A Subsurface Ribbon of Cool Water over the Continental Shelf off Oregon

Adriana Huyer and Robert L. Smith

School of Oceanography, Oregon State University, Corvallis 97331

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ABSTRACT

Observations of the hydrographic regime over the continental shelf off Oregon from the R/V *Yaquina* during the summer of 1972 showed the presence of an alongshore, subsurface ribbon of relatively cool water. Its properties and its evolution during the 1972 season are described. Examination of earlier observations showed that evidence of the ribbon was found during the upwelling season in almost every year between 1961 and 1971. It is usually observed when the upwelling index (the monthly mean Ekman transport directed offshore) is high. The ribbon can be accounted for by southward advection of subarctic water due to the coastal jet associated with upwelling. A warm temperature anomaly, occurring at somewhat higher salinity, is frequently observed inshore of the ribbon.

1. Introduction

Detailed hydrographic observations in a small area off the Oregon coast were made during the summer of 1972 as part of the Coastal Upwelling Experiment (CUE-I). These observations showed the existence of a subsurface ribbon of relatively cool (<7.8C) water at a depth of about 25–50 m, roughly parallel to the coast. The purpose of this paper is to present the evidence for the existence of the ribbon, to describe its properties, and to present hypotheses for its origin and its relation to the coastal upwelling regime.

2. The observations

A grid of hydrographic stations adjacent to the coast of Oregon was surveyed five times by the R/V *Yaquina* between the middle of May and the end of August 1972 (Anon., 1972a, b, c, 1973a, b). Observations were made with a Geodyne conductivity-temperature-depth (CTD) system. Usually at least one set of values was obtained for every 2 m depth interval. Stations were along six lines between 44°35′N and 45°00′N (Fig. 1). Station separation was no greater than 8 km along each line. Each grid survey was completed in about 2 days. Usually one line in the grid was occupied more than once during the survey. Although significant differences were observed in such repeated sections, the major features were still present.

As an early step in analyzing the data, vertical distributions of temperature, salinity and sigma-*t* were drawn for every offshore line of stations (Huyer, 1973). Temperature inversions were common, but salinity usually increased monotonically with depth and inversions were rare; sigma-*t* always increased with depth. In contouring the temperature distributions we initially assumed a two-dimensional interpretation of the temperature inversion (Pak *et al.*, 1970; Mooers *et al.*, 1972) as a guide; i.e., we assumed all temperature inversions were due to sinking, approximately along the 26.0 sigma-*t* surface, of an anomalously warm, salty water mass formed locally by surface heating of upwelled water. However, it was not possible to draw all sections to be consistent with this interpretation. By increasing the station density inshore, thereby decreasing the ambiguity in contouring, we found a different interpretation that was more consistent with the data.

3. Results

Sections from three lines observed during the June cruise are shown in Fig. 2. The temperature distribution along 44°40′N appears to be consistent with the two-dimensional interpretation: the water warmer than 7.8C could reflect an intrusion of a warm, salty water mass generated locally. However, the sections along 44°50′ and 45°00′N show that, in the two-dimensional plane, the relatively cool, shallow water is isolated from its surroundings; it is restricted to a rather narrow zone over the continental shelf. When the evidence from the three lines is combined, we see that there is a ribbon of shallow cool water roughly parallel to the coast. In May and early July the hydrographic regime was similar to that observed in June, but it appeared to be more complex during the early and late August surveys (Huyer, 1973). Typical vertical temperature distributions from these surveys are shown in Fig. 3.

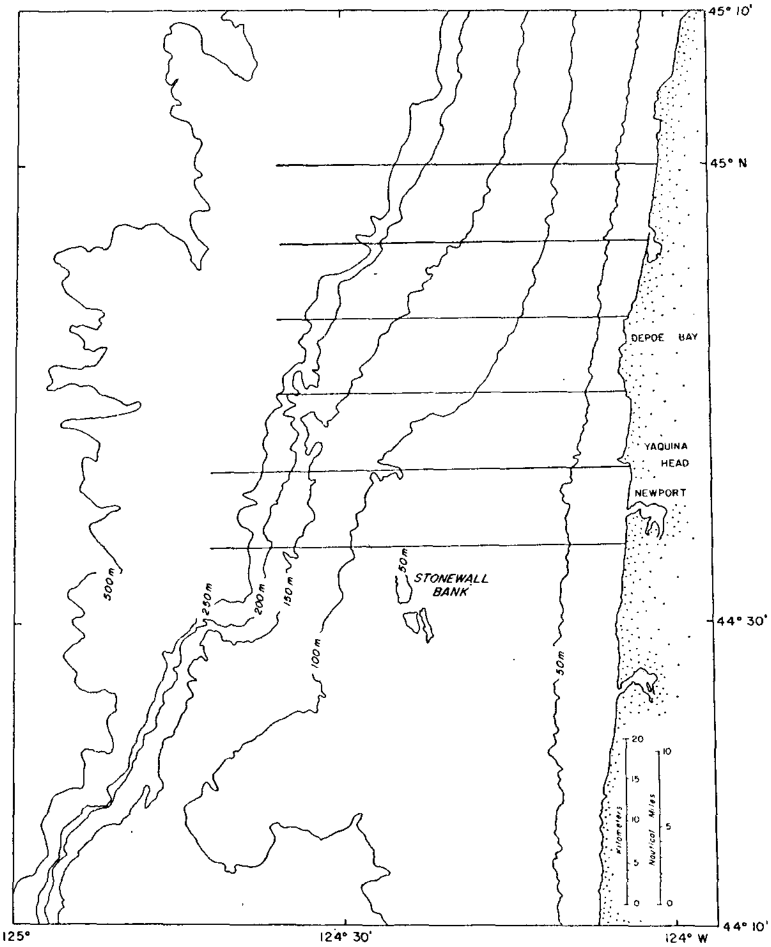


FIG. 1. The location of the grid surveyed by the *Yaquina*, summer 1972. Lines show the position and length of sections occupied several times during the summer.

