Dynamic Time Warping for Stochastic Stratigraphic Well Correlation*

Florent Lallier[1], Guillaume Caumon[2], Jean Borgomano[3], Sophie Viseur[3], Christophe Antoine[4]

Search and Discovery Article #40473 (2009)
Posted December 11, 2009

*Adapted from oral presentation at AAPG Annual Convention and Exhibition, Denver, Colorado, June 7-10, 2009

[1]CRPG, Nancy-Universite, Vandoeuvre les Nancy, France (lallier@gocad.org)
[2]CRPG, Nancy-Universite, Vandoeuvre les Nancy, France
[3]Laboratoire de Géologie des Systèmes et des Réservoirs Carbonatés, Université de Provence, Marseille, France
[4]ASGA / Gocad Consortium, Nancy, France

Abstract

The stratigraphic correlation of well cores and logs is a fundamental step in reservoir studies. Since it is the basis for the static and dynamic model and seismic processing, it is subject to many uncertainties.

Several authors have discussed the approach to achieve well correlation, but the proposed methods mainly lead to a unique correlation path. Therefore, uncertainties due to stratigraphic well correlations cannot be handled and integrated in existing subsurface uncertainty assessment workflows.

We propose a new method of stochastic stratigraphic well correlations: the aim is to generate automatically several possible sets of well correlations accounting for interpretations made along well paths. This method is based on the Dynamic Time Warping (DTW) algorithm, used in speech recognition and bioinformatics. In practice, the probability of correlation of each stratigraphic marker and interval identified along the well path is computed using:

- information available on the interpreted well (e.g. paleobathymetry, lithology)
- some reference lines coming from clear, first-order stratigraphic boundaries
- sedimentological scenario about the studied area
- sedimentological concepts deemed applicable

Then, using these probabilities, several possible sets of well correlations are stochastically generated with a modified version of the DTW algorithm.

Moreover, the method acts hierarchically. For example, low level stratigraphic events or high confidence data (e.g. biostratigraphic boundary, regional MFS) will be correlated first and will constrain the correlation of higher-order events.

This method is applied to the sequence-stratigraphic well correlation in a carbonate ramp system. Correlation probabilities are obtained by:

- evaluating the consistency of the paleo-angle formed by correlated couple of well markers and the paleo-horizontal
- comparing depositional environment trends interpreted along each well interval (e.g. more distal or proximal)

Selected References

Borgomano, J.R.F., F. Fournier, S. Viseur, and L. Rijkels, 2008, Stratigraphic well correlations for 3-D static modeling of carbonate reservoirs: AAPG Bulletin, V. 92/6, p. 789-824.

Durand-Riard, P., P. Kedzierski, J. Gari, 2007, Thalassa facies simulation and geological reality face-to-face: Application to the Bausset basin: Proceedings of Gocad Meeting, June 2007.

Myer, L.E., 1981, Survival functions induced by stochastic covariate process: Journal Applied Probability, v. 18, p. 523-529.

Dynamic Time Warping for Stochastic Stratigraphic Well Correlation

F. Lallier, G. Caumon,
J.Borgomano, S. Viseur

Nancy-Université

GOCAD®

Stratigraphic Correlation

- Aims:
  - Support reservoir characterization
    - 3D Modeling of undrilled area
    - Define stratigraphic units
      - 3D reservoir architecture
      - Stationary nature of the system for geostatistics simulations
      - Flow units geometry
  - Seismic inversion
  - Study of spatial and temporal evolution
- Input data:
  - Geological concept (data analysis)
  - Prior knowledge (analog)
  - Horizon (seismic)

Stratigraphic Correlation

- Aims:
  - Support reservoir characterization
    - 3D Modeling of undrilled area
    - Define stratigraphic units
      - 3D reservoir architecture
      - Stationary nature of the system for geostatistics simulations
      - Flow units geometry
  - Seismic inversion
  - Study of spatial and temporal evolution
- Input data:
    - Geological concept (data analysis)

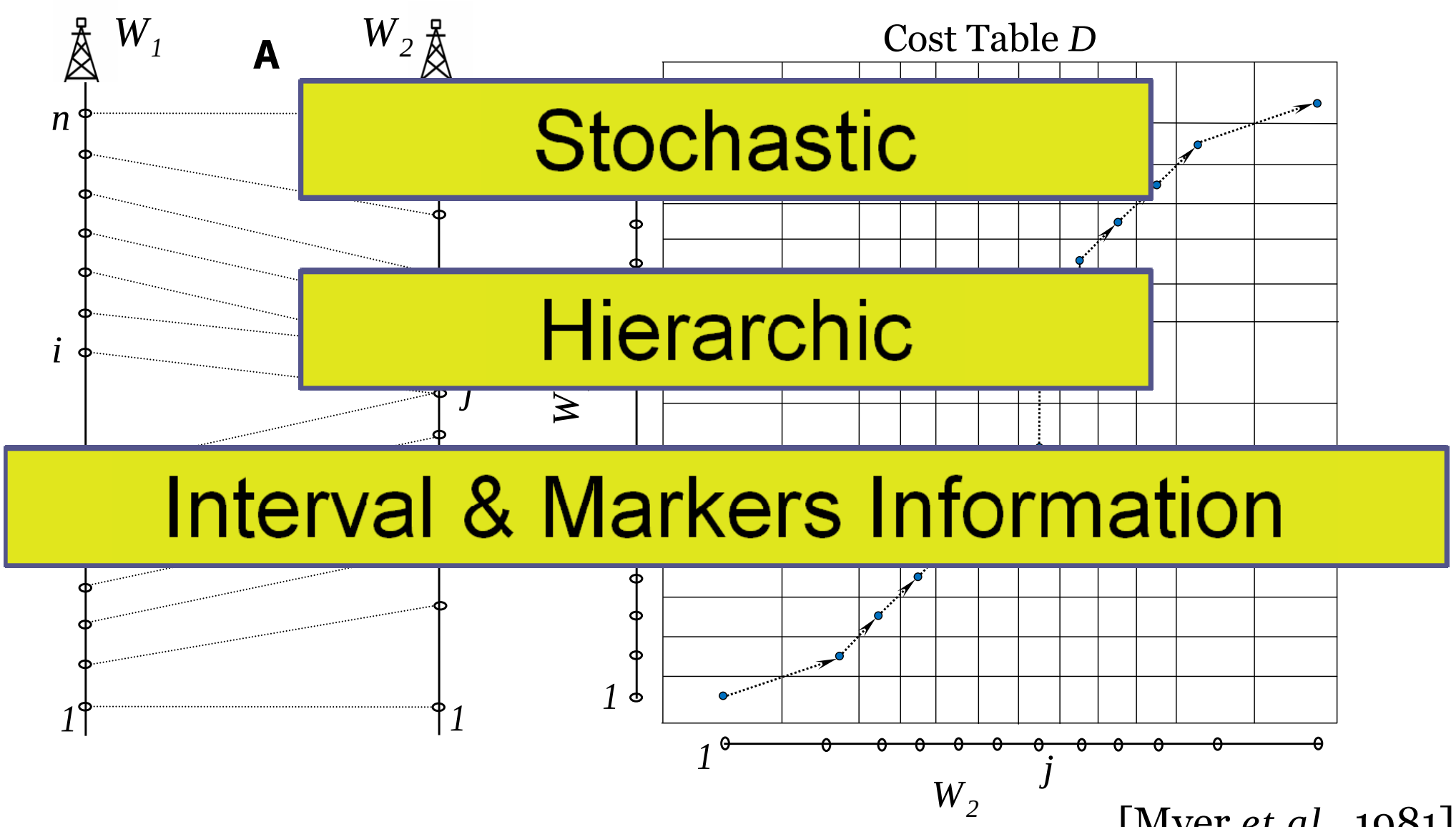
Prior Hypothesis ↔ Stratigraphic Correlation

    - Horizon (seismic)

Aims of the project

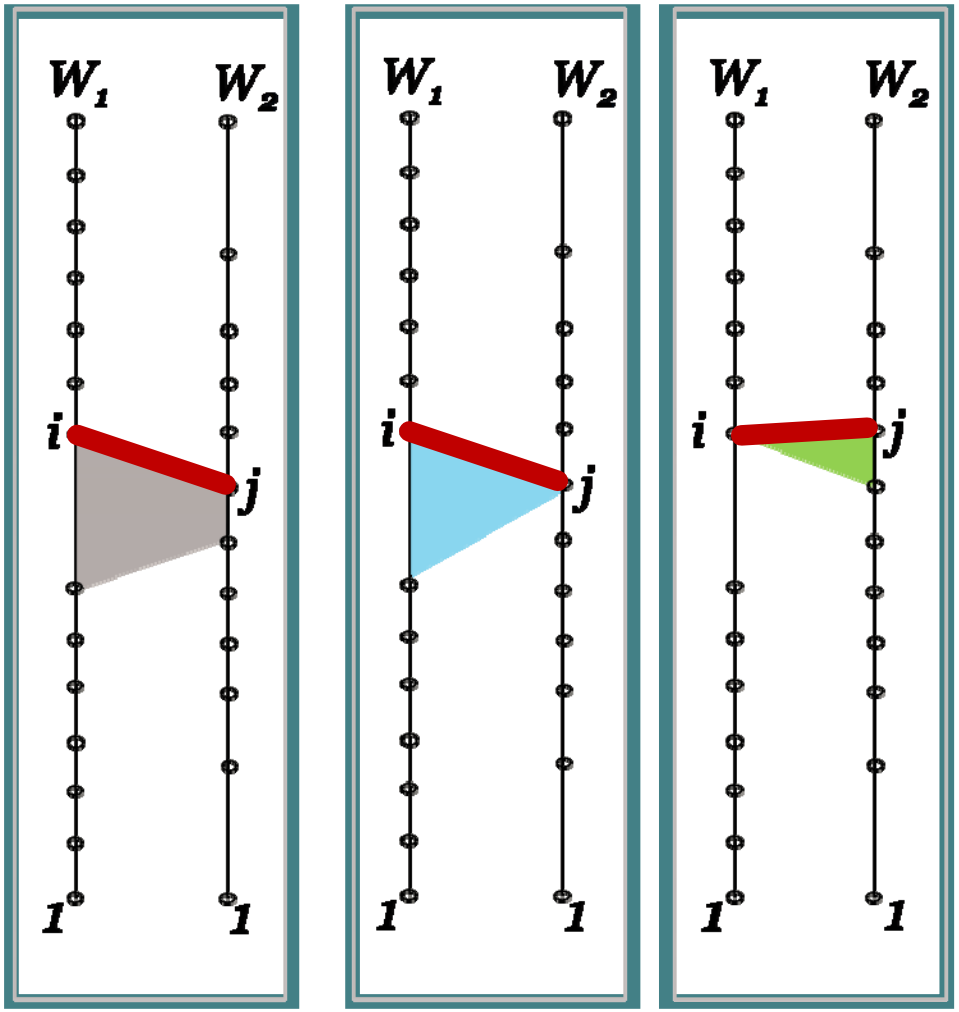
- Determinist step:
  - Wells are incomplete and biased samples of the geological reality → Uncertainty assessment
- Handle stratigraphic correlation uncertainties by generating several possible sets of correlation
- Way :
  - Develop an automatic algorithm for stratigraphic correlation:
    - Test geological assumptions by generating efficiently stratigraphic correlation
    - Generate stochastically several possible correlations **according to prior Hypothesis**

Dynamic Time Warping (DTW)

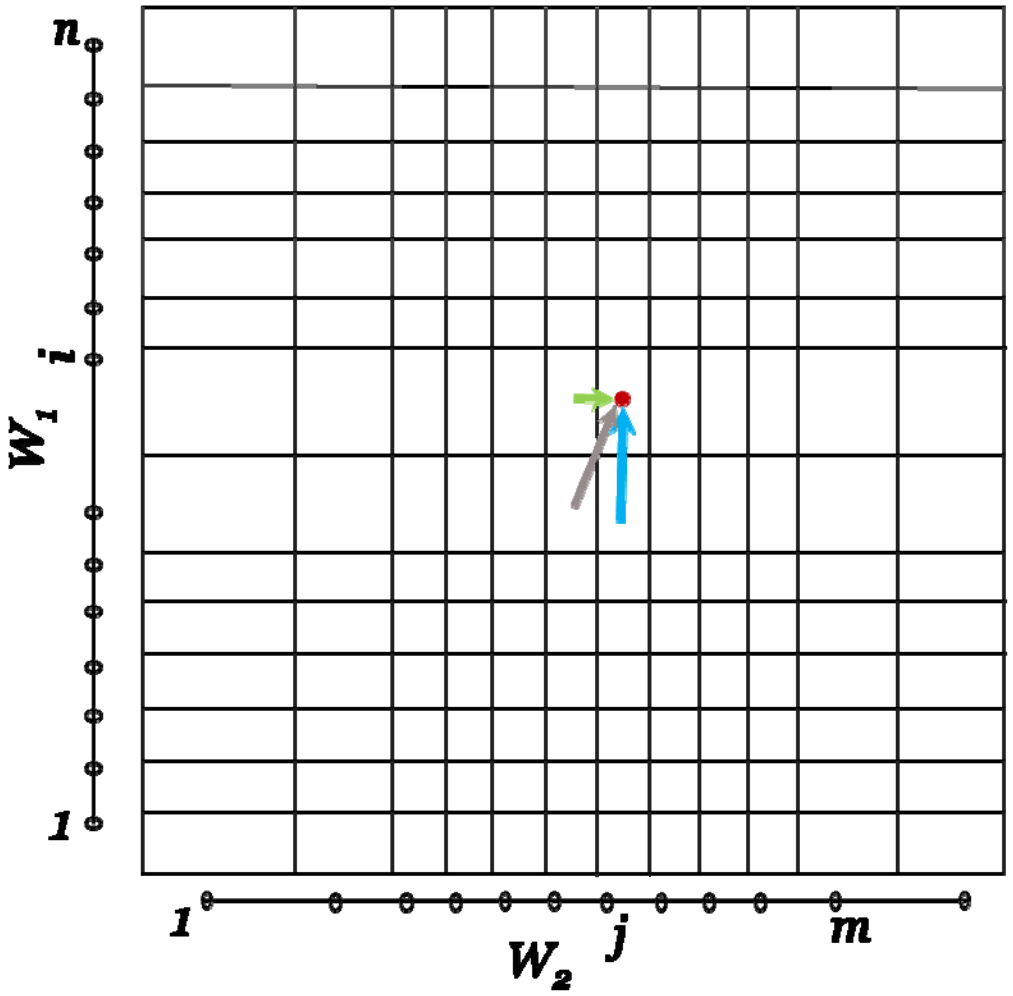


[Myer *et al.*, 1981]

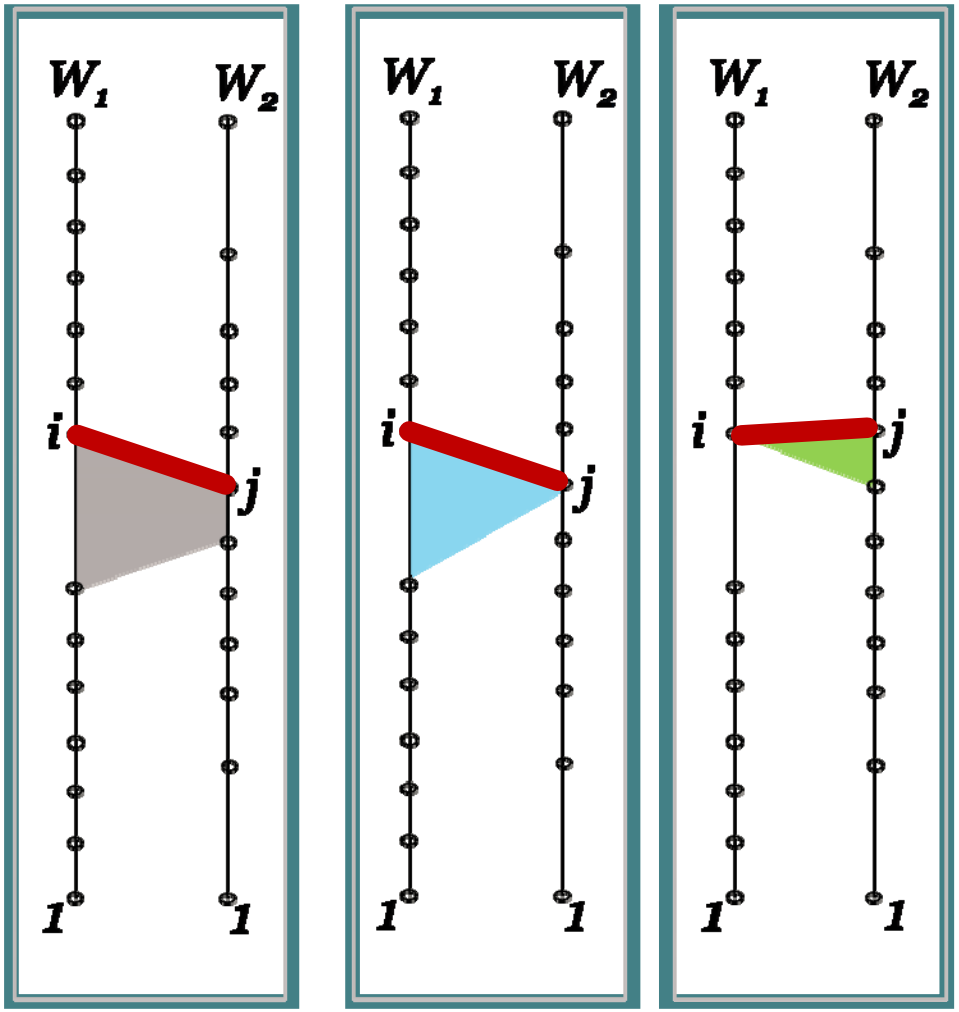
DTW: Definition

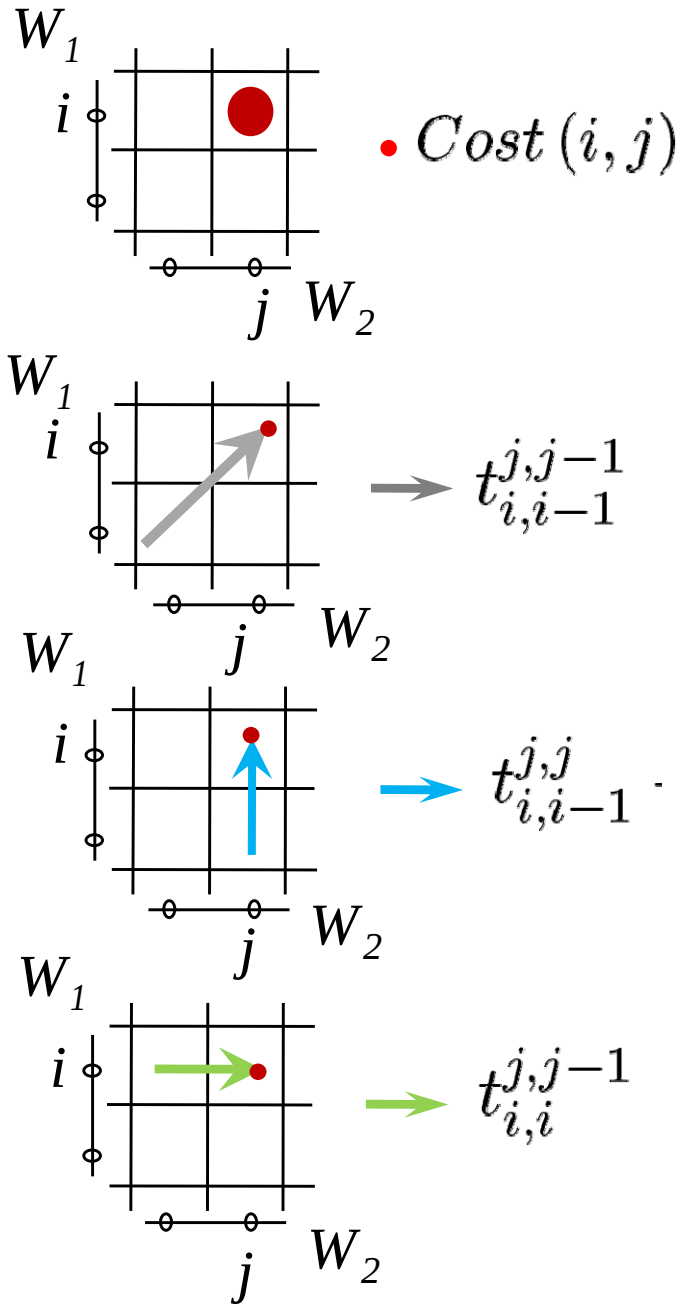


Cost Table *D*



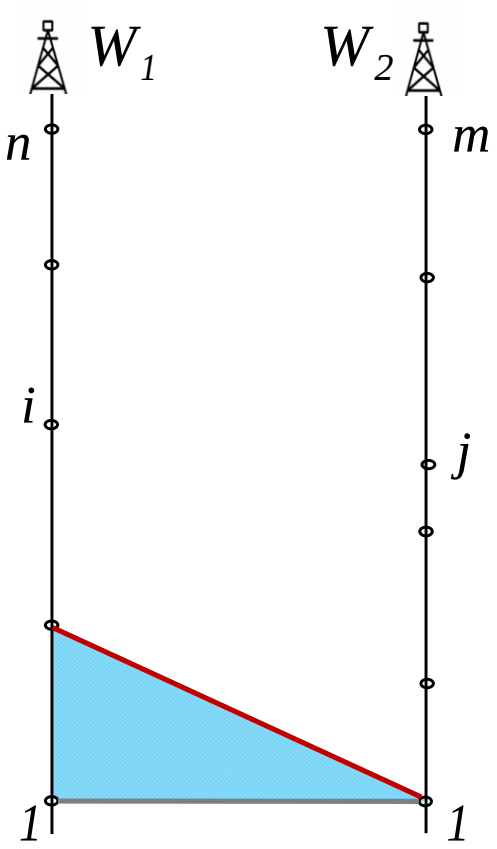
DTW: Definition

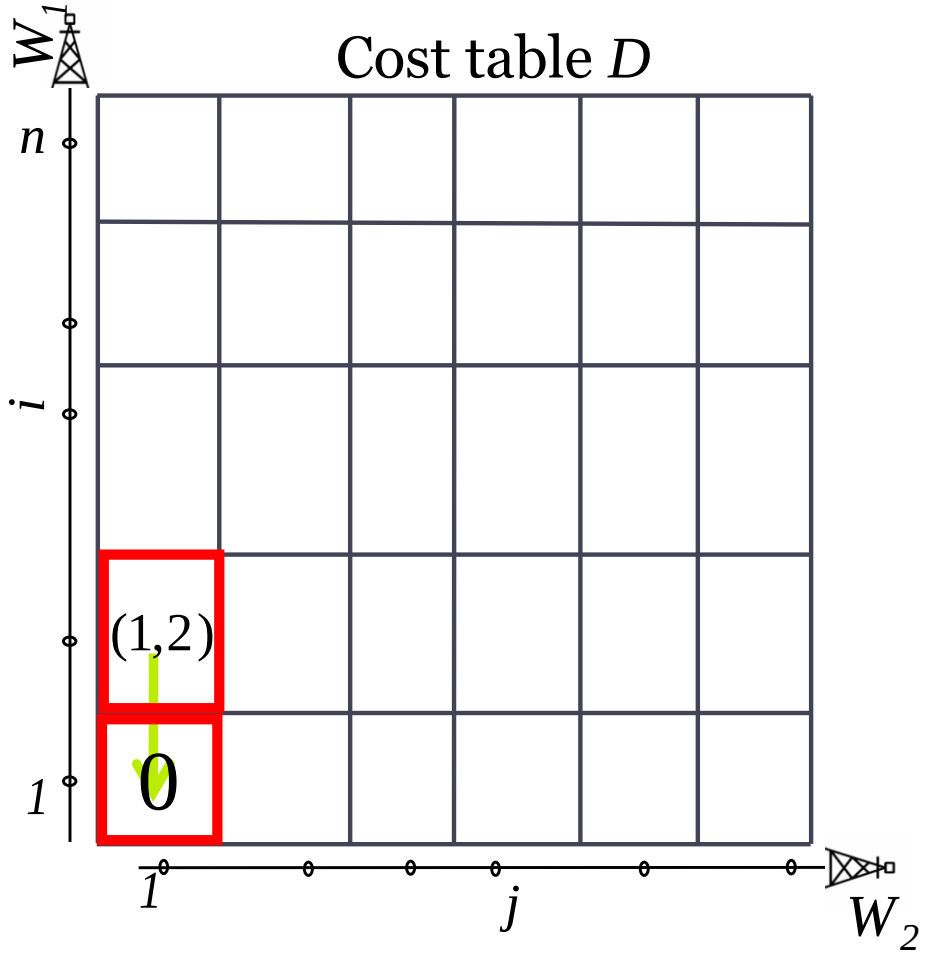




DTW:

Cost Table Filling and Correlation Path Building



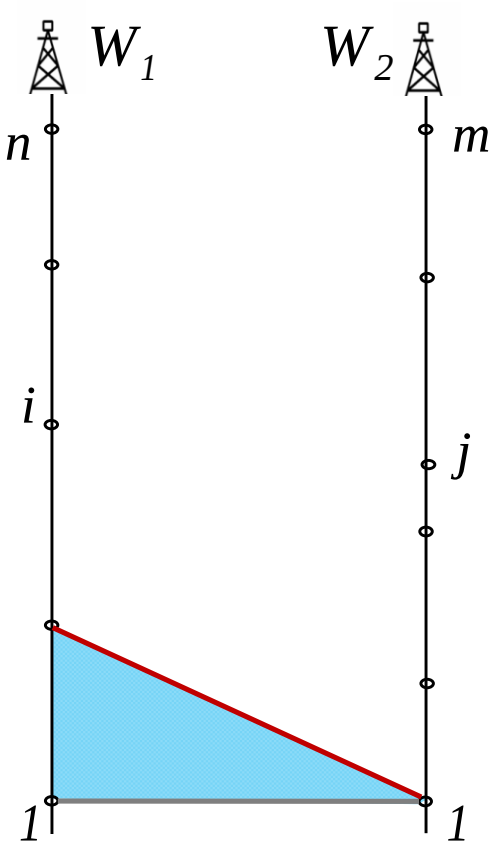


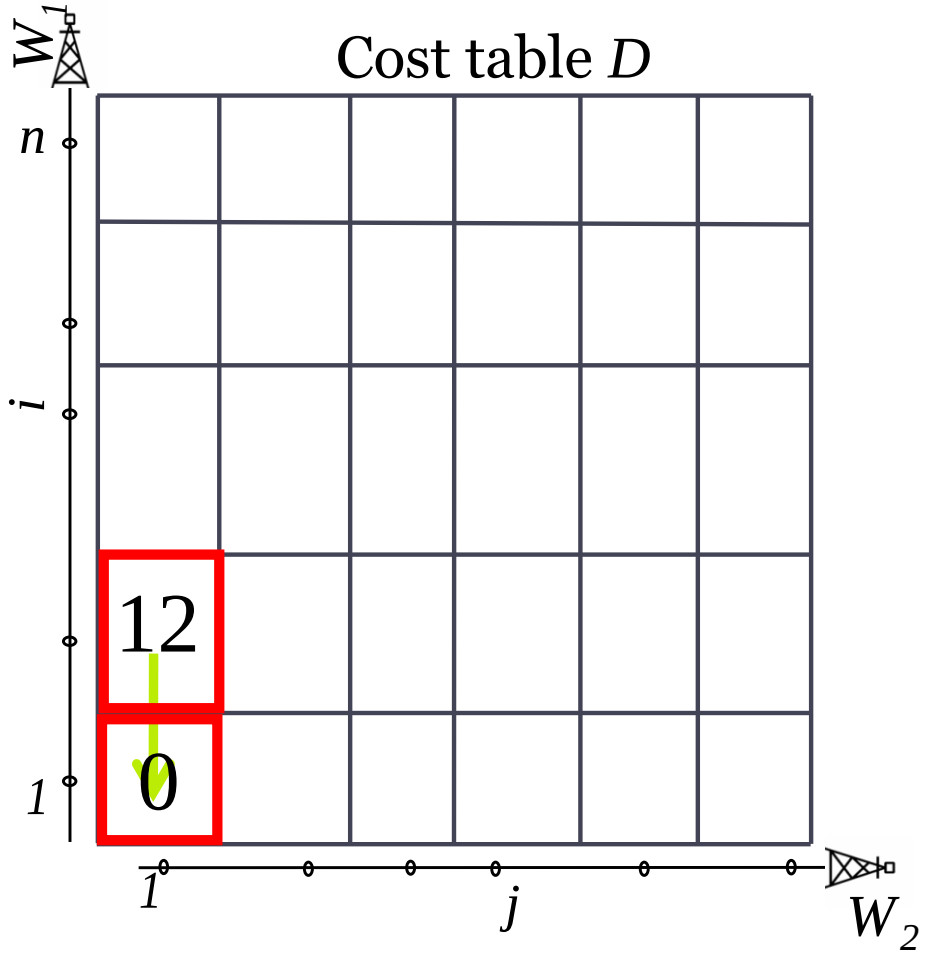
$Cost\,(1,2) = 2$

$t_{1,1}^{1,2} = 10$

DTW:

Cost Table Filling and Correlation Path Building





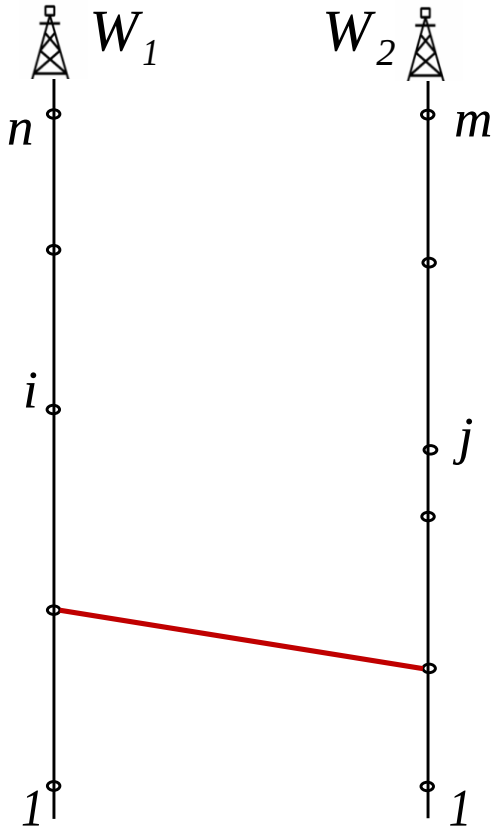
$Cost\,(1,2) = 2$

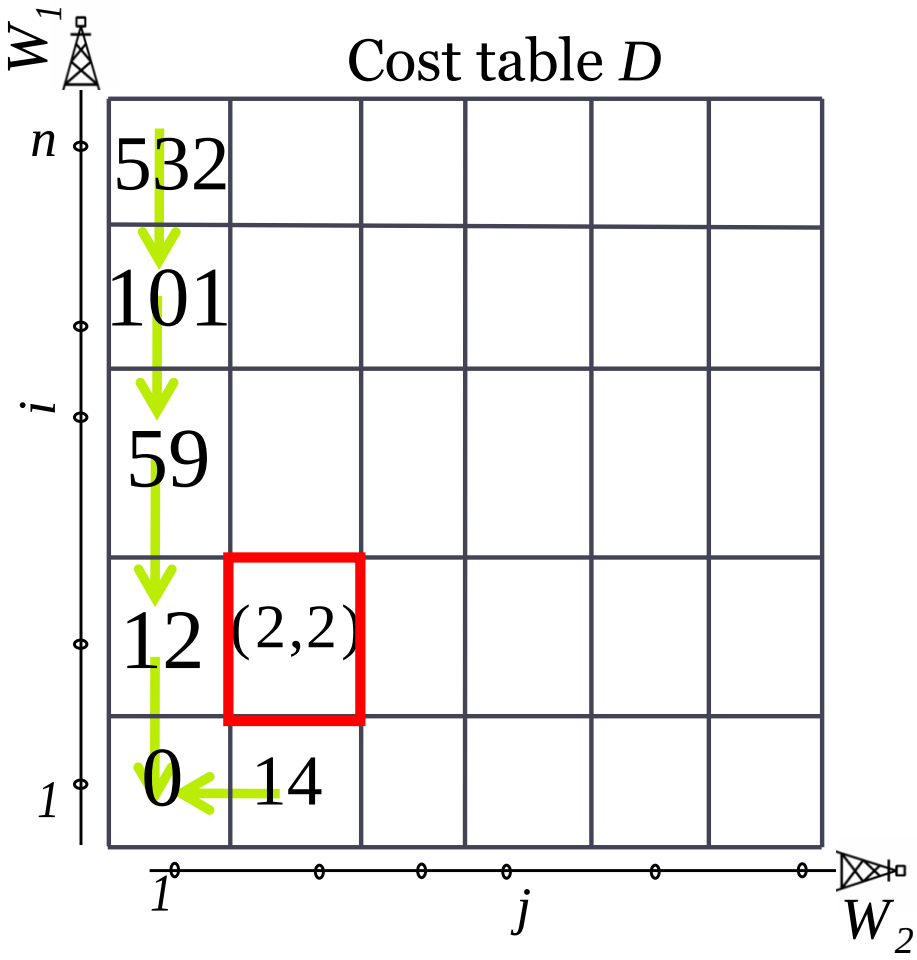
$t_{1,1}^{1,2} = 10$

DTW:

Cost Table Filling and Correlation Path building

Stochastic



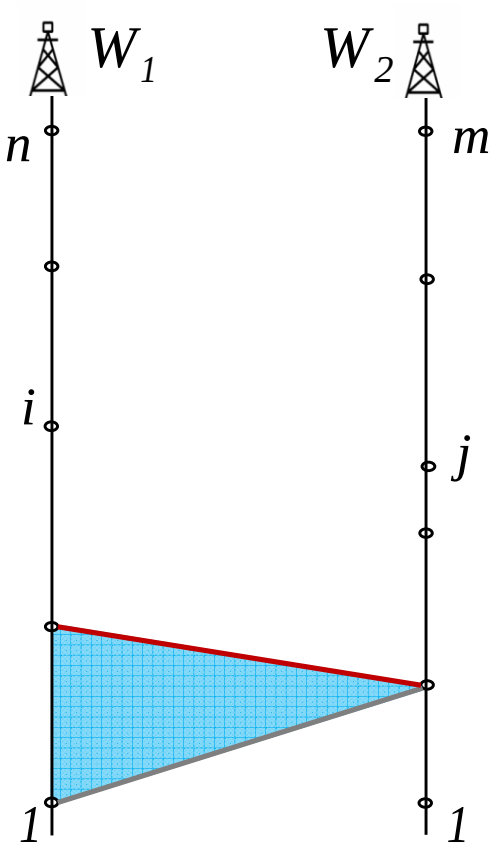


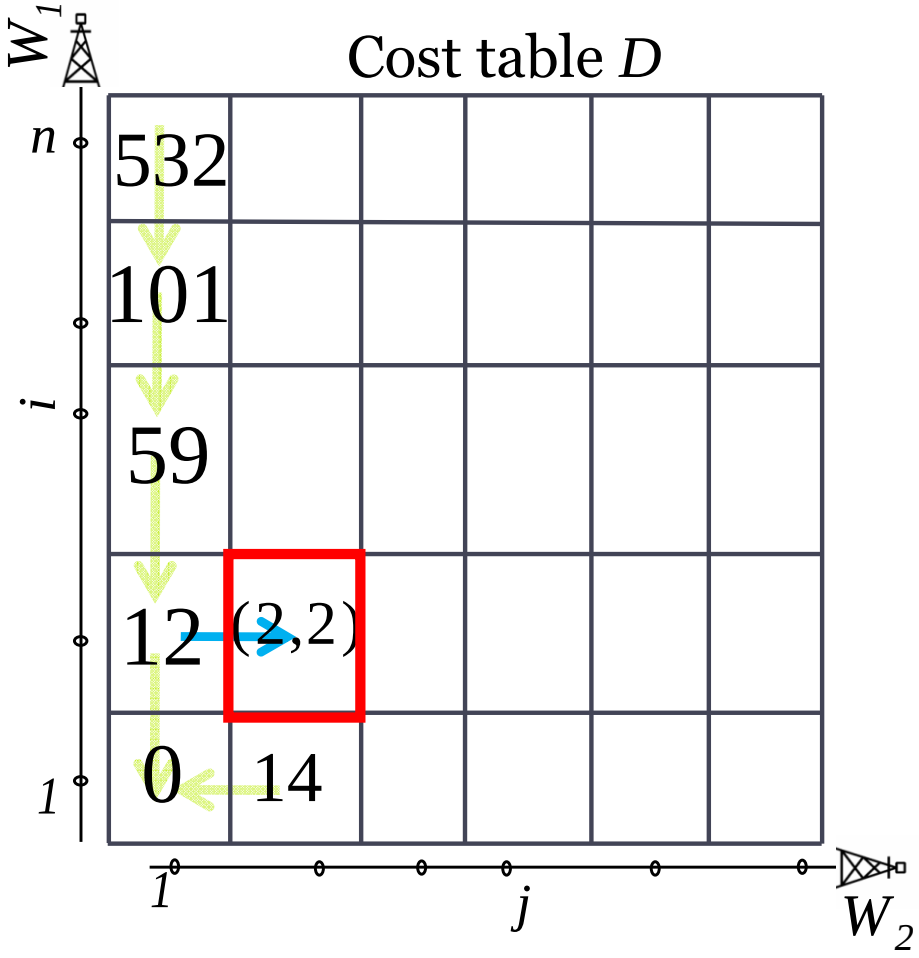
$$Cost\,(2,2) = 1$$

DTW:

Cost Table Filling and Correlation Path building

Stochastic





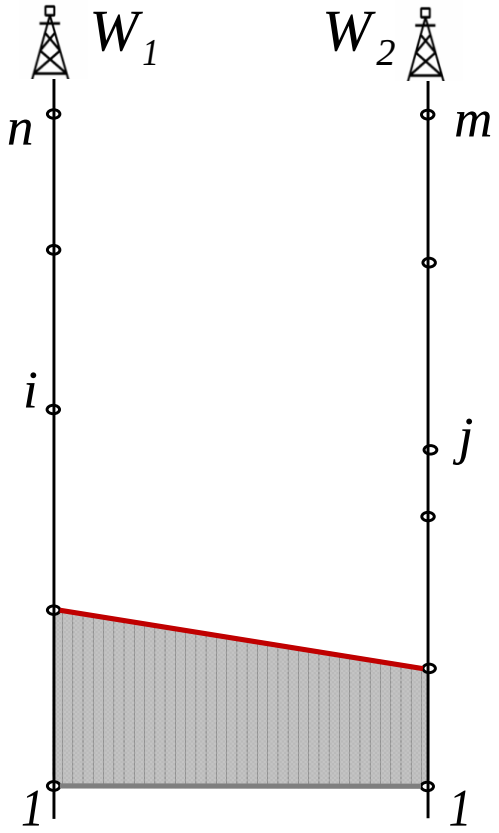
$$Cost\,(2,2) = 1$$

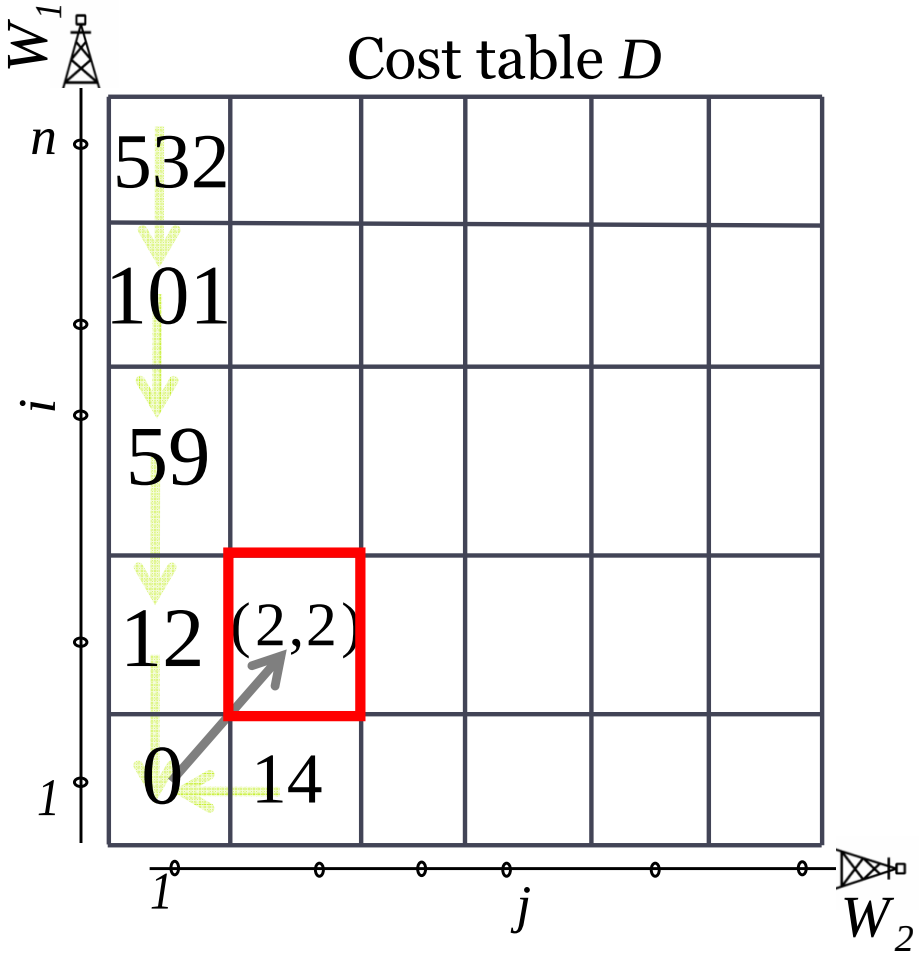
$$t_{1,2}^{2,2} = 15$$

Stochastic DTW:

Cost Table Filling and Correlation Path building

Stochastic





$Cost\,(2,2) = 2$

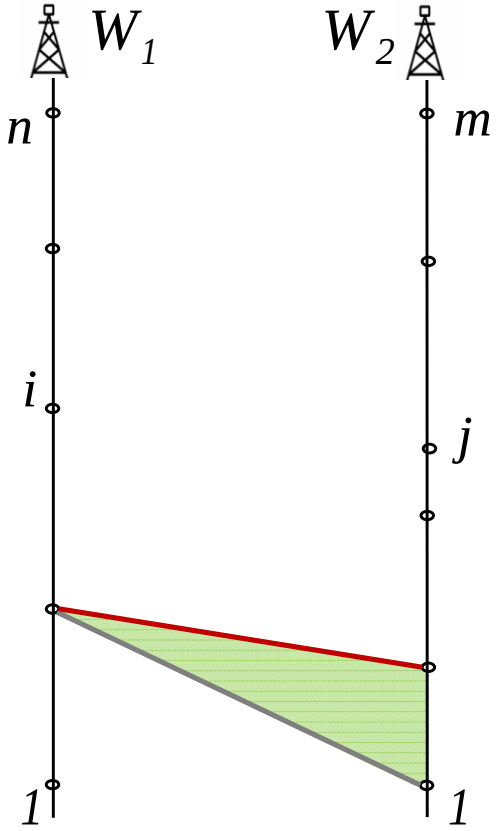
$t_{1,1}^{1,2} = 10$

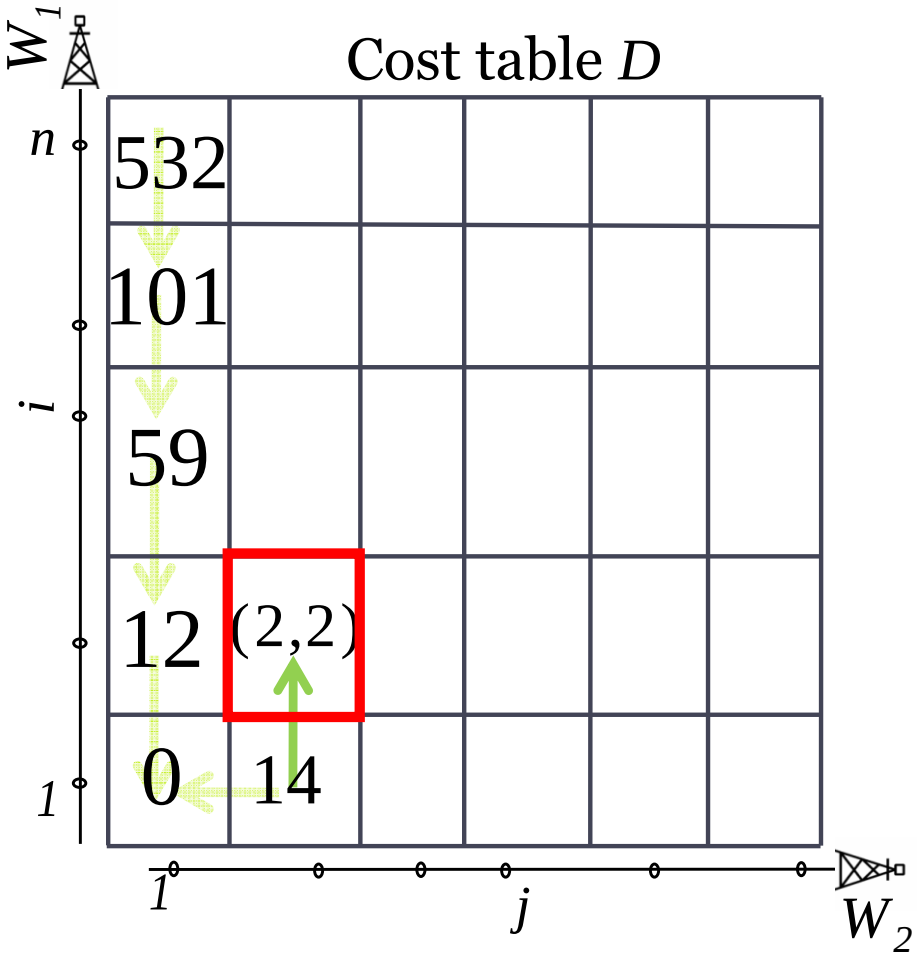
$t_{1,2}^{1,2} = 0$

Stochastic DTW:

Cost Table Filling and Correlation Path building

Stochastic





$Cost\,(1,2) = 2$

$t_{1,1}^{1,2} = 10$

$t_{1,2}^{1,2} = 0$

$t_{2,2}^{1,2} = 21$

Stochastic DTW:

Cost Table Filling and Correlation Path Building

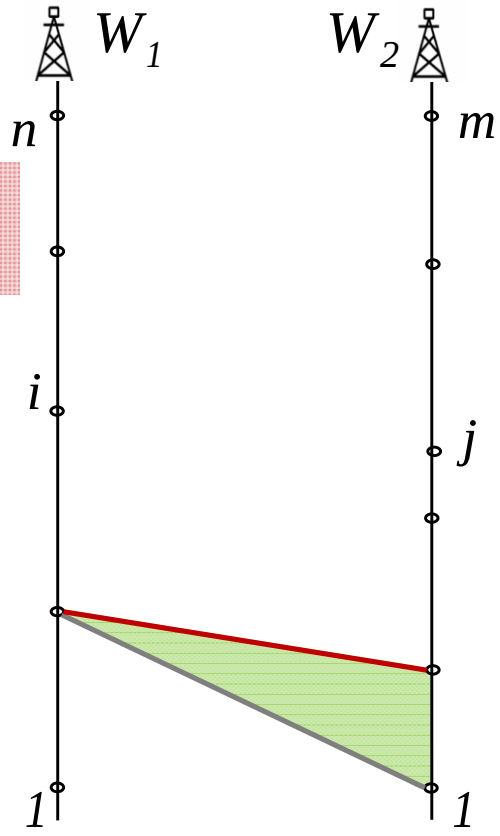
Stochastic

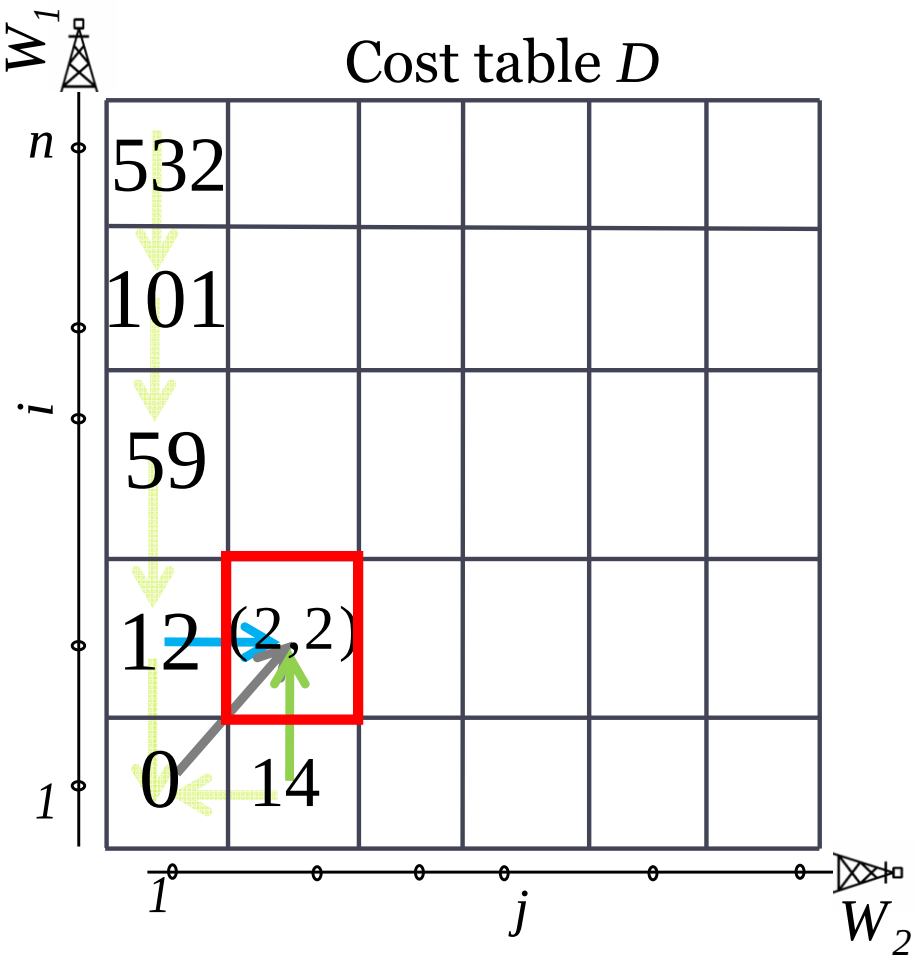
$$Cost\,(2,2) = 1$$

$$t_{1,2}^{2,2} = 15$$

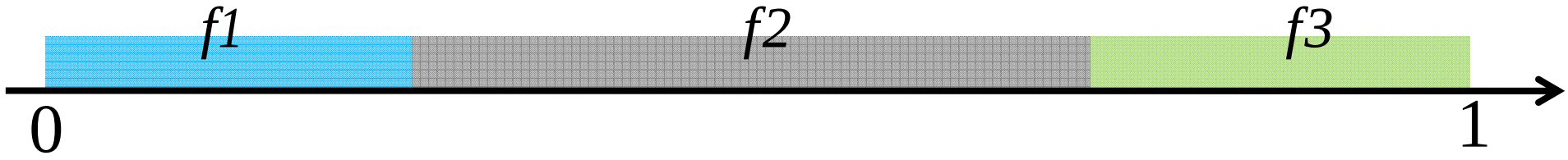
$$t_{1,2}^{1,2} = 0$$

$$t_{2,2}^{1,2} = 21$$





- From costs, *f1*, *f2* and *f3* are computed as inverse distance



Stochastic DTW:

Cost Table Filling and Correlation Path building

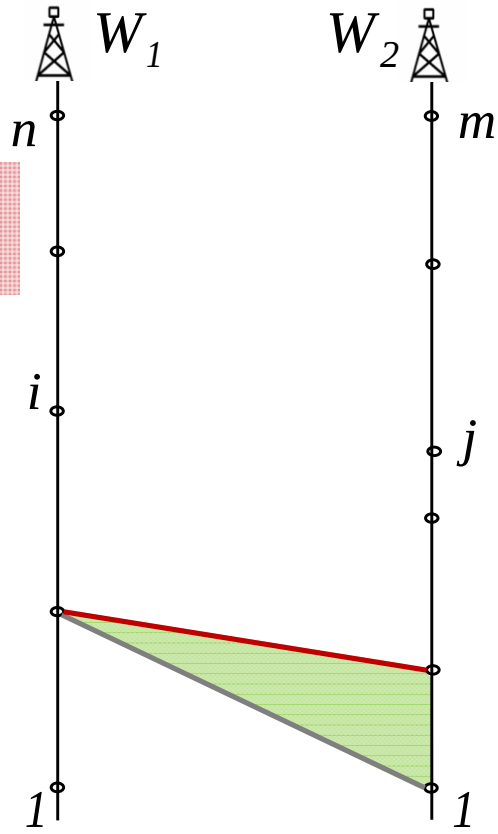
Stochastic

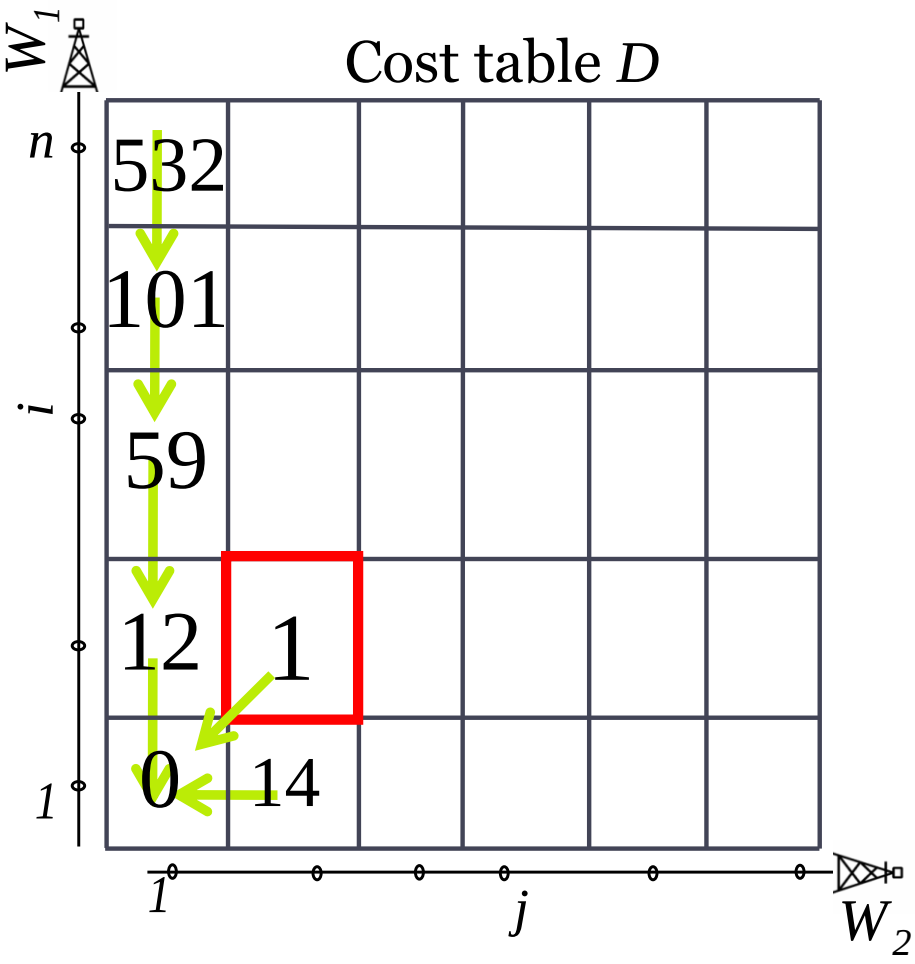
$$Cost\,(2,2) = 1$$

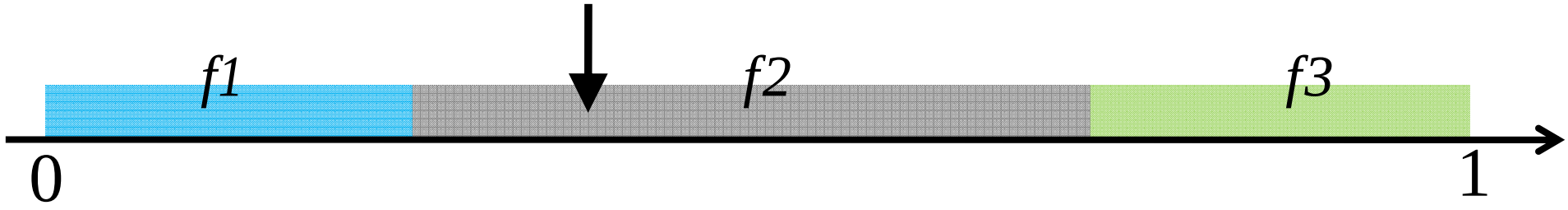
$$t_{1,2}^{2,2} = 15$$

$$t_{1,2}^{1,2} = 0$$

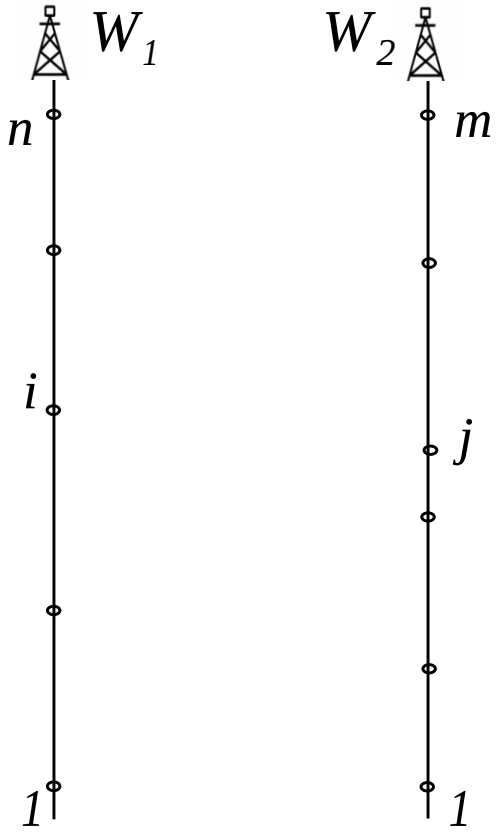
$$t_{2,2}^{1,2} = 21$$

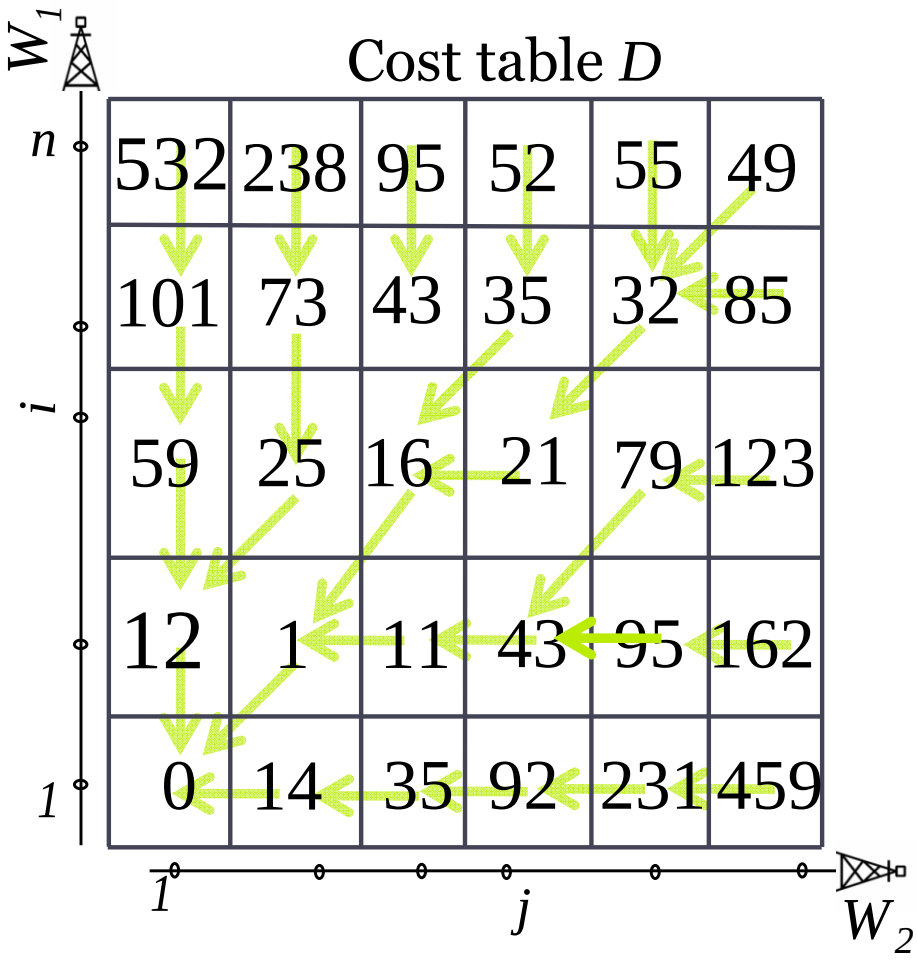




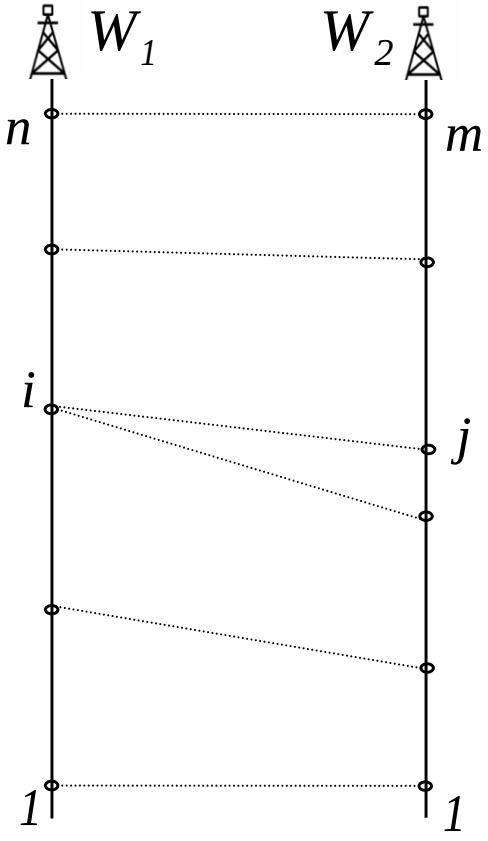


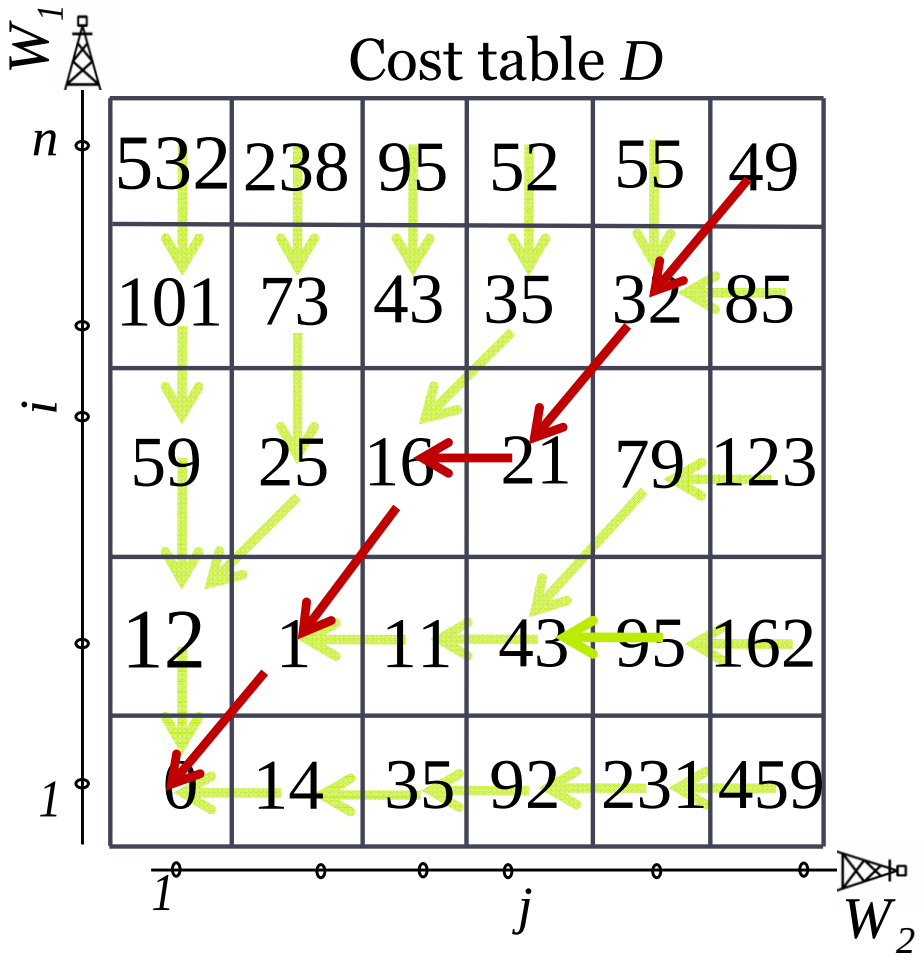
DTW:
Correlation building



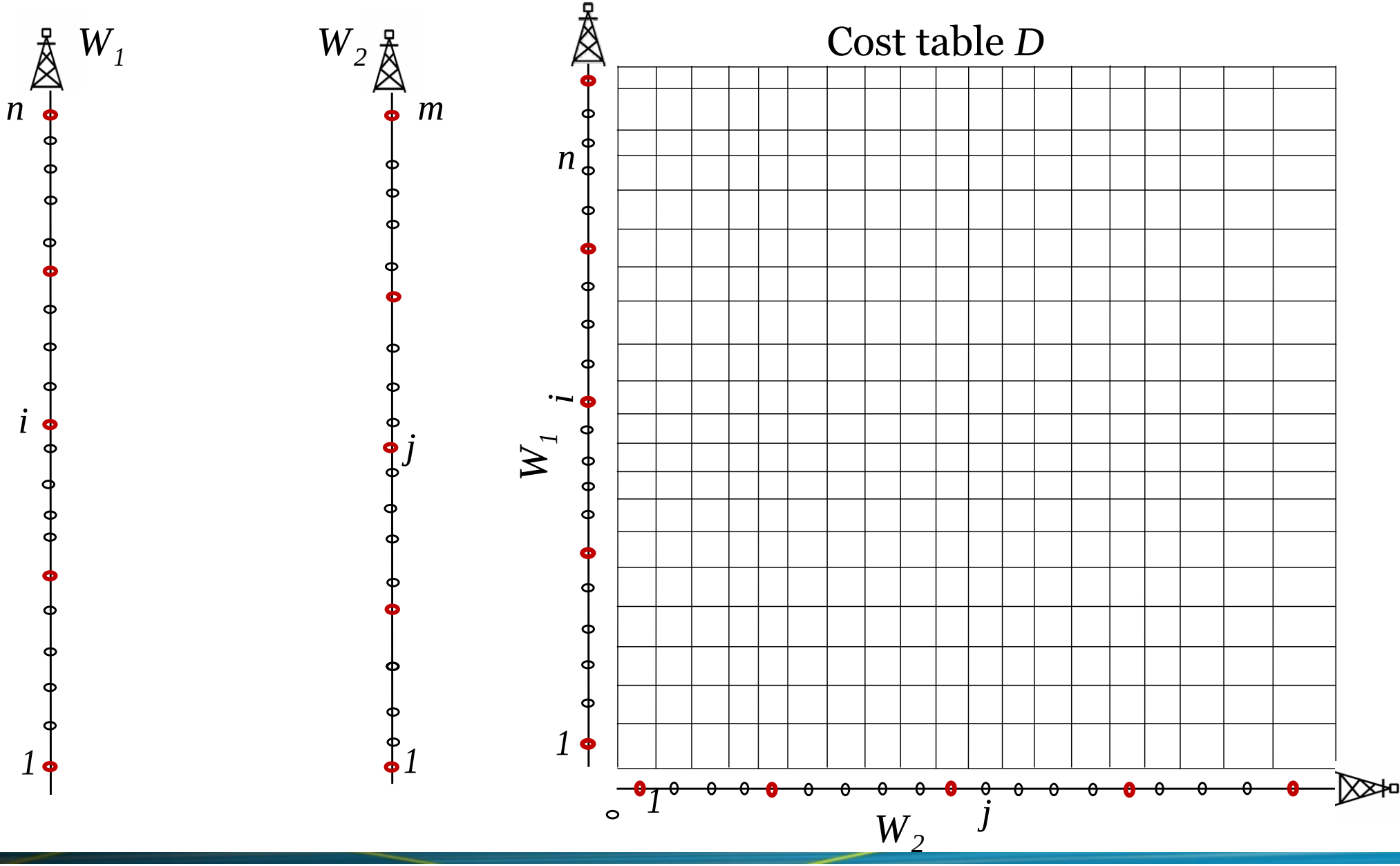


DTW:
Correlation Path Building

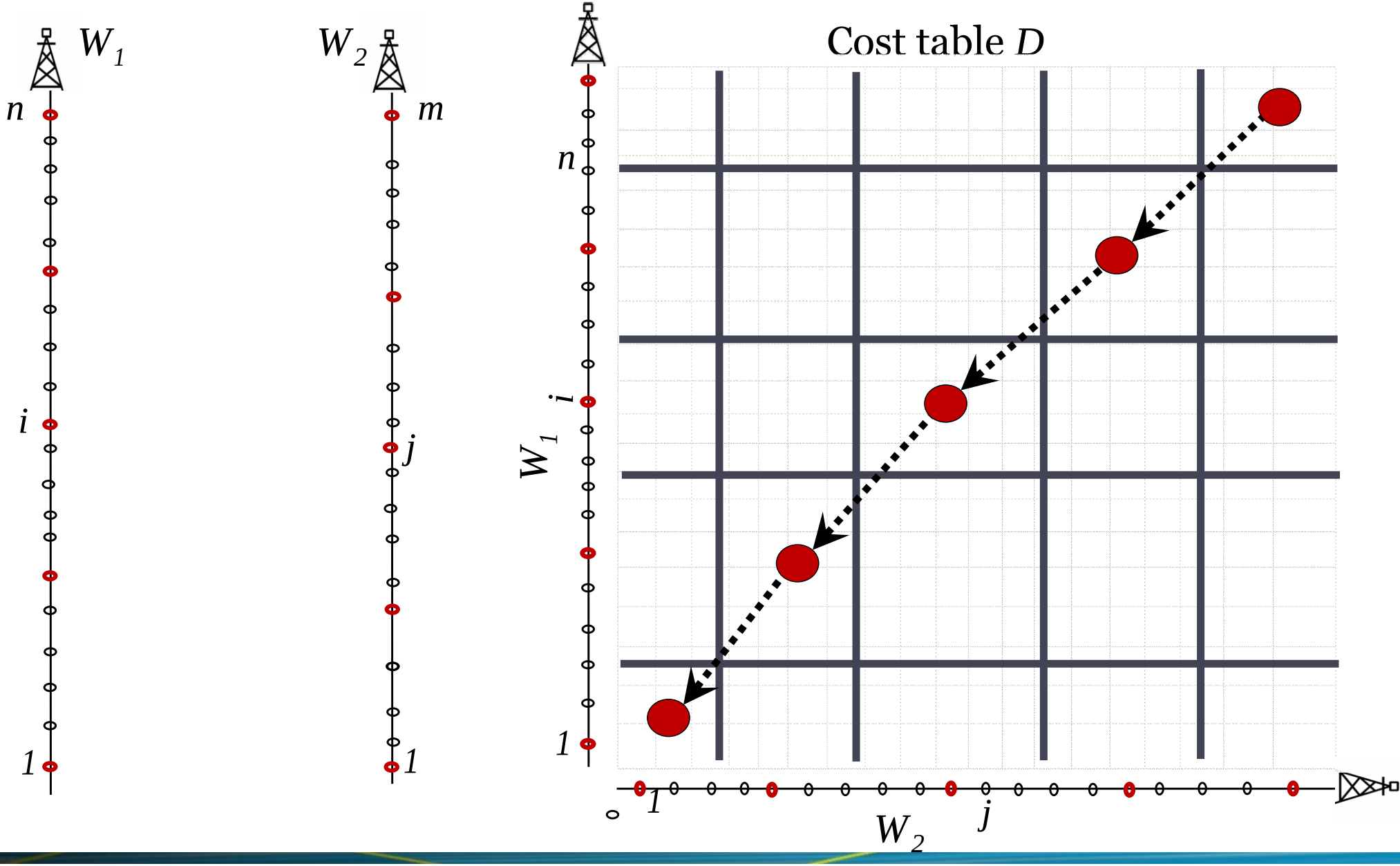




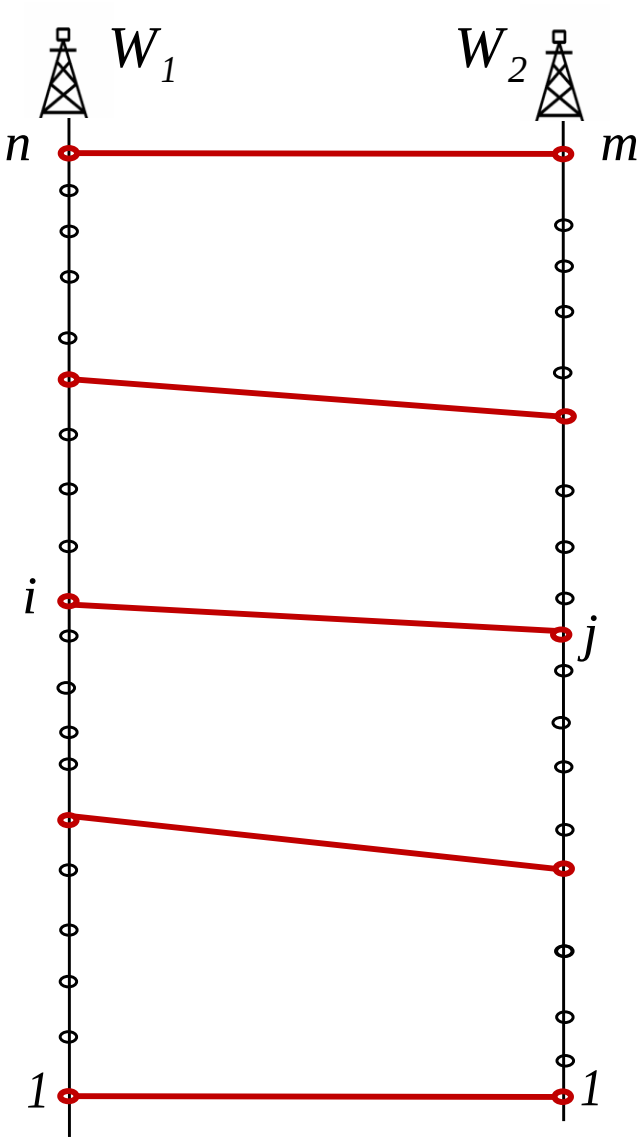
Hierarchic DTW

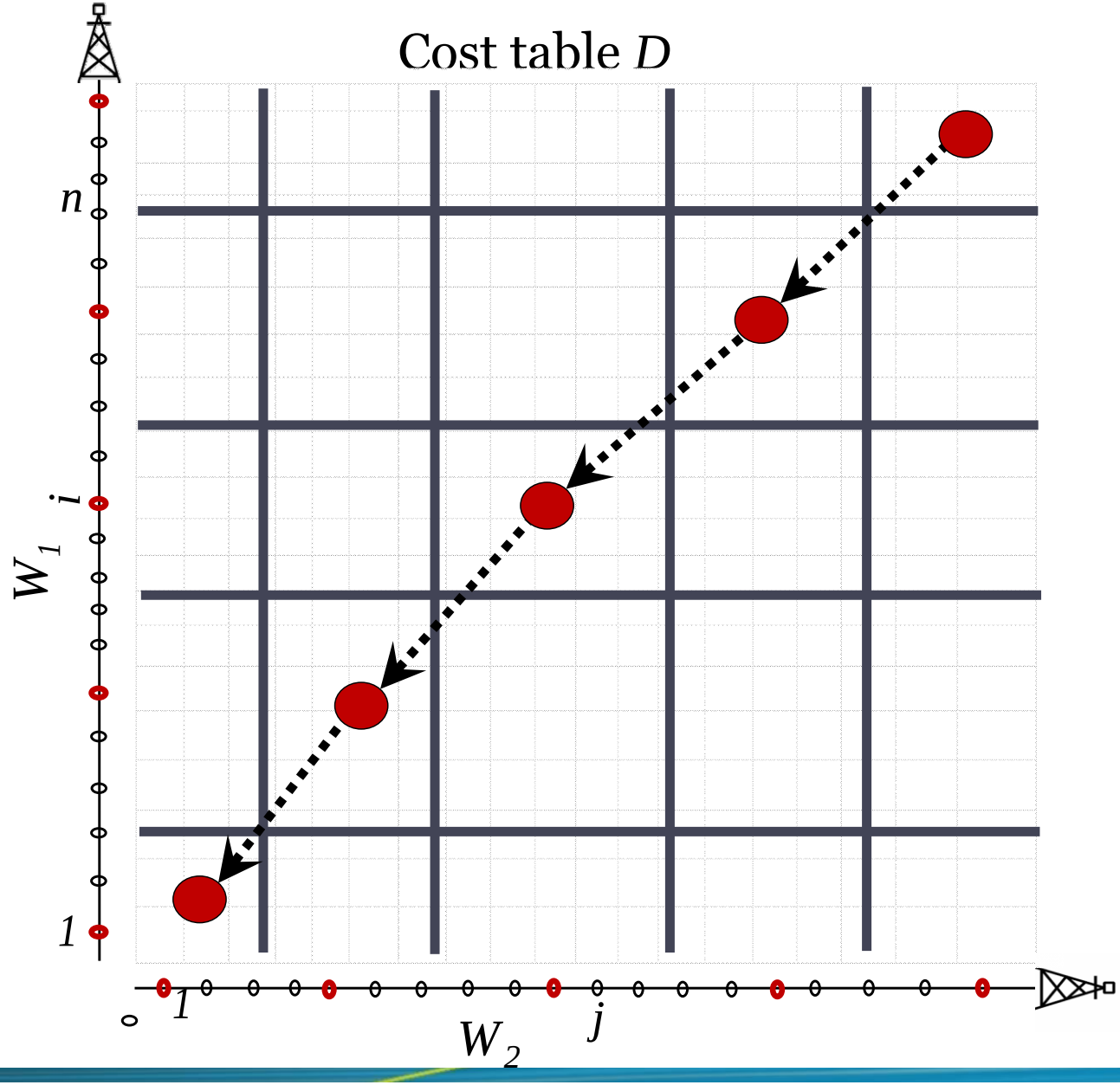


Hierarchic DTW

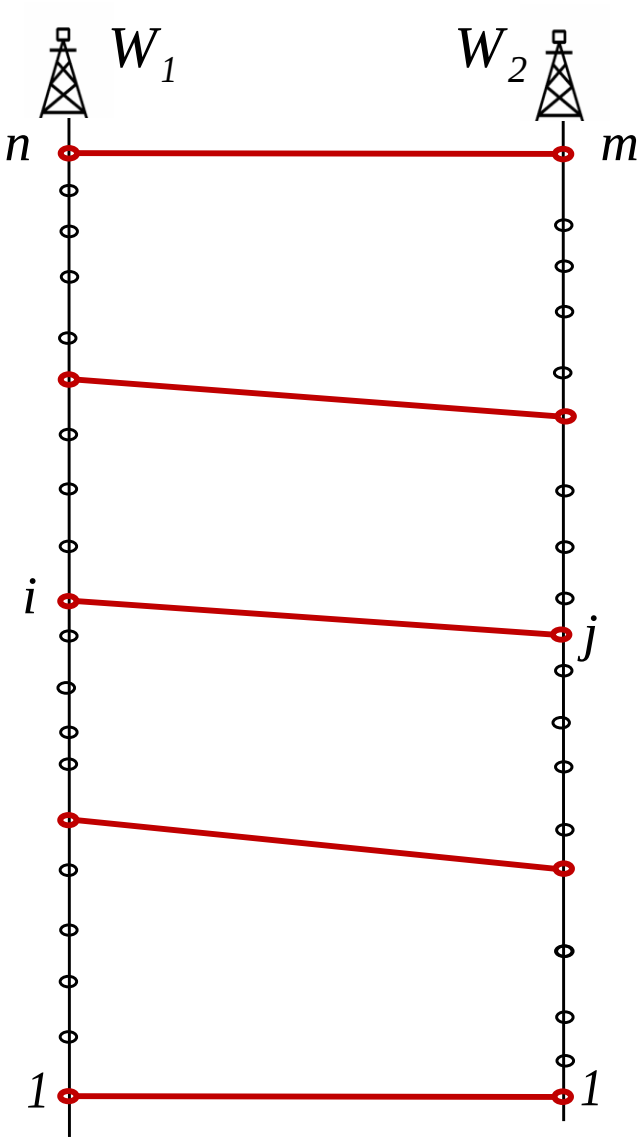


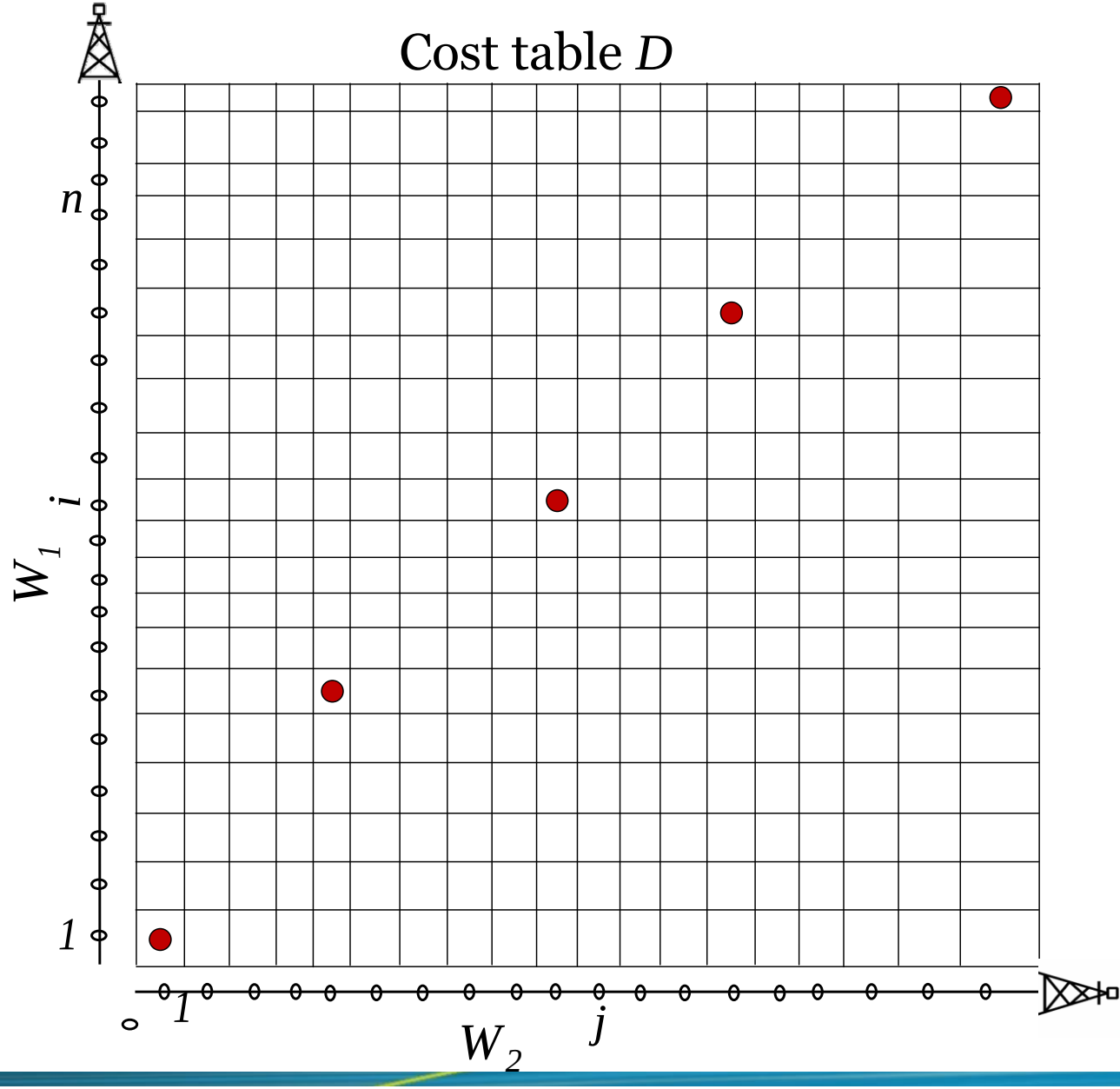
Hierarchic DTW



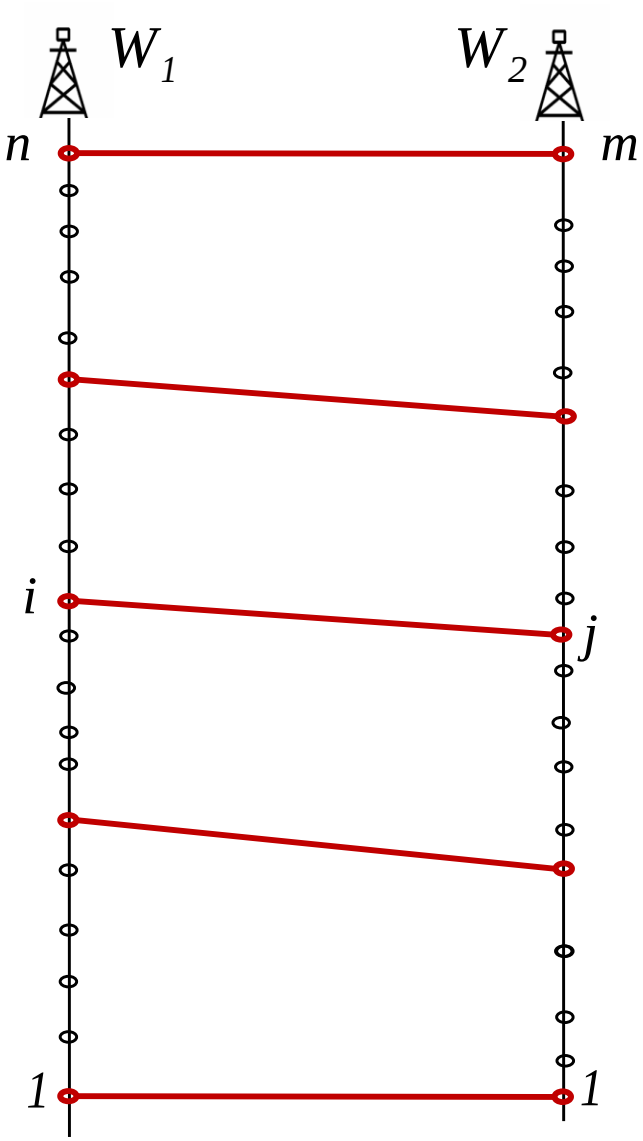


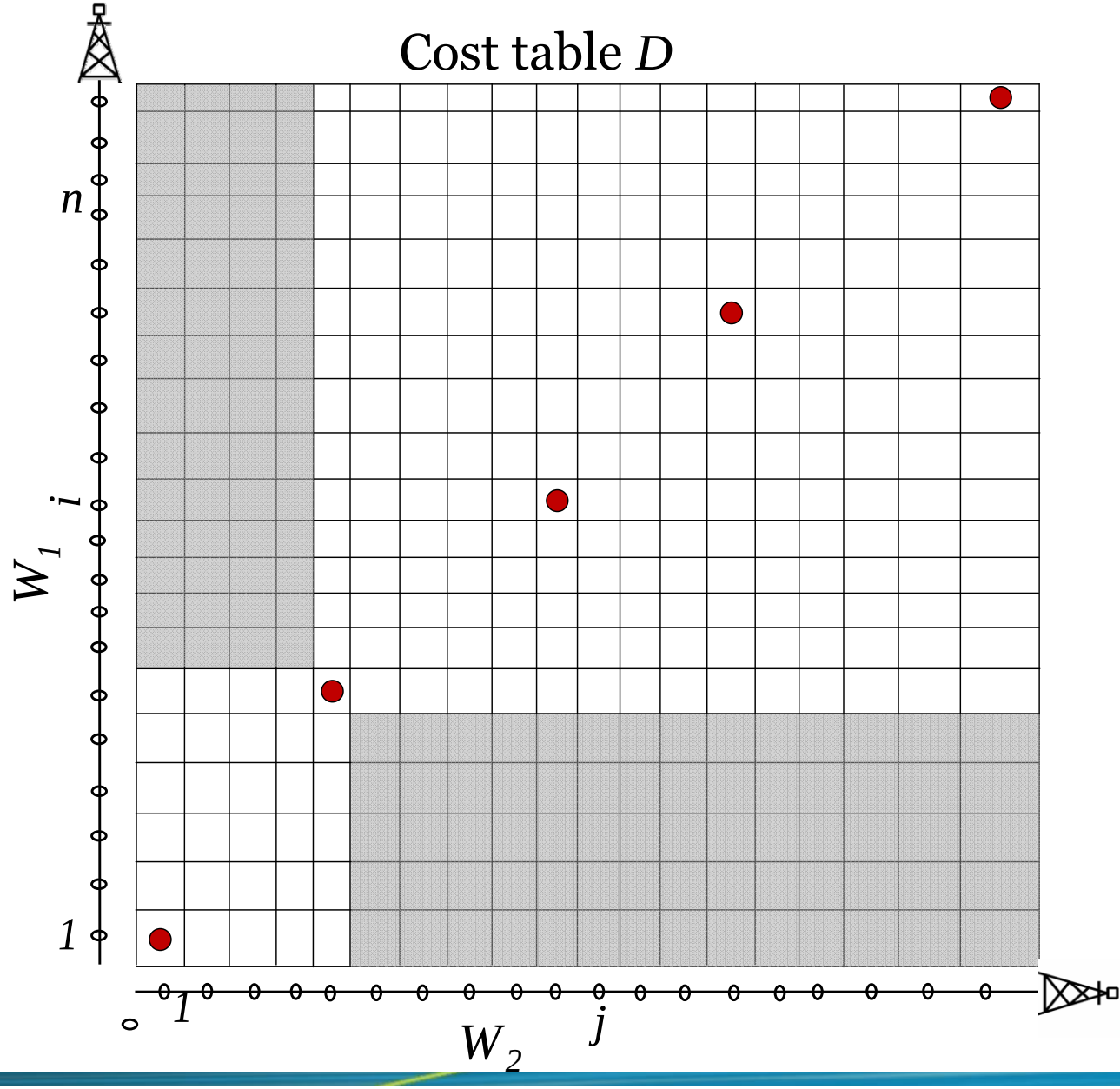
Hierarchic DTW



