Stratigraphic surfaces in the depositional and chronostratigraphic (Wheeler-transformed) domain

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One of the controversial and still debated issues of sequence stratigraphy is the assessment of stratigraphic surfaces in a chronostratigraphic framework (Catuneanu, 2006.) To assess whether the bounding surfaces of systems tracts or sequences are isochronous or diachronous is of paramount importance for stratigraphic correlation. New software developments enable us to study stratigraphic surfaces within such a chronostratigraphic framework and allow us to predict something about their "time attributes."

This new software allows seismic data to be studied in the chronostratigraphic domain. Numerous chronostratigraphic events are autotracked per sequence bounded by (conventionally) mapped horizons. Figure 1 shows a 3D chronostratigraphic diagram or "Wheeler transform" (Wheeler, 1958) in which seismic data and (meta-) attribute volumes are flattened in 3D so that erosional events and nondepositional hiatuses are honored (de Groot et al., 2006; Ligtenberg et al., 2006; de Bruin et al., 2006). Furthermore, sequences can be subdivided into systems tracts (Figure 2).

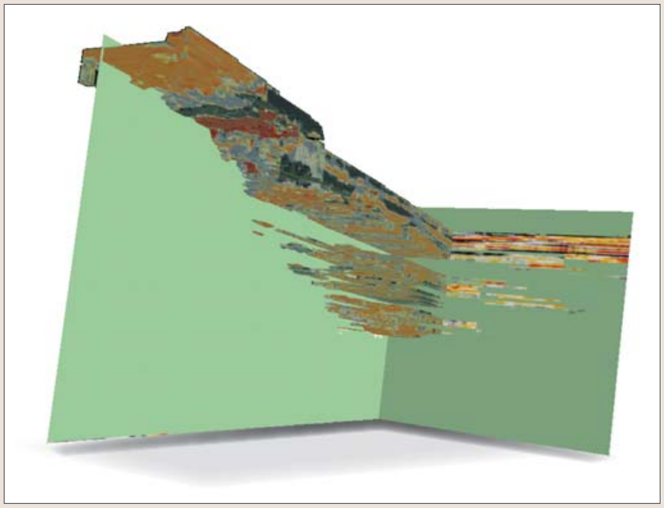

Figure 1. Example of a automatically constructed 3D Wheeler transform (chronostratigraphic diagram); seismic data displayed in the chronostratigraphic domain. Vertical axis is relative geologic time.