During the three earlier surveys, the ribbon was relatively well defined, and it was possible to map its thickness, depth, temperature and salinity (Fig. 4). The thickness of the ribbon was defined as the difference between the depth of the relative temperature maximum beneath the minimum and the depth at which the same temperature was observed above the minimum. The depth, temperature and salinity of the ribbon were defined as being those at the relative temperature minimum. For the two later surveys, there was often more than one temperature inversion. The deepest minimum was mapped for the early August survey, and the shallowest minimum was mapped for the later survey (Fig. 5).

The maximum thickness of the ribbon appears to be about 50 m. The direction of its axis is roughly parallel to the local bottom contours. The width of the ribbon is of the same order as the offshore extent of the grid, about 50 km. The width of the thicker part of the ribbon (e.g., over 20 m) increases between the May and July surveys from about 20 km to about 40 km. The ribbon is sloped upward toward the coast. Its greatest depth is less than 100 m, and its shallowest is less than 20 m. The slope is most uniform during the June survey, and least uniform during the early August survey. The slope appears to be greatest during the May and June surveys.

Lateral temperature gradients in the ribbon were usually strongest at the shoreward and seaward edges. During the three earlier surveys, when the ribbon was well defined, temperature increased almost monotonically from the axis to the edges of the ribbon. Patchiness in the temperature distribution appeared in the early July survey and was a prominent feature in the early August survey. Warm patches are shown for the late August survey, but these may be connected, and part of a longer band of warm water.

The lowest temperature (7.2C) was observed in early July. The lowest temperature observed in early August (7.4C) was about the same as in June. However, most of the ribbon had a very uniform temperature (7.5C) during the June survey. The coolest temperatures observed in May and late August were very similar (7.7C) but the highest temperatures ob-

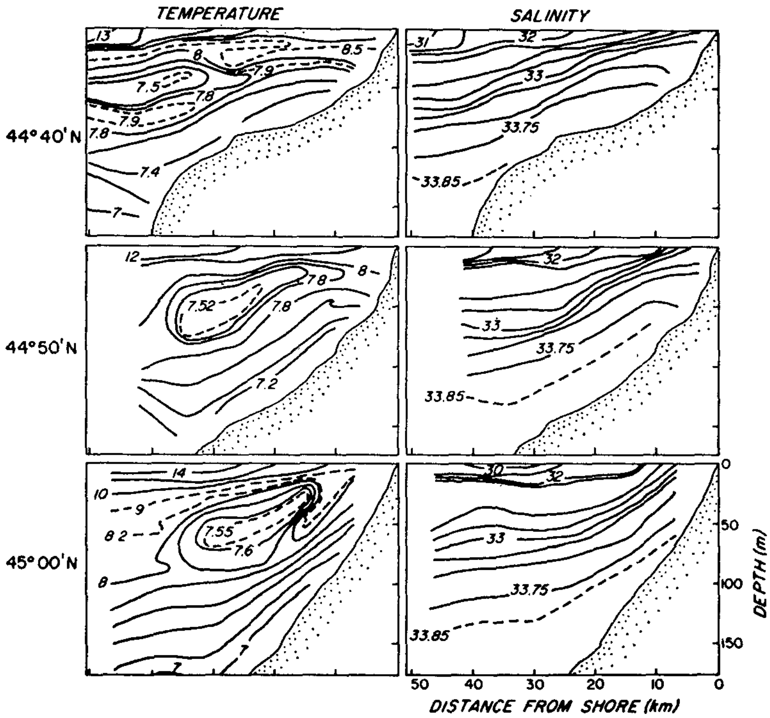


Fig. 2. Vertical distributions of temperature, salinity and sigma-t during the *Yaquina* survey of 21–22 June 1972.

served in late August (9.0C) were much warmer than those in May (8.3C). Only the early July survey showed some evidence of a north-south temperature gradient within the ribbon.

Most of the water in the ribbon has salinity between 32.6 and 32.8‰. Salinities along the edges are higher, especially along the shoreward edge, where salinities exceeded 33.6‰ during the early July and early August surveys. During each survey, some of the water in the ribbon was fresher than 32.6‰.

Direct current measurements obtained as part of CUE-I made it possible to examine the vertical distribution of the current along 44°40′N. Comparison of the vertical distribution of the temperature and the current shows that the ribbon is within the southward surface flow rather than in the northward undercurrent frequently observed on the Oregon continental shelf (Huyer *et al.*, 1973; Smith, 1974).

4. Discussion

a. Seasonal evolution of the ribbon

Between May and June, the ribbon became better defined and the minimum temperature decreased. The June and July surveys show a very well-defined ribbon, with very smooth distributions of ribbon thickness and depth. The minimum temperature continues to decrease until the early July survey. There is some suggestion that the ribbon was thickest in June and early July, and that the length scales were greatest during these surveys. The ribbon was less well defined during the early and late August surveys and the minimum temperature increased after the early July survey.

