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1 **Pressure and Basin modelling in foothills belts: A Ceres study of** 2 **the Kutubu area, Papua New Guinea fold and thrust belt.**

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10 **Abstract**

11 The Papua New Guinea fold and thrust belt petroleum system is studied along a 200km long
12 transect. The kinematic scenario includes the Jurassic rifting and passive margin, the erosion
13 during the Upper Cretaceous related to the Coral Sea rifting and Plio-Pleistocene shortening,
14 with an early growth of the Hedinia anticline limiting lateral migration of oil, in the adjacent
15 Darai Plateau. Data from seven wells and two fields were used to calibrate section boundary
16 conditions and properties. Apart from the high pressure trend in the Kutubu/Moran structures,
17 all data are well reproduced, and the modelled section appears quantitatively predictive. The
18 modelling demonstrates three major pathways for water: (1) topographically driven flow,
19 from the onset of mountain building, (2) deep updip basinal flux, flowing along the tilted
20 reservoirs, and (3) across fault escape from connected reservoir bodies. Type II or mixed type
21 II/III are used to model the Triassic and Jurassic source rock. Maturation starts in the mid
22 Cretaceous and increases strongly during the late tectonic burial, with three main
23 accumulations: (1) the deep part of the Mubi zone, with vertical migration along faults; (2) the
24 Hedinia and Kutubu anticlines charged during Orubadi and Era deposition; and (3) the Darai
25 plateau.

26
27 **Keywords:** Papua New Guinea, Fold and Thrust Belt, Basin Modelling, Pressure, Petroleum
28 system

30 **1. Introduction**

31 Globally, most of the easy-to-find oil and gas prospects have been drilled and the industry is
32 exploring in increasingly difficult terrains such as in tectonically complex mountain belts or
33 in deep water. Discoveries are often at great depth and structural complexity and require

34 sophisticated geological and geophysical modelling. The recent improvements in seismic
35 imaging (e.g. Naville et al., 2010) have led to the discovery of giant petroleum fields in deep
36 underthrust prospects of the Sub-Andean basins in Venezuela (El Furrial discovery) and
37 Colombia (Cusiana discovery, Carnevalli, 1988; Cooper, 1995; 2007), and similar efforts are
38 being made in the Papua New Guinea fold and thrust belt (hereafter termed the Papuan Fold
39 Belt; Hill et al., 2008). However, these structurally complex areas retain a high risk and it is
40 imperative to understand the whole petroleum system to mitigate that risk. In particular,
41 charge risk can be assessed from estimates of paleothermal gradients, paleofluid flow and
42 pore pressure, and the relative timing between the structural evolution and the petroleum
43 system maturity.

44 Estimates of paleo-burial and -temperatures in foothills belts are difficult due to the dominant
45 processes of uplift and erosion. In foreland settings or extensional basins where there is
46 limited erosion, the use of well data such as BHT, and paleo-thermometers such as vitrinite
47 reflectance (Ro) and Rock-Eval (Tmax) data are usually sufficient to invert the heat flow and
48 geothermal gradients along a section. However, in the foothills domains erosion affects paleo-
49 burial estimates and the corresponding calibration of the past thermal evolution of the section
50 is biased (e.g. Deville and Sassi, 2006). In particular, it is generally not possible to obtain a
51 single solution for paleo-burial and paleo-thermal gradients if based solely on maturity ranks
52 of the organic matter (e.g. Osadetz et al., 2004; Hardebol et al., 2009; Roure et al., 2009;
53 2010). An integrated thermo-kinematic approach is required, which allows for predictive
54 modelling of the temperature as a combined effect of sedimentary and tectonic loading, heat
55 advection and erosional process (e.g. Forster and Smith, 1989; Bodri and Rybach, 1998;
56 Husson and Moretti, 2002; Deville and Sassi, 2006; Hardebol et al., 2009).

57 Pore fluid pressure and overpressure building are an additional challenge in fold and thrust
58 belt exploration. Dewatering of sediments during the compaction phase and associated
59 overpressures has been widely documented in modern accretionary wedges (e.g. the Nankai
60 prism, Tobin and Saffer, 2009). The increasing load of syn-flexural sediments deposited in
61 foredeep basins results in a vertical escape of formation water during mechanical compaction
62 with mainly dominantly hydrostatic pore fluid pressures. However, this process develops a
63 regional pressure seal localized where the vertical permeability reaches a minimum, killing
64 the vertical connectivity and any further escape of compaction-related fluids towards the
65 surface. This process accounts also for the building of an over-pressured horizon in the
66 foreland, which strongly decreases the friction locally, and helps to localize and propagate

67 forelandward the decollement and the deformation front (e.g. Henry and Wang, 1991; Saffer
68 and Bkins, 1998; Skarbek and Saffer, 2009).

69 From a simple geometric and structural point of view, fold and thrust belts have many points
70 in common with underwater accretionary wedges, but they differ strongly when considering
71 the fluid pathways, the boundary conditions (pressure and temperature) and the nature of the
72 pre-orogenic and syn-orogenic sequences. In contrast to accretionary wedges, which integrate
73 mostly young and poorly compacted syn-flexural sequences, fold and thrust belts involve
74 dominantly pre-orogenic passive margin sequences, already buried, compacted and
75 dewatered. The origin of the fluids involved during the deformation processes also differs in
76 that fold and thrust belts mix sedimentary fluids with meteoric water and older deeper basinal
77 fluids whereas accretionary wedges are usually entirely marine fluids in offshore accretionary
78 prisms. Thus, aerial fold and thrust belts are generally under-saturated in fluids in contrast to
79 completely saturated submarine belts. Thus the driving pressure gradients will not be
80 similarly distributed, and the topographically driven flows may play a first order role. It is
81 particularly true considering the "squeegee" fluid flow associated with the inception of belt
82 building, and with major changes in foreland reservoir properties and oil migration (Oliver,
83 1986; Machel and Cavell, 1999; Roure et al., 2005; 2010)

84 Fold and thrust belts are thus characterized (1) by fluid flow controlled by lateral permeability
85 barriers, and (2) by topography-driven, gravitational flow of surface water, following the
86 topographical gradients towards the valleys and the foreland basin (Schneider et al., 2002;
87 Callot et al., 2010; Gonzalez-Mercado et al., 2013). This gravitational flow remains, however,
88 mostly confined above the compaction-induced permeability barrier (see above). Due to the
89 difficulties in acquisition, processing and interpretation of onshore seismic data, the
90 architecture of the subsurface reservoir is usually poorly imaged and its internal
91 compartmentalization is poorly defined. The analysis of fluid dynamics in such a setting
92 requires integrated basin modelling techniques, as documented below, to predict the
93 distribution of pore fluid pressures and hydrocarbon (HC) potential before drilling. Another
94 key factor in sub-thrust plays is reservoir damage due to diagenesis, the understanding of
95 which requires integrating the geometrical evolution of the play, the diagenetic history and the
96 strain history in the framework of the larger scale geometrical evolution, comprising input
97 data from the burial, thermal and pore fluid pressure evolution (e.g. Vilasi et al., 2009; Roure
98 et al., 2009; Gonzalez-Mercado et al., 2013).

99 Thus, qualitative and quantitative appraisal of the petroleum system evolution and HC
100 potential of given plays in foothills belts requires the integration of various data differing both

101 in time and space. Basin modelling tools are now better able to reconstruct palinspastic
102 structural cross sections (e.g. Schneider et al., 2003; Roure et al, 2005; 2010; Vilasi et al.,
103 2009; Callot et al., 2010) and compute the history of temperature, pore fluid pressure and
104 fluid flow circulations in complex structural settings. They constitute an efficient tool to
105 integrate, within the framework of the basin geometrical evolution, the various key
106 phenomena controlling the evolution of reservoir properties (e.g. Roure et al., 2005; Vilasi et
107 al., 2009).

108 Hill et al. (2010) presented a 110 km regional balanced and restored cross-section over the
109 Papuan Fold Belt from the foreland to the hinterland deformed internal belts and passing near
110 the giant Kutubu oil and gas field. Utilising that section, the aim of this paper is to present an
111 integrated study of fluid flow and fluid pathway analysis in the Papuan Fold Belt. The
112 structure of the Papuan Fold Belt is well documented and it formed during the Late Miocene
113 and Pliocene so the timing is well constrained. This allows us to test the ability of the basin
114 modelling tools to predict, in the framework of the fold belt evolution, both the porosity, the
115 pore fluid pressure, and the temperature field evolution through time. The steps involved
116 include kinematic restoration and testing of the section, prediction of temperatures, porosities
117 and pressures through time, constrained by borehole and surface data. This allows
118 hydrocarbon generation and fluid flow to be modelled and tested against known oil and gas
119 fields and well data. This constitutes the first step toward a more predictive description of the
120 potential fluid rock interaction at the fold-belt scale through time, and toward a quantitative
121 assessment of the petroleum potential (e.g. Hill et al., 2010).

122

123 **2. Geological setting**

124 **2.1 Tectonostratigraphic setting**

125 New Guinea forms the northern margin of the Australian plate, within the convergent plate
126 boundaries between the Indo-Australian Plate, the Pacific Plate, and several smaller plates
127 (Figure 1). Following the Triassic New England orogeny, New Guinea underwent extension
128 in the Jurassic, subsidence during the Cretaceous, uplift in the Paleogene and subsidence
129 followed by a compressional orogeny in the Neogene to Recent. The tectonic evolution of
130 New Guinea was reviewed by Hill and Hall (2003), and the reader is referred to that paper
131 and references therein for further details. Here, we only review the events and kinematic
132 evolution relevant to the pressure and basin modelling.

133 The island of New Guinea has been divided into four tectonic regions based on the Miocene
134 to Holocene orogenesis affecting the northern part of the Australian Plate (Dow, 1977; Hill et
135 al., 1996; Hill et al. 2003). In the south is the Stable Platform, which is the northern
136 continuation of Australian continental crust that preserves Mesozoic and possibly Palaeozoic
137 extensional structures (Cole et al., 2000; Kendrick 2000). To the north, the adjacent Fold Belt
138 comprises the same crust deformed into fold and thrust structures following Late Oligocene–
139 Miocene arc–continent collision. Most of the northern half of New Guinea is made up of the
140 Mobile Belt, including ophiolites of Mesozoic to Palaeocene age (Davies and Jaques, 1984;
141 Rogerson et al., 1987). The Mobile Belt also includes distal Mesozoic–Tertiary sediments,
142 abundant Miocene and some Cretaceous volcanic and intrusive igneous rocks, and medium-
143 to high-grade metamorphic rocks with common Early Miocene and some Mesozoic cooling
144 ages. The northern margin of New Guinea comprises accreted volcanic arcs.

145

146 The Tasman Line in Australia (Scheibner 1974) separates Proterozoic basement to the west
147 from accreted Palaeozoic terranes to the east and can be correlated into New Guinea from
148 surface geology and tomographic modelling. In New Guinea, the Tasman Line is roughly
149 north-south along the PNG-Indonesia border, such that basement in PNG largely comprises
150 accreted terranes (Figures 1 and 2). Those dated are of Permian to Early Triassic age and
151 intruded by Middle Triassic granites (Van Wyck and Williams 2002; Crowhurst et al. 2004).
152 The active post-Triassic tectonic history of PNG and the tomographic studies both suggest a
153 young hot and weak lithosphere and geological analyses suggest a strong northeasterly
154 structural grain (Davies 1991; Corbett 1994; Hill et al. 1996).

155

156 In the Late Triassic to Jurassic (figure 2A), post-orogenic collapse and rifting occurred in
157 what is now the fold belt and probably led to the breakaway of microcontinental slivers from
158 the northern New Guinea margin. From the late Jurassic through the Cretaceous, the margin
159 underwent passive subsidence with clastic sediment supply from the Australian continent to
160 the south (figure 2B). This steady state was interrupted by uplift of southern and eastern PNG
161 in the Palaeogene, thought to be a thermal response to opening of the Coral Sea to the east
162 (figure 2C). As Australia commenced rapid movement to the north in the Eocene, ophiolites
163 were emplaced along the northern New Guinea margin and carbonates were deposited in the
164 adjacent basins.

165

166 The initial collision with an island arc was probably in the late Oligocene (figure 2D), but the
167 Early Miocene was a time of strike slip and extensional tectonics in northern New Guinea,
168 including the unroofing of metamorphic core complexes (Figure 2E). These events coincided
169 with the rapid subsidence of the entire New Guinea margin and the widespread deposition of
170 thick carbonate sequences in the south and volcanics in the north. The onset of regional
171 compression and uplift occurred in the Middle Miocene (figure 2F) and migrated south into
172 what is now the fold belt in the Late Miocene to Pliocene (Hill, 1991; Hill and Raza 1999;
173 figures 2G-H). In the western part of the Papuan Fold Belt a foreland basin formed and filled
174 and is preserved to the south of the current mountains. In the eastern fold belt, the area of
175 study, a Pliocene-Pleistocene foreland basin is inferred from vitrinite reflectance and fission
176 track data, but the sediments were mostly eroded off during formation of the fold belt.

177

178 **2.2 Papuan Fold Belt stratigraphy**

179 The basement underlying the Fly Platform and the fold belt comprises Upper Palaeozoic
180 rocks, mainly Permian phyllites, which were deformed during the Triassic New England
181 Orogeny and intruded by granites (Van Wyck and Williams 2002; Crowhurst et al. 2004).
182 Subsequent erosion exposed the granites at that time. Late Triassic to Middle Jurassic rifting
183 created graben in which the Kana Volcanics, Magobu Coal Measures and Barikewa Mudstone
184 were deposited, the latter two being probable source rocks (Figures 3 and 4). Regional Late
185 Jurassic subsidence flooded the margin allowing deposition of the Imburu Formation, Toro,
186 Digimu, Iagifu and Hedinia sandstone reservoirs and the Cretaceous Ieru Formation seal. In
187 distal facies of the northeastern Fold Belt, both the Imburu and Ieru mudstones are
188 hydrocarbon source rocks. Latest Cretaceous to Palaeocene uplift of southern PNG caused
189 erosion of some Upper Cretaceous sediments in the fold belt and Fly Platform area and
190 deposition did not resume until Late Oligocene flooding allowed widespread deposition of
191 Miocene shallow marine carbonates, the Darai Limestone. Carbonate deposition was halted
192 by the Late Miocene onset of compressional deformation, which was also responsible for
193 generation and migration of most hydrocarbons.

194

195 **2.3 Papuan Fold Belt structure**

196 The southern portion of PNG comprises the Fly Platform, which is relatively undeformed by
197 Cenozoic compression. APC (1961) divided the Papuan Fold belt into three northwest-
198 southeast trending belts, the Gently Folded Belt in the south, the Strongly Folded Belt in the
199 centre and the Imbricate Belt to the north (Figures 3 and 4). Hill et al (2010) discussed the

200 structural styles of these belts and presented a regional balanced and restored cross-section
201 across all of them, which was the input for the current modelling (Figure 4). The section was
202 constructed in 2D Move (®) and was incrementally restored to help validate the interpretation
203 and show the likely forward kinematic evolution. It was (1) drawn to honour all stratigraphy
204 and dips from outcrop and 10 boreholes in addition to synthetic aperture radar images and
205 limited potential field data; and (2) constructed along or close to seismic lines, particularly the
206 semi-regional line PN05-404 (shown in Hill *et al.* 2008) across the Fold Belt.

207

208 *Fly Platform and Gently Folded Belt*

209 On Figure 4, it can be seen that the thickness of sediments beneath the Darai Plateau is more
210 than double that of the adjacent Fly Platform (4,800m vs 2,200m) indicating a major basin-
211 bounding extensional fault that subsequently underwent mild inversion. Sediment growth
212 across the fault appears to have been continuous through geological time, indicating a
213 relatively stable platform to the south. Compressional offset of the Darai Limestone and
214 continuing earthquake activity suggest that inversion was Pleistocene to Recent, but a
215 component of Late Miocene inversion cannot be ruled out.

216

217 The significance of the unconformity between the Cenomanian upper Ieru Formation and the
218 Late Oligocene basal Darai Limestone has been assessed by apatite fission track analyses (*eg.*
219 Hill & Gleadow 1989; 1990) combined with vitrinite reflectance profiles in the Kanau-1 well.
220 These analyses indicate that, prior to Darai Limestone deposition, there was at least 2 km of
221 erosion of the upper Ieru Formation beneath the Darai Plateau, but less than 1 km of erosion
222 beneath the foreland. Thus it is likely that the old normal fault beneath the Darai Plateau was
223 inverted in the Early Tertiary, and that the hanging-wall was eroded prior to regional Oligo-
224 Miocene subsidence.

225

226 *Strongly Folded Belt*

227 Seismic data and regional gravity data suggest that basement dips at ~6 degree to the NE
228 beneath much of the strongly fold belt with relatively little offset. Although inversion of
229 extensional faults is suspected, for instance the Zongwe structure (Hill *et al.* 2010), it is minor.
230 Thus the large folded structures within this belt, such as Zongwe, Ai-Io and SE Hedinia, are
231 interpreted to be detached within the sedimentary section (Fig. 3). The SE Hedinia anticline
232 has been drilled by three wells, which indicate a tight anticline with an overturned or sheared
233 out forelimb, all detached near the top of the Koi-Iange section. Between SE Hedinia and East

234 Kutubu (Figure 4) basement faulting is interpreted to have deformed the top Koi-Iange
235 Formation detachment so that at least some basement faulting occurred after the overlying
236 thin-skinned deformation (Hill et al 2010).

237

238 *Imbricate Belt*

239 Over a distance of 10 km to the NE of the Kutubu East Anticline, interpretation of the seismic
240 data (Hill *et al.* 2008, 2010) indicates a planar gently NE-dipping panel of strata from
241 basement to top Darai Limestone (Figure 4). Geological maps show that this panel is overlain
242 by thrust repeats of Darai Limestone and thin upper Ieru Formation, the start of a major Darai
243 duplex that crops out over a band that is 24 km wide from Lake Kutubu to the Wage
244 Anticline. Beneath the mapped Mubi Anticline the step-up in basement, inferred from seismic
245 data, clearly folds the overlying Darai Limestone duplex, so the basement thrusting occurred
246 after the thin-skinned deformation. The Darai Limestone duplex exposed at surface represents
247 considerable shortening in the Darai Limestone and upper Ieru Formation. Below, or to the
248 NE this must be balanced by equivalent shortening in the lower Ieru Formation to Koi-Iange
249 Formation. On the cross-section, this has been represented as a simple duplex forming the
250 Mount Castle and Wage Anticlines. However, numerous other interpretations are possible,
251 including basement involvement.

252

253 **2.4 Papuan Fold Belt hydrocarbons**

254 Exploration for hydrocarbons in the Papuan Fold Belt commenced in the 1950's on the
255 accessible mountains, resulting in significant gas discoveries such as Barikewa in 1958 and
256 Juha in 1983. Commercial oil was discovered in 1987 in the Iagifu-Hedinia anticlines (termed
257 the Kutubu oilfield, eg. Bradey et al. 2008) followed by nearby discoveries at Agogo, SE
258 Mananda, Moran and Gobe, which have, collectively, been on production since 1992.
259 Recoverable reserves in the known fields are well over 500 million barrels of low viscosity
260 oil. Along strike, the giant Hides gas field (Johnstone & Emmet, 2000), with over 5 trillion
261 cubic feet (tcf) reserves, was discovered in 1986 and has recently been developed for LNG
262 production. Please note that there is some confusion over the term 'Kutubu'. Lake Kutubu lies
263 just northeast of the Iagifu-Hedinia Anticlines, the main oil producing area in PNG, which is
264 now called the Kutubu Oilfield (Figure 4). Immediately south of the Lake is the separate
265 anticline that makes up Kutubu Mountain, here termed the East Kutubu Anticline. This
266 structure has been drilled by Kutubu-1 and Kutubu-2 wells without success. These wells are
267 analysed as part of this study.

268

269 Three oil and gas fields lie near the regional cross-section that is analysed here and nine wells
270 are along or very close to the section. The thermal properties from key wells, such as present
271 temperature and VR data, pore fluid pressure and water table location, have been used to
272 calibrate the modelling and the nearby oil and gas fields have been used to validate models of
273 hydrocarbon generation and migration. In the foreland, the Bujon-1 well drilled a subtle and
274 local basement high and did not encounter significant hydrocarbons. On the giant Darai
275 Plateau (Figs 1 and 3) neither the Kanau-1 nor the Bosavi-1 wells recovered hydrocarbons
276 thought to be due to lack of charge. It is notable that the Toro sandstone reservoir in both
277 wells is near sea level (Fig 4) and that to the SW it almost abuts the basal Darai Limestone
278 across the Darai Fault. It is considered likely that along strike the Toro connects to the basal
279 Darai Limestone and hence is in pressure communication with the foreland, consistent with
280 the low pressures recorded in the Kanau-1 well.