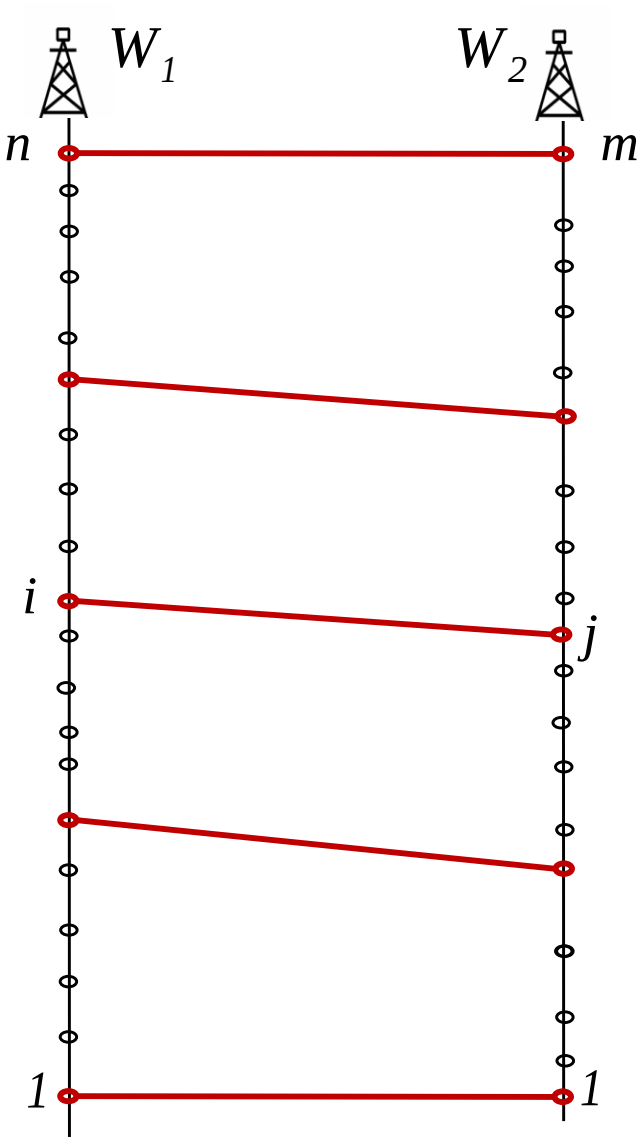


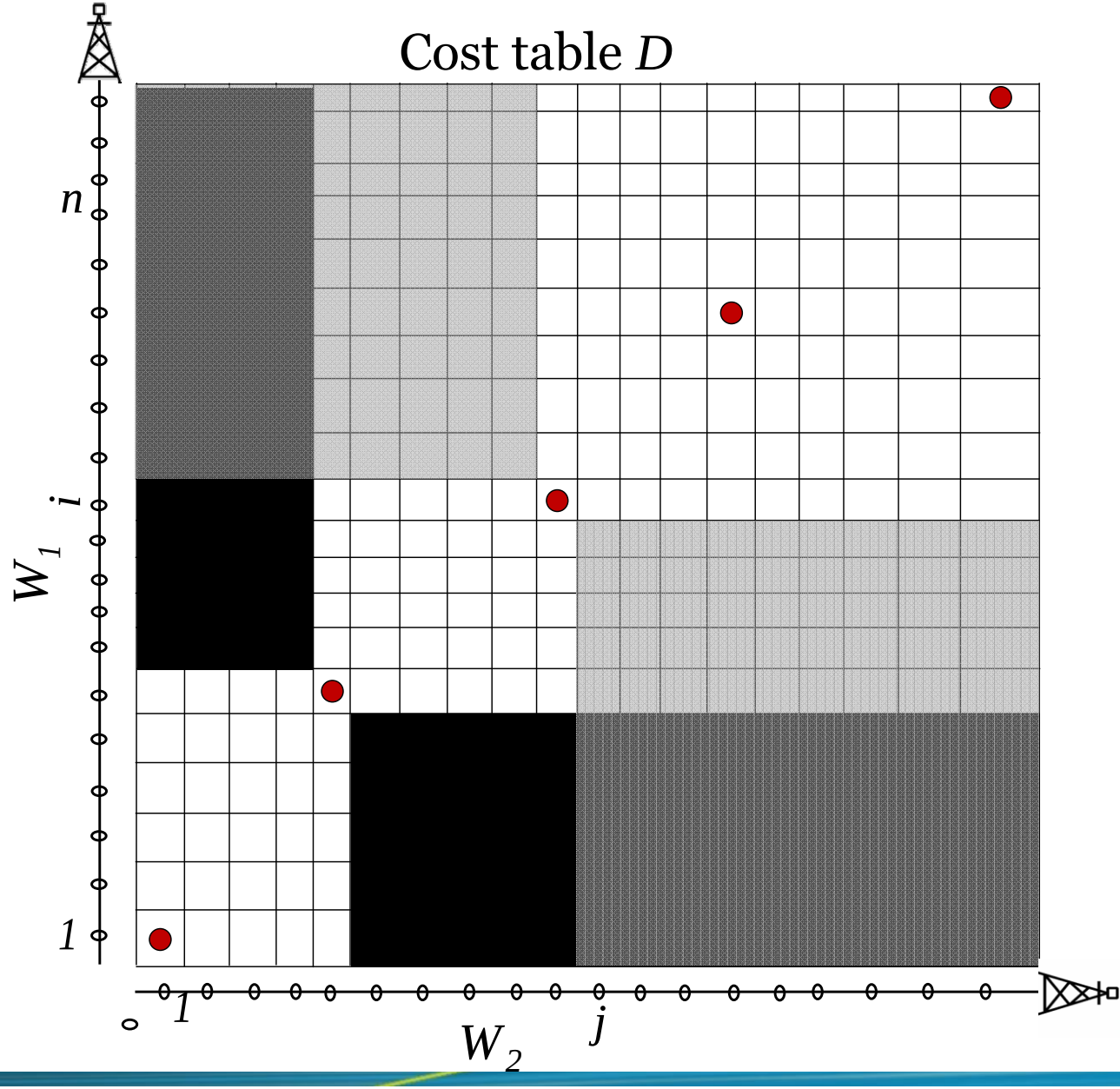
Hierarchic DTW



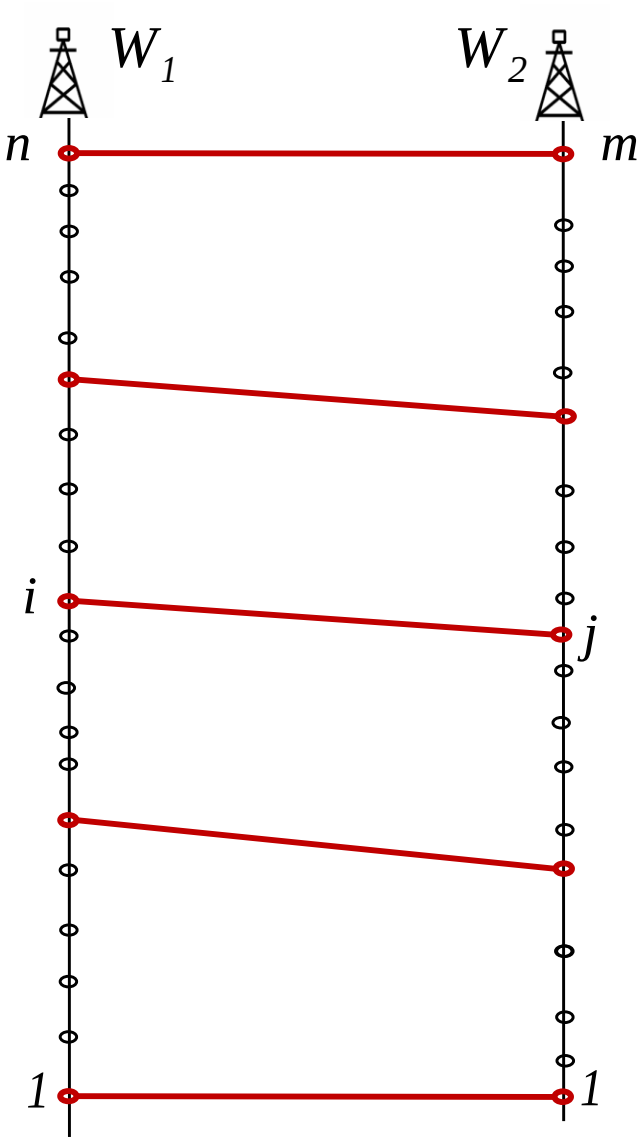


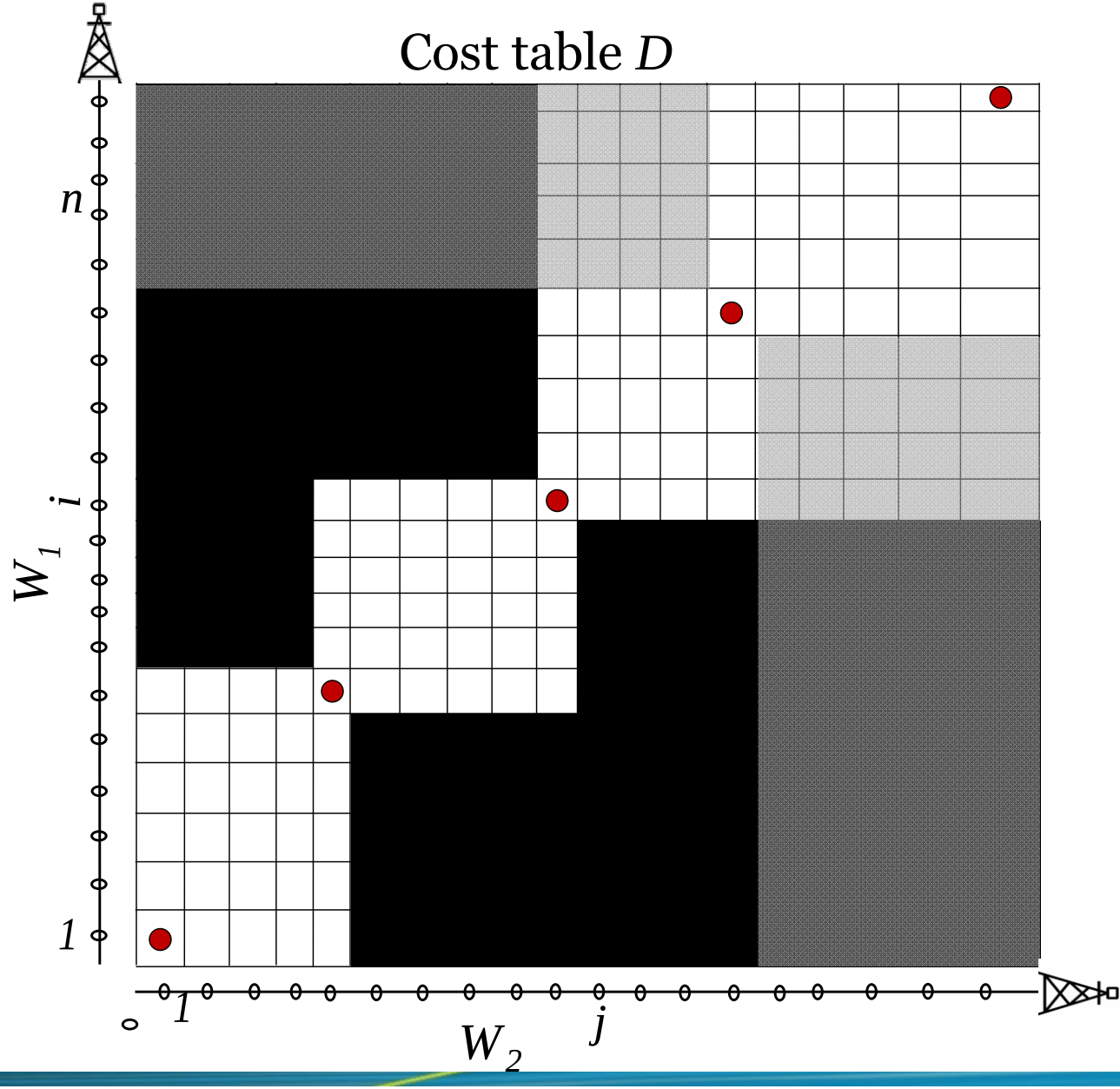
Hierarchic DTW



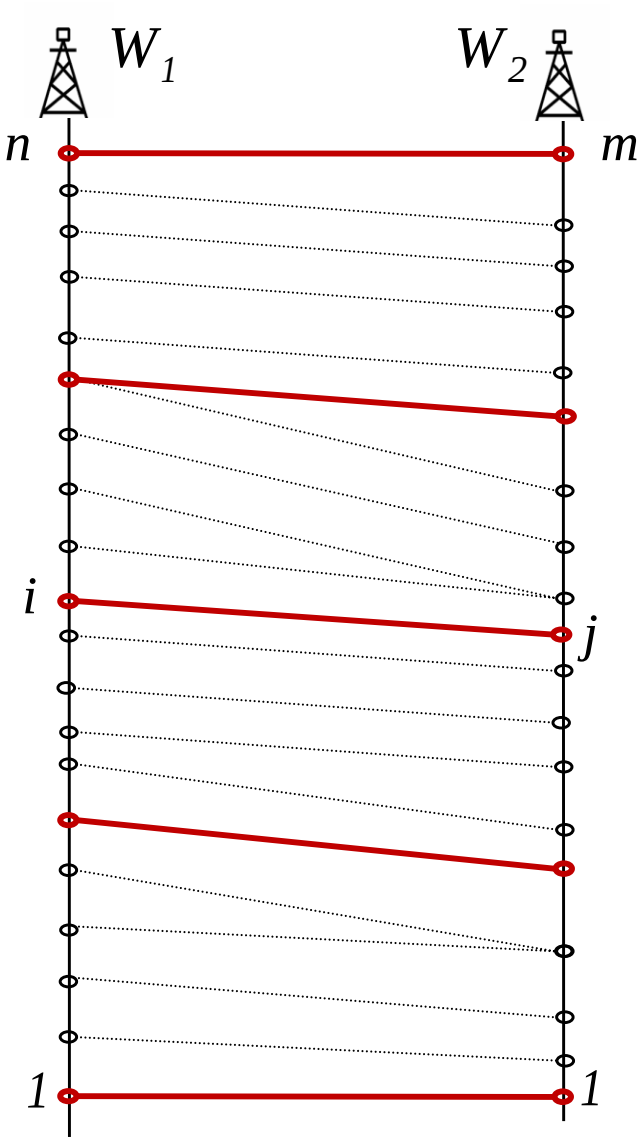


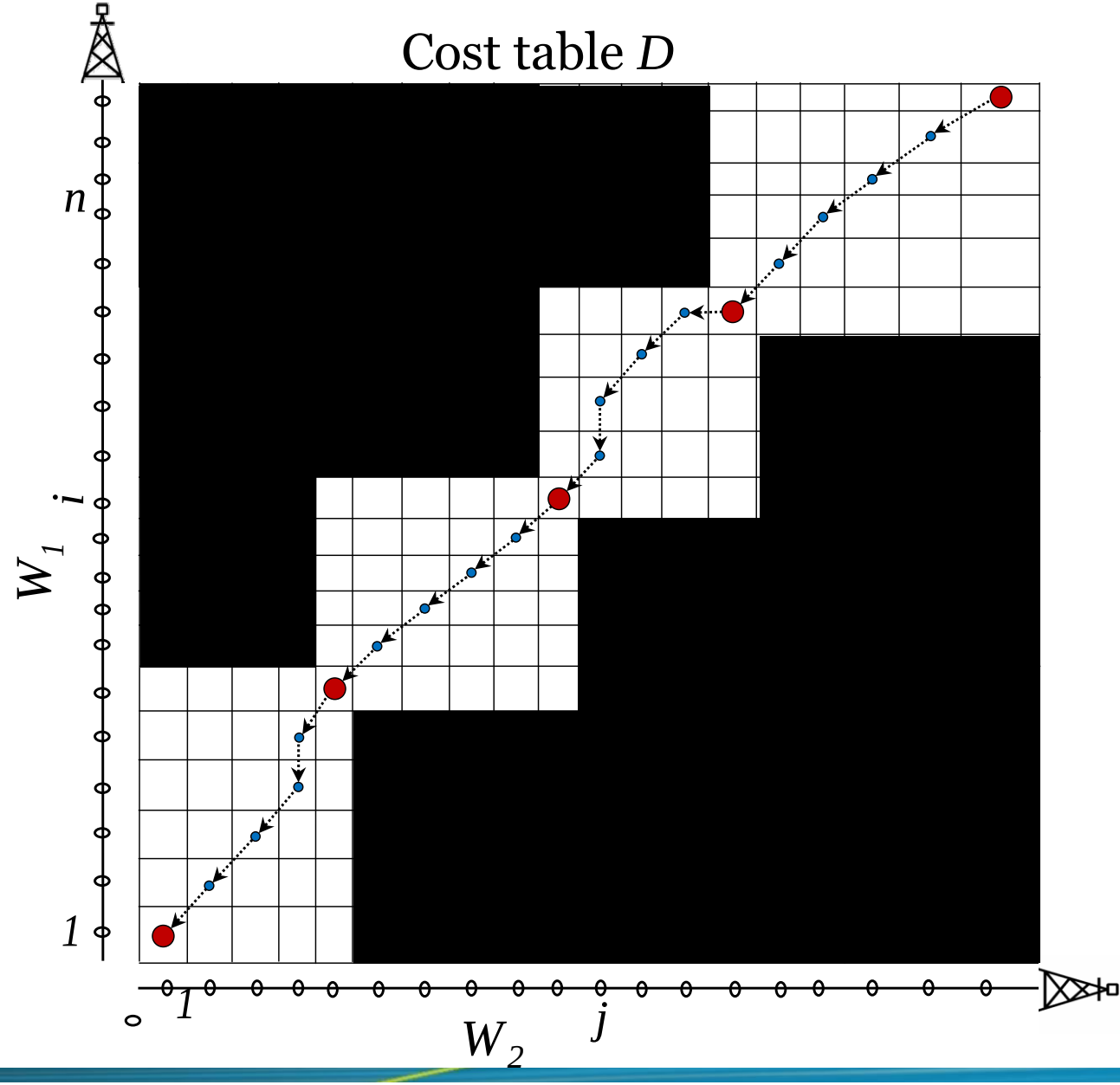
Hierarchic DTW



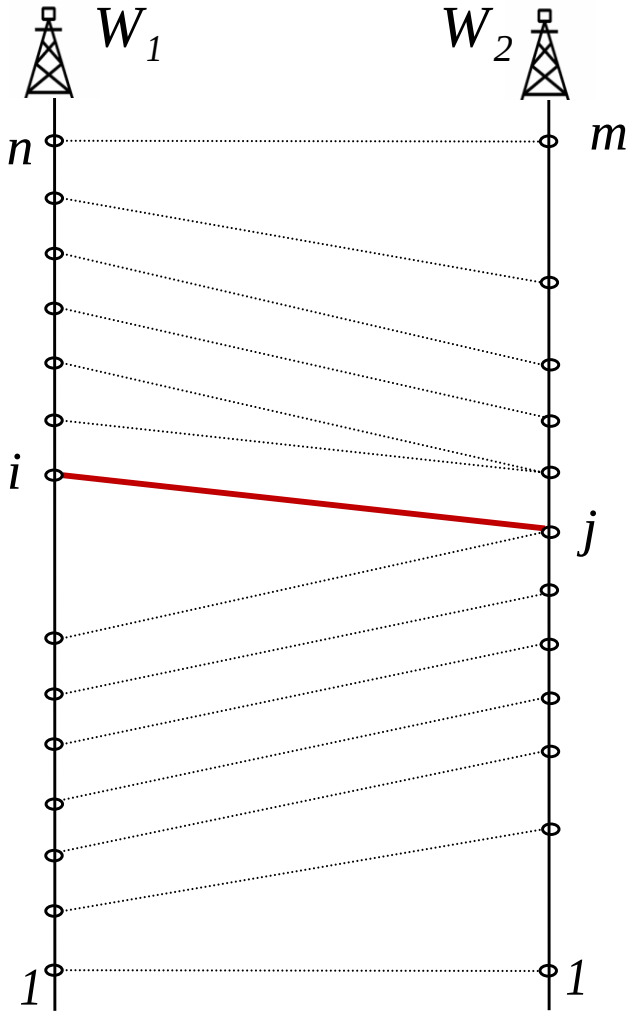


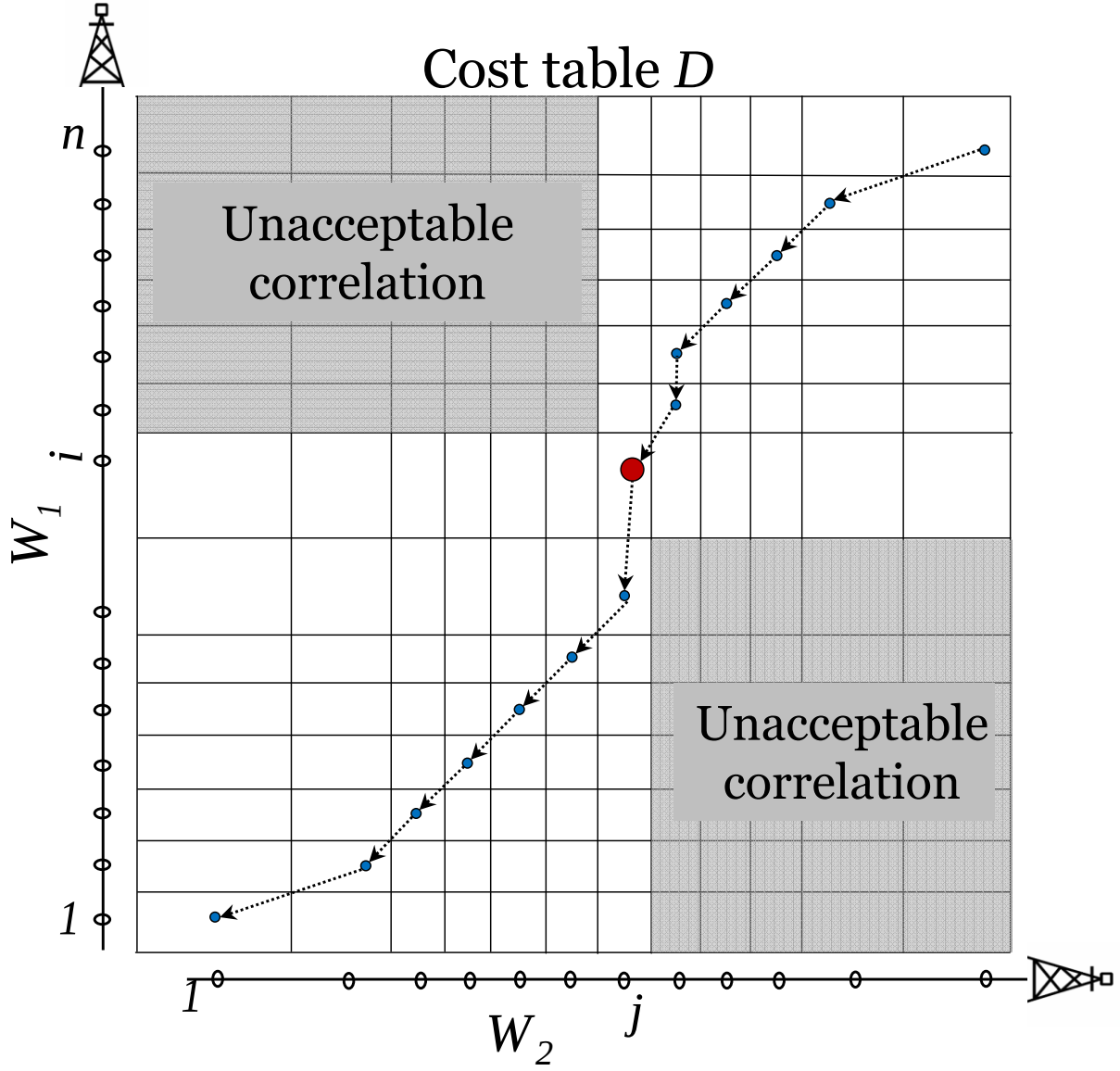
Hierarchic DTW





Constraining DTW





Applicability

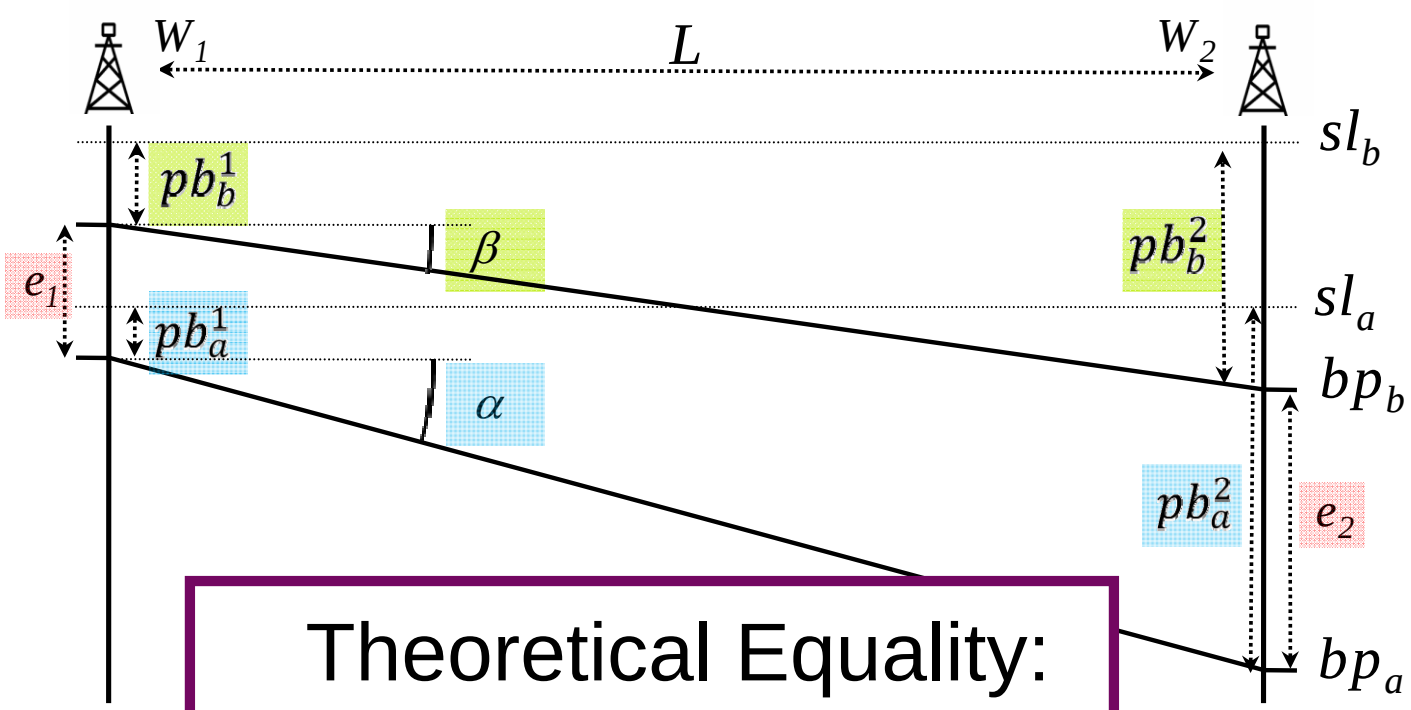
- Magneto-stratigraphy
- Litho-stratigraphy
- Sequence stratigraphy
- …

Depends on defined cost computation rules

- Application to low angle carbonate ramp

Markers Correlation Cost
Trigonometric relationship

- Trigonometric relationship between bathymetry of deposition pb and sediment thickness e



$$\tan\alpha = \frac{pb_a^1 - pb_a^2}{L}$$

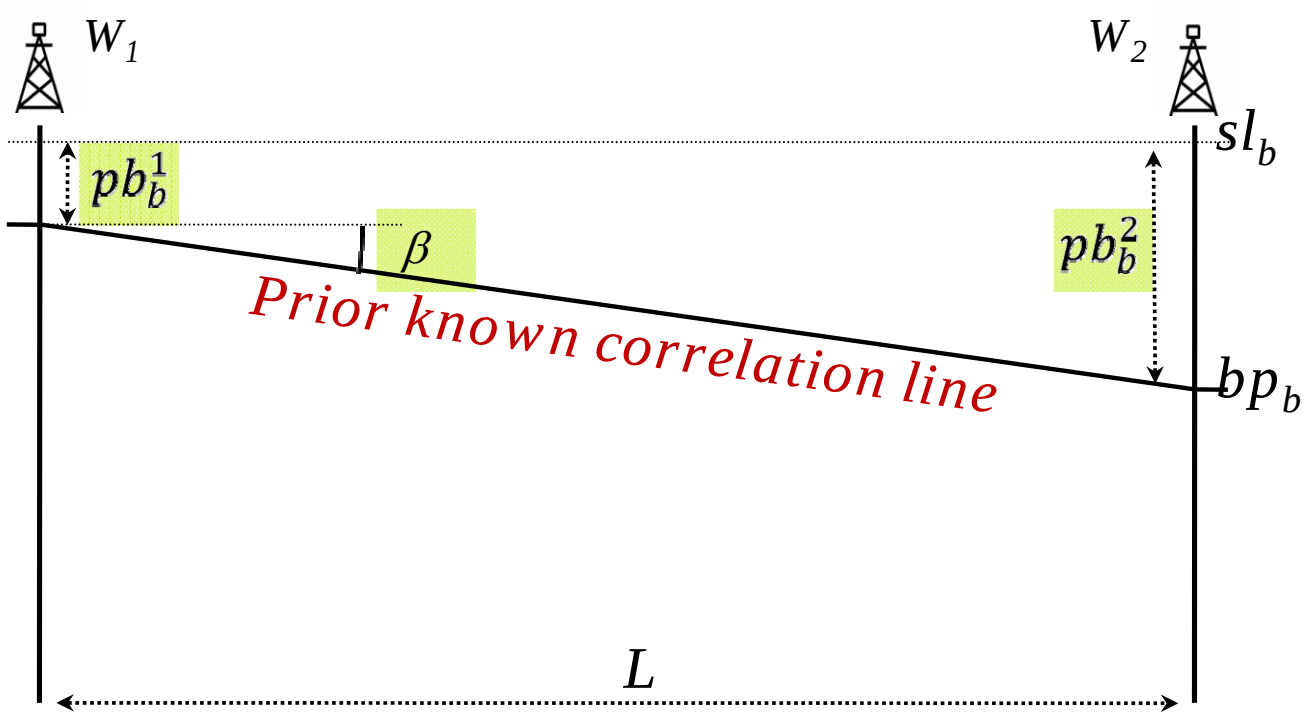
$$\tan\beta = \frac{pb_b^1 - pb_b^2}{L}$$