A monthly index of upwelling, the component of the Ekman transport normal to the coast based on the wind computed from the mean atmospheric pressure distribution, shows that in 1972 the upwelling began in April, reached a maximum in June, remained at that intensity until August, and was weaker but still occurring during September and October (Bakun, 1972). We note that the ribbon was both best-defined (in June) and had its lowest temperatures (in early July) relatively early in the upwelling season. Continued upwelling may lead to instabilities (Mooers *et al.*, 1972; Huyer *et al.*, 1973) which limit the growth and intensity of large-scale features in the regime.

b. The ribbon as a semi-permanent feature

Hydrographic observations have been made frequently off the coast of Oregon by Oregon State University since 1961. Data from all cruises during the upwelling season were examined for evidence of the ribbon. On most cruises, station spacing was not close enough to examine the details of the ribbon; a relative temperature minimum at salinities between 32.5 and 33.2‰ that did not extend offshore was taken to be evidence of the ribbon. If the inversion was very

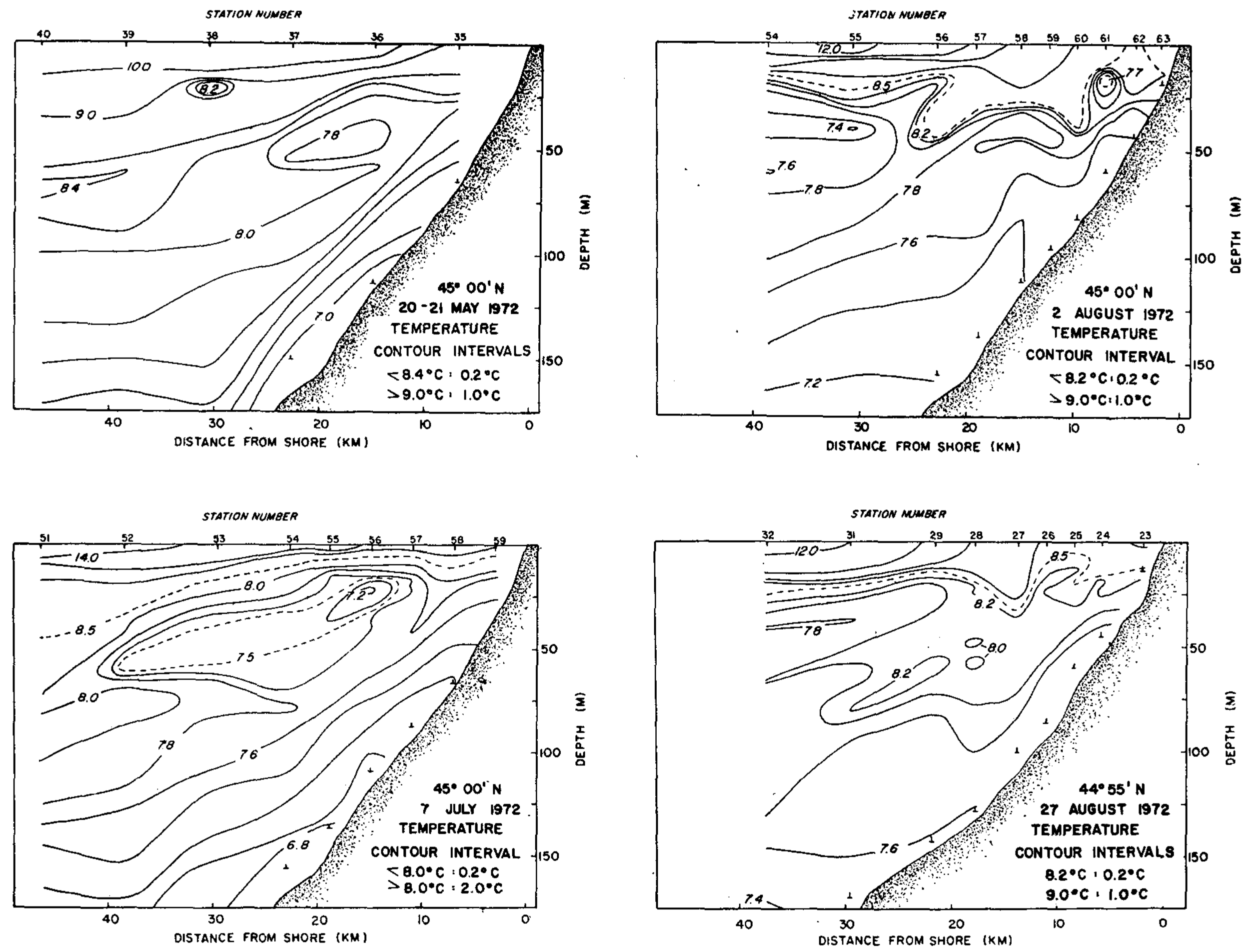


FIG. 3. Vertical distributions of temperature at 45°00′N, 20–21 May, 7 July, 2 August 1972 and at 44°55′N, 27 August 1972.

small, and observed at only one depth at only one station, it was not judged to be evidence of the ribbon. On some cruises, station spacing was of the same order as the width of the ribbon. In spite of this and other limitations of the data set, the ribbon was observed at some time during the upwelling season of all years between 1961 and 1971 except 1961 and 1963. The ribbon was observed only once in April, twice in May and frequently in June. It was usually observed in July and August and part of the time in September. During the fall and winter, i.e., October to March, there is usually no evidence of the cool ribbon, and subsurface temperatures over the continental shelf are warmer than in summer.

c. *Spatial extent of the ribbon*

The distributions of ribbon properties suggest that ribbon length scales greatly exceed the width scales. We computed the correlation between the temperature-salinity curves of pairs of stations within each survey. For each station we determined the temperature at intervals of 0.1‰ over a common salinity range (e.g., 32.0 to 33.8‰) and computed the correlation between the temperature at that station and the temperature at a particular reference station. During the two later surveys, surface salinities were very high, and the common salinity range for all stations was too small to result in meaningful estimates of the correlation. The distribution of the correlation between temperature-salinity curves at a reference station and each other station of the survey is shown for the three earlier surveys (Fig. 6); the reference station was chosen to be along the axis of the ribbon. If we arbitrarily define the length scale to be the distance at which the correlation drops through 0.7, the width scale was of the order of 20 km and the length scale exceeded 50 km during the June and early July surveys.

