The use of Foraminiferal Colouration Index (FCI) as a thermal indicator and correlation with vitrinite reflectance in the Sherbrook Group, Otway Basin, Victoria.

S.J. Gallagher1*, I.R. Duddy2*, P.G. Quilty3, A.J. Smith1, M.W. Wallace1, G.R. Holdgate1, and P.J. Boult4&5

Abstract

While palynomorph and conodont colour indices are widely used as thermal indices in rocks of various age, enhancing more quantitatively understood analyses such as vitrinite reflectance and fission track data, it is not generally known that agglutinated foraminiferal colour changes in a consistent manner with increasing temperature. The foraminiferal assemblages in the Late Cretaceous Sherbrook Group in the Otway Basin show a systematic colouration change down hole, which is not specifically related to the colour of the host lithology. Analyses of over 7,000 agglutinated foraminiferal specimens of Haplophragmoides in core, sidewall core and ditch cuttings from Voluta-1, Port Campbell-2 and Flaxmans-1 wells show a similar foraminiferal colour variation to that observed in wells drilled in Canada studied by McNeil et al. (1996). McNeil et al. experimentally calibrated these changes to increasing temperature and established a Foraminiferal Colouration Index (FCI) for evaluation of thermal histories in Mesozoic to Cenozoic well sections. Our data from the three wells have been directly compared and correlated to existing VR data. There is a high correlation between the FCI, VR data and the variation is consistent down hole whether in core, sidewall core or ditch cuttings. Based on the predicted maturity profiles for each well from basin modelling we propose a preliminary correlation that directly relates VR to FCI values. The advantages of including FCI analysis in foraminiferal studies are: 1) The FCI data is quick and easy to collect; 2) FCI is a most effective thermal indicator in the early stages of hydrocarbon generation; 3) FCI can be used to determine the amount of caving and reworking in samples and therefore can be collected from ditch cuttings; and 4) FCI can be applied in marine sequences where vitrinite is either rare or absent. These facts make FCI analyses a potentially useful tool for thermal history analyses of fine-grained marine strata. Future studies will be directed towards verifying and refining the correlation between the FCI and VR data.

Keywords: Otway Basin, Sherbrook Group, Late Cretaceous, Foraminiferal Colouration Index, Vitrinite Reflectance.

Introduction

The Sherbrook Group in the Otway Basin is a sandstone/mudstone sequence deposited in marginal marine to deep marine environments during the Late Cretaceous (Fig. 1). With the exception of the Waarre Formation—where foraminifers are absent—all units yield common marine agglutinated foraminiferal assemblages (textulariids) (Taylor 1964, 1965). The foraminiferal yield is relatively low in the shallow marine Flaxman Formation and increase in abundance in the overlying shale foraminiferal assemblages (textulariids) (Taylor 1964, 1965). The foraminiferal assemblages for palaeoenvironmental indicators in the Sherbrook Group, Otway Basin, Victoria.

1. School of Earth Sciences, The University of Melbourne, VIC 3010, Australia.
2. Geotrack International Pty Ltd, 37 Melville Road, Brunswick West, VIC 3055, Australia.
3. School of Earth Sciences, University of Tasmania, Private Bag 79, Hobart, TAS 7001, Australia.
4. PIRSA, GP0 Box 1671, Adelaide, SA 5001, Australia
5. Australian School of Petroleum, University of Adelaide, SA 5000, Australia.

* Equal first authors.

Corresponding authors’ email addresses:
sjgall@unimelb.edu.au (Gallagher)
mail@geotrack.com.au (Duddy).

Figure 1. The Late Cretaceous stratigraphy of the Otway Basin. The stratigraphy is modified from Boyd and Gallagher (2001) and Partridge (2001). The palynological zonal scheme is that of Schoerner et al. (2002) modified from Helby et al. (1987). The chronology of the stages and zones is that of Hardenbol et al. (1998). Note: the symbol ? in the Turonian interval indicates that the lower age limit of these units is unconstrained within this stage.