281

282 The SE Hedinia-1, -2 and -3 wells drilled the SE Hedinia gas field, whilst along strike the
283 Kutubu oil and gas field (drilled by the Iagifu and Hedinia wells) has produced over 350
284 million barrels of oil and contains ~1 tcf of gas. Thus on a regional basis, any modelling needs
285 to account for significant oil and gas charge. The East Kutubu anticline (Figs 1 and 3) was
286 drilled by the Kutubu-1 and -2 wells, which encountered minor gas and high pressures at
287 reservoir level, but fractures and oil staining above the reservoir indicate breaching. The
288 Strongly Folded Belt to the southwest preserves normal to low pressures, suggesting a sealing
289 fault underlying the East Kutubu anticline separating the high-pressure belt to the northeast
290 from the adjacent SE Hedinia gasfield and Kutubu oilfield to the southwest. The Nembi well
291 at the NE end of the section (Fig 4) drilled through distal Tertiary limestones and shales and
292 was not analysed here.

293

294 **2.5 Hydrodynamics in the Papuan Fold Belt**

295 Little has been published about fluid flow in the Papuan Fold Belt. Eisenberg (1993)
296 discussed a hydrodynamic gradient across the Iagifu/Hedinia area (Kutubu oilfield) and noted
297 that, although the reservoir sandstones are all marine, the recovered formation water is quite
298 fresh, typically in the range of 6000-15000 ppm NaCl equivalent. On a regional basis, from
299 maps of hydraulic potential, he inferred that water flows from both SE and NW along the
300 Papuan Fold Belt to the Usano-SE Hedinia area (Fig. 1) where it exits the fold belt to the SW

301 towards the low pressure foreland. This inferred exit point is very close to the line of cross
302 section studied here.

303

304

305 **3. Data set and modelling principles**

306 **3.1 Basin modelling in structurally complex areas**

307 Basin modelling aims at reconstructing the time evolution of a sedimentary basin in order to
308 make quantitative predictions of geological phenomena leading to pressure generation and
309 ultimately, to hydrocarbon accumulations. It accounts for porous medium deformation, heat
310 transfer, hydrocarbon formation and multiphase fluid migration (e.g. Schneider et al., 2000).

311 Since the pioneer works on the modelling of hydrocarbon formation (Tissot, 1969), several
312 generations of basin models have been built. Initially, 1D models such as Genex were used to
313 simulate the temperature evolution and the maturation of the organic matter. In a sedimentary
314 basin context, the 1D approach is satisfactory for these purposes because the thermal transfers
315 are mostly vertical. Indeed, thermal convective transfers are most frequently negligible.
316 Subsequently, 2D models such as Temispack (Chenet et al., 1986; Bessis et al., 1987;
317 Doligez, 1987; Bessis et al., 1990; Ungerer, 1990; Ungerer et al., 1990) were built. These 2D
318 models made it possible to evaluate the pressure history and to predict hydrocarbon migration
319 and reservoir charge. However, these evaluations are only qualitative because fluid (water,
320 oil, and gas) migration is mainly convective and therefore sensitive to 3D geometry and
321 anisotropy. For these reasons, a generation of 3D basin models, such as Temis 3D or
322 PetroMod was designed (e.g. Schneider et al., 2000).

323 The previous sedimentary basin models however are only able to handle relatively simple
324 geometries resulting from deposition, erosion and vertical compaction. As exploration is now
325 focusing on complex areas, such as fold belts, a new generation of models able to handle
326 faults is needed (figure 5). The CERES 2D software used in the current study is composed of
327 several modules managed by a study browser. The main modules are a section editor, a
328 restoration module and a forward simulation simulator. The other modules are a
329 chronostratigraphy editor, a lithology editor, a kerogen editor, fluid editors, a mesh editor, a
330 run editor, and visualization modules. The main steps to carry out a case study (figure 5A)
331 are: (1) production of the initial section (figure 5B), (2) restoration of the section (figure 5C)
332 and (3) forward simulation of the section.

333

334 **3.2 Ceres 2D**

335 **3.2.1 Initial section**

336 The initial section is composed of a 2D cross section, which can be edited directly from
337 scratch or can be imported from other software. It is recommended, at this stage to use
338 structural tools to balance the section. The present day geometry of the section is defined first.
339 The geological attributes are then assigned, including labelling of horizons and faults,
340 definition of decollement levels, and finally the distribution of lithology, which may evolve
341 spatially but not in time.

342 At this stage the blocks, which represent the smallest kinematic units, are defined and meshed
343 with their own grids, with no constraint coming from the other blocks. The fault grids are
344 created dynamically during the forward simulation. The initial section includes the upper
345 mantle, the ductile lower crust, the brittle upper crust and the sedimentary basin.

346

347 **3.2.2 Kinematic scenario**

348 Once production and editing of the initial section is complete, the evolutionary stages of the
349 sections are created working backward from the present, including kinematic restoration,
350 backstripping, and thickness modification.

351 For each restoration scenario, the backward process is composed of different steps (Schneider
352 et al., 2002). The first step is restoration of the eroded parts if erosion has occurred during the
353 considered period. Importing templates from other software such as Thrustpack or 2DMove,
354 which can handle forward kinematic modelling, may help the production of intermediate
355 stages. The second step is an automatic backstripping of the section. Once the erosion and the
356 sedimentation have been accounted for, the resulting section is uncompactd using porosity
357 depth relationships. The section is then restored from a kinematic point of view. At this stage,
358 the displacements along faults are accounted for, using translations, vertical shear, and/or
359 flexural slip mechanisms.

360 The last step of the backward simulation requires the correction of local inconsistencies in the
361 computed thicknesses which result from the use of the vertical shear mode of deformation.
362 This step allows accounting for salt or mud tectonics. Correction of the restored eroded
363 section may be done at this stage. These steps must be performed for each layer as initially
364 defined in the present day section.

365

366 **3.2.3 Forward simulations**

367 In these complex geometries, faults cut the basin into blocks that naturally define
368 computational subdomains, using Domain Decomposition Methods (DDM, e.g. Faille et al.,
369 1998). In each block, the model accounts for compaction of the porous medium, erosion, heat
370 transfer, and the formation and migration of hydrocarbons (Schneider et al., 2002, 2004;
371 Schneider, 2003). The equations incorporate mass conservation of solid and fluids (water, oil,
372 and gas) coupled with Darcy's law and a compaction law. The faults have a constant thickness
373 and their permeability may evolve with time. The prototype allows using three permeability
374 models for the faults. Faults can be 1) pervious 2) impervious, being a flow barrier, or 3) their
375 permeability can evolve through time according to the properties of neighbouring lithologies.
376 Permeability can also change with the strain rate. Whichever option is chosen, the faults are
377 considered as inactive when their velocities are lower than the defined speed limit of 50m/Ma.

378

379 **3.2.4 Drawbacks**

380 Although Ceres-2D is a powerful tool, the software still faces numerical limitations that the
381 user must take into account in order to perform reliable modelling and analysis of results.

382 Two main drawbacks need to be discussed:

383 (1) The restoration mode: due to the numerical requirements for fast solution solvers of fluid
384 flow equations, the mesh is based on a set of gridded horizons, representing the real
385 geological events. The grid cells are laterally limited by borders, which remain vertical
386 throughout the simulation. This precludes any displacement between layers, i.e. the flexural
387 slip or flexural flow mode, which is the main deformation mode of a layered sedimentary
388 section in a compressive setting. Thus the modules, which are defined as layered units
389 separated by faults, topographic surfaces, model edges or section base, are only restored
390 through vertical shear. At a given restoration step, only the pre-restoration length and vertical
391 thicknesses are kept constant, although the real lengths and bed-perpendicular thicknesses
392 should be preserved. Therefore, at each restoration step, thickness modifications must be
393 applied to retrieve reliable lengths and thicknesses for each restored model. This is partly
394 automated by a geometric algorithm preserving the bed lengths and correcting the thicknesses
395 in order to preserve the bed surfaces. Such automated procedure limits the amount of manual
396 correction required, but this step remains compulsory.

397 (2) The topology: It is also compulsory to preserve the ordering of the blocks within the
398 section, each block being a unit separated from the others by faults, model boundaries, and
399 topography/bathymetry. Thus out-of-sequence thrusting is forbidden, as it would change the
400 topological ordering by placing deep blocks on top of blocks that formerly overlay them. One

401 artificial solution that allows an emerging out-of-sequence thrust to be rooted at depth is to
402 draw fictitious triangle zones.

403 (3) The faults: faults are fundamental objects for fluid flow pathways in basin modelling
404 (Yielding et al., 1999; Billi et al., 2003). Fault behaviour may range from completely pervious
405 (e.g. active fault or fault having a drain activity, without a cemented or brecciated core) to
406 completely impervious and hence acting as a barrier (e.g. cemented inactive fault or fault
407 sealed by clay smearing) (e.g. Brown 2003; Bretan et al., 2003). The geographic zone
408 surrounding the fault plays itself a role, because the damaged zone can be either a barrier
409 (grain size reduction in numerous shear bands, which constitute cemented zones) dividing the
410 reservoir into compartments, or a drain at a large scale (coalescence of open faults at various
411 scales). The behaviour of the faults can be tuned in different ways in Ceres: either pervious,
412 impervious, or with controlled anisotropic permeabilities. The fault element permeability in
413 the latest case is calculated from the closest rock element permeabilities through a harmonic
414 mean for the transversal permeability and an arithmetic mean for the longitudinal
415 permeability. Taking into account the fault slip rate can modify this anisotropic behaviour.
416 Above a given threshold value, the fault activity will enhance its permeability. In addition,
417 fault rocks can integrate the capillary pressure mechanisms in the computation of the coupled
418 water and hydrocarbon flow.

419

420 **3.3 Dataset and constraints**

421 Calibration of the basin model was performed against data coming from the nearest wells,
422 projected on the section plane. Nine wells were used (Figures 4 and 6): the Bosavi well in the
423 Fly Platform, the Bujon and Kanau wells from the Darai Plateau, the Iorogabaiu well drilled
424 in the Zongwe trend, the Hedinia 1X and 3X wells drilled in the Hedinia major structures, the
425 Iagifu and Usano wells in the tectonic slices separating Hedinia from Kutubu, and finally the
426 Kutubu wells, which are located near the top of the major Kutubu anticline. Field data from
427 the Mubi tectonic units in the imbricate zone have also been integrated. At each well,
428 reservoirs tops were used to define burial through time. The water table level was used to
429 determine the reference level for the hydrostatic curves. Both values have been used to
430 propose static corrections of the predicted pressure regime. Present day temperature of the
431 reservoirs and maturity data (mostly vitrinite) have been used to constrain the heat flow
432 scenario.

433 The heat flow evolution with time is a major thermal boundary condition. It is numerically
434 applied at the base of the crust, but incorporates the effect of the radioactive heat production

435 within the crustal rocks. As this effect is difficult to assess from field, well or potential data, it
436 is included within the total basal heat flow applied at the base of the sedimentary section. The
437 crustal part below the sedimentary basin is therefore transparent to heat. Note that the model
438 takes into account the effect of a possible heat production within the sedimentary section
439 (even if based here on a default value in the absence of control data, such as the amount of
440 radioactive elements for a given lithology).

441 We consider here a thermal scenario that integrates a first pulse of heat flow related to the
442 Triassic to early Jurassic rifting. The maximum value of heat flow applied here is 80 mW.m-
443 2. The heat flow then decays to a value of 37 mW.m-2 in the mid Cretaceous, followed by a
444 second heat pulse associated to the Coral Sea rifting, reaching a maximum value of 53
445 mW.m-2. This pulse is associated with uplift of the Papuan margin and erosion of the Ieru
446 Shale. Then the heat flow again decreases close to the present day value of 35 mW.m-2. This
447 scenario is in accordance with the scenarios proposed by AFTA analysis (Cawley and Taylor,
448 1991, TFN463; Duddy et al., 1991; Geotrack report 282; Green, 2001, Geotrack report 801).

449 A second boundary condition relates to the surface temperature and the atmospheric gradient.
450 The latter is chosen at 5°C.km-1 and is not considered as a variable for the fit. In contrast, the
451 surface temperature records a progressive increase during the Mid to Late Tertiary, from
452 initial values of ~5°C at sea level during the Palaeozoic and Mesozoic, toward a present value
453 of 30°C at sea level. This boundary condition will have only a minor affect on the deep
454 evolution of the temperature field, but will affect the present day distribution of temperature
455 at shallow depths (up to 1000m).

456

457 **3.4 Kinematic scenario**

458 The structural evolution of the section is based on a previously studied regional cross section
459 running from the Fly Platform to the Mubi-Wage hinterland, and crossing the Hedinia and
460 Kutubu trends (Hill et al., 2010). The section has been balanced, although the deep structures
461 in the hinterland, below the imbricate belt, remain speculative.

462 Several simplifications from the interpreted present day section (Figure 6) have been made. In
463 particular and at a large scale, it is not possible to account for out-of-sequence thrusting,
464 which will locally change the topological ordering of blocks. For instance we have deleted the
465 connection between thrust faults in the cover and their lateral extent within the basement
466 blocks. These faults were activated later in the structural evolution, cutting across the initial
467 decollement level along the deep contact between the Koi-Iange layers and the underlying
468 synrift series. However we kept the spatial and temporal association between the late

469 inversion of the extensional blocks at depth and the activation/reactivation of thrust slices
470 in the sedimentary cover. For the purpose of simplification, the Zongwe tectonic slices have
471 been represented as a single thrust unit. In addition, we kept only four tectonic units in the
472 Mubi/Wage area. At depth, we proposed a shallow ramp to account for the vertical uplift
473 associated with these units, with a deep decollement accommodating only a limited amount of
474 shortening.

475 The kinematic scenario reproduces the following steps in the section evolution (Figure 7):

- 476 • Late Triassic rifting and development of tilted blocks, inception of the passive margin
477 stage;
- 478 • Infill of the platform/slope/basinal parts during the Jurassic to Cretaceous evolution,
479 with a marked thickening of the Koi-Iange and Iagifu sequences toward the north-east;
- 480 • Upper Cretaceous deposition and then erosion of the Ieru Shale, associated with the
481 Coral Sea rifting and regional intraplate uplift;
- 482 • Deposition of the Darai carbonates;
- 483 • Inception of shortening during the Miocene. Here we assume that shortening
484 propagated first to the southern margin of the basinal setting, and that each structure
485 nucleated at the first thrust fold structure at the location of the former slope, as
486 observed analogue models (Grelaud et al., 2002, for the Salt Range/Potwar Basin in
487 Pakistan, Letouzey et al., 1995, for salt basins in general);
- 488 • Late inversion of the tilted fault blocks, associated with a marked propagation of the
489 shortening and the main episode of folding and thrusting in the frontal belt.

490

491 **4. Modelling results**

492 **4.1. Temperature and maturity calibration**

493 The modelled temperature field is displayed in figure 8A. The comparison with well data
494 provides a rather good fit. Temperatures from wells, using either Horner or WR corrections,
495 have less than 10% mismatch on average, with the exception of the deep value at 2500m in
496 the Bosavi well. Present day temperature gradients are also reproduced with a good match.

497 Another constraint is based on the temperature evolution of the Toro reservoir obtained from
498 well data and core analysis: It should be close to 50°C at present day, and has never reached
499 temperature higher than 90°C, as no quartz remobilization was observed. In addition, oil
500 charge occurred after cooling below 50°C. The maximum temperature proposed by the
501 modelling is 93°C, in accordance with fluid inclusion data, but the predicted present day

502 temperature is a bit too high and close to 63°C. This misfit may originate from two important
503 effects: (1) an excessive surface temperature, but this should also increase local misfits in
504 other wells; or (2) an underestimated cooling in the upper sedimentary section, due to the
505 karstic surface water flow which is not taken into account in the modelling.

506 Most of the maturities recorded in the wells are closely matched (Figure 8B), as well as the
507 maturity gradient at depth. This is particularly true for the Kanau-1 well, which is a major
508 control point as it is also the locus of the most detailed AFTA study, where the erosional
509 episode following Ieru sequence deposition was defined. A major discrepancy is observed in
510 the Iagifu well, which shows a consistently higher maturity both at the contact between Darai
511 and Ieru levels, and for the Toro sandstone reservoir. This is partly explained by a 300 m
512 difference between the depth recorded in the well (top Toro at 2400 mMD) and the modelled
513 geometry (top Toro at 2150 mMD), which will corresponds to a positive shift in maturity of
514 0.05%Ro, closer therefore to the observed values.

515

516 **4.2 Porosity calibration**

517 Porosity evolution is obtained through the use of porosity/depth curves from a standard basin
518 simulator, during the back-stripping and decompaction process. This is done during the
519 building of the kinematic scenario to rebuild the past geometry at each step of backstripping,
520 taking the compaction into account. Based on the scenario, the highly porous zones are
521 mainly the flexural basin deposits of Orubadi and Era beds due to their low amount of burial,
522 together with the Toro sandstone reservoir at depth below the Darai Plateau and Hedinia area,
523 where this horizon remains poorly compacted due to its low amount of burial.

524 By doing so, it appears that the porosity depth law for sandstones was nevertheless a bit too
525 optimistic, thus predicting higher porosities than those observed. As a result, we have defined
526 a new Toro lithology, which computes porosities at present day that are in good agreement
527 with the well data. Average porosity at depth reaches more than 20 % in the shallow
528 reservoirs from the Fly Platform to less than 13% in the Hedinia fold trend, consistent with
529 the excellent hydrocarbon reservoirs.

530

531 **4.3 Pressure calibration**

532 This step is the most important one for the CERES2D fluid flow modelling, as the pressure
533 gradients and hydraulic heads related to topography are the major cause of water flow. The
534 dynamics of fluid circulation can be estimated only if the pressure field is representative of
535 the real distribution of pressure. The predicted present day pressure field is shown on figure

536 9a. When comparing the predicted values to the observed ones, two major corrections were
537 applied.

- 538 • First, one should determine what is the difference in burial between the real reservoir
539 (Toro or Hedinia sandstone mostly) and the modelled one. A shift in depth of 100 m
540 will correspond to an increase in pressure of 1 MPa (145 psi).
- 541 • A second major shift is due to the misfit in water table depth. The modelling assumes
542 that the water table is at surface, whatever its elevation. If the observed water table is
543 500 m below the surface, the modelled hydrostatic pressure would be 5 MPa (725 psi)
544 higher than the observed one.

545 For each well, elevation, formation tops and pressure (RFT data mostly) as well as water table
546 depth (if observed) were used to compute the misfits.

547 The Bujon 1 (Figure 9b) well shows a Toro at 13.8 MPa, at 1400 mss, with a total burial of
548 1465 m. The modelled Toro is at 15.5 MPa, but with a present day elevation of 350 m, a
549 depth of 1150 mss, and a burial of 1500 m. The water table shift is similar (30 m) and the
550 pressure correction is then of $0.3+0.35=0.70$ MPa. The misfit is then reduced to 1.3 MPa
551 between the predicted and observed pressure. The modelling proposes a hydrostatic trend
552 similar to the one observed.

553 The Kanau 1 well (Figure 9c) did not encounter a water table in the Darai Limestone.
554 Therefore, we assume it is currently at the contact between the karstified carbonates and the
555 Ieru Shale. The Toro reservoir at 370m sub-sea shows a 3.9 MPa pressure, at a total burial
556 depth of 1330m. The Hedinia reservoir shows a 6.3 MPa pressure at 576m sub-sea. The same
557 Toro horizon is at 1300m of burial in the modelled section, implying there is no correction of
558 reservoir depth to apply there, with a predicted pressure of 7.2 MPa. The proposed water table
559 at 400m sub-sea corresponds to a pressure shift of -4 MPa, which allows for a residual
560 pressure of $7.2-4=3.2$ MPa, close to the 3.9 MPa measured pressure. Taking into account the
561 postulated water table depth, the modelled trend of pressure with depth can match the data
562 points with a drop of pressure below the hydrostatic trend within the Ieru Shale.