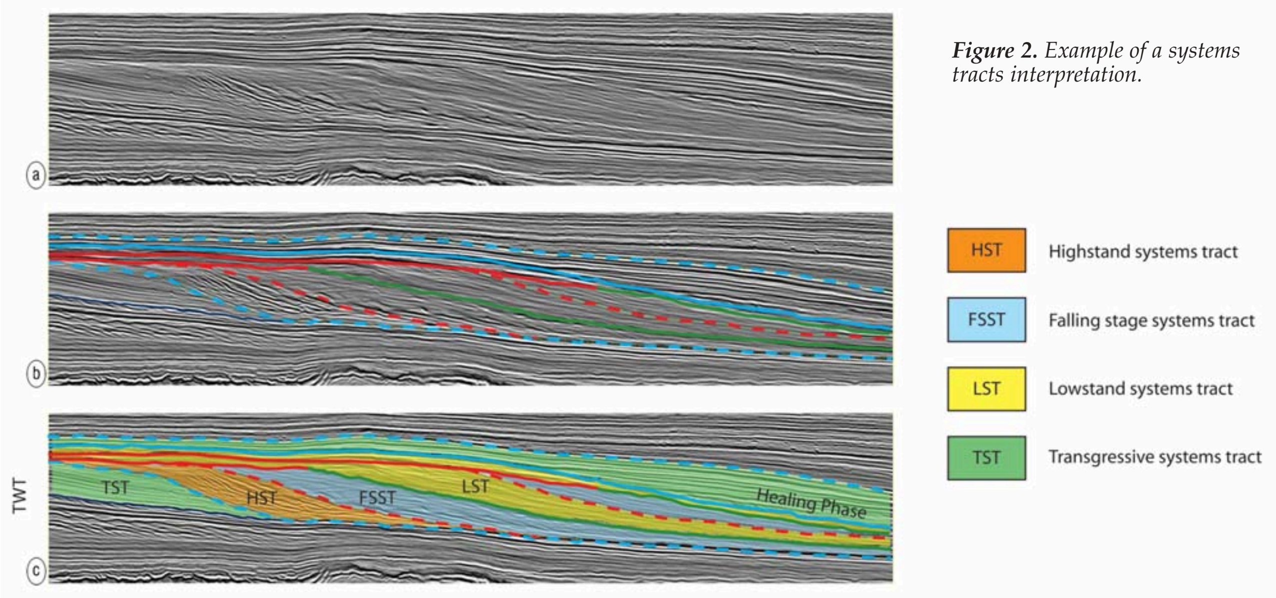

Figure 2. Example of a systems tracts interpretation.

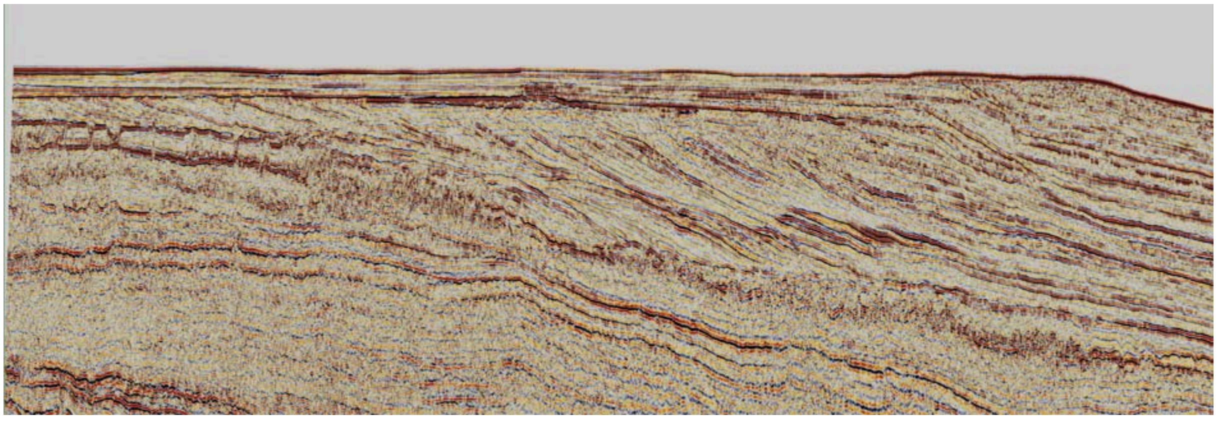

Figure 3. Seismic data from Møre South Basin, Norway.