PESA Eastern Australasian Basins Symposium II
Adelaide, 19–22 September, 2004
643
lithologies—generally getting darker downward. The colours observed in the Sherbrook Group foraminifera, matched directly the agglutinated foraminiferal colour changes from Mesozoic to Cenozoic siliciclastic successions in oil wells drilled in Canada studied by McNeil et al. (1996). In these successions McNeil et al. (1996) outlined a low magnification (x 250) relatively rapid technique to determine the relative thermal maturity of sequences using laboratory calibrated changes in colour of agglutinated foraminifera with changing temperature. This scale is called the Foraminiferal Colouration Index (FCI). The colour of the foraminifers is calibrated using the Munsell Soil Colour Chart (Fig. 3, for examples from the Otway Basin). The colouration is related to the thermal maturation of the organic cement (glycosaminoglycan) that coats each grain of the agglutinated foraminiferal test (McNeil et al. 1996). The temperature range over which the technique is most effective is in the early stage of hydrocarbon generation. FCI has also been used to chart buried intrusive systems in marine shales in Papua New Guinea for mineral exploration (Gunson et al. 2000). The purpose of this contribution is to: 1) document and illustrate the distribution of foraminiferal colouration in the Sherbrook Group; 2) relate this colouration to the FCI scheme of McNeil et al. (1996); 3) to correlate the FCI data to vitrinite reflectance (VR) data in each well; and 4) to calibrate the VR and FCI data to arrive at a palaeotemperature proxy for VR in sections that either lack measure VR data or lack common vitrinite (deeper marine Sherbrook Group sequences).

Methods

The data for this study comes from three wells in the Otway Basin: Voluta-1, Port Campbell-2 and Flaxmans-1 (Fig. 2). Wiltshire Geological Services supplied the wireline log data. The primary palynological biostratigraphic data for each well was obtained from the STRATDAT Database of Geoscience Australia and from Partridge (2000). The biostratigraphic data for Voluta-1 is modified herein with the recognition of a thick Coniacian section based on the occurrence (in cores 13 and 16) of the zonally important inoceramid bivalve Cremnoceramus bicorrugatus (Crampton 1996; Crampton et al. 2001). The typical colouration of the foraminifera in the Sherbrook Group is shown on Figure 3. Over 5,000 Haplophragmoides specimens were

Figure 2. The location of the wells used in this study.

Figure 3. The Foraminiferal Colouration Index tied to the Munsell Colour Chart. Note: the samples are from the Sherbrook Group, the codes for each sample are listed in Table 1. The photographs were taken in reflected light using a tungsten cold light source lamp and Tungsten Film.
Figure 4. The stratigraphy and FCI values for Voluta-1 (note: red values=core, white=ditch cuttings).
Figure 5. The stratigraphy and FCI values for Flaxmans-1 (note: red values=core, white=ditch cuttings).
Figure 6. The stratigraphy and FCI values for Port Campbell-2 (note: red values=core, white=ditch cuttings).
logged for their FCI in 117 ditch cutting (DC) and 29 core/sidewall core samples in Voluta-1. In addition, 1,640 Haplophragmoides specimens were logged in 38 ditch cutting and four core samples in Flaxman-1 and 533 Haplophragmoides specimens were analysed in 31 ditch cutting and nine core samples in Port Campbell-2. The average FCI score and a standard deviation was calculated for each sample. The stratigraphic distribution of the data collected is shown in Figures 4, 5 and 6. The VR data for Voluta-1, Flaxmans-1 and Port Campbell-2 are tabulated on Figures 8, 9 and 10. Based on these data a calculated VR equivalent for FCI values in each well is also shown.

FCI variation in the Otway Basin wells

All three wells studied show a consistent down hole increase in FCI values from around one below log level 1,000 m to between 3.5 to 4.5 at their bases. In detail, there are variations. For example, the FCI values in Voluta-1 range from around two in the Timboon Sandstone and Paaratte Formation, increasing to around three in the basal Paaratte Formation, Skull Creek and Nullawarre Greensand. A clear linear trend of increasing FCI occurs in these units whether the data is derived from core or ditch cuttings. FCI values average around 3.5 in the upper Belfast Mudstone, increasing to around four near the top of the Coniacian (the arrowed section (a) on Fig. 4). At this level an interval of higher velocities occurs associated with a decrease in FCI values to an average of around 3.5 (between (a) and (b) on Fig. 4). Below this high velocity interval, values gradually increase down well to FCI values of around four. However the core and sidewall core values diverge slightly with higher values up to 4.5 recorded in the core compared to four in the ditch cuttings. The high velocity interval in the Belfast Mudstone is interpreted to be a unit with low porosity and stronger cementation compared to the upper Belfast mudstone unit. It is possible that a diagenetic factor has suppressed the FCI values in this interval such as fluid overpressure. Similar FCI and porosity variations in thick prodelta shales due to compaction and overpressure were noted by McNeil et al. (1996) and Issler et al. (2002) in the Beaufort-Mackenzie Basin of Northern Canada. The slight discordance in the FCI data for the ditch cutting and core data in the lowermost section of the well probably reflects some caving at this level.

