Maximizing Recovery from Unconventional Resources Requires More Than Conventional Knowledge

Answers for Unconventional Resources

DeGolyer and MacNaughton (D&M) offers a diverse range of services supporting the evaluation and development of unconventional resources. In addition, the firm provides support in the design of reservoir testing programs that can guide development plans. Finally, the firm is able to conduct economic evaluations and estimate resources and reserves for these unconventional reservoirs. D&M also offers training courses that cover all of these activities.

The following list illustrates some of the technical capabilities D&M offers for unconventional reservoirs:

- Expertise in reservoir characterization (geological, geophysical, petrophysical, and engineering evaluations)
- Assistance with planning and implementation of coring and core-analysis programs, including the interpretation of data and integration with petrophysical and production/well-test information
- Insights regarding basin potential, applicability of the most cost-effective emerging enhanced recovery practices
- Field development support (geocellular modeling, well performance analysis, reservoir simulation, etc.)
- Integrated studies/reservoir modeling

The estimation of resources requires an understanding of the parameters controlling gas in place and production, together with the knowledge of how these vary across a given area, and the impact of factors such as drilling and completion practices on ultimate recovery. D&M uses both deterministic and probabilistic approaches for this work, in accordance with industry standards.

D&M has extensive experience with unconventional resources:

Shale gas and shale oil
In the United States: Bakken, Barnett, Bone Springs, Eagle Ford, Fayetteville, Haynesville, Horn River, Marcellus, Montney, Niobrara, Spraberry, Wolfcamp, and Woodford shales
Internationally: Algeria, Argentina, Australia, Brazil, Colombia, Europe, Kuwait, and Russia

Tight oil and tight gas
In the United States: Delaware, Granite Wash, Green River, Gulf Coast, Mississippi Lime, Permian, Piceance, San Juan, and Val Verde Basins
Internationally: Algeria, Australia, Brazil, China, Kuwait, and the Ukraine

Coal seam gas
In the United States: Appalachian, Arkoma, Black Warrior, Cahaba, Cherokee, Powder River, Raton, and San Juan Basins
Internationally: Australia, China, England, Europe, and the Ukraine

Training and Workshops

D&M regularly provides industry training and workshops on unconventional reservoirs. Through these programs, D&M has helped many clients around the globe to develop clearer pictures of how unconventional reservoirs work. D&M offers the following training courses related to unconventional reservoirs:

- Reservoir characterization
- Development planning
- Petrophysical interpretation
- Production analysis and forecasting

Knowledge
D&M employs experienced petroleum engineers, exploration geologists, geophysicists, petrophysicists, and economists to support its work in analyzing and estimating reserves and development recovery strategies for unconventional reservoirs.

Integrity
Through training programs and engagements in major projects, the firm has helped hundreds of clients around the globe develop clearer pictures of how unconventional reservoirs work.

Service
D&M provides guidance to help clients develop the most effective development and recovery plans, from first wells to enhanced recovery.

Support
D&M's personnel travel around the world to provide one-on-one support to clients, and D&M staff are readily available for conference-call consultations.

Advanced Technology
D&M has made significant investments in computing resources and software development to deliver the answers that clients need.

Solutions
D&M offers a wide range of services to help clients appraise, evaluate the potential of, and improve access to unconventional reservoirs.

DeGolyer and MacNaughton

Reservoir Characterization

Geological Analysis

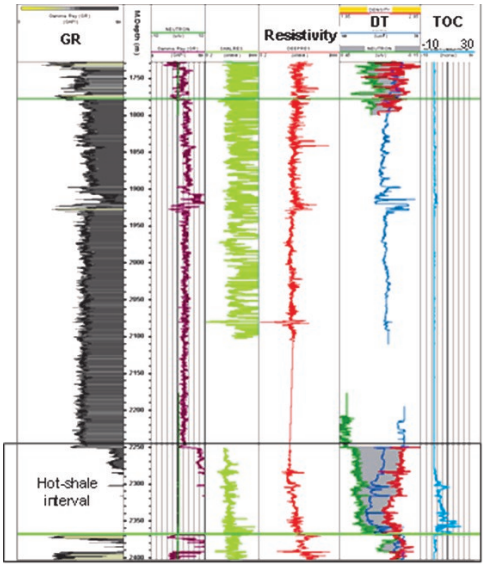
The D&M geological assessment of organic-rich shale and tight sandstone intervals is a part of the collaborative studies with geophysics, petrophysics, and geochemistry. The primary objectives of the geological studies that are performed on wells around the world are to determined hydrocarbon intervals by the following:

