Cenozoic Submarine Canyon Systems in Cool Water Carbonates from the Otway Basin, Victoria, Australia

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**ABSTRACT**

Well preserved submarine canyon systems are present in the Oligocene-Miocene cool water carbonates of the Heytesbury Group and the Pliocene-Recent Whalers Bluff Formation of the offshore Otway Basin. From seismic profiles, two morphologically distinct submarine canyon types are present in the cool water carbonates:

1. Miocene canyon systems;
2. Pliocene to Recent canyon systems.

Miocene canyon systems consist of long-lived laterally migrating canyons. These systems are found on the eastern side of the offshore Otway Basin, with two major canyons systems being present. The Miocene canyons migrate laterally towards the west, with each progressively younger canyon within the system being located slightly to the west of the underlying canyon. The fill within each canyon similarly progrades towards the west.

Pliocene to Recent canyons have been seismically mapped offshore in the vicinity of Portland. The fill within Pliocene to Recent canyons is generally symmetric or slightly eastward-oriented. The oldest Pliocene canyons are visible on magnetic images of the shelf, indicating a magnetic (probably clastic) component in the canyon-fill. Modern canyons are also found in the vicinity of Portland around the slope. The larger modern canyons occupy positions immediately seaward of their Pliocene counterparts. There is no evidence that these canyons overly transfer faults, as previously suggested.

The change in canyon migration direction, from westerly during the Miocene to easterly during the Pliocene, is probably the result of a major seafloor spreading change, occurring around the Mid-Miocene boundary. A strong westerly-directed current appears to have dominated the region in the Miocene, while a weak easterly-directed current appears to have existed during the Pliocene to Recent. It is likely that Late Miocene-Early Pliocene tectonics also affected the development of the canyons, with distinctly different canyon regimes being formed before and after uplift.

**INTRODUCTION**

Modern submarine canyons have been described from many continental margins. Significantly fewer examples of ancient canyons have been documented, either from seismic data or outcrop sections. The surprising lack of information on ancient canyons has meant that the evolution of canyon systems is, in general, poorly understood. The offshore Otway Basin contains canyon systems within cool water carbonates ranging in age from Oligocene to Recent (Figure 1). These Cenozoic canyons have been imaged by high quality industry seismic data, while the modern canyons can be observed in bathymetric data. This 3D data set provides an ideal opportunity to examine the evolution of long-lived canyon systems. Similar submarine canyons of the Tertiary Seaspray Group in the Gippsland Basin have caused considerable problems in the seismic interpretation of reservoir structures. This paper seeks to describe the geometry and evolution of canyon systems in the Heytesbury Group and Whalers Bluff Formation.

**GEOLOGICAL SETTING**

The Otway Basin formed during the separation of Australia and Antarctica, which began during the Late Jurassic. The oldest sediments in the basin (Upper Jurassic to Upper Cretaceous) are largely of syn-rift origin and include the Crayfish, Otway, Shipwreck, and Sherbrook Groups. The Tertiary Wangerrip, Nirranda, and Heytesbury Groups are of post-rift origin (Norvick & Smith 2001). The Oligocene to Miocene Heytesbury Group is a typical southern Australian cool water carbonate sequence, which consists largely of prograding shallow water carbonates and deeper water marls (Figure 2).

The upper Oligocene to Miocene Heytesbury Group carbonates consist of the basal upper Oligocene Clifton Formation (relatively shallow water carbonates), overlain by the Lower Miocene Gellibrand Marl and the Lower to Middle Miocene Port Campbell Limestone. The Gellibrand Marl to Port Campbell Limestone sequence is a shallowing upwards sequence which records the progradation of a cool water carbonate shelf (Figure 2).