In Flaxmans-1 (Fig. 5) FCI values increase consistently to the base of the Nullawarre Greensand (FCI=3.5) and then decrease slightly (less than 3) towards the top of the Belfast Mudstone, below this level values lie in the 3.5 to 4 FCI range. In Port Campbell-2 (Fig. 6), FCI values also increase in a regular manner from the Timboon Sandstone (FCI=1.5) to the Nullawarre Greensand (FCI=3). FCI values decrease to 2.5 in the upper Belfast Mudstone and remain relatively stable before increasing in a linear manner from the basal Belfast Mudstone to the Flaxman Formation.

Calibration of FCI to vitrinite reflectance

Vitrinite reflectance (VR) is a widely used thermal indicator which has a well-established kinetic understanding (Burnham & Sweeney 1989), and the Flaxmans-1, Port Campbell-2 and Voluta-1 wells provide near ideal geological situations in which to calibrate FCI to vitrinite reflectance. Open-file VR data is available for all three wells (Constantine et al. 2001) and the sampled sections in these wells also allow us to readily calibrate FCI to VR. This arises because the entire drilled Tertiary and Cretaceous sequences in these Port Campbell Embayment wells are at, or very near, maximum post-depositional temperatures at the present-day (Duddy 1997; Duddy & Erout 2001; Duddy et al. 2003), making for the simplest geological calibration of any
Figure 8. The measured VR% and equivalent VR (%) estimated from FCI values for Voluta-1.
Figure 9. The measured VR% and equivalent VR (%) estimated from FCI values for Flaxmans-1.
Figure 10. The measured VR% and the equivalent VR (%) estimated from FCI values for Port Campbell-2.
thermal indicators, including AFTA (e.g. Green et al. 1989).

Figure 7 shows the burial and thermal histories for Flaxmans-1 derived from the preserved stratigraphy and the regional thermal history deduced for the Otway Basin from Duddy (1997), the key aspects of which are a palaeogeothermal gradient of 55°C/km at 95 Ma declining to a value of 34.1°C/km, equivalent to the present-day value, at 80 Ma. The paleo-surface temperature is assumed to be 15°C throughout the history. Similar histories are applicable to the Port Campbell-2 and Voluta-1 wells, but with present-day gradients of 33.7 and 31.5°C/km, respectively. In fact, the highly elevated mid-Cretaceous palaeogeothermal gradient will have no discernable effect on thermal indicators as it is quite clear from inspection of the thermal history illustrated in Figure 7 that the drilled section is at maximum post-depositional temperatures at the present-day. Thermal histories for Port Campbell-2 and Voluta-1 are similar. The VR profile predicted for this history using the kinetic description of Burnham & Sweeney (1989) is shown in Figure 8 together with open file VR data from several sources. While there is some scatter in the measured data, there is a generally a very good match between the majority of the data and the predicted profile, providing strong support for the geological interpretation that the sampled section is at, or close to, maximum post-depositional temperatures at the present-day. In such situations, the predicted VR profile provides a reliable trend with which to calibrate the FCI data, as illustrated in the right hand plot of Figure 8, which shows equivalent VR levels determined from each FCI value for VR values between approximately 0.3 and 1.0. A single correlation between VR and FCI was established using FCI data from Voluta-1, Flaxmans-1 and Port Campbell-2, and as shown in Figure 8, the FCI-derived VRE values show a similar degree of scatter of about the VR calibration profile as that shown by the measured VR data itself. Equivalent plots are presented for the Flaxmans-1 and Port Campbell-2 wells in Figures 9 and 10, respectively, which also show that the measured VR and the FCI-derived VRE values show similar degrees of scatter throughout the sampled section, for VR values between approximately 0.4 and 0.7%.

Discussion and conclusions

The colouration of organic walled agglutinated foraminifera of the Sherbrook Group show a clear relationship increasing palaeotemperatures down well from VR data. The correlation derived from this approach is illustrated as a plot of FCI versus VR presented in Figure 11 with a schematic tabulation provided in Figure 12. We emphasise that this correlation is an initial attempt
derived from wells from a small area of the Otway Basin where the heating rate is similar (approximately 1°C/Myr), and that extension to sequences that have undergone different heating rates is yet to be tested. This will form the basis of further research. Nevertheless, we are hopeful that further research will be able to establish FCI as a new, quantitative thermal indicator that can be used confidently in conjunction with organic (e.g. VR, biomarkers, spore colour) and inorganic (e.g. AFTA) thermal indicators in providing