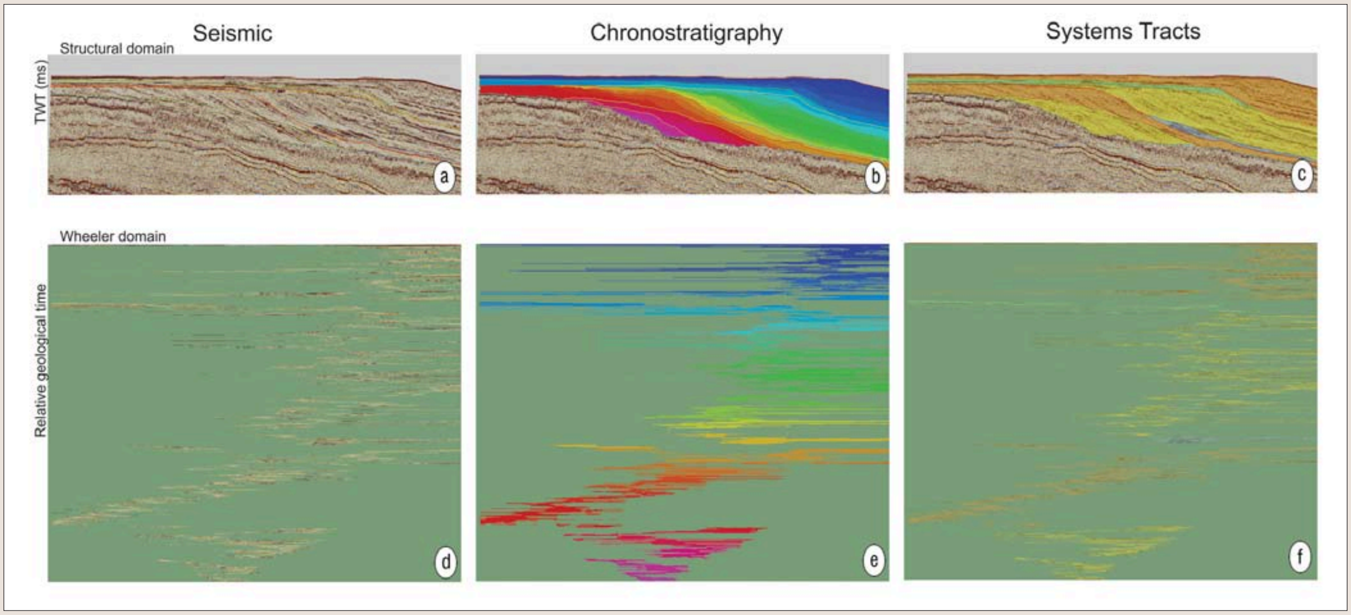

__Figure 4.__ New software developments enable a full sequence stratigraphic analysis, including autodetection of chronostratigraphic events, automated Wheeler transforms, and full systems tracts interpretations. (a) Seismic data with conventionally mapped bounding surfaces. (b) Autotracked chronostratigraphic events. Color indicates the relative geologic age; purple = oldest deposits, blue = youngest. (c) Systems tracts interpretation on top of seismic data (for color coding see Figure 2). (d) Wheeler-transformed seismic data (chronostratigraphic diagram). (e) Chronostratigraphic events in the Wheeler domain. f) Systems tracts interpretation in the Wheeler domain (for color coding see Figure 2).

Example. Figure 3 is a seismic line from Møre South Basin, Norway. The lower boundary (Figure 4a) of the section analyzed in this paper coincides with the regional unconformity at the Oligocene–Miocene boundary. The progradations are of Miocene to Pleistocene age, and the top coincides with the present-day seafloor.

The first step in analyzing the data is to map the bounding surfaces (Figure 4a), and let the software autotrack numerous chronostratigraphic events in between these horizons (Figure 4b). Next, the seismic data are flattened along the chronostratigraphic events (Figure 4d–e). Note that the vertical axis of the Wheeler domain is relative geological age (i.e., chronostratigraphic events/horizons are numbered; therefore, the age relative to each other is known). Finally, the sequences are subdivided into systems tracts (Figures 4c and 4f).

The synchronized analysis in both the depositional and Wheeler domain helps us to unravel the depositional history. The depositional history is depicted in Figure 5.

Because progradation and aggradation occur while sea level is rising, time steps 1 and 2 are normal regression deposits. After the deposition of the Miocene lowstand wedge, a rapid rise in sea level occurred and a depositional shift landward (actually outside our data set).

At time steps 3 and 4, a series of downlapping clinoforms prograde over the lowstand wedge. The base of these packages is the downlapping surface. Time steps 3 and 4 are also normal regression deposits (highstand).