The Pliocene-Quaternary Whalers Bluff Formation (Figure 2) and equivalents (Hanson Plain Sand, Moorabool Viaduct Formation, Grangeburn Formation) are mixed clastic/carbonate sediments which record a compressional tectonic regime, beginning in the Late Miocene (Dickinson et al. 2001). In onshore and near-shore sections, there is a significant unconformity separating the Heytesbury Group carbonates from the Pliocene sediments. The submarine canyons described in this paper are found in the offshore Heytesbury Group and Whalers Bluff Formation.

![Location map of southeastern Australia with the position of the study area. The position of modern submarine canyons is also shown (in orange). Depths in metres.](Fig 1)

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METHODS
Extending from the South Australia/Victoria border to Cape Otway, the study region makes up a considerable portion of the offshore Otway Basin (Figure 1). The bulk of the study focuses on high-quality 2D seismic lines from surveys shot between 1980 and 1991 (OE80A, OP80, OH91). The line spacing varies from 1.25 to 2 kilometres (Figure 3).

The major stratigraphic reflectors used for mapping are the base of the Heytesbury Group (Clifton Formation), the base of the Port Campbell Limestone (where present) and the Miocene-Pliocene boundary. Thirteen wells lie within the study area, but no wells penetrate canyon fill. The age of the canyons was determined by correlations with wells in the region. The positions of the Pliocene canyons and their fill was also mapped using a total magnetic intensity image, a residually filtered magnetic image (in both black and white, and colour) and a vertical derivative magnetic image (black and white).

CANYON TYPES
The submarine canyons within the offshore Otway Basin are confined to the Oligocene to Miocene Heytesbury Group and the Pliocene to Quaternary Whalers Bluff Formation. The two major types of submarine canyons mapped according to their age and morphology are:
1. Miocene canyons; and
2. Pliocene-Recent canyons (Figure 3).

The Miocene canyons are found on the eastern side of the Otway Basin, while the Pliocene to Recent canyons have a broader distribution (Figure 1). The Pliocene sediments also display a dramatic thickening towards the west and seawards. In most cases, the Pliocene-Recent canyons are unrelated to the Miocene canyons, being geographically separated from the older canyons and generally not underlain by older canyons. Only in some places did Pliocene-Recent canyon development occur in the same position as the older canyons (Figure 3).

**Fig 2** - Eocene to Recent stratigraphy of the eastern (Victorian) Otway Basin (modified from Tickell et al. 1992 and Gallagher & Holdgate 2000).

**Fig 3** - Study area in the Otway Basin, with the location of the various modern and ancient submarine canyons that have been mapped seismically. The position of seismic lines used in the study (black lines) and illustrated seismic lines (red lines) are also shown.
Miocene canyons

The Miocene canyons are found on the eastern side of the offshore Otway Basin, in the Heytesbury Group. The oldest canyons occur just above the Clifton Formation, and are probably of Early Miocene age. Two types of Miocene canyons are present in the Eastern Otway Basin:

1. simple, isolated cut and fill canyons; and
2. complex stacked canyon systems consisting of laterally migrating and aggrading canyons.

Several isolated canyons are present within the eastern half of the Otway Basin. On seismic profiles these canyons are broad U-shaped canyons, ranging from 2 to 7 km wide, and at least 30 km long and cut approximately 400 m into the slope sediments. These isolated canyons are characterised by a simple history of erosion, followed by canyon filling. The fill within each canyon progrades towards the west. All of these isolated canyons are of Middle Miocene age.

Two major stacked canyons are present in the study area. The main sections of these canyons are sub-parallel to each other and run approximately perpendicular to the modern coast, trending NE-SW (Figure 3). Many of the canyon heads curve strongly towards the west, becoming sub-parallel to the coastline in near-shore positions (Figure 3). In cross section, the stacked canyons are all U-shaped, and up to 14 km wide and 60 km long. Towards distal offshore positions, the canyons cut deeper into the sediments (up to 400 m) and become wider and more complex. The offshore portion of the canyons are more stable through time than their shoreward heads.

