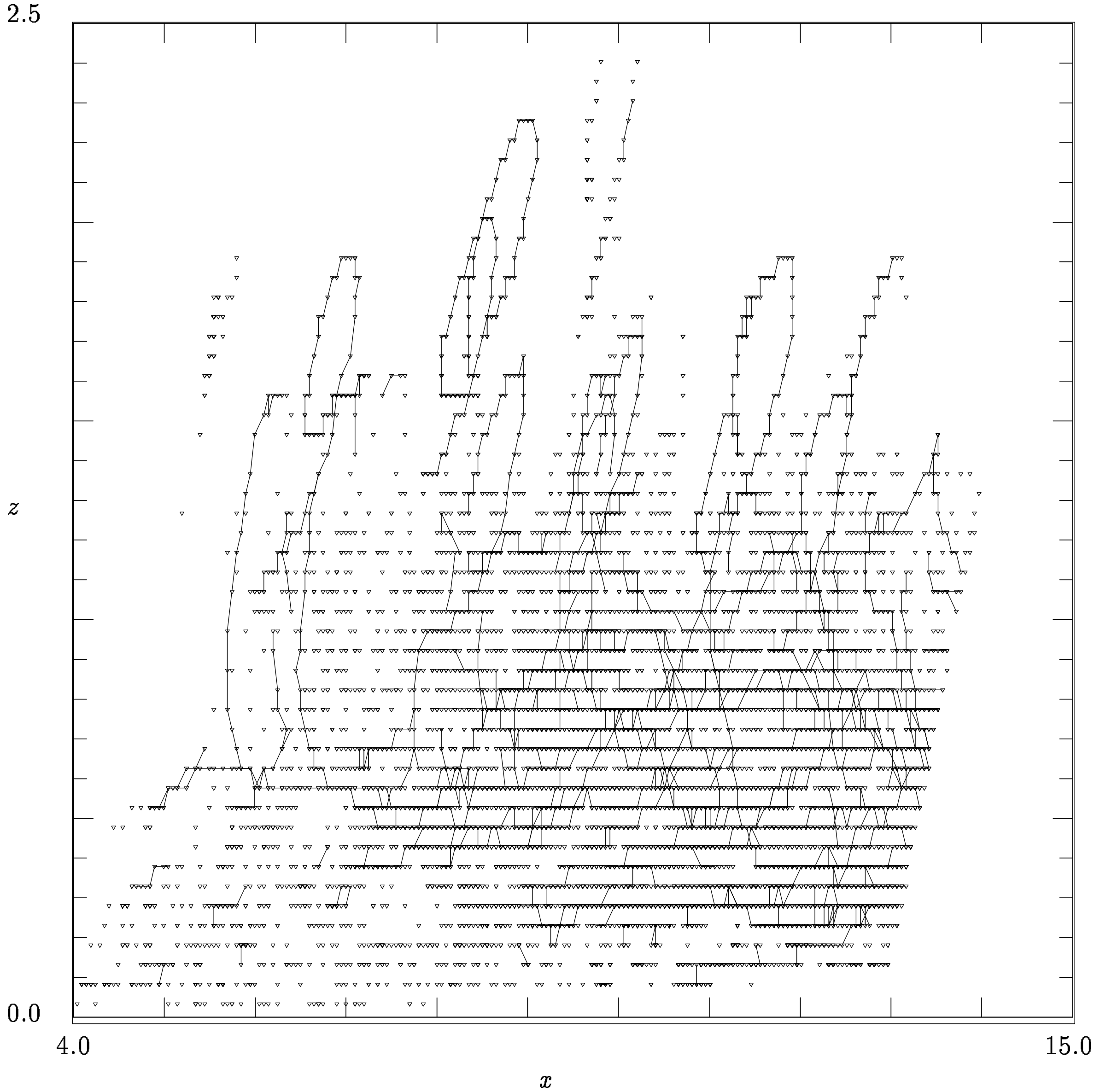

Figure 7: Particle tracks in the density-driven regime. The centre of the frame is at $x = 9.5 \pm 0.1$. Each dot represents a particle at 0.2 s intervals. The dimensions of the region shown are 11.0 in x and 2.5 in z (22.0 by 5.0 cm). Thirty seconds' data are shown on this frame, beginning immediately after thermal release. Solid lines join the particle images that particle-tracking algorithms confirm as belonging to the same particle. Groups of particles appear to be organized into horizontal bands because the aspect ratio of the plot, chosen to emphasize the vertical structure, magnifies the pixel resolution in the vertical. The wave is travelling from left to right across the frame and those particles in orbital paths are rotating counter-clockwise.