Table 1. The number codes, sample locations and depths for the FCI specimens illustrated on Figure 3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Well</th>
<th>Depth (feet)</th>
<th>Depth (metres)</th>
<th>CORE/DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Voluta-1</td>
<td>10700</td>
<td>3264</td>
<td>DC</td>
</tr>
<tr>
<td>1</td>
<td>Voluta-1</td>
<td>10700</td>
<td>3264</td>
<td>DC</td>
</tr>
<tr>
<td>2</td>
<td>Voluta-1</td>
<td>11988</td>
<td>3654</td>
<td>CORE</td>
</tr>
<tr>
<td>3</td>
<td>Voluta-1</td>
<td>12230</td>
<td>3731</td>
<td>DC</td>
</tr>
<tr>
<td>4</td>
<td>Voluta-1</td>
<td>12230</td>
<td>3731</td>
<td>DC</td>
</tr>
<tr>
<td>5</td>
<td>Voluta-1</td>
<td>7990</td>
<td>2438</td>
<td>DC</td>
</tr>
<tr>
<td>6</td>
<td>Voluta-1</td>
<td>11700</td>
<td>3569</td>
<td>DC</td>
</tr>
<tr>
<td>7</td>
<td>Voluta-1</td>
<td>11710</td>
<td>3569</td>
<td>DC</td>
</tr>
<tr>
<td>8</td>
<td>Voluta-1</td>
<td>Core #5 piece 20</td>
<td>3264</td>
<td>DC</td>
</tr>
<tr>
<td>9</td>
<td>Voluta-1</td>
<td>5484.6</td>
<td>1672</td>
<td>CORE</td>
</tr>
<tr>
<td>10</td>
<td>Voluta-1</td>
<td>6270</td>
<td>1914</td>
<td>DC</td>
</tr>
<tr>
<td>11</td>
<td>Voluta-1</td>
<td>6387</td>
<td>1948</td>
<td>CORE</td>
</tr>
<tr>
<td>12</td>
<td>Voluta-1</td>
<td>5600</td>
<td>1710</td>
<td>DC</td>
</tr>
<tr>
<td>13</td>
<td>Flaxmans-1</td>
<td>10700</td>
<td>3264</td>
<td>DC</td>
</tr>
<tr>
<td>14</td>
<td>Flaxmans-1</td>
<td>5484.6</td>
<td>1672</td>
<td>CORE</td>
</tr>
<tr>
<td>15</td>
<td>Flaxmans-1</td>
<td>6270</td>
<td>1914</td>
<td>DC</td>
</tr>
<tr>
<td>16</td>
<td>Flaxmans-1</td>
<td>6387</td>
<td>1948</td>
<td>CORE</td>
</tr>
<tr>
<td>17</td>
<td>Flaxmans-1</td>
<td>5600</td>
<td>1710</td>
<td>DC</td>
</tr>
</tbody>
</table>

Discussion and conclusions

The colouration of organic walled agglutinated foraminifera of the Sherbrook Group show a clear relationship increasing palaeotemperatures down well from VR data. The correlation derived from this approach is illustrated as a plot of FCI versus VR presented in Figure 11 with a schematic tabulation provided in Figure 12. We emphasise that this correlation is an initial attempt
derived from wells from a small area of the Otway Basin where the heating rate is similar (approximately 1°C/Myr), and that extension to sequences that have undergone different heating rates is yet to be tested. This will form the basis of further research. Nevertheless, we are hopeful that further research will be able to establish FCI as a new, quantitative thermal indicator that can be used confidently in conjunction with organic (e.g. VR, biomarkers, spore colour) and inorganic (e.g. AFTA) thermal indicators in providing
rigorously constrained thermal histories for hydrocarbon exploration.

The technique has the following advantages:

(a) FCI is rapid and relatively simple technique for determining thermal maturity, especially in shale dominated sequences.
(b) FCI is effective for maturity levels equivalent to the early stages of hydrocarbon generation (0.5–0.9 VR%).
(c) FCI data can easily be vetted for down hole caving or reworking, making ditch cutting data acquisition feasible.
(d) Changes in FCI profiles can possibly chart overpressure zones in shale-dominated successions.
(e) FCI data can be collected from marine sequences where vitrinite is either rare or absent.

Acknowledgements

This project was supported by an ARC SPIRT Grant (No. C00106901: The stratigraphy of late Cretaceous to early Tertiary petroleum prospective strata of southeast Australia and southern ocean evolution) with industry partners ESSO, Santos, Geoscience Victoria and PIRSA. Geoscience Australia is thanked for access to their STRATDAT Database. Wiltshire Geosciences kindly donated the wireline digital log data. We would like to thank David McNeil (Geological Survey of Canada) for reprints and discussion on the FCI technique.

References