563 The Bosavi-1 well (Figure 9d) has an elevation of 840masl, and shows a Toro reservoir at 300
564 mss and 3.7 MPa with a total burial of ~1100 m. The water table at 150m below the
565 Ieru/Darai contact is poorly constrained. The modelled Toro is at 700 mss at 11.5 MPa, with a
566 burial of 1300 m. The shift in the Toro burial corresponds to a 2 MPa correction, and the
567 water table shift to a correction of 6 MPa. Thus the corrected pressure from the modeling is
568 3.5 MPa, close to the observed one. Again the three data points can be properly matched by
569 the pressure trend obtained from the modelling and corrected.

570 The Iorogabaiu-1 well (Figure 8e) shows a Toro reservoir at 16.2 MPa at 1600 mss, with a
571 total burial of 2200m (RT elevation of 640 masl). The modelled Toro gives a 24 MPa
572 pressure at 2400 m of burial (practically hydrostatic). The corrected pressure output is thus 22
573 MPa. The aquifer is not observed but postulated at roughly 200 mss (middle part of the Darai
574 limestone), which is compatible with both a hydrostatic trend, and a shift of the predicted
575 pressure by 600 m or 6 MPa to fit the observed values.

576 The Hedinia structure is the most interesting one. The modelling output is a single well, but it
577 can be compared to at least two real wells, Hedinia 1X (Figure 9f) and Hedinia 3X (Figure
578 9g). Hedinia 1X has an elevation of 1120 masl, and a water table at 370 masl. The Toro
579 reservoir is encountered at 880 mss at 13.8 MPa, with a burial depth of 2000 m. The modelled
580 Toro is at 900 mss, at a burial depth of 2100 m, and 15 MPa. The predicted pressure is
581 effectively fitted if one takes into account the burial shift of 1 MPa, but is apparently above
582 the hydrostatic value considering the water table depth. Thus it is not possible to fit the data
583 point with the predicted pressure trend. Hedinia 3X has an elevation of 950 masl, and the
584 Toro reservoir there is found at 1000 mss (burial of 2000 m) at a pressure of 13.8 MPa. The
585 pressure correction due to burial is then of 1 MPa. Contrarily with Hedinia 1X, the water table
586 is found at 900 masl, which corresponds to a correction due to water table shift of less than 1
587 MPa. Therefore, the fit is almost perfect, the three data points being in agreement with the
588 predicted trend of pressure at depth. The pressure drop within the Ieru Shale allows
589 connecting the hydrostatic trend in the upper layers to the mild under-pressure values
590 observed below the Ieru Shale. It is important to note that the pressure appears regionally
591 consistent in the structures below the shale, based on the two wells Hedinia-1X and Hedinia-
592 2X which are similar. The major difference in the fitting is the water table depth, and we
593 suspect that Hedinia-1X well encountered a deep karst network connected to the base of the
594 carbonate.

595
596 Results from the Iagifu well (Figure 9h) are quite different between the model and the reality
597 because the modelled well passes across a fault. The real well has an elevation of 1200masl, a
598 water table at 915masl. The Toro reservoir is encountered at 2400 mBRT, at 15.1 MPa. A
599 good fit was obtained between the under-pressurization trend and the three data points.

600 The Kutubu anticline is the only data point which is definitively not fitted (Figure 8i). The
601 well elevation is at 1200masl with a water table at 800 masl. The Toro reservoir is found
602 highly over-pressured at 40 MPa at 800 mbsl. The proposed pressure is again slightly under-
603 pressured at 16 MPa at 650 mbsl.

604

605 The main conclusions of the pressure calibration are as follows

- 606 • Real hydrostatic trend occurs in the foreland,
- 607 • Within the Darai Plateau and the Hedinia, Iagifu, Zongwe and Iorogabaiu structures,
608 there is a shifted hydrostatic trend, with pressures that are below hydrostatic values
609 beneath the Ieru Shale.
- 610 • A shift of the water table by 300-700 m is possible (data in review):
- 611 • CERES2D is water saturated up to the surface, which is not the case in reality. The
612 shift in pressure values in most wells can thus be explained firstly by a simple shift in
613 the top of formation between the virtual well and the real one, and secondly by a shift
614 in the water table (100m will equal 1MPa) in the karstified limestones
- 615 • Underpressurization below the Ieru Shale: A suction effect explained by the important
616 flow of water from the summit of the anticlines toward adjacent topographical lows,
617 onto the impervious shales. Such underpressurization has already been observed in
618 other similar settings (Canadian Rocky Mountains, Colombian and Bolivian sub-
619 Andean zones, Roure et al., 2003; Faure et al., 2004; Toro et al., 2004), and clearly
620 reproduced by simple numerical experiments.
- 621 • No overpressurization is simulated in the Kutubu anticline, even if taking into account
622 capillary effects for the seal, or decreasing the porosity/depth laws to diminish the
623 porosity at a given depth, or increasing by two order of magnitude the specific surface
624 (so decreasing in the same range the permeabilities). This implies that the
625 overpressurization in the Kutubu field requires another explanation.

626 The major conclusion is that the modelling of pressure is able to predict quantitatively the
627 pore fluid pressure values and trends if one takes into account the correction of reservoir
628 depth and of water table level. The pressure prediction is, in contrast, not possible along the
629 high pressure trend of the Kutubu anticline.

630

631

632 **5 Petroleum system modelling**

633 **5.1 Source rock potential and characteristics**

634 Oil discoveries in PNG, particularly those in the foldbelt trend were examined by Chevron
635 following the discovery of oil and gas during the late 80's and early 1990's. Key studies
636 include those of Moldowan and Lee (1987), Ahmed et al. (1988) and Kaufman (1994) and

637 they are the source of the following summary. This discussion refers to the commercial fields,
638 which includes the Iagifu, Hedinia, Gobe and SE Gobe oil fields.

639 Light oil, condensate and gases obtained from seeps and subsurface reservoirs in PNG are
640 genetically similar and have hydrocarbon compositions that are typically associated with
641 generation from Type II/III to Type III kerogens. Based on the available geochemistry and
642 rock extract data the source rock contains a mixture of marine and terrestrial organic matter
643 deposited under mildly oxygenated conditions probably in an open marine to deltaic
644 environment. The likely source rocks are of Jurassic age and show good to marginal potential
645 and are comparable in organic facies and petroleum potential to the other Upper Jurassic
646 source rocks present on the Northwest Shelf of Australia.

647 In the oil and gas fields in the PNG fold belt, rich source is not generally intersected in wells,
648 however zones with marginal source potential are identified within the Upper Jurassic which
649 contain low to moderate quantities of Type II/III to Type III (mixed marine and terrestrial)
650 organic matter. These organic constituents will produce a mixture of oil and gas when mature
651 with a concept that the source rock improves in richness into a basinal deep called the Kubor
652 Kitchen thought to be the likely source of fold belt hydrocarbons, although local burial due to
653 overthrusting is also a plausible charge model (Kaufman et al. 1994). The formation
654 responsible is believed to be the Upper Jurassic Imburu Formation, with some potential in the
655 Lower Jurassic (Chevron 1990, Waples and Wulff 1996). The Late Jurassic as a source rock
656 concept is supported by oil – source correlations, demonstrating that the oils and source rocks
657 are genetically similar (Moldowan and Lee, 1987).

658 In addition to the commercial fields, two other oil systems have been identified in the Papuan
659 Basin. These include a distinctive Tertiary oil source as well as a probable Cretaceous oil
660 source. The source rocks for these systems are poorly understood and are largely inferred
661 from biomarker and isotopic evidence from the oils (Kaufman, 1994).

662

663 **5.2 Maturity distribution and evolution**

664 Figure 10 shows the present day distribution of the transformation ratio, which marks the
665 maturation of the source rocks. This maturation is dependent upon the activation energy
666 coefficient used to compute the thermal cracking of the organic matter. For that purpose, two
667 types of source rocks have been used: (1) Marine type II source for the Lower Cretaceous and
668 Upper Jurassic shale layers occurring between the reservoirs horizons, and (2) Continental
669 type III source rock for the coal measures in the Lower Jurassic synrift deposits.

670 For each source rock, maturation starts in the Mid Cretaceous (Barremian). Maturation is
671 mostly acquired in two steps: first during the regular burial in the Upper Cretaceous and
672 Lower Tertiary, secondly due to the rapid burial in the foreland and below tectonic slices
673 during compressional deformation (Upper Miocene to present day).

674 Synrift sequence are not mature below the Darai plateau, but their maturities below the
675 tectonic units can reach 12% in the frontal slices, and up to 50% of transformation ratio below
676 Mubi/Wage.

677 Modelling shows that for the Lower Cretaceous and Upper Jurassic source rocks half is the
678 maturity was acquired during Mio-Pliocene time. Below Mubi, it reached 10% by late
679 Oligocene, more than 25% in Late Miocene, and up to 50% for Lower Cretaceous source,
680 60% for Upper Jurassic at Present Day. Below the Darai plateau, it evolves from 2-6% by
681 Late Oligocene, 5-12% for Late Miocene, and at present day reaches less than 10% in the
682 Lower Cretaceous, 16-20% for Upper Jurassic. In most places, the Upper Jurassic source rock
683 has the highest maturity due to its low activation energy distribution typical of type-II source
684 rock, and highest thermal/burial history. Note that if we only consider type III source, the only
685 location where the expulsion saturation will be obtained is the Mubi Wage zone.

686

687 **5.3 Overall pattern of oil and gas migration and accumulation**

688 To simulate oil and gas migration from the source rocks, viscosity, TOC and expulsion
689 saturation have to be defined. A law regarding the temperature parameter describes the
690 viscosity of oil, which is around 5 cP at surface conditions, corresponding to $5 \cdot 10^{-3}$ Pa s.
691 Similarly, a law regarding the temperature parameter describes the viscosity of gas, around
692 0.03 cP at surface conditions, corresponding to $3 \cdot 10^{-5}$ Pa s.

693 The lithologies used in the modelling are defined by a mixture of sand and shale from pure
694 lithologies. We changed the expulsion saturation parameters to the value of 5% for oil and 2%
695 for gas, although the classic default value in the library of CERES2D was at a higher level
696 (between 10 and 20%). We made this change to ease the migration process.

697 We used a total organic content of 1% for all the source rock layers present in the model.
698 Indeed, the thickness of those layers is big, from 100m to 800m in the thickest parts. It
699 corresponds to an average for the whole thick layer of a more realistic source rock layer that is
700 inhomogeneous: a few tens of meters thickness with a richer content that may reach 10% of
701 organic matter.

702 A first direct simulation of hydrocarbon charge and pathways is based on the reference model
703 (figure 11A), based on the calibrated scenario and three source rock layers (type II source in

704 the Upper Jurassic and Cretaceous, and type III source only in the Triassic and lower Jurassic
705 synrift sequence). This model shows two major results: oil is largely produced and reaches
706 high saturation in several accumulations after a rapid migration, whereas little gas is
707 produced, apart from in the deepest core of the belt, with small ranges of migration leading to
708 small, low saturation accumulations (Figs 11A). Oil accumulations are located principally in
709 structural traps, namely the Hedinia and Kutubu anticlines, and the deep Mubi duplex, with
710 secondary accumulation located in the core of the antiform backlimb of Kutubu and in the
711 fold controlled by the initiation of the out of sequences thrust below the Zongwe slices. In
712 these accumulations, oil saturation ranges from 10 to more than 60%, indicating potential
713 economic accumulation. In contrast, gas is mostly confined within the source rock layers and
714 along the main carrier beds where it reached the expulsion saturation (Figure 11 B). There is
715 no economic accumulation, although gas saturation is higher than 50% at the source rock
716 level and adjacent carrier beds. This result is inconsistent with the known gas accumulation in
717 the Hedinia area. In our case, a large amount of gas is produced but poorly migrated.

718 Adding layers of type II source rocks in the deep part of the basin (i.e. in the lower Jurassic)
719 enhances slightly the amount of generated oil (Figure 11B), reaching up to 60% saturation in
720 the main accumulation, but does not change at all the general pattern of oil distribution. On
721 the contrary, it increases the gas migration ability through a better expulsion at saturation,
722 allowing for a small increase of saturation levels in the carrier beds and traps, up to 5%. There
723 is still no economic accumulation developed.

724 A last step of modelling (Figure 11C) introduces the ability of secondary cracking to occur by
725 decreasing the activation energy for secondary cracking from 57 to 54 Kcal.mol⁻¹, keeping the
726 Arrhenius coefficient at 3.10¹⁴.s⁻¹. By doing so, the gas saturation is practically doubled, and
727 in the Kutubu anticline reaches up to 10%. Oil accumulation is slightly increased as an
728 increase in gas content enhances oil flow. Nevertheless, there is still very little gas
729 accumulation, which is inconsistent with the known distribution.

730

731 **5.4 Hydrocarbon migration paths**

732 Considering the hydrocarbon pathways, the flow scenario shows three major steps (Figure
733 12). During the Late Cretaceous, after the erosion of the Ieru shale level, the modelling shows
734 an early expulsion at saturation in the deep source rock beds. As the Ceres numerical scheme
735 is highly diffusive in case of two-phase fluid flow, the seals around the source are also highly
736 saturated, despite a very low porosity. This is followed, during the deposition of the Darai

737 carbonates by an early lateral migration in the reservoirs as early as Eocene, and coherent
738 with the medium temperature recorded at 60°C in the fluid inclusion (1 in figure 12).

739 During the early stages of flexure and development of the imbricated units of the Mt Castle-
740 Mubi-Wage area (from 7 to 2 My), we note the onset of the main lateral escape of
741 hydrocarbon from the basin as a squeegee fluid flow updip to the flexure foreland (2 in figure
742 12). Hydrocarbons are mostly trapped in the early-formed Hedinia anticline (3 in figure 12).
743 This prevents charge of the Darai plateau (4, 7 and 8 in figure 12). At the same time, oil is
744 also trapped below the Mt Castle area.

745 In the late stages of fold and thrust belt evolution (2 My to present day) the main hydrocarbon
746 migration occurs toward the upper part of the Darai plateau and into the Kutubu structure (5
747 and 6 in figure 12), toward the northernmost units in the Wage zone (5 in figure 12), and in
748 the Darai plateau unit corresponding to the Zongwe slices, and deeper folds (8 in figure 12).

749 Migration velocities are quite small, ranging from 10 to 10³ m.My⁻¹ ()which is in the range of
750 typical values between 20 to 300 m.My⁻¹ (see Roure et al., 2010; Vilasi et al., 2009; Schneider
751 et al., 2002), but on the low side, precluding long range migration paths owing to the age of
752 migration inception at less than 4 Ma. The longest migration range would be no more than
753 five kilometres.

754

755 **7 Conclusions**

756 The basin modeling CERES2D tool has been used to propose a valid scenario of hydrocarbon
757 generation, migration and trapping within the Papua New Guinea fold and thrust belt, based
758 on a 120km long balanced cross-section and 9 wells. Present day temperature, pore fluid
759 pressure and maturity are well fitted apart from the high-pressure trend of the Kutubu
760 anticline. Modelling results suggest a recent (i.e. less than 7My) maximum maturity with a
761 short-range migration from the Cretaceous, Upper Jurassic and Triassic known source rock
762 levels. Modelling results account for the know oil accumulation and potential migration
763 pathways, but gas charge cannot be accounted for except by considering a second deep
764 sediment accumulation below the main gas accumulation. Such a postulated Hedinia Trough,
765 similar to the Swan graben in the Vulcan sub basin would help to produce larger amount of
766 gas if secondary cracking of migrated oil occurs, with a short distance of migration. The high
767 pressure trend, associated with an early charge and breaching of the anticline, is explained by
768 taking into account a greater extent of the imbricate belt, which buried the Kutubu structural
769 trend after its early charge and breaching, allowing for (1) the rebuilding of the sealing

770 capacity through clay diagenesis, and (2) for high pressure to build up at depth. Late, out of
771 sequence reactivation of the trend explains the present day high pressure which is not yet re-
772 equilibrated.

773

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777

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971

972 **Figure captions**

973 Figure 1: A) Tectonic map of New Guinea and the southwest Pacific region with principal
974 geographical locations referred to in the text. Barbed lines are active subduction zones and
975 thick lines are active spreading centres. The light blue shaded areas, drawn at the 200 m
976 isobath, are the continental shelves of Eurasia and Australia and areas of thickened oceanic
977 crust/arcs. B) New Guinea showing simplified tectonic belts and the principal tectonic
978 features. AB, Amanab Block; AR, Adelbert Ranges; BB, Bintuni Basin; BG, Bena Bena–
979 Goroka Terrane; B–T, Bewani–Torricelli Mountains; CM, Cyclops Mountains; COB, Central
980 Ophiolite Belt; DF, Derewo Fault; FR, Finisterre Ranges; G, Gauttier Terrane; GM, Grasberg
981 mine; HG, Huon Gulf; HP, Huon Peninsula; In, Indenburg Inlier; K, Kubor Range; La,
982 Landslip Ranges; LF, Lagaip Fault; MB, Meervlakte Basin; Po, Porgera Intrusive Complex
983 and mine; RB, Ramu Basin; SB, Sepik Basin; SG, Strickland Gorge; ST, Sepik Terrane; Wa,
984 Wandaman Peninsula; WT, Weyland Terrane. (from Hill and Hall 2002). C). Sun-shaded,
985 digital elevation model showing the main features of the Papuan Fold Belt. The main
986 structural belts are labelled, after APC (1961). The Darai Plateau is a very large asymmetric
987 anticline overlying an inverted extensional fault that was active from Triassic to Miocene
988 times. The structure is offset by a tear fault, the Bosavi Lineament, to underlie the mountain
989 front in the NW part of the fold belt. All the producing oil and gas fields lie within the
990 Strongly Folded Belt. Key wells are labelled and oil field and gas field outlines are shown in
991 green and red, respectively. Wells within the fields are shown by white dots but, for clarity,
992 are not labelled.

993

994 Figure 2: 3D sketch evolution of the paleogeography of New Guinea, from the Jurassic to
995 present day structure, illustrating the role of the Tasman line in dividing New Guinea in two
996 contrasted zones (from Hill and Hall, 2002). a) Jurassic; b) Cretaceous, from the subducting
997 slab and accretionary prism to the Coral Sea rift; c) Paleogene, opening of the Coral Sea and
998 denudation on the eastern Papua New Guinea; d) Oligocene, arrival of the Philippine Arc; e)
999 Early Miocene, differential subsidence with carbonates deposition in the South and
1000 exhumation of core complexes in the North; f) Mid Miocene; g) Pliocene arrival of the
1001 Carolina Arc and development of the fold belt above a weak hot plate; h) Pleistocene and
1002 basement reactivation, but still no foreland basin.

1003

1004 Figure 3A Simple chronostratigraphic chart for the New Guinea fold belt (after Hill and Hall,
1005 2002). It shows the preserved Palaeozoic section west of the Tasman line, and the lower
1006 Mesozoic which is locally intruded to the east. Following the Jurassic break-up, the Mesozoic
1007 clastic succession is relatively homogeneous. The lower Tertiary uplift in the east led to an
1008 important unconformity below the Darai limestone, prior to the foreland basin clastic
1009 succession. B) Simplified stratigraphy across the Papuan Fold Belt (after Hill et al. 2000)
1010 flattened on the top Miocene. The Mesozoic section is dominantly mudstone, but contains the
1011 Upper Jurassic to Neocomian Iagifu, Hedinia, Digimu and Toro sandstone reservoirs. These
1012 are collectively modelled as Toro Sandstone. The Cretaceous Ieru Mudstone is the regional
1013 seal and is unconformably overlain by the thick Miocene Darai Limestone and Orubadi Marls.
1014 The Upper Triassic and Lower Jurassic syn-rift sequence is schematic on this section.

1015

1016 Figure 4: Present day balanced cross section modified from Hill et al. (2008). The closest
1017 wells used in the study have been shown, but the Iagifu-1s Usano-1 and Iorugabai-1 wells are
1018 not shown although used with a longer projection distance.

