts of siliciclastic sequence stratigraphy have been considered, including the key stratigraphic surfaces, such as the transgressive surface, the maximum flooding surface, the ravinement surface and many others, and their geologic meaning.

The control factors on the deposition of sequences and system tracts have been considered, including the sea-level fluctuations, the sediment supply and the accommodation space [68].

Some applications of siliciclastic sequence stratigraphy have been given in the recognition of depositional sequences and system tracts from well logs coupled with seismic profiles and biostratigraphic data [69]. The integration of these stratigraphic methods has been applied to the Gulf of Mexico and has allowed for the prediction of reservoirs, seals and source rocks, useful in the petroleum exploration. The stratigraphic architecture has evidenced the occurrence of a complete depositional sequence, consisting of lowstand system tract (LST), transgressive system tract (TST), and highstand system tract (HST), whose stratigraphic signature has been identified based on well log interpretation. High-resolution paleobathymetric and biostratigraphic interpretation of well logs has detailed the general stratigraphic setting.

Some key concepts of sequence stratigraphy, particularly referring to the stratigraphic unconformities, are given in the Chapter 5 of this book. The stratigraphic unconformities are considered as main stratigraphic surfaces and their identification in outcrops can be constrained using the relative weathering maturity of the subaerial profile, the calibration through cyclostratigraphy, the absolute dating and the biostratigraphy. At the scale of the seismic profiles, the disconformities show concordant strata overlying and underlying the stratigraphic surface. In the sense of this chapter, they are considered to include the ravinement surfaces, which are important stratigraphic surfaces, related to the erosion during the transgressive movement of the landward margin of the transgressive system tract (TST) [70–72]. Moreover, the concept of drowning unconformity has been reviewed, considering this stratigraphic surface as one of the most important stratigraphic surfaces in carbonate platform settings [73–76]. These surfaces develop when the rate of vertical aggradation of the carbonate platform is lower than the rate of the accommodation space. Perhaps the deep water sedimentation tends to prevail on the shallow carbonate sedimentation, as evidenced by the individuation of the drowning unconformity. These kind of unconformities have been individuated offshore of the Apulian region in the Southern Adriatic Sea [62] and onshore in the Gargano Promontory, showing a well-developed carbonate platform margin-slope-basin succession [77].

4. Integrated stratigraphy

In this book, different studies on integrated stratigraphy have been presented, which are grouped in the second section of the book. These studies are based on the integration of several stratigraphic methodologies, including the lithologic and paleobotanical data, the three-dimensional seismic models, the biostratigraphy, the paleopedology and paleoaquifer studies, the lithologic logs of cores and their subaerial exposure profiles, the individuation of the eroded paleosols, the lithologic and lithofacies logs of wells and some corresponding measurements and, finally, the facies analysis aimed at individuating the depositional architecture and the sequence stratigraphic setting.

Different stratigraphic methods are involved in the integrated stratigraphy, including the chemostratigraphy, the isotopic stratigraphy, the oxygen isotopes, the carbon isotopes, the strontium isotopes, the orbital cyclostratigraphy, the response of the climate system to the orbital forcing, the orbital forcing and the sedimentary environments, the identification of cyclical features and the spectral analysis of time series. Particular attention must be given to the methods of absolute dating and to the geological timescale.

Numerous papers have been produced in the field of the integrated stratigraphy, covering a wide range of competences. The stratigraphic record of Gubbio (Central Apennines, Italy) is one of the most studied research topics in the integrated stratigraphy [78]. Cretaceous and Paleogene stratigraphy of the Central Apennines has been deeply studied from the beginning of 1900. A pioneer of these studies was Otto Renz (1906–1992). Many paleomagnetic investigations have also been carried out on the Mesozoic-Paleogene stratigraphic record of the Umbria–Marche basin. One of the most significant lithological types is represented by the Scaglia limestones, whose directions of remnant magnetization have indirectly given indications on the geodynamic evolution of the Adria African Promontory [79]. Starting from the Middle Jurassic, the magnetic stratigraphy of the Mesozoic-Paleogene succession of the Umbria–Marche basin has allowed to individuate a record of the geomagnetic polarity [78]. The value of this record has been confirmed from its correlation with the oceanic paleomagnetic records. The integrated stratigraphic studies of the Gubbio section include the individuation of an Early Cretaceous tectonic event in the Adria promontory, having insights from the Umbria-Marche pelagic basin, the Barremian-Aptian boundary in the Poggio Le Guaine core, giving evidence on the magnetic polarity chron M0r and on the oceanic anoxic event 1a, the *Rotalipora cushmani* extinction at Gubbio, a planktonic foraminifer testifying the emplacement of a large volcanic province and the evaluation of the environmental fluctuations during the late Cenomanian at Gubbio based on the ichnofabric [78].

In my opinion, another main research topic in the integrated stratigraphy is represented by the Messinian Global Stratotype Section and Point (GSSP) [80]. High-resolution integrated stratigraphy has been presented by Hilgen et al. [80], based on the integration of different stratigraphic methodologies, including the calcareous plankton biostratigraphy, the magnetic stratigraphy and the cyclic stratigraphy. The Messinian GSSP has been individuated at the base of the red layer of the cycle n. 15 in the section Oued Akrech. It coincides with the first occurrence of *Globorotalia mitumida* and is dated back at 7.251 My [80]. For the upper part of the Miocene, the Messinian is the standard chronostratigraphic unit, whose knowledge is due to the corresponding salinity crisis occurring in the Mediterranean Sea.

5. Outline of this book

Different stratigraphic studies have been carried out in this book. First, they include the sequence stratigraphic architecture of siliciclastic- and carbonate-dominated shales in USA and China, focusing on the implications in the reservoir prediction. The sequence stratigraphy of alluvial depositional environments has also been studied, defining a new type of fluvial facies, representative of the Bohai Bay Basin, which is located in Eastern China in extensional tectonic setting. In the northern Taiwan offshore, the main regional unconformities (U1 and U2) and the related seismic units (SU I, SU II, SU III) have been singled out as an answer to the collapse of the fold and thrust belt located in the emerged areas. A new stratigraphic scale for the Jurassic deposits of western Siberia has been constructed based on the correlation of these deposits with the surrounding regions. The theoretical aspects of the stratigraphic unconformities have been reviewed, focusing on the drowning unconformities (Middle Devonian drowning unconformity). The significance of this study is the integration among different aspects of stratigraphy. Most of the work which has been described in this book derives from detailed in situ observations and sophisticated stratigraphic analyses.

This book contains six chapters, as follows:

Chapter 2 (Sequence Stratigraphy of Fine-Grained "Shale" Deposits: Case Studies of Representative Shales in USA and China).

Chapter 3 (Sequence Stratigraphy of Fluvial Facies: A New Type Representative from Wenliu Area, Bohai Bay Basin, China).

Chapter 4 (Seismic Stratigraphic Features of the Late Miocene-Present Unconformities and Related Seismic Units, Northern Offshore Taiwan).

Chapter 5 (Stratigraphy of Jurassic Sediments of the Southern Siberian Platform (Russia) Studied Through Lithologic and Palaeobotanical Data).

Chapter 6 (Stratigraphic Unconformities: Review of the Concept and Examples from the Middle-Upper Paleozoic).

Chapter 7 (Integrated Stratigraphy of the Cenozoic Andean Foreland Basin (Northern Argentina)).

Author details

Gemma Aiello

Address all correspondence to: gemma.aiello@iamc.cnr.it

Institute of Marine and Coastal Environment (IAMC), National Research Council of Italy (CNR), Napoli, Italy

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