- Sedimentological analysis of core and core-cuttings
- Biostratigraphic evaluation of available biodata (nannofossils, microfossils and macrofossils)
- Sequence stratigraphy, sequence biostratigraphy, and seismic stratigraphy
- Facies modeling
- Structural modeling
- Property modeling
- Burial history modeling
- 3-D geocellular modeling

The geocellular modeling is implemented to capture the geological and petrophysical characteristics of these hydrocarbon reservoirs by integrating the seismic, petrophysical, sedimentological, and stratigraphic data. The development of the geocellular model follows a standard workflow that includes stratigraphic and structural modeling and property distribution of the TOC values.

The resulting geological work is a key input for other project disciplines because it captures the following:

- Target intervals
- Size of the area for OGIP calculations
- Interval thickness for OGIP calculations
- Lateral and vertical variations in reservoir quality
- Regionwide estimates of OGIP through geocellular modeling



Silurian hot shale interval and TOC range depicted by well-log signature

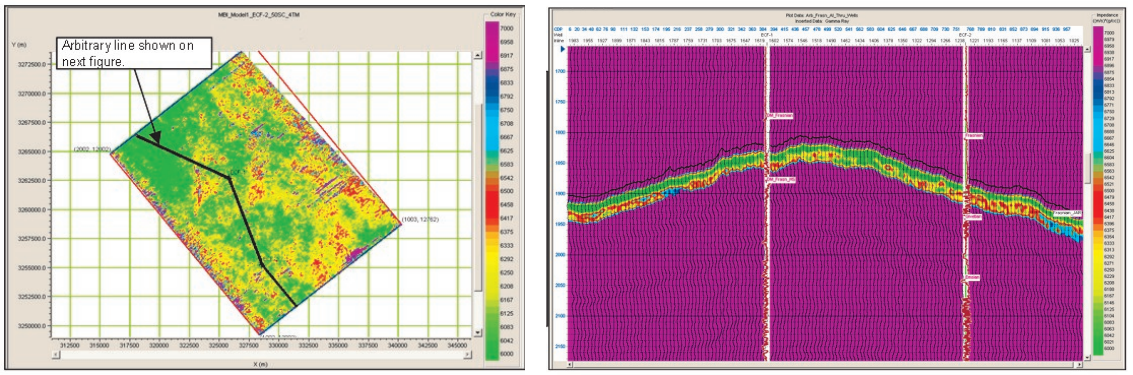
Geophysics

The D&M unconventional hydrocarbon reservoirs studies are enhanced by including geophysics. In collaborative work with geology, petrophysics, and geochemistry, D&M geophysics teams have performed detailed studies that documented the distribution, gas in place, and reservoir potential of the Mesozoic (Cretaceous) and Paleozoic (mainly Silurian and Devonian) organic-rich shales and tight sandstones in the United States and North Africa. Thousands of 2–D lines and multiple 3–D seismic data volumes were used in tracing key shale intervals through the regions, and seismic attributes were used to identify favorable well locations. The conducted geophysical work was useful in understanding the character of the targeted shale intervals and the determination of proposed well locations, as well as guiding the exploration and appraisal programs.

The primary objectives of a geophysical study are as follows:

- Determining regional structural control:
  - To provide structural surfaces for the organic-rich shale and tight sandstone intervals for use in the estimation of original gas in place (OGIP), and to identify areas within the prospective depth range for proposed wells
  - To provide structural surfaces for the burial history modeling
  - To define the well target window
  - To interpret faults and identify fracture zones
  - To extract both structural and stratigraphic information that are required to map properties away from the well
  - To determine mechanical properties from seismic attributes
  - To identify areas of higher total organic content (TOC), higher porosity, or a combination of both through lithostratigraphic attributes

The seismic data are used to identify sweet spots and specific well locations using a combination of the structural interpretation and seismic attributes.