1019

1020 Figure 5A: Schematic workflow of the CERES2D tool used for modelling fluid flow in
1021 complex setting (e.g. Schneider et al., 2002; 2003). B: The four steps of the present days
1022 section edition; a) editing the section geometry; b) editing the geological properties of the
1023 section; c) creation of the section topology (i.e. definition of the kinematic mobile blocks); d)
1024 building of the calculation grid for each block. C: Each restoration step comprises four steps
1025 repeated for each stage of evolution of the kinematic (i.e. at minimum each sedimentary
1026 layer): 1) edition of the eroded parts in the initial section, i.e. at the youngest age of the stage;
1027 2) back-stripping of the layer deposited during the modelled stage; 3) kinematic restoration;
1028 4) management of thicknesses discrepancies related to block adjustments.

1029

1030 Figure 6: Present day section used for the basin modelling phase, with the approximate
1031 location of the well used for the calibration process, together with the interpreted section from
1032 Hill et al. (2008).

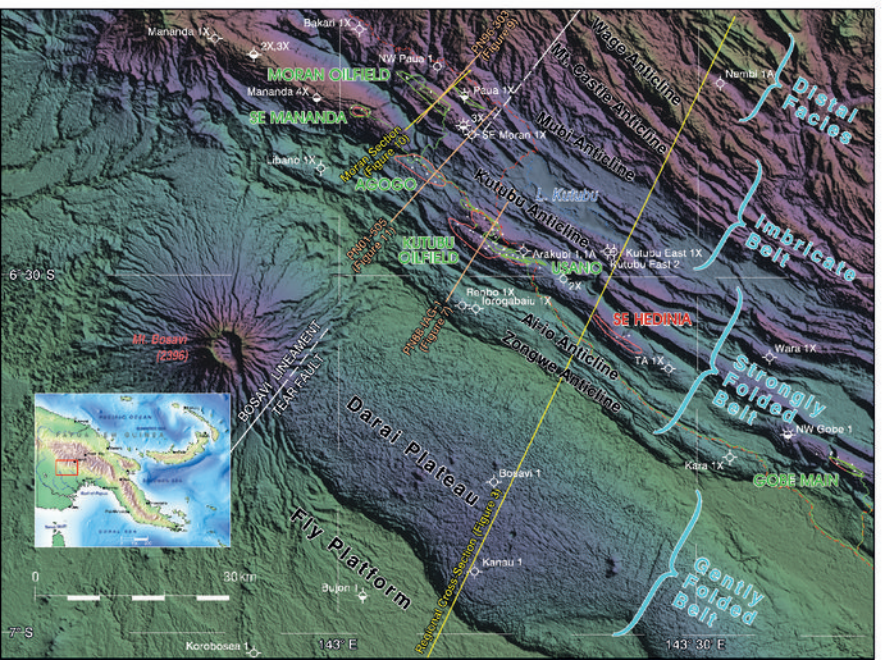
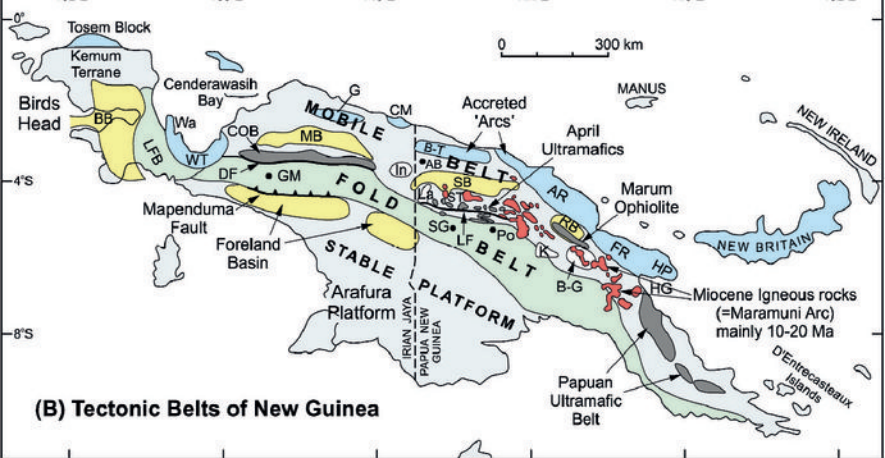
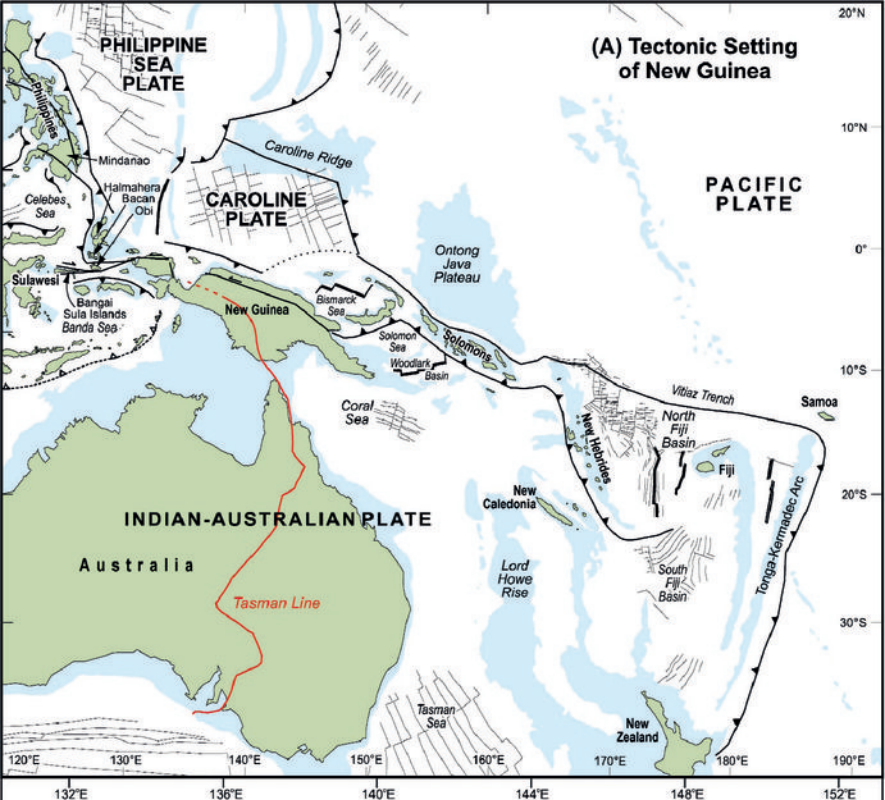
1033

1034 Figure 7. Kinematic scenario based on the structural interpretation by Hill et al. (2008),
1035 assuming a weak lithosphere, roughly 1 km of erosion for the Ieru Shale, and an early
1036 activation of the frontal thrust fault limiting the Hedinia structure.

1037

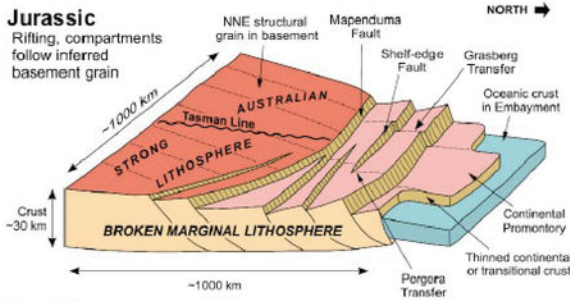
1038 Figure 8A. Temperature calibration A1) Temperature distribution in the present day section.
1039 A2-7) Comparison between the predicted (continuous lines) and observed (dots, white for
1040 WR, red for Horner correction) temperatures at various calibration wells (depth in meter).
1041 8B) Maturity calibration. B1) Distribution of maturity Comparison between the predicted
1042 (continuous lines) and observed (white dots) value of vitrinite reflectance at various
1043 calibration wells (depth in meters).
1044
1045 Figure 9. Calibration of the pressure distribution along the section. B1) Present-day
1046 distribution of pressure along the section. B2-9): Comparison between predicted (red line and
1047 squares with log on the right) and observed (white crosses and line with log on the left side)
1048 pressure data for the calibration wells. The blue lines correspond to the expected real trend,
1049 obtained by shifting the predicted trend after applying all corrections. The water table depth is
1050 here proposed at the contact between Darai carbonates and Ieru shales.
1051
1052 Figure 10: A) Distribution of transformation ration at present day and evolution with time for
1053 three main area; Evolution of the transformation ratio for the Darai plateau (B) Hedinia-
1054 Kutubu (C) and Mubi-Wage (D), for the three source rocks (Red: Lower Cretaceous, Green:
1055 Upper Jurassic, Blue, syn rifit coal sequence).
1056
1057 Figure 11: Oil and gas accumulations for various sets of simulation. A) reference model with
1058 three source rocks (Lower Cretaceous type II, Upper Jurassic type II, syn rifit coal sequence
1059 type III). B) Similar as previous model with a mixture of type II and III source rocks for the
1060 lower productive unit in the Triassic. C) Similar as previous model with secondary cracking
1061 enabled (see text for explanations).
1062
1063 Figure 12. Three steps of evolution of the hydraulic head (i.e. the piezometric high above the
1064 reference level, here in CERES2D the sea level), which expresses the potential energy driving
1065 fluid motion. Three time steps are represented, from bottom to top Top Darai (7Ma), Top
1066 Orubadi (5Ma), Present Day (0Ma). Arrows denotes oil velocity, the arrow size ranging from
1067 1 to 50m/Ma. (1) Onset of lateral migration; (2) Main squeegee fluid flow episode; (3) early
1068 development of the Hedinia anticline charge; (4) Southward extent of the squeegee fluid flow,
1069 accumulation against the Darai plateau bounding fault; (5) Maximum oil and gas escape from
1070 the deep kitchen, charge of the inner Mubi and Wage zones; (6) Late emplacement of the
1071 Kutubu anticline with late oil charge, closure of the flow toward Hedinia; (7) beginning of oil

1072 accumulation in the Darai plateau due to flexure; (8) beginning of oil charge in the Zongwe
1073 units.
1074

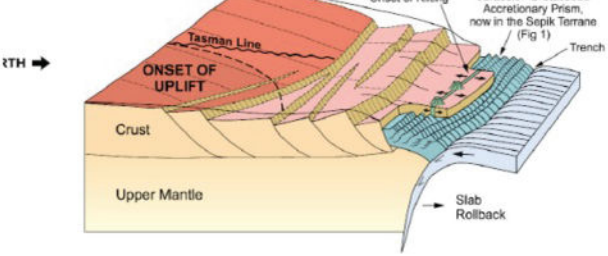


Jurassic

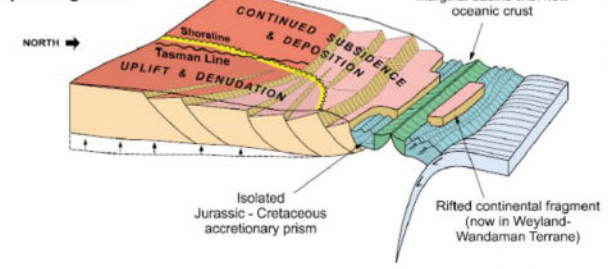
Rifting, compartments follow inferred basement grain



