

Appendix 1: Geomorphic analyses for terrace identification.

Kelsay M. Stanton¹, Department of Earth and Space Science, University of Washington, Seattle, Washington

Overview

Sediments south of Grays Harbor and east of Willapa Bay were originally mapped collectively as “Quaternary terrace” deposits (Wagner 1967a, b; Walsh et al., 1987) although multiple terraces sets were acknowledged (Clifton, 1983). Marine terraces can form by erosion from wave action or from the buildup of sediments or reef material (Palmer, 1967; Lajoie, 1986). Regardless of their origin, marine terraces generally are low relief (smooth), with low slope angle (flat), originally dipping seaward between 1-5 degrees, although later tectonic deformation can warp the surfaces. Marine terraces are also laterally continuous along a shoreline (Bradley and Griggs, 1976; Lajoie, 1986; Keller and Pinter, 2002). Tectonic uplift or sea-level change can create multiple sets, or flights, of terraces along a coast (Lajoie, 1986; Bradley and Griggs, 1976).

Digital elevation models at 10m and 1m allow for an automated identification of geomorphic features using GIS analyses. To identify terraces, whether the origin is erosional or depositional, we use multiple criteria, including low angle, laterally continuous slopes, common elevation ranges, low relief and field observations showing related and continuous deposits (Table 1).

Figures

Figure 1. Swath profiles showing maximum elevation in red and minimum elevation in yellow. Blue lines indicate flat and smooth surfaces.

Figure 2. Standard deviation of elevation colored by elevation using a). lidar and b). 10m DEM. Yellow-green are elevations between 10-25m a.s.l., blue are elevation between 25-50m a.s.l., and pink are elevations between 50-68m a.s.l.

Figure 3. Standard deviation of elevation below 2 from 10m DEM colored by elevation.

Figure 4. Slope from 10m DEM. Cooler colors are lower slopes with slope range between 0-80 degrees.

Figure 5. Slope aspect of region south of Grays Harbor colored by aspect direction.

¹ Author email: kelsst@uw.edu

Tables

Table 1. Criteria of geomorphic features to identify as marine terrace.

CRITERIA	MEASURE
Topography	Continuous slope, common elevation ranges
Relief	Low relief (low standard deviation of elevation)
Slope	Low slope (<1-3 degrees)
Field observations	Related and continuous deposits or facies

Table 2. Elevation ranges and slope of geomorphic features.

FEATURE	ELEVATION RANGE (M)	SLOPE (DEGREES)
1	13-22	0-3
2	35-48	0-3
3	50-75 (?) near Grays Harbor only	0-12
4	>60	3-80

Methodology and Results

Swath profiles

I used a swath profile plugin tool for ArcGIS which takes topographic profiles for 500 m on either side of a profile line to calculate the maximum elevation (red line) and minimum elevation (yellow line) topographic profile (Figure 1). In the figure, the grey lines represent individual profiles. The figure shows swath profiles at two locations south of Grays Harbor where DEMs suggest possible terrace flights (Figure 1a, 1b), as well as a location from South Bend to near Bay Center on the eastern side of Willapa Bay (Figure 1c).

Swath profiles indicate dissection by streams of all surfaces at all locations in the field area. The maximum elevation likely represents a pre-erosion surface. Swath profiles show distinct elevation breaks at lower elevations, with common elevations having low slope angles between approximately 13-22m and 28-40m a.s.l. There are two possible continuous surfaces with low slope angle at around 45m and 60-75m a.s.l. but only in swaths A and B. Regions above 75m a.s.l. are more highly dissected.

In addition to these examples, I used the swath profile tool at numerous locations in the field area. There are gently sloping, low relief surfaces with average elevations between 13-22m a.s.l. and between 35-48m a.s.l. along the southern side of Grays Harbor, and all along the eastern side of Willapa Bay. Except for the locations 1a and 1b in Figure 1, all regions above 60m a.s.l. in the field area are highly dissected when seen in profile.

Standard deviation of elevation

The standard deviation of elevation characterizes relative relief. Low standard deviation of elevation represents low relative relief, or in other words, flat and smooth regions. I used the Focal Statistics tool in ArcGIS to determine the standard deviation of elevation for a region south of Grays Harbor that appears to have terrace flights. I used both a 10m DEM and the 1m DEM, using a 10X10 rectangular moving cell and a 3X3 rectangular moving cell to calculate standard deviation of elevation. Both cell sizes and both DEMs specify similar regions of low standard deviation of elevation (Figure 2) with the 1m DEM providing more detail. This analysis is

¹ Author email: kelsst@uw.edu

intended to locate regions likely to be flat and smooth (terraces) and the detailed analysis provided by the 1m DEM is not necessary for this study. Because the study region is approximately 2000 km², for computational efficiency I used a 10X10 rectangular moving cell on the 10m DEM to determine standard deviation of elevation for the entire field area.

The areas with the lowest standard deviation (flat and smooth) correspond with the low slope and low relief elevations ranges from the swath profiles (Figure 3). South of Grays Harbor, the elevation range between approximately 60-75m a.s.l. also has a relatively low standard deviation of elevation, although this elevation range in other parts of the study area does not show continuous low standard deviation of elevation. Northern Willapa Bay is mostly devoid of broad, continuous regions of low standard deviation of elevation. For most of the study region, elevations higher than 60m a.s.l. have low standard deviation of elevation only along ridgelines.

Slope and Aspect

The study region has slopes between 0 and 80 degrees, as determined for the 10m DEM (Figure 4). Approximately three quarters of the region have slopes less than 18 degrees, with a quarter of the region with slopes below 3 degrees. Areas appearing the most flat and smooth from standard deviation of elevation have slopes between 0 and 3 degrees. These slope seaward as indicated by swath profiles. Slopes in the field area do not show distinct alignment in terms of slope aspect, although coastal features tend to have seaward slope aspects (Figure 5).

Discussion

Along the south side of Grays Harbor and the east side of Willapa Bay are two geomorphic flat and smooth features, that also have low slope angle. Generally, these correspond to elevations between 13-22m a.s.l. and 35-48m a.s.l. These features do not have distinct back edges, and both are dissected by streams. We infer these flat, smooth, low angle, continuous surfaces to be terraces. These features are absent along the northern side of Willapa Bay, and between Westport and North Cove.

Although there are regions that are geomorphically flat and smooth at elevations above 60m a.s.l., these are not as continuous, as flat or smooth, nor with as shallow angle slopes as the two lower elevation terraces. The flat and smooth regions tend to be along ridge lines. It is possible these represent a relict surface and are erosional remnants.

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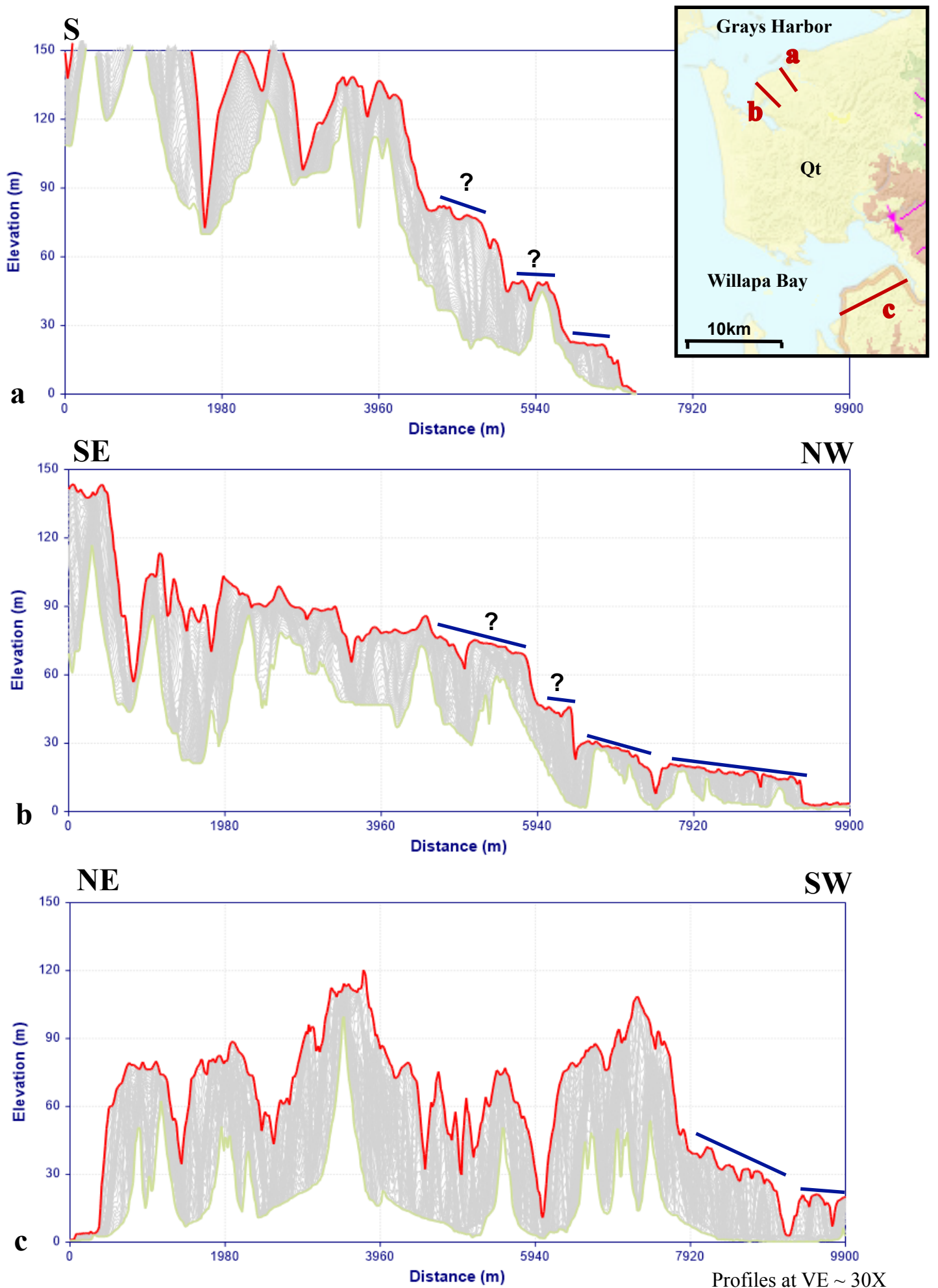


Figure 1. Swath profiles showing maximum elevation in red, and minimum elevation in yellow. Blue lines indicate flat and smooth surfaces.

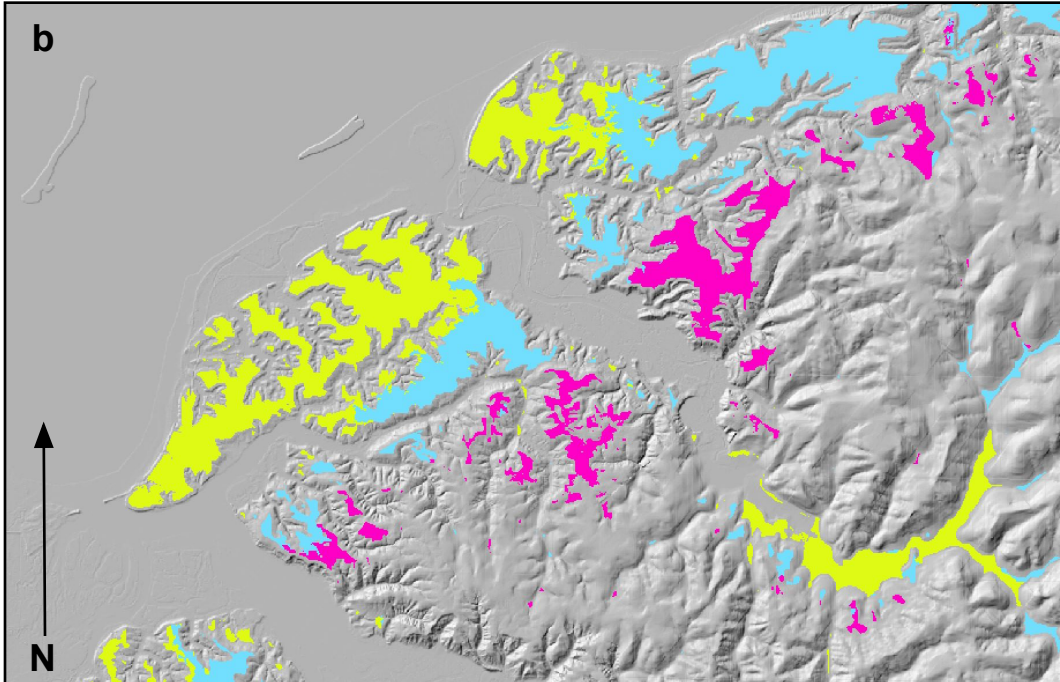
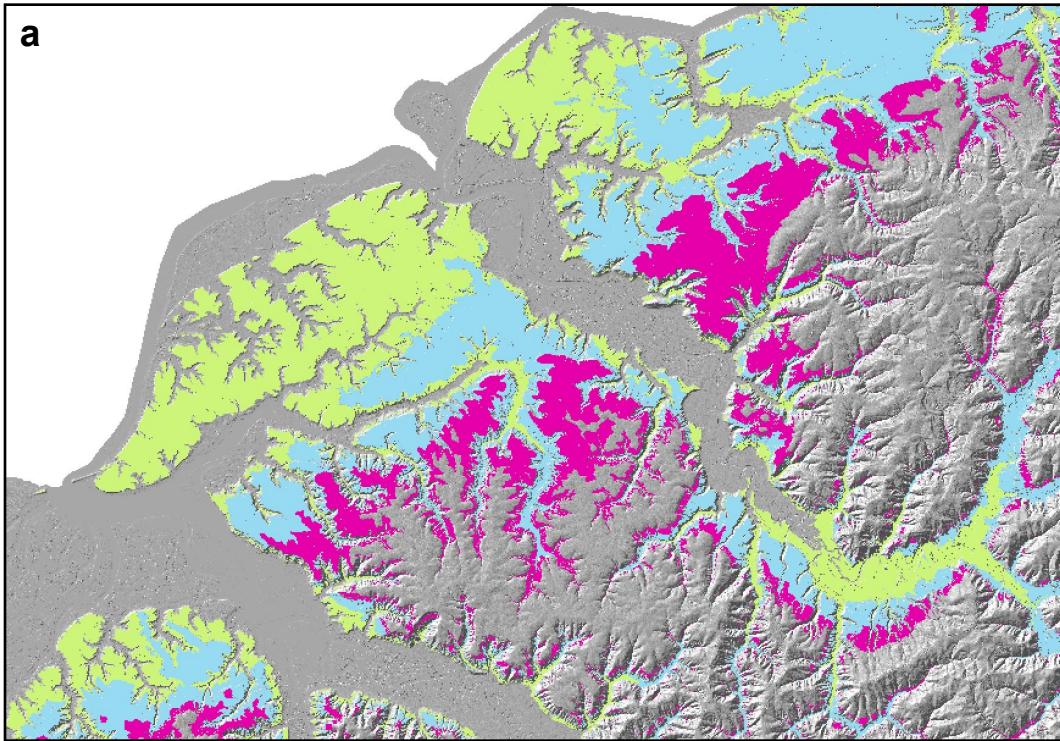


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Figure 3. Standard deviation of elevation below 2 from 10m DEM colored by elevation.

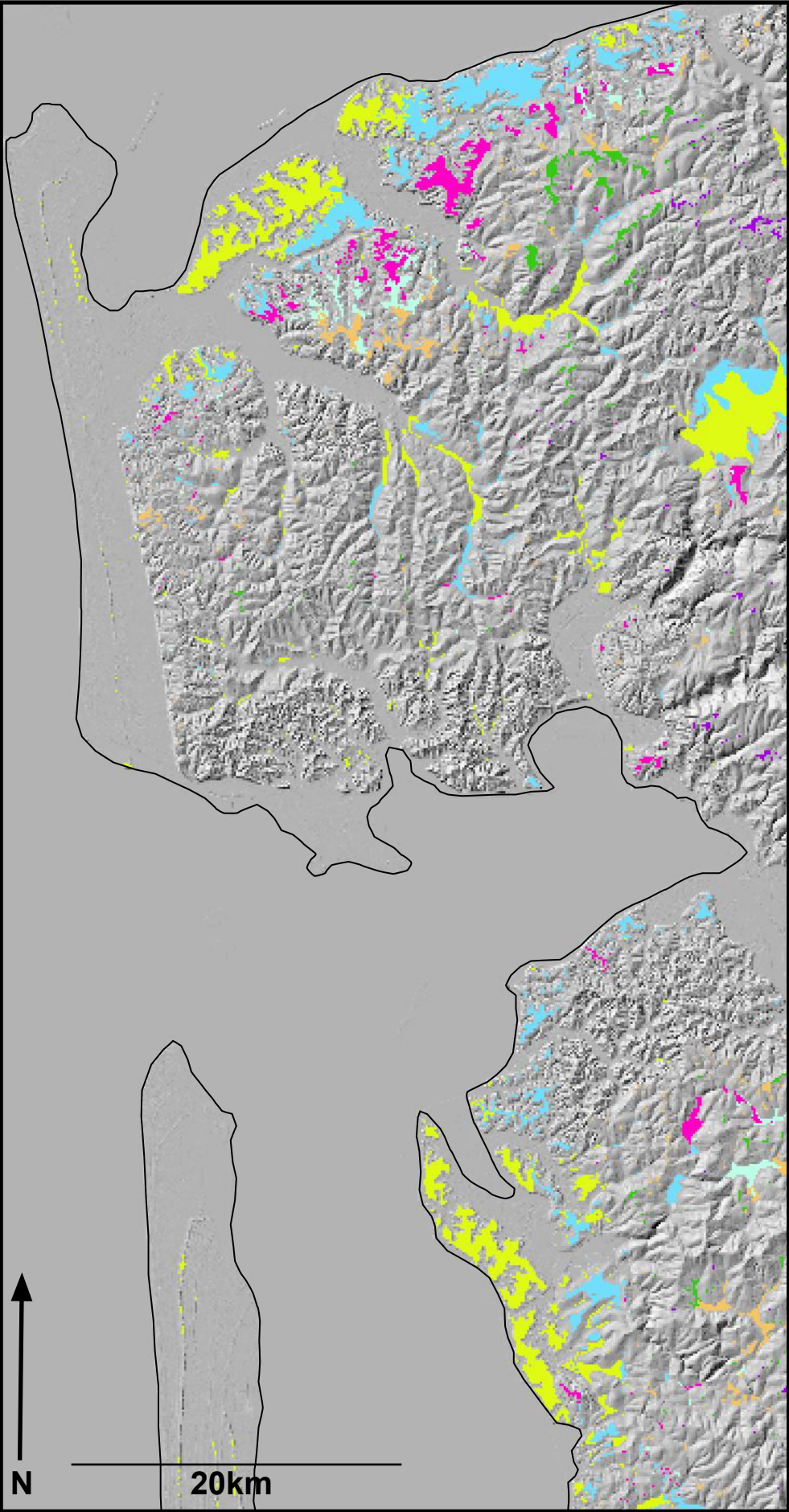




Figure 4. Slope from 10m DEM. Cooler colors are lower slopes with slope range between 0-80 degrees. Three quarters of region have slopes less than 18 degrees, with one quarter of region with slopes between 0-3 degrees (blue).

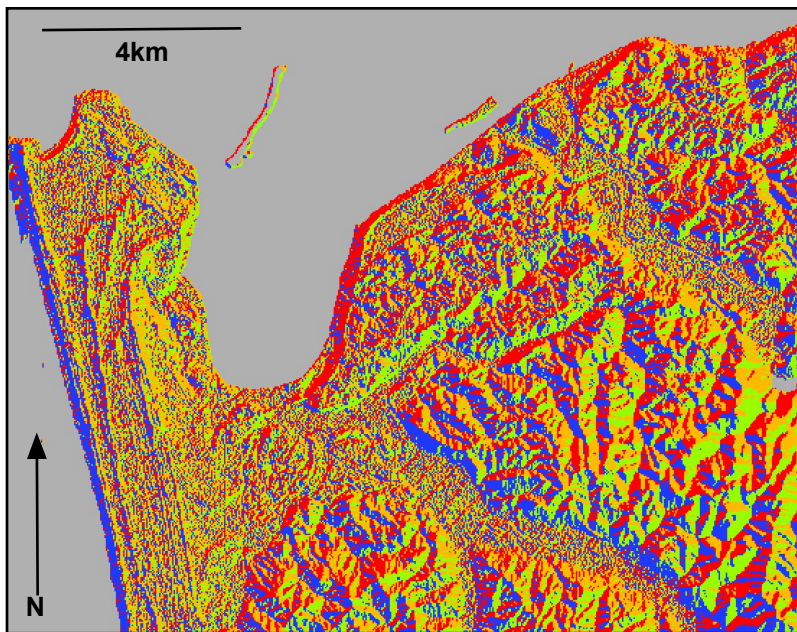


Figure 5. Slope aspect of region south of Grays Harbor colored by aspect direction.