Beginning in the Early Miocene, between six to ten major cutting and filling events occurred, which make up the stacked canyons. The western canyon system is more complex and is made up of even more erosional events. Within both canyon systems, erosion began on the slope within the Gellibrand Marl during Early Miocene time and continued into the Late Miocene. In near-shore positions, all the Miocene stacked canyons migrate laterally towards the west. Each progressively younger canyon is located slightly west of the underlying older canyon (Figure 4). As with the isolated canyons, the fill within each stacked canyon also progrades towards the west.

The fill within the Miocene canyons has distinctive seismic attributes relative to the host slope sediments (Figure 4). The reflectors within the canyon-fill facies have limited continuity, a high amplitude and dip towards the west. The reflectors are generally concave upwards, being concordant with, or overprinting the downlapping at the top and base of the canyon respectively (Figure 4). In most cases, the canyon-fill facies onlaps the western wall of the canyon. In contrast, the Miocene slope facies has moderate amplitude, and continuous sub-parallel reflectors (Figure 4).

All of the Miocene canyons display well developed velocity ‘pull-ups’ (Figure 4), indicating that the canyon-fill has higher velocities than the strata into which it is incised.

Pliocene-Recent canyons

The Pliocene canyon systems display a similar geometry to the Quaternary canyons. Although the main body of the Pliocene canyons is U-shaped, the shoreward sections are V-shaped (Figures 5 & 6). They range from one to 12 kilometres wide and are at least 20 to 30 kilometres long (Figure 7). In contrast to the Miocene canyons, the fill in the Pliocene canyons is largely symmetric or trends slightly eastward (Figures 5 & 6). Pliocene canyon-fill is also characterised by relatively continuous, high amplitude reflectors. Seismic data beneath the Pliocene canyons are generally poor, with many multiples and other disruptive effects (Figures 5 & 6). Pliocene canyons appear to produce both 'pull-up' and 'push-down' structures.

![Figure 4](image-url) - Uninterpreted and interpreted version of a portion of seismic line OE80A-1039 (position shown on Figure 2), illustrating a westward migrating Miocene canyon system.
Fig 5 - Uninterpreted and interpreted version of a portion of seismic line OP80-36 (position shown on Figure 2) illustrating a Pliocene canyon which has filled from west to east. Note the poor quality of seismic data beneath the canyon.

Fig 6 - Uninterpreted and interpreted version of a portion of seismic line OP80-30 (position shown on Figure 2) illustrating two Pliocene V-shaped canyons with symmetric fill geometries.
The oldest Pliocene canyons can be distinguished on total magnetic intensity images of the region (Figure 7). Dendritic shapes are present on the magnetic image, which correspond to the position of the seismically-mapped Pliocene canyons (Figure 7). This suggests that the Pliocene canyons may have a silicilastic component to their fill, since carbonate canyon-fill would probably not have a magnetic contrast to the surrounding Heytesbury Group carbonates.

Modern canyons are present in the western half of the Otway Basin and their positions coincide approximately with those of infilled Pliocene canyons (Figure 3). Two of these canyons have been previously mapped by Boutakoff (1963) and were named the Keble canyon and the Nelson canyon (Figures 1 & 3). The Rivoli Canyon (Boutakoff 1963) is present towards the northwest of the Keble and Nelson Canyons. Sprigg (1952) and Boutakoff (1963) have suggested that the Keble and Rivoli canyons were both at some time related to exit points for the Glenelg River.

The modern canyons are essentially extensions of the Pliocene canyon systems (Figure 3). Based on bathymetric data, they are up to 12 km wide and at least 100 km long, and erode up to 600 m into the present slope. Like the Pliocene canyons, the modern canyons fill symmetrical or slightly eastward. Modern (and Pliocene) canyons have been seismically mapped in the eastern half of the study area, but there is insufficient seismic data to map the aerial extent of these canyons.