Time step 5 is just after the onset of forced regression (falling stage systems tract), where the top of the normal regression highstand deposits are subjected to erosion. A subaerial unconformity forms, while in the basin a submarine fan complex is deposited on top of the basal surface of forced regression. Time step

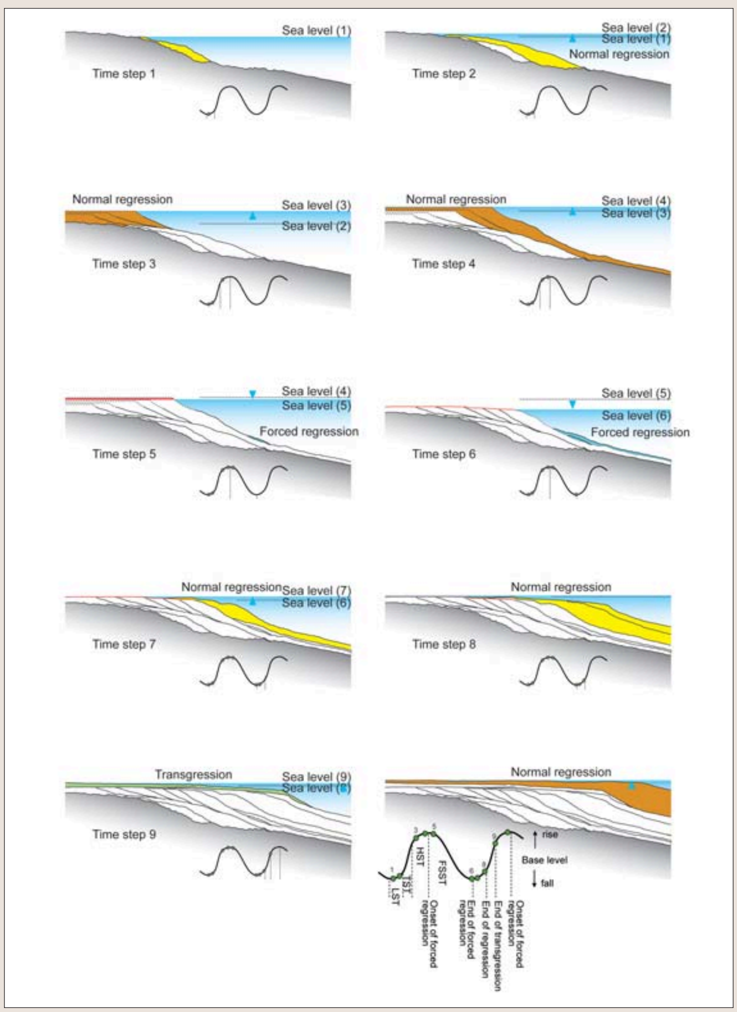

__Figure 5.__ Cartoon of the deposition history (yellow = lowstand system tract (LST); orange = highstand systems tract (HST); blue = falling stage systems tract (FSST); green = transgressive systems tract (TST).

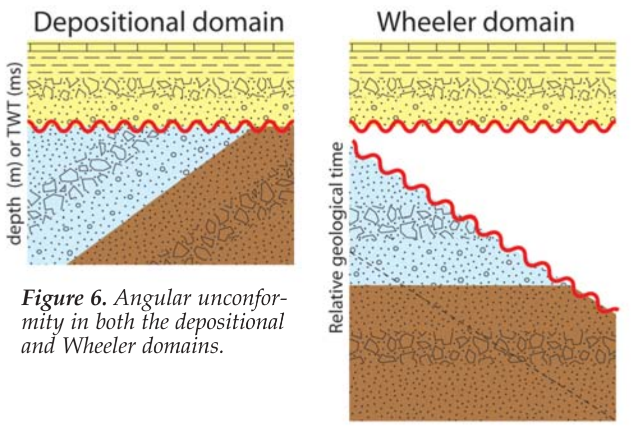

Figure 6. Angular unconformity in both the depositional and Wheeler domains.

6 is at the end of forced regression, the base level is at its lowest point and the subaerial unconformity is at its "point of maximum erosion."