Data from a *Yaquina* cruise in June 1968 (Barstow *et al.*, 1969b) indicates that the ribbon extended at least 300 km, with a width of about 30 km; it was apparent in all five sections between 43°20′ and 46N.

d. *Relationship between the ribbon and upwelling*

Bakun (1973) has computed values of the upwelling index for each month for the years 1946 to 1971. We compared the monthly values of the index for the

Table 1. Values of the upwelling index at 45N, 125W, and observations of the presence of the cool ribbon during the upwelling season off Oregon, 1961–1971. An asterisk indicates the ribbon was observed; a dagger indicates observations were made but there was no evidence of the ribbon. Units of the upwelling index are m³ sec⁻¹(100 m)⁻¹.

	April	May	June	July	August	September	Reference for hydrographic observations
1961	11†	1†	21†	51†	33†	42	Wyatt and Kujala (1962, 1963)
1962	−7†	42†	29†	107*	21	11	Wyatt and Gilbert (1967)
1963	−9	8†	72†	38†	35	−5†	Wyatt and Gilbert (1967)
1964	57*	45	32*	51*	40	32	Wyatt and Gilbert (1967)
1965	5†	84	103*	99*	48	75	Wyatt *et al.* (1967)
1966	43†	101	20†	80*	110	6	Barstow *et al.* (1968)
1967	11†	88†	135*	134*	93*	15	Barstow *et al.* (1969a)
1968	47†	33†	59*	104*	21*	18†	Barstow *et al.* (1969b)
1969	−21†	13*	61*	106	46*	6*	Wyatt *et al.* (1970)
1970	25	33*	46*	71	73	11	Wyatt *et al.* (1971)
1971	−2†	66	13*	65	24*	8	Wyatt *et al.* (1972)

upwelling season for the years 1961 to 1971 with the results of the survey of hydrographic data (Table 1).

Table 1 shows that, in general, the ribbon was observed when the upwelling index was high, and it was not observed when the index was small. However, there are a number of exceptions to this rule. The ribbon was observed in conjunction with low values of the index in September 1966, August 1968, May 1969 and September 1969. In three of these cases, the value of the index was high in the previous month. In May 1969, although the upwelling index was small, the hydrographic section off Newport obviously reflected the effects of upwelling—the near-shore surface salinity was greater than 33.7‰. Relatively high values of the upwelling index without evidence of the ribbon also occurred on a number of occasions: July 1961, May 1962, June 1963, May 1967 and April 1968. However, each of these occurrences was preceded by a month with a low upwelling index. We tentatively conclude that the cool ribbon is a permanent feature of the upwelling regime off Oregon; it develops within about a month after the mean wind becomes favorable for upwelling and it persists about a month after the mean wind becomes unfavorable.

e. Source of the ribbon

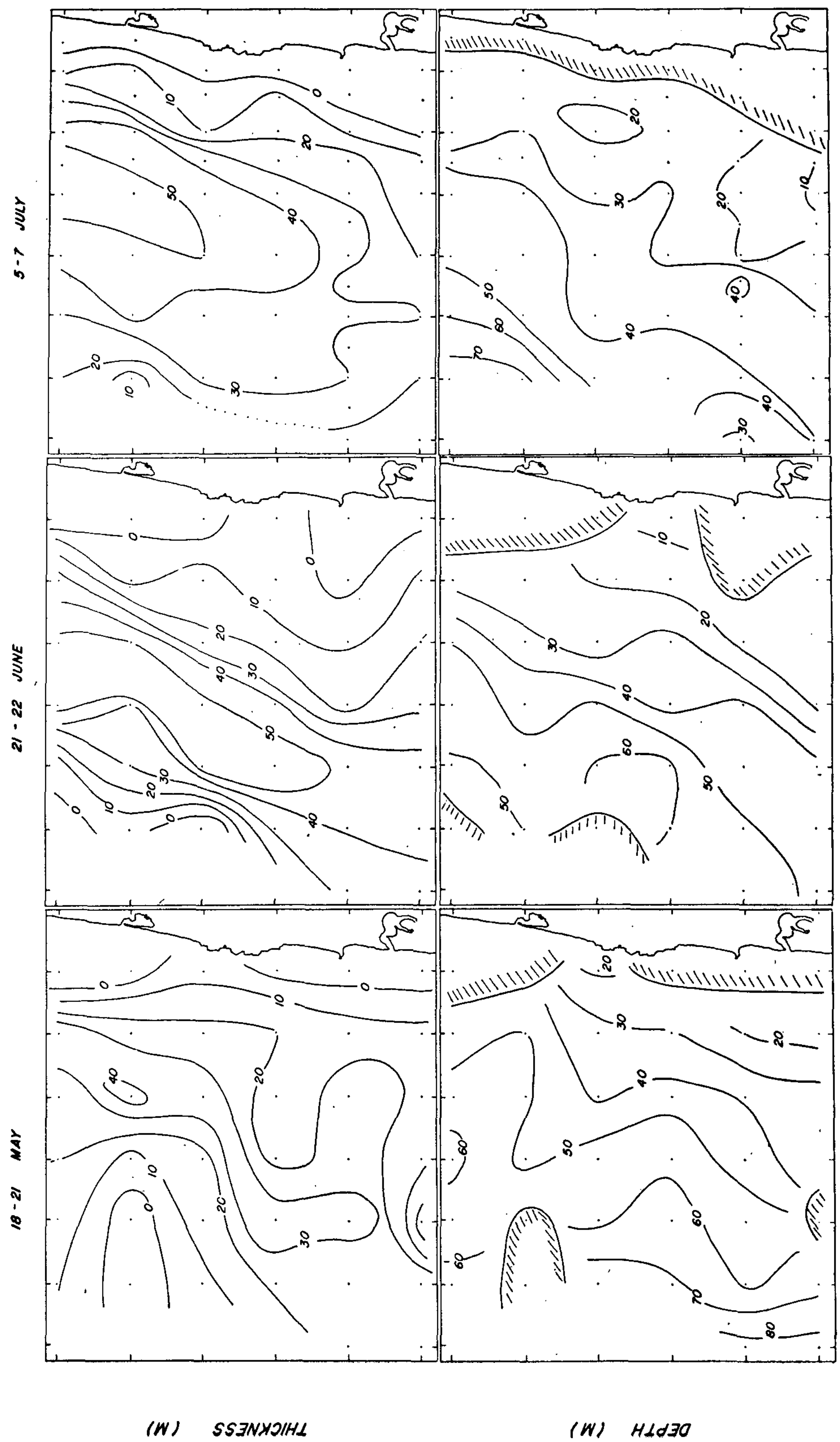
The properties of the cool ribbon in the CUE-I area seem very similar to a relative temperature minimum layer observed further north between Cobb Seamount (47°N, 131°W), Cape Flattery and Vancouver Island in September and October 1972 (Reed and Halpern, 1973). Its salinity is about 32.6‰; its depth decreases from over 100 m near Cobb Seamount to less than 50 m near Cape Flattery; and its temperature increases eastward from less than 7.0C near Cobb Seamount. This layer seems to be part of the large-scale temperature minimum layer which is normally observed in the subarctic Pacific at the top of the permanent halocline (Bennett, 1959; Uda, 1963). We conclude that the water in the cool ribbon is likely of subarctic origin.