**DISCUSSION**

The Miocene and Pliocene-Recent canyons are geographically and morphologically distinct from each other. Morphologically, the Miocene canyons are characterised by westward progradation, while the Pliocene-Recent canyons are characterised by symmetrical or slight eastward progradation. The Miocene canyons are only present in the east of the study area, while the Pliocene-Recent canyons have a broader distribution. The two canyon systems are dealt with separately, and the relationship between the canyon episodes is discussed below.

**Westward-migrating Miocene canyons**

In plan view, the Miocene canyons have headward sections which are deflected towards the west (Figure 3), and in cross section, they display a strong and consistent westward lateral migration down their length (Figure 4). Furthermore, individual canyons fill from east to west, with the fill dipping west. This consistent westward lateral accretion of the Miocene canyons is their most distinctive morphological feature. McHargue & Webb (1986) suggested three processes that could cause inclined canyon fill:

1. slumping of canyon walls;
2. point bar deposition; and
3. slope sediment influx.

Slumping of canyon walls consistently from the same direction would seem unlikely, and therefore appears an improbable explanation for the westward dipping canyon-fill. Point bar migration is expected in the fill of meandering canyons, with the direction of dip and lateral accretion reflecting the position of the inner side of the meander. In this situation, the direction of dip of the lateral accretion surfaces should alternate down the canyon, depending on the direction of the meander. This is not consistent with the invariably westward lateral accretion of the Otway canyons down their length. Furthermore, the westward deflection of the canyon heads is the opposite of what would be expected if lateral accretion had been caused by point bar deposition.

Slope sediment influx into the canyons appears to be the most likely explanation for the westward lateral accretion of the Otway canyons. The dipping reflectors of the Otway canyons are continuous with the adjacent inter-canyon slope reflectors, as described by McHargue & Webb (1986). The westward slope sediment transport direction may be explained by a shelf-break parallel westward palaeocurrent existing during the Miocene.

The westward deflection of the canyon heads may also be explained by a westward palaeocurrent. If the intensity of the palaeocurrent was greater in shallower water, the heads of the canyons might be expected to laterally migrate to a greater degree, causing the concave shape of the canyons.

Very similar laterally migrating canyons have been described from offshore Gabon, in West Africa (Rasmussen 1994). In offshore Gabon, the canyons consistently migrate towards the northwest. Rasmussen (1994) suggested that this resulted from a northwest-directed palaeocurrent along West Africa during the Middle Miocene. The present day slope currents in West Africa are also northwest-directed (Séranne & Né Zé Abeigné 1999) and the northwest-directed canyon structures do persist into the Recent. However, Séranne & Né Zé Abeigné (1999) suggested an upwelling origin for the Gabon canyons (termed 'mots' by Séranne & Né Zé Abeigné 1999). These authors suggested that up-slope directed currents under the influence of the Coriolis force were responsible for northwest lateral migration.

As the Miocene canyons of the Otway Basin are very similar, Séranne & Né Zé Abeigné’s (1999) suggestion that such laterally migrating canyons are not caused by turbidity currents, but by up-slope currents is significant. In the case of the Otway canyons, several points are important:

1. the Otway structures branch shoreward, suggesting a drainage pattern from shallow to deep (Figure 3); and
2. the Otway canyons display clear evidence of erosion (Figure 4).

Both of these factors support an origin by mass flow downslope, rather than by upwelling currents.

As no wells penetrate the Miocene canyon-fill, sedimentological interpretation of the canyon-fill can only be based on seismic data. The canyon-fill facies has reflectors with limited continuity and strong amplitude. The strong amplitude of the reflectors may suggest that these sediments are more carbonate-rich than the surrounding rocks, like those observed in the Gippsland Basin (Holdgate et al. 2000). The pull-up structures beneath the canyons also suggest a higher carbonate content than the surrounding slope sediments.