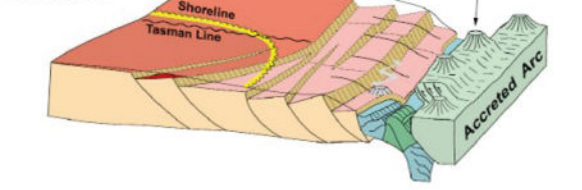
Late Cretaceous sediment fill



Palaeogene Uplift and Coral Sea spreading to SE

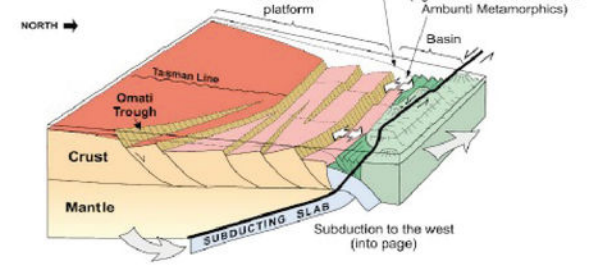


Late Oligocene Incipient Arc collision with promontory; minor margin subsidence

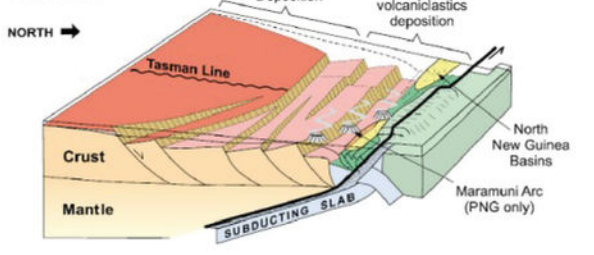


Early Miocene

- Margin subsidence
- Extension
- Transension

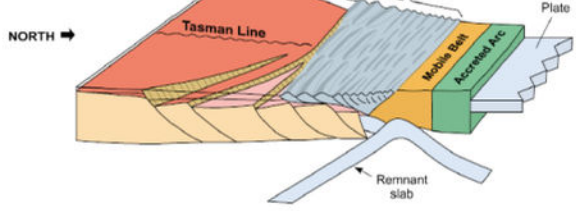


Middle Miocene Volcanism

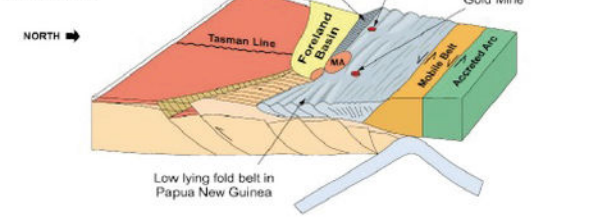


(B) Pliocene

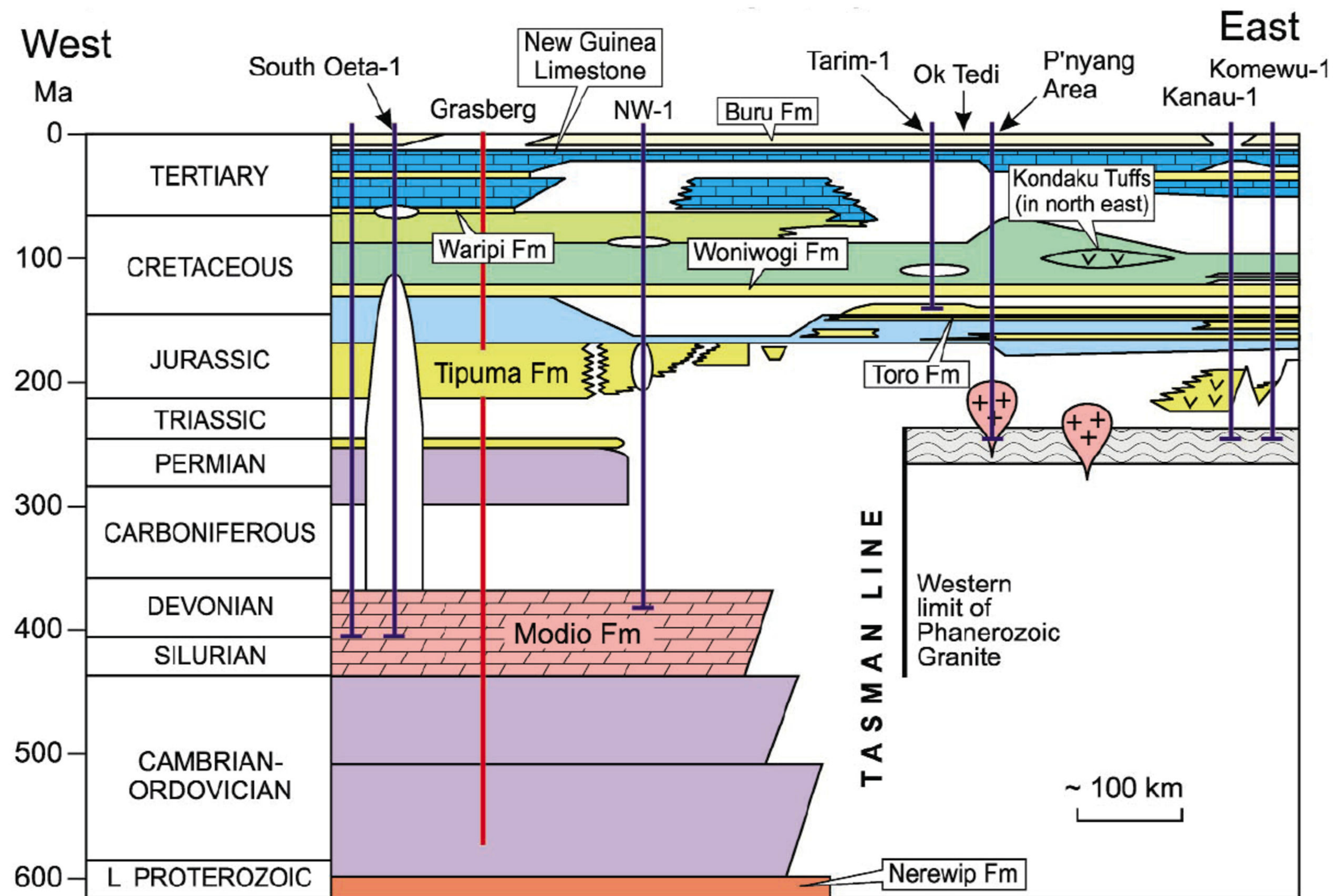
- Fold and Thrust Belt
- Compression



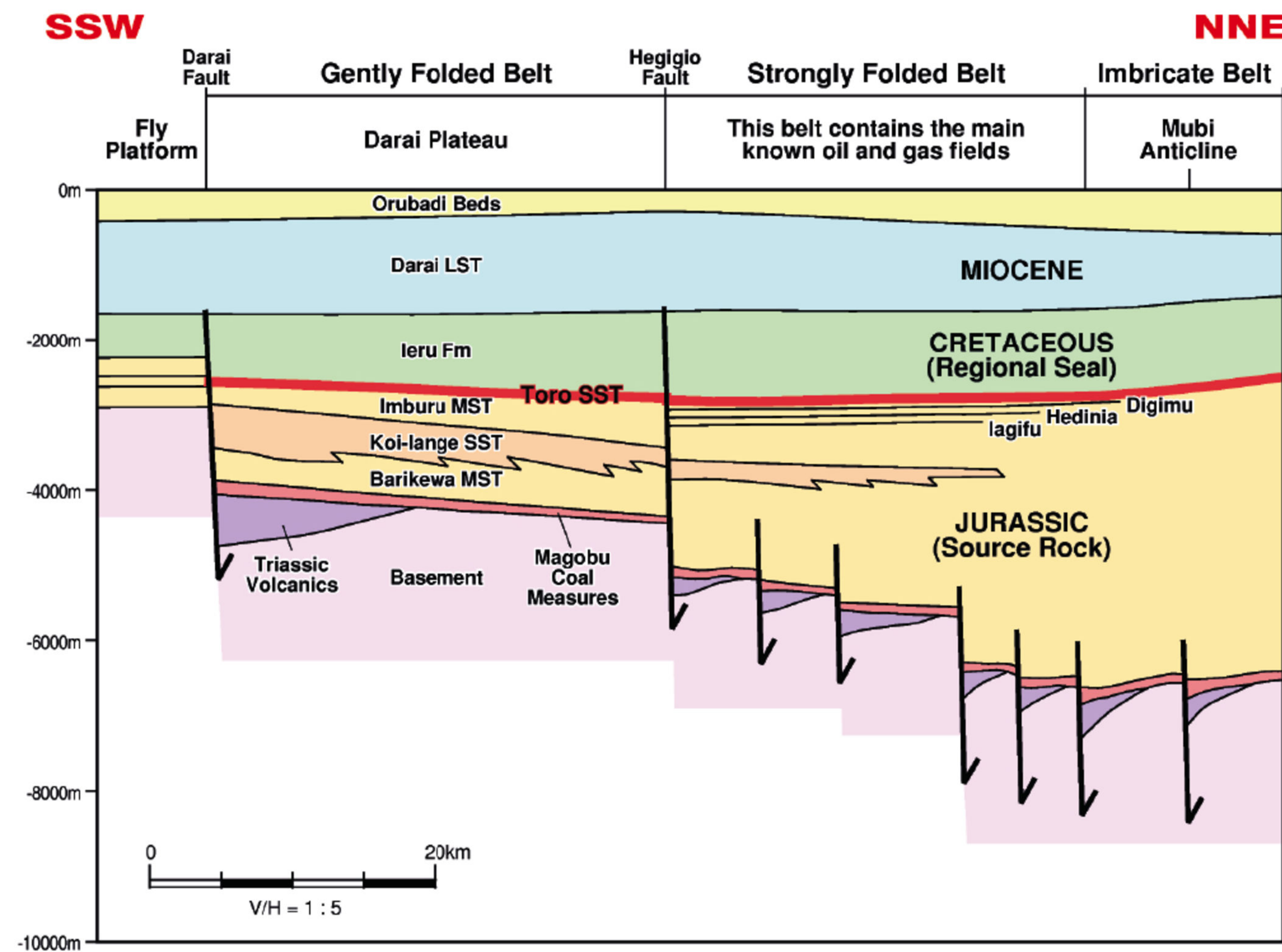
Pleistocene Basement Reactivation

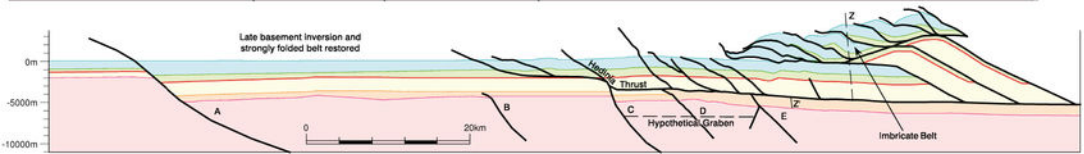
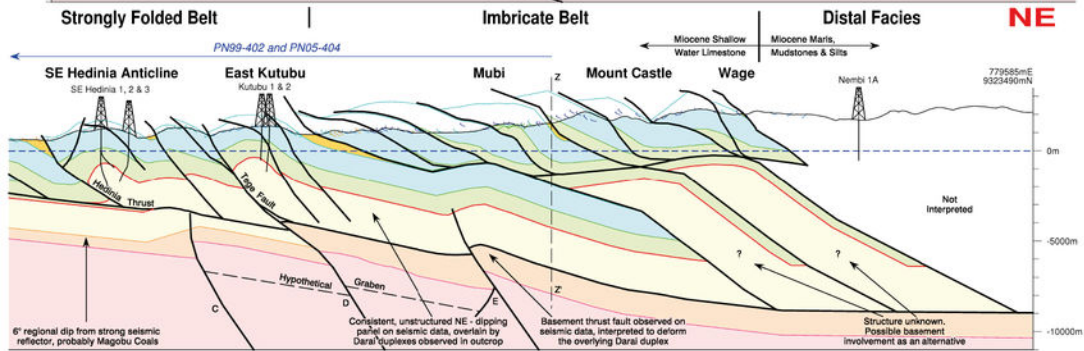
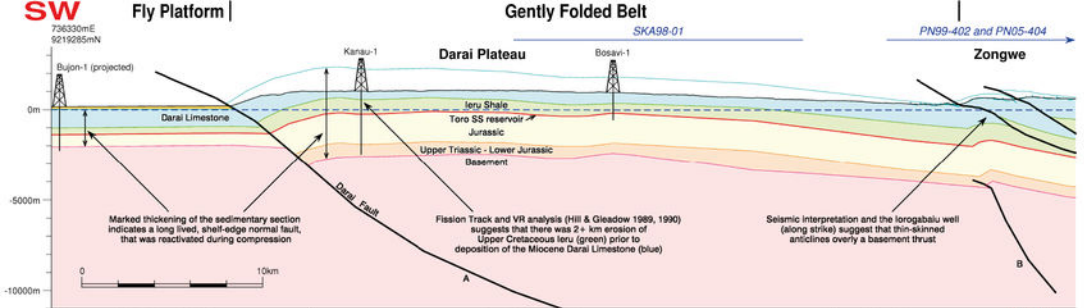


A

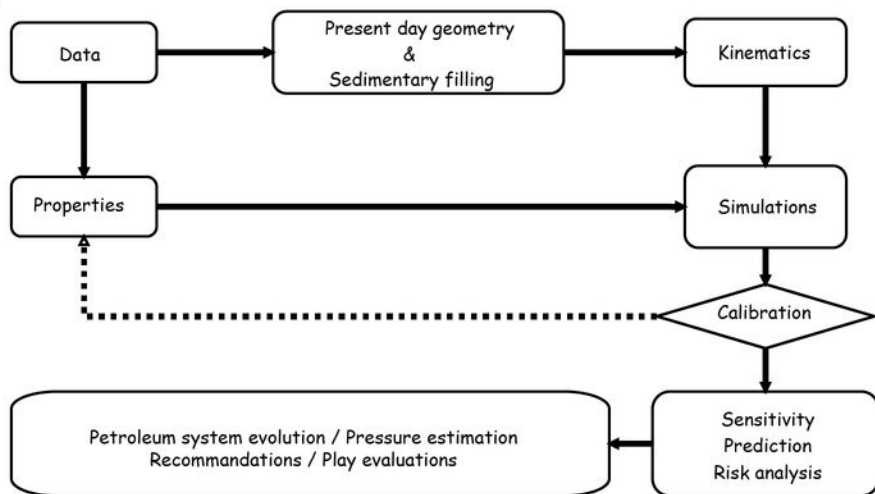


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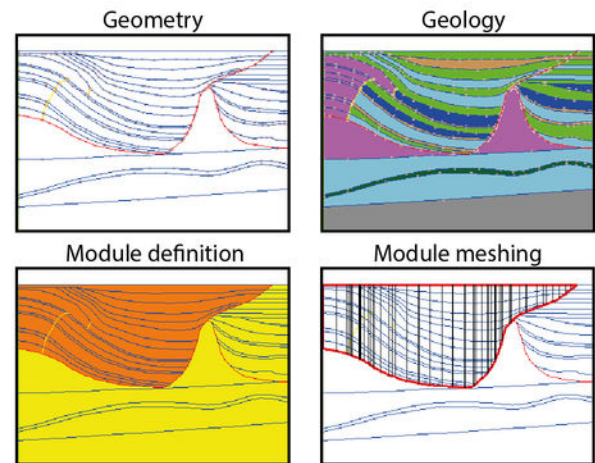




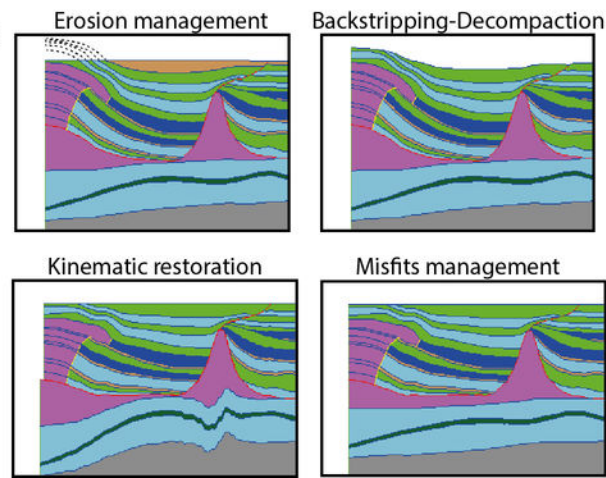
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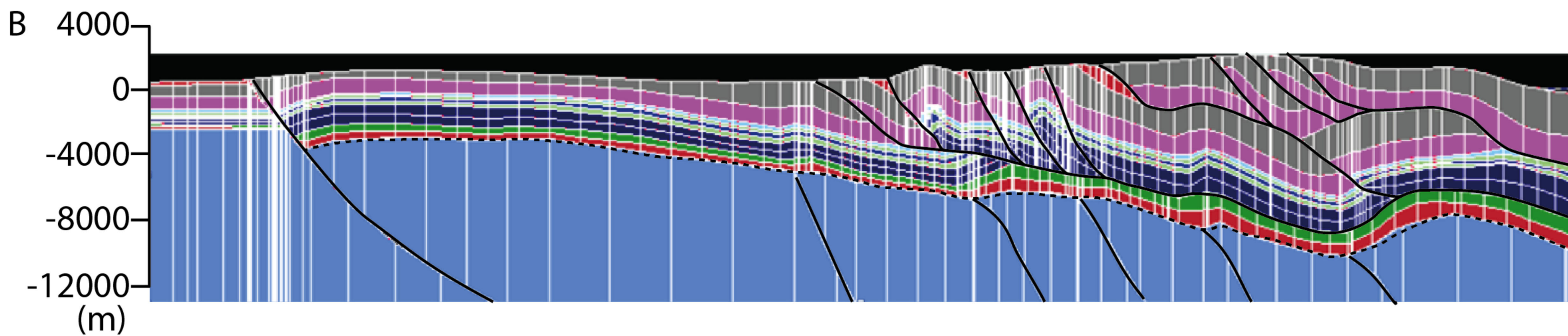
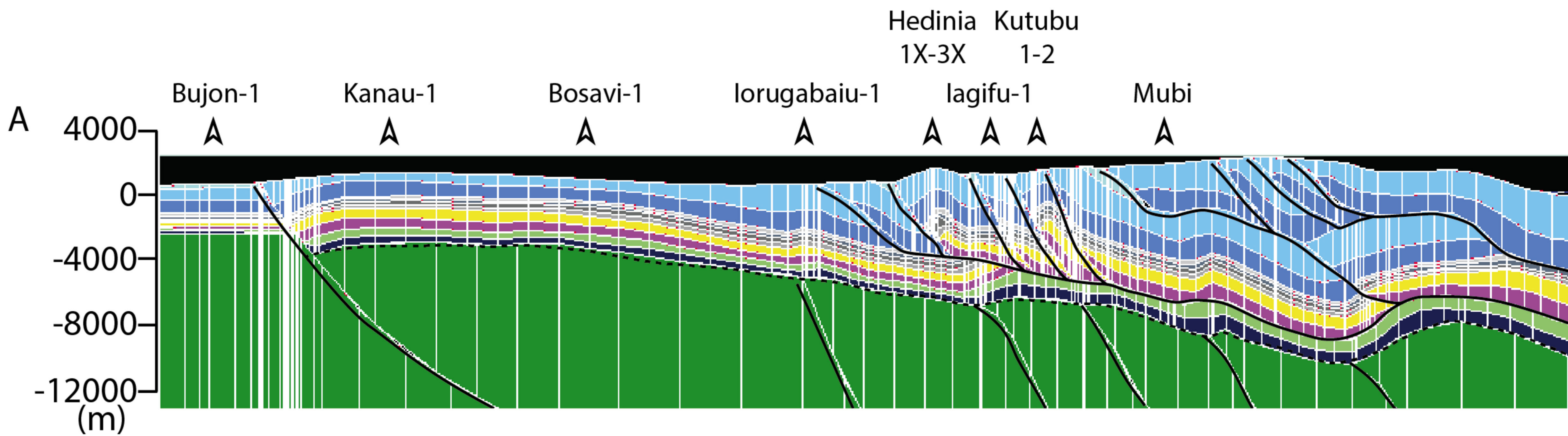


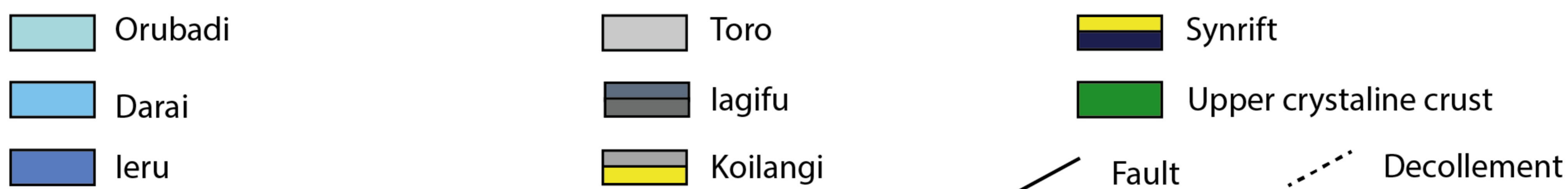
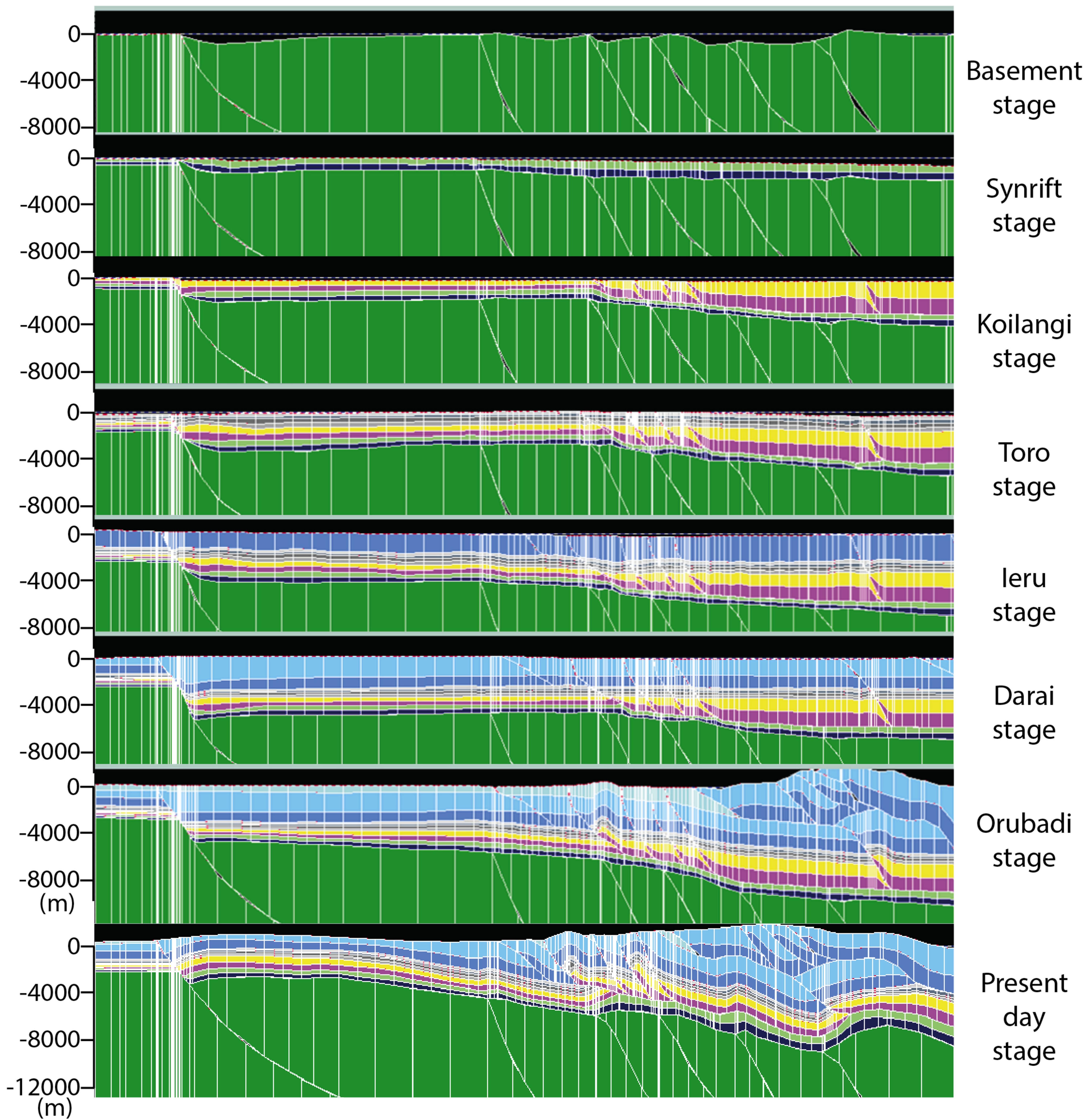
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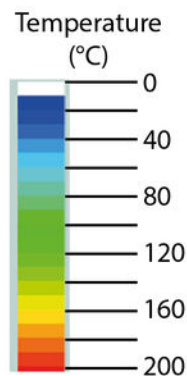
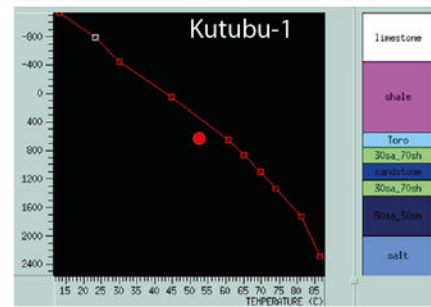
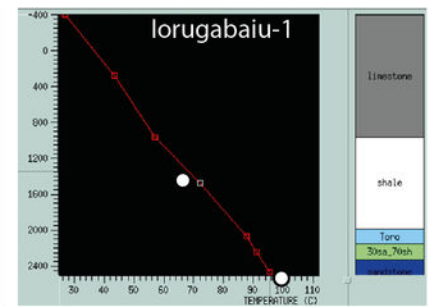
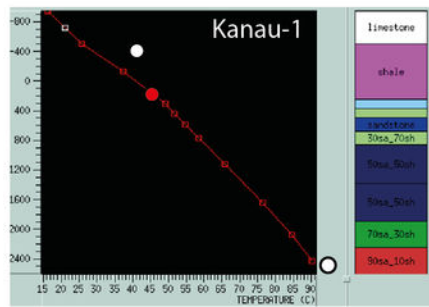
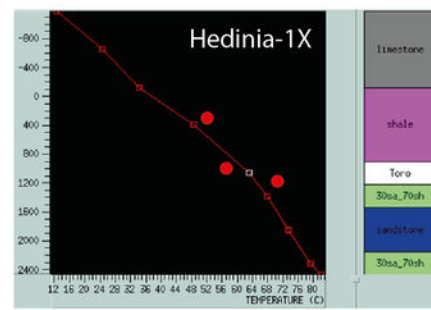
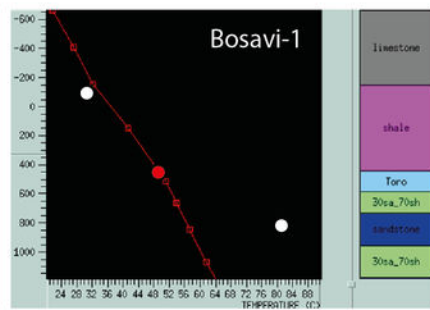
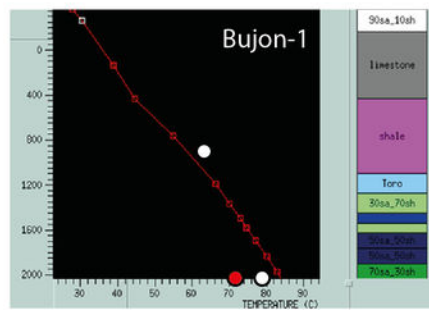
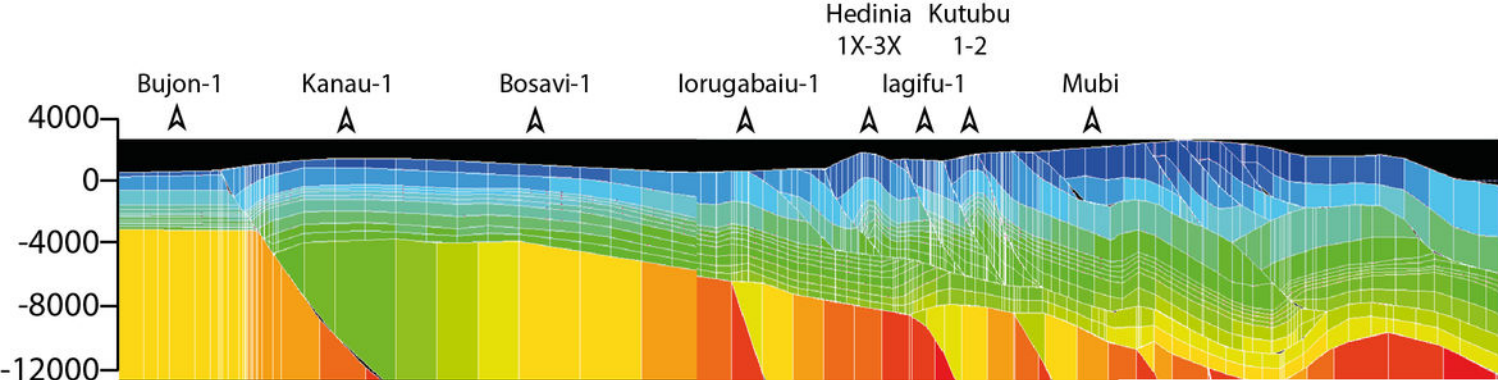