Section of AI for Frasnian Shale

Geochemical Analysis

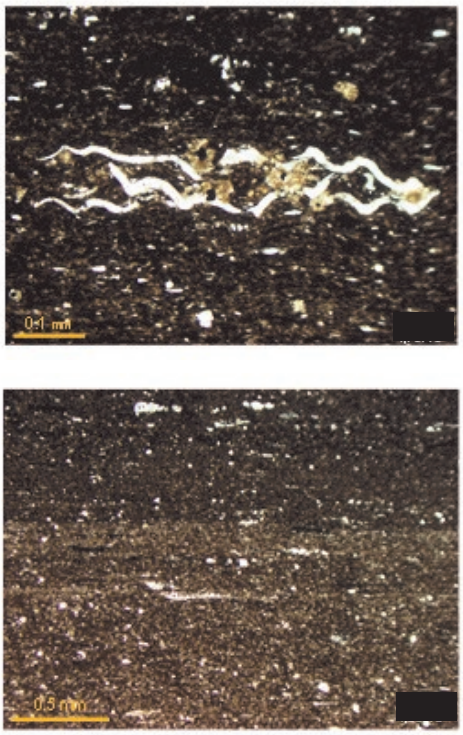
The ability of a potential shale reservoir to generate, store, and produce hydrocarbons is a function of the shale's geochemical and geomechanical properties. In an exploration setting, any evaluation of a potential shale reservoir by wireline log and seismic data response should be calibrated by a sample-based analytical program. Preferred samples are from conventional cores, preferably spanning the entire interval of interests, although cuttings can yield valuable data as well. The geochemical analysis of a potential shale reservoir provides a reliable basis for estimation of the quantity and quality of organic material. These factors, related to the type, abundance, and thermal maturity of the kerogen in the shales, have a significant impact on the hydrocarbon storage and flow capacity of the shale interval. The objectives of a geochemical study include:

- Calibration of the wireline log analysis of TOC and sorbed gas content using geochemical properties obtained from core
- Provision of a regional perspective and geologic rationale for observed variations in shale reservoir quality (thickness, mineralogy, organic richness, thermal maturity)
- Improved understanding of geochemical uncertainties by sensitivity testing basin models of hydrocarbon generation and expulsion

During the early stages of assessing the unconventional reservoir potential of a new basin, the availability of geochemical data is usually very limited. Where possible, it is very useful to sample and analyze legacy core material to determine key geochemical parameters. Parameters of interest include: sample measured depth, type (cuttings or core), lithology, stratigraphic age, TOC, and carbonate content. Standard geochemical tests include programmed pyrolysis (RockEval) to assess the hydrocarbon content, remaining hydrocarbon generation potential, and the thermal maturity of the kerogen in the samples.

In addition to the geochemical characterization of the samples, routine modern core analysis of unconventional reservoir rocks includes petrophysical properties (porosity, permeability, bulk, and gain densities) and mineralogy (x-ray diffraction, thin section petrography), as well as a range of geomechanical tests. D&M has considerable experience in the planning and supervision of core analytical programs for unconventional reservoirs.

Burial history modeling, based on individual wells and of an entire basin, is a very useful tool for quantifying the characteristics and the uncertainty of hydrocarbon generation in organic-rich shales. The emphasis is on *capturing the natural variability of the source rock intervals and on assessing the potential impact of sig*nificant uncertainties in model input parameters on the volume and distribution of hydrocarbons in the potential shale reservoirs.



Photomicrographs of organic-rich Frasnian Shale samples.

Petrophysical Analysis

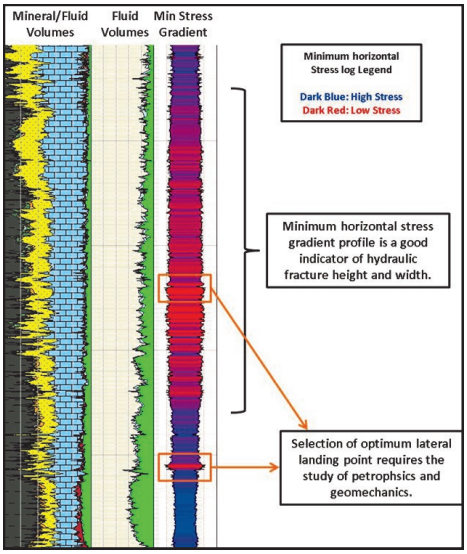
The study of well petrophysics and geomechanics provides a better understanding of production capacity of the potential unconventional reservoirs.