The presence of a band of subarctic water over the continental shelf, resulting in a "cool ribbon," i.e., a narrow relative temperature minimum layer, could result from more rapid southward advection within the near-shore region. The existence of a coastal jet associated with upwelling has been theoretically derived (Allen, 1973). A near-shore maximum in the southward surface velocity (a coastal jet) has been observed in the coastal upwelling regime off Oregon (Mooers *et al.*, 1972; Huyer *et al.*, 1973; Huyer, 1974): its maximum velocities exceed 20 cm sec⁻¹ and its width is of the order of 20 km. Fig. 7 shows the vertical distribution of temperature and of the northward velocity component for a particular date; the positions of the ribbon and the coastal jet appear to agree well.

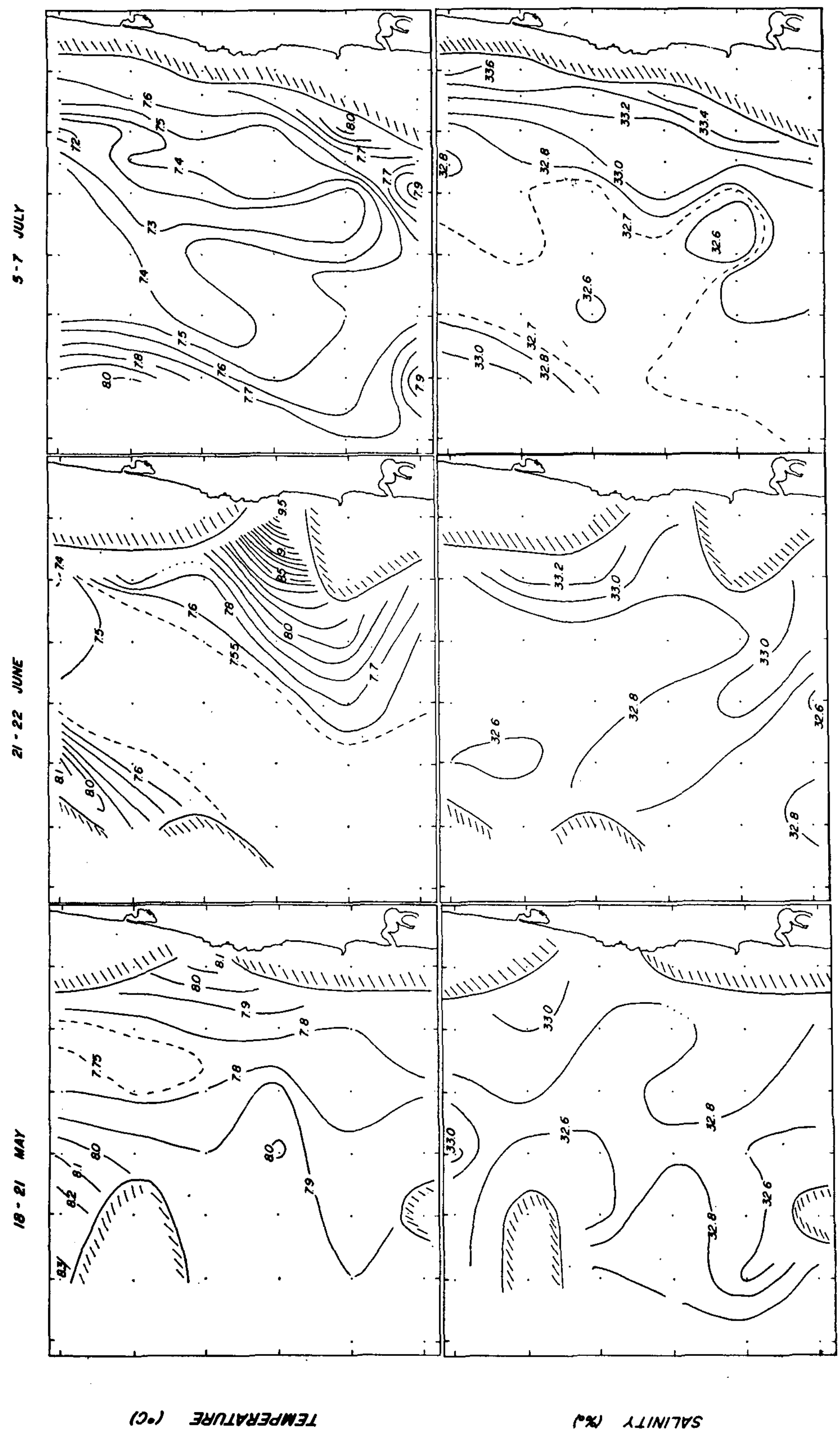
The California Current must also bring subarctic water southward further offshore, and may produce a similar but wider "cool ribbon." Temperature inversions are sometimes observed offshore but temperatures offshore are about 1C warmer than nearshore in the 32.5–33.0‰ salinity range (Fig. 8). The temperature difference may be due to the lower speeds further offshore in the California Current; maximum surface velocities in the mainstream of the California Current vary between 5 and 15 cm sec⁻¹ (Pavlova, 1966).