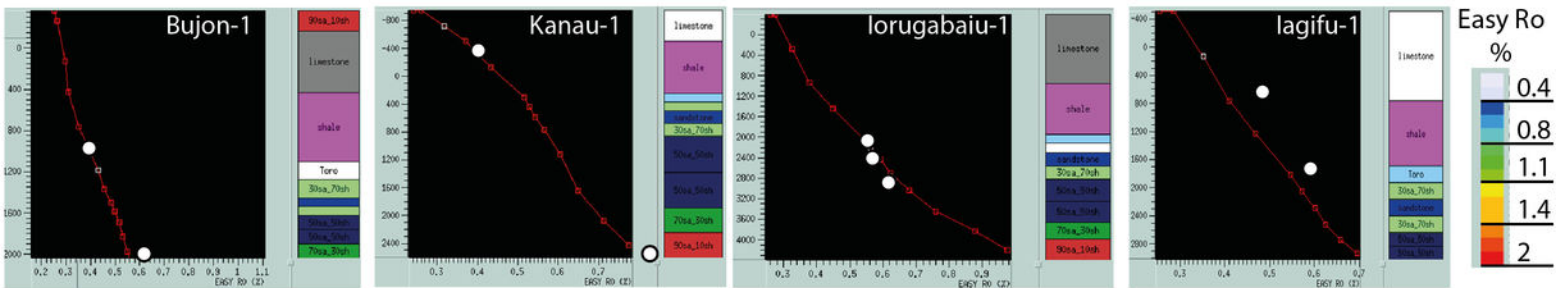
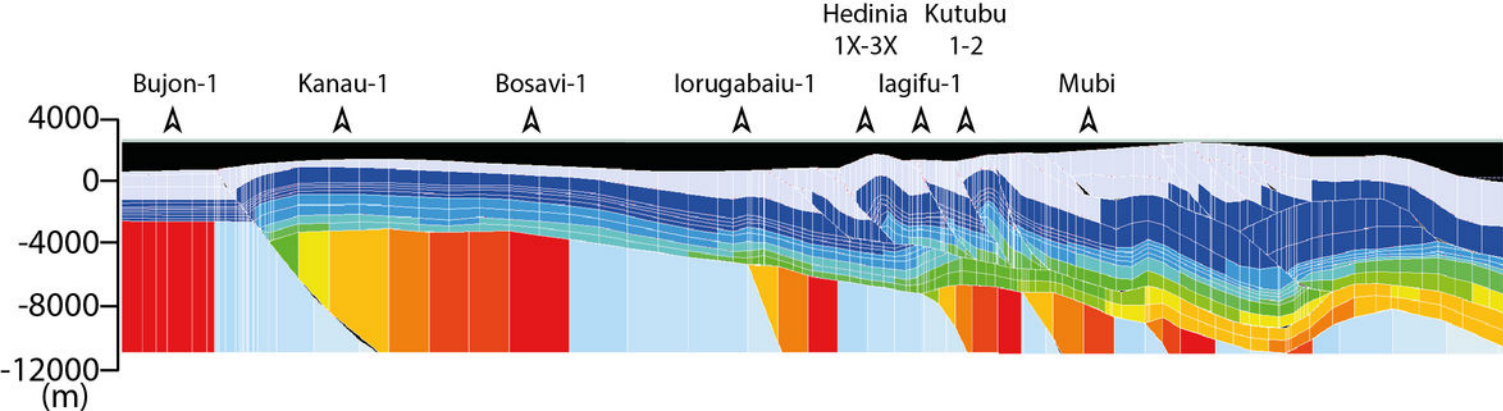
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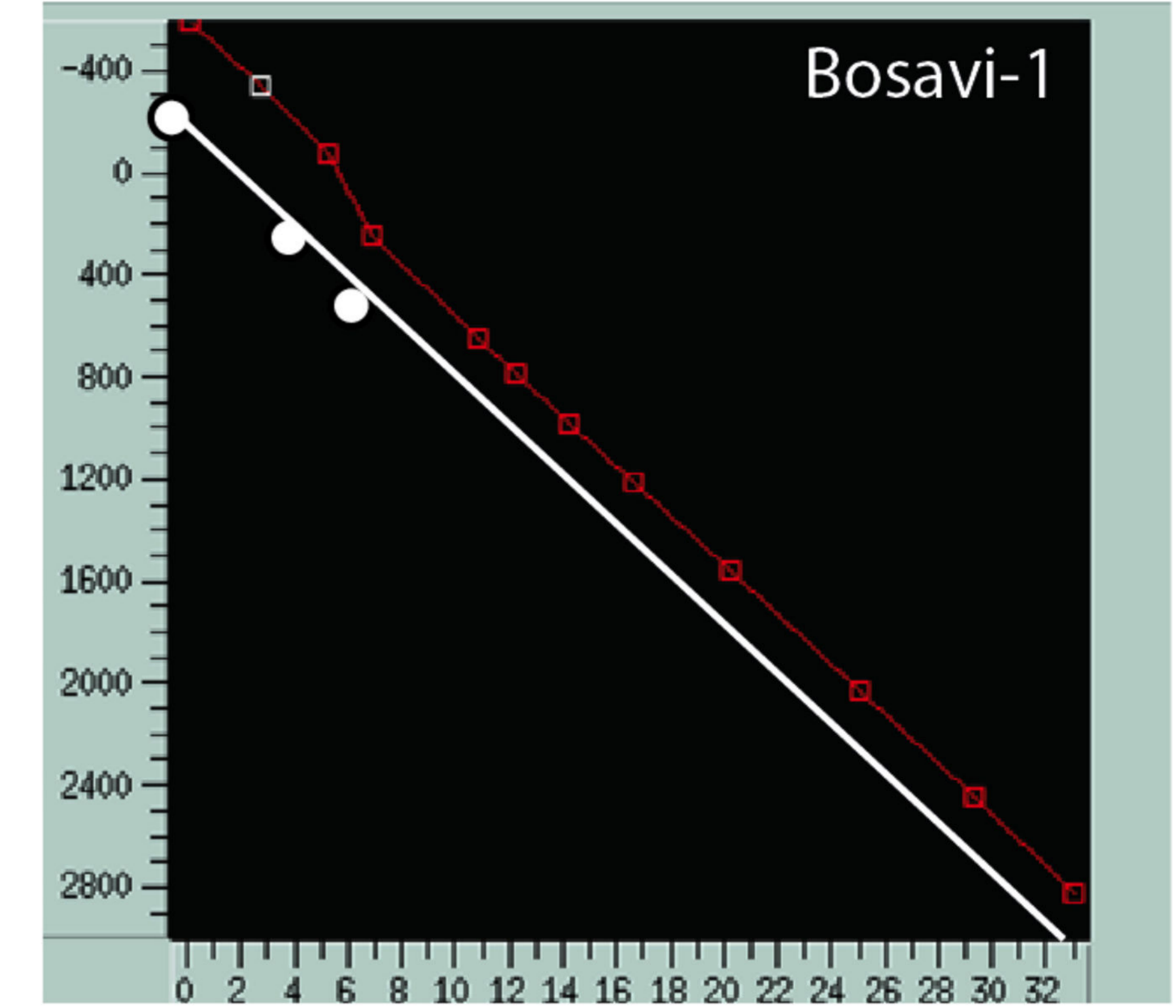
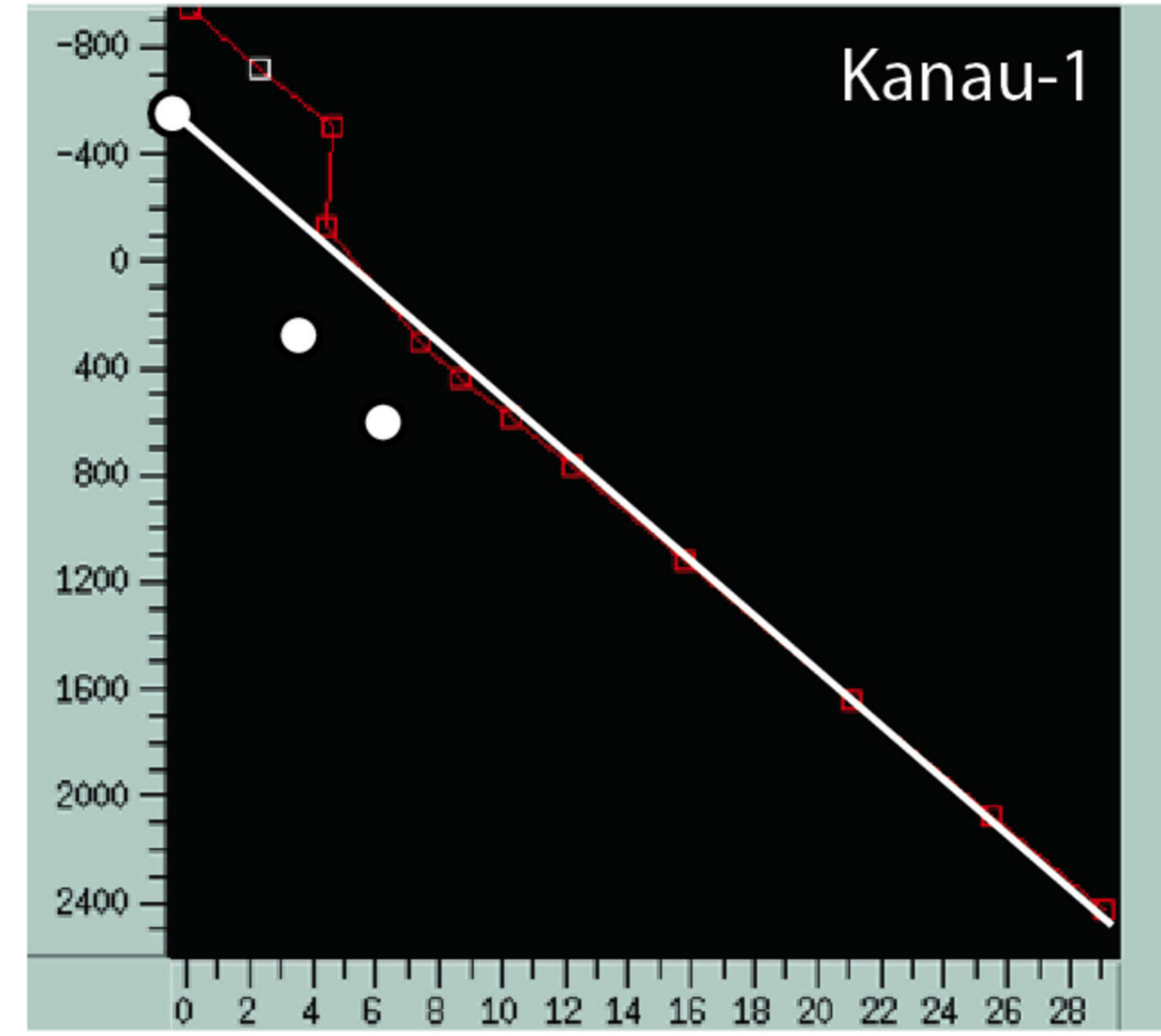
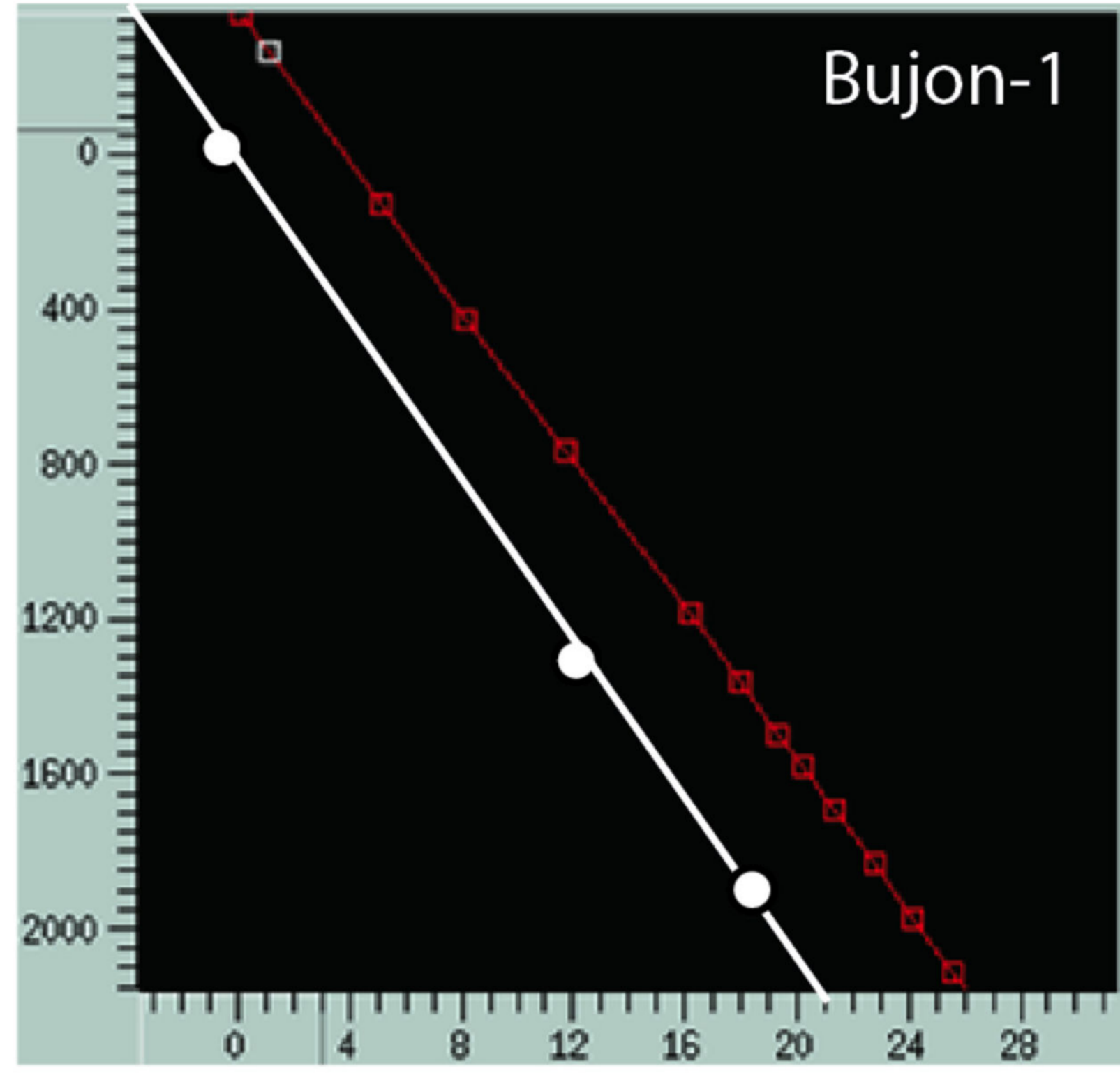