Petrophysics and Wellbore Geomechanics

The main objective of a petrophysical analysis is to assess hydrocarbon volumes. Due to nano-pore scale characteristics of shale oil/gas reservoirs, assessment of clay types and clay volumes are essential to calculation of porosity and water saturation. Wellbore geomechanics study combined with petrophysics significantly aid in the design of hydraulic fracture and selection of horizontal well lateral landing point.

Well-Log Analysis/Petrophysical Interpretation

The tasks performed for petrophysical interpretation of unconventional reservoirs:

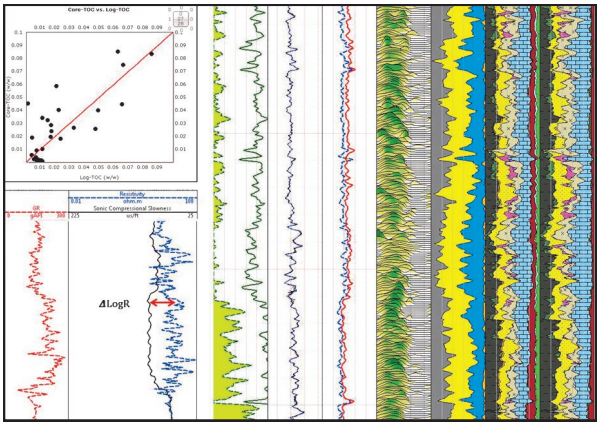


- Computation of total organic carbon content for logs, via application of deterministic and/or probabilistic methods.
- Building a multi-mineral model, using all available logs (conventional and advanced logs) as input for the model.
- Verification of the lithology from the multi-mineral model and rock petrophysical properties with core data.
- Application of the multi-mineral model to the field.

***Wellbore Geomechanics Analysis*:**

A generic well geomechanics analysis provides the following:

- Development of a minimum horizontal stress profile using advanced dipole sonic density logs.
- Calibration of geomechanical data from logs to static geomechanical tests from core or dynamic data from formation fracturing tests.
- Investigation of hydraulic fracture propagation based on fracture initiation interval.
- Selection of horizontal lateral landing point based on formation petrophysical and geomechanical rock properties.
- Design of optimum hydraulic fracture stages based on well stress profile and rock petrophysical properties (application for horizontal well).



Experience

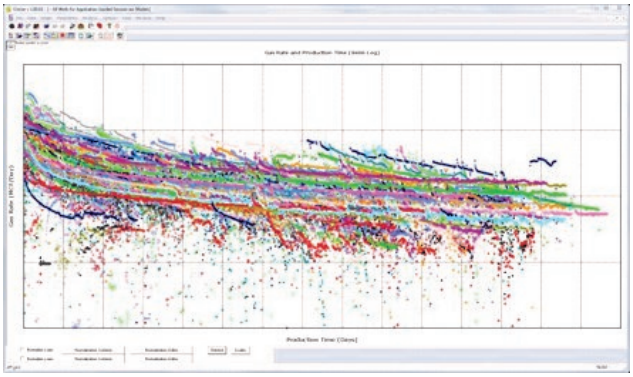
The following are select examples of recent petrophysical studies of unconventional reservoirs performed at D&M.

2016-2017	Petrophysical analysis and wellbore geomechanic study and completion design – Shale and tight Reservoirs /Middle East
2015	Petrophysical analysis and wellbore geomechanics study—shale gas and tight oil reservoirs in Ordos and Sichuan Basins (China)
2014	Petrophysical analysis and wellbore geomechanics study – Neuquen Basin (Argentina) and Eagle Ford Shale (USA)
2013	Petrophysical analysis – Jurassic Shale/Western Siberia (Russia)
2013	Petrophysical analysis and wellbore geomechanics study – Perth Basin (Australia)
2012	Petrophysical analysis and investigation of wellbore drilling damage through study of wellbore geomechanics – Cooper Basin (Australia)
2011	Petrophysical analysis and wellbore geomechanic study – Potential Shale Reservoirs/ Middle East