Theoretical Equality:

$$\tan\beta - \tan\alpha = \frac{e_1 - e_2}{L}$$

[Borgomano 2008]

Markers Correlation Cost



$$\tan\alpha = \frac{pb_a^1 - pb_a^2}{L}$$

$$\tan\beta = \frac{pb_b^1 - pb_b^2}{L}$$

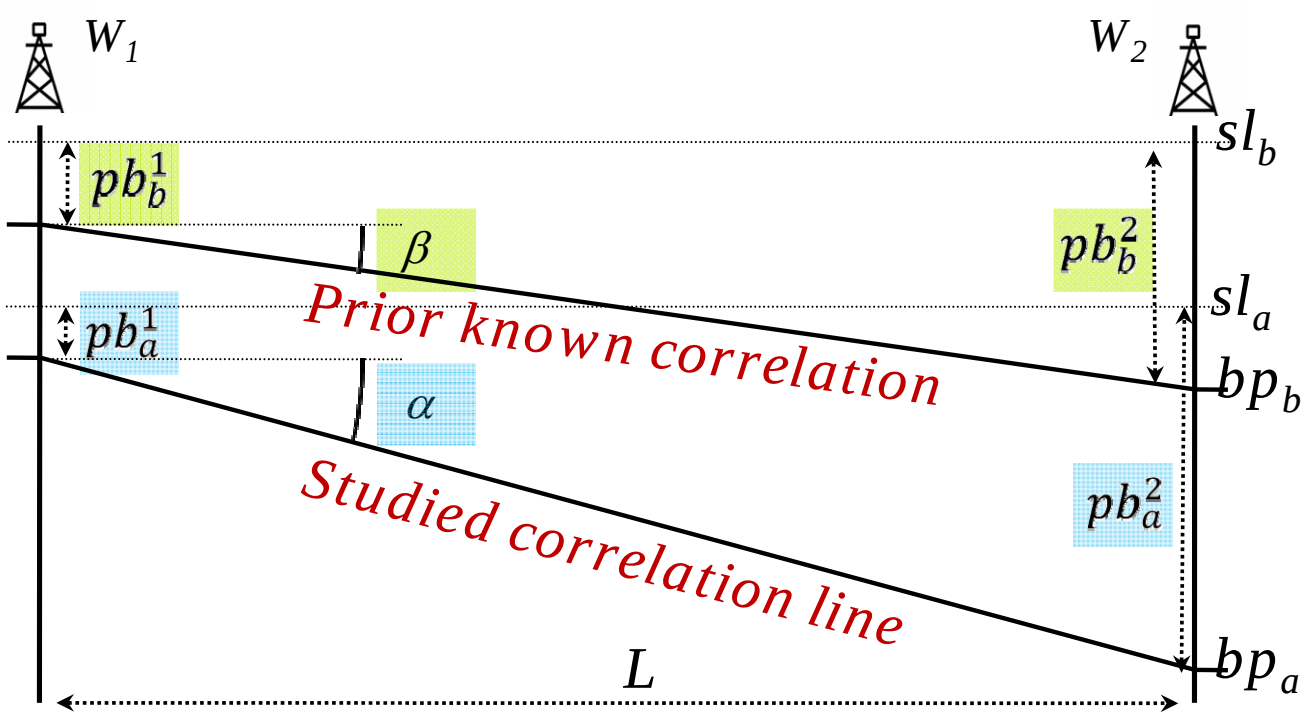
Theoretical Equality:

$$\tan\beta - \tan\alpha = \frac{e_1 - e_2}{L}$$

Cost computation as distance to theoretical equality:

$$Cost(i,i) = (pb_b^1 - pb_b^1)$$

Markers Correlation Cost



$$\tan\alpha = \frac{pb_a^1 - pb_a^2}{L}$$

$$\tan\beta = \frac{pb_b^1 - pb_b^2}{L}$$

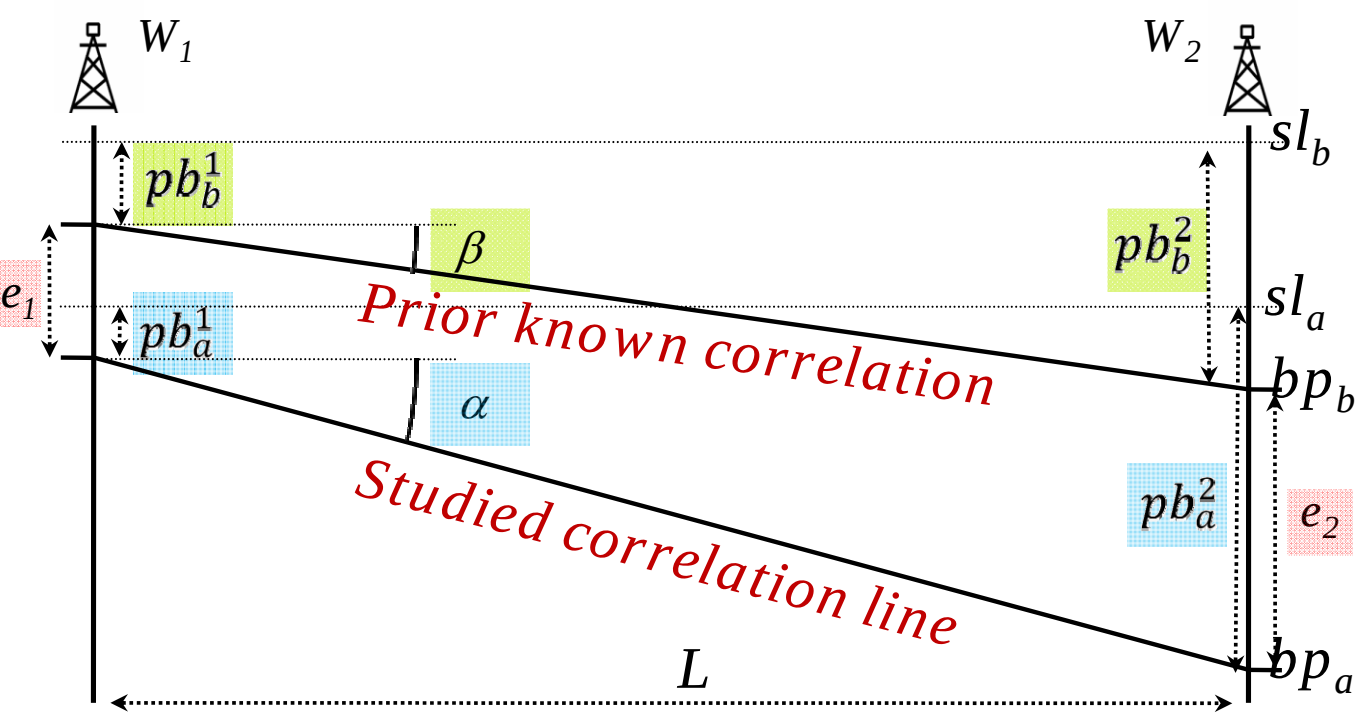
Theoretical Equality:

$$\tan\beta - \tan\alpha = \frac{e_1 - e_2}{L}$$

Cost computation as distance to theoretical equality:

$$Cost\,(i,j) = (pb_a^1 - pb_a^2) - (pb_b^1 - pb_b^2)$$

Markers Correlation Cost



$$\tan\alpha = \frac{pb_a^1 - pb_a^2}{L}$$

$$\tan\beta = \frac{pb_b^1 - pb_b^2}{L}$$

Theoretical Equality:

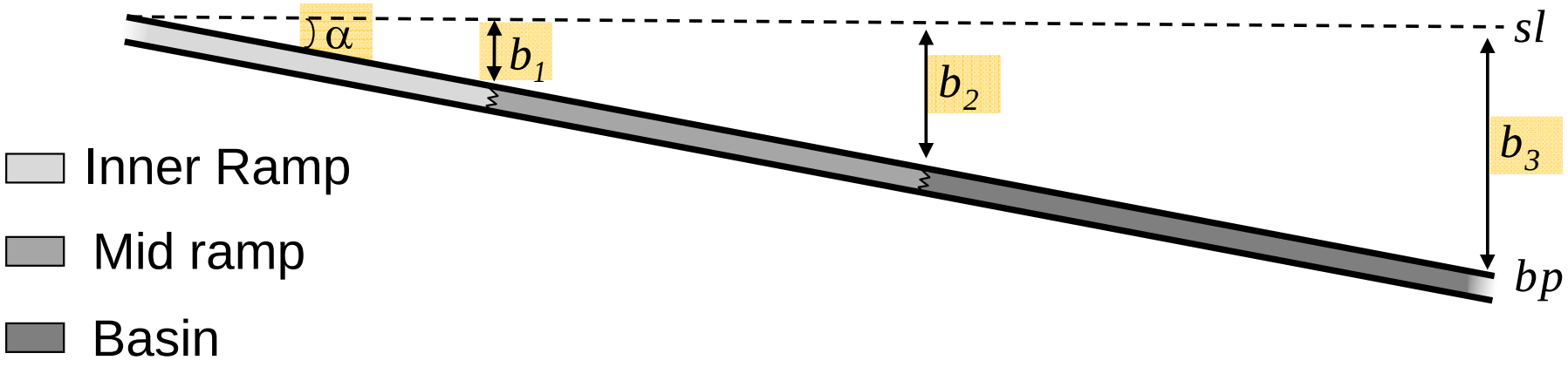
$$\tan\beta - \tan\alpha = \frac{e_1 - e_2}{L}$$

Cost computation as distance to theoretical equality:

$$Cost\,(i,j) = (pb_a^1 - pb_a^2) - (pb_b^1 - pb_b^2) - (e_1 - e_2)$$

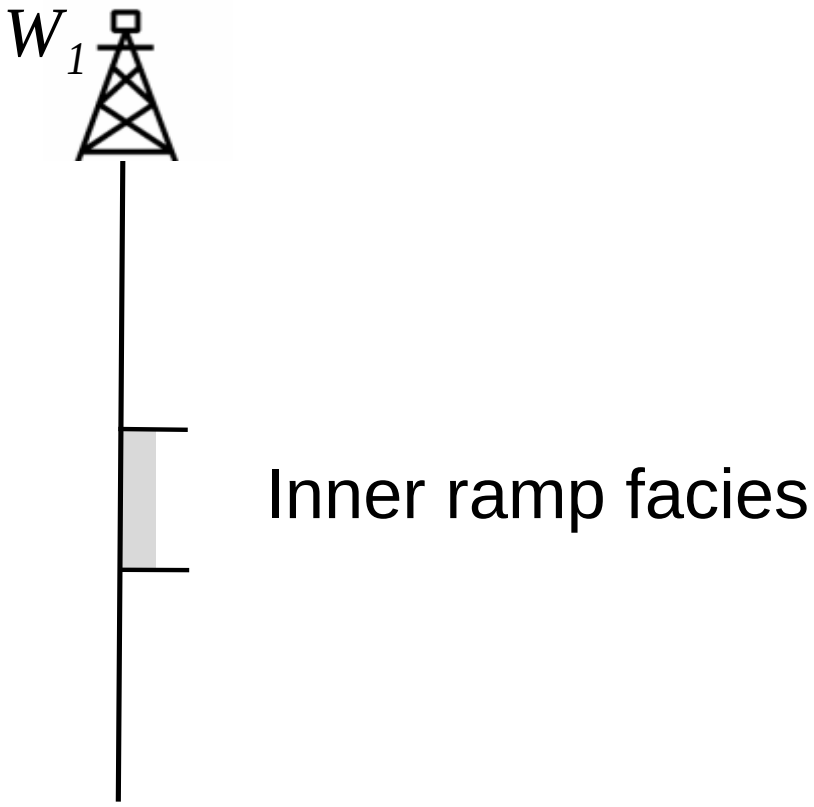
Interval Correlation Cost

Input : α, b_1 , b_2 and b_3



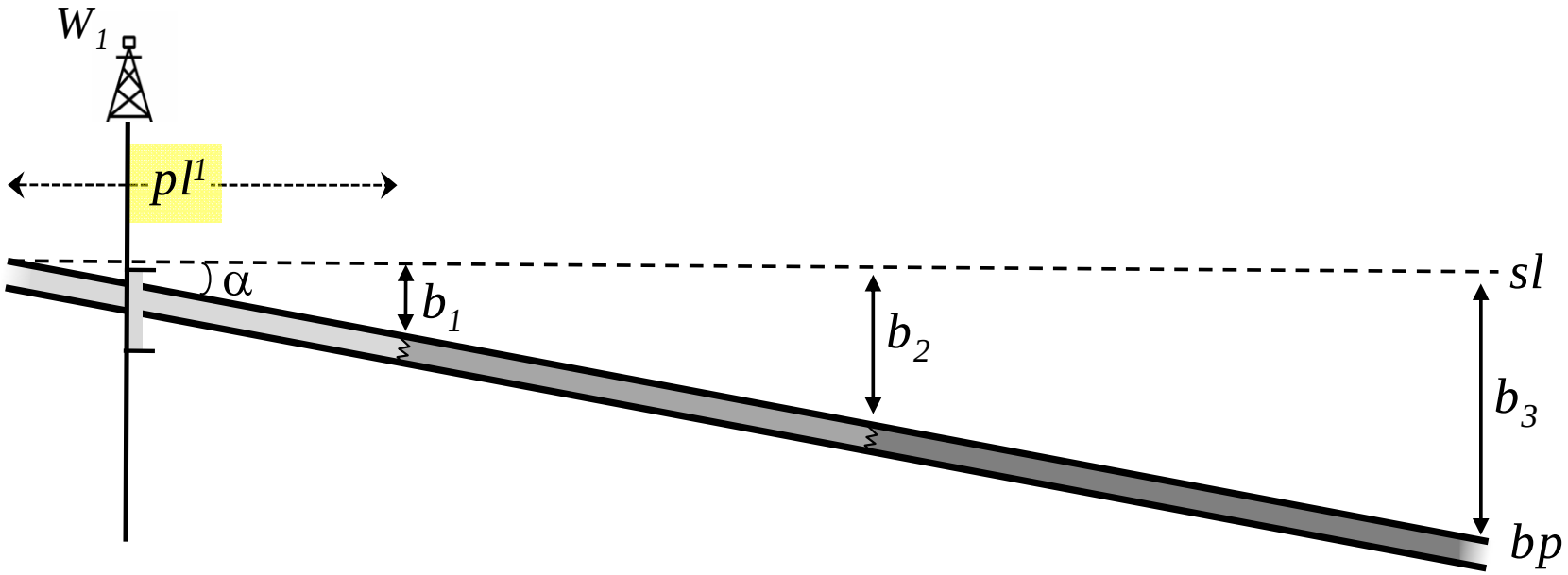
Computation of $t_{i-1,i}^{j,j}$ $t_{i,i}^{j-1,j}$ and $t_{i-1,i}^{j-1,j}$ from a theoretical base profile

Interval Correlation Cost



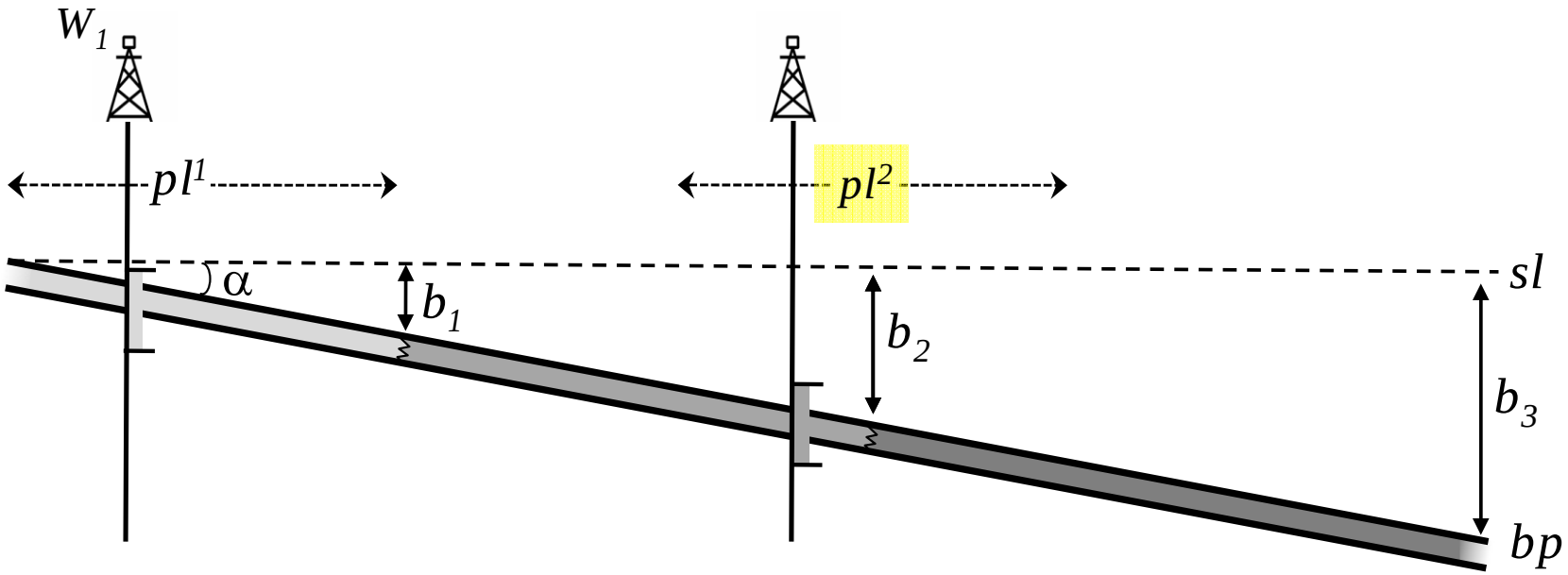
- The first well is located on the base profile using the observed facies

Interval Correlation Cost



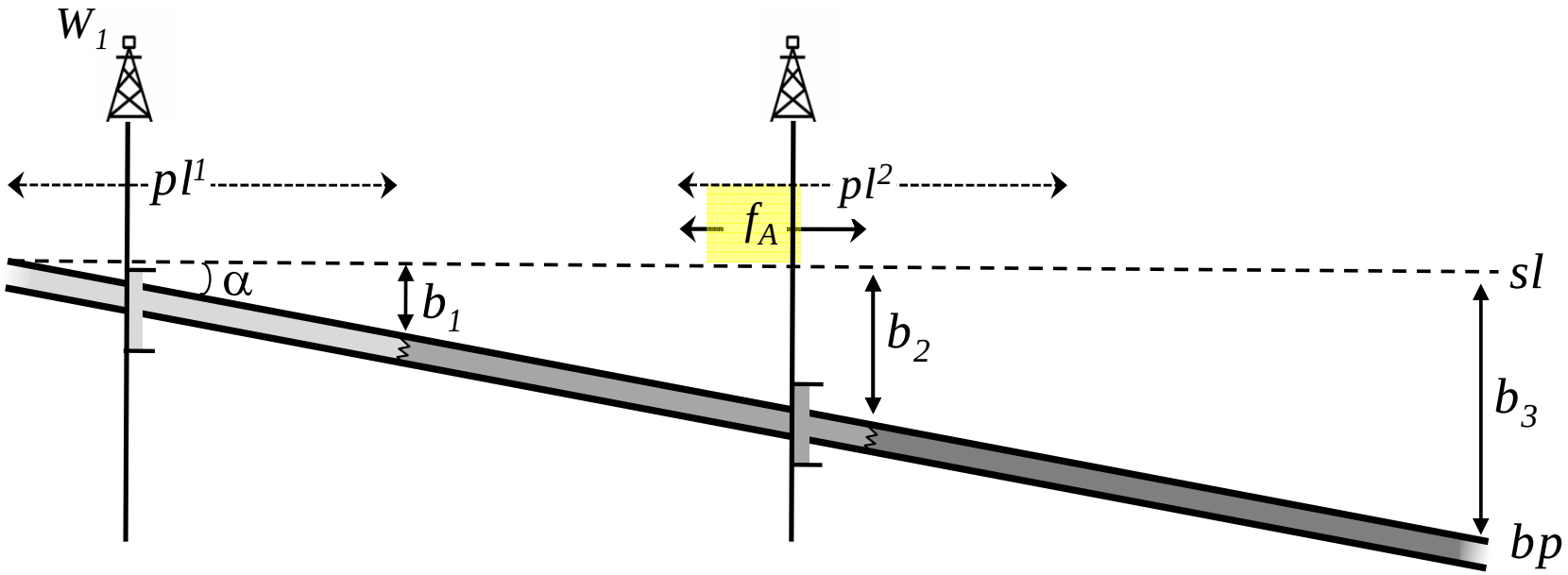
- The first well is located on the base profile using the observed facies

Interval Correlation Cost



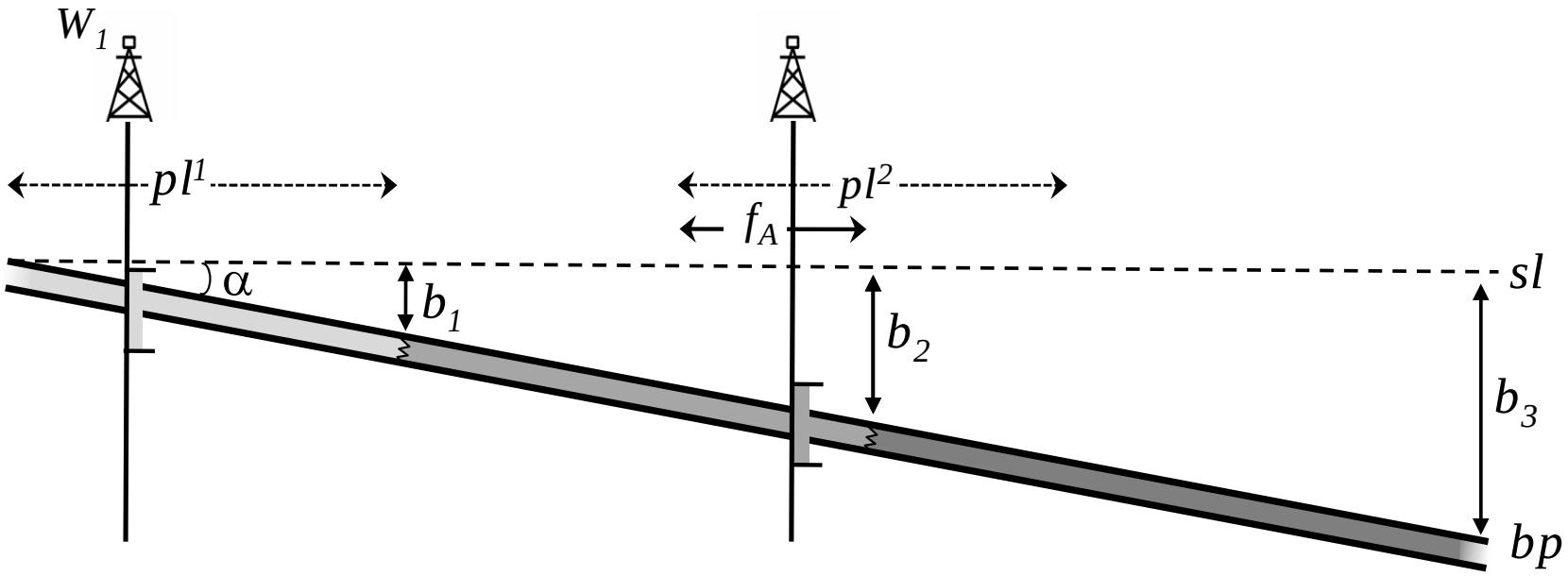
- According to W_1 possible locations, W_2 possible locations are defined