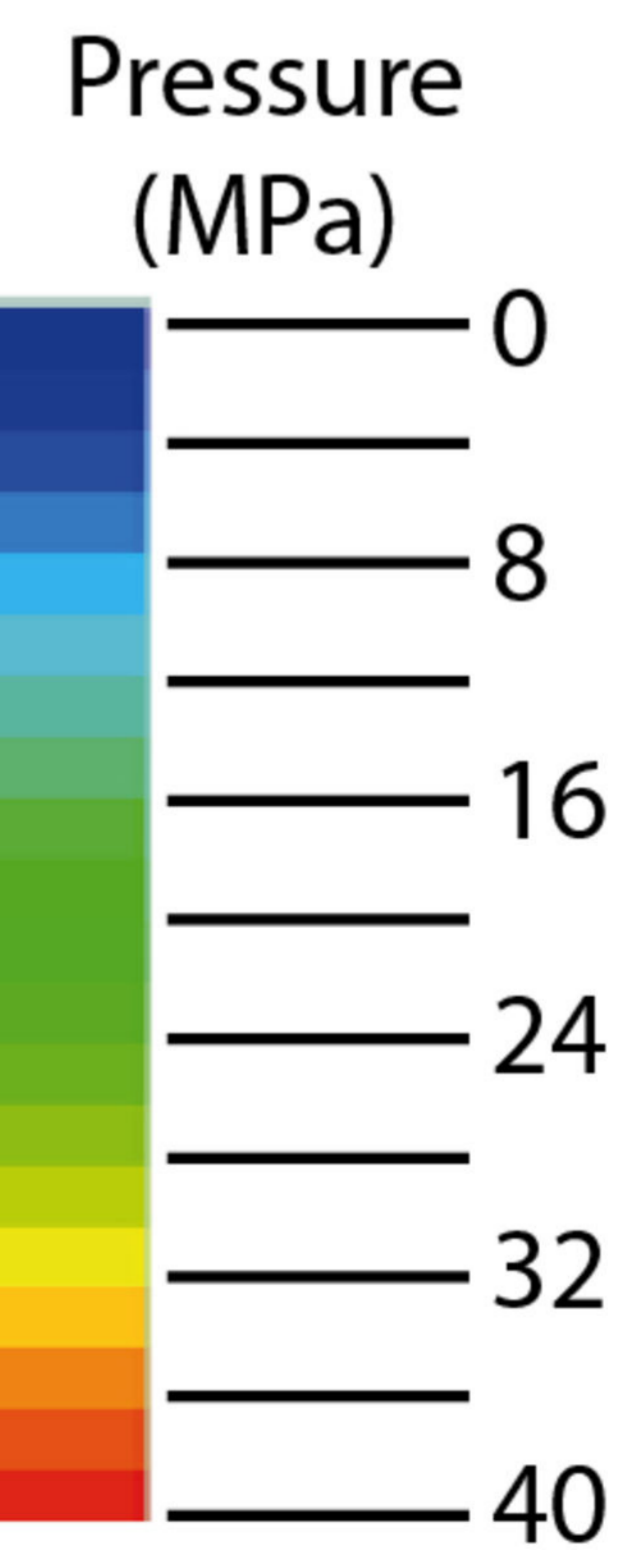
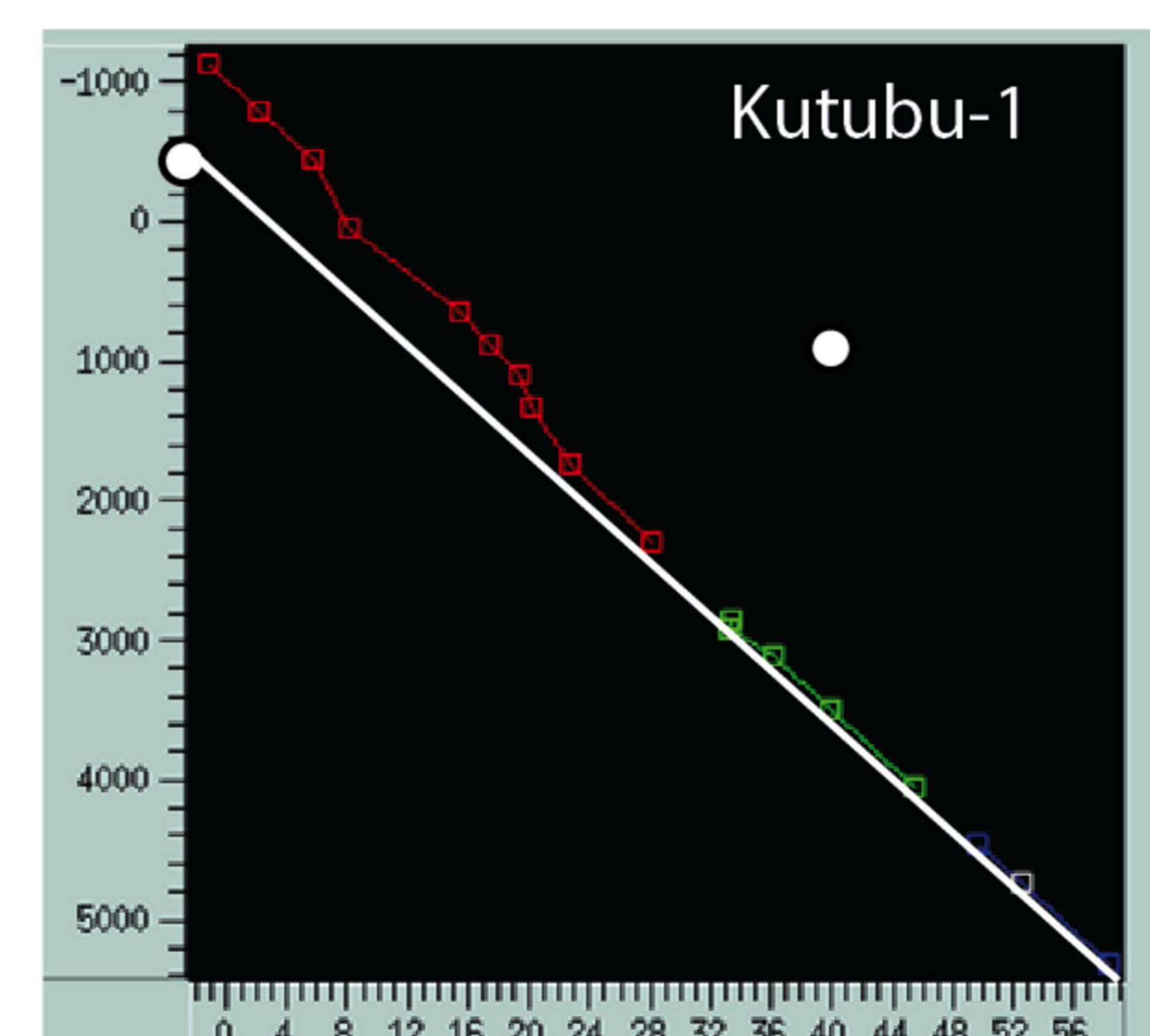
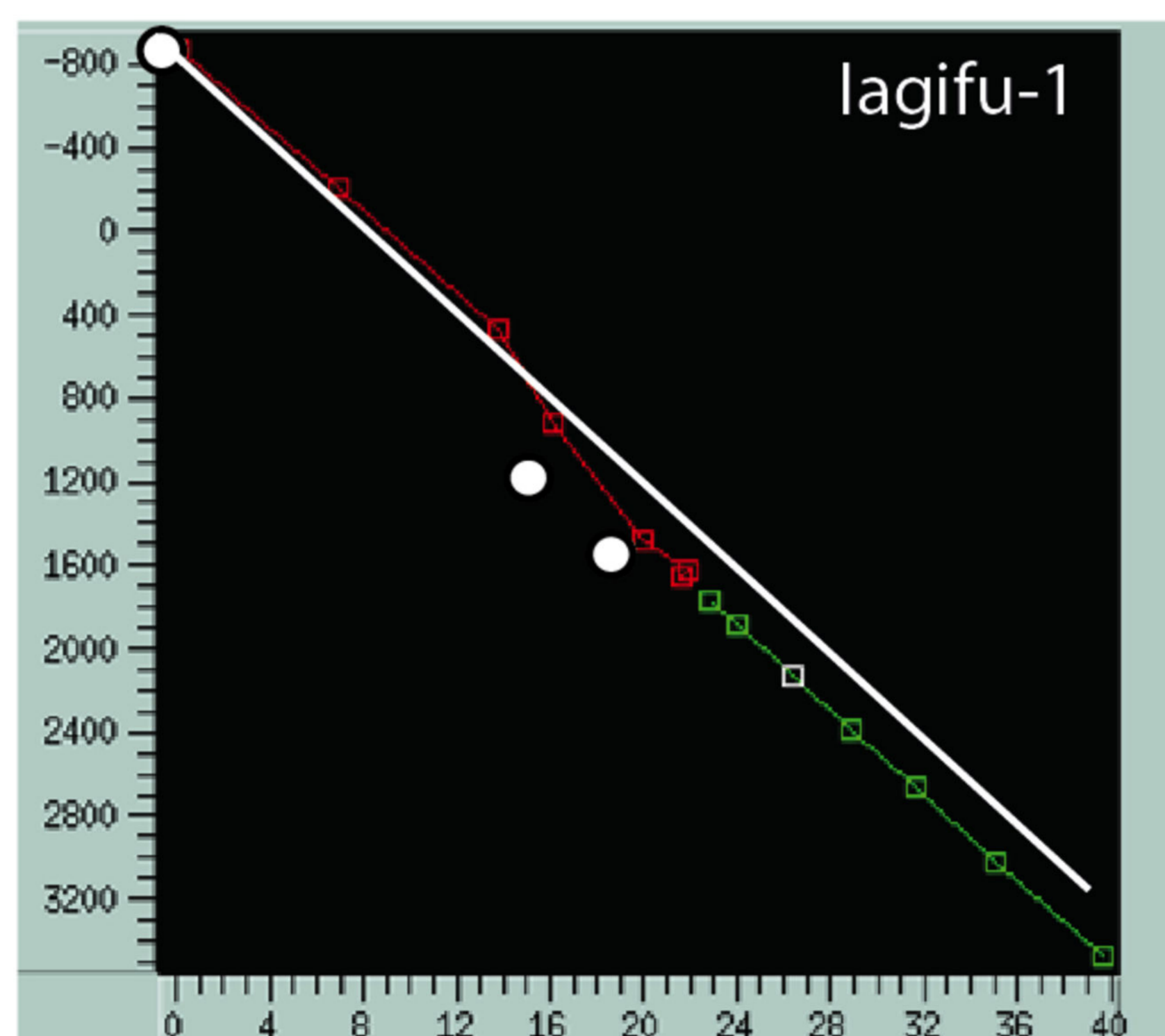
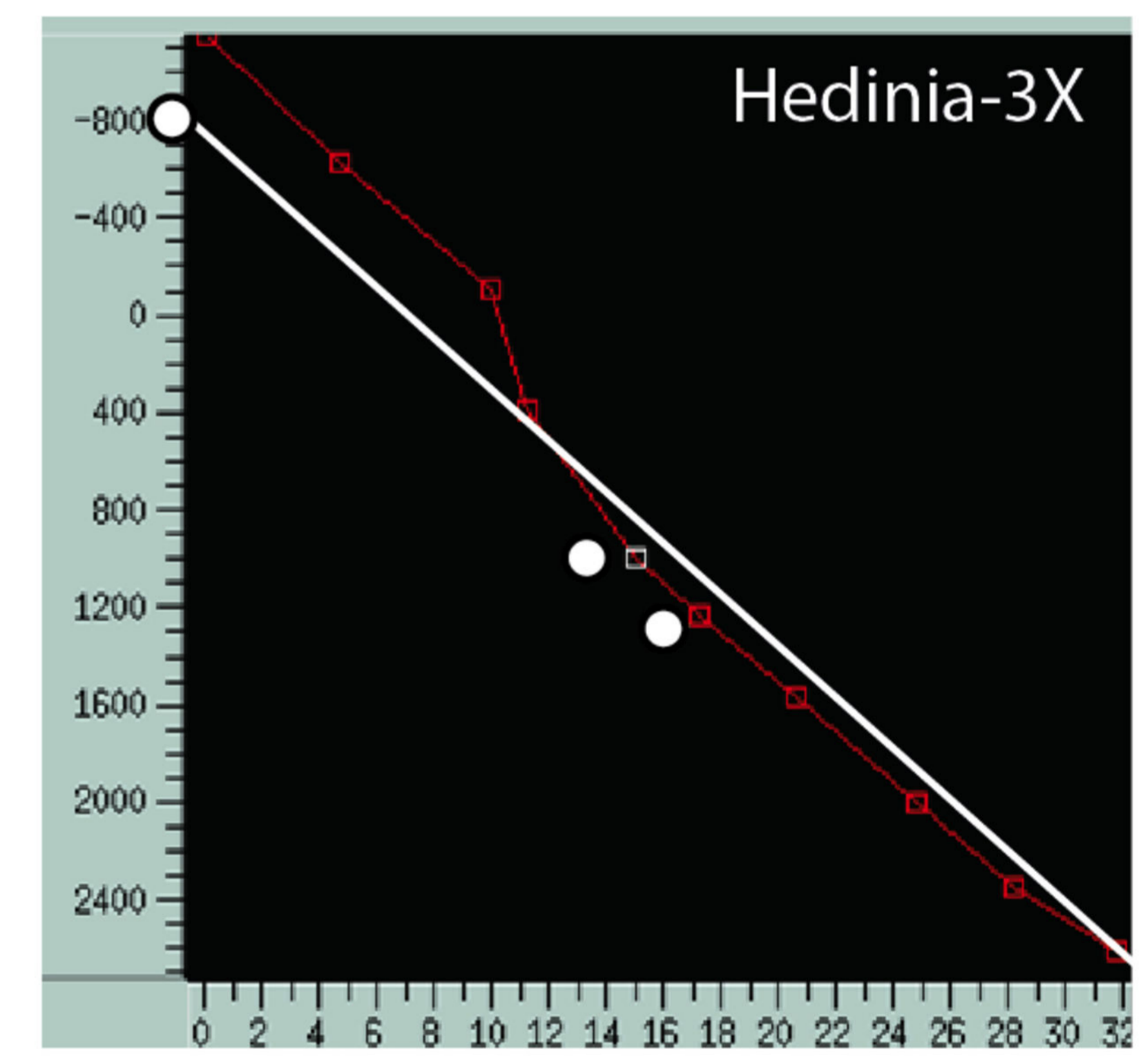
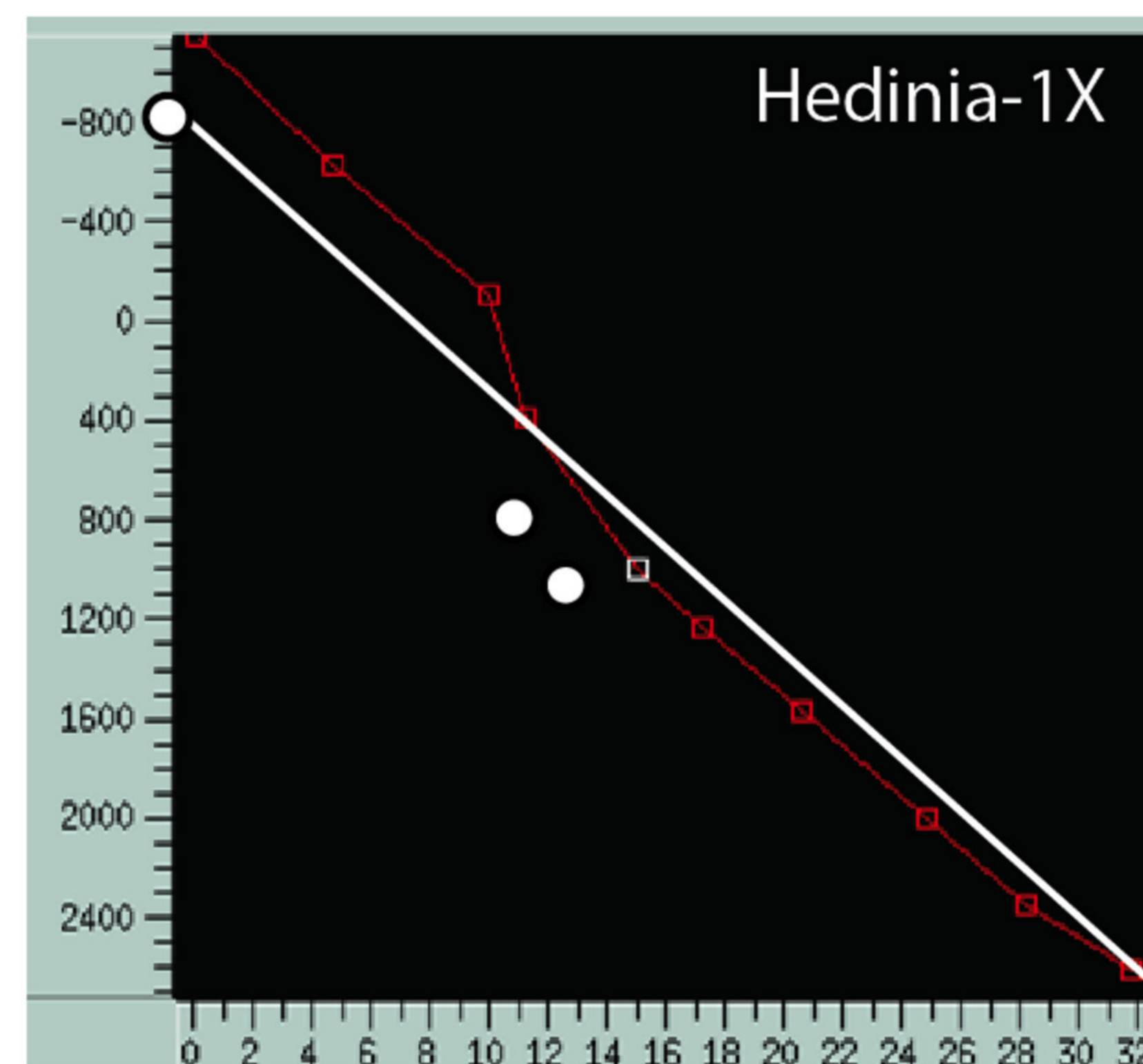
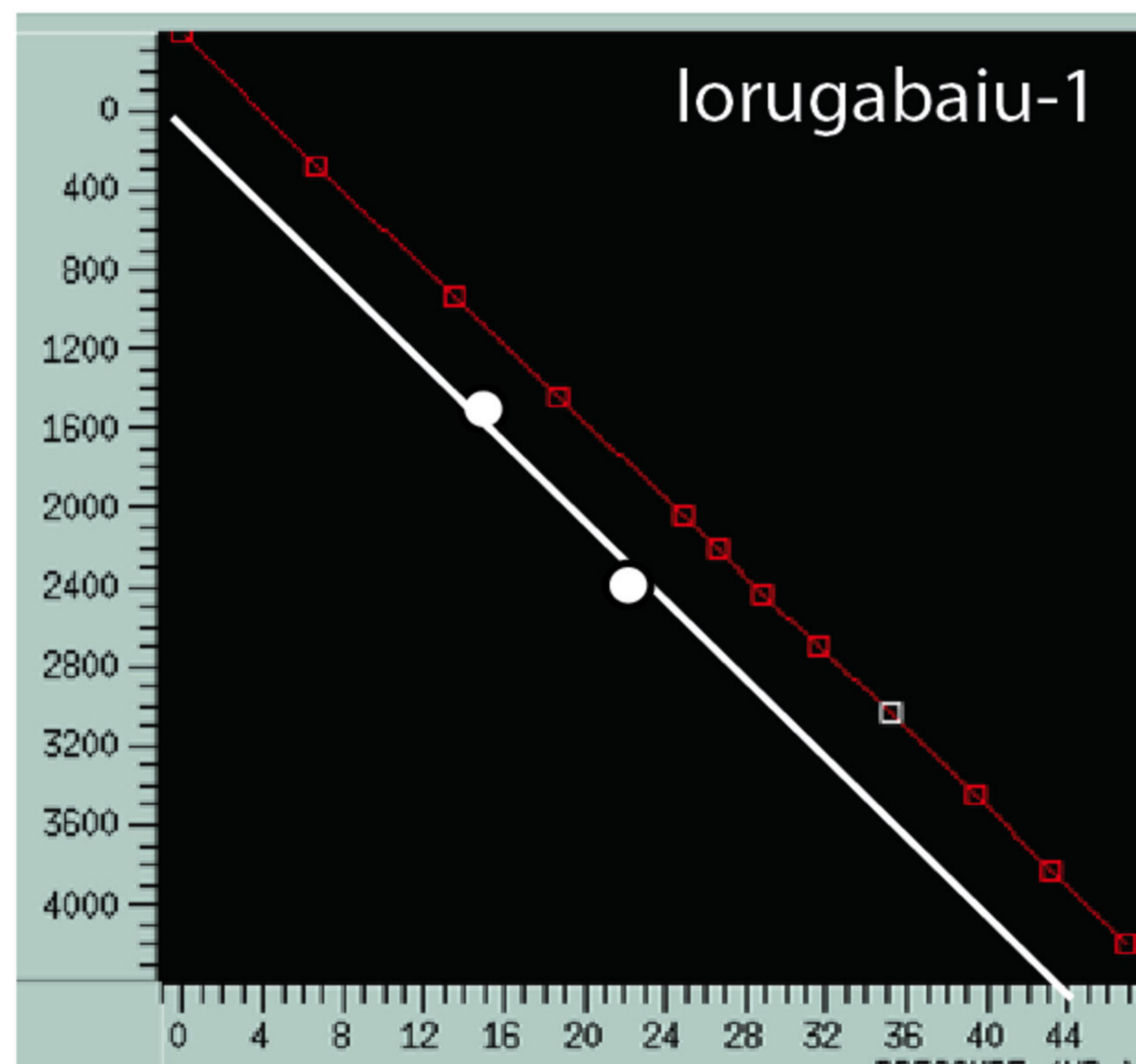
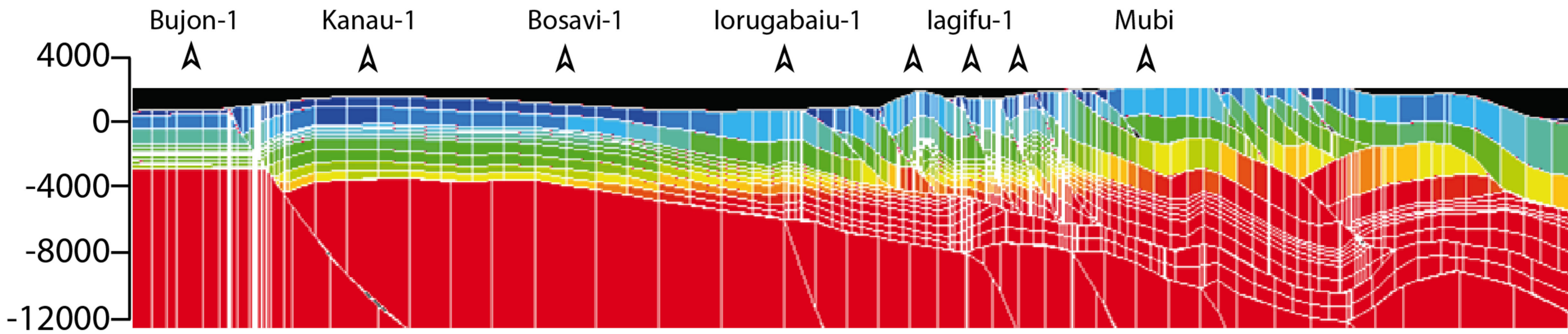