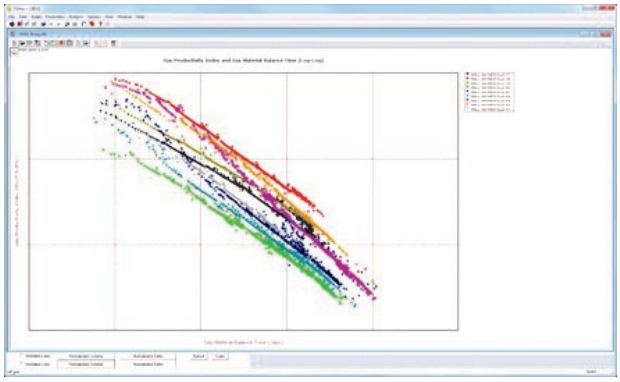
Well Performance Analysis

D&M is a recognized industry leader in the estimation of oil and gas reserves using PRMS, SEC, COGEH, and other reporting standards. D&M uses multiple techniques, including well performance analysis, analytical and numerical modeling, and analogous reservoirs in the estimation role, and D&M has developed software for these purposes. D&M has also collaborated with KAPPA Engineering to create a software solution (Citrine) that can be used for field production analysis.

Citrine permits the rapid load of mass public, client, or simulation sources for the processing of multi-well data. Using visualization, trend identification, and multi-well comparison, the user can fully understand and interpret field performance using diagnostics and decline-curve analysis. An option generates a statistical curve that can then be used as a type well for decline analysis on a wider scale. Citrine can retrieve analytical or numerical forecasts from reservoir simulation software and use them as a seed for multi-well analysis and forecast.



Example Citrine Project: Wells from Unconventional plays in North America: Gas rate vs Production Time semi-log plot



Example Diagnostic Plot: Wells from Unconventional plays in North America -- Gas productivity index and gas material-balance time plot

Experience

D&M has performed the following global well performance analysis studies.

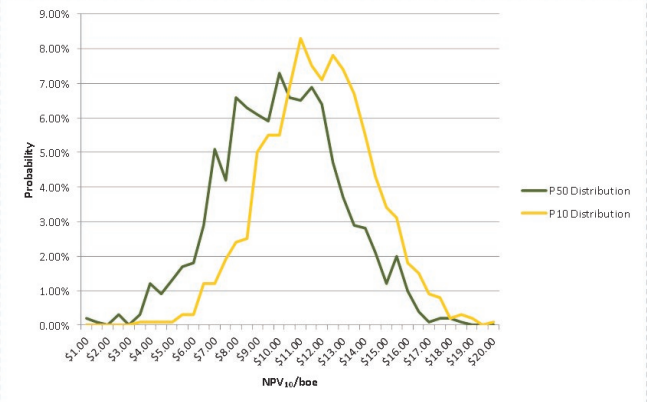
2016	Performance-based reservoir characterization: tight gas field, Neuquen Basin (Argentina)
2016	Evaluation of a specific proppant technology on well performance using a model-based analysis in Bakken, Eagle Ford, Utica and Niobrara plays (USA)
2016	Petrophysics, well-performance analysis, and numerical simulation of field development, Eagle Ford
2016	Due diligence and well performance analysis in Wolfcamp play: Midland and Delaware Basins (USA)
2015	Reservoir modeling, well performance analysis, completion optimization and field development—Sichuan and Ordos Basins (China)
2015	Well performance analysis, completion optimization and field development—liquid-rich Eagle Ford Shale gas condensate/volatile oil window
2015	Probabilistic assessment of well spacing and its impact on reserves—liquid-rich Eagle Ford Shale oil window
2014	Well performance analysis and reservoir modeling—Neuquen Basin (Argentina) and Eagle Ford Shale
2013	Well performance analysis and modeling—Marcellus Shale (USA)
2013	Field performance analysis and reservoir modeling—Eagle Ford Shale
2012	Well performance analysis and modeling—Cooper Basin (Australia)
2011	Well performance analysis and modeling—Haynesville Shale (USA) Montney Formation (Canada)

Prospective Resources

D&M is an industry leader in the evaluation of prospective resources for both conventional and unconventional reservoirs. D&M's experience in the valuation of prospective resources is recognized by large international exploration firms, national oil companies, and financial institutions. It has quantified the values and the geologic and/or economic chance factors and volumetric uncertainties associated with the probabilistic estimation of thousands of potential hydrocarbon volumes in more than 100 countries. These analyses have varied in scope from large portfolio-level appraisals encompassing many countries and basins, to volumetric estimates of prospects in one license block. Moreover, the firm has made presentations and seminars to explorationists, national oil companies, and investors around the world.