Interval Correlation Cost



- According to W_2 observed facies f_A is defined

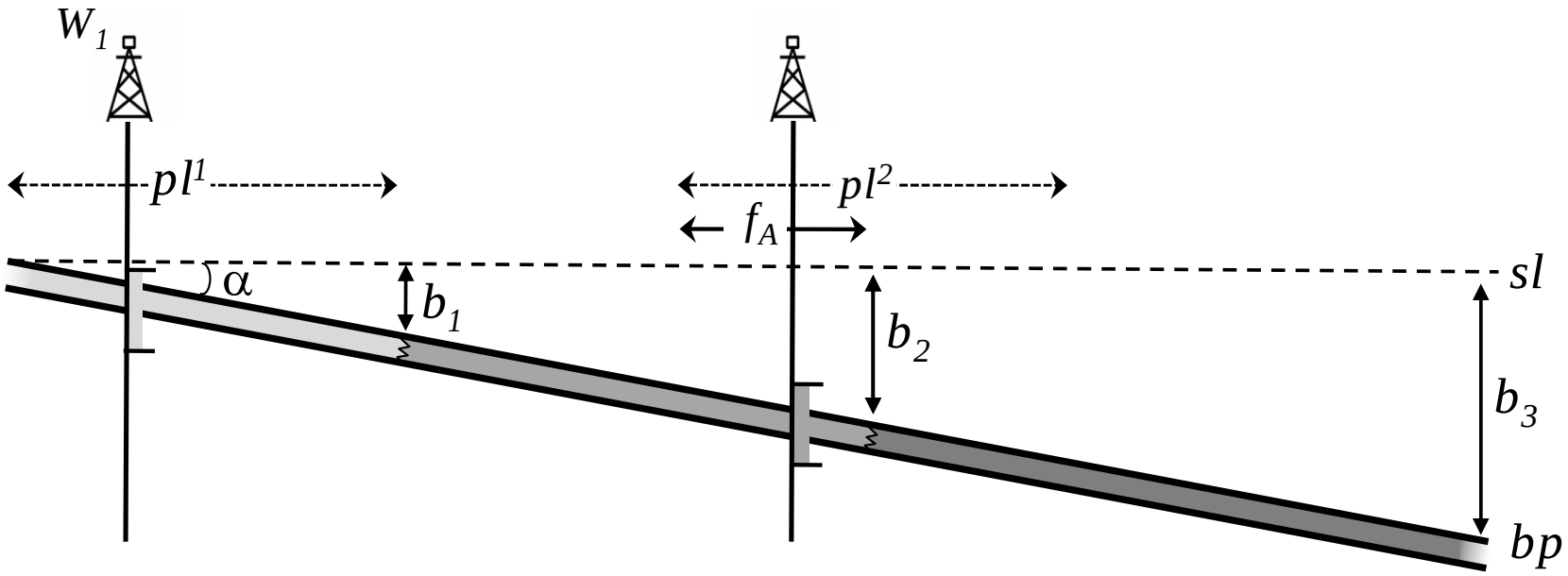
Interval Correlation Cost



- The ratio x between possible locations and right locations is computed:

$$x = \frac{f_A}{pl^2}$$

Interval Correlation Cost

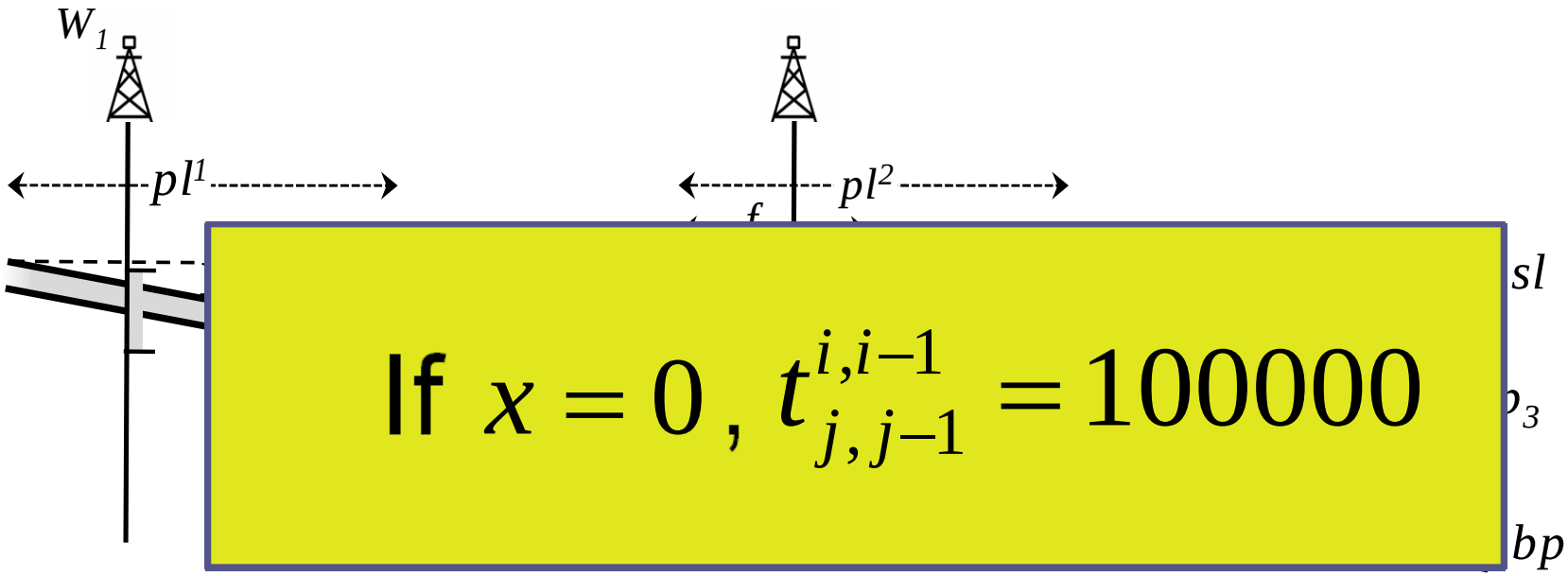


- And then the cost of the correlation is computed:

$$x = \frac{f_A}{pl^2}$$

$$t_{j,j-1}^{i,i-1} = \frac{1-x}{x}$$

Interval Correlation Cost



- And then the cost of the correlation is computed:

$$x = \frac{f_A}{pl^2} \qquad t^{i,i-1}_{j,j-1} = \frac{1-x}{x}$$

DTW cost computation

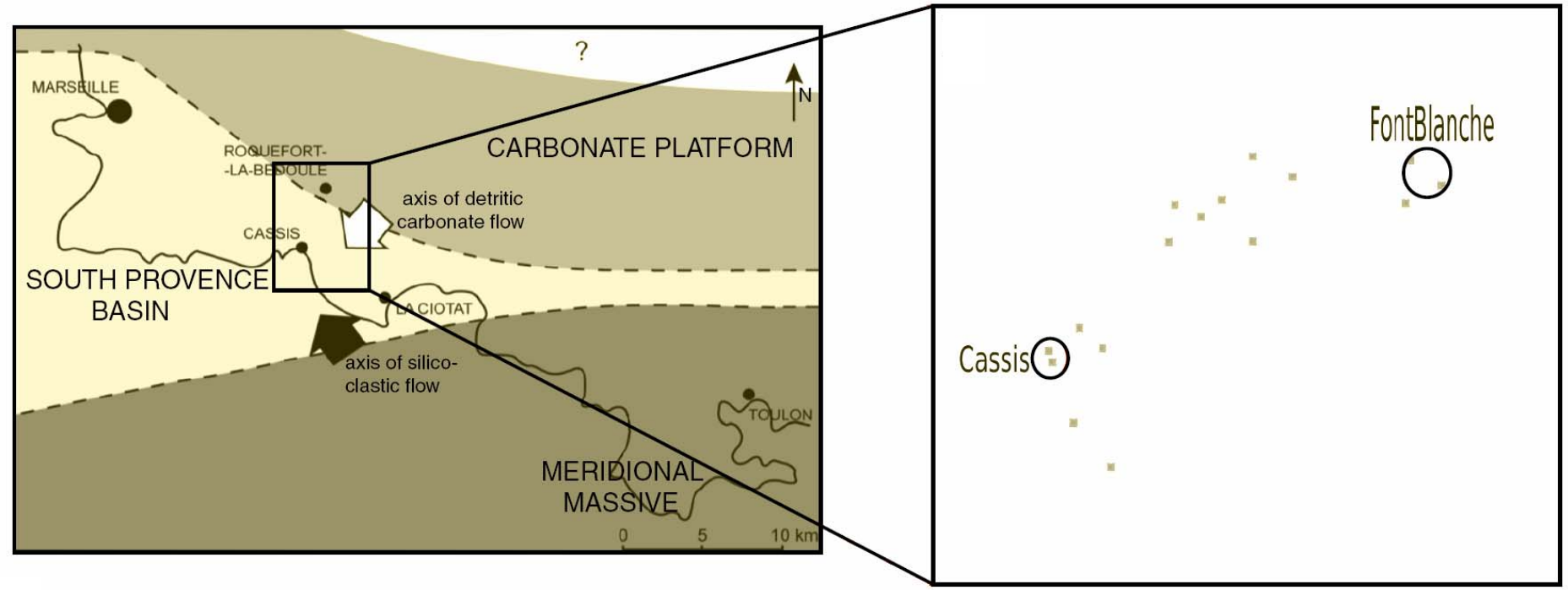
$$D(i,j) = \begin{cases} Deterministic\ computation \\ Stochastic\ \ computation \end{cases}$$

- Markers correlation cost:

$$Cost(i,j) = (pb_a^1 - pb_a^2) - (pb_b^1 - pb_b^2) - (e_1 - e_2)$$

- Interval correlation cost: $x = \frac{f_A}{pl^2}$ $\quad t_{j,j-1}^{i,i-1} = \frac{1-x}{x}$

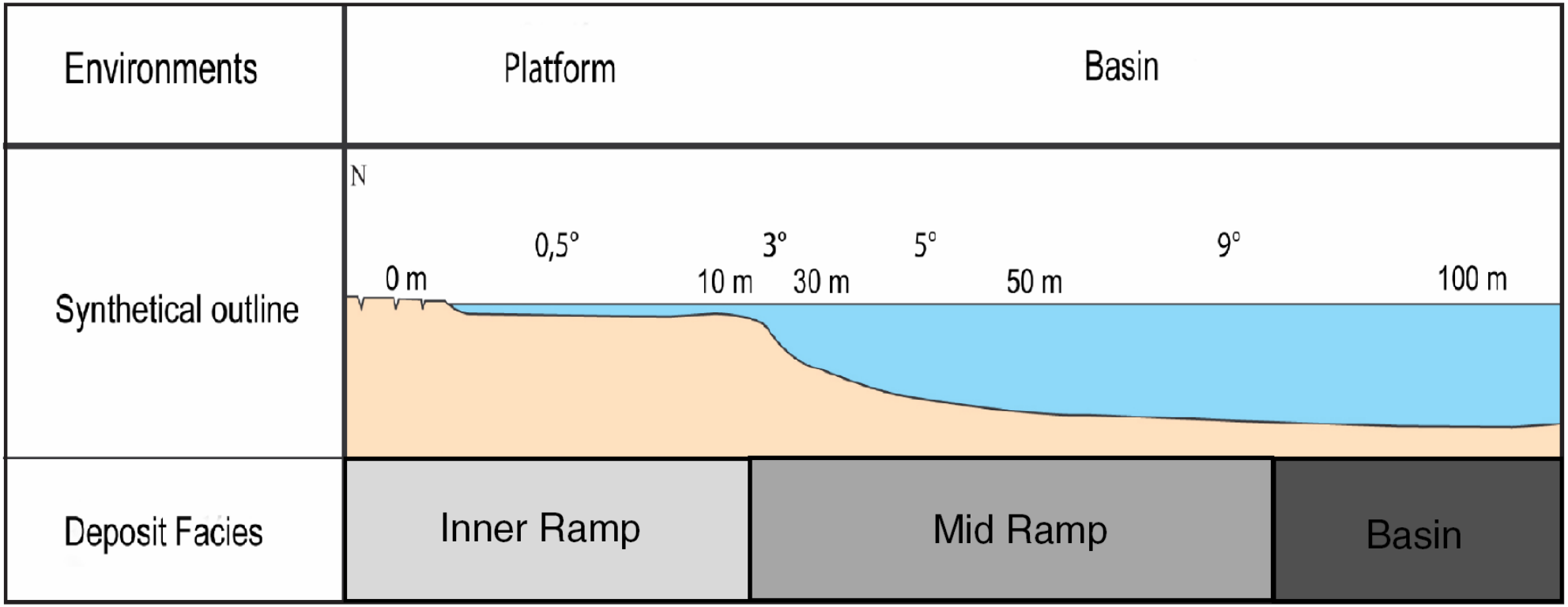
Sequence stratigraphic correlation of a carbonate ramp : the Beausset Basin



[Durand-Riard 2007]

- Location : Provence, SE France
- Font Blanche : Platform reference outcrop
- Cassis : Basin reference outcrop

Sequence stratigraphic correlation of a carbonate ramp : the Beausset Basin

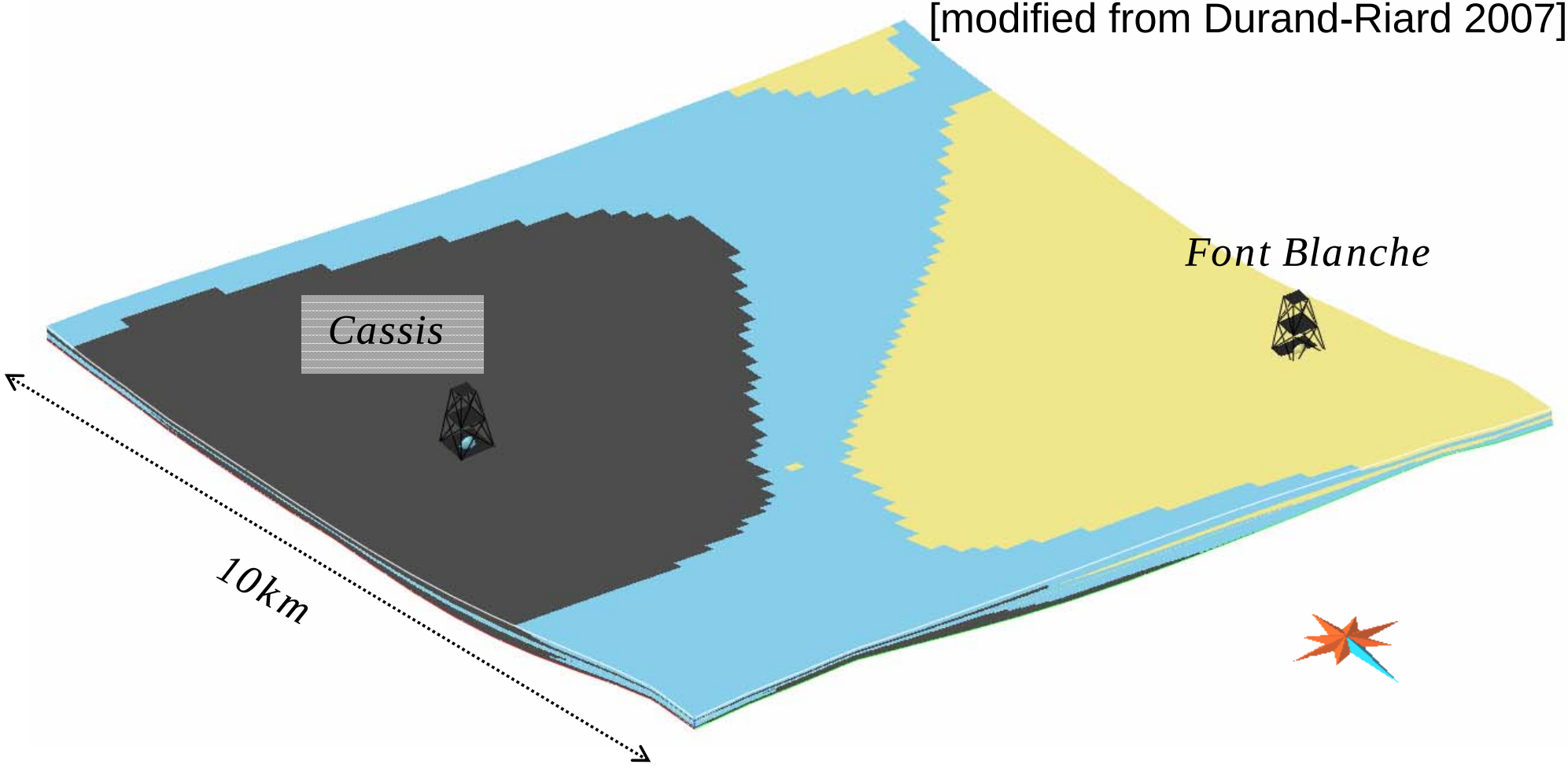


modified from [Gari 2007]

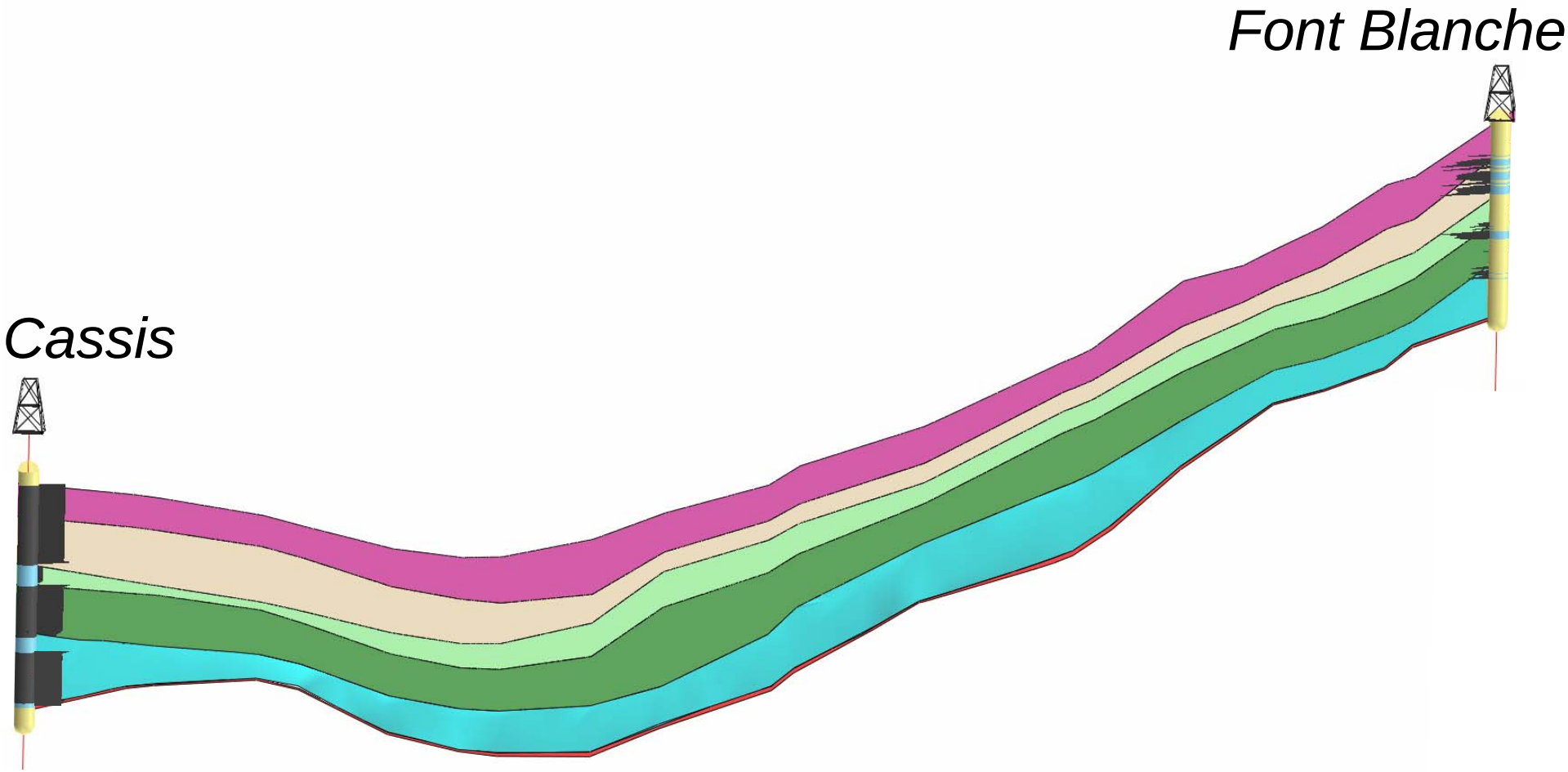
- Inner ramp maximum deposition bathymetry : 40m
- Mid ramp maximum deposition bathymetry : 100m
- Average angle : 0,5°

Facies model

[modified from Durand-Riard 2007]