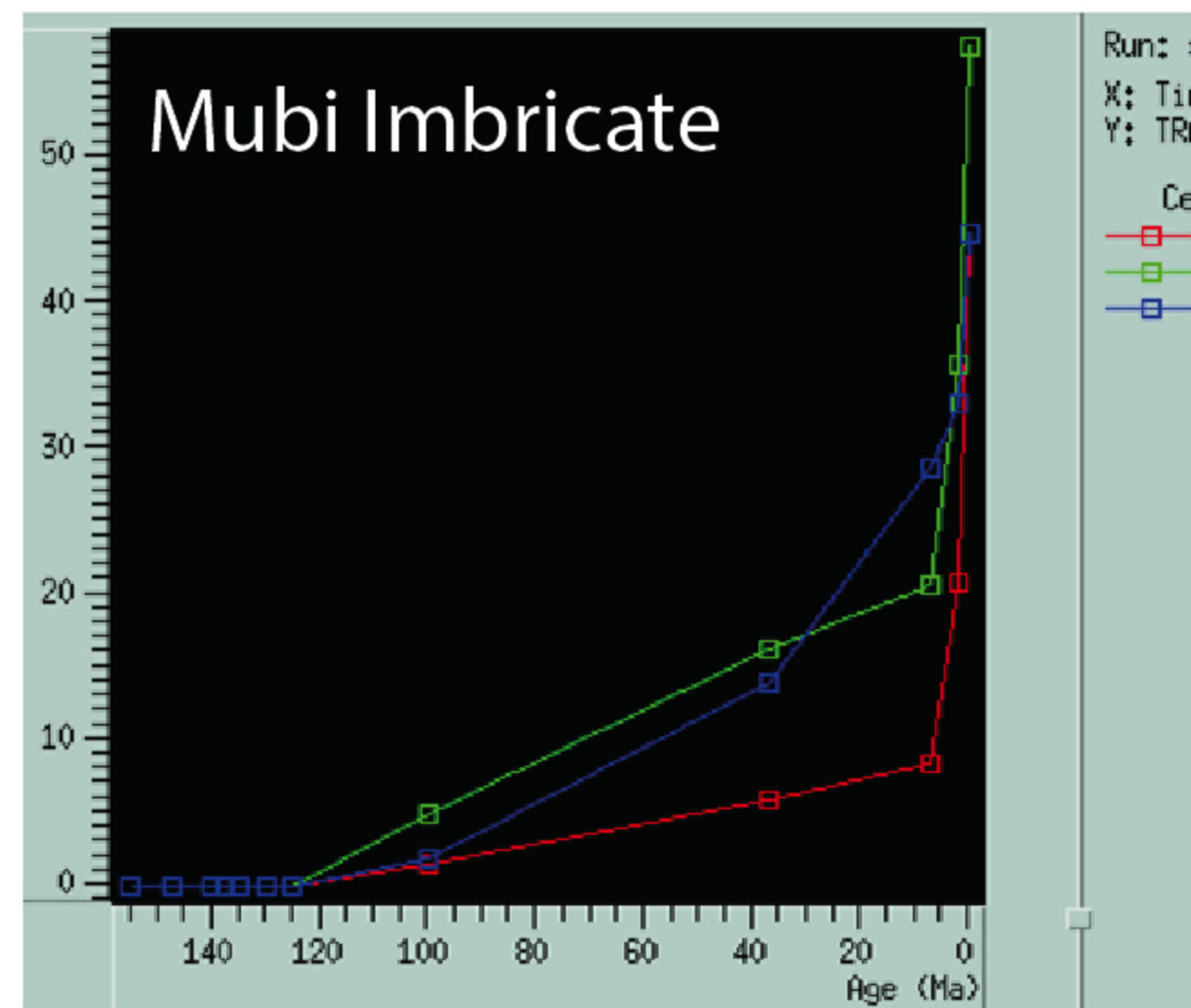
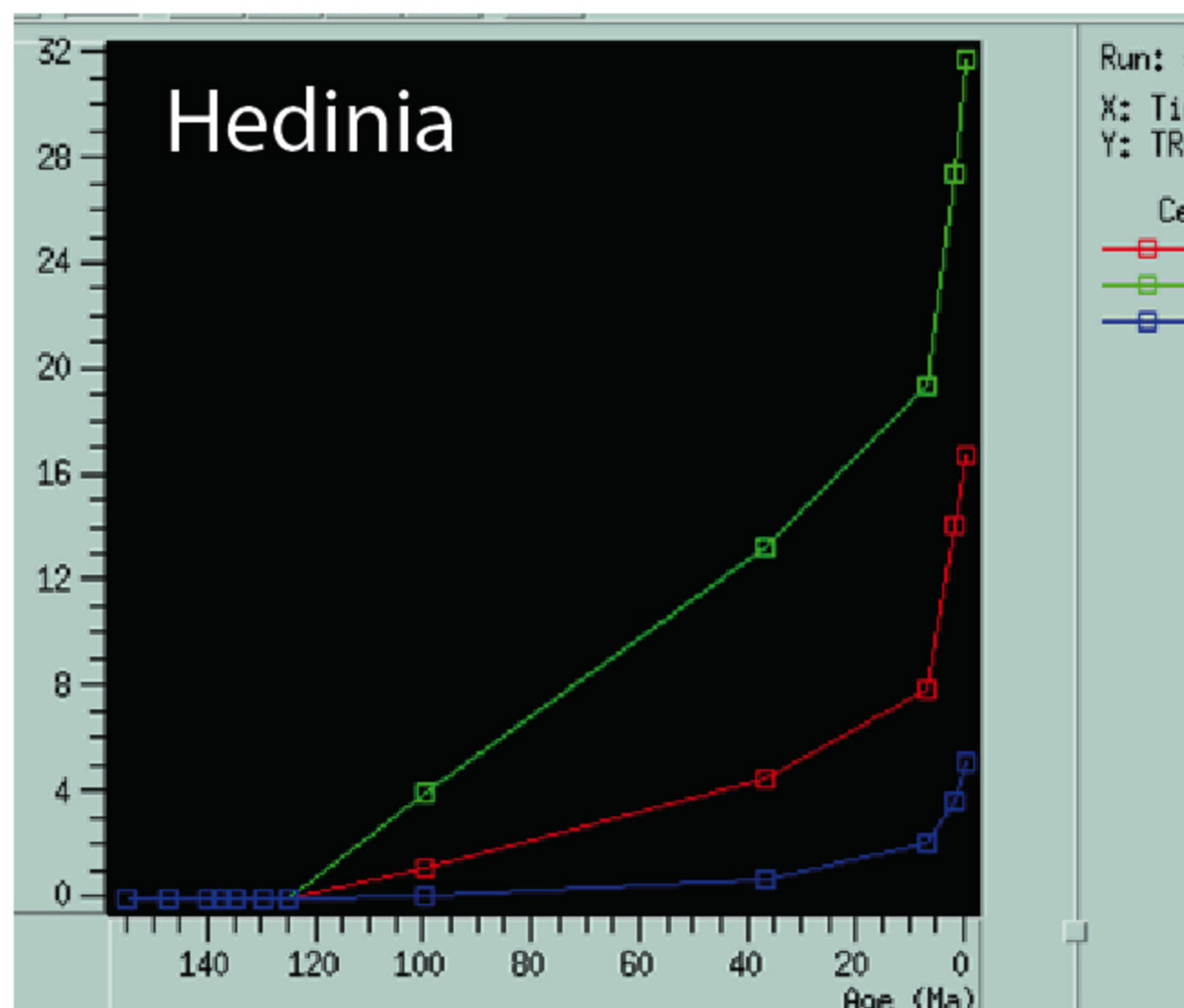
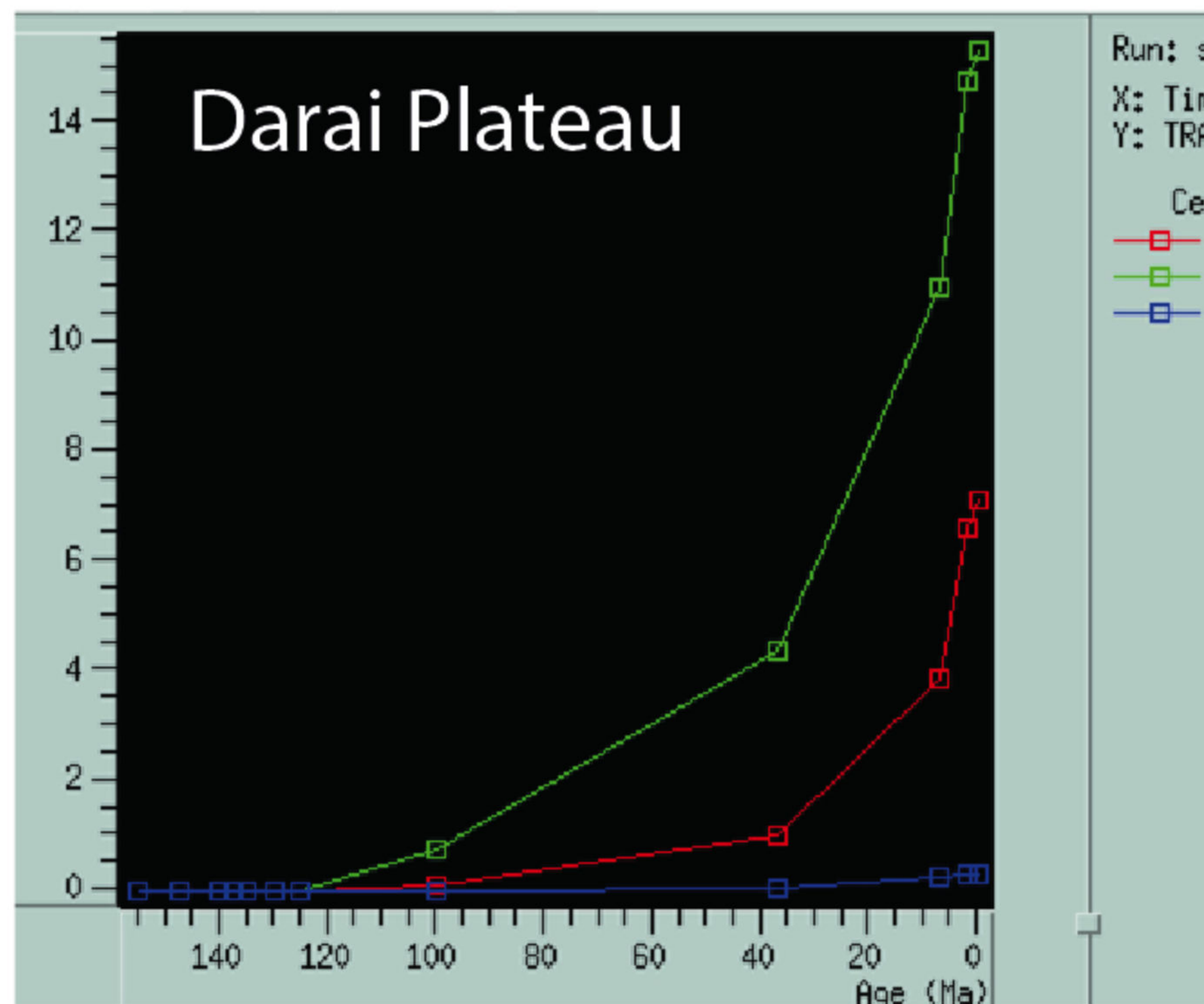
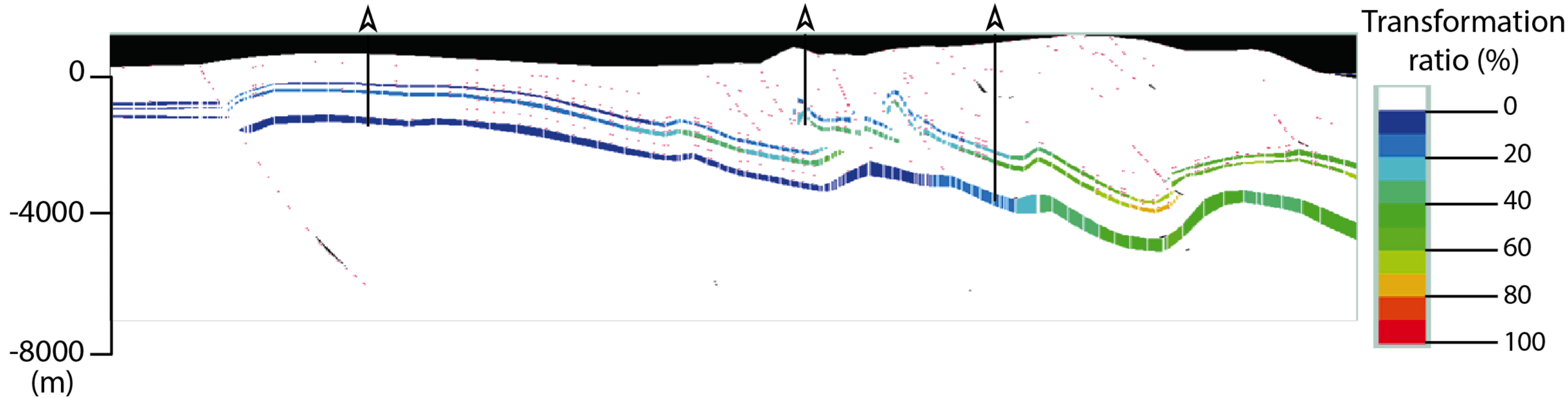
Hedinia Kutubu
1X-3X 1-2



Darai Plateau

Hedinia

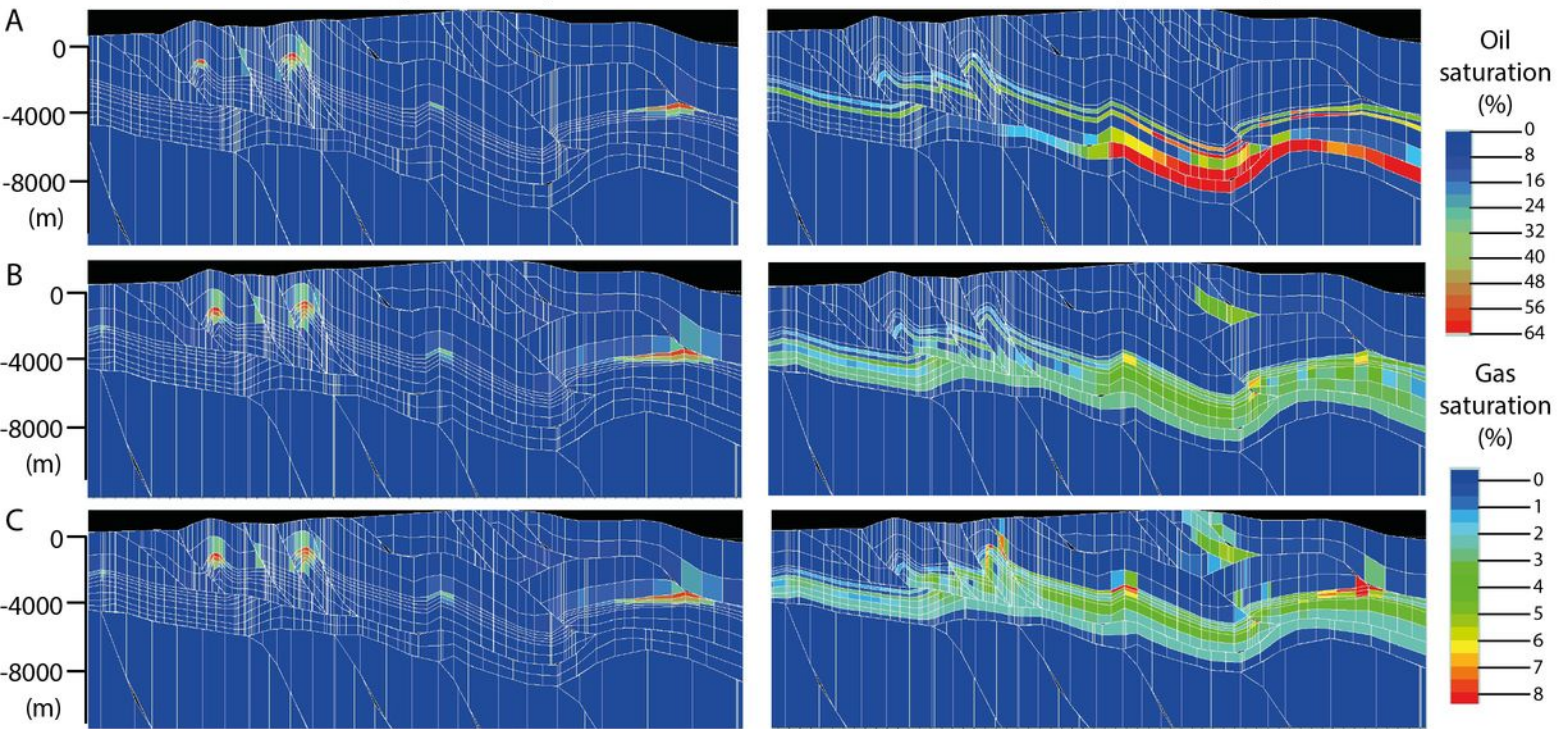
Mubi Imbricate

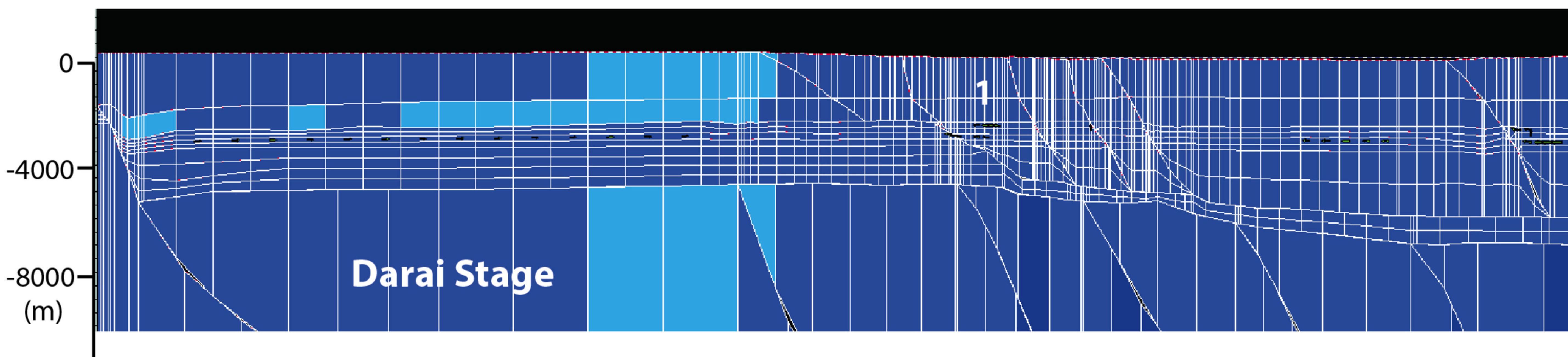
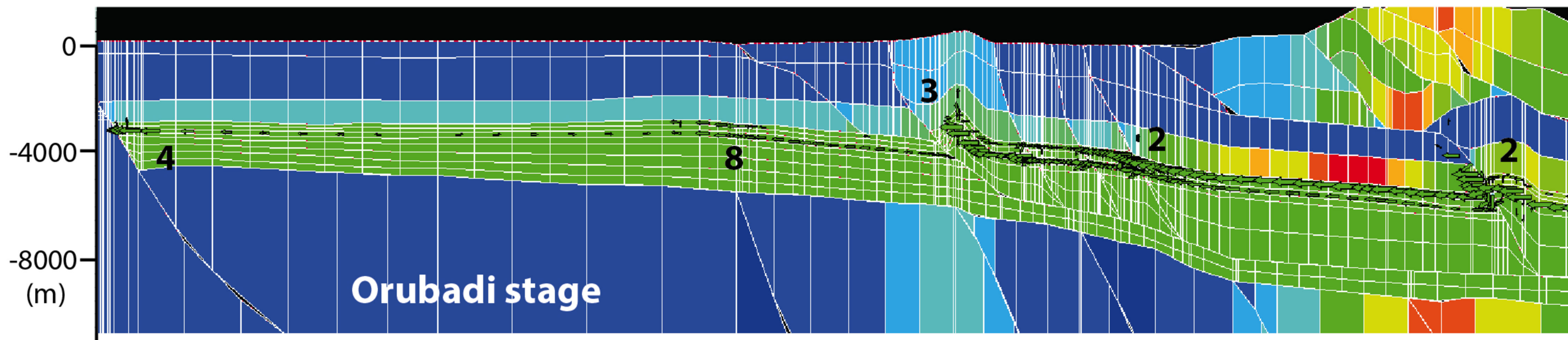
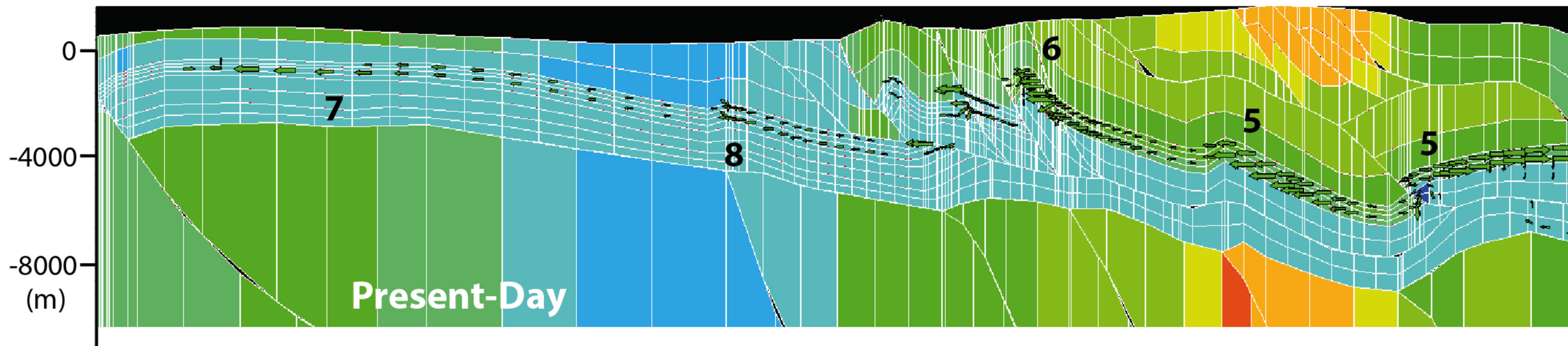


- 1
- 2
- 3

Oil Saturation, present-day

Gas Saturation, present-day





Hydraulic head (MPa)