meant that after completing the orbit the particle's position appears to be the same as before its motion began. Furthermore, in the mass-transport zone there seems to be virtually no shear or net circulation. This is consistent with the observation noted in §4.1 above, where the dyed thermal mass appeared to be virtually motionless in a frame moving with the IPF. Note that in figure 8 the curved paths in the top zone represent particles travelling on the elliptical orbits typical of wave flows; they do not appear to have been caught up in turbulent eddies, and no significant turbulence was noted in the shadowgraph experiments for these parameters. Eddies associated with gravity-current motion should show some net translation, whereas these motions do not. The sense of rotation of the particles on their orbits is counter-clockwise, which is the same as the positive vorticity initially created by the thermal vortex. These orbits only exist in the wave-activity zone. The thermal-vortex structure apparently facilitates the formation of wave-dynamical particle orbits.

The next stage in flow evolution occurs when significant transport of particles ceases. This point is hard to determine precisely from the particle tracking measurements but occurs after about $x = 30$. The IPF now appears to have been replaced by a solitary wave that does not transport mass. The behaviour appears wave-dynamical throughout the vertical structure.

Finally, the vertical structure after the IPF has degenerated consists of a smoothly-varying and essentially horizontal velocity that is a maximum near the floor and decreases with height through the stratified layer. This is the basic vertical structure predicted by the first-vertical-mode ($n = 1$) linear solution corresponding to (3). The weakly nonlinear analysis separates the streamfunction into vertical and horizontal functions; the vertical eigenfunctions are obtained identically as for the linear analysis. Therefore, flows consistent with weakly nonlinear solutions should have the same vertical structure as the linear solution. The sense of vorticity observed from the shear in the flow is