f. A warm temperature anomaly

Another kind of temperature inversion occurs within the upwelling region; it is observed inshore of the ribbon. Although the cool ribbon has been overlooked in past studies, the warm inversion has received a great deal of attention (e.g., Mooers *et al.*, 1972). Pak *et al.* (1970) have shown that the anomalously warm water of this inversion was associated with high turbidity. Their mechanism for the generation of the warm anomaly seems essentially correct: cold saline water is brought to the surface by intense upwelling, is then subject to solar heating, and is carried offshore by the Ekman transport. When it approaches lighter surface water (usually lighter because of lower salinity)



a.



b.

FIG. 4. Properties of the cool ribbon observed during surveys in May, June and early July, 1972, showing thickness and depth (a) and temperature and salinity (b).

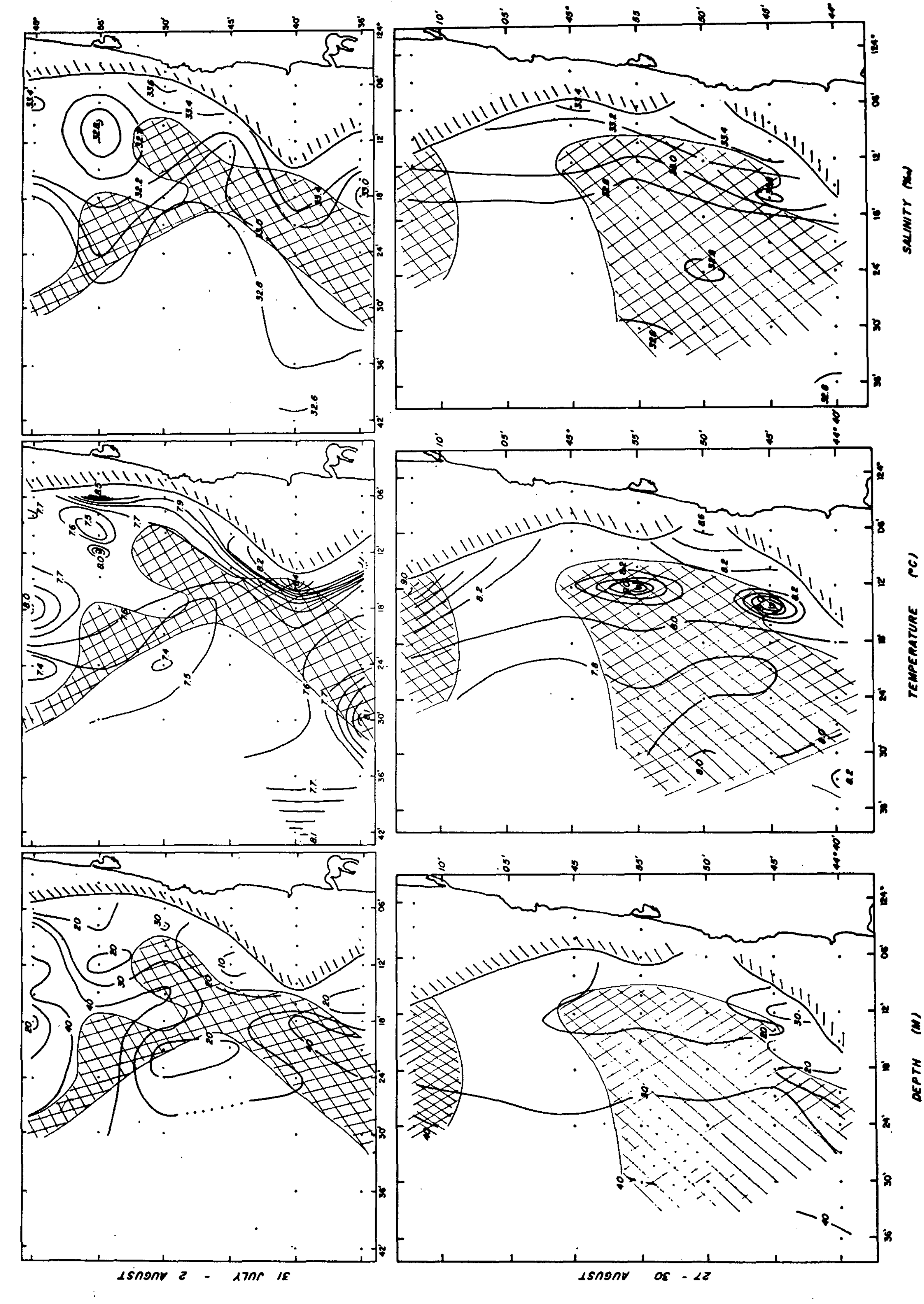


FIG. 5. Properties of a relative temperature minimum layer during surveys in August. Areas where more than one relative minimum were observed are cross hatched.

it tends to sink and to be mixed with the surrounding water. The warm temperature anomaly results from the onshore-offshore component of the flow. The resulting warm tongue does not appear to extend seaward of the axis of the cool ribbon. The section at 45°00′N on 22 June (Fig. 2) is a clear example of the presence of both the cool ribbon and the warm temperature anomaly. The *T-S* curve for the station with the warm anomaly (no. 44) is shown with those in the ribbon and further offshore in Fig. 9; the anomalously warm water occurs at salinities between 33.0 and 33.5‰. Later in the 1972 upwelling season (September), the intensity of this anomaly exceeds 1C and is associated with a salinity inversion (Anon., 1973c).