Critical to these types of analyses is the objective quantification of the various geologic chance factors (trap, reservoir, migration, and source) and range of volumetric uncertainty. Moreover, an understanding of the engineering and economic chance factors is crucial to developing an integrated analysis that is consistent with the PRMS and NI 51-101 guidelines.

D&M evaluates prospective resources using a fully integrated, probabilistic methodology that begins with a rigorous, independent review of technical data and analogous fields. Potential production profiles associated with prospective resources are subsequently generated through D&M's proprietary software SYPHER following probabilistic volumetric analysis. Economic modeling of each prospective reservoir incorporates various economic factors and development practices based on the potential probabilistic resources quantities estimated.



An Integrated Methodology

D&M's geologic interpretation is fully integrated and probabilistically modeled. Each individual volumetric parameter is investigated using a probabilistic approach with attention to variability. The volumetric parameter variability is based on the structural and stratigraphic un-certainties due to the depositional environment and quality of the seismic data. Analog field data are statistically incorporated to derive uncertainty limits and constraints on the net pore volume. Uncertainty associated with the depth conversion, seismic interpretation, gross sand thickness mapping, and net hydrocarbon thickness interpretations are also derived from studies of analogous reservoirs, multiple interpretative scenarios, and sensitivity analyses.

Statistical measures describing the probability distributions are input to a Monte Carlo simulator to produce low , best, high, and mean estimate prospective resources for each prospect. These estimates represent the volumetric uncertainty associated with each reservoir. The probability of geological success is estimated by quantifying the probability of each of the following individual geologic factors: trap, source, reservoir, and migration. The product of these four probabilities is computed as P_g.

Integrated Studies/Reservoir Modeling

Integrated reservoir simulation studies can be used to more clearly characterize reservoir behavior and identify strategies to optimize recovery. Integrated studies accumulate the knowledge gained from individual geoscientific analyses to create a comprehensive view of the drive mechanisms and hydrocarbon properties. D&M is able to apply specific disciplines to help clients with pre-drilling exploration work and post-drilling development work.

The workflow employed by D&M for the evaluation of unconventional resources places a strong emphasis on the integration of the petrophysical, mineralogical, geochemical, and geomechanical characteristics of the reservoir interval, supplemented by an extensive internal database of analog field examples, to develop a consistent picture of in-place volumes, sweet-spot distribution, and well-performance models that can ultimately serve to guide economic forecasts.

For example, in 2013 D&M completed a three-phase study covering multiple fields in Algeria. Phase I included a fast-track approach to perform the geophysical, geological, and petrophysical analyses to estimate the OGIP of the Lower Devonian and the Ordovician Formations. Phase II included model construction and simulations for the southern region of the area being studied. Phase III was dedicated to model construction and simulations for the fields in the northern region of the asset. The results from D&M gave the operator a clearer understanding of how to continue development of the reservoir and how to analyze ongoing production output.

The development of an unconventional reservoir is a capital-intensive learning and optimization process. D&M strongly believes that an important part of any assessment of a potential unconventional play is the development of an appraisal and development plan customized to the expected reservoir characteristics and local operational constraints.

Experience

***Jurassic Shale, Western Siberia*:**
Duration: 10 months

Objective was to estimate shale resources using multiple independent approaches. A basin-modeling approach was also incorporated into the project. The workflow identified sweet-spot locations and estimates of hydrocarbon properties with calibration to evidence in conventional fields.

Assessment of Potential Shale Reservoirs, Middle East
Duration: 2.5 years

This project focused on the assessment of all potential shale oil and gas reservoirs. The project methodology covered a full range of tasks, such as basin modeling, seismic, core description, petrophysics, fluid properties, and modeled recovery. The project also helped identify potential sweet spots and offered an estimation of original hydrocarbon in-place volumes.

Shale Gas and Tight Oil Reservoirs, China
Duration: 12 months

The objectives of these joint projects included evaluation of reserves and resources, performance assessment of horizontal wells with multiple fracture stages, and identification of areas for improvement, such as data collection, completion optimization, fracture stimulation recommendations, field development studies, and knowledge transfer through training courses.

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