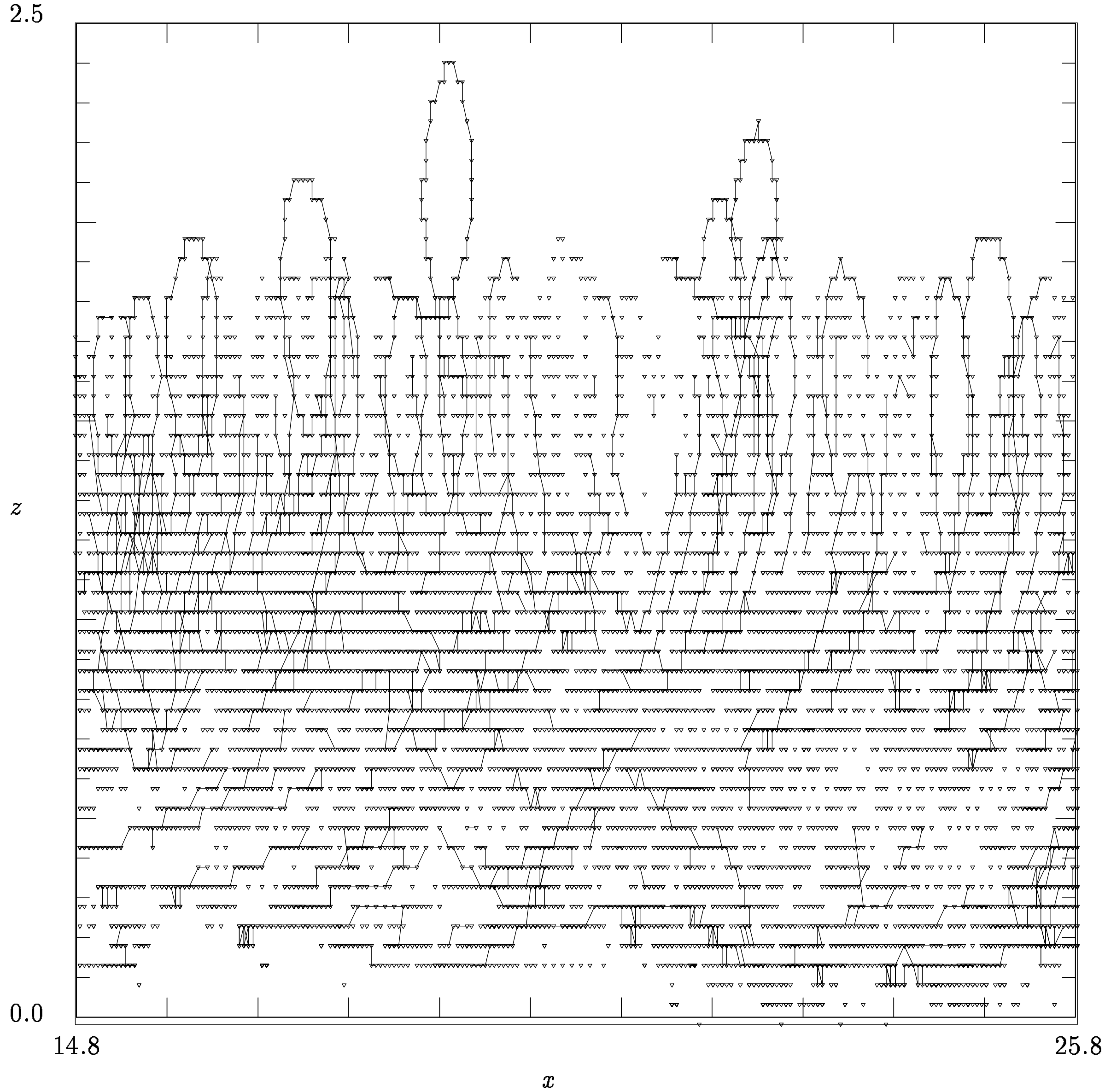

Figure 8: Particle tracks in the transitional stage of flow evolution, corresponding to an IPF. The centre of the frame is at $x = 20.3 \pm 0.1$. The wave-activity zone is above about $z = 1.0$ (the thick dashed line) and the mass-transport zone is below. This stage corresponds to figure 2(d), in which the transported mass is hatched. Other details as figure 7.

still positive.

The speed of the IPF for the conditions of figure 8, obtained from an average of several repeated runs, was estimated at 1.06 ± 0.3, scaled relative to c_0, or 1.63 ± 0.4 cm s^{-1} in dimensional units. This speed is subtracted from the horizontal component of the particle velocities to give a pathline pattern in a frame of reference moving with the IPF. This is shown in figure 9. Pathlines are not the same as streamlines unless the flow is steady. While the flow at the stage of figure 9 is non-turbulent, it strictly ought to be described as unsteady, since it evolves with time. Nevertheless, since major changes in the flow structure are not occurring during the time-frame represented by figure 9, there is reasonable justification for treating it as an approximate streamline pattern for the IPF.

It can be seen from figure 9 that there is a smooth, symmetric pattern characteristic of soliton solutions (*eg.* Benjamin 1967). The mass-transport zone appears below the crest of the wave, in the region marked 'MTZ'; it is identifiable because pathlines, as plotted in the frame of reference moving with the wave, can be observed either diverting above the mass-transport zone or stagnating at it. In this frame of reference there is no discernible motion of particles in the mass-transport zone, again confirming the visual observations in §4.1 that there seemed to be no net circulation in this zone. When the equivalent pattern for the earlier, density-dominant regime (the data of figure 7) is plotted in this fashion, it looks similar, though it is not symmetric. As for the later, wave-dominant regime, curvature in the streamlines is found closer to the floor. Close examination of figure 9 shows a smaller 'hump' trailing the main soliton structure, marked 'TW'. Similar trailing waves were often noticed in the density probe traces, although they could not be seen by eye during the experiments or on the videotapes.

To make the pattern of particle tracks in figure 9 clearer, selected