**Pliocene-Recent canyons**

The buried Pliocene canyons are essentially contiguous with the modern canyon systems and have the same general orientation and morphology. The contiguous nature of Pliocene and Recent canyons is a result of shelf progradation. The Pliocene canyon systems were almost certainly situated on the continental slope, as are the modern canyon systems. As shelf progradation occurred, the canyons on the slope also migrated seaward, resulting in the relative stability of the major canyon systems through time.

The Pliocene-Recent canyons differ from the Miocene canyons in that they:

1. fill symmetrically or slightly eastward;
2. have a more widespread distribution; and
3. can be distinguished magnetically.

The Pliocene canyons also cause much disruption to seismic data below the canyons. From the previous interpretation of Miocene canyon lateral migration, it appears likely that the near-symmetric or slightly eastward fill of the Pliocene-Recent canyons is a result of a weak eastward current. This is consistent with the modern oceanographic circulation in the region, which produces an eastward-directed current at the shelf break (Bye 1999).

469

Fig 7 - (a) Position of Pliocene canyons from seismic mapping (yellow) and magnetic interpretation (grey). Seismic grid used for mapping is also shown. (b) Uninterpreted total magnetic intensity image with the position of canyons shown.
As previously discussed, the Pliocene canyons can be clearly distinguished on total magnetic images of the Portland region (Figure 7). The magnetic images correspond very closely with the seismically mapped positions of Pliocene canyons. This suggests that there is a magnetic and probably clastic component to the Pliocene canyon fill. Furthermore, the fact that the Pliocene canyons are visible magnetically suggests that the magnetic-fill only occurred in one episode, and was not continuous into the Quaternary or Recent. The position of the magnetic canyon fill suggests that the magnetic component may be the oldest fill within the canyons.

Gunn et al. (1995) commented on the presence of linear magnetic anomalies offshore from Portland and interpreted the seismic data to show that these anomalies were due to magnetic material being deposited in channel systems. However, these authors suggested that these channels (here correlated with Pliocene canyons) and modern canyons were developed on transfer faults. This interpretation was based largely on disruption of seismic data beneath the Pliocene magnetic canyons. We can find no evidence for the presence of transfer faults beneath the canyons as there is no displacement of reflectors. It appears more likely that the disruption of seismic data beneath the canyons is related to the magnetic canyon fill, which may have a large sonic velocity contrast with adjacent sediments.

The magnetic component of the Pliocene canyons may be related to Pliocene volcanism. It appears unlikely that the magnetic material is basalt, since all of the Pliocene canyons are magnetic, and the anomalies are not particularly intense. A more plausible explanation is that magnetic material derived from the erosion of basalts has been incorporated into the basin canyon fill.

It is also possible that the magnetic signature of the Pliocene canyons is linked to the heavy mineral deposits of similar age within the Murray Basin. The dominantly Pliocene barrier sands of the Murray Basin (Loxton-Parilla Sands) contain large quantities of heavy minerals, including magnetite, ilmenite, leucoxene, zircon, rutile and tourmaline (Belpetro & Bluck 1990; Roy et al. 2000). It appears possible that some of these heavy mineral-bearing sands may have been transported offshore to be fed into the canyon systems.

Initiation of canyons

The initiation of submarine canyon systems has been a controversial subject, with many possible causes suggested, including sediment supply, sea level change, and shelf evolution. Early studies of modern North American canyons emphasised the relationship with modern river systems and sediment supply (e.g. Shepard 1934; Gorseine 1970). Similarly, relative sea level fall to the shelf break was suggested as being important for canyon formation (Emery & Uchupi 1972). Like North American researchers during this period, Sprigg (1952), Boutkoff (1963) and Hopkins (1967) suggested the modern canyons of the Portland area were related to modern river systems.