The top of the submarine fan complex is the correlative conformity (*sensu* Hunt and Tucker, 1992) and is overlain by a normal regressive package (lowstand of time steps 7 and 8). Time step 8 is at the end of regression, and the top of the deposits corresponds with the maximum regressive surface.

Time step 9 corresponds with transgressive deposits (transgressive system tract) and the top with the maximum flooding surface. The final time step corresponds to normal regressive deposits and the top of the deposits to the current seabed.

Time attributes of stratigraphic surfaces. Before addressing the issue of time attributes of stratigraphic surfaces, it is important to understand the difficulties one encounters when trying to assign an age to a particular event or horizon as we see it in seismic data. Figure 6 depicts an angular unconformity in the depositional and Wheeler domain. In the depositional domain, the unconformity appears as a single event but in the Wheeler domain it is present at two places, at the top of the blue/brown package and at the base of the yellow package. It is possible to assign a (relative) geologic age to the deposits just above and just below the unconformity, but these do not necessarily correspond to the timing of erosion.

Downlapping surface. The first stratigraphic surface in our data set is the downlapping surface (Figures 5 and 6). The downlapping surface is a marine-flooding surface onto which the toes of prograding clinoforms in the overlying highstand systems tract downlap or terminate. The downlapping and termination of the clinoforms is clearly visible in the depositional domain. In the Wheeler domain, the downlapping surface is depicted as the base of the highstand systems tract. Consequently, it is highly diachronous and occurs from about 35 until 42 relative geologic time (Figure 7).

Subaerial unconformity. The subaerial unconformity is a highly diachronous event. When the strata just below the subaerial unconformity are studied closely in the Wheeler domain, one can observe that it has a "feathered" structure rather than an expected smooth diachronous trend. This can be explained by small multiples that run through the dipping clinoforms. When the amplitudes of the multiples become stronger than those of the clinoforms, the software will track these events instead of the dipping clinoforms. A good example of such an event can be seen in Figure 7b, just above the end of the subaerial unconformity and left of the basal surface of forced regression. The shaded area just above the subaerial unconformities represents the strata that are eroded, emphasizing the erosional nature of the subaerial unconformity.

The timing of the erosion does not correspond with the red line in the Wheeler transform. The erosion started after the last strata of the highstand were deposited—i.e., at the same time as the basal surface of forced regression was formed (30.3 relative geologic time). The erosion stopped at the end of forced regression—i.e., at the same time as the correlative conformity was formed (28.6 relative geologic time). The duration of erosion, measured in relative geologic time, is 1.7.

Basal surface of forced regression. Figures 7 and 8 show that the basal surface of forced regression (*sensu* Hunt and Tucker, equivalent to the correlative conformity of Posamentier and Allen, 1999) corresponds to the seafloor at the onset of forced regression (Catuneanu, 2006). This is a highly isochronous (30.3 relative geologic time) event that coincides with the start of erosion at the top of the normal regression highstand deposits and the formation of the subaerial unconformity.

Correlative conformity. The correlative conformity corresponds with the end of the forced regression and is present at the top of the submarine fan complex. The correlative conformity coincides with the end of erosion of the highstand deposits and is highly isochronous (28.6 relative geologic time).

Maximum regressive surface. The maximum regressive surface or transgressive surface marks the end of normal regression and the onset of transgression. In our case the base level rise is very limited or at a stand still during normal regression, while sedimentation rates are relatively high. Therefore, we observe a thick prograding package, with very little aggradation. The top of this prograding package is therefore a moderately isochronous event, but the point of maximum regression occurs at 10.5 relative geologic time.

Maximum flooding surface. The maximum flooding surface marks the end of the transgression and the onset of normal regression. The sediments that correspond to the top of the transgressive systems tract are for the large part isochronous, only a small part appears to be diachronous. The point of maximum transgression occurs at 8.3 relative geologic time.