Cross section

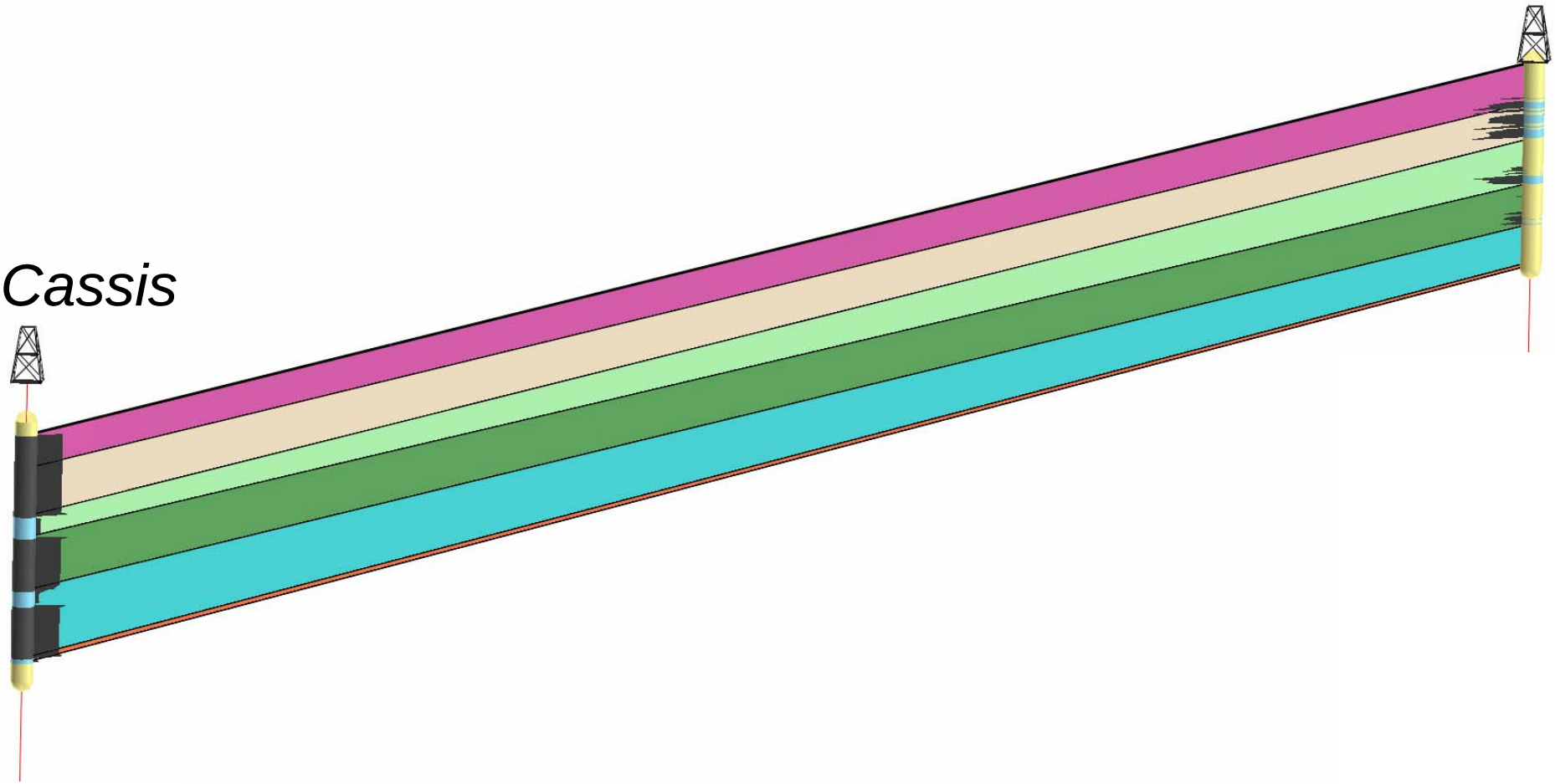


Results

Cost = 379

Font Blanche

Cassis

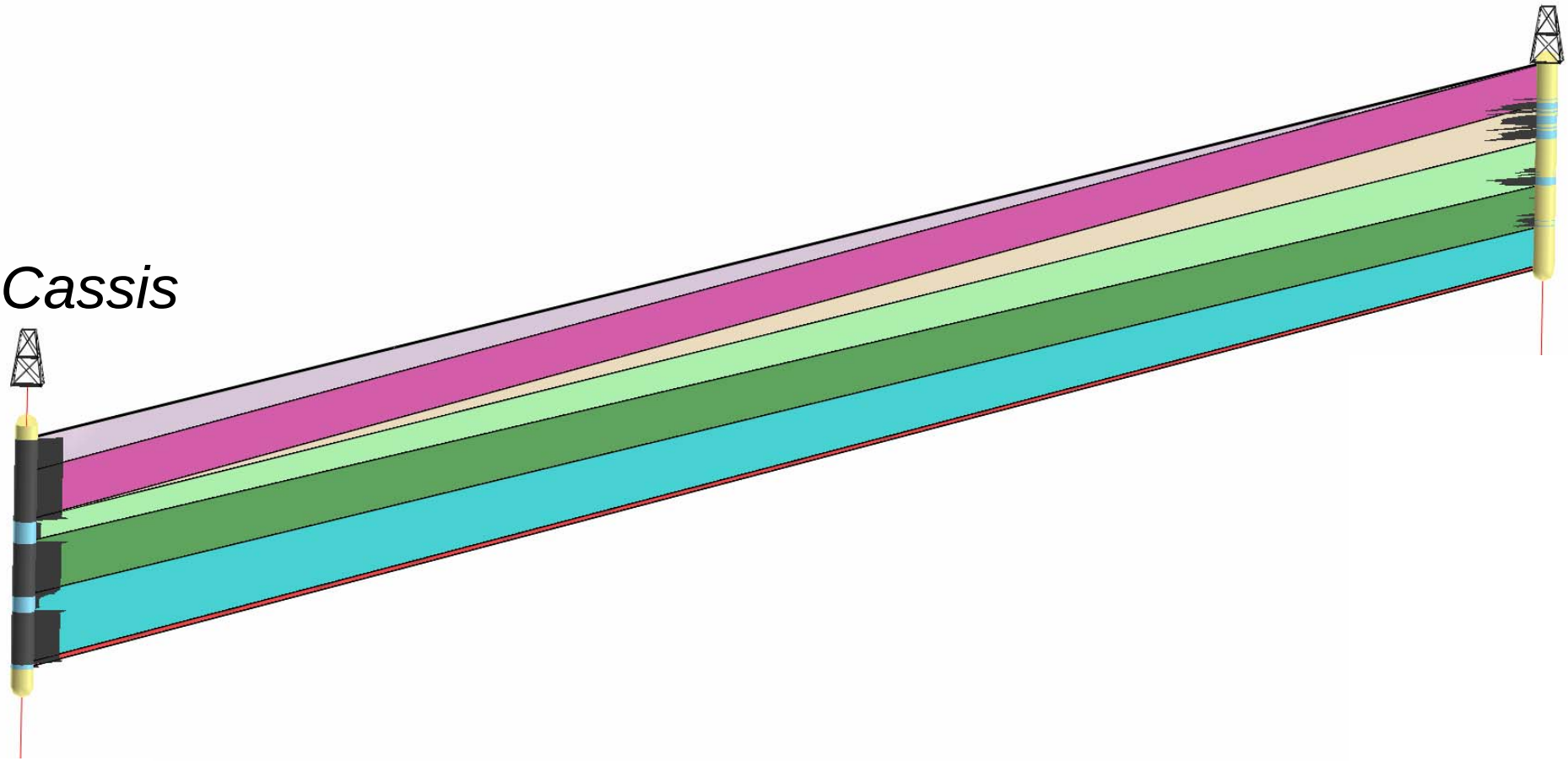


Results

Cost = 100339

Font Blanche

Cassis

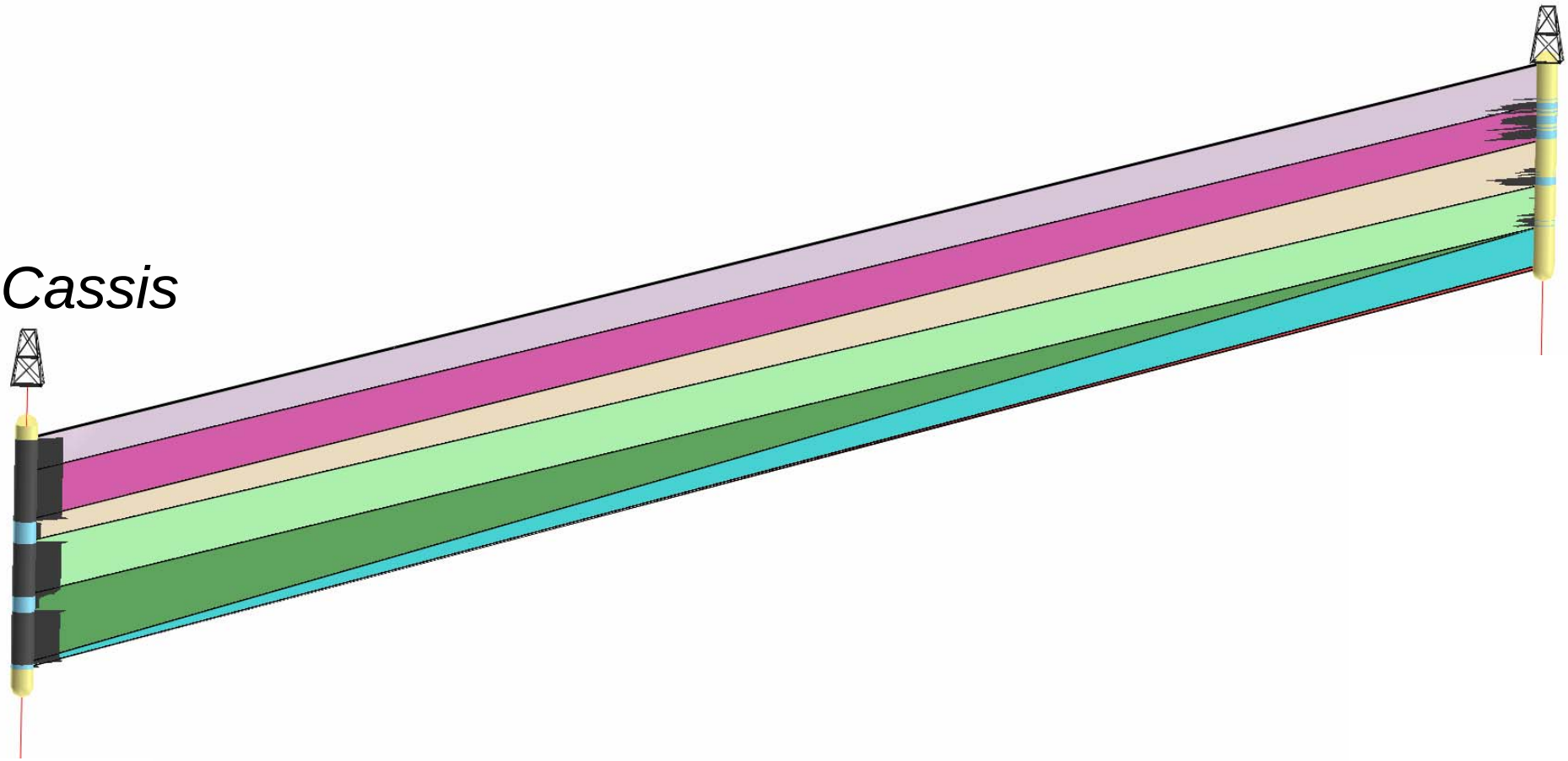


Results

Cost = 100452

Font Blanche

Cassis

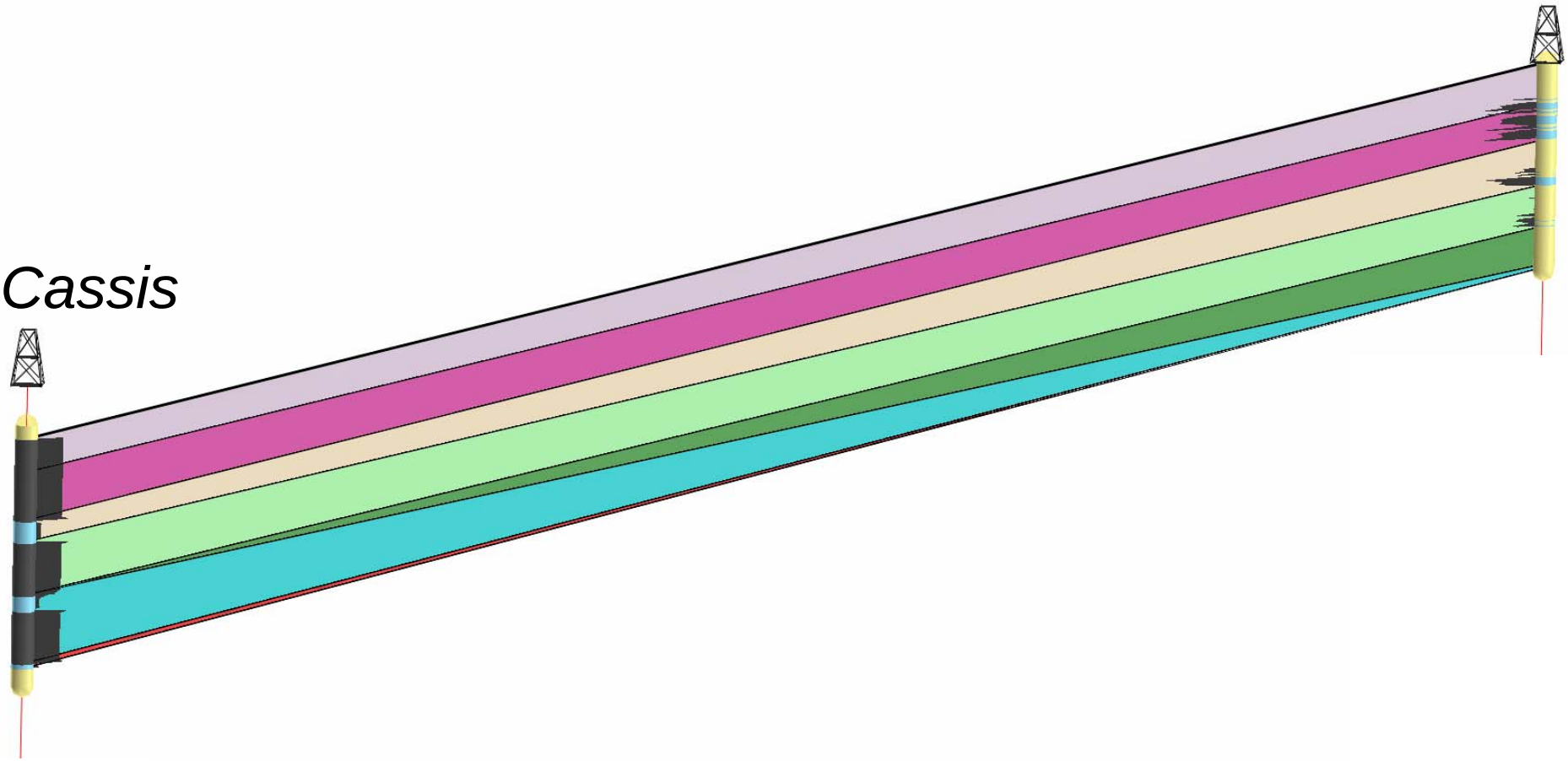


Results

Cost = 100476

Font Blanche

Cassis

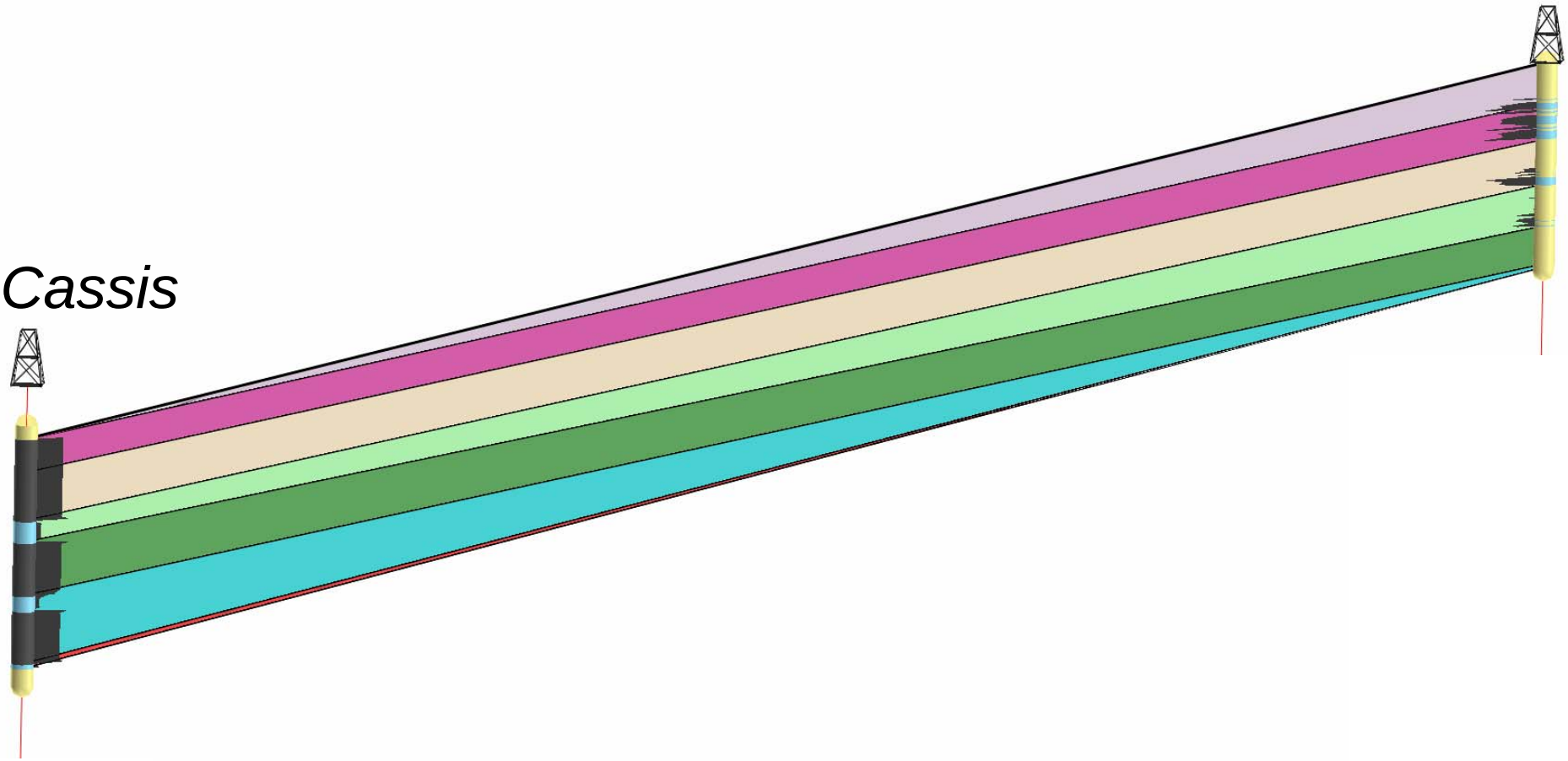


Results

Cost = 100789

Font Blanche

Cassis

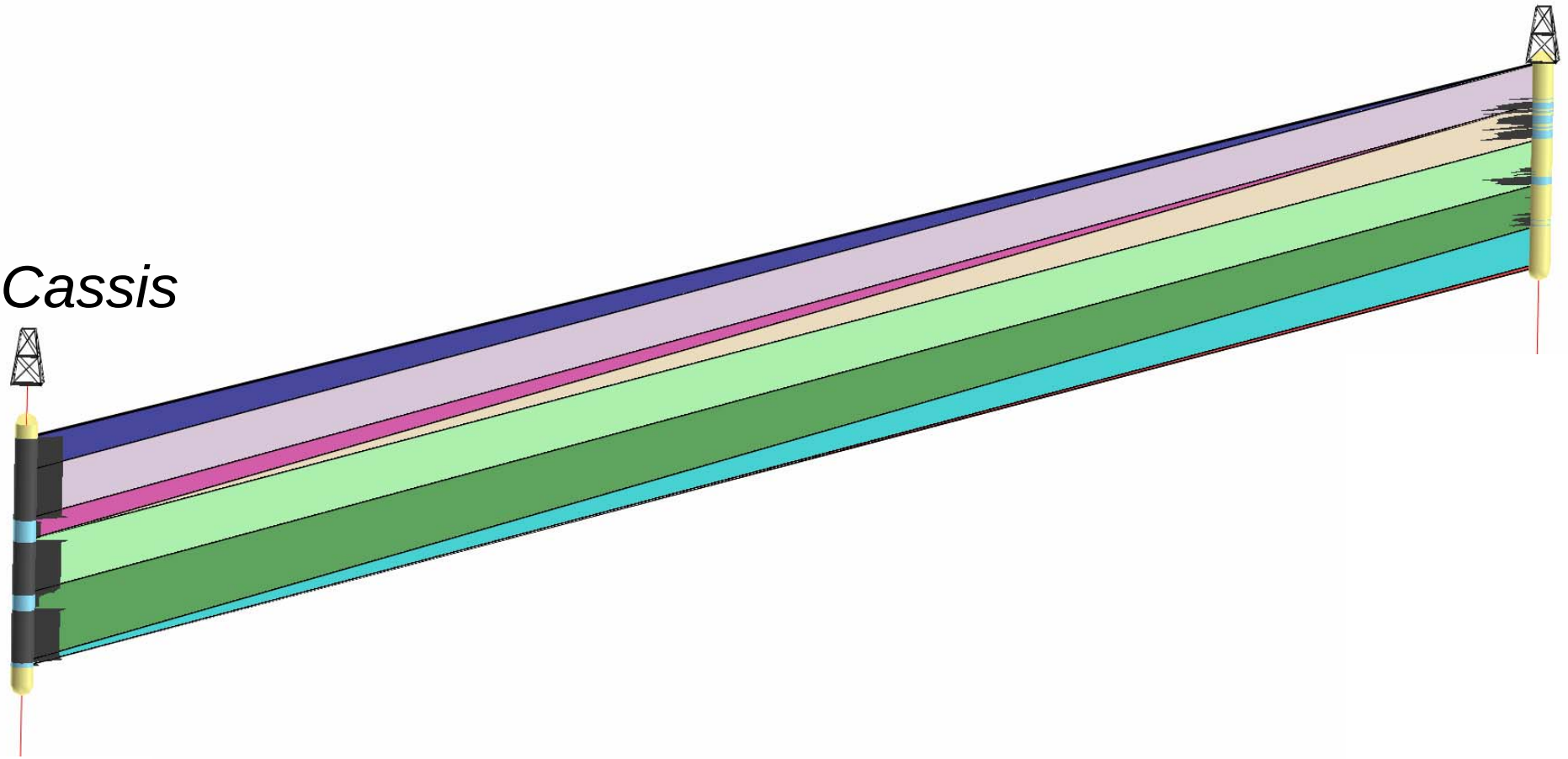


Results

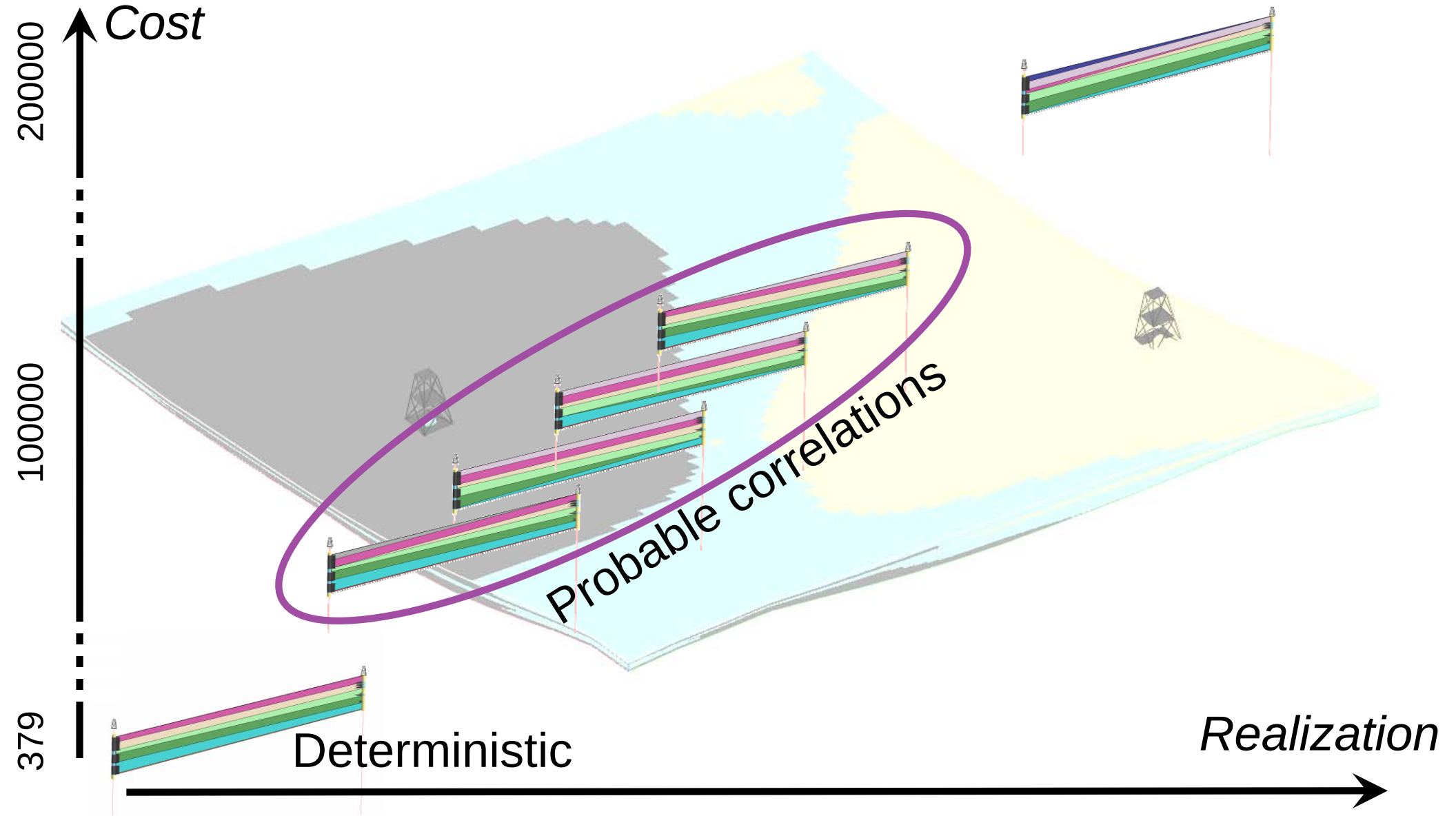
Cost = 200411

Font Blanche

Cassis



Results


Cost
200000
100000
379
Probable correlations
Deterministic
Realization

Conclusions

- Core for automatic and stochastic stratigraphic well correlation
- Possibility to test efficiently several hypothesis
- Basis for uncertainty assessment attached to:
  - Facies an property modeling by defining several stratigraphic grids
  - Seismic inversion
  - Geochronological modeling

Acknowledgements

- Gocad Research Consortium for funding this work
- Paradigm for providing the Gocad software and API

Nancy-Université