The warm temperature anomaly resulting from the local heating of highly saline upwelled water frequently has a complex structure (for examples, see Huyer, 1973). It appears that the exact location of the sinking of relatively warm water is sensitive to changes in very local surface conditions, so that a particular section may show evidence of two or more downward intrusions of anomalously warm water, for example, on 16 July and 13 September, 1972 (Huyer, 1973). When this occurs, it may modify the structure of the subsurface cool ribbon. The ribbon can also be modified if the warm intrusion is not at the inshore edge of the ribbon, but instead intersects it; this apparently occurred on 2 August 1972 (Fig. 3). Such interactions between the warm temperature anomaly which is determined mainly by the onshore-offshore component of the flow, and the cool ribbon which is determined by the alongshore flow, likely contributed to the frequent observation of more than one relative temperature minimum.

5. Conclusions

An alongshore subsurface ribbon of relatively cool water was observed over the continental shelf off Oregon during each of five grid surveys by the *Yaquina* during the upwelling season of 1972. The ribbon was of the order of 50 km wide and 50 m thick. It was relatively shallow, and was observed to be within the southward surface flow associated with the upwelling regime. The temperature of the ribbon was a few tenths of a Celsius degree colder than water beside and below it. Its salinity was between 32.5 and 33.0‰.

There appeared to be a seasonal evolution of the ribbon. Its minimum temperature was observed fairly early in the upwelling season (July), and it appeared to be most clearly defined early in the season (June). The axis of the ribbon appeared to move offshore as the season progressed. There was some suggestion that it widened, but observations were not made far enough from the coast to define the seaward edge during the later surveys.

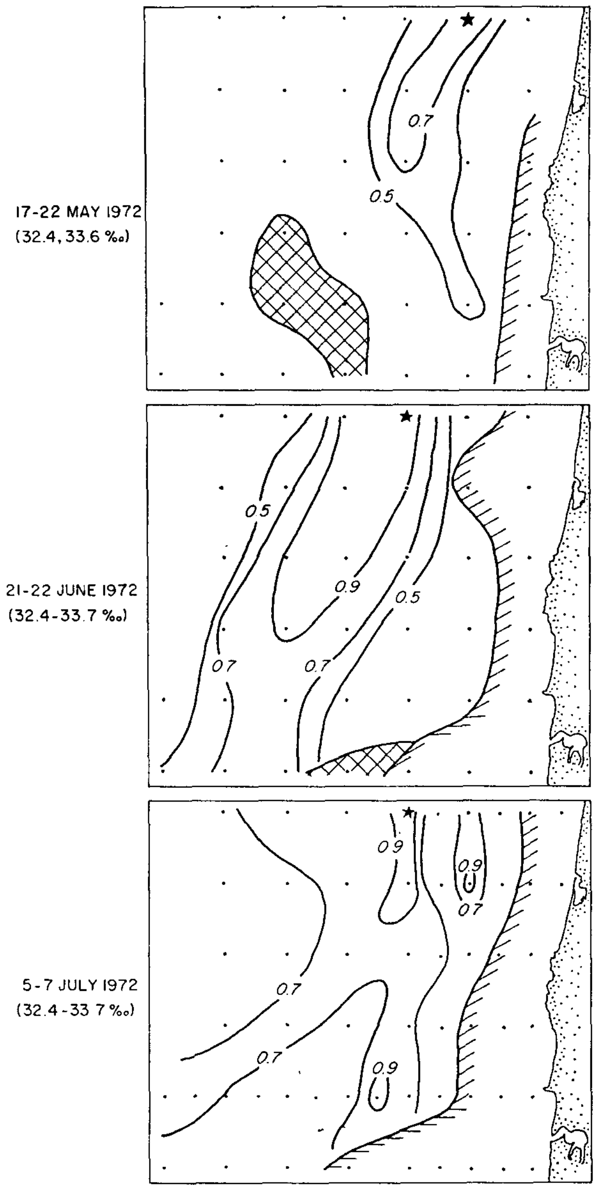


FIG. 6. Distribution of the correlation between the temperature-salinity curves of a reference station (*) and each other station of each survey. Cross-hatched areas show regions where the bottom salinity was less than the maximum of the common range; the near-shore region had surface salinities exceeding 32.4‰.

Data from a June 1968 survey indicated the ribbon is at least 300 km long. Observations from other years also indicated the presence of the ribbon. Comparisons of the observations with an upwelling index showed that evidence for the ribbon was generally found when the upwelling index was high. There is some suggestion that there is a lag of about a month between the upwelling index and the presence of the ribbon.