The rise of sequence stratigraphy enhanced the popularity of this river-dominated - low-stand model. For example, Rasmussen, (1994) interpreted Middle Miocene West African canyons to be cut during sea level low stand, and filled in the highstand. Using the same sequence stratigraphic model, other ancient canyons were re-interpreted as incised valleys, (Von der Burch et al. 1982; Christie-Blick et al. 1990). However, in the 1980’s, research on modern submarine canyon systems began to emphasise the development of canyons well below the shelf break (Twichell & Roberts 1982). This led to the up-slope erosion theory, with slope failure as a major cause of initiation.

Modern canyons offshore from Portland are evenly spaced along the modern slope and are present where there are no onshore river systems. This observation indicates that the modern canyon systems are not related to the position of modern river systems such as the Glenelg. Furthermore, the modern canyons systems are contiguous with Pliocene canyons, indicating that the position of the modern canyons is largely controlled by the position of Pliocene canyons.

The oldest Miocene canyons in the cool water carbonates of the Otway Basin occur near the base of the Heytesbury Group, above the Clifton Formation. This suggests that canyon growth began during the Early Miocene. In onshore sections, this interval would be within the basal Gellibrand Marl, which appears to represent a major transgression.

In the case of both the Miocene and Pliocene-Recent canyons, it is difficult to determine the cause for initiation of the canyons. However, it does appear that the earlier suggestion of Sprigg (1952) and Boutkoff (1963) that the canyons are related to the position of modern river systems is unlikely. The even spacing of the Pliocene-Recent canyons is more suggestive of a slope-controlled process.

Relationship between Miocene and Pliocene canyons

An abrupt change in canyon morphology occurs at approximately the Miocene-Pliocene boundary. Several canyon changes occur across this boundary, including:

1. a change from Miocene westward lateral accretion (and westward-dipping canyon-fill) to Pliocene-Recent symmetric or eastward canyon-fill; and
2. greater and more widespread development of canyons in the Pliocene-Recent.

These changes in canyon style must reflect several major changes on the Otway shelf margin. The change from Miocene westward lateral accretion to Pliocene aggradation probably reflects a change in paleocurrent, from a strong shelf break-parallel westward current, to a weak easterly or non-existent Pliocene to Recent current. However, the more widespread development of Pliocene-Recent canyons is unlikely to be the result of paleocurrent alone.

Based on stratigraphic evidence, Dickinson et al. (2001) have documented a major uplift event at around the Miocene-Pliocene boundary in SE Australia. Furthermore, Dickinson et al. (2001) suggested that the uplift event may have been particularly intense in the region of the Otway Ranges, with up to one kilometre of exhumation occurring in this area. It appears probable that such a significant uplift event would affect the palaeogeography and perhaps the palaeoceanography of the Otway shelf.

A Late Miocene-early Pliocene uplift event would have produced a greatly increased sediment supply offshore, with widespread stripping (regionally hundreds of metres of erosion, Dickinson et al. 2001) of Cretaceous and Tertiary sequences onshore. This may provide an explanation for the more widespread development of submarine canyons in the Pliocene. Also, the distinct episode of magnetic (and probably clastic) canyon fill during the Pliocene may be explained by Early Pliocene erosion following earlier uplift of clastic Tertiary sequences.

Another possibility for the more widespread development of Pliocene-Recent canyons is the extent of the shelf, which could have had an effect on the sediment supply to the slope. During the Miocene, the shelf was probably quite narrow to the west of Portland. This narrow shelf may not have been able to provide enough sediments to the slope in order to form canyons. Progradation and growth of the Otway shelf during the Miocene may have lead to a greater development of canyons in the Pliocene. Late Miocene uplift has probably also influenced the extent of Pliocene to Recent shelves in the Otway Basin.
Palaeoceanographic evolution

If the lateral migration and asymmetry of canyon fill is related to shelf break-parallel paleo currents, then the canyons provide a unique record of palaeoceanography for the region. The geometry of the Otway canyons suggests a long-lived and strong west-directed current existed on the slope from the Early to Late Miocene. At approximately the Miocene-Pliocene boundary, a major change occurred in the canyon systems, and a weak east-directed current was established.