Discussion. Studying stratigraphic surfaces simultaneously in the depositional and the Wheeler domains enhances our understanding of time attributes of these surfaces, but some caution is needed when interpreting events in the Wheeler domain.

First of all, reflections must be geologically meaningful. As seen in the example, some multiples are tracked instead of the dipping clinoforms while calculating the chronostratigraphy, hence giving the subaerial unconformity a feather appearance in the Wheeler domain. The presence of multiples also explains why some events are assigned an incorrect relative geologic time.

Secondly, a horizon appears as a single event in the depositional domain, but in the Wheeler domain it can be present at two places, at the top of the package below the event and at the base of the package above it. It is possible to assign (relative) geologic ages to the deposits just above and just below the event, but these ages do not necessarily correspond to the timing of the event. This is especially true when dealing with subaerial unconformities or other highly diachronous events.

Finally, since the current implementation of the Wheeler transform yields a Wheeler domain in relative geologic time,

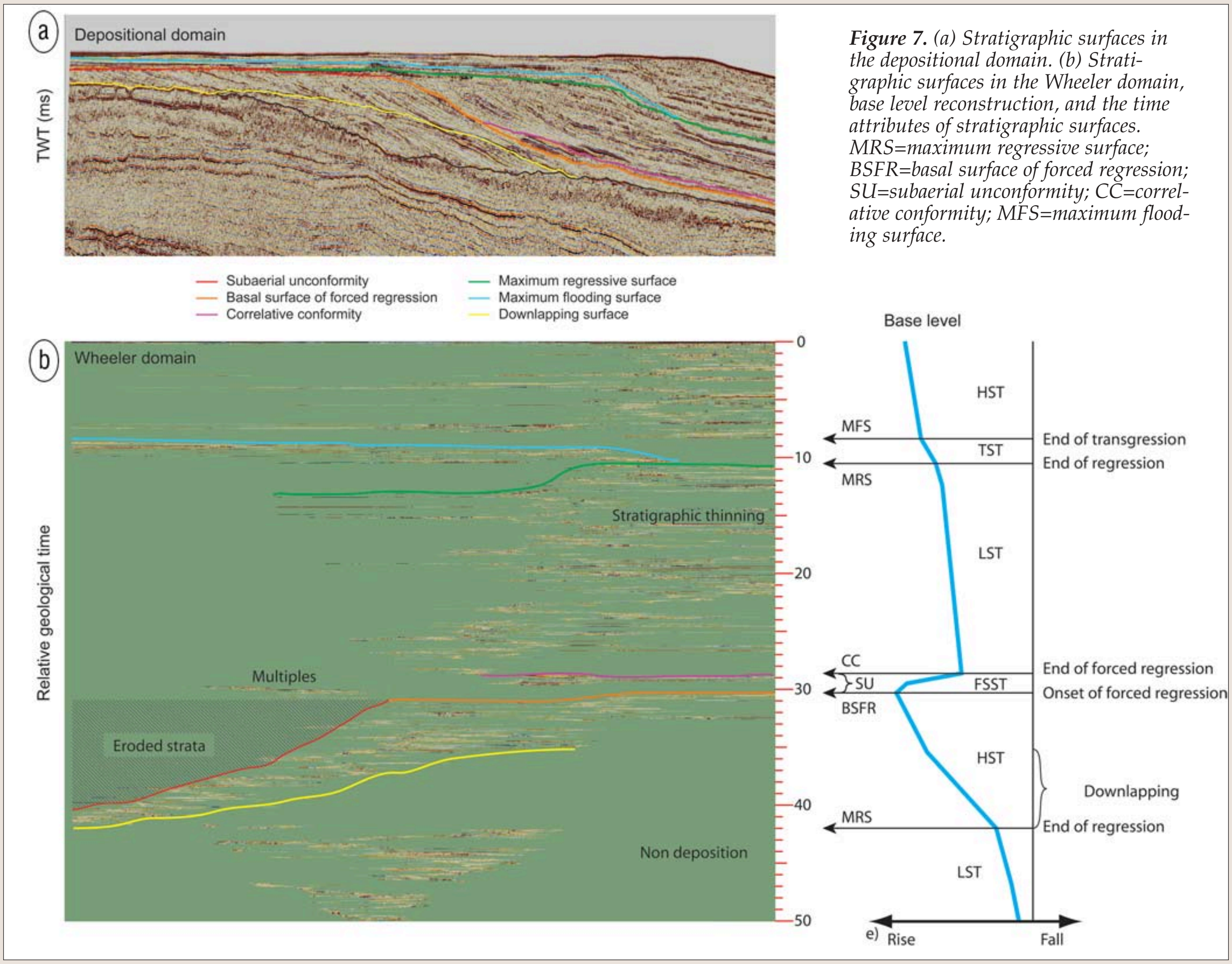

Figure 7. *(a) Stratigraphic surfaces in the depositional domain. (b) Stratigraphic surfaces in the Wheeler domain, base level reconstruction, and the time attributes of stratigraphic surfaces. MRS=maximum regressive surface; BSFR=basal surface of forced regression; SU=subaerial unconformity; CC=correlative conformity; MFS=maximum flooding surface.*

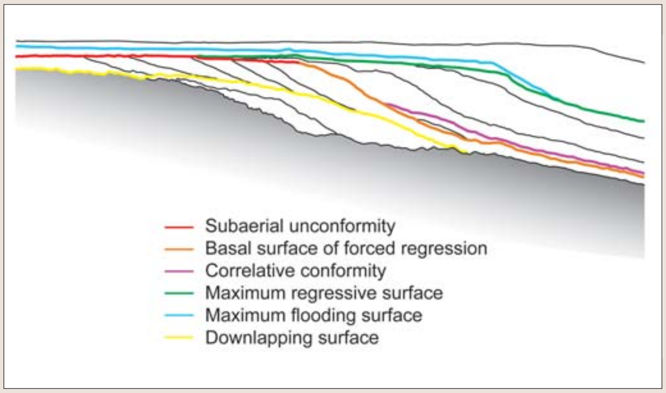

Figure 8. *Overview of stratigraphic surfaces in the depositional domain.*

it is only possible to interpret the relative timing of highly isochronous events, and the relative duration of erosional events. Future developments of OpendTect SSIS aim to calibrate the Wheeler transform to absolute geologic time. It will then be possible to assign a geologic age to isochronous events or to date the occurrence of erosion. Furthermore, sedimentation rates (when depth-converted seismic is available) and duration of hiatuses can then be calculated.

Suggested reading. *Principles of Sequence Stratigraphy* by Catuneanu (Elsevier, 2006). "Synchronized sequence stratigraphic interpretation in the depositional and chrono-stratigraphic (Wheeler transformed) domain" by de Bruin et al. (EAGE Research Workshop, 2006). "How to create and use 3D Wheeler transformed seismic volumes" by de Groot et al. (*SEG 2006 Expanded Abstracts*). "OpendTect SSIS—sequence stratigraphic interpretation system" by de Groot et al. (*Drilling & Exploration World*, 2006). "Sequence stratigraphic interpretation in the Wheeler transformed (flattened) seismic domain" by Ligtenberg et al. (*EAGE 2006 Extended Abstracts*). "Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall" by Hunt and Tucker (*Sedimentary Geology*, 1992). "Siliciclastic sequence stratigraphy: concepts and applications" by Posamentier and Allen (SEPM, 1999). "Time stratigraphy" by Wheeler (AAPG *Bulletin*, 1958).

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Acknowledgments: We are grateful to TGS-NOPEC for permission to publish parts of its seismic data set. Further, we acknowledge RWE DEA Norway for funding this study, providing the data set, and giving all geologic information. For more information on the software, see: http://www2.dgb-group.com/ssis.html *or* http://www.opendtect.org/

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