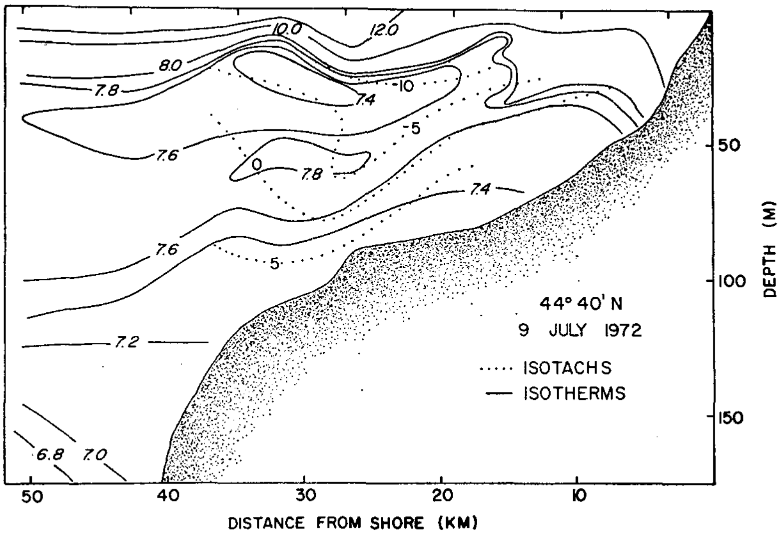


FIG. 7. The vertical distributions of both temperature and the northward component of velocity at 44°40′N, 9 July 1972 [after Huyer *et al.* (1973)].

The ribbon can be accounted for by southward advection of subarctic water due to the coastal jet associated with the upwelling regime. We expect a similar temperature minimum to exist further offshore in the California Current, although southward advection is slower there. A warm temperature anomaly due to the sinking of modified upwelled water is frequently observed inshore of the cool ribbon. These different temperature inversions can be distinguished by close station spacing and to some extent by their temperature-salinity characteristics.

Acknowledgments. This is a contribution to the Coastal Upwelling Ecosystems Analysis program

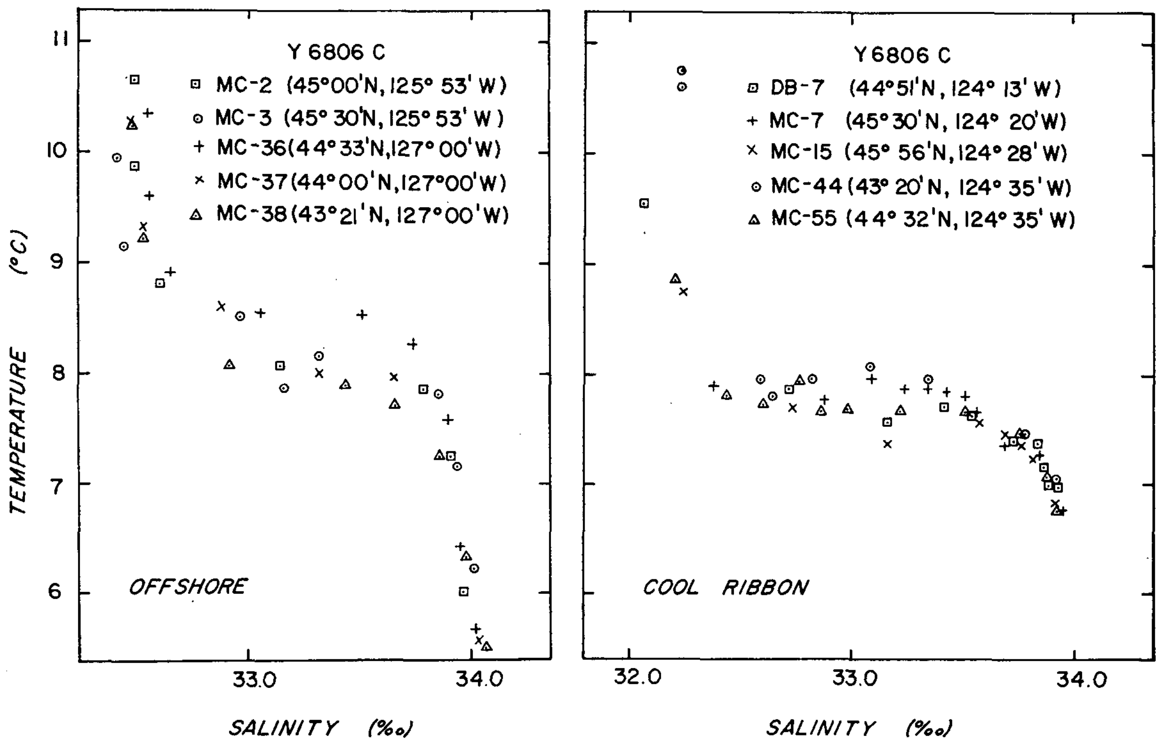


FIG. 8. Temperature-salinity characteristics both offshore and along the cool ribbon, June 1968.

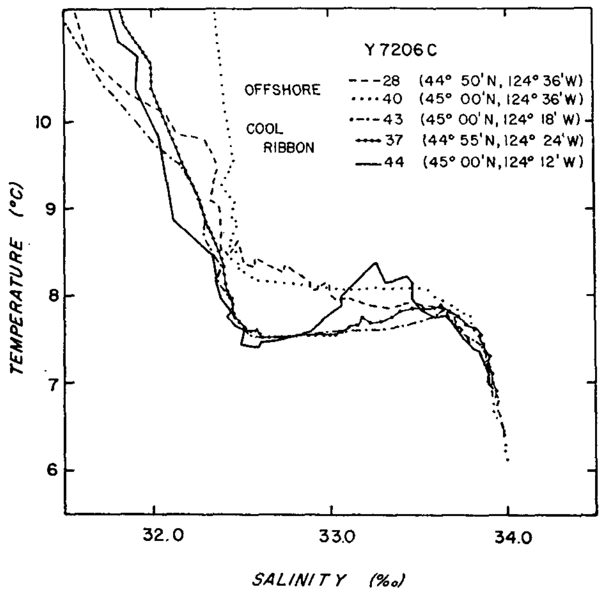


FIG. 9. Temperature-salinity curves for selected stations from the June 1972 grid survey.

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