The present oceanographic situation is dominated by an east-directed current at the shelf break (Godfrey et al. 1986), and the west-directed Flinders Current further offshore (Bye 1972; 1999). The modern Leeuwin current (west and south-west of the continent) and South Australian current are driven by strong thermal gradients. If thermal latitudinal gradients were reduced during the Miocene, as has been suggested by many researchers (e.g. Wright & Thunnell 1988), then the south and east-directed Leeuwin current-South Australian current system may not have been present, and oceanographic circulation may have been dominated by west and north-directed currents.

The inferred west-directed Miocene palaeocurrent is at odds with the suggestion of McGowan et al. (1997) of a warm east-directed current (an extension of the modern Leeuwin current) at this time. The interpreted warm east-directed current of McGowan et al. (1997) is based on foraminiferal data indicating warm conditions at various stages in the Miocene. From this data, McGowan et al. (1997) extrapolated the modern Leeuwin current and its extension back to the Miocene. However, the evidence for warm conditions during the Miocene in SE Australia can be explained by many factors other than the Leeuwin current.

Comparison with Gippsland submarine canyons

Like the Heytesbury Group of the Otway Basin, the Oligocene-Recent Seaspray Group carbonates of the Gippsland Basin also contain submarine canyons, and these have caused considerable problems in seismic interpretation (Holdgate et al. 2000). In the Gippsland Basin, submarine canyons have been present at least since the Oligocene. However, during the Middle Miocene, a particularly intense episode of submarine canyon development occurred and it is the Middle Miocene canyons that produce most of the sonic velocity problems associated with seismic interpretation.

Intense canyon development also occurred in slope sediments from the Middle Miocene (1997) is the Recent in the Gippsland Basin (Holdgate et al. 2000). The history of the Gippsland Basin submarine canyons shows some similarities with the Otway Basin canyons. In both basins, many submarine canyons were initiated during the Middle Miocene. However, the intensity of Middle Miocene submarine canyon development in the Gippsland Basin is much greater than that in the Otway Basin.

There are also significant differences in the morphology of submarine canyons in the Otway and Gippsland Basins. The Otway Basin canyons (of both Miocene and Pliocene-Recent age) tend to be isolated, widely spaced single canyons, whereas the Gippsland Basin canyons are generally much more closely spaced and display complex lateral and vertical migration over time. The Gippsland Basin canyons also feed into a single large deep-water canyon (the Bass Canyon) at the base of the slope, whereas the Otway canyons show no evidence of this.

The very different patterns of submarine canyon development in the Otway and Gippsland Basins may be caused by the presence of the Bass Canyon in the Gippsland Basin, and the absence of such a major deep-water canyon in the Otway Basin. The differing shelf geometry in the two basins (concave in the Gippsland Basin vs more linear in the Otway Basin) may also have an influence on canyon development.

CONCLUSIONS

1. Two major sets of canyons are present in the cool water carbonates of the Otway Basin:
   • Miocene canyons, and
   • Pliocene-Recent canyons.
2. Canyon growth began in the Early Miocene, after deposition of the Clifton Formation. Miocene canyons are located in the east of the Otway Basin and display strong westward lateral migration.
3. Canyon development, displaying symmetric or east-directed filling geometries, occurred continuously in the vicinity of Portland from the Pliocene to the Recent. Modern canyons occupy roughly the same position on the shelf as did the Pliocene canyons. This suggests that the canyons advanced seaward, as shelf progradation occurred.
4. The position of modern canyon systems is not controlled by the position of modern rivers systems (like the Glenelg River).
5. It appears likely that Late Miocene-Early Pliocene tectonics has influenced the development of the canyon systems.
6. The lateral migration and asymmetry of canyon-fill is probably related to shelf-break-parallel paleo currents. This suggests that a strong west-directed palaeocurrent existed during the Miocene, and a weak east-directed palaeocurrent existed during the Pliocene-